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ORIGINAL ARTICLE

The Geoheritage of Mount Ararat and its Vicinity: An Assessment of Geodiversity with a Focus on Glaciation and Mountaineering

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Abstract
Mount Ağrı (Ararat), located at the intersection of Turkey, Iran, and Armenia, is a region of exceptional geodiversity where iconic volcanic and glacial processes converge. In response, this study offers a systematic assessment of the geoheritage of Mount Ararat and its vicinity. By identifying, classifying, and prioritizing its key geosites, it aims to provide a structured knowledge base to support future conservation and sustainable geotourism initiatives. Using Brilha's (2016) methodology, geosite and geomorphosite scores were assessed for sixteen key locations, supported by SWOT analysis, Last Glacial Maximum paleo-ELA estimations, and glacier retreat studies. High scientific and cultural values are evident in preserved glacial landforms, eruptive vents, and archaeological-historical features, while the mountain's global symbolism and mountaineering appeal enhance its geoheritage potential. Strengths include the preservation of rare geomorphology, high geodiversity, and geotourism opportunities. Weaknesses highlight limited research, inadequate infrastructure, and environmental pressures from uncontrolled mountaineering and pack animals, as well as overtourism driven by excessive visitor numbers. Opportunities arise from potential geopark designation, cross-border scientific collaboration, and sustainable tourism initiatives, whereas threats involve climate-driven glacier retreat, natural hazards, and security restrictions in the border zone. The scoring results underline Ahura Valley, Summit Glaciers, and Noah's Ark Site as priority geosites, with high scientific and cultural relevance but varying degradation risks. Overall, this assessment demonstrates that Mount Ağrı offers significant opportunities for integrating geoheritage conservation, scientific research, and sustainable geotourism, provided that management strategies address the identified environmental, political, and safety challenges.

Keywords Geoheritage assessment · Geotourism · Geopark · Glacial tourism · Ağrı dağı - mount ararat

Introduction

Geodiversity, the natural variety of Earth's abiotic components, forms the structural framework of landscapes and ecosystems and underpins geoheritage features of scientific, educational, and cultural value. It encompasses the variety of rocks, minerals, fossils, soils, landforms, and geological processes within a site (Gray 2004). Unlike single features, geodiversity may cover an entire area or region containing numerous geological and geomorphological elements. Geoheritage is defined by the scientific, educational, cultural, and aesthetic values of geodiversity. These values are concretized in specific geosites, which constitute significant geoheritage assets. However, these assets are often at risk, and their degradation would cause the permanent loss of crucial geological information. These geosites include landforms, rocks, minerals, fossils, stratigraphic structures, fault lines, and water and soil properties that possess outstanding scientific, educational, cultural, or aesthetic value and therefore require preservation for future generations (Zouros 2007; Reynard et al. 2007; Gray 2013; Brilha 2016; Coratza et al. 2021; Turoğlu 2025). As an umbrella concept, geoheritage provides the rationale for creating specific protective

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designations, such as geosites or geomonuments, for elements of geodiversity with exceptional value.

Geoheritage status is primarily justified by scientific significance, yet at local scales, other attributes such as cultural, aesthetic, or economic value may be emphasized. Accurately defining the value of sites is therefore crucial for determining the appropriate selection criteria, a point strongly emphasized in the geoheritage literature (Wimbledon et al. 1995; Panizza 2001; Reynard and Panizza 2005; Reynard et al. 2007, 2011; Gray 2008, 2013; Henriques et al. 2011; Brilha 2016; Louz et al. 2023). This awareness fosters appreciation and encourages the sustainable use of geomorphological features, which are recognized as valuable elements worthy of protection, conservation, and transmission to future generations (Reynard 2009; Gordon 2012; Gray 2013; Martin et al. 2014; Coratza and Hoblea 2018).

For effective conservation and management, the accurate classification and assessment of geoheritage units are fundamental (Wimbledon et al. 1995; Reynard 2004a; Prosser et al. 2006; Reynard and Brilha 2018; Dede and Zorlu 2023). Within this framework, a geosite is broadly defined as a locality, area, or territory with particular importance for understanding Earth's scientific history (Wimbledon et al. 1995; Brilha 2016). A geomorphosite constitutes a specific subtype of geosite, distinguished by its focus on geomorphological features that hold scientific, cultural/historical, aesthetic, and/or socio-economic value (Panizza 2001; Reynard 2004b; Reynard and Panizza 2005; Panizza and Mannella, 2007; Santos et al. 2020). Thus, while every geomorphosite is a geosite, the converse is not necessarily true. It is acknowledged that subjective factors can still influence these evaluations (Zouros 2007; Reynard et al. 2016; Suzuki and Takagi 2018; Herrera-Franco et al. 2022).

Beyond their scientific and educational roles, geoheritage and its well-defined sites support socio-economic development through geotourism, which fosters sustainable cultural, economic, and environmental practices (Brilha 2016; Ruban et al. 2021; Khalaf 2024).

In Turkey, the conceptualization of geosites and their defining characteristics are subjects of ongoing study. A prominent definition by Çiftçi and Güngör (2016), based on the ProGeo Group (1998), classifies geosites into ten main scientific categories: stratigraphic, paleoenvironmental, petrological, mineralogical-economic, structural, geomorphological, meteorite-related, plate tectonic-scale, submarine, and historical-cultural. While their core value is scientific, forming the essential components of a Geopark, they may also possess additional aesthetic or cultural-historical value. Complementing this, Turoğlu (2025) emphasizes a holistic geomorphological perspective, defining a geosite as a specific area requiring conservation due to its geological and geomorphological features. These landforms, shaped by various morphodynamic processes across diverse landscapes, are integral to Earth's geodiversity and represent a fundamental component of natural heritage that bridges biotic and abiotic elements.

Glaciers and their associated landforms cirques, moraines, glacial valleys, and roche moutonnées represent exceptional geoheritage features, preserving Earth's geological history and providing crucial evidence of past climate fluctuations. Glaciers function simultaneously as scientific repositories of palaeoclimatic information, open-air educational laboratories, cultural symbols with spiritual meanings, and aesthetic landscapes with high touristic potential (Gordon 2018). Globally, their preservation is increasingly recognized, exemplified by the UNESCO-listed Jungfrau-Aletsch Glacier (Bussard and Reynard 2023). Recent studies highlight the multifaceted significance of glaciers as geoheritage elements, from their scientific rarity and aesthetic value to their cultural role (Comănescu et al., 2011; Irfan et al. 2024). Glaciers have become tourist destinations (Groulx et al. 2017; Salim et al. 2021a, b; Salim 2023) Climate change threatens these features physically, scientifically, and culturally. Glacier retreat reduces opportunities for observation, erases palaeoclimatic records, diminishes local symbolic values, and transforms tourism dynamics as visual and aesthetic appeal declines (Welling et al. 2020; Zekollari et al. 2025; Gerber et al. 2025). Digital and virtual reality (VR) applications may help maintain educational and touristic value even when physical access is limited (Salim 2023; Drinia et al. 2022; Spyrou et al. 2024).

High mountain regions are key intersections of geoheritage, glaciers, and mountaineering. Geotourism should integrate scientific interpretation, using glaciers as indicators of climate change and geomorphological processes, advocating that they be interpreted not only for their scenic qualities but also in terms of underlying processes (Bussard and Reynard 2023). Mountain glaciers located at the outlets of mountain valleys are often characterized by favorable hydrothermal conditions, striking glacial landscapes, and a diverse range of glacial landforms, which together form the basis for mountain glacier tourism a branch of mountain tourism in which glaciers and relics of ancient glaciation serve as the main attractions (Wang et al. 2010). This type of tourism fulfills multiple functions, including recreation, relaxation, physical activity, education, scientific dissemination, environmental awareness, and the cultivation of visitors' appreciation of nature, generally encompassing glacier sightseeing and guided tours (Shijin and Jiao 2013). Mountaineering expeditions can combine recreation and education, demonstrating how adventure tourism coexists with conservation goals. In addition to their geomorphological and glacial significance, mountains in Anatolia have held cultural and spiritual importance for local communities, with traditional beliefs and practices linked to their veneration persisting even after the conversion to religion (Efe et

al. 2014). Integrating scientific culture into mountaineering and mountain tourism is essential for the sustainable transmission of geoheritage values across generations.

While mountain geoheritage studies are well-established for major ranges like the Alps, Andes, and Himalayas, systematic geoheritage assessments of Turkey's high-mountain regions, particularly those integrating glacial landforms, are still emerging. A limited number of pioneering studies have begun to address glacial geoheritage in Turkey (Kaymaz et al. 2020; Zorlu and Dede 2022; Zorlu & Dede 2023). However, this leaves a persistent gap in comprehensive evaluations of complete high-altitude glacial-volcanic geoheritage complexes. Mount Ağrı (Mount Ararat), and its surrounding area is unique for its combination of volcanic and glacial features, epitomizes this gap, as it has not been fully evaluated within an integrated geoheritage and geotourism framework. Previous studies mainly provide geological and geomorphological descriptions without systematically linking geodiversity to geoheritage or human impacts. Recently, with the decline of security issues, tourism and mountaineering have increased, yet their effects on geosites, such as erosion, waste, and uncontrolled routes, remain underexplored. To address these gaps, this study presents the first integrated geoheritage assessment of the Mount Ağrı (Ararat) region. Its primary objectives are threefold: (1) to systematically identify, inventory, and quantitatively evaluate the key geosites and geomorphosites within the mountain's massif and its immediate surroundings using Brilha's (2016) methodology; (2) to contextualize this inventory within both past and present glacial dynamics by reconstructing Last Glacial Maximum ice extent, estimating paleo-equilibrium line altitudes (paleo-ELAs), and analyzing current glacier distribution and retreat; and (3) to assess the conservation status and future potential of these geoheritage assets through a SWOT analysis, with a specific focus on the dual pressures of climate change and increasing mountaineering tourism. The overarching goal is to establish a foundational scientific framework to inform sustainable geoconservation and geotourism strategies for this unique and diverse geoheritage landscape.

Study Area

Geological and Geomorphological Features

Mount Ağrı is one of stratovolcano, located in eastern Turkey near Armenia, Iran, and the Nakhchivan exclave of Azerbaijan (Fig. 1), lies close to the intersection of the Anatolian, Arabian, and Eurasian plates. This tectonic setting underpins its complex volcanic history, altitudinal gradients, climatic contrasts, and geomorphological diversity. As a major representative of Eastern Anatolian volcanism, it has a polygenic structure with pyroclastic deposits, andesitic and basaltic lava flows, completed in 11 stages. K/Ar dating indicates ages from 1.5 million to 70,364 years (Sanver 1968; Lambert et al. 1974; Gülen 1982; Yılmaz et al. 1998; Ercan et al. 1990). The mountain exemplifies the convergence of volcanism, tectonism, glaciation, and geomorphology, with lithological diversity, volcanic cones, lahar traces, and extensive lava flows offering exceptional geodiversity, making it a region containing numerous geosites. Its pronounced topographic prominence (>4,000 m relative relief) strongly influences geomorphological processes and landscape formation. According to Karakanian et al. (2006), volcanic activity at Mount Ararat likely also occurred during the 3rd, 4th, and 6th centuries AD. Furthermore, Karakanian et al. (2002, 2006) reported that the 1840 earthquake was accompanied by volcanic activity, including an eruption, ash emissions, and a lahar-induced landslide. However, Haroutiunian (2006) critically re-evaluated this interpretation, arguing that the proposed link between the 1840 earthquake and volcanic activity is not supported by geological evidence.

Mount Ararat is significant in the scientific world due to its geomorphology, glacial cover, and volcanic history. The first scientific observations of its glaciers were recorded by Parrot (1834) during his 1829 summit ascent (Parrot, 1846). The 1840 Ahura disaster highlighted the links between glacial dynamics and volcanic activity; Voskoboinikov (1840) reported it as an earthquake-triggered landslide, Abich (1846) attributed it to glacial meltwater-saturated slopes, and Wagner (1848) first linked it to a volcanic eruption. Stuart (1876) and Bryce (1878) later debated the connection between the disaster, glacial melting, and volcanic activity.

In the 20th century, Lynch (1910) photographed the glaciers, Blumenthal (1958) mapped their distribution, and Arpat and Güner (1976) studied lava tubes and ice formations in a glacial cave. 21st-century satellite studies documented significant glacial loss: Sarıkaya (2012) reported a 29% shrinkage between 1976 and 2011; Karakhanian et al. (2002) examined volcanic influences on melting; Azzoni et al. (2017, 2019) mapped glacial landforms; Yalcin (2019) showed glaciers receding to lower elevations; and Kaya and Karataş (2025) found a 47% reduction over 46 years, with a total area of 8.11 km² including seven newly discovered debris-covered glaciers, 38% of which resist melt due to debris cover.

Climate Conditions and Ecosystems

Mount Ağrı exhibits pronounced climatic gradients due to its steep elevation differences. In the north, the Iğdır Plain, located

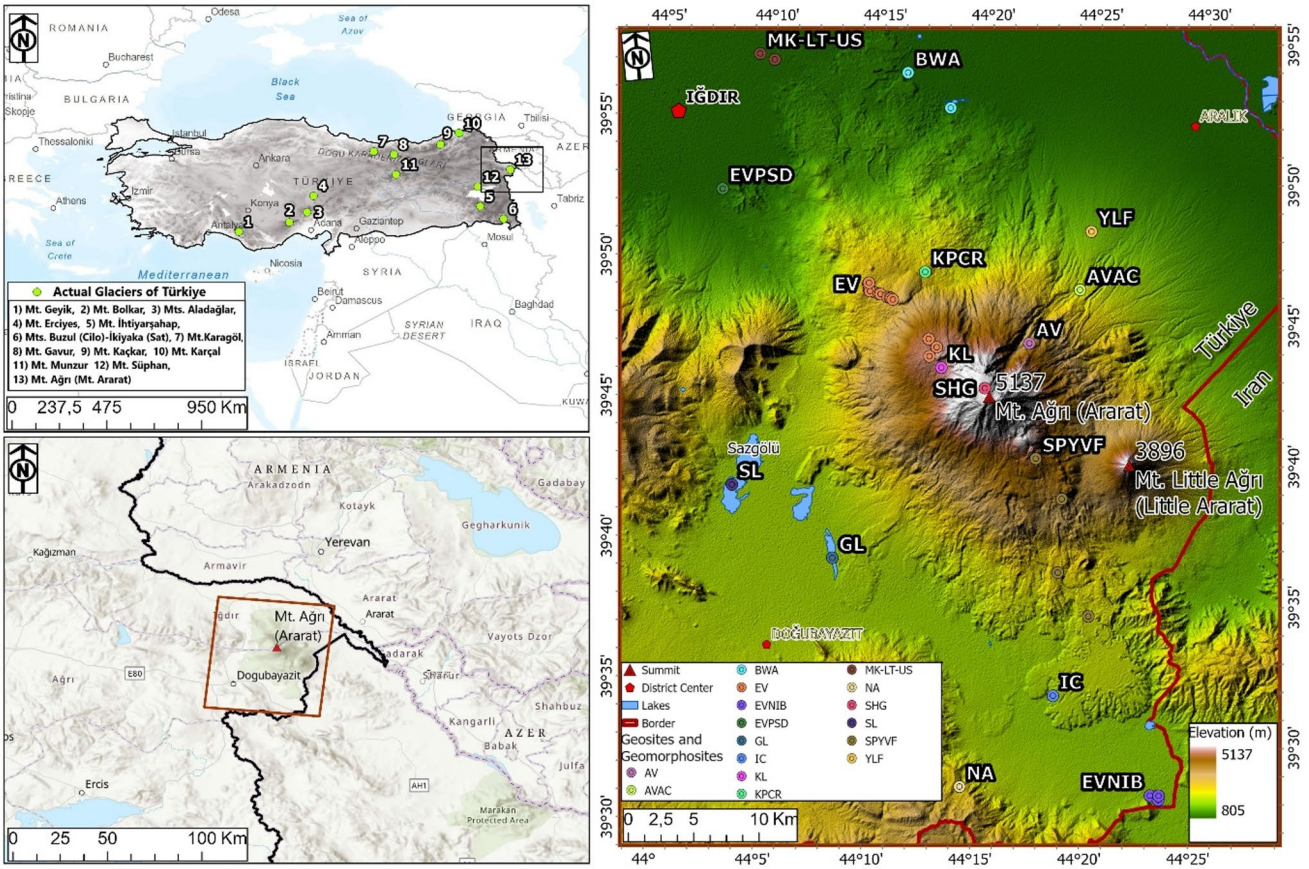


Fig. 1 Location of study area

at an elevation of 860 m, receives relatively low annual precipitation (~260 mm) and experiences mild mean annual temperatures (~12 °C), whereas in the southwest, Doğubayazıt, at 1,640 m, has an annual precipitation of approximately 330 mm and mean annual temperatures of around 9 °C (MGM, 2023). Considering these station elevations, it is expected that conditions at elevations above 4,000 m on Mount Ağrı would exceed 2,000 mm of annual precipitation, with mean annual temperatures near −5 °C. Vegetation reflects centuries of human influence: historical forests have been largely replaced by shrublands and anthropogenic steppes (Küçüköner 2023; Yulu 2020). Mid-elevations host fragmented birch, juniper, and trembling poplar stands; alpine meadows dominate higher zones; and volcanic rocks above 4,200 m are largely covered by permanent snow and ice.

Cultural and Mythological Values

Myth and geology are intertwined in multiple ways, reflecting humanity's enduring attempt to interpret and give meaning to the natural world (Vitaliano 2007). In this context, Mt. Ağrı occupies a unique position: while its volcanic origin and glacial features provide invaluable insights for scientific research, its symbolic resonance is profoundly shaped by the legend of Noah's Ark. The cultural narrative not only reinforces Mt. Ararat's spiritual and historical significance but also elevates its status as a geoheritage site of global relevance. This convergence of geological processes, climatic dynamics, and mythological traditions transforms Ararat into a natural laboratory an exceptional landscape where scientific inquiry and cultural memory intersect, offering rich opportunities to explore the complex dialogue between geomorphology, climate, and human imagination.

Natural Hazards and Risks (Earthquake, Drought, Climate Change)

Mount Ağrı is located in a seismically active region, as evidenced by historical records. The 1840 Ahura disaster highlighted the interplay between glacial dynamics, volcanic activity, and seismic hazards (Voskoboinikov 1840; Abich 1846; Wagner 1848). The 1664 earthquake led to the destruction of Korhan Castle and the surrounding settlements, while the 1840 event, which severely affected Ahura village (Azzoni et al. 2019), further underscores the persistent seismic hazard that has long characterized the

region. In the mid-19th century, Wagner, who also visited Doğubayazıt, reports in his book Travel in Persia, Georgia and Koordistan that the palace where the local governor Behlül Bey resided had suffered severe damage due to the 1840 earthquake (Wagner 1856). Indeed, in connection with the earthquake of 1840, the German geologist Otto Wilhelm Hermann von Abich was dispatched to the region by the Russians to conduct research; he climbed to the summit of Mount Ağrı and carried out a comprehensive study of the area (Abich 1858). Thus, these accounts provide important evidence regarding the impacts of the earthquake on the region. Modern studies also consider the impacts of climate change on glacier retreat, while increasing human activities, including mountaineering and tourism, add further pressures such as ice calving events, rapid glacier melting, snow avalanches, and the formation of glacial crevasses (Purdie et al. 2015; Steiger et al. 2022; Askheim 2022). These factors, combined with regional aridity and extreme climatic variability, underscore the mountain's exposure to multiple natural hazards and environmental stresses.

Materials and Methodological Approach

This study adopted a multi-method approach, integrating complementary techniques to comprehensively characterize, evaluate, and project the future of the geoheritage of Mount Ağrı and its vicinity. The methodology is structured around four sequential pillars: (1) Data Acquisition and Spatial Analysis (RS & GIS) to characterize the present landscape; (2) Paleoglacier Reconstruction and Equilibrium Line Altitude (ELA) Analysis, involving the modeling of past glacial extents and the calculation of key paleoclimatic indicators; (3) Climate Data Processing and Trend Analysis to examine historical and projected climate variables; and (4) Geomorphological Heritage (Geosite - Geomorphosite) Inventory and Integrated Evaluation. This final and comprehensive pillar encompasses the systematic inventory and quantitative evaluation of geoheritage sites based on established scientific, educational, and additional value criteria, followed by a strategic synthesis via SWOT analysis. The SWOT analysis integrates the quantitative geoheritage assessments with insights from the paleoglaciological and climate trend analyses to provide a consolidated strategic overview of the geoheritage's current status, vulnerabilities, and future management opportunities. The results from each methodological pillar are presented separately in the Findings section, while the Discussion section provides a synthesized interpretation, comparing all results including the integrated SWOT synthesis within the broader literature context.

Data Acquisition and Spatial Analysis (RS & GIS)

This study combines Remote Sensing (RS), Geographic Information Systems (GIS), and field investigations to map glacier distribution and evaluate the geomorphological heritage of the Mount Ağrı region. The Landsat satellite series, providing long-term records, were used to trace the historical distribution of glaciers, while the ALOS PALSAR 12,5 m resolution Digital Elevation Model (DEM) supported topographic analyses. High-resolution visual material was generated through aerial imagery obtained with a Mavic 3 Enterprise drone, which also served to verify field observations. This multi source dataset enabled a comprehensive characterization of both large-scale and detailed morphological features of the study area.

Paleoglacier Reconstruction and Equilibrium Line Altitude (ELA) Analysis

Paleoglacier Reconstruction

Paleoglacier reconstruction was conducted using the PalaeoIce model, which automatically derived ice thickness, flowlines, and paleo-surface products from geomorphological evidence such as moraines and trimlines. The model integrates advanced versions of the GlaRe and VOLTA algorithms, incorporating flowline extraction, removal of present-day glaciers from bed topography, application of a shape factor (f) to represent surface friction, and optimization of basal shear stress against trimline constraints (Li 2023; Pellitero et al. 2016; Nye 1952). Ice surface and thickness fields were interpolated to ensure smooth transitions between geomorphological constraints and preserve spatial continuity of the reconstructions (James and Carrivick 2016).

Equilibrium Line Altitude (ELA) Calculation

Equilibrium Line Altitude (ELA) calculations were automated using the ArcGIS-based ELA calculation toolbox, applying the Area-Altitude Balance Ratio (AABR), Accumulation Area Ratio (AAR), Maximum Glacier Elevation (MGE), and Toe-to-Headwall Altitude Ratio (THAR) 0.50 and 0.60 methods (Pellitero et al. 2015). "ELA was conceptualized as the annual mass balance elevation separating accumulation and ablation zones (Porter 2001; Cogley et al. 2011). While AAR values for equilibrium mountain glaciers typically range between 0.5 and 0.8, with 0.67 commonly adopted, recent studies indicate AAR = 0.58 and AABR = 1.56 yield more consistent ELA estimates for paleoglacier reconstructions (Kern and László 2010; Oien et al. 2022). Although other studies frequently apply AABR

ratios of 1.67–2.2, the value of 1.56 adopted here aligns with the 1.6 ratio reported for modern glaciers (Benn and Lehmkuhl 2000; Benn and Ballantyne 2005; Ballantyne 2007; Rea 2009; Oien et al. 2022). Accordingly, the primary ELA estimate was derived using AABR 1.56, with AAR 0.58 and other methods applied for comparative analysis.

Climate Data Processing and Trend Analysis

To analyze long-term climate change in the Mount Ağrı region, historical annual series (1950–2024) for 2 m air temperature and total precipitation, were derived from the ERA5-Land reanalysis dataset, spatially averaged over the study area and, aggregated to yearly values (Muñoz-Sabater et al. 2021). Future projections (2025–2099) were based on the ACCESS-CM2 SSP2-4.5 model within the CMIP6 framework, with monthly ts (surface temperature) and pr (precipitation flux) series processed, converting pr from kg m^{-2} s^{-1} to mm/year (Eyring et al. 2016). A bias correction was applied for the overlap period (2015–2024) between ERA5 and CMIP6 data: a constant offset for temperature and linear scaling for precipitation, methods which preserve long-term trends and are widely used in hydroclimatic studies (Teutschbein and Seibert 2012; Hempel et al. 2013). Climatic trends were assessed using the robust Theil–Sen median slope estimator, while their statistical significance was evaluated through the non-parametric Mann–Kendall test, both standard tools in hydroclimatology (Sen 1968; Mann 1945; Kendall 1975; Hirsch et al. 1982).

Geoheritage Inventory and Integrated Evaluation

Inventory and Quantitative Evaluation of Geosites and Geomorphosites

The identification of geosites and geomorphosites was based on distinct geomorphological characteristics, integrity, and historical significance, utilizing integrated data from field observations, drone and satellite imagery, and literature review. For their systematic evaluation, this study applied the quantitative methodological framework proposed by Brilha (2016). This method was selected for its comprehensive, structured, and widely recognized approach (Somma et al. 2025), which provides a standardized and transparent procedure for scoring intrinsic and potential use values, facilitating the ranking and selection of sites for effective geoheritage management.

In the Brilha (2016) method for assessing geosites or geomorphosites, evaluations were conducted based on four main criteria: Scientific Value (SV) (7 sub-criteria), Potential Educational Use (PEU) (12 sub-criteria), Potential Touristic Use (PTU) (13 sub-criteria), and Degradation Risk (DR) (5 sub-criteria). Each sub-criterion was scored on a scale from 1 to 4. Subsequently, the average of the scores provided by experts was calculated to determine the value for each criterion. It should be noted that while the analysis for the value criteria (SV, PEU, PTU) primarily relies on whether the final average score is relatively high or low, a standardized interpretative threshold has been established specifically for the Degradation Risk (DR) criterion. According to this threshold: A score less than 2.0 is considered LOW risk. A score between 2.0 and 3.0 is considered MODERATE risk. A score between 3.1 and 4.0 is considered HIGH risk. Following this framework, the sixteen key locations were evaluated and scored based on its four defined criteria along with their respective sub-criteria. The scoring was conducted by the experts involved in the study, based on expert judgment informed by field data, literature, and contextual insights derived from Last Glacial Maximum paleo-ELA estimations and glacier retreat studies. Crucially, the preliminary identification of internal and external factors through an initial SWOT framework directly informed the scoring process within Brilha's system. For example, factors identified as 'Weaknesses' (e.g., high hazard risk) influenced the 'Conservation Priority' score, while 'Opportunities' (e.g., high tourism potential) related to 'Accessibility' and 'Aesthetic Value' evaluations. This ensured that the quantitative scoring was grounded not only in the intrinsic values of the sites but also in the practical realities influencing their management and vulnerability.

Strategic Synthesis Via SWOT Analysis

A formal SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis, a strategic planning tool used in environmental and geoconservation management (Wall 2002; Wang et al. 2025), was conducted to synthesize the quantitative evaluation and translate it into actionable management insights. This process served a dual and iterative purpose. Initially, the SWOT framework provided essential contextual understanding that informed the expert judgment during the Brilha scoring, ensuring the quantitative assessment reflected on-the-ground realities. Subsequently, the completed SWOT analysis acted as the primary tool for strategic synthesis, integrating the finalized Brilha scores, paleoglacier reconstructions, climate projections, and field observations into a coherent overview of internal Strengths and Weaknesses and external Opportunities and Threats. Therefore, the SWOT analysis functioned not as a standalone step, but as an integrative mechanism throughout the study, ultimately producing the strategic framework for conservation and sustainable use presented in Table 2.

Results

Recent Glaciers and Glacial Geomorphology

In Turkey, glaciers are primarily found in the Eastern Black Sea Mountains, the Buzul (Cilo)-İkiyaka (Sat) Mountains, and on Mount Ağrı (Fig. 1). Beyond these ranges, they are also present in the Central Taurus Mountains, the Munzur Mountains, and on high volcanic peaks such as Erciyes and Süphan. The glaciers in the country are predominantly of the cirque and valley types, with Mount Ağrı hosting Turkey's only ice cap (Fig. 2).

Although previous studies have examined the contemporary glaciers and glacial geomorphology of Mount Ağrı (Sarıkaya 2012; Azzoni et al. 2017, 2019; Yalcin 2019; Kaya and Karataş 2025), the precise thickness and distribution of its current glaciers, rock glaciers as well as the full extent of its paleo-glaciers, remain inadequately constrained. This knowledge gap is largely attributable to the mountain's volcanic origin and its history of intermittent volcanic activity during the Quaternary, the period which was characterized by glacial cycles. Recent volcanic activity has deformed glacial landforms in some areas, while glacial processes have, in turn, eroded volcanic features and buried them under moraines or ice. As a result of this polygenetic topography, it remains unknown whether the summit area of Mount Ağrı, currently occupied by the ice cap, conceals cirques or a volcanic crater beneath the ice. Furthermore, rapidly eroding volcanic material from the steep slopes often covers valley glaciers, locally complicating the identification of active ice. Consequently, successive research campaigns continue to reveal new debris-covered glaciers.

The total area of contemporary glaciers on Mount Ağrı is 7.749 ± 0,47 km², manifesting in three main types: an ice cap, valley glaciers, and debris-covered glaciers. The ice cap covers an area of 4.892 ± 0.294 km². On the northeastern flank, it descends to elevations of around 4000 m in the form of hanging glaciers. While smaller hanging glaciers on the northeastern side extend slightly below 4000 m, the ice cap has receded significantly on the southern slope, retreating to near the summit at around 5000 m. On the western side, hanging glaciers emanating from the ice cap terminate at approximately 4500 m (Fig. 2).

Valley glaciers, which originate from the ice cap but have become detached due to the steep slopes and are now thinly covered with debris, cover an area of 0.617 ± 0.04 km². They are observed in four valleys on the northeastern, eastern, and southern flanks. There are six debris-covered glaciers, which typically begin at the termini of the valley glaciers and are completely blanketed by rubble; they cover a total area of 2.240 ± 0,13 km². The valley glaciers reach a maximum length of 1.3 km, whereas the debris-covered glaciers attain their maximum length of 4.6 km in the northern Ahura Valley (Figs. 2c and 3c). This debris-covered glacier, which descends to about 2100 m, exhibits surface depressions that expose the underlying ice in sections (Fig. 3b).

In addition to its contemporary glaciers, Mount Ağrı also preserves a record of past glaciations. Recently deglaciated, polished surfaces are observed near the summit. Lateral moraines, which indicate the maximum ice thickness

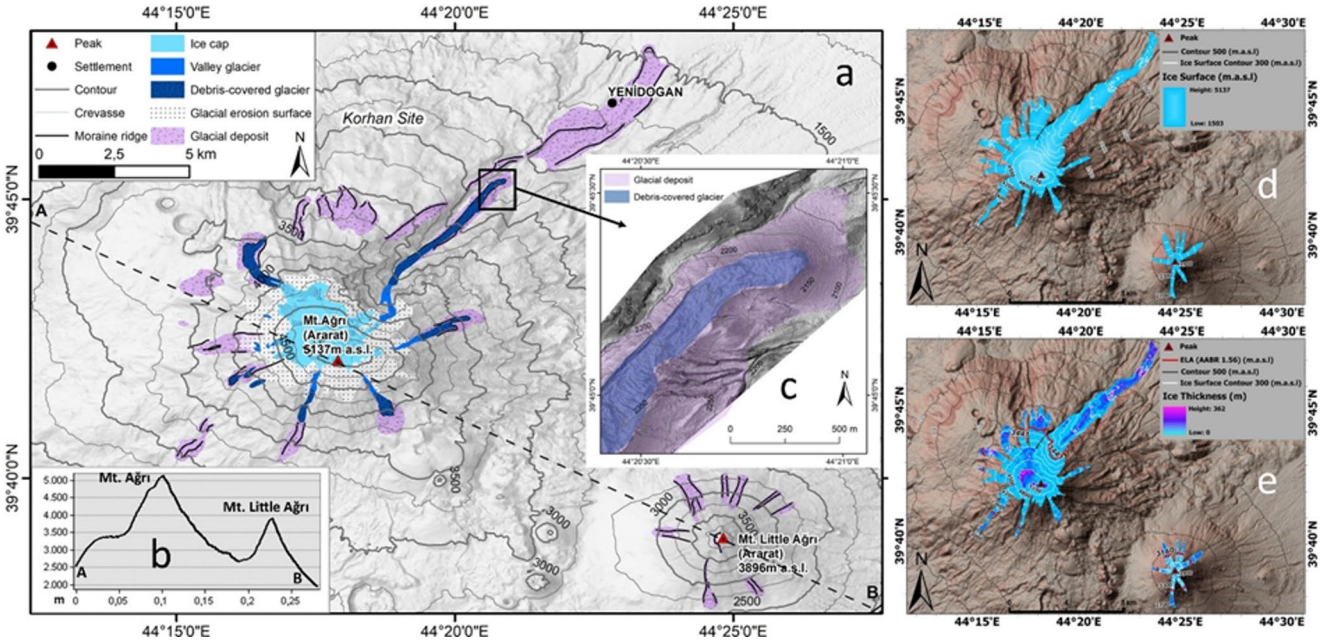


Fig. 2 **a** Glacial geomorphology map of Mount Ağrı (Ararat), **b** NW-SE profile of Mount Büyük Ağrı and Mount Küçük Ağrı, **c** Debris-covered glaciers in the Ahura valley, **d** Palaeoglacier reconstructions (LGM), **e** Palaeoglacier thicknesses (LGM)

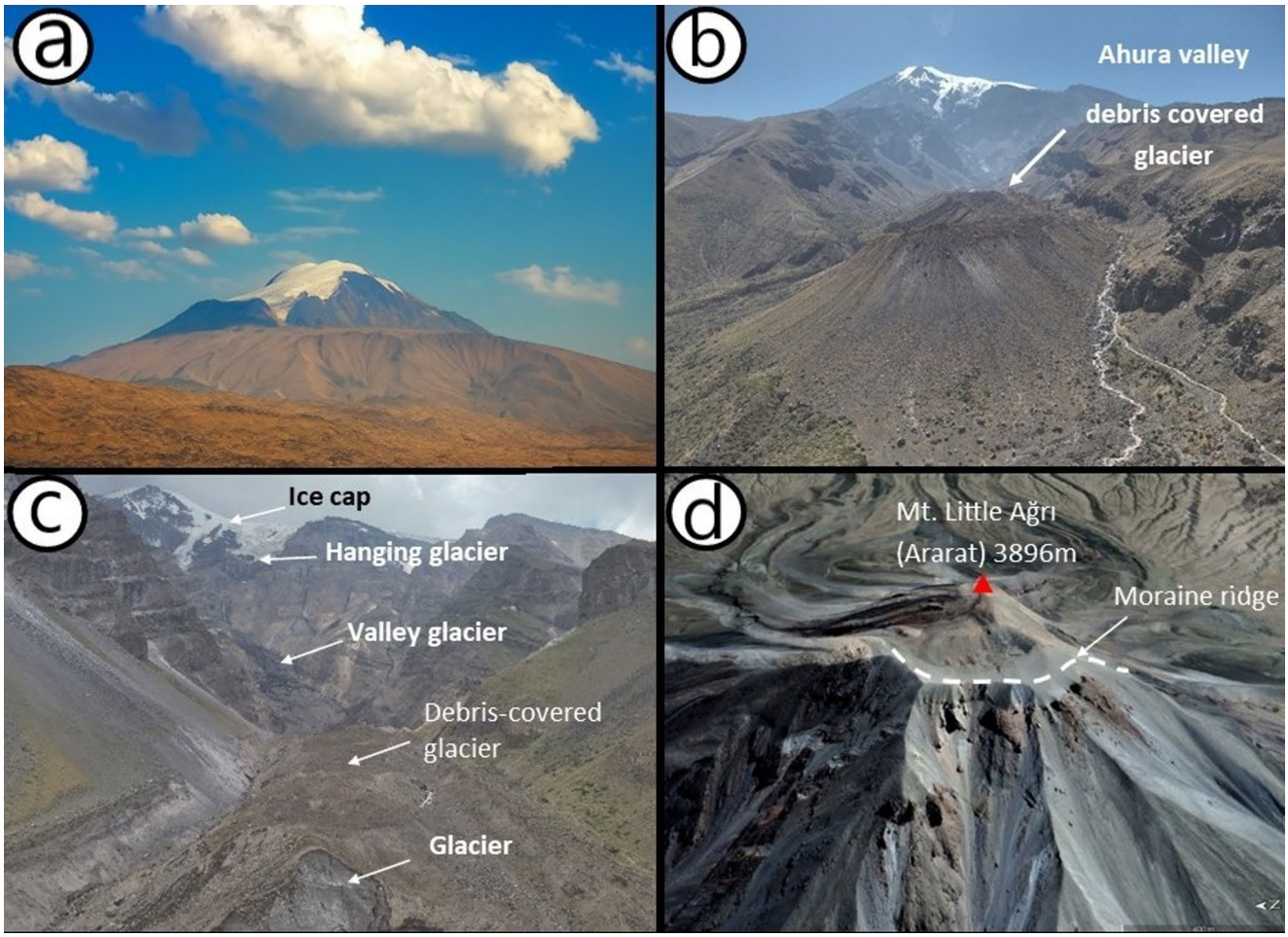


Fig. 3 **a** View of the Mount Ağrı (Ararat) ice cap from the west, **b** Debris-covered glaciers in the Ahura Valley, **c** Ice cap, hanging glacier, debris-covered glacier, and exposed glaciers in the Ahura Valley, **d** Moraines belonging to the old ice cap on Küçük Ağrı Dağ (Little Ararat)

during the Last Glacial Maximum (LGM), and terminal moraines, marking the lowest glacial extents, are evident on the mountain. Notably, lateral moraines at 3250 m in the northern Ahura Valley suggest that the glaciers on Mount Ağrı were up to 360 m thick during the LGM. Similarly, terminal moraines in the Ahura Valley indicate that glacier tongues descended to elevations as low as 1500 m (Fig. 2e).

Previous studies on Mount Ağrı have not reported the descent of paleo-glaciers to these low elevations, nor did they mention any glaciation on Little Ağrı Mountain. However, geomorphological evidence indicates that a small ice cap existed on Little Ağrı Mountain during the LGM, with glaciers advancing in all directions and descending to around 2500 m (Figs. 2d and 3d).

Geosites and Geomorphosites

Within the scope of this study, based on field observations and literature review, the research team decided to evaluate and score 16 geoheritage units according to Brilha (2016). These 16 units were analyzed in terms of Scientific Value (SV), Potential Educational Use (PEU), Potential Touristic Use (PTU), and Degradation. One of them, Mount Ağrı assessed in the context of mountaineering, was not evaluated for SV but was considered in terms of PEU, PTU, and Degradation.

While all inventoried features constitute part of the region's geoheritage and can broadly be termed 'geosites', a more specific classification was applied to highlight their dominant characteristics and spatial hierarchy. The assessed sites were thus categorized as Geosites or Geomorphosites based on their primary value, with a further sub-classification for those where cultural heritage is inseparably linked to the geomorphology such as Cultural/Geomorphosites. Mount Ararat itself is recognized as the paramount geomorphological entity or key geosite of the region. It provides the integrated geomorphological context (a stratovolcanic landscape) within which all other inventoried features are situated and from which they derive part of their significance. Features defined

primarily by their landform and geomorphological process are labelled as Geomorphosites. Sites where a significant cultural heritage layer is intrinsically tied to a specific geomorphological setting are classified as Cultural/Geomorphosites. The Erhacı Village deposits, valued primarily for their stratigraphic record, are classified as a Geosite. For ease of reference and readability in maps and figures, the names of geosites and geomorphosites were coded (Table 1; Fig. 1).

The geosites in this region can be systematically classified based on their dominant geological, geomorphological, glacial, volcanic, and hydrographic formative processes. Mount Ağrı (Mt.A), Ahura Valley (AV), Küp Lake (KL), and the Yenidoğan Lahar Fan (YLF) are complex sites shaped by an interplay of volcanic, glacial, and hydrographic factors, featuring stratovolcanic structures, glacio-fluvial erosion, and lahar deposits. Summit and Hanging Glaciers (SHG) are direct products of contemporary glacial processes. Formations such as the Eruptive Vent (Locally Called Meteor Crater) (EV), the Eruptive Vents on the Southwestern Slopes of Little Ağrı (EVNIB), and the Ice Cave (IC) are representative of pure volcanic geomorphology. In contrast, the Serdarbulak Pass young volcanic cones, lava flows, and ancient settlement Remains (SPYVF), featuring young volcanic cones and lava flows alongside ancient settlement remains, represents a mixed volcanic and cultural geosite. The Bulakbaşı Wetland Area (BWA) and the Saz Lake and Gölyüzü Lake Marshes (SL-GL) are primarily governed by geomorphological and hydrographic processes, forming significant wetland systems. Erhacı Village Pliocene Sandstone Deposits (EVPSD) stand out as key geological-lithological formations. Finally, sites like the Korhan Plateau and Korhan Castle Ruins (KPCR), which blend volcanic morphology with cultural heritage, and the predominantly cultural-archaeological sites Melekli Kültepe and Lanetli Tepe Urartian Settlements (MK-LT-US), Durupınar Noah's Ark (NA), and Ahura Village Armenian Cemetery (AVAC) highlight the confluence of natural and anthropogenic values within the landscape.

Ahura Valley (AV)

Ahura Valley (Ahora, Ahuri, Akkori), located on the northeastern slopes of Mount Ağrı, begins at around 1800 m and deepens towards the mountain, hosting significant high-mountain ecosystems. The valley was shaped by the 1840 earthquake and the subsequent possible volcanic activity and mass movements (lahar and debris flows) (Azzoni et al. 2019), which destroyed the Ahura settlement and caused more than 1,000 fatalities. Today, rock glaciers and hanging glaciers descending from the mountain are present within the valley, while its fluvial system, fed by snow and ice melt, supplies water for irrigation and livestock needs of the surrounding highland pastures (Fig. 4a). With its rich flora, endemic plant species, natural landscape, and historical-cultural traces, Ahura Valley stands out as a remarkable natural site and holds strong potential for trekking and mountaineering activities. However, due to the risk of loose materials being mobilized by sudden snow and ice melts, the valley slopes are considered more suitable for use than the valley floor.

Table 1 Geosite and geomorphosite and their map codes with score results

	Geoheritage Units	Classification	Map Code	SV Total	PEU Total	PTU Total	Degredation
1	Ahura Valley	Geomorphosite	**AV**	3,5	3,25	2,85	205
2	Ahura village Armenian Cemetery	Cultural/Geomorphosite	**AVAC**	1,85	2,4	2,35	335
3	Bulakbaşı Wetland Area	Geomorphosite	**BWA**	1,65	2,3	2,7	300
4	Eruptive Vent (Local People Called Meteor Crater)	Geomorphosite	**EV**	1,95	2,65	2,65	225
5	Eruptive Vents on the Southwestern Slopes of Little Ağrı, Close to the Iran–Turkey Border	Geomorphosite	**EVNIB**	1,85	2,45	2,5	245
6	Erhacı Village Pliocene Sandstone Deposits	Geosite	**EVPSD**	1,55	2,3	2,2	245
7	Ice Cave (Hallaç Village)	Geomorphosite	**IC**	2,8	2,25	2,4	215
8	Küp Lake	Geomorphosite	**KL**	2,3	2	2,05	190
9	Korhan Plateau and Korhan Castle Ruins	Cultural/Geomorphosite	**KPCR**	2	2,15	2	245
10	Melekli Kültepe and Lanetli Tepe Urartian Settlements	Cultural/Geomorphosite	**MK-LT-US**	1,95	2,5	2,3	280
11	Durupınar Noah's Ark	Geomorphosite	**NA**	3,7	2,45	2,65	295
12	Summit and Hanging Glaciers	Geomorphosite	**SHG**	3,25	2,7	2,55	225
13	Saz Lake and Gölyüzü Lake Marshes (Doğubayazıt Marshes)	Geomorphosite	**SL-GL**	1,55	2,6	2,75	280
14	Serdarbulak Pass young volcanic cones, lava flows, and ancient settlement Remains	Geomorphosite/Cultural	**SPYVF**	2,5	2,2	2,3	155
15	Yenidoğan lahar fan	Geomorphosite	**YLF**	1,95	2,4	2,35	190
16	Mount Ağrı (Ararat) (in terms of Mountaineering)	Key Geosite	**Mt.A**	….	2,95	2,8	210

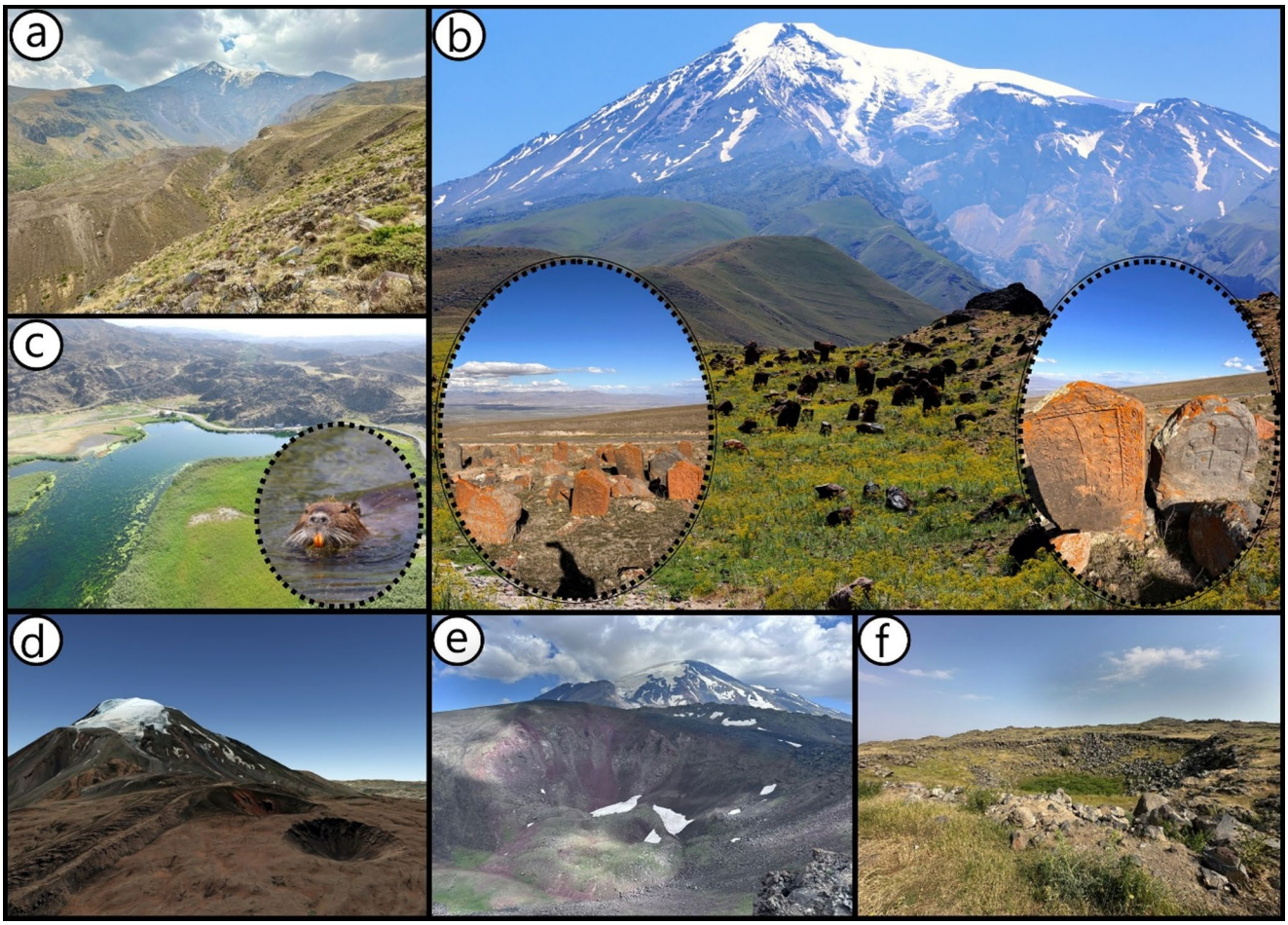


Fig. 4 **a** Ahura Valley and rock glacier example within the valley (AV); **b** Armenian Cemetery in Ahura Village (AVAC); **c** Bulakbaşı Wetland Area (BWA); **d**–**f**. Eruptive vents (locally known as Meteor Craters) (EV). Image (d) is from Google Earth

Ahura Village Armenian Cemetery (AVAC)

The cemetery belonging to the historic Ahura settlement, which was buried under debris, is located on a gently sloping hillside southeast of Yenidoğan Village. Although originally a cultural site, the Armenian Cemetery has been strongly modified by geomorphological processes such as erosion and surface degradation, makes its geomorphological context relevant for assessment. In addition, the cemetery holds significant cultural and historical value, thus representing a geoheritage site with combined natural and cultural importance. The size of the cemetery suggests that Ahura was once a large settlement. Although the Armenian inscriptions on the gravestones are still legible, most of them have toppled and are covered with moss (Fig. 4b). The graves are generally ruined, and many of the headstones have collapsed. When integrated with the geomorphological and natural areas of the region, the cemetery could contribute to the development of holistic tourism routes centered on history, culture, and nature. In particular, it holds strong appeal for culturally sensitive tourists, historians, and researchers.

Bulakbaşı Wetland Area (BWA)

Bulakbaşı Wetland area is located at a distance of around 30 km from the city center of Iğdır, the Bulakbaşı Wetland (Fig. 4c) is fed by the melting glacial waters of Mount Ağrı. Owing to the absence of any pollutants and the support of groundwater, the area has consistently preserved its natural structure and occupies an ecologically significant position within the Karasu Basin. Hosting a rich biodiversity with various bird species and wild animals, the wetland also serves as an important site for nature excursions and recreational activities (Çelik et al. 2021a). In its close vicinity, the Karasu Stream merges with the Aras River. Research has also identified the presence of Myocastor coypus (nutria) in this area (İliker et al. 2008).

Eruptive Vent (Locally Known as Meteor Crater) (EV)

In the southwest of Korhan Plateau, numerous volcanic depressions and pit structures draw attention. Some of these

depressions, locally referred to as "Meteor Craters," are bowl-shaped and generally occur in sequences. This distribution pattern is related both to the orientation of the fault identified in the area by MTA (Sümengen 2013) and to the fact that these depressions are located on the same volcanic system. The pits are understood to have formed mainly through explosions caused by gas trapped within volcanic material, followed by subsequent collapses. The largest of these explosion craters is the Kırmızıkül Depression, located south of Korhan Castle (Fig. 4d-e), with a diameter of about 1,000 m and a depth of approximately 85 m Another volcanic explosion and collapse pit, also referred to as a meteor crater, is situated north of the Iğdır–Korhan Plateau road (Fig. 4f), measuring about 100 m in diameter and 12 m in depth. The fractured and fissured basaltic blocks at its base are significant indicators of the collapse structure.

Eruptive Vents on the Southwestern Slopes of Little Ağrı, Close To the Iran–Turkey Border (EVNIB)

These are volcanic pits formed by explosions and collapses. They are located about 2,2 km east of the Gürbulak border gate, near the Turkey–Iran border, and consist of three pits with nearly circular geometries. Except for the westernmost one, the pits contain small lakes. The largest pit in the area has a diameter of 107 m, while the smallest measures 35 m The small pit, located at the westernmost point, is circular and deep, resembling a well, and is locally referred to as the 'Meteor Crater.' Despite its name, this feature is volcanic in origin, formed through volcanic processes and subsequent collapses. Near the Iran border in Doğubayazıt, the Meteor Crater is interpreted by Arpat and Güner (1976; as cited in Yiğitbaşıoğlu 2020) as resulting from the collapse of a lava tunnel within the basaltic lava flows of Little Ağrı Volcano. Alternatively, some researchers propose that the crater developed as a sinkhole due to the collapse of young basaltic lavas overlying Tertiary limestones (Yiğitbaşıoğlu 2020). These interpretations underscore the complex interplay of volcanic and geomorphological processes that have shaped the region.

Erhacı Village Pliocene Sandstone Deposits (EVPSD)

In the southeastern part of the Iğdır Plain, yellowish-colored hills rising approximately 200–250 m attract attention. Surrounded to the south by volcanic material derived from Mount Ağrı, these hills consist of Pliocene sandstones. The sandstones are generally fractured and contain abundant petrified wood fossils (Fig. 5a-b), as well as Thracia, Lamellibranchia, and gastropod (Trebralia) fossils (Atalay 1976). Within the sandstone strata, particularly at higher elevations, cave-like cavities and historic cemeteries are found (Yardimciel 2018). On the Kızılkayalıklar near Erhacı Village, two fortresses are located. These structures, believed to date back to the Middle Bronze Age, have remarkably thick walls, yet their identification as fortresses is not immediately apparent due to the high degree of structural damage. The site is distinguished by the presence of both marine and terrestrial fossils, fossilized trees, and trace fossils, which collectively provide valuable insights into past ecosystems and paleoenvironments.

Ice Cave (Hallaç Village) (IC)

The Doğubayazıt Ice Cave is located on the southern foothills of Mount Ağrı, at the northeastern edge of the Doğubayazıt Plain, approximately 3 km northeast of Hallaç Village. The cave entrance opens into a depression, about 100 m in its long axis, which formed as a result of collapse within volcanic material. This depression is approximately 8–10 m deep. Inside the cave, ice masses have formed from the freezing of infiltrating water. Situated within a collapsed lava tube system, the cave is also notable for its unique formation characteristics. The most critical factor in its development is the strong cold air current rising from the tunnel depths, which lowers the cave's internal temperature to freezing levels even in summer. As water drips from the ceiling and freezes, spectacular ice stalactites and stalagmites are formed, covering the interior of the cave. The sharp contrast between the scorching heat outside and the freezing cold within makes the cave a geological marvel and a unique natural wonder (Arpat and Güner 1976).

Küp Lake (KL)

Küp Lake is located on the northwestern slopes of Mount Ağrı at an elevation of approximately 3,430 m The lake lies within a depression measuring 91 m in length and 75 m in width and undergoes seasonal fluctuations in surface area (Fig. 5c). It is fed by precipitation as well as snow and ice melt within volcanic lithological units. Water from the lake is transferred via pipes to the Korhan Plateau, where it is supplied to households and used both for drinking and livestock. However, excessive water consumption combined with above-average air temperatures poses a serious risk of the lake drying up (Korkusuz and Kaban 2022). Küp Lake and its surroundings also have high potential for horseback trekking and nature-based tourism (Büyükhan, 2020).

Korhan Plateau and Korhan Castle Ruins (KPCR)

The modern city of Iğdır lies in a low tectonic depression, and it's established at an elevation of 890 m, was relocated from an earlier settlement. Following the 1664 earthquake,


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Fig. 5 **a-b** Erhacı vllage Pliocene sandstone deposits (EVPSD) samples. **c**. Küp Lake (KL), **d-f** Korhan Plateau and Korhan Castle Ruins (KPCR), **g** Durupınar Noah's Ark (NA), **h-i** Summit and Hanging Glaciers (SHG), **j** Saz Lake and Gölyüzü Lake Marshes (Doğubayazıt Marshes) (SL-GL), **k** Yenidoğan Lahar Fan (YLF)

which caused significant destruction, the old city of Korhan (Korgan) was abandoned, and the this settlement was founded on a defensible rocky hill on the northwestern slopes of Mount Ağrı, 30–35 km south of today's city center. Historical sources and surviving walls suggest that the castle's initial construction dates back to the Urartians. In his work Anatolia, Central Asia, and Timur (1403), the Spanish traveler Ruy Gonzales de Clavijo recorded observations regarding Mount Ağrı, noting that Korhan Castle (Egida) had long served as a refuge for bandits who would waylay and rob travelers passing through the area (Clavijo 1859). Korhan Plateau offers opportunities for rest and recreation, and features such as Korgan (Iğdır Castle), Korhan Water Reservoirs, Korhan Cemetery, Korhan Kırkdirek Cave, and Korhan Church are located on the plateau (Fig. 5d-e-f). Existing natural and cultural assets, along with planned infrastructure, could draw inspiration from highland settlements in the Black Sea region (Korkusuz and Kaban 2022).

Melekli Kültepe and Lanetli Tepe Urartian Settlements (MK-LT-US)

Melekli-Kültepe and Lanetlitepe are significant Urartian settlements located on the northern slopes of Mount Ağrı, along the transition route between the Iğdır Plain and the Aras Valley. These complex sites, continuously inhabited from the Late Chalcolithic to the Late Iron Age, feature mounds, fortresses, cemeteries, and columbaria. The Melekli settlement, established in connection with Minuahinili (Karakoyunlu), the provincial administrative center during the reign of Urartian King Minua, functioned as a strategic outpost and road station along the Mount Ağrı–South Caucasus–Northwest Iran corridor. Lanetlitepe Castle, as part of this system, held both military and administrative importance and served as a key point linking the region to external connections of Eastern Anatolia. The Melekli Urartian settlement was likely established either when King Minua first incorporated the area into Urartu or during the reorganization north of the Aras River by King I. Argishti (c. 785/80–756 BCE) (Özfırat 2017). Today, the site is notable for its castle wall remains and rock-cut tombs.

Durupınar Noah's Ark (NA)

The Durupınar Formation, located south of Mount Ağrı and east of Üzengili Village, is a natural geological formation resembling a ship. Approximately 150 m long, it was discovered in 1948 by pilot İhsan Durupınar and later associated with the "Noah's Ark" legend found in the Torah, Bible, Qur'an, and various ancient cultures, attracting international attention (Fig 5g). Geomorphologically, the formation resulted from tectonic and erosional processes; the accumulation of slope debris, mudflows, and diverse lithological units over time created a characteristic ship-like morphology (Güner 1986).

From a tourism and cultural perspective, Durupınar is one of the region's most visited sites for faith-based and cultural tourism. Observation areas and visitor centers in its surroundings support this potential.

In 1987, following an examination by experts from the Turkish Ministry of Culture, Atatürk University, Ağrı Governorship, Doğubayazıt District, and the General Directorate of MTA, the formation near Telçeker Village was registered as a 1 st Degree Natural Protected Area "in memory of the Noah Flood and Noah's Ark" (Belli 2019). The decision emphasized closing the area to agriculture and grazing, protecting it against landslide risks, and preventing unauthorized excavations or stone removal.

A brief research chronology: In 1959, İlhan Durupınar first noticed the formation in aerial photographs. In 1960, a U.S. team conducted a survey. Radar imaging studies were carried out in 1984–1985, and Turkey's first official study in collaboration with Atatürk University and Los Alamos Laboratory (1985–1987) reported that the formation showed "human-made, hull-like traces" and recommended detailed archaeological excavation. In 1987, the area was officially designated as a protected cultural property. In 2014, a New Zealand–U.S. team conducted 3D underground imaging and detected a three-dimensional hull, supporting the consensus that the formation may be man-made and warrants archaeological investigation.

Summit and Hanging Glaciers (SHG)

The high elevation of Mount Ağrı generates unique microclimatic conditions that sustain its contemporary glaciers. At the summit lies the main ice cap (Fig. 5h), covering 4.892 ± 0.294 km², surrounded by smaller hanging glaciers, valley glaciers that descend along steep slopes. These glaciers not only shape a striking alpine landscape but also highlight the interaction of climate, topography, and ice at high altitudes. Among the most remarkable features are the debris-covered glaciers, which descend from the ice cap and cloak the mountain's flanks with thick layers of volcanic rubble. The largest example, in the northeast-facing Ahura Valley, stretches 4,6 km and reaches down to ~2100 m Here, depressions in the debris reveal vivid blue ice, offering visitors dramatic visual contrasts that enhance the mountain's geotouristic appeal.

Beyond their geomorphological significance, these glaciers provide vital ecosystem services. Seasonal meltwater feeds rivers and high-mountain ecosystems, supporting both biodiversity and local communities. The combined presence of clean ice, debris cover, meltwater channels, and microclimatic niches makes Mount Ağrı a living laboratory of glacier–volcano interactions.

With its dynamic glacier systems, visually captivating landforms, and critical hydrological role, Mount Ağrı represents not only a key site for understanding Quaternary glacial history but also a valuable natural attraction for geotourism, where science, ecology, and landscape aesthetics intersect.

Saz Lake and Gölyüzü Lake Marshes (Doğubayazıt Marshes) (SL-GL)

The marshes and lakes located within the Doğubayazıt district of Ağrı Province cover an area of approximately 8,750 km². The site lies at an average elevation of 1,520 m The waters of these lakes are freshwater, gradually transitioning to marshy and reed-covered zones toward their edges (Fig. 5j). Although the area lacks a formal management plan, it is classified as a Wetland of National Importance. The marshes host a rich diversity of bird species, including the Eurasian Stone-curlew, Black-winged Stilt, Great Bustard, Little Bustard, Purple Heron, Gadwall, Northern Shoveler, Crane, Black-tailed Godwit, and Redshank. Additionally, these reed beds provide habitat for the Bendimahi Lizard, an endemic species in Turkey.

Agricultural activity around the lakes and marshes primarily involves cereal cultivation, while large-scale livestock farming is also significant. Seasonal fluctuations and water extraction often cause the lakes to dry up in summer (http://www.turkiyesulakalanlari.com/portfolio/dogubayazit-sazliklari-agri/). Observations of Saz Lake and Gölyüzü Lake within the Doğubayazıt Marshes indicate significant changes in both depth and surface area. Between 1980 and 2020, the marshlands, pastures, and nearby settlements within the study area also experienced notable transformations (Çelik et al. 2021b).

Serdarbulak Pass Young Volcanic Cones, Lava Flows, and Ancient Settlement Remains (SPYVF)

Serdarbulak Pass, located between Mount Ağrı and Little Ağrı, is an important mountain pass distinguished by young volcanic cones, lava flows, ancient settlement remains, and highland settlements in its vicinity. The young volcanic cones around the pass reflect recent volcanic activity in the region, providing an important geological and geomorphological record. Lava flows highlight the morphological traces of volcanic processes, further enhancing the geological significance of the pass. The ancient settlement remains offer valuable insights into human–environment interactions within a volcanic landscape. Additionally, a historical Russian military barracks, now largely in ruins, stands at an elevation of 2,330 m, dating back to the period when Russians controlled the area.

Together, these remnants indicate that Serdarbulak Pass has historically served as a transportation route and settlement area, making it a rare example where natural and cultural heritage elements are closely intertwined.

Yenidoğan Lahar Fan (YLF)

The alluvial fan deposits extending from Yenidoğan Village, from Ahura Valley toward the northeast into Aralık district, consist of coarse volcanic blocks and fine-grained materials (Fig. 5k). Despite the gentle slope, the transport of large blocks indicates a dense mudflow, confirming the lahar origin. The major earthquake on 2 July 1840, along with snow and ice melt, triggered the flow that formed this fan. Lahar-derived fans, typical in volcanic regions, form when volcanic mudflows exit valleys and spread over lower slopes, depositing mud, ash, tuff, and large blocks in fan-shaped cones. Lahar formation can be triggered by heavy rainfall, snow and ice melt, lake overflows, or sudden crater lake drainage.

Mount Ağrı (Ararat) (in Terms of Mountaineering) (Mt. A)

Mount Ağrı was once described by Marco Polo as a mountain that could not be climbed. The first recorded ascent was on 9 October 1829 by F. Parrot and his team, following several earlier attempts. Subsequent ascents include H. Abich in 1845, M. Wagner in 1848, and A. Oswald in 1900. In 1937, Major Cevdet Sunay reached the summit with fifteen officers and fifty soldiers. In 1955, geologists such as M. Blumenthal conducted ascents to study the mountain's structure (Doğanay 2003).

Historically, many climbs of Mount Ağrı were undertaken for religious purposes. Among the expeditions aimed at finding Noah's Ark, James Bryce climbed the mountain in 1876, reporting a carved wooden piece about 122 m long trapped among lava deposits at 4000 m elevation. The search for Noah's Ark on Mount Ararat has attracted considerable attention from both the scientific community and the general public for over a century. Numerous expeditions since the late 19th century have reported sightings of a large wooden structure; however, none have yielded fully verifiable or reproducible evidence. Systematic efforts by organized research teams, such as the Institute for Creation Research in the 1970 s, sought to document and analyze

potential remains using structured observational and recording methods (Morris 1975).

After 1980, American amateur archaeologist Ron Wyatt claimed to have found traces of Noah's Ark near Durupınar, close to Doğubayazıt, while David Fasold, in his book The Ark of Noah, identified the Durupınar formation as remains of the Ark.

Brilha Assessment Results

The evaluation of Mount Ağrı and its surrounding areas reveals a highly diverse profile of geological and geomorphological heritage values. The 16 geosites examined exhibit varying potentials in terms of scientific, educational, and touristic significance.

According to Brilha's (2016) geomorphosite assessment framework, the sites with the highest Scientific Value (SV) are Durupınar Noah's Ark (SV: 3.7) and Ahura Valley (SV: 3.5). The elevated score of Durupınar Noah's Ark reflects both its unique geomorphological characteristics and the scholarly and public debates associated with the site. Ahura Valley demonstrates high scientific importance due to its diverse attributes, including valley geomorphology, geological formations, and glacial geomorphological features. Other sites of notable scientific significance include the Summit and Hanging Glaciers (SV: 3.25), which are critical for understanding climate change impacts and glacial geomorphology in the region. Conversely, Saz Lake and Gölyüzü Lake Marshes (SV: 1.55) and Erhacı Village Pliocene Sandstone Deposits (SV: 1.55) are among the sites with lower scientific value. These lower scores may be attributed to their more localized character and the limited description of their geological and geomorphological relevance within the broader regional context.

Overall, SV values exhibit the greatest variability among all evaluated criteria (1.55–3.7), highlighting substantial differences in scientific importance across the studied geomorphosites (Table 1).

When examining the Potential Educational Use (PEU) scores, the site with the highest educational potential is Mount Ağrı (Mountaineering Perspective) with a score of 2.95. This is due to the mountain's diverse geological and geomorphological features as well as its rich biological diversity. Additionally, mountaineering activities provide practical learning opportunities in map reading and mountain ecosystem studies. Mount Ağrı and its surrounding area serve as a field site and a natural laboratory for educational purposes (Yulu 2024a, b).

Other sites with high PEU scores include Ahura Valley (PEU: 3.25) and Summit and Hanging Glaciers (PEU: 2.7). These areas serve as natural open-air laboratories for understanding regional geomorphological processes. Overall, PEU values range from 2.0 to 3.25, showing a relatively narrow spread (average: 2.48) and indicating that nearly all sites can be used for educational purposes, though some are more suitable than others (Fig. 3).

In terms of Potential Touristic Use (PTU), the top-ranked sites are Ahura Valley (PTU: 2.85), Mount Ağrı (Mountaineering) (PTU: 2.8), Saz Lake and Gölyüzü Lake Marshes (PTU: 2.75), and Bulakbaşı Wetland (PTU: 2.7). Mount Ağrı's international fame, status as the region's highest peak (5,137 m), and popularity for mountaineering tourism contribute to its prominence. Durupınar Noah's Ark (PTU: 2.65) maintains its touristic potential due to religious, cultural, and mysterious appeal (Fig. 6a).

Interestingly, Saz Lake and Gölyüzü Lake Marshes (PTU: 2.75) and Bulakbaşı Wetland (PTU: 2.7), despite having the lowest scientific values (SV: 1.55 and SV: 1.65 respectively), rank among the highest for tourism. This is because these wetland ecosystems provide opportunities for birdwatching, nature photography, hiking, and other recreational activities. Bulakbaşı, in particular, forms around a natural spring and has potential as a traditional picnic site for locals and visitors. Its proximity to the confluence of the Karasu and Aras Rivers also supports high avian biodiversity.

PTU scores (2.05–2.85, average ~ 2.46) show a distribution similar to PEU scores, suggesting that areas with high educational potential are often also attractive for tourism.

Based on Brilha's (2016) methodology, the following general conclusions can be drawn for the Mount Ağrı region:

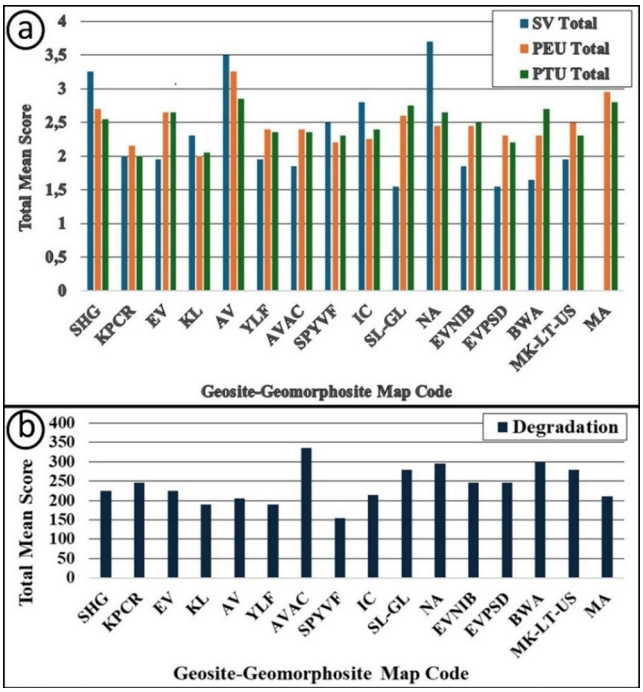


Fig. 6 **a** Graph of SV, PEU, PTU total scores based on Brilha (2016) **b** Graph of Degradation total scores based on Brilha (2016)

Ahura Valley and Durupınar Noah's Ark stand out for their high scientific values (SV) as well as strong educational and touristic potential (PEU, PTU). These sites should be the highest priority for protection, promotion, and sustainable use. Similarly, Summit and Hanging Glaciers are critically important as symbols of climate change. Sites such as Saz Lake and Mount Ağrı (Mountaineering) are more significant for tourism and education than scientific value, making them ideal for ecotourism and outdoor educational projects. Sites with low scores, like the Erhacı Village Sandstones, may not be regionally prioritized unless they are included within an integrated geopark or conservation project.

The degradation risk assessment reveals a generally moderate impact across the geosites, as the majority of the scores fall within the 200 to 300 range. However, there is a significant disparity in conservation status, with sites like AVAC (335) and BWA (300) classified as facing a high degradation risk. On the other end of the spectrum, SPYVF (155) and KL (190) are in a more favorable position, being the only sites categorized as having a low degradation risk (Fig. 6b).

SWOT Analysis

The evaluation of Mount Ağrı's geomorphological heritage has been conducted through the scoring of geosites and geomorphosites, with SWOT analysis findings compiled (Table 2). Mount Ağrı stands out as a remarkable geomorphological area due to its impressive height and grandeur, the presence of glaciers and glacial landforms, and well-preserved volcanic morphologies. Its historical and religious significance as Ağrı further enhances the importance of the site. As the highest point in Turkey, the area holds significant potential for mountaineering and nature tourism. The use of pack animals provides logistical advantages and adds to the cultural value of the region. Recognizing its natural and cultural importance, Mount Ağrı was declared a national park in 2004 by a decree of the Council of Ministers.

However, there are notable weaknesses, including difficult access, limited scientific research, and insufficient promotion of the area. Uncontrolled and uncoordinated mountaineering activities pose risks, while first-aid facilities remain inadequate. Environmental impacts from pack animals and potential damage from tourism activities further challenge management efforts. Opportunities exist in the form of geosite or geopark designation, multi-party scientific research, and sustainable tourism development initiatives. Nevertheless, threats such as border security issues, political restrictions, and climate change-induced glacier retreat complicate conservation. Additional risks include the drying or loss of ecologically important wetlands,

Table 2 SWOT framework for the geoheritage potential of Mount Ağrı

Strengths	- Preservation of rare glacial geomorphology
	- High scientific value for understanding volcanic processes
	- Geotourism potential (mountaineering, nature tourism)
	- Contribution to regional geological diversity
	- Historical and religious significance as Mount Ağrı
	- Use of pack animals provides logistical support and cultural value
Weaknesses	- Difficult access and transportation (steep terrain, border region)
	- Limited detailed geological and geomorphological studies
	- Lack of promotion and awareness
	- Missing informative signage
	- Uncontrolled/undocumented mountaineering activities
	- Lack of coordination among mountaineering operators
	- Insufficient first-aid facilities
	- Ambiguous protection status despite national park designation since 2004
	- Environmental impacts from pack animals (vegetation damage, pollution, animal welfare issues)
Opportunities	- Potential geosite/geopark designation and inclusion in tourism routes
	- Field study opportunities for universities/research institutions
	- Strategic location for multinational scientific projects (Turkey–Iran–Armenia border)
	- Contribution to education, nature tourism, and sustainable development
	- Presence of tourism development initiatives and entrepreneurs
Threats	- Border security issues and political restrictions
	- Risks from terrorism, smuggling, uncontrolled human activities
	- Natural erosion and adverse climate conditions affecting morphology
	- High slopes and loose volcanic material prone to lahars (water/ice melt, earthquakes)
	- Glacier retreat due to climate change
	- Risk of damage to geosites due to lack of protection
	- Waste and pollution from mountaineering
	- Uncontrolled climbing on multiple routes causing accidents/fatalities
	- Sudden weather changes, fog, heavy rainfall, hail cause problems for mountainers.
	- Floods, debris flows, rockfalls
	- Drying/loss of nearby ecologically important wetlands
	- Destruction of historical structures (nomadic shelters, stone architecture)

earthquakes, lahars, pollution from tourism, and insufficient supervision. Considering these factors, the sustainable management of Mount Ağrı's geotourism values requires integrated planning that balances the protection of natural and cultural heritage with visitor management and active involvement of local communities.

Climate Change Findings

Evaluation of trend analyses for temperature and precipitation in the field indicates that combined annual series for Mount Ağrı (ERA5-Land 1950–2024+ACCESS-CM2/SSP2-4.5 2025–2099) show a clear warming trend and a weak-to-moderate decrease in precipitation. The temperature trend slope (TS) is +0,45 °C/decade, and the Mann-Kendall (MK) test shows high significance; the mean temperature increased from 7,8 °C in 1950 to 10,4 °C in 2024, with projections suggesting it may reach 13,6 °C by 2100 (Fig. 7a). Annual precipitation totals exhibit a TS slope of −6.8 mm/decade, with the MK test indicating a weak-to-moderate decreasing trend (Fig. 7b). Precipitation was 556 mm/year in 1950 and is expected to decline to approximately 504 mm/year by 2100. The TS/MK combination was chosen because it is robust against volatility and extreme years in the series and does not require distributional assumptions, ensuring trend estimates remain consistent despite interannual variability (Sen 1968; Hirsch et al. 1982). These findings are consistent with regional warming and probable precipitation decrease expectations under the medium-emission scenario SSP2-4.5 (Eyring et al. 2016).

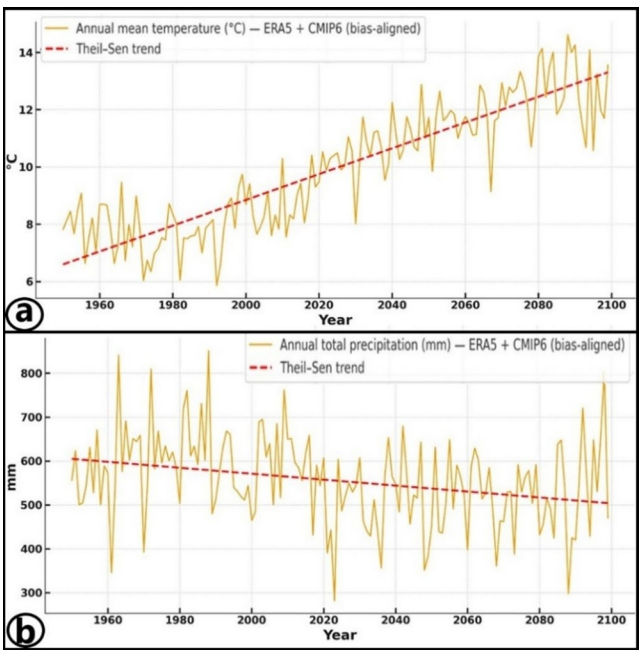


Fig. 7 **a** Graph of annual mean temperature, **b** Annual total precipitation trend

Retreat of Glaciated Areas (map)

For the glaciers on Mount Ağrı, the results obtained from different ELA (Equilibrium Line Altitude) estimation methods (AABR 1.56, AAR 0.58, MGE median, THAR 0.50, and THAR 0.60) are compared. In general, the ice cap ELA is calculated at around 4600–4700 m, while smaller hanging glaciers fall within the 4200–4500 m range, and debris-covered glaciers display values between 3700 and 4100 m This variation indicates that small, high-altitude hanging glaciers have higher equilibrium lines, whereas debris-covered glaciers extending down to lower elevations yield comparatively lower ELA values. The differences between methods are typically around 50–100 m; however, in some exceptional cases, such as Debris-Covered Glacier 8 (Cehennemdere), significantly lower values are produced (AABR: 2589 m). Looking at the averages, the arithmetic mean varies between 4037 m (AABR) and 4113 m (THAR 0.60), while the area-weighted means cluster between 4137 and 4266 m (Table 3). This demonstrates that AABR and AAR methods generally provide lower estimates, whereas MGE and THAR methods yield higher values, but the overall tendency converges around 4200 m Thus, while different methods introduce considerable uncertainties in ELA determination, large-scale assessments reveal that the current ELA on Mount Ağrı is approximately at the 4200 m band.

Table 4 presents the results of paleo-glacier modeling, comparing glacial morphometric characteristics: On Mt. Ağrı, the paleo-glacier length was calculated as 11,48 km, with a head altitude of 5137 m, a terminal altitude of 1503 m, and a glacier area of 34.352 km². These values indicate a pronounced vertical relief of approximately 3630 m and long flow paths (Fig. 2a-b). In contrast, on Little Ağrı, the paleo-glacier length was measured at 2.478 km, with a head altitude of 3908 m, a terminal altitude of 2542 m, and an area of 3.749 km². This reflects a more limited vertical relief of about 1366 m, alongside short-flow, small-volume glaciation patterns. These findings demonstrate a clear scale difference between the two mountains in terms of area, relief, and flow distance, indicating that the topography and elevation of Mt. Ağrı supported a much more extensive paleo-glaciation.

Table 5 presents a comparative analysis of ELA calculations using five different methods (AABR 1.56, AAR 0.58, MGE-median, THAR 0.50/0.60). For Mt. Ağrı, the ELA values were found to range between 3318 and 3685 m (AABR 3441 m, AAR 3503,32 m, MGE 3685 m, THAR-0.50 3318 m, THAR-0.60 3681 m; Zmin/Zmax 1503/5133 m, area 34.351 km²). For Little Ağri, the results from the methods clustered within a 3160–3361,6 m band (AABR 3160 m, AAR 3361,6 m, MGE 3276 m, THAR-0.50 3225 m, THAR-0.60 3361,6 m; Zmin/Zmax 2542/3908 m, area 3.751 km²).

Table 3 Results obtained from different ELA (Equilibrium line Altitude) Estimation methods

Glacier	AABR 1.56	AAR 0.58	MGE median	THAR 0.50	THAR 0.60
Ice Cap	4628	4675	4725	4476	4607
Valley Glacier 1	3528	3425	3525	3604	3691
Valley Glacier 2	4194	4175	4225	4287	4345
Valley Glacier 3	4464	4425	4475	4507	4558
Valley Glacier 4	4501	4475	4525	4565	4620
Valley Glacier 5	4402	4425	4425	4420	4427
Valley Glacier 6	4388	4375	4375	4393	4407
Valley Glacier 7	4251	4225	4275	4257	4268
Valley Glacier 8	4305	4325	4325	4315	4327
Debris-Covered Glaciers 1	2589	2525	2575	2705	2799
Debris-Covered Glaciers 2	3716	3725	3775	3719	3781
Debris-Covered Glaciers 3	4081	4075	4075	4137	4173
Debris-Covered Glaciers 4	4002	3975	4025	4057	4110
Debris-Covered Glaciers 5	3947	3925	3975	3966	3988
Debris-Covered Glaciers 6	4020	4025	4025	4038	4053
Debris-Covered Glaciers 7	3898	3875	3925	3905	3921
Debris-Covered Glaciers 8	3711	3675	3675	3797	3853
Arithmetic mean (m.a.s.l)	4037	4019	4054	4067	4113
Area weighted mean (m.a.s.l)	4206	4220	4266	4137	4244

Table 4 The results of paleo-glacier modeling, comparing glacial morphometric characteristics

Palaeo Glacier	Ice Length (km)	Ice Terminal Elevation (m)	Ice Head Elevation (m)	Area (km^2)
Mt. Ağrı (Ararat)	11.48	1503	5133	34.352
Mt. Little Ağrı (Little Ararat)	2.478	2542	3908	3.749

This distribution shows that the sensitivity of the methods is higher for Mt. Ağrı due to its vast area and significant relief, whereas Little Ağri provides more stable results because of its narrower relief range. A 100–400 m difference in ELA was detected between the two mountains, depending on the method used (Fig. 2a). The median of the five values was taken as a central estimate, determined as 3503 m for Mt. Ağrı and 3225 m for Little Ağrı. These values were found to be consistent with the AABR-based pELA results obtained in the study and suggest a methodological uncertainty band of approximately ± 180 m and ± 100 m, respectively.

Natural Hazards and Pressures

Seismicity

Apart from the ambiguous 1840 eruption of Mount Ağrı whose occurrence remains uncertain there has been no historically confirmed volcanic activity in recent times. However, due to its geographical setting, the area lies within an extremely active and hazardous tectonic zone. The main source of seismic activity in this region is the continuous and intense collision of the Arabian Plate pressing northward against the Anatolian Plate. This tectonic stress activates a series of complex fault systems, most notably the massive East Anatolian Fault, exposing the region to destructive earthquakes throughout history. Historical records document numerous catastrophic events, such as the 1840 earthquake (Mw 7.4), which triggered massive avalanches on the mountain's slopes, obliterating the village of Ahora (Ahuri) and claiming thousands of lives. Similarly, the 1893 Malazgirt (Mw 7.1) and the 1966 Varto (Mw 6.9) earthquakes caused widespread devastation over the centuries. In the 20th century and beyond, large-scale earthquakes such as the 1976 Çaldıran (Mw 7.0), the 1983 Şenkaya-Erzurum (Mw 6.6), the 2004 Doğubayazıt (Mw 5.1), and the 2011 Van (Mw 7.1) events (AFAD 2025) have tragically demonstrated the ongoing and hazardous nature of tectonic activity. Even when the epicenters were located far from the mountain, these earthquakes inflicted severe damage and loss of life in Ararat and its surroundings.

Hazards Related To Mountaineering (Climbing Mt. Ağrı and Associated Pressures of Mountaineering and Tourism Intensity)

The geomorphological structure and climatic conditions of Mt. Ağrı, combined with rising temperatures and shifting precipitation patterns, render mountaineering tourism increasingly fragile. Sudden summer glacial melts, prolonged dense fog, debris flows, rockfalls, and flash floods directly threaten both safety and tourism activities.

Table 5 Comparison of Equilibrium-Line altitude (ELA) estimates calculated using different methods (AABR, AAR, MGE, THAR) for Mt. Ağrı and little Agri mountains

Palaeo Glacier	AABR 1.56 (m)	AAR 0.58 (m)	MGE median (m)	THAR 0.50 (m)	THAR 0.60 (m)	Zmin (m)	Zmax (m)	Area (km^2)
Mt. Ağrı (Ararat)	3441	3503.32	3685	3318	3681	1503	5133	34.351
Mt. Little Ağrı (Little Ağrı)	3160	3190.23	3276	3225	3361.6	2542	3908	3.751

For example, tourists arriving in summer via connecting flights from various cities in Turkey and from many countries worldwide are often unable to summit due to days of persistent fog and adverse weather conditions; this reduces the economic returns of the destination and undermines its international reputation. In recent years, images recorded by climbers in camp areas, social media content, and reports in the national press have clearly revealed that geo-risks pose serious threats to climbers (URL 1 2025; URL 2 2025; URL 3 2025). Indeed, in the summer of 2024, sudden dense fog accompanied by adverse weather conditions on the summit of Mount Ağrı resulted in the deaths of three climbers; the inability to recover the bodies for days due to continuing bad weather starkly illustrated the fragile impacts of climatic changes on mountaineering tourism. Beside this global warming has significantly intensified the rate of glacier melting and disintegration. These processes are particularly pronounced during the summer months, when increased temperatures contribute to the detachment of glacier masses and the formation of extensive crevasses. Such dynamic glacier responses pose considerable hazards to human safety (Steiger et al. 2022). For instance, during the summer of 1996, a large ice block calving from the Miage Glacier (Mont Blanc Massif, Italy) generated a surge wave that resulted in injuries to tourists (Tinti et al. 1999) At the terminus of the Nigardsbreen Glacier, located in Vestland County, Norway, incidents have occurred in which icefall impacts have resulted in the deaths of six tourists (Askheim 2022). Besides this, glacier destabilization increases the frequency of rockfall events (Purdie et al. 2015).

The risks stemming from changing climatic conditions affect not only climbers but also the living conditions of the local population in the southern foothills, where mountaineering tourism is concentrated. Climatic pressures increasingly drive the rural population toward livelihood strategies beyond animal husbandry and intensify migration trends (Sevgi and Yulu 2024; Yulu 2024a, b). This process leads to the detachment of local communities who have been integrated with the mountain for millennia from the mountain itself. As a result, their participation in conservation and tourism activities diminishes, weakening the sense of ownership of both natural and cultural heritage and preventing the direct transfer of tourism revenues to the local population. Recent observations confirm this trend, as the nomadic groups who once sold local products along the climbing paths are no longer present. Clearly, climate change undermines not only the natural environment but also the social and economic foundations of mountain tourism. For this reason, ensuring the future of mountaineering tourism in the region requires the establishment of a functional database across different levels from local businesses to public institutions along with strengthening safety and search-and-rescue infrastructure and implementing effective risk management strategies.

Mountaineering tourism on Mt. Ağrı has historically followed a discontinuous and unstable trajectory due to political and security-oriented regulations. Following the first ascent in 1829 (Parrot 1846), the 1950 s witnessed scientific and religious expeditions (Imhof 1956; Blumenthal 1958; Bailey 1977), the official opening in 1966 (Ülker 1992), and the designation of national park status in 2004. However, the region also experienced various closures in 1974, 1992, and the 2000s. Mountaineering tourism was largely interrupted in the 1980 s and 1990 s due to terrorist incidents and security concerns, and although there were partial reopenings in the early 2000 s, stable activity could not be established. During this period, military restrictions and security policies hindered tourism development, and mountaineering activities were largely suspended. As of 2021, the area has been reopened for mountaineering (Yulu 2020) (Fig. 8a-b). This irregularity in the mountaineering process has been one of the greatest obstacles to sustainable tourism planning in the region.

Since 2021, the rapid and uncontrolled increase in the number of climbers has begun to exceed the mountain's physical and ecological carrying capacity. Records show that while there were only 318 summit climbers in 2021, this number soared to 6,978 in 2023 an increase of more than twentyfold. Concentrated human and pack-animal traffic along a single route has led to soil compaction and vegetation degradation (Fig. 8c), while the accumulation of solid waste in camp areas has created visual pollution and threatened freshwater resources. The use of primitive waste disposal methods, such as burning or burying, further exacerbates air and soil pollution (Fig. 8d-f).

One of the most serious environmental threats arises from human-derived biological waste. The fecal and urinary waste produced by the dense human presence directly infiltrates soil and water, disrupting ecosystem balance and posing public health risks. As on Kilimanjaro and Everest (Kaseva and Moirana 2010; Neupane et al. 2025), the near-total absence of waste management infrastructure on Ararat, combined with a lack of coordination among stakeholders and low levels of awareness, manifests typical signs of "overtourism" (Capocchi et al. 2019). The current situation urgently calls for a multi-stakeholder, participatory, and sustainable management plan.

Discussion

This study provides an integrated assessment of the geoheritage of Mount Ağrı and its surrounding area by applying Brilha's (2016) evaluation method, SWOT analysis, and by

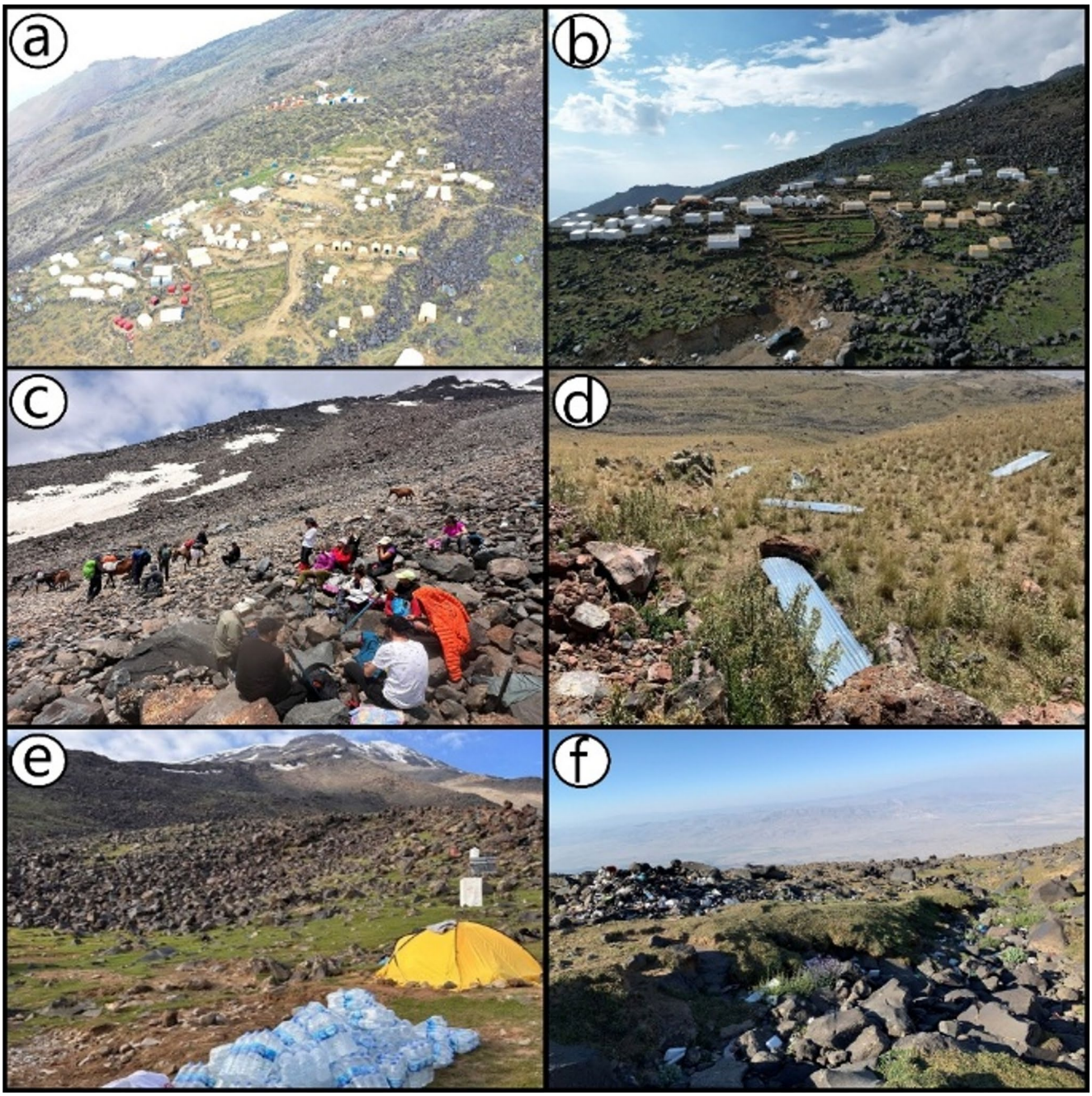


Fig. 8 **a-b** Base camp for mountaineers **c** Climbing traffic of mountaineers and pack animals **d-e-f**. Pollution of the campsite and its surroundings

examining paleoglacial evidence and current climate trends. The findings reveal a landscape of exceptional but fragile value, facing complex management challenges that require tailored, multi-faceted strategies.

1. Interpretation of Geoheritage Values and Management Implications
   The quantitative geosite evaluation clearly demonstrates that the heritage value of a site extends beyond its intrinsic scientific worth (Brilha 2016; Reynard and Brilha 2018). While sites like "Durupınar Noah's Ark" and "Ahura Valley" possess high scientific value (SV), others such as "Saz Lake" score higher in potential touristic use (PTU). This disparity underscores the need for a differentiated management approach, as advocated in geoheritage literature (Brilha 2016; Gordon 2018). High-SV sites (e.g., Summit Glaciers, Ahura Valley) must be prioritized for strict geo-conservation and scientific monitoring, aligning with the core principle of protecting irreplaceable geological records (Prosser et

al. 2018). Conversely, areas with high PTU can be strategically developed for controlled ecotourism, ensuring economic benefits without compromising core scientific assets. The case of "Ahura Valley," which excels in SV, potential educational use (PEU), and PTU, highlights its suitability as a cornerstone for a potential Geopark, integrating conservation, education, and sustainable tourism (UNESCO 2016).

2. Climate Change Impacts and Paleoglacial Context
The observed rapid warming and shifting precipitation patterns in the region are consistent with broader Eastern Anatolian and global climate trends (IPCC 2022; Sarıkaya and Çiner 2015). The significant retreat of Mount Ağrı's glaciers, a key geomorphological feature, mirrors the fate of glaciers across Turkey and the Mediterranean (Sarıkaya et al. 2017). This is not merely an aesthetic loss; glacier decline directly threatens regional hydrology, water resources, and dependent ecosystems (Huss and Hock 2018). Furthermore, increased meltwater raises the probability of glacial hazards such as debris flows and outburst floods, a growing concern in high-mountain regions (Sattar et al, 2022). These climate driven changes also critically impact mountaineering safety, as evidenced by the tragic 2024 climbing accident. The convergence of paleoglacial evidence (indicating past sensitivity) with current rapid melt underscores the site's acute vulnerability and the urgent need for climate adaptation strategies integrated into any management plan.
3. Synthesis of Management Challenges Through SWOT Analysis
The SWOT analysis synthesizes the region's potential and perils. The primary Strengths lie in its unique geobiodiversity and high cultural touristic appeal. However, these are countered by critical Weaknesses: inadequate infrastructure, a lack of effective visitor management, and insufficient scientific monitoring capacity. The exponential growth in climbers since 2021 exemplifies "overtourism," leading to environmental degradation familiar from peaks like Everest and Kilimanjaro (Nepal and Chipeniuk 2005; Upadhyay 2025). Current waste practices are unsustainable and exacerbate pollution. The Opportunity for developing high-value geotourism and achieving UNESCO Geopark status is significant. Yet, it is severely challenged by multifaceted Threats: accelerated climate change, increasing natural hazards, socio-political complexities due to the tri-border location, and outmigration weakening local stewardship. This analysis confirms that management challenges are not solely ecological but deeply socio-political, requiring solutions that address governance, community engagement, and transboundary cooperation.
4. Theoretical and Practical Contributions of the Study
This research makes several key contributions. Theoretically, it demonstrates the utility of combining Brilha's quantitative assessment with SWOT analysis and climate data, providing a more holistic and actionable understanding of geoheritage sites than single-method approaches (Brilha 2016; Vandelli et al. 2024). Practically, it offers a concrete, evidence-based framework for conservation prioritization, identifying which sites require strict protection (high SV) and which are suitable for sustainable use (high PTU). From a management perspective, the study translates integrated findings into specific, actionable recommendations. For instance, the link between glacier retreat (from climate data) and increased hazard risk directly justifies the proposal for early warning systems. Similarly, the overtourism identified in the SWOT analysis provides the rationale for implementing a carrying-capacity-based visitor management system. Thus, the recommendations are not generic but are directly derived from the synthesis of the study's methodological pillars.
In summary, this study provides the necessary theoretical, practical, and strategic foundations for the sustainable management of the geological heritage of Mount Ağrı and its immediate surroundings. Its theoretical contribution lies in proposing a dynamic assessment framework that directly shapes conservation strategies. By integrating the quantitative results of the applied Brilha method, the strategic perspective of the SWOT analysis, and the risk assessment derived from glaciation, glacial retreat, and climate data, the study moves beyond static inventory studies. The practical contribution is twofold: (1) It clarifies the focus of conservation action by identifying, based on scientific criteria, critical areas requiring absolute protection (such as Ahura Valley, summit glaciers) and areas suitable for sustainable use (such as Saz Lake, Bulkabaşı Wetland), and (2) it reveals the new and complex threat created by climate change combined with increasing tourism pressure, demonstrating why the conservation approach must be not only site-based but also risk-oriented. From a managerial perspective, this study does not so much offer a direct prescription for the question "How do we protect?" but rather lays out the essential components and guiding principles that an effective conservation, use, and management model must possess. Our findings indicate that a lasting protection system is only possible through an integrated approach encompassing: science-based prioritization for area management, control of tourism capacity, and monitoring and early-warning systems for climate risks. Therefore, the study brings together the disparate questions of conservation, use,

and climate adaptation within the logical framework of an actionable strategic plan for practitioners.

5. In conclusion, the geoheritage of Mount Ağrı is both a significant asset and a major management challenge. Its sustainable future depends on recognizing the multidimensional values of its geosites, confronting the accelerating impacts of climate change, and systematically addressing the pressures of unregulated tourism. The following integrated recommendations are proposed, each rooted in the synthesis of our findings:

   Priority-Based Zoning: Implement a zoning plan derived from Brilha's evaluation results, enforcing strict protection in high-SV areas (glaciers, Ahura Valley) and permitting managed tourism in high-PTU zones.

   Regulated Visitor Management: To directly address the critical weakness of "overtourism" and lack of funding identified in the SWOT analysis, a scientifically determined carrying capacity for climbing must be established and enforced through an online permit and fee system. This model, proven effective in managing fragile mountain destinations (Eagles et al. 2002), is particularly crucial for high-SV sites like the Summit Glaciers and the Ahura Valley, which are both most vulnerable to degradation and most in need of conservation funding. Such a system would control visitor numbers while generating essential revenue for the protection of these priority geosites.

   Comprehensive Waste Management: The SWOT analysis revealed that poor waste management is a major problem, harming the environment and beauty of the area. To solve this, all climbers must be required to follow a strict "Pack it in, Pack it out" rule, and climbing groups must be provided with portable toilets. This combined measure, which has become a benchmark for sustainable mountaineering globally (Kaseva and Moirana 2010; Apollo 2017), is essential to eliminate the current practice of on-mountain waste disposal and protect sensitive high-altitude environments.

   Climate Adaptation Measures: The paleoglacial reconstruction and current climate data converge to reveal the extreme vulnerability of Mount Ağrı's cryosphere, necessitating proactive risk management. Therefore, initiating a permanent glacier monitoring program and developing early warning systems for glacial hazards like outburst floods are critical, non-negotiable adaptations. These measures, aligned with established protocols for climate risk reduction in high mountains (Carey et al. 2012; Wang et al. 2022) must be coupled with integrating real time hazard alerts for climbers to directly address the mounting safety risks underscored by recent tragic events.

   Geopark Development Initiative: The Brilha (2016) assessment confirms that the region, with key sites like the Ahura Valley, possesses outstanding geoheritage value. These results demonstrate that the area has the fundamental attributes required for a UNESCO Global Geopark. Therefore, pursuing this formal designation emerges as a compelling strategy. It would provide an integrated framework to conserve the area's scattered geological treasures, coordinate management efforts, and foster sustainable development, in line with successful global models for territorial conservation (UNESCO 2016).

   Community Empowerment: The SWOT analysis highlights outmigration and a lack of local stewardship as a key threat to the long-term sustainability of conservation efforts. To directly counter this, tourism cooperatives and targeted training programs must be developed to anchor economic benefits within the community. This approach ensures that local residents have a direct stake in conservation (Bennett et al. 2019) moving from being passive observers to becoming key partners in protecting the geoheritage. This creates a virtuous cycle where successful conservation supports community well-being, and community support, in turn, ensures the long-term protection of the sites.

Conclusions

Mt. Ağrı and its immediate surroundings stand out as a geosite of exceptional importance at both national and global scales, with its summit glaciers, glacial valleys, lahar deposits, eruptive craters, volcanic cones, and basaltic–andesitic lava flows. These landforms preserve traces of climatic oscillations from the Late Quaternary while simultaneously reflecting the rapid impacts of contemporary climate change. The marked retreat of summit and hanging glaciers, together with the persistence of debris-covered glaciers, clearly demonstrates the sensitivity of high-mountain glaciation to global warming.

Evaluation based on Brilha's (2016) criteria confirms the high scientific, educational, and touristic value of the geosites in the Mt. Ağrı region. The Durupınar "Noah's Ark" Formation, the Ahura Valley, and the summit glaciers are of particular scientific interest, while sites such as Saz Lake and the Bulakbaşı Wetland highlight the region's touristic potential. The sixteen identified geosites collectively underscore the richness of opportunities for trekking,

mountaineering, highland tourism, and cultural heritage. Yet, the sharp rise in climbing activity after 2021 has also led to increased environmental and safety concerns, with the 2024 fatalities underscoring the seriousness of these risks.

SWOT analysis indicates that rare morphologies and scientific significance represent major strengths, while infrastructure deficiencies and glacier retreat linked to climate change remain critical challenges.

Overall, the Mt. Ağrı region constitutes a unique open-air laboratory where scientific, educational, and touristic values converge. A sustainable management plan focusing on its most significant geosites, supported by a geopark framework, offers the most effective means of safeguarding this exceptional heritage while promoting sustainable tourism and local development. This study calls for an integrated and actionable strategy built on key principles such as priority-based conservation, capacity-controlled visitor management, and climate risk adaptation derived from the synthesis of quantitative assessment, SWOT analysis, and climate data. In this way, the geological heritage of Mt. Ağrı can be preserved for future generations as both a repository of knowledge and a foundation for sustainable development.

Author Contributions Declaration Ergin Canpolat: Writing review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. Adem Yulu: Writing – review & editing, Writing – original draft, Visualization, Data curation, Conceptualization. Ferhat Keserci: Data Visualization, Formal analysis, Data curation. Ezgi Demir: Writing original draft, visualzation Cihan Bayrakdar: Writing original draft, Visualization, Formal analysis, Data curation, Conceptualization.

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Data Availability The datasets used and/or analyzed during the current study are available in the article/from the corresponding author on request.

Declarations

Ethical Conduct The authors declares that this research article complies with the ethical standards of this journal.

Conflict of Interest The authors declare no competing interests.

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