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ORIGINAL ARTICLE

Evaluation of Granite Topography in the Ida Madra Geopark in the Context of Geoheritage

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Abstract

This study evaluates the granite topography of the Ida Madra Geopark in northwestern Türkiye as a significant geoheritage resource. Seven representative geosites were systematically assessed using the Kubalíková (2013) methodology, integrating scientific, educational, economic, conservation, cultural, and aesthetic values. Field surveys revealed that tors, boulders, exfoliation domes, and spheroidal weathering features constitute the most distinctive landforms of the region. These granite landscapes provide valuable insights into long-term geomorphological evolution while simultaneously reflecting strong cultural associations, including pastoral traditions, and ancient quarrying activities. The results show that scientific and educational values are high, whereas economic utilization remains limited, underscoring the need for improved conservation strategies, legislative protection, and community-based geotourism initiatives. Overall, the Ida Madra Geopark emerges as a distinctive geoheritage territory where geological processes and cultural identity converge, offering important contributions to geoconservation and sustainable regional development.

Keywords Granite landforms · Geoheritage · Tors · Geosite assessment · Ida Madra Geopark

Introduction

Granite landforms exhibit distinctive morphological characteristics that differentiate them from those developed on other lithologies. Features such as tors, boulders, granite sands, and a variety of other granitic forms are widely distributed across many parts of the world and occur more frequently than comparable landforms on other rocks (Palmer and Neilson 1962; Twidale 1982; Ballantyne 1994; Migoń 1996, 2006; Aguilera Emilia et al. 2014). Granite topography has therefore attracted considerable scientific attention, with numerous studies examining its general properties, the diversity of associated landforms, and their geomorphological and scientific significance (Palmer and Neilson 1962; Eden and Green 1971; Ballantyne 1994; Migoń 1996; Gunnell et al. 2013; Aguilera Emilia et al. 2014; Migoń and Vieira 2014; Michniewicz 2019).

Although the scientific importance of granite landscapes has long been recognized, their evaluation within a geoheritage framework is relatively recent. This perspective highlights not only their scientific significance but also their educational, cultural, economic, and aesthetic values, thereby enhancing their relevance for promotion, geotourism, and conservation (Druguet et al. 2015; Michniewicz et al. 2015; Migoń and Pijet-Migoń 2017; Gordon 2018; Migoń et al. 2018, 2019; Nazaruddin 2020; Migoń 2021). Geoheritage, broadly defined as elements of Earth's geological diversity with significance for science and society (Brocx and Semeniuk 2007; Brilha et al. 2018; Migoń 2021), increasingly forms the basis for geoconservation and geotourism initiatives, often within geoparks, though its scope extends beyond them (Gordon 2018).

Granite weathering occurs in multiple stages, influenced by both mineral composition and duration of exposure. These processes—granular disintegration, block-by-block separation, exfoliation, and spheroidal (onion-skin) weathering—typically

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initiate along joint systems and progress toward the development of blocks or tors (Twidale 1982; Migoń 2006; Vasile and Vespremeanu-Stroe 2016). In the field, distinctions between granite and granodiorite landforms are often subtle, as many features described as granite-supported may in fact have developed within granodiorite (Migoń 2006). Conversely, granite can transform into granodiorite without altering the overall landscape appearance. Isolated rock masses, commonly granite, gneiss, or quartzitic bedrock, that have undergone extensive weathering along joint systems often evolve into tors, which are characterized by distinctive and sometimes peculiar shapes (Twidale 1982; Migoń 2006). While tors are most frequently associated with granite, they can also develop on other lithologies such as sandstone, dacite, schist, dolerite, and ignimbrite (Twidale 1982; Migoń 2006).

In Türkiye, studies are mostly concerned with the scientific importance of granitic rocks. These studies cover topics such as magmatism, geochemical aspects (Akgündüz et al. 2012, Bingöl et al. 1982), mineralization (Yücel-Öztürk and Helvacı 2008, Delaloye and Bingöl 2000; Delibaş et al. 2012). There are also studies related to the cultural and archaeological value of granites, particularly in connection with ancient granite quarries in Western Anatolia, due to their use as building stones (Gasparini et al. 2018; De Vecchi 2000, Pensabene et al. 2018; Ponti 1995; Rodà et al. 2012). On the other hand, there are a few studies on granite topography in Türkiye, but these only address the scientific aspect and do not touch upon its geoheritage characteristics (Gürgen 1991; Uzun 1995; Uzun et al. 2023).

Tourism, while offering opportunities for regional development, also poses challenges for sustainability. Ensuring the sustainability of geotourism is therefore crucial for nature conservation (Akıncı and Kasalak 2016 l and Gül 2016; Doldur 2016). Granite landscapes, particularly those characterized by tors and boulders, represent distinctive geomorphological features that combine aesthetic appeal with significant scientific value (Linton 1955; André 2004). Compared with other granite landforms, such as inselbergs, tors and boulders are more widespread and frequently encountered in the landscape (Migoń 2006). These features provide valuable opportunities for investigating long-term geomorphological evolution, weathering and erosion processes, and the interactions between natural environments and human cultural development.

Granite and granitic landforms play a central role in defining geosites within the Ida Madra Geopark. These sites encompass not only geological features but also geomorphological, cultural, and archaeological values. Granite-dominated landscapes display distinctive morphologies shaped by tors, boulders, weathering pits, tafoni, and exfoliation structures. Such landforms are particularly concentrated in the Kozak, Madra, Kapıdağ, Şaroluk, Kestanbol, and Eybek granitoid areas, where they contribute significantly to both the scientific importance and cultural identity of the region.

Assessing these landforms within a geoheritage framework enables a deeper understanding of their value and provides a scientific basis for geoconservation and sustainable management. Accordingly, this study evaluates the granite topography of the Aspiring Ida Madra Geopark in northwestern Türkiye as a key geoheritage asset. It documents and characterizes granite landforms at selected geosites, assesses their scientific, educational, cultural, and aesthetic values using established geoheritage assessment methodologies, and discusses the implications for geoconservation planning and sustainable geotourism development.

By situating the analysis within the broader geoheritage discourse, this research highlights the role of granite landscapes in supporting conservation and sustainable geotourism, while addressing a notable gap in the Turkish geoheritage literature. Despite the global recognition of granite tors and boulders as distinctive geoheritage features, systematic evaluations of such landforms remain limited in Türkiye. Previous studies have largely focused on geomorphological characteristics, with less attention to their broader heritage significance. The Ida Madra Geopark is one of the few regions where granite tors are both abundant and closely integrated with local cultural traditions, yet their geoheritage value has not been quantitatively assessed. Addressing this gap provides an opportunity to integrate Turkish granite landscapes into the international geoheritage framework while strengthening geoconservation initiatives and sustainable geotourism strategies.

Study Area

The Ida Madra Geopark, situated in northwestern Türkiye (Fig. 1), is bounded by the Sea of Marmara to the north, the Aegean Sea to the west, Mount Madra to the south, and Mount Simav to the east. The territory records nearly 400 million years of Earth's history, with diverse and lithologically complex units from the Cambrian to the Quaternary making it one of the country's most geologically intricate regions. Among these, granitoid intrusions of varying ages represent a fundamental element of the regional geological framework, shaping both the geomorphological character and the geoheritage significance of the area.

Geological Setting Western Türkiye is characterized by widespread volcanic and plutonic rocks, including lava flows, pyroclastic deposits, genetically related hypabyssal intrusions, and extensive granitoid bodies (Fig. 2). Numerous studies have documented the temporal and spatial relationships between volcanic and plutonic activity in

Fig. 1 Geographic location and boundaries of the Ida Madra Geopark

the region (Altunkaynak and Yıldırım 2006; Bozkurt and Mittwede 2005; Genç and Altunkaynak 2007).

Geotectonically, the geopark is situated within the Sakarya Zone, one of four northeast–southwest trending tectonic zones that represent the eastern continuation of the Pelagonia Region of Greece and form the Biga and Gallipoli peninsulas. This zone occupies the southern sector of the Pontides (Okay and Satır 2006).

Following the collision between the Sakarya Zone and the Anatolide–Tauride continental blocks during the early Eocene, the İzmir–Ankara–Erzincan Ocean closed, triggering

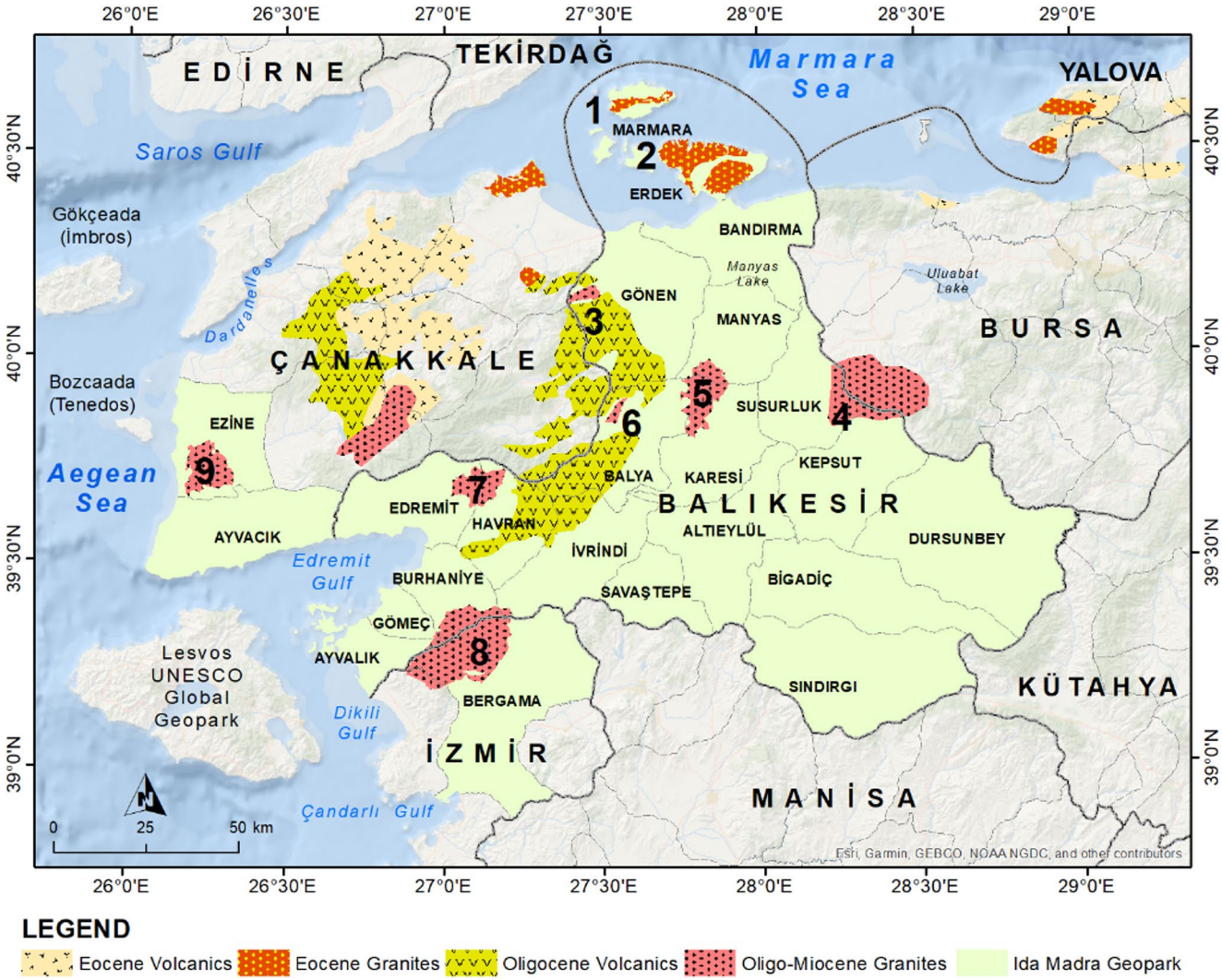

Fig. 2 Spatial distribution of plutonic bodies exposed within the Ida Madra Geopark territory, representing intrusive magmatism from the Eocene to Miocene. Eocene–Oligocene plutons comprise İlyasdağ and Kapıdağ, whereas the younger Oligocene–Miocene suite includes the Şaroluk, Çataldağ, Ilıca (Sularya), Göloba (Balya), Eybek, Kozak/Madra, and Kestanbol plutons. Modified after Akgündüz et al. (2012)

widespread magmatism and plutonism. Asthenospheric upwelling caused significant thermal disturbances, resulting in partial melting of the upper mantle lithosphere. This process generated extensive volcanism and granitic plutonism along the İzmir–Ankara suture zone and within the Sakarya continental domain (Altunkaynak and Yıldırım 2006; Altunkaynak et al. 2012). Magmatic activity was particularly concentrated north of the suture zone, especially on the Kapıdağ Peninsula, Marmara Island, and the Biga Peninsula (Yılmaz 1989, 1990; Güleç 1991; Seyitoğlu and Scott 1991). A second phase of magmatism occurred during the late Oligocene to Miocene (Okay and Satır 2006; Okay et al. 2024).

Cenozoic magmatism in northwestern Anatolia is represented by approximately west–east trending granodioritic plutons. The Kozak, Eybek, and Kapıdağ plutons are notable examples of the intrusive phases of this activity (Genç and Altunkaynak 2007). Granitoids—coarse-grained igneous rocks composed predominantly of quartz, plagioclase, and alkali feldspar—form through the slow cooling and crystallization of magma at depth. Subsequent uplift and erosion expose these rocks at the surface. Their slow crystallization produces high mechanical strength, while their coarse crystalline textures and varied colors provide distinctive aesthetic qualities that contribute to both geomorphological and geotouristic value.

Chemical weathering of granitic bedrock is typically concentrated along fractures and joint intersections. Corners and edges weather more rapidly than interior portions, producing rounded blocks surrounded by decomposed material. This process leads to the development of characteristic

granitic landforms such as tors, corestones, boulders, weathering pits, grus, and granite sand.

Paleogene and Neogene intrusive rocks are widely distributed throughout northwestern Türkiye. Within the Ida Madra Geopark, granitoid intrusions are exposed in nine distinct areas: the Kapıdağ, İlyasdağ, Kestanbol, Eybek, Kozak, Şaroluk, Ilıca, Göloba, and Çataldağ plutons. While the oldest pluton dates back to the Cretaceous, Paleocene and Neogene intrusions are more widespread (Delaloye and Bingöl 2000).

Geomorphological features of the area have evolved through a combination of fluvial erosion, marine processes, chemical weathering, volcanic activity, and tectonic movements. Distinct landforms with geoheritage significance have developed on volcanic, sedimentary, and metamorphic rocks throughout the Geopark. Rock outcrops reflect the region's paleogeography, while the landforms they form carry visual and cultural value alongside their scientific importance. Chief among these is the tor topography, which develops on granitoids and is widely represented in the Ida Madra Geopark.

The structural orientation of mountain ranges reflects the influence of neotectonic regimes, which continue to shape the landscape. Elevations vary from sea level along the coast to 1,774 m at Mount Ida (Kazdağı), with a mean altitude of approximately 425 m.

The Mediterranean climate dominates the region, with warm, dry summers and cool, rainy winters, while continental influences are evident inland. Climatic variability across coastal, lowland, and high mountain zones has contributed to diverse weathering processes affecting granite outcrops (Cürebal 2003; Cürebal et al. 2012).

Method

The study was conducted through an integrated workflow combining literature review, field investigation, spatial analysis, and quantitative geosite assessment. First, the geological and geomorphological framework of the study area was established through a review of published geological maps, technical reports, and previous scientific studies. These sources provided baseline information on lithology, structural setting, and landscape evolution.

Second, primary data were collected through systematic field surveys, supported by secondary data derived from satellite imagery and existing cartographic materials. Geological maps at scales of 1:25000 and 1:100000 were used to delineate granite and granodiorite outcrops and to guide field investigations. During fieldwork, granite landforms were identified and documented, and their distribution, morphology, and morphometric characteristics were recorded.

Structural controls on landform development were analyzed by examining joint orientation, fracture density, and weathering patterns within the host rocks. These parameters were evaluated to determine their influence on tor formation and block disintegration processes. Each landform was photographed, georeferenced, and mapped using GPS measurements (Fig. 3).

Over the last three decades, various methods for the protection, development and evaluation of geotourism and geoheritage have been developed (Pralong 2005; Pereira et al. 2007; Zouros 2007; Vujicic et al. 2011; Reynard et al. 2007; Fassoulas et al. 2012; Brilha 2016; Brilha et al. 2018; Kubalíková 2013; Kubalíková and Kirchner 2016; Migoń and Pijet - Migoń 2017).

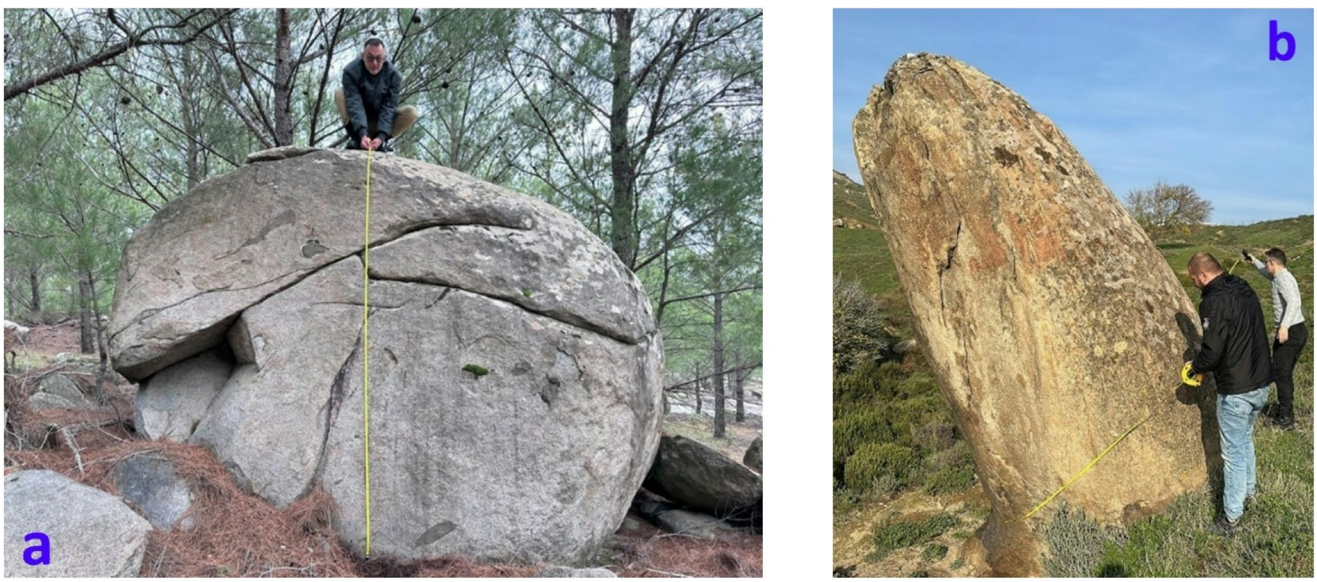

Fig. 3 (**a**, **b**) Field-based measurements of granitic landforms illustrating their morphology, scale, and weathering-controlled development, supporting geomorphological and geoheritage evaluation (Photographs by the authors)

The assessment of the geosites of a geopark not only has a scientific purpose but also aims at the management and conservation of its geological heritage at a certain territorial and legislative context and under the operational framework induced by UNESCO. In this regard geodiversity needs to be considered in a wider view, combining sustainable development with the conservation of geoheritage.

Each assessment method evaluates geosites using different criteria in order to identify their distinctive characteristics and relative significance. While some approaches primarily emphasize aesthetic appeal and scientific importance, others adopt a more comprehensive framework that considers the overall value of geosites by integrating scientific, educational, and geotourism dimensions. Such holistic evaluations enable a more balanced understanding of both the intrinsic and societal contributions of geoheritage sites (Bruschi et al. 2011; Brilha 2016).

Selected geoheritage areas and geosites in the study area were evaluated according to the method proposed by Kubalíková (2013). In the method proposed by Kubalíková, the evaluation criteria are grouped into five main categories: scientific and intrinsic, educational values, economical values, conservation values and added values (Table 1). According to these criteria, the geoheritage areas or geosites, were scored and evaluated.

Seven geosites—GS1 (Bağyüzü), GS2 (Hacıbozlar), GS3 (Kırtık), GS4 (Sinekli), GS5 (Gölcük), GS6 (Tatlısu), and GS7 (Tortepe)—were selected for assessment. The evaluation was conducted by a panel of five independent experts to ensure objectivity and methodological rigor. The panel consisted of two geomorphologists, one geologist, one tourism specialist, and one geographer, thereby providing interdisciplinary perspectives. Each expert assessed the geosites according to the criteria proposed by Kubalíková (2013), using a scoring scale ranging from 0 to 4 with 0.5-point increments. Each criterion was evaluated independently by five experts. The individual scores were summed and divided by five to compute the arithmetic mean, which was then rounded to the nearest 0.25 interval for standardization. The numerical values presented in Table 3 represent the average scores derived from these expert evaluations. The prevalence of whole and half-point values reflect the scoring framework, which was intentionally designed to allow only such increments. This procedure ensured consistency across assessments and facilitated meaningful comparison among sites.

The relationship between granite landforms and human activities was also assessed. Spatial proximity analyses were conducted to evaluate connections with settlements, historical quarries, and cultural features. Field observations were complemented by interviews with local stakeholders and a review of historical sources to document human–environment interactions and the cultural relevance of the sites.

Seven geosites representative of the granite topography of the Madra Mountain and Kapıdağ areas were selected based on criteria including representativeness, integrity, accessibility, and cultural significance. These sites were evaluated using the quantitative assessment method proposed by Kubalíková (2013), widely applied in geoheritage and geopark studies. This method classifies the assessment criteria into six main categories: (i) scientific and intrinsic value, (ii) educational value, (iii) economic value, (iv) conservation status and (v) added values. Each category is evaluated using standardized scoring thresholds (low <6, medium 6–12, high ≥ 12), enabling systematic and objective comparisons among geosites.

Finally, the spatial distribution of the selected geosites was mapped in a GIS environment to illustrate their geographic relationships and clustering patterns within the Ida Madra Geopark. The resulting geosite inventory and distribution map support both conservation planning and geotourism development.

Results

Granitoid intrusions are widespread in northwestern Türkiye and form the basis of the unique granite landforms in the Ida Madra Geopark. These granitoids provide the geological framework for the development of tors, boulders, and associated weathering features.

Tors and boulders, the main elements of granite topography (Table 2), not only create spectacular and aesthetically appealing landscapes. They represent the most significant geological heritage elements of the study area. Granitoid rocks occur at nine locations within the Ida Madra Geopark. Among these, Mount Madra and the Kapıdağ Peninsula—where the most striking examples of granite topography are found—were selected as case studies and examined in detail. The western slopes of Mount Madra are covered with granitic rock surfaces forming the southernmost part of the Kozak Pluton. Granite hills and tors particularly emphasize the distinctive features of the region and are recognized as important natural assets for geotourism.

Deep chemical weathering has been recognized as a fundamental process in the evolution of granite landforms, contributing to the development of tors and corestones (Twidale 1982; Migoń 2006; Scarciglia et al. 2016). Granite weathering occurs through granular disintegration, block breakdown, exfoliation, and spheroidal weathering. Joint systems play a critical role in initiating tor and boulder formation. In the study area, tors and boulders appear in diverse shapes and sizes, often associated with weathering pits, tafoni, and

Table 1 Geosite evaluation criteria (Kubalíková 2013)

Criteria		Geosite properties	Points
Scientific and intrinsic values	Integrity	totally destroyed site	0
		disturbed site. but with visible abiotic features	0.5
		site without any destruction	1
	rarity (number of similar sites)	more than 5 sites	0
		2–5 similar sites	0.5
		the only site within the area of interest	1
	diversity (number of different partial features and processes within the geosite or geomorphosite)	only one visible feature/processes	0
		2–4 visible features/processes	0.5
		more than 5 visible features/processes	1
	scientific knowledge	unknown site	0
		scientific papers on national level	0.5
		high knowledge of the site. monographic studies about the site	1
Educational values	representativeness and visibility / clarity of the features / processes	low representativeness/clarity of the form and process	0
		medium representativeness. especially for scientists	0.5
		high representativeness of the form and process. also for the laic public	1
	exemplarity, pedagogical use	very low exemplarity and pedagogical use of the form and process.	0
		existing exemplarity. but with limited pedagogical use	0.5
		high exemplarity and high potential for pedagogical use. goedidactics and geotourism	1
	existing educational products	no products	0
		leaflets. maps. web pages	0.5
		info panel. information at the site	1
	actual use of a site for educational purposes (excursions, guided tours)	no educative use of the site	0
		site as a part of specialized excursions (students)	0,5
		guided tours for public	1
Ecomonical values	accessibility	more than 1000 m from the parking place	0
		less than 1000 m from the parking place	0,5
		more than 1000 m from the stop of public transport	1
	presence of tourist infrastructure	more than 10 km from the site existing tourist facilities	0
		5–10 km tourist facilities	0,5
		less than 5 km tourist facilities	1
	local products	no local products related to a site	0
		some products	0.5
		emblematic site for some local products	1
Conservation values	actual threats and risks	high both natural and atrophic risks	0
		existing risks that can disturb the site	0.5
		low risks and almost no threats	1
	potential threats and risks	high both natural and athrophic risks	0
		existing risks that can disturb the site	0.5
		low risks and almost no threats	1
	current status of a site	continuing destruction of the site	0
		the site destroyed. but now with management measures for avoid the destruction	0,5
		no destruction	1
	legislative protection	no legislative protection	0
		existing proposal for legislative protection	0.5
		existing legislative protection (Natural monument. Natural reservation…)	1

Table 1 (continued)

Criteria			Geosite properties	Points
Added values	cultural values: presence of historical / archaeological / religious aspects related to the site		no cultural features	0
			existing cultural features but without strong relation to abiotic features	0.5
			existing cultural features with the strong relations to abiotic features	1
	ecological values		not important	0
			existing influence but not so important	0.5
			important influence of the geomorphologic feature on the ecologic feature	1
	Aesthetic values	number of colours	one color	0
			2–3 colors	0.25
			more than 3 colors	0,5
		structure of the space	only one pattern	0
			two or three patterns clearly distinguishable	0.25
			more than 3 patterns	0.5
		viewpoints	none	0
			1–2	0.25
			3 and more	0.5
Total Score				18.5

Table 2 Classification of granite landforms in the Ida Madra Geopark

Landform Type	Formative Process	Geoheritage Value
Tors	Deep chemical weathering along joint systems; block isolation and rounding	Scientific uniqueness; iconic landscape features; cultural associations
Boulders	Mechanical and chemical disintegration of granite masses; detachment from parent rock	Visual distinctiveness; educational examples of weathering
Exfoliation Domes	Pressure release and expansion causing onion-skin weathering	Aesthetic appeal; demonstration of physical weathering
Weathering Pits	Localized chemical dissolution on exposed surfaces	Scientific importance; micro-scale geomorphological processes
Tafoni	Weathering and granular disintegration in cavities	Educational potential; striking visual forms
Grus and Granite Sand	Advanced chemical weathering producing loose granular material	Economic and educational value; link to soil formation
Other granite outcrops with blocky morphology	Joint-controlled disintegration forming irregular clusters	Landscape diversity; cultural and archaeological associations

grus. These features are especially well developed in the Madra and Kapıdağ fields, where the geosites selected for this study are located.

On the tors of the Bağyüzü, Hacıbozlar, and Kırtık geosites in the Madra Mountains, localized pits and tafoni cavities reflect selective granular disintegration and moisture-controlled weathering processes, although their overall development remains limited. In contrast, these features are comparatively rare on the surrounding boulders, where more intensive onion-peel (exfoliation) weathering dominates, producing sheet-like spalling and rounded surfaces that give the blocks their characteristic smoothed and layered appearance. Distinct granitic domes and are uniquely developed within the Gölcük (GS5) geosite, distinguishing it from other areas of the geopark.

Geosite Descriptions

Seven geosites (GS1–GS7) were selected for detailed evaluation, each exhibiting distinctive geomorphological and cultural attributes. Of the seven geosites examined, five are situated on Mount Madra (Bağyüzü, Hacıbozlar, Kırtık, Sinekli, Gölcük) and two on the Kapıdağ Peninsula (Tatlısu, Tortepe). Together, these sites represent the most characteristic examples of granite landforms in the Ida Madra Geopark, encompassing tors, boulders, exfoliation domes, and spheroidal weathering features. Their distribution highlights the dual importance of Mount Madra as the core area of granite geoheritage and Kapıdağ as a complementary landscape where geomorphological diversity intersects with cultural traditions.

- GS1 (Bağyüzü): Extensive tor clusters reaching heights of 10–15 m, associated with stone pine (Pinus pinea) forests and traditional nut harvesting. Accessibility is high due to local roads.
- GS2 (Hacıbozlar): Large boulder fields shaped by spheroidal weathering, closely linked with nomadic pastoral culture. Ancient quarries in the area highlight its cultural significance.
- GS3 (Kırtık): Prominent tors and granite outcrops, representing diverse geomorphological forms.

- GS4 (Sinekli): Boulders and tors with moderate accessibility, valued for their aesthetic contribution to the landscape.
- GS5 (Gölcük): High-altitude tors offering panoramic views and strong educational potential for geomorphology and geotourism.
- GS6 (Tatlısu): Granite outcrops and tor formations, showcasing some of the finest examples of spheroidal weathering and exfoliation.
- GS7 (Tortepe): Striking tors and boulders of varied shapes, scientifically valuable for studying joint-controlled weathering and forming visually distinctive landscapes with tourism potential.

Taken together, the seven geosites demonstrate how granite landforms in the Ida Madra Geopark embody multidimensional geoheritage values. They reveal the interplay between geological processes, geomorphological diversity, and cultural traditions, while also offering strong educational and geotourism potential. This diversity underscores the importance of the geopark not only as a scientific archive of long-term landscape evolution but also as a cultural landscape where human activities and natural features are deeply intertwined.

General Characteristics of the Madra Mountain

Madra Mountain is located to the southwest of the study area and covers approximately 1250 km². Its highest peak, Maya Hill, reaches an elevation of 1344 m. The slopes are less steep in the southern and western parts, where the Kozak Pluton is located, while the northern slopes are dissected by deep valleys. Madra Mountain is a horst rising between the Bergama and Edremit Grabens, separated from the surrounding areas by normal faults. The Kozak vicinity, extending in the same direction, lies in the central part of Madra Mountain. Granite landforms occur on the northwestern slopes of the mountain (Efe et al. 2011a, b, 2012; Cürebal et al. 2012).

Granite landforms are found in five geosites (Gölcük, Sinekli, Kırtık, Bağyüzü, and Hacıbozlar) on the slopes of Mount Madra, all located within the granite field of the Kozak Pluton (Fig. 4).

Spheroidal weathering is particularly common in these geosites. It affects jointed bedrock and produces concentric or spherical layers of decayed rock. When exposed by erosion, these shells peel away like the layers of an onion. This process, also known as onion-skin or concentric weathering (Fairbridge 1968; Ollier 1971; Twidale and Romani 2005, Migoń 2006; Campbell et al. 1998), often creates rounded boulders known as corestones. Rounded tors are interpreted as evidence of emergence from the weathering mantle.

Kozak Pluton and Madra Tor Topography Northwestern Anatolia hosts numerous intrusive granitoid bodies. Among them, the Kozak pluton is the most extensive, covering an area of approximately 500 km². The pluton was regionally deformed and was emplaced during the Late Oligocene–Early Miocene. Although a high-level intrusion, it exhibits characteristics typical of deeply emplaced granites. Emplacement mechanisms range from diapiric intrusion at depth to passive emplacement, followed by tectonic movements that placed the pluton into subvolcanic levels (Altunkaynak and Yılmaz 1999; Altunkaynak et al. 2012). The Kozak granitoid pluton is surrounded by diverse magmatic and metamorphic rock units. Its structural development is controlled by NW–SE-trending fault systems, and it is bounded by grabens to both the south and north.

Kozak granites develop a characteristic tor topography, where exfoliation of the bedrock generates spherical to oval, meter-scale boulders that dominate and characterize the landscape. These features are concentrated on the northwestern slopes of Madra Mountain, with notable examples around Bağyüzü, Hacıbozlar and Kırtık villages. Many tors are characterized by rounded shapes, interpreted as evidence of emergence from the weathering mantle. Corestones near Bağyüzü and Hacıbozlar villages, created by spheroidal weathering and exposed through erosion of surrounding saprolite (Figs. 5 and 6), provide clear evidence of long-term geomorphological evolution.

Bağyüzü (GS1) Located on Madra Mountain in the southwestern sector of the Geopark, about 25 km from Ayvalık district, the Bağyüzü geosite lies near Bağyüzü village and benefits from easy access via a paved road. This accessibility enhances its suitability for educational visits, scientific observation, and sustainable geotourism development. The site is characterized by gently undulating topography with low-gradient slopes and lies at an elevation of about 460 m above sea level.

The boulders and tors are irregularly distributed across the area, occurring both as isolated blocks and as clustered groups. Some are fully exposed, while others remain partially embedded. Surface weathering is evident on both boulders and tors. Boulder diameters generally range from 1 to 3 m, with occasional examples reaching up to 5 m.

Five distinct locations feature boulders notable for their shape and visual appeal. The geosite lies at approximately 550 m elevation and covers an area of 1.6 km². It is largely covered by stone pine (Pinus pinea) forest, making it suitable for exploration on foot. The first boulder cluster is located in the southwest, while the remaining four are situated in the northeast. Distances between clusters are 100 m,

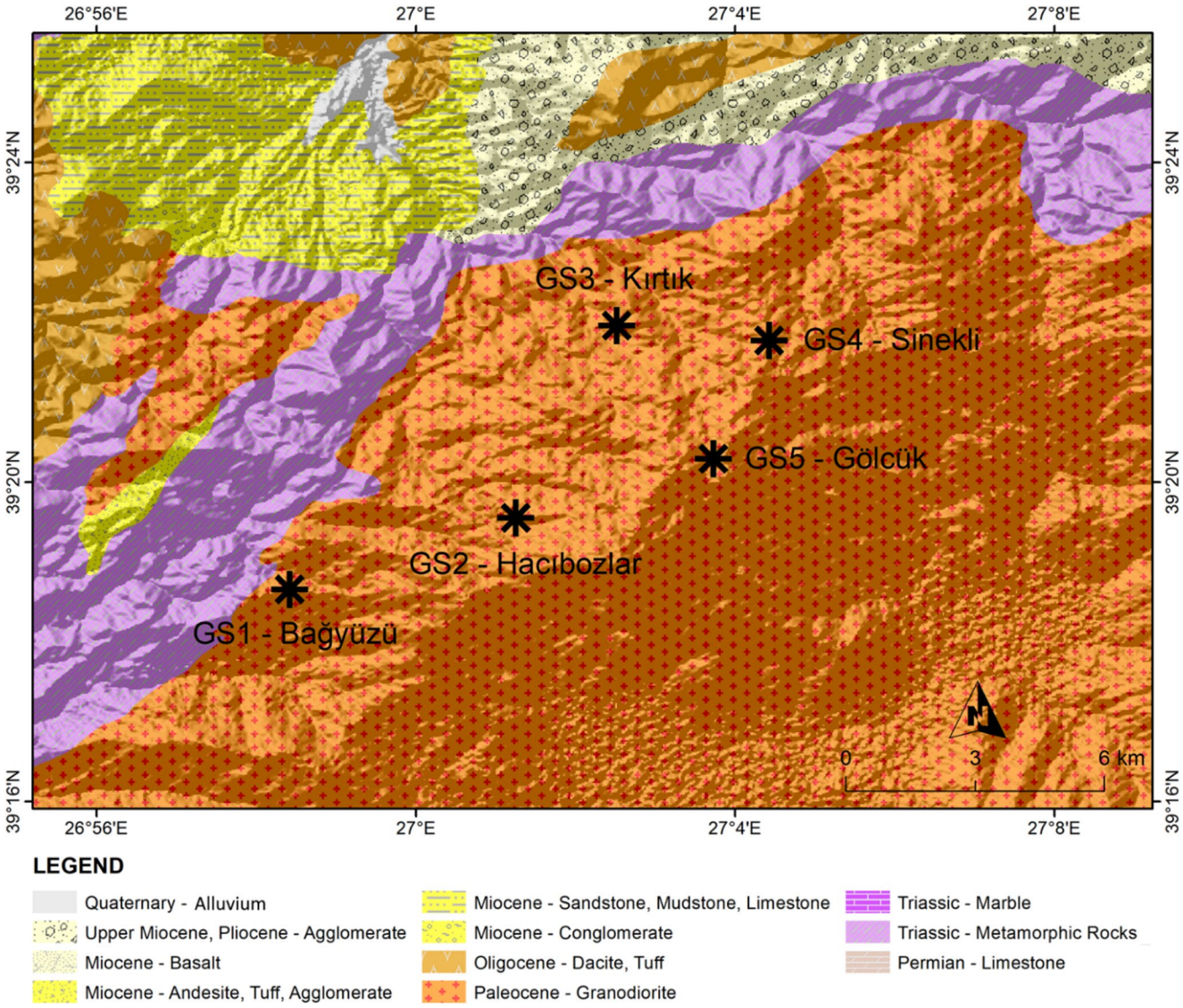

Fig. 4 Geological map of geosites in Mount Madra. (Source: Authors)

196 m, 97 m, and 105 m, respectively. Clusters 1 and 2 are within dense forest, whereas clusters 3, 4, and 5 occur in areas with sparser vegetation.

The boulders are generally aggregated, with some reaching 2.5 m in diameter. Vertical rock blocks exceed 4 m in height, displaying deep cracks, flaking, and splitting. Several blocks exhibit fissures formed by the widening of vertical joints (Fig. 5). Some tors contain shallow erosional pits, while smaller boulders are scattered in the southern part of the site. Sand and grus deposits are found on and adjacent to the local bedrock in the northwestern sector.

Overall, Bağyüzü offers a compact area where numerous visually and aesthetically distinctive tors and boulders can be observed within walking distance, making it a valuable geosite for both scientific study and geotourism.

Hacıbozlar (GS2) The second geosite is located near the village of Hacıbozlar, approximately 22 km southeast of Burhaniye. It lies on a low-inclination slope, with elevations ranging from 750 to 860 m above sea level. Tors and boulders are densely distributed around the village.

The Hacıbozlar site possesses both geological and cultural significance. To the west of the village, a large association of bedrock outcrops and boulders occurs within an open pine forest, offering striking examples of weathering features. Various forms of tor topography are present, including boulders, tors, and pits. Numerous boulders are scattered across the slopes, some reaching lengths of up to 10 m. Rounded granite surfaces emerging above ground level may represent boulders partially embedded in the grus

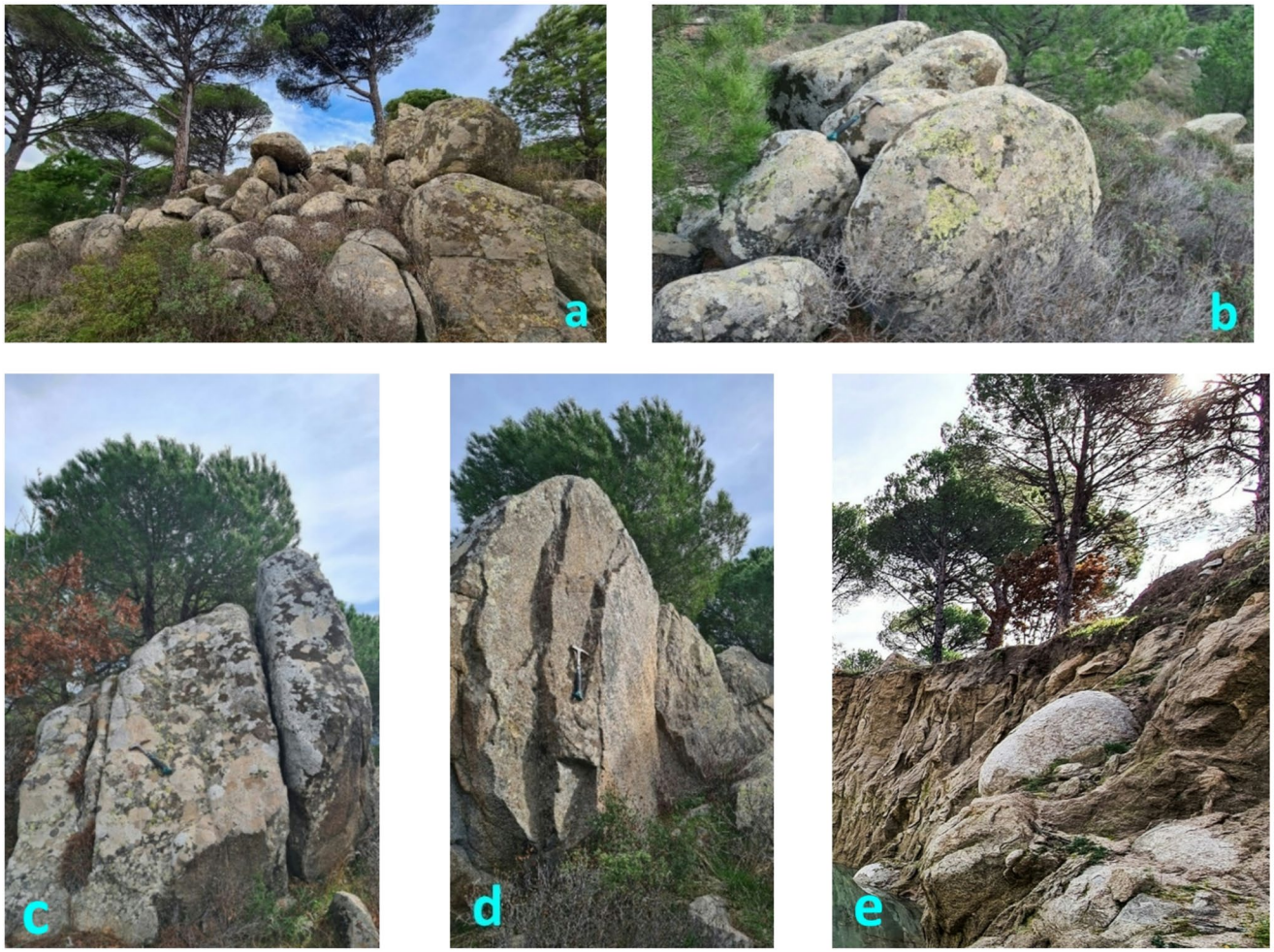

Fig. 5 Photographs from geosite 1 (GS1): (**a**) Granite terrain characterized by abundant large boulders and tors; (**b**) granite boulders exposed following the erosion of the weathering mantle, (**c**) A block split along two parallel joints, (**d**) A granite boulder affected by various weathering and breakdown processes, including flaking and splitting, (**e**) boulders partially embedded in the grus (photographs by the authors)

Fig. 6 Photographs from geosite GS2: (**a**) Jointed granite outcrop controlling blocky disintegration, (**b**) Armchair-shaped hollow formed by corestone removal through spheroidal weathering, (**c**) Rounded corestones within a deep weathering profile on coarse granite (Photographs by the authors)

weathering mantle or solid bedrock. Several outcrops are particularly distinctive due to their unusual shapes (Fig. 6).

This geosite contains rare specimens, especially those developed in coarse granite, with rounded corestones within a deep weathering profile. Some rocks exhibit hollowed forms where the inner core has been removed, leaving seat-like structures (Fig. 6). Five specific locations have been identified for their size, appearance, and geomorphological interest. The first, located 2 km northwest of the village, consists of scattered boulders with irregular shapes. Two additional areas, situated 2 km northeast, contain dense clusters of large boulder blocks.

Kırtık (GS3) The Kırtık geosite is located approximately 3 km southeast of Kırtık village, within an area surrounded by pine forests. It is encircled by hills ranging in elevation from 780 to 914 m, while the tors and boulders themselves occur between 600 and 650 m above sea level on the western slopes of Madra Mountain.

Numerous tors and boulders of varying sizes have been identified at several locations within the site. The tors here are particularly notable, being both larger and more abundant compared to those observed in other geosites. Among the most prominent features is the Andık (Hyena) Rock Tor, situated near plateau dwellings. Measuring 14 m high, 7 m wide, and 11 m long, this fractured tor consists of five stacked granite blocks, with more fragments at the base and fewer toward the top. Its south-facing side is steep, while the north-facing slope is gentler. Although pine trees surround the area, they do not obscure the rock, which retains strong aesthetic appeal. Other outcrops are striking due to their unusual shapes, such as a 5 m-high block with a shield-like form and deep basal incision. Located on a high hill, this rock also holds historical significance, reportedly serving as a bandit shelter and later as a Roman watchtower.

The geosite also contains nearly spherical, well-rounded boulders whose distinctive forms create an attractive and visually striking landscape (Fig. 7). Some of the deeply weathered granites have decomposed into sandy residual material, leaving behind granite grit and larger fragments. This sandy soil, formed through erosion and weathering, provides ideal conditions for local villagers to cultivate vegetables such as beans, peppers, squash, and strawberries. During the summer months, livestock raising and small-scale farming are actively practiced.

Depending on the granite type, weathering sometimes breaks the rock into smaller fragments, resulting in the formation of arena deposits (granite sand) alongside grus. Arena formation is particularly common in the tor zones around the Kırtık highland (Kajdas et al. 2017).

Sinekli (GS4) The Sinekli geosite is located approximately 5 km southeast of Kırtık village. The average elevation is about 940 m above sea level. It represents a plateau where tors and boulders formed on the Kozak granite pluton are widespread. During the summer months, local villagers engage in small-scale agriculture and animal husbandry in the area.

The site is characterized by extensive black pine (*Pinus nigra*) forests, with granite landforms occurring both within the forest and in partially open areas. Boulders of various sizes are scattered across the plateau, with some blocks reaching heights of up to 5 m. In other parts of the site, numerous boulders measuring 5–6 m are irregularly distributed, creating a distinctive granite landscape (Fig. 8).

Gölcük (GS5) The Gölcük geosite is located approximately 4 km south of the Sinekli geosite, near the summit of Mount Madra. It represents the highest plateau of the mountain, with an average elevation of about 1080 m above sea level. Surrounded by gently rising hills, the granite-dominated topography within the site ranges between 1050 and 1108 m.

Compared to other geosites in the area, Gölcük covers a relatively large surface area. Granite tors and numerous large boulders are widely distributed across nearly 4 km². Owing to the plateau's gentle slopes and generally flat topography (Fig. 9), the area can be easily explored on foot, while access by all-terrain vehicles is also possible.

Geologically, the plateau developed on the granitic bedrock of the Kozak Pluton and is encircled by dense black pine (*Pinus nigra*) forests. During humid seasons, a temporary shallow lake forms in topographic depressions, adding seasonal hydrological and ecological value to the landscape. The site is characterized by scenic beauty, open vistas, and a well-preserved natural environment, as well as relatively rich water resources (Efe et al. 2011a, b, 2012).

The plateau also maintains traditional pastoral land use. Approximately twelve households inhabit the area during the summer months, primarily engaging in livestock breeding, with goats being the dominant species (Fig. 9). Used as a seasonal pasture by residents of Kuyumcu Village, the site reflects a harmonious interaction between geomorphological features, wildlife, and human activity.

Overall, the combination of extensive granite tors, forested surroundings, seasonal wetlands, and ongoing pastoral practices makes Gölcük Plateau a distinctive geomorphological and cultural landscape within the Ida Madra Geopark.

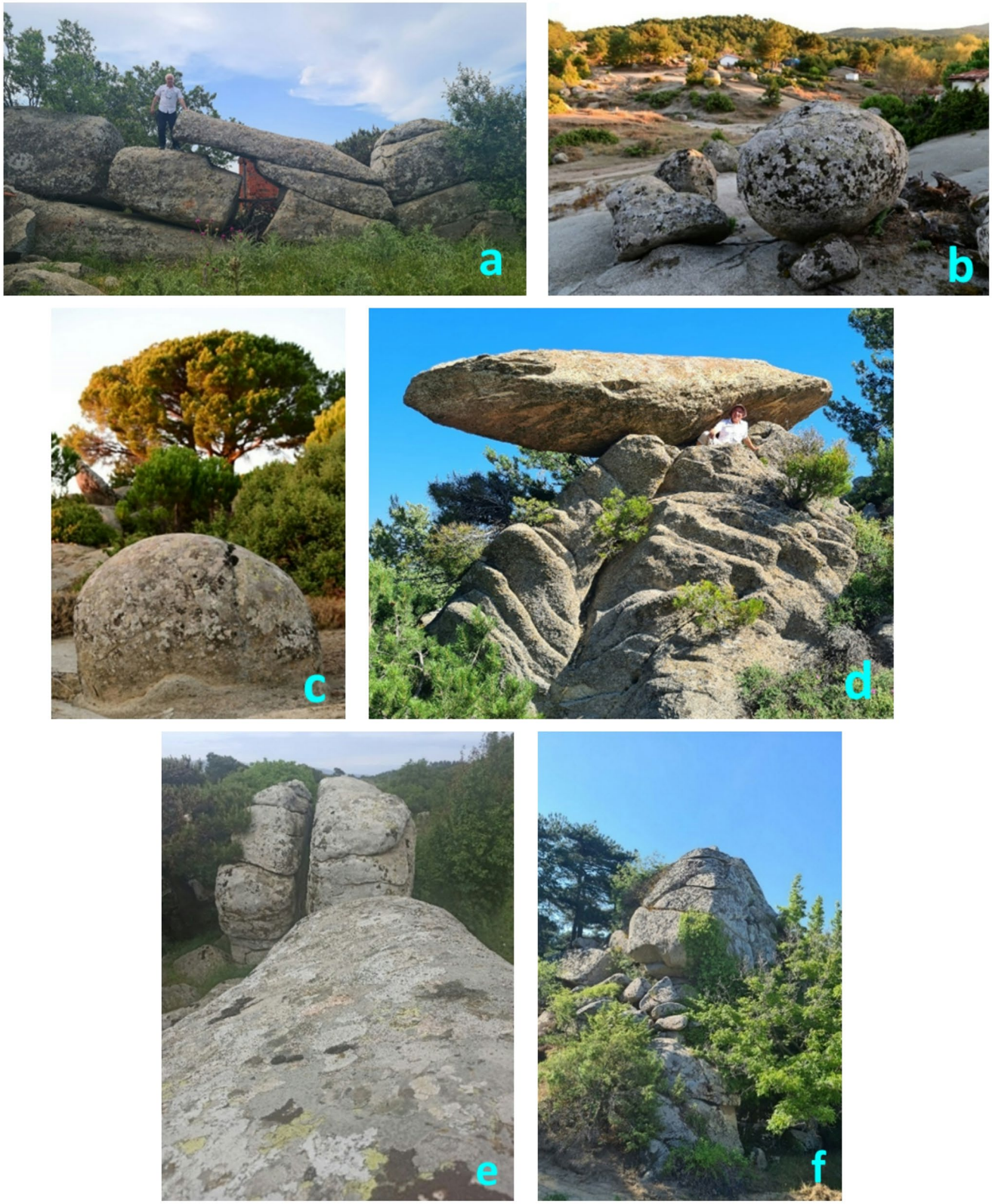

Fig. 7 Field photographs from the Kırtık Highland geosite illustrating characteristic granite tors and associated weathering features: (**a**) Tors near Kırtık highland, (**b**) Deeply weathered granite and boulders, (**c**) Rounded shape boulder under the pine trees, (**d**) Tor and exposed rock platform at Kırtık geosites, (**e**) Oval and split tors, (**f**) Andık tor at Kırtık (Photographs by authors)

Fig. 8 (**a**) Tors in the Sinekli highland, (**b**) Researchers on granite tors (Photographs by authors)

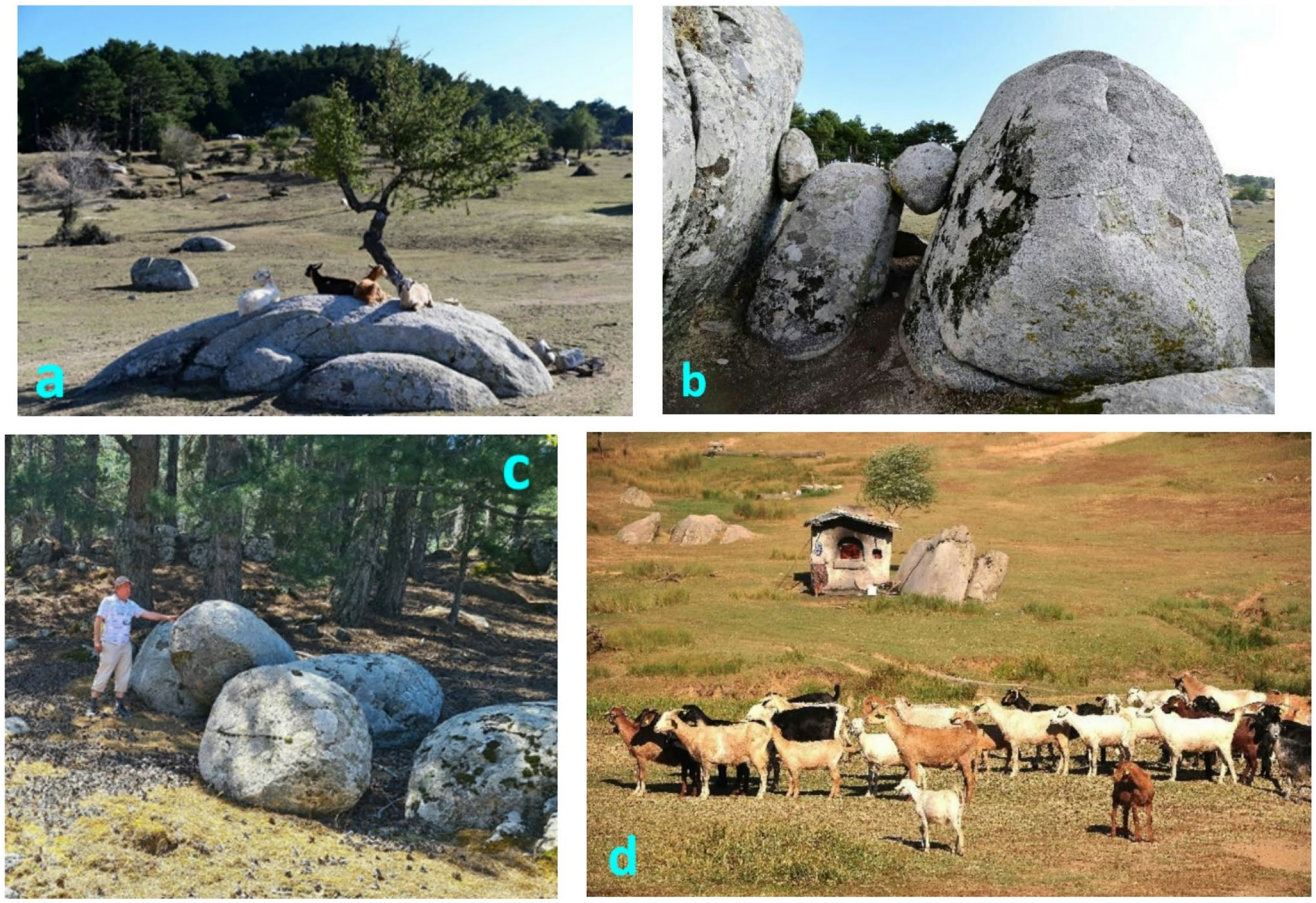

Fig. 9 (**a**) Corestones in the Gölcük locality formed by spheroidal weathering and subsequently exposed through the erosion and removal of the surrounding saprolite. (**b**, **c**) Tors and boulders in the Gölcük plateau geosites, (**d**) The Gölcük Plateau geosite represents a distinctive landscape where granite-dominated topography harmoniously coexists with traditional livestock grazing and small-scale natural vegetable cultivation, reflecting the long-standing interaction between geological features and rural land-use practices (Photographs by the authors)

Kapıdağ Peninsula

The Kapıdağ Peninsula represents a structural and geomorphological continuation of the southern mainland. Tectonic activities occurring during the late Pliocene and early Quaternary played a significant role in shaping both the Kapıdağ massif and the present-day morphological characteristics of the southern mainland (Cürebal et al. 1998).

The Kapıdağ pluton within the study area is Upper Cretaceous in age and displays granitic to granodioritic lithological characteristics (Fig. 10). The Kapıdağ Granite intruded into Lower Paleozoic and Precambrian crystalline schists. Subsequently, a steeply dipping, left-lateral strike-slip fault forming the western branch of the North Anatolian Fault Zone (NAF) cut through and deformed the granite intrusions (Aksoy 1996).

Kapıdağ Pluton and Granite Landforms Tatlısu (GS6)

A distinctive tor topography occurs along the eastern coast of the Kapıdağ Peninsula near the Erdek district. These formations are notable for their characteristic features, with spheroidal weathering (Fig. 11), exfoliation, and onion-skin weathering commonly observed in the granitic rocks around Tatlısu village. Several outcrops are particularly striking due to their unusual shapes. Granite landforms are widely distributed across the eastern part of the Kapıdağ Peninsula, which constitutes the northern sector of the Ida Madra Geopark.

The Tatlısu geosite is situated on a sea-facing slope along the northern coast of Bandırma Bay, approximately 2.5 km east of Tatlısu village and about 100 m inland from the shoreline. The site displays some of the finest examples of exfoliation (onion-skin weathering) developed on granitic rocks. Within the area—formerly used as a quarry—distinct

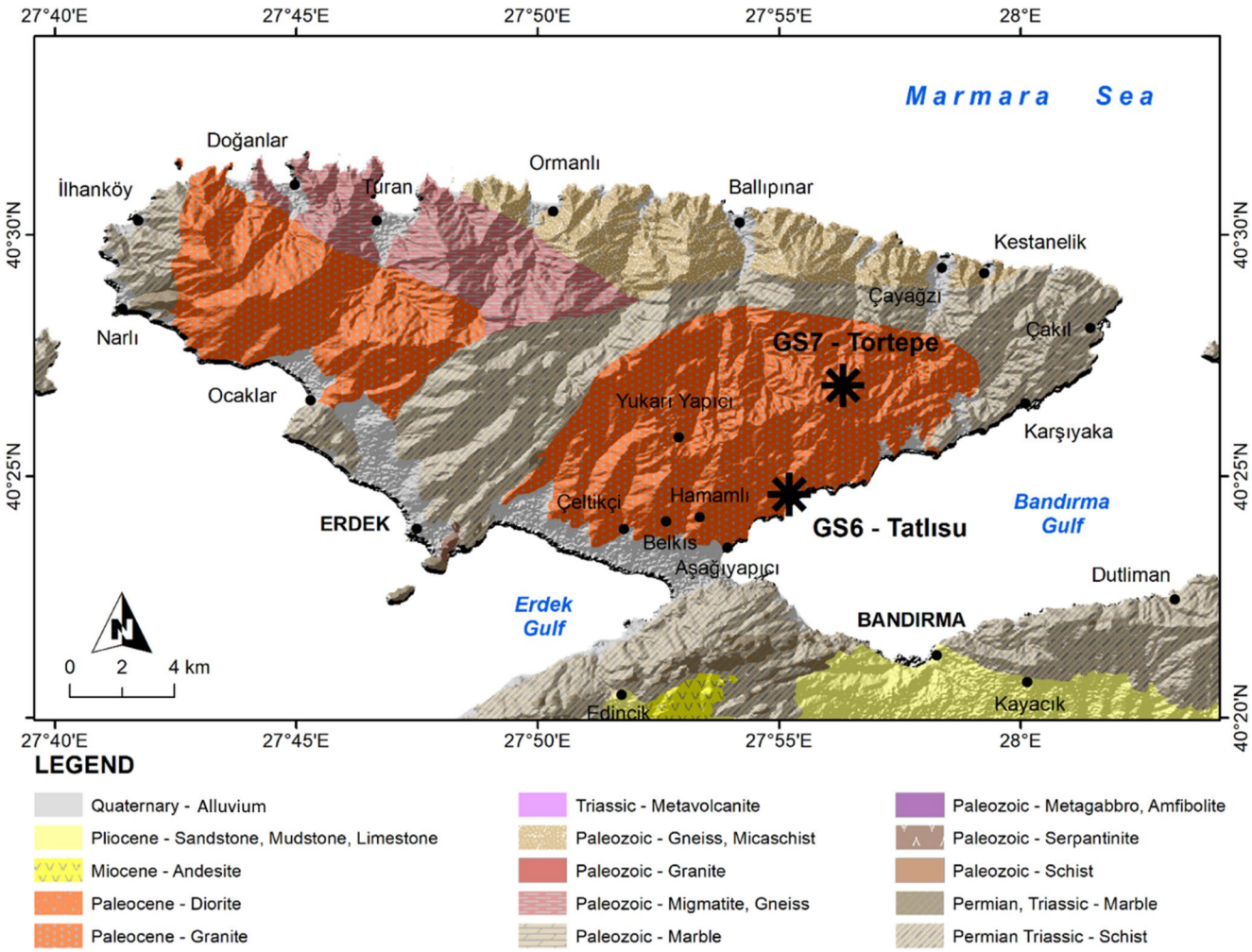

Fig. 10 Geological map of geosites in Kapıdağ peninsula (Source: Authors)

Fig. 11 (**a**, **b**) Spheroidal weathering and exfoliation on granitic rocks near Tatlısu village (Photographs by authors)

stages of granite weathering can be clearly observed, offering valuable insights into physical weathering processes.

Due to its proximity to the settlement and easy accessibility, the Tatlısu geosite can be conveniently visited by a wide range of visitors. Its combination of geological distinctiveness and accessibility makes it highly suitable for both educational purposes and geotourism activities.

Tors of high visual value, boulders, and rock outcrops have been identified at seven different locations within the site. Six of these are spread across an area of 1.5 km², while another lies approximately 500 m to the west. A single granite block, measuring 4 m high and 12 m wide, presents a striking appearance. Adjacent to this block is a sheep pen, reflecting the integration of traditional livestock farming with the natural landscape. This feature lies at an elevation of 50 m above sea level.

Overall altitude within the geosite ranges between 85 and 110 m. Granite formations are located on slopes overlooking the sea, with blocks displaying diverse shapes—round, vertical, oval, and horizontal. Some granitic outcrops resemble "horns," forming visually striking and geomorphologically distinctive rock features that are relatively rare in the landscape (Fig. 12c). Sparse shrub vegetation ensures that the granite topography remains clearly visible. The site is easily accessible via a stabilized road extending about 550 m from the main asphalt road, suitable for both pedestrians and off-road vehicles.

The site also provides opportunities to observe the initial stages of tor and boulder formation. Overlying layers have gradually eroded, exposing granite at the surface, where it has undergone intense weathering. Diagonal and rectangular joint systems formed by surface fractures play a critical role in controlling the weathering process. These discontinuities facilitate water infiltration and enhance both physical and chemical weathering. Vegetation growing along the cracks further accelerates decomposition through root penetration and biological activity (Fig. 12).

Tortepe (GS7) The Tortepe geosite is characterized by impressive granite outcrops, tors, and large boulders that form a distinctive landscape. A prominent hill in the southeastern part of the Kapıdağ Peninsula overlooks the sea and exhibits striking examples of granite topography. Hundreds of tors and scattered boulders are distributed along the seaward slopes, creating remarkable geomorphological scenery and highlighting the effects of long-term weathering and erosion (Fig. 12).

Geosite and Geoheritage Assessment

One of the most important outcomes of geoheritage diversity is its support for local communities through geotourism. Before planning for tourism purposes, geoheritage must first be identified and evaluated. Once defined, its use can be organized by considering scientific, educational, aesthetic, cultural, economic, and other values. After these aspects are examined, geological heritage assets can be utilized more effectively and sustainably.

The numerical values in Table 3 represent the mean scores calculated from expert evaluations. The predominance of whole and half-point values reflects the predefined scoring framework, which was intentionally designed to allow only such increments. This standardized procedure ensured consistency across assessments and enabled meaningful comparisons among the geosites.

The Kubalíková (2013) assessment revealed clear contrasts among the seven geosites, reflecting differences in geomorphological distinctiveness, cultural associations, and conservation status. Beyond the numerical scores, the following synthesis connects the results to the geological and cultural features described earlier.

High-value sites such as Gölcük (GS5) and Bağyüzü (GS1) exemplify the scientific uniqueness of granite tors, boulders, and stratigraphic exposures. Gölcük's high-altitude

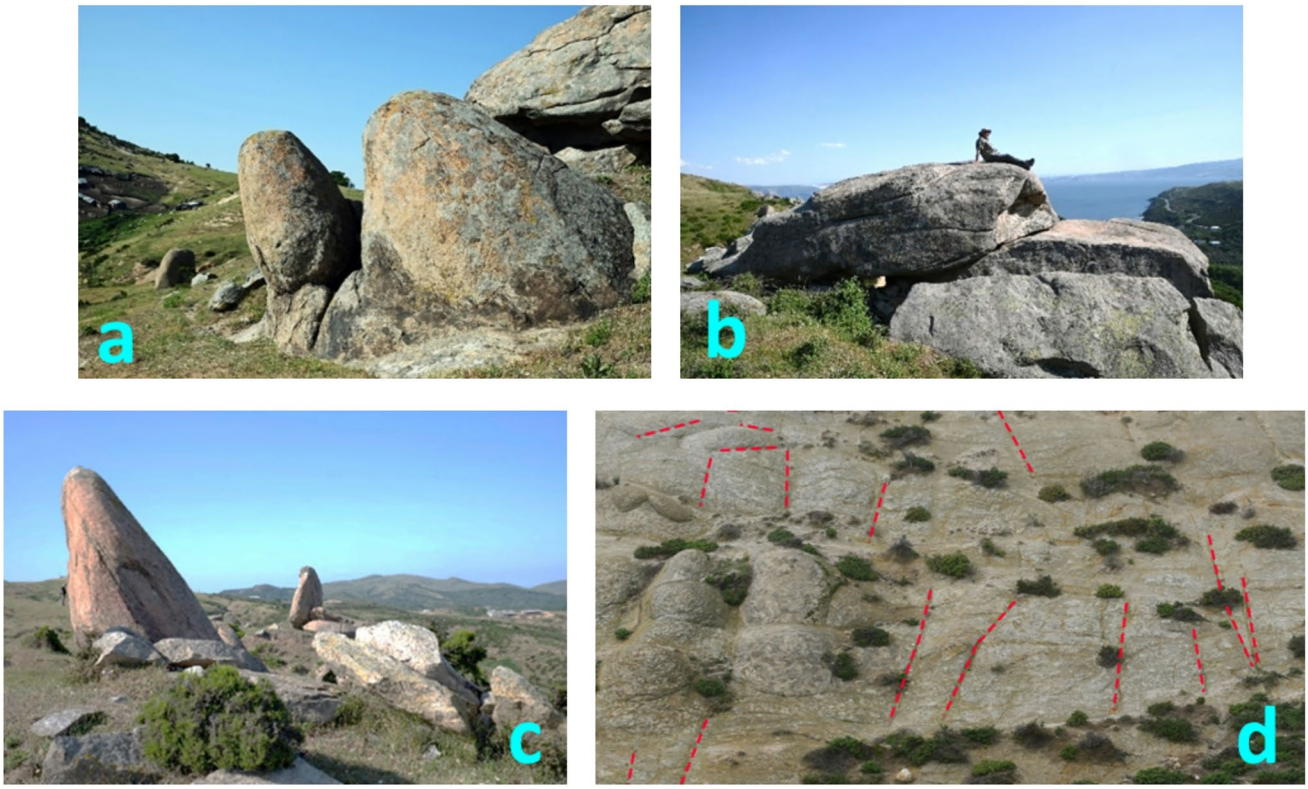

Fig. 12 (**a**, **b**) Granite landforms, tors and boulders near Tatlısu village, (**c**) A distinctive horn-shaped granitic outcrop (horn rock), representing a unique geomorphological feature confined to this geosite within the study area. (**d**) Tor formations in initial stages of development associated with cracks on the granitic bedrock near Tatlısu village. Dashed red lines are joint traces (Photographs by authors)

tors, formed through spheroidal weathering, provide panoramic viewpoints and strong cultural associations, explaining its top ranking. Bağyüzü's stratigraphic sections, noted for their role in interpreting regional geological and geomorphological evolution, justify its high scientific score. Both sites benefit from relatively intact conservation conditions, making them priority areas for geopark management.

Hacıbozlar (GS2) and Kırtık (GS3) scored highly due to added values. Boulder fields shaped by spheroidal weathering are closely linked with pastoral traditions, highland transhumance practices, and local agriculture, thereby enhancing both cultural significance and aesthetic value. These examples illustrate how human–landscape interactions elevate geoheritage significance beyond geology alone.

Moderate-value sites—Sinekli (GS4), Tatlısu (GS6), and Tortepe (GS7)—highlight the importance of accessibility, conservation, and cultural context. Sinekli's granite morphology supports educational use but faces grazing pressures. Tatlısu's low conservation score reflects settlement proximity, sparse vegetation, intensive grazing, and ongoing erosion. Tortepe's tors and boulders, while scientifically valuable, lack strong cultural associations, limiting their added values. These sites require targeted interventions such as protective measures, interpretive panels, and infrastructure improvements.

Overall, the assessment confirms that all seven geosites are significant geoheritage resources. High scientific and educational values contrast with uniformly low economic scores, revealing a gap between inherent site quality and practical utilization. Addressing this gap through strategic planning, infrastructure development, and community-based tourism will be essential to maximize both heritage protection and local socioeconomic benefits.

Discussion

Cultural and Archaeological Significance

In the Madra Mountain, where tor topography is widespread, strong relationships link geological features, landforms, and human activities across time. The region has long functioned as a settlement area and seasonal migration route for Anatolian nomads (Yörüks). Granite-dominated highlands continue to serve as summer pastures, supporting livestock grazing and small-scale agriculture.

Sandy soils formed through granite weathering favor the growth of stone pine (*Pinus pinea*), whose canopies create a harmonious landscape with scattered boulders and tors.

Table 3 Geosite assessment values granitic geosites of Ida Madra Geopark*

Criteria			Geosites						
			GS1	GS2	GS3	GS4	GS5	GS6	GS7
1. Scientific and intrinsic value (max. 4 points)	Integrity		1	0.5	0.5	0.5	0.5	0.5	1
	Rarity		1	0.5	0.5	0.5	1	1	1
	Diversity		1	1	1	1	1	0.5	1
	Scientific knowledge		1	1	0.5	0.5	0.5	0.5	0.5
Total			4.0	3.0	2.5	2.5	3.0	2.5	3.5
2. Educational values (max. 4 points)	Representativeness and visibility		1	1	1	1	1	1	1
	Exemplarity, pedagogical use		1	1	1	1	1	1	1
	Existing educational products		0.5	0.5	0.5	0.5	0.5	1	1
	Actual use of a site for educational purposes		0	0.5	0	0	0	0	0
Total			2.5	3.0	3.0	2.5	2.5	3.0	3.0
3. Economical values (max. 3 points)	Accessibility		0.5	1	0.5	0.5	0.5	0.5	0.5
	Presence of tourist infrastructure		0.5	0	0	0	0	1	1
	Local products		0.5	0.5	1	1	1	0	0
Total			1.5	1.5	1.5	1.5	1.5	1.5	1.5
4. Conservation values (max. 4 points)	Actual threats and risks		1	0.5	0.5	0.5	1	0	0.5
	Potential threats and risks		1	0.5	0.5	0.5	1	0	0.5
	Current status of a site		1	0.5	0.5	1	1	0.5	1
	Legislative protection		0	0	0	0	0	0	0
Total			3.0	1.5	1.5	2.0	3.0	0.5	2.0
5. Added values (max. 3.5 points)	5a. Cultural values (max. 1 points)		0.5	1	1	1	1	0	0
	5b. Ecological values (max. 1 points)		0.5	1	1	1	1	0.5	0.5
	5c. Aesthetic values (max. 1.5 points)	Number of colors	0.25	0.5	0.5	0.5	0.5	0.5	0.5
		Structure of the space	0.5	0.5	0.5	0.5	0.5	0.5	0.5
		Viewpoints	0.25	0.5	0.5	0.25	0.25	0.25	0.25
Total			2.0	3.5	3.5	3.25	3.25	1.75	1.75
Overall Total			13.0	12.5	12.00	11.75	13.25	9.25	11.75

* The table was created using the Kubalíková (2013) method. As shown in Table 3, GS1 and GS5 stand out for their scientific and conservation values, while GS2 and GS3 are elevated by cultural and ecological contributions

These soils also support vegetable cultivation, viticulture, and pine nut production—an economically valuable product widely used in Anatolian cuisine. Traditional pastoral practices have helped maintain the natural landscape and indirectly contributed to the conservation of granite landforms. At the Gölcük geosite, the combination of natural habitats, livestock farming, and tor topography enhances both geoheritage value and opportunities for nature-based tourism.

Madra Mountain hosts outstanding ancient quarries, giving the site geo-archaeological value. The "Marmor Misium" granite was widely used in antiquity, especially for columns and slabs (De Vecchi et al. 2000). Quarried locally from the Roman period onward, it was later exported to other Mediterranean centers. Remnants such as monoliths, fragmentary columns, and sarcophagi, along with wedge holes and quarrying traces, highlight the region's historical significance (Özgen and Denktaş 2018).

Three ancient quarries are located on the northwestern slopes of Madra Mountain (Fig. 13). The first is at Tüğlü Hill, 2 km northeast of Hacıbozlar village; the second at Çamtepe, 2.5 km southeast of Kuyumcu village; and the third on the southern and western slopes of Kaktaş Hill near Kuyumcu village. These quarries, exploited during the Roman period, contain partially processed building materials such as columns and sarcophagi, with grooves and wedge holes revealing extraction techniques.

The granite tor topography demonstrates strong interconnections between landforms and human use. This cultural dimension is reflected in evaluation results: geosites such as GS1, GS2, GS3, and GS5, which scored in the high-value category (≥ 12 points), owe part of their elevated scores to cultural and added values. For example, GS2 and GS3 achieved maximum points in added values, underscoring the importance of cultural and ecological dimensions (Table 4).

Economically, the Madra region is renowned for pine nut production, a highly valued ingredient in Anatolian cuisine. The integration of pine forests with spherical granite boulders enhances both aesthetic and economic values. Olive cultivation in the foothills (Efe et al. 2008, 2011a, b), supported by granite crushing stones used for millennia, further strengthens ties between geology and human activity.

Fig. 13 (**a**, **b**, **c**) Roughly hewn column shafts and unfinished architectural fragments in the ancient quarries of Çamgedik and Kaktaş Hill. (Photographs courtesy of Özgen H.M., Adramytteion Researches Archive)

Table 4 Cultural Drivers of Geosite Scores

Geosite	Cultural Drivers	Score Highlights	Weaknesses Limiting Scores
GS1 (13.0, High)	Summer pastures, livestock farming traditions, integration of tors into daily life	Strong scientific (4.0), good conservation (3.0), cultural added value (1.0)	Limited educational use (0 actual use), modest economic (1.5)
GS2 (12.5, High)	Pine nut production, cultural/ecological values at maximum	High educational (3.0), added values (2.0), aesthetic (1.5)	Weak conservation (1.5), no legislative protection
GS3 (12.0, High)	Archaeological use (Andık Rock as Roman watchtower), cultural farming practices	Educational (3.0), added values (2.0), aesthetic (1.5)	Lower scientific knowledge (0.5), weak conservation (1.5)
GS4 (11.75, Medium)	Bandit shelter (Kalkan Rock), small-scale farming traditions	Balanced scientific (2.5) and conservation (2.0)	No legislative protection, modest aesthetic (1.25)
GS5 (13.25, High)	Olive oil production with granite crushing stones, nomadic heritage	Strong scientific (3.0), conservation (3.0), added values (2.0)	Limited educational use (2.5), modest aesthetic (1.25)
GS6 (9.25, Medium)	Educational potential from farming practices, cultural landscape	Educational (3.0)	Very weak conservation (0.5), low added values (0.5), no legislative protection
GS7 (11.75, Medium)	Livestock farming and summer migration traditions, tors as cultural symbols	Strong scientific (3.5), educational (3.0)	Added values low (0.5), conservation moderate (2.0), aesthetic modest (1.25)

The nomadic Yörük culture has historically embraced and preserved granite boulders, creating strong links between geology, archaeology, and local traditions. This is particularly evident in GS5, which achieved one of the highest overall scores (13.25), supported by strong scientific and conservation values alongside cultural significance. Similarly, GS6, despite its lower overall score (9.25), demonstrates high educational potential but suffers from weak conservation, underscoring the need for management interventions.

Cultural factors influencing geosite scores vary considerably across the study area. High-value geosites (GS1, GS2, GS3, and GS5) demonstrate strong cultural and ecological linkages through pine nut harvesting, olive oil production, pastoral practices, and archaeological heritage. Medium-value geosites (GS4, GS6, and GS7) contain cultural elements but are constrained by insufficient conservation and limited legal protection. GS6 appears particularly vulnerable, despite its considerable educational potential.

Specific examples highlight the anthropic use of granite landforms: Kalkan Rock (Kırtık geosite) served as a bandit shelter, while Andık Rock functioned as a Roman watchtower. In rural settlements, granite blocks are used as simple building materials, reinforcing the cultural integration of geology into daily life.

The Gölcük, Kırtık, and Sinekli geosites exemplify geocultural significance, where local populations engage in livestock and small-scale farming during summer months. Their scores in educational and added values confirm their role as geocultural geosites. Recent methodological approaches (Kubalíková 2013; Reynard and Giusti 2018; Pereira et al. 2007; Reynard et al. 2016; Fassoulas et al. 2012; Różycka and Migoń 2018) emphasize integrating cultural values into geosite evaluation. The Madra case study demonstrates that combining quantitative scoring with cultural and archaeological narratives provides a holistic understanding of geoheritage significance.

Geoheritage, Geoconservation and Provisions for Geotourism

Granite topography in the Ida Madra Geopark represents significant geoheritage assets with considerable tourism potential. These formations possess strong aesthetic qualities that

Fig. 14 Directional signage along the access routes to the geosites, together with interpretive panels located within the site areas, guide visitors while providing educational and explanatory information on the geological heritage, geomorphological features, and associated cultural values, thereby enhancing visitor awareness, interpretation, and sustainable geotourism experiences

appeal to the general public, while their geological and geomorphological characteristics are easily understood even by non-experts. The sites are therefore convenient to visit and provide quick access to meaningful geoheritage experiences. Although they do not currently benefit from strict conservation status, their location within forest land ensures partial protection, as unauthorized rock extraction or tree felling is prohibited. Establishing a systematic inventory of the granite topography would allow for more comprehensive protection, particularly for the large boulders and monoliths regarded as natural monuments. The absence of quarrying activity further preserves the integrity of these landforms, enabling their sustainable use for tourism through careful planning.

All geosites are situated on public land. Sites 1 to 3 are located on property owned by the Ministry of Forestry, where trees and other natural assets are directly protected, while areas with reduced forest productivity are available for local villagers, primarily for animal husbandry. Geosites 4 and 5 are owned by village legal entities and serve as pastures. The area encompassing geosites 6 and 7 is publicly owned and predominantly used for livestock farming. The distribution of granite topography across these sites varies between 0.15 km² and 4 km². To maintain visibility of the most significant rock blocks, invasive plants and shrubs are regularly cleared. Their proximity to Ayvalık, Burhaniye, and Erdek—centers of active tourism—combined with well-maintained access roads, makes them popular destinations. These areas attract nature enthusiasts and are actively promoted as geotourism destinations, where visitors can engage directly with distinctive geomorphological landscapes. Easily accessible by both vehicle and on foot, the sites enable exploration of prominent rock formations, scattered stone blocks, and monolithic structures along designated hiking trails. Directional signage facilitates safe movement and encourages structured interpretation of the terrain.

Interpretive panels provide comprehensive information on the geology, geomorphology, cultural heritage, flora, and fauna of the area, often supported by diagrams that explain the processes responsible for the formation and long-term evolution of the granite landforms (Fig. 14). Thematic walking routes link the most representative geological features, allowing visitors to connect scientific understanding with the cultural and environmental context of the landscape. Consequently, these geosites function not only as recreational spaces but also as open-air classrooms, enhancing public awareness, appreciation, and conservation of geological heritage.

Conclusions

The evaluation of granite landforms in the Ida Madra Geopark confirms their outstanding significance as geoheritage resources. Tors, boulders, exfoliation domes, and spheroidal weathering features not only document long-term geomorphological processes but also demonstrate strong cultural and ecological associations. These granite landforms represent distinctive geoheritage elements with high scientific, educational, and aesthetic value. Their close integration with local traditions

and their considerable geotourism potential further highlight the need for effective conservation and sustainable management.

The systematic assessment of seven representative geosites revealed high scientific and educational values, particularly at Bağyüzü (GS1) and Gölcük (GS5), where granite tors and boulders are preserved in relatively intact conditions. Sites such as Hacıbozlar (GS2) and Kırtık (GS3) further highlight the integration of geological features with pastoral traditions, pine nut production, and archaeological heritage.

Despite these strengths, the uniformly low economic scores indicate limited infrastructure and legislative protection, underscoring the need for strategic interventions. Enhancing accessibility, developing interpretive materials, and promoting community-based geotourism would help bridge the gap between inherent geoheritage quality and practical utilization. Conservation measures are equally critical to safeguard vulnerable sites such as Tatlısu (GS6) and Tortepe (GS7), where settlement pressures and grazing activities pose risks to geomorphological integrity.

Overall, the Ida Madra Geopark emerges as a distinctive landscape where geological processes and cultural identity converge. Strengthening conservation strategies, legislative frameworks, and sustainable tourism initiatives will ensure that its granite landforms continue to serve as valuable resources for science, education, and local development, while contributing to the broader objectives of geoconservation in Türkiye.

Author Contribution *Recep Efe* Conceptualization, Fieldwork, Background Literature Survey, Geosite Evaluation, Data Collection and Analysis, Validation, Draft of The Manuscript, Writing – Review & Editing. *Isa Cürebal* Data Compilation and Curation, Methodology, Conception, Design, Preparation of Tables, Formal Analysis. *Abdullah Soykan* Fieldwork, Geosite, Conception, Evaluation. All authors have read and approved the final manuscript.

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Declarations

Competing interests The authors declare no competing interests related to the submitted work.

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