



**The First Surveyed Lava Tube on Mount Ağrı Volcano (Türkiye):
A Geological Heritage Assessment of the Ice Cave**

Ağrı Dağı Volkanı'nda İlk Kez Araştırılan Lav Tüneli (Türkiye): Buz Mağarası'nın Jeolojik Miras Açısından Değerlendirilmesi

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Abstract: Türkiye hosts numerous geological formations that qualify as natural monuments, commonly referred to as geological heritage sites. These sites represent exceptional examples of key stages in Earth history, including active geological processes, distinctive geomorphological features, and significant physiographical characteristics. Within this framework, this study presents the Ice Cave, a lava tube developed within basaltic lava flows on Mount Ağrı volcano, as an important geological heritage site.

The Ice Cave is a non-renewable natural lava tube distinguished by well-preserved volcanic morphology and recording aspects of the volcanic and geomorphological evolution of the region. The cave was documented through detailed cave surveying and mapping, supported by microclimatic and gas measurements conducted within a geological heritage assessment framework. The Ice Cave represents the first lava tube on Mount Ağrı volcano to be systematically surveyed and mapped in detail.

The geological, morphological, and microclimatic characteristics of the Ice Cave indicate strong potential for scientific research, geoscience education, and sustainable geotourism as a complementary activity to existing mountaineering tourism in the region. Furthermore, the results suggest that similar investigations on Mount Ağrı and surroundings may reveal additional lava tubes, contributing both to scientific understanding and to the sustainable management of Türkiye's volcanic geological heritage.

Keywords: Cave, geological heritage, ice cave, lava tube, Mount Ağrı.

Öz: Türkiye, jeolojik miras alanı olarak değerlendirilebilecek ve doğal anıt niteliği taşıyan çok sayıda jeolojik oluşuma sahiptir. Jeolojik miras alanları; yerkürenin tarihindeki önemli evreleri temsil eden, aktif jeolojik süreçleri yansıtan, ayırt edici jeomorfolojik ve fizyografik özellikler sergileyen istisnai örnekler olarak tanımlanmaktadır. Bu

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bağlamda, bu çalışma Ağrı Dağı volkanizmasına ait bazaltik lav akıntıları içerisinde gelişmiş bir lav tüneli olan Buz Mağarası'nı önemli bir jeolojik miras alanı olarak ele almaktadır.

Buz Mağarası, iyi korunmuş volkanik morfolojisi ve bölgenin volkanik ve jeomorfolojik evrimini yansıtmaya potansiyeli ile öne çıkan, yenilenemez nitelikte doğal bir lav tünelidir. Mağara, ayrıntılı mağara ölçümleri ve haritalama çalışmaları ile birlikte mikroklimatik ve gaz ölçümleri kullanılarak jeolojik miras değerlendirme çerçevesinde belgelenmiştir. Elde edilen bulgular, Buz Mağarası'nın Ağrı Dağı volkanizmasına ait lavlar içerisinde sistematik olarak ölçülüp ayrıntılı biçimde haritalanan ilk lav tüneli olduğunu ortaya koymaktadır.

Buz Mağarası'nın jeolojik, morfolojik ve mikroklimatik özellikleri; bilimsel araştırmalar, yerbilimleri eğitimi ve mevcut dağcılık turizmine tamamlayıcı nitelikte sürdürülebilir jeoturizm faaliyetleri açısından yüksek bir potansiyel sunmaktadır. Ayrıca bu çalışma, Ağrı Dağı ve çevresinde yapılacak benzer araştırmaların yeni lav tünellerinin belirlenmesine katkı sağlayarak Türkiye'nin volkanik jeolojik mirasının bilimsel olarak belgelenmesi ve sürdürülebilir biçimde yönetilmesi açısından önemli bir temel oluşturacağını göstermektedir.

Anahtar Kelimeler: Ağrı Dağı, buz mağarası, jeolojik miras, lav tüneli, mağara.

INTRODUCTION

Many natural caves around the world formed predominantly within carbonate rocks through karstic processes. Approximately one-third of the surface rocks in Türkiye consist of carbonate lithologies, making the country particularly rich in karst caves. In addition to these well-known karst systems, caves may also develop within volcanic rocks, independent of dissolution processes, where they are commonly referred to as lava tubes or lava tunnels.

Lava tubes form during volcanic eruptions when low-viscosity lava flows beneath a rapidly cooled surface crust, creating insulated conduits that may remain as hollow tunnels after lava drainage. The longest known lava tubes are typically found in regions with sustained volcanic activity, such as the Hawaiian volcanic province. For example, Kazumura Cave (Hawaii) has a continuous traversable length of approximately 41.8 km, although its total mapped system exceeds 65 km when side passages are included (Allred and Allred, 1997; Allred, 2019). Although less studied than karst caves, lava tubes represent important volcanic landforms that record lava emplacement dynamics and post-eruptive geomorphological processes. Lava tubes have been widely documented in volcanic regions worldwide and provide important insights into

lava flow dynamics and cave development (e.g., Kempe, 2012; Allred, 2019). Türkiye hosts numerous volcanic fields related to Neogene-Quaternary volcanic activity extending across Anatolia. Previous studies indicate that this volcanism was associated with complex tectonic processes following the collision of the Arabian and Eurasian plates (Ercan et al., 1990; Yılmaz et al., 1998). Eastern Anatolia represents one of the most extensive volcanic regions in the country and hosts several major volcanic centers, including Mount Ağrı, Süphan, and Tendürek (Yılmaz et al., 1998). These volcanic edifices are predominantly composed of basaltic and andesitic volcanic products of Quaternary age, including extensive lava flows that form volcanic plateaus in many parts of Eastern Anatolia (Ercan et al., 1990; Yılmaz et al., 1998).

Mount Ağrı, located in eastern Türkiye, is one of the most prominent Quaternary volcanic edifices in the region. Despite its geological significance and extensive lava flows, volcanic caves associated with Mount Ağrı volcanism have received limited scientific attention. The Ice Cave (lava tube) investigated in this study was previously known only to local inhabitants and was not subject to detailed geological, morphological, or microclimatic investigation.

Although only a limited number of studies reported volcanic caves and lava tube occurrences in Türkiye, including the Karahasan Lava Tunnel in Eastern Anatolia (Kıraşan and Şengün, 2017) and volcanic provinces such as the Karacadağ volcanic field (Çakır et al., 2022), studies focusing specifically on well-documented lava tube systems remain limited compared to the extensive research on karst caves. Existing studies are generally descriptive or focus on specific features (e.g., ice formation), and comprehensive geological and morphological surveys of lava tubes are still scarce. In this context, the Ice Cave investigated in this study represents the first lava tube within the Mount Ağrı volcanic system to be systematically surveyed and documented through detailed geological and morphological measurements.

Unlike volcanological studies focusing on eruptive history, this research emphasizes the geological heritage significance of the lava tube and its potential value in scientific, educational, and geotourism terms. By presenting the first systematic survey of a lava tube on Mount Ağrı, this study aims to contribute to the documentation of volcanic cave systems in Türkiye and to highlight their importance as geological heritage sites worthy of conservation and sustainable geotourism development.

The objectives of this study are to document and characterize the Ice Cave through detailed field measurements, cave mapping, and environmental observations, and to evaluate its significance as a geological heritage site.

MATERIALS and METHODS

This study employed a systematic methodological approach to document, map, and evaluate the geological heritage significance of the Ice Cave (lava tube) within the Mount Ağrı volcanic system. The methodology combined desk-based analyses, field investigations, cave surveying,

microclimatic and gas measurements, and biological observations.

Prior to fieldwork, geological maps (1:25,000–1:100,000 scale), satellite imagery, and digital elevation models were analyzed to assess lava-flow morphology, stratigraphic relationships, and access conditions. Previous studies about Mount Ağrı volcanism were reviewed, and spatial analyses were performed using GIS-based tools (e.g., ArcGIS environment) to support field interpretations.

Field investigations were conducted by a multidisciplinary team. The cave entrance and key geomorphological features were recorded using handheld GPS devices, while lithology, lava-flow textures, jointing, and collapse structures were documented through systematic field observations. Lava thicknesses and structural orientations were measured using standard geological instruments.

Cave surveying was carried out following standard speleological mapping techniques commonly applied in volcanic cave studies. Horizontal and vertical distances were measured using laser distance meters, and slope angles and ceiling-height variations were recorded with digital inclinometers. Survey stations were established at regular intervals along the cave axis. The collected data were processed to produce scaled cave plans and longitudinal sections.

Microclimatic conditions were investigated through in situ measurements of air temperature, relative humidity, and gas composition at the cave entrance and at several interior locations. Measurements were conducted in November 2024 and July 2025 under stable weather conditions. Air quality was assessed by monitoring oxygen (O₂), hydrogen sulfide (H₂S), and methane (CH₄) concentrations to evaluate potential gas accumulation.

Biological observations were based on direct field observations and photographic

documentation of vertebrate and invertebrate traces within and around the cave. The geological heritage assessment of the Ice Cave was conducted using an evaluation framework based on the criteria defined by UNESCO and IUGS (2023) and the Natural Assets Requiring Protection inventory standards adopted by the General Directorate of Mineral Research and Exploration (MTA), including scientific value, rarity, integrity, educational significance, accessibility, and vulnerability.

GEOLOGICAL SETTING of MOUNT AĞRI VOLCANO

Mount Ağrı (Ararat) is the largest stratovolcano in Türkiye and one of the most prominent Quaternary volcanic centers in the Eastern Anatolia region. It is located within the Eastern Anatolian High Plateau, a tectonically active zone shaped by post-collisional volcanism following the convergence of the Arabian and Eurasian plates. This tectonic setting facilitated widespread and long-lived volcanic activity across Eastern Anatolia, including the development of large composite volcanoes such as Mount Ağrı.

Mount Ağrı volcanism consists predominantly of basaltic and andesitic lava flows accompanied by pyroclastic deposits. The volcanic edifice evolved through multiple eruptive stages, producing ash, lapilli, volcanic bombs, lava flows, and domes. Earlier studies classified Mount Ağrı as a Quaternary stratovolcano composed mainly of basalt and hypersthene andesite (Ercan et al., 1990; Hepşen, 2009). Radiometric age determinations indicate that andesitic units on Lesser Mount Ağrı are approximately 270 ka old, whereas andesitic lavas on Greater Mount Ağrı range between approximately 450 and 490 ka (Ercan et al., 1990). Strontium isotope data further suggest that the magmas feeding Mount Ağrı derived from a relatively homogeneous mantle source with limited crustal contamination (Gülen, 1980).

Basaltic lava flows associated with the later stages of Mount Ağrı volcanism are dark-colored, massive to vesicular, and exhibit well-developed flow structures observable in the field. These basaltic units form widespread lava surfaces surrounding the volcanic edifice and represent some of the youngest volcanic products of the Mount Ağrı volcanic system (Yılmaz et al., 1998). Recent volcanological studies also suggested that large-volume lava flows of Mount Ağrı were supplied by a deep magmatic reservoir beneath the volcanic edifice, indicating sustained magma supply during the Quaternary evolution of the volcano (Karaoğlu et al., 2017). The Ice Cave (lava tube) investigated in this study developed within one of these basaltic lava flow units belonging to the Quaternary volcanic evolution of Mount Ağrı.

ICE CAVE (LAVA TUBE-MOUNT AĞRI)

Location and General Characteristics

Located approximately 140 km from the center of Ağrı province and 50 km from the center of Doğubayazıt district, the Ice Cave (Lava Tube) is situated within the basaltic lava fields of Mount Ağrı, north of Hallaç village, along the route from Doğubayazıt to Gürbulak border gate (Figure 1). The relatively flat morphology of the surrounding lava plateau makes the cave entrance difficult to detect from a distance.

The geographic coordinates of the Ice Cave are 38°26'31" N, 42°43'13" E, at an elevation of approximately 1478 m above sea level (UTM Zone 37, WGS84). The cave has a total measured length of 101 m, an average ceiling height of approximately 20 m, and a maximum vertical difference of approximately 2.34 m from the entrance. It represents a semi-horizontal to horizontal volcanic lava tube developed within basaltic lava flows associated with volcanism on Mount Ağrı.

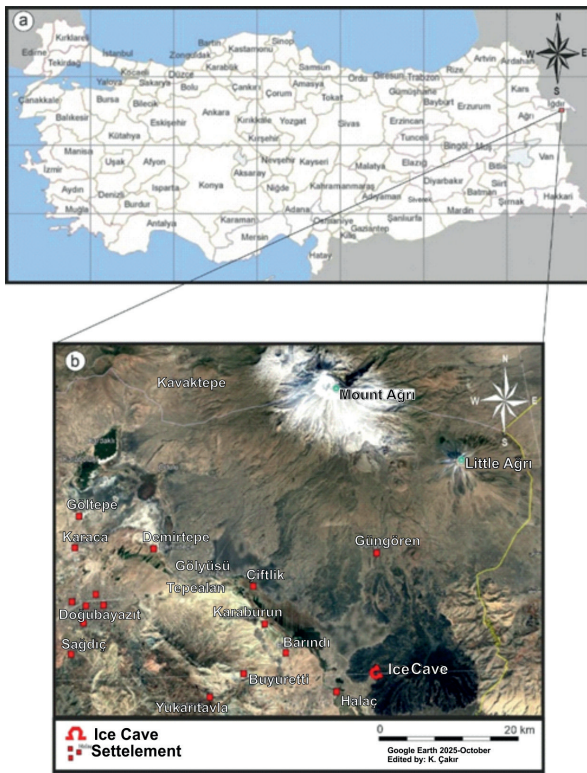


Figure 1. Regional and local location of the Ice Cave (lava tube) within the Mount Ağrı volcanic field. **a)** Location of Mount Ağrı in Türkiye, **b)** Satellite image showing the detailed location of the Ice Cave relative to surrounding lava flows and settlement areas (satellite imagery from Google Earth, edited in 2025).

Şekil 1. Buz Mağarası'nın (lav tüpü) Ağrı Dağı volkanik alanı içerisindeki bölgesel ve yerel konumu. **a)** Ağrı Dağı'nın Türkiye içindeki konumu, **b)** Buz Mağarası'nın çevredeki lav akıntıları ve yerleşim alanlarına göre konumunu gösteren uydu görüntüsü (Google Earth, 2025 yılında düzenlenmiştir).

Local Geology of the Ice Cave

The Ice Cave developed within a basaltic lava flow belonging to the late-stage eruptive products of Mount Ağrı volcanism (Figure 2). Stratigraphically, this basaltic lava flow is mapped as part of the Quaternary basaltic units of the Mount Ağrı Volcanic Complex, corresponding to

basaltic lava flows exposed in the Doğubayazıt area, north of Hallaç village (Yılmaz et al., 1998; Hepşen, 2009). The host basalt is dark-colored, massive to locally vesicular, and exhibits well-developed flow textures observable in the field. Field observations indicate that the morphology of these basaltic lava flows is locally favorable for the development of lava tubes, particularly in areas where lava flowed along pre-existing topographic lows such as riverbeds and shallow valleys. The basalt hosting the Ice Cave corresponds to a young lava flow unit with an estimated thickness of approximately 45–50 m, consistent with nearby outcrops. The mechanical strength and preservation of the basalt suggest relatively limited surface weathering, supporting a Quaternary age. Based on field relationships and regional geological mapping (Yılmaz et al., 1998; Hepşen, 2009), this lava flow is interpreted as part of the late-stage basaltic activity of Mount Ağrı volcanism during the Quaternary period. The lava tube formed within the interior part of this basaltic lava flow beneath the solidified upper surface during lava emplacement. The preserved morphology of the Ice Cave reflects the internal drainage of molten lava within the basaltic flow, leaving behind a hollow conduit.

Morphological Features of the Ice Cave

The entrance of the Ice Cave, formed by basaltic lava flows originating from the stratovolcano Mount Ağrı, is characterized by a collapse doline (Figure 3a). In areas where the lava tube roof is relatively thin, localized roof failure has created vertical openings that provide access to the cave (Figure 3b). Depending on the morphology of the valley floors and riverbeds exploited by the lava flows, the entrance occurs as isolated or partially connected collapse dolines (Figure 3c).

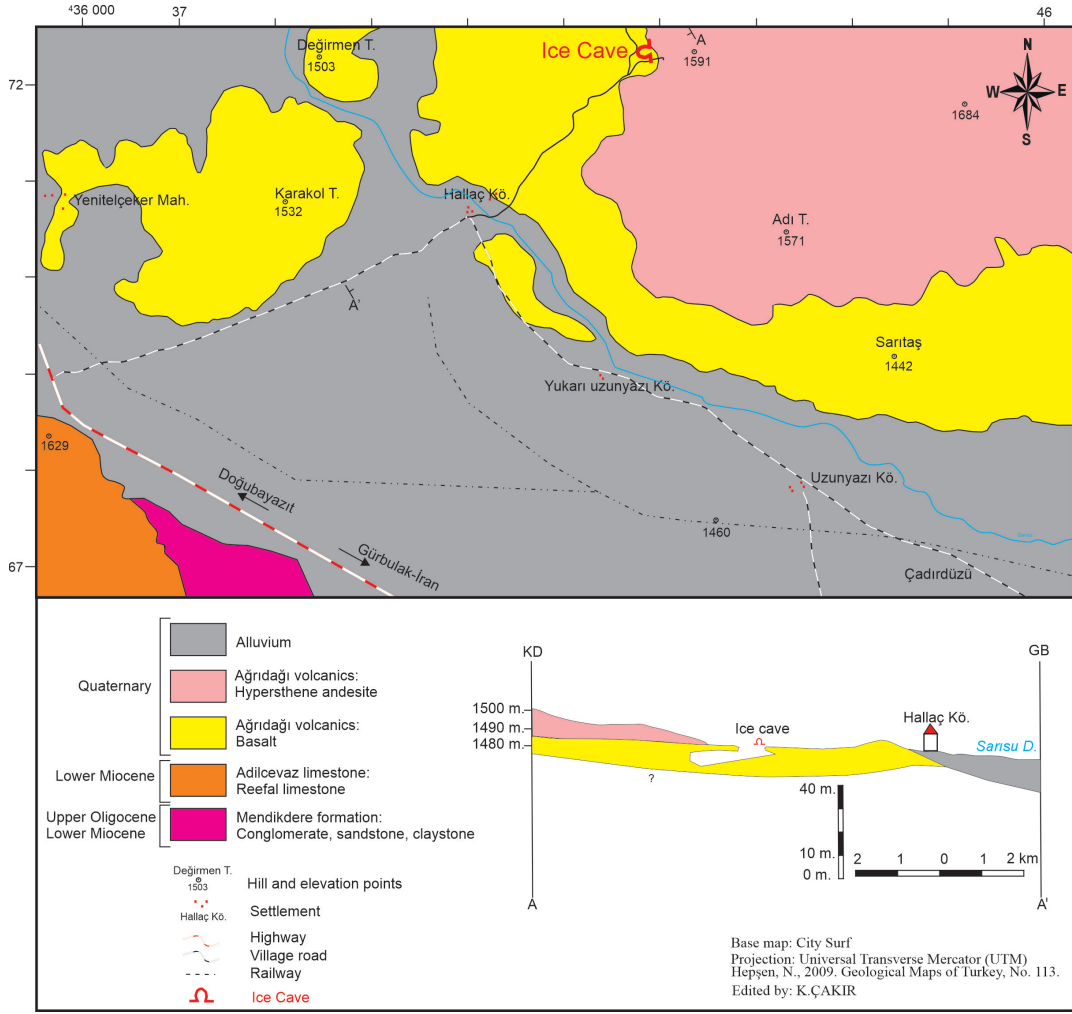


Figure 2. Simplified geological map of the Ice Cave (lava tube) area showing the distribution of Quaternary basaltic and andesitic volcanic units of Mount Ağrı and surrounding deposits (modified after Hepsen, 2009). The location of the Ice Cave is indicated, and the lava tube is hosted within Quaternary basaltic lava flows.

Şekil 2. Buz Mağarası (lav tüneli) ve yakın çevresinin sadeleştirilmiş jeoloji haritası; Ağrı Dağı'na ait Kuvaterner yaşlı bazaltik ve andezitik volkanik birimlerin ve çevresel çökellerin dağılımını göstermektedir (Hepsen, 2009'dan değiştirilerek). Buz Mağarası'nın konumu işaretlenmiş olup, lav tünelinin Kuvaterner yaşlı bazaltik lav akıntıları içerisinde geliştiği görülmektedir.

The Ice Cave extends from the collapse entrance in a predominantly southwesterly direction (Figure 4a, e). The entrance width reaches approximately 34 m, with an open ceiling attaining a maximum height of 24 m, while the total measured length of the cave is 101 m (Figure 4). The lava tube exhibits a semi-horizontal to horizontal geometry, with an average width of

approximately 25 m and a mean ceiling height of about 15 m. Toward the inner sections of the cave, the ceiling height gradually decreases, and blocky debris with steep internal slopes becomes more common (Figure 5a, b), reflecting post-emplacement mechanical breakdown of the lava tube roof.

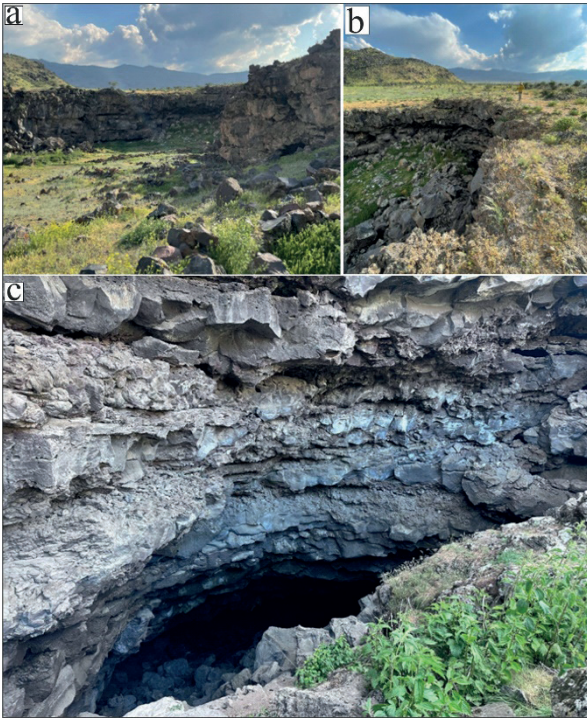


Figure 3. Field photographs showing collapse-doline development at the entrance of the Ice Cave (lava tube). **a)** Main collapse doline forming the principal entrance, **b)** Vertical opening produced by localized roof collapse in a sections with thin roof, **c)** Isolated or partially connected collapse dolines developed along the valley floor.

Şekil 3. Buz Mağarası (lav tüpü) girişinde gelişen çökme dolinlerini gösteren arazi fotoğrafları. **a)** Ana girişi oluşturan başlıca çökme dolini, **b)** Tavanın ince olduğu bir kesimde yerel tavan çökmesiyle gelişmiş düşey açıklık, **c)** Vadi tabanı boyunca gelişmiş izole veya kısmen bağlantılı çökme dolinleri.

The preserved internal morphology, including smooth wall surfaces, remnant flow linings, and drained lava marks, confirms that the Ice Cave represents the hollow interior of a former lava conduit. These morphological characteristics are consistent with lava tube morphologies commonly observed in basaltic lava flows.

Hydrology and Biological Observation of the Ice Cave

Although no active surface water flow is present within the Ice Cave, localized puddles and muddy areas occur due to infiltration of precipitation from the surface. Water percolating through fractures and porous zones of the overlying basalt freezes within the cave, leading to the formation of ice coatings and accumulations (Figure 6a, b). These features reflect seasonal freeze–thaw processes controlled by surface climate conditions and cave ventilation.

Located on the lava plateau of Mount Ağrı, the Ice Cave serves as a temporary shelter for various animal species, particularly during harsh climatic conditions. During field observations conducted in November 2024 and July 2025, several biological traces were documented within the cave. Fecal remains attributed to large mammals were frequently observed, and direct observations of bears were recorded during the survey (Figure 7a). In addition, feathers and egg fragments indicating avifaunal use were identified near the cave entrance (Figure 7b).

These biological observations should be considered preliminary, as no systematic biological inventory or species identification was conducted during the geological survey. Nevertheless, the documented traces suggest that the Ice Cave may function as a natural shelter for wildlife within the high-altitude environment of Mount Ağrı volcano.

RESULTS

Field investigations and measurements carried out within the Ice Cave provide field-based data about its morphology, geological setting, microclimate, and biological use. The cave represents a semi-horizontal to horizontal lava tube developed within young basaltic lava flows associated with the Quaternary volcanism of Mount Ağrı.

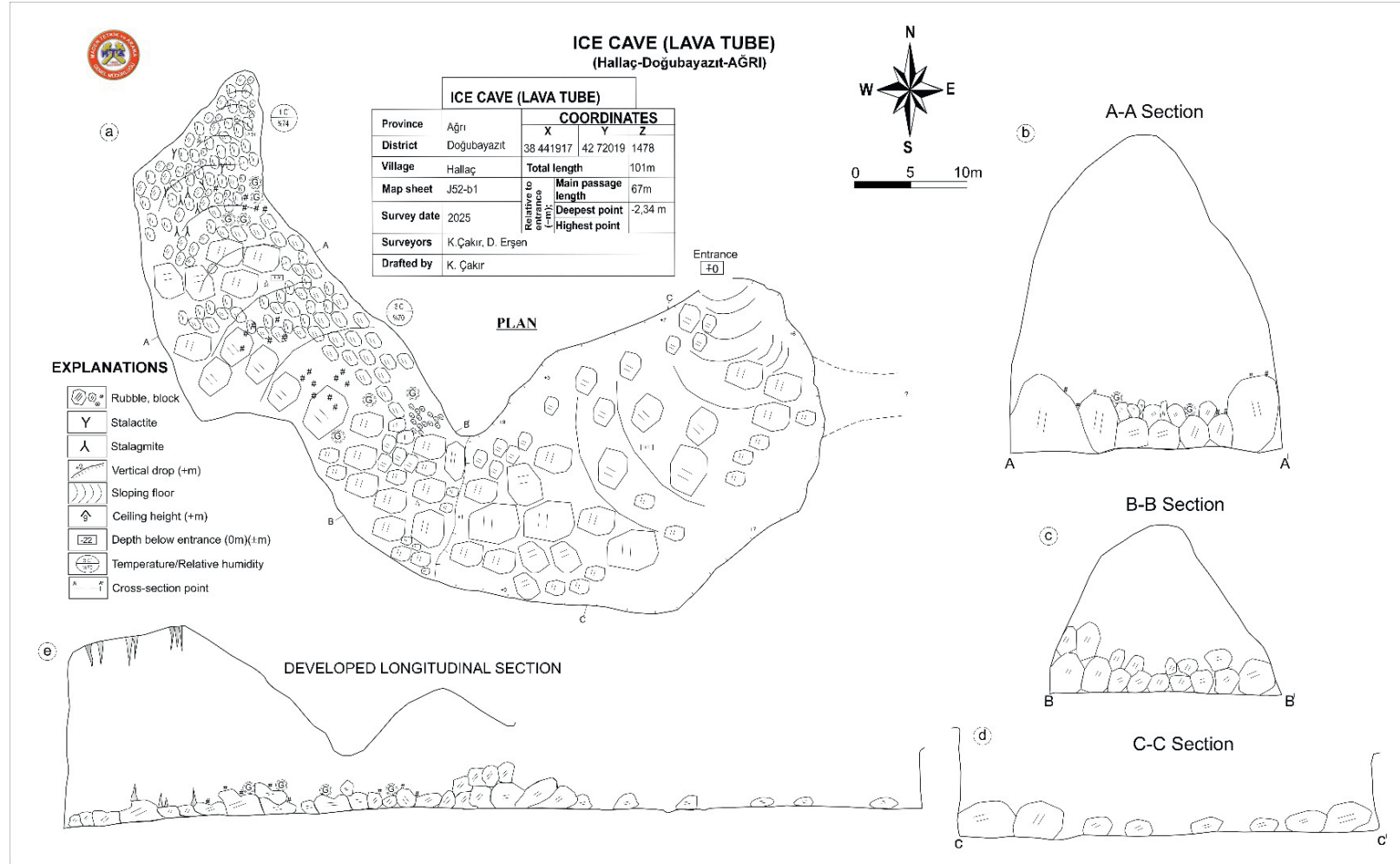


Figure 4. Detailed cave map of the Ice Cave (lava tube) based on original survey data. **a)** Plan view of the cave. **b–d)** Cross-sections along profiles A–A', B–B', and C–C'. **e)** Developed longitudinal section. The figure illustrates cave geometry, internal morphology, block distribution, ceiling height variations, and measurement points.

Şekil 4. Buz Mağarası'nın (lav tüpü) bu çalışma kapsamında elde edilen özgün ölçüm verilerine dayalı detaylı mağara haritası. **a)** Mağaranın plan görünümü. **b–d)** A–A', B–B' ve C–C' kesitleri. **e)** Açılmış boyuna kesit. Şekil, mağara geometrisini, iç morfolojiyi, blok dağılımını, tavan yüksekliği değişimlerini ve ölçüm noktalarını göstermektedir.

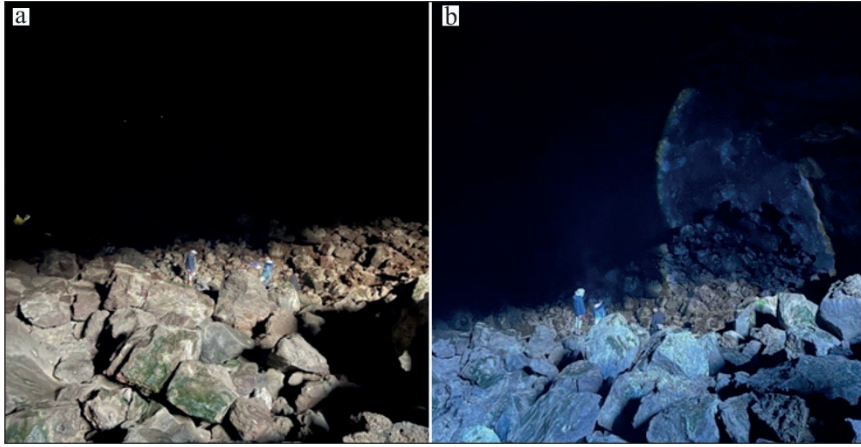


Figure 5. a, b) Interior views of the lava tube showing variations in ceiling height and the distribution of blocky debris resulting from post-emplacment roof collapse.

Şekil 5. a, b) Lav tüneli içinden görünüşler; tavan yüksekliğindeki değişimler ve yerleşim sonrası tavan çökmesine bağlı olarak gelişmiş bloklar.

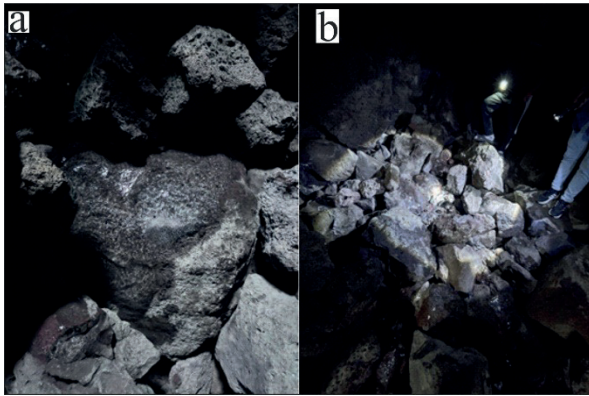


Figure 6. Ice features within the lava tube. **a)** Thin ice coatings formed on rock surfaces by freezing seepage water. **b)** Ice accumulations observed among collapsed blocks on the cave floor.

Şekil 6. Lav tüpü (Lav tüneli) içerisindeki buz oluşumları. **a)** Sızıntı suların donması sonucu kaya yüzeyleri üzerinde gelişmiş ince buz kaplamaları. **b)** Mağara tabanındaki bloklar arasında gelişmiş buz birikimleri.

Morphological observations indicate that the cave entrance formed as a collapse doline resulting from localized roof failure of the lava tube, while the interior preserves characteristic lava tube features such as smooth wall surfaces, remnant flow linings, and drained lava marks.

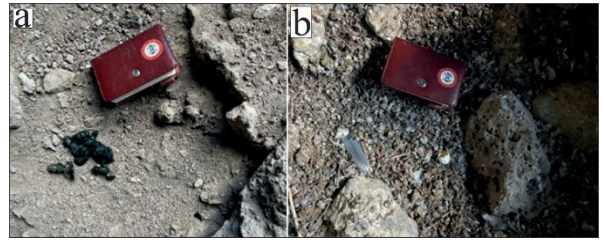


Figure 7. Biological traces observed at the entrance of the lava tube. **a)** Droppings attributed to large mammals. **b)** Eggshell fragments indicating avifaunal use of the cave. The field notebook visible in the photographs is approximately 15 cm in length and is provided as a scale reference.

Şekil 7. Lav tüneli girişinde gözlenen biyolojik izler. **a)** Büyük memelilere atfedilen dışkı kalıntıları. **b)** Kuşlara ait yumurta kabuğu parçaları. Fotoğraflarda görülen arazi defteri yaklaşık 15 cm uzunluğunda olup ölçek referansı olarak kullanılmıştır.

The Ice Cave Lava Tube has a total measured length of 101 m, with an entrance width of approximately 34 m and a maximum ceiling height of 24 m near the entrance. The average width of the tunnel is about 25 m, and the ceiling height gradually decreases toward the inner sections. Blocky debris and steep internal slopes observed inside the cave reflect post-emplacment mechanical breakdown of the lava tube roof following lava drainage.

Microclimatic measurements were conducted during two field campaigns in November 2024 and July 2025 at the cave entrance and within the cave interior. During the November 2024 campaign, the air temperature at the cave entrance was approximately -2 °C with relative humidity of about 82%, while temperatures inside the cave ranged between -4 and -6 °C. Oxygen concentration within the cave air was measured at around 20%, whereas hydrogen sulfide (H₂S) and methane (CH₄) were below the detection limits of the instrument. During the July 2025 field campaign, the air temperature at the cave entrance was approximately 13 °C with relative humidity of about 75%, whereas temperatures inside the cave ranged between 2 and 4 °C. Oxygen concentration was measured at approximately 21%, while hydrogen sulfide (H₂S) and methane (CH₄) were again below the detection limits. These observations indicate that the Ice Cave maintains a consistently colder microclimate than the entrance zone in both cold and warm seasons and exhibits a clear thermal contrast that favors the preservation of ice formations.

Hydrological observations show no active water flow within the cave; however, infiltration from surface precipitation leads to localized puddles and the formation of ice stalactites and stalagmites as seepage water freezes in low internal temperatures (Figure 6a, b). Biological observations document the use of the cave as a temporary shelter by various animal species, including large mammals and birds, as indicated by fecal remains, feathers, and egg fragments observed during field surveys.

DISCUSSION

The results obtained from the Ice Cave Lava Tube highlight its significance as a well-preserved lava tube formed within the basaltic lava flows of Mount Ağrı. The morphological characteristics, including collapse doline entrance geometry,

internal lava flow structures, and drained conduit structures, are consistent with lava tube systems documented in other basaltic volcanic provinces worldwide (e.g., Kempe, 2012; Allred, 2019). These features confirm that Ice Cave Lava Tube represents the preserved interior of a hollow lava conduit formed during basaltic lava emplacement. The stable cold microclimate documented within the cave plays a key role in the development and preservation of ice formations, distinguishing the Ice Cave from other volcanic caves reported in Anatolia (e.g., Kırışan and Şengün, 2017). The microclimatic measurements presented in this study were made during two field campaigns in November 2024 and July 2025 and therefore represent seasonal observations obtained under different climatic conditions. Although these measurements provide useful insights into the thermal regime of the cave, longer-term monitoring including additional seasons would provide a more comprehensive understanding of the cave's microclimatic dynamics and the processes controlling ice preservation.

The relatively low temperatures observed inside the cave compared to the entrance zone suggest that the Ice Cave may function as a cold-air trapping system, where dense cold air accumulates within the cave interior and promotes the preservation of ice deposits. This mechanism is consistent with cold-air trapping processes documented in alpine ice cave systems, where static air circulation enables the development of thermal anomalies and the preservation of ice (Luetscher & Jeannin, 2004). Such microclimatic conditions, combined with the cave's accessibility and clear volcanic features, enhance its scientific and educational value. In addition to its geological and microclimatic characteristics, the Ice Cave also shows evidence of ecological use by wildlife. These biological observations should be considered preliminary, as no systematic biological inventory or species identification was conducted during the geological survey. Nevertheless, the documented

traces suggest that the Ice Cave may function as a natural shelter for wildlife within the high-altitude volcanic environment of Mount Ağrı.

From a geological heritage perspective, the Ice Cave possesses high scientific, educational, and esthetic value due to its rarity, preservation state, and clear representation of volcanic processes. When evaluated against the geological heritage criteria defined by UNESCO and IUGS (2023) and the Natural Assets Requiring Protection inventory standards adopted by the General Directorate of Mineral Research and Exploration (MTA), the Ice Cave satisfies several key criteria. In this study, the geological heritage assessment of the Ice Cave was conducted using a qualitative evaluation framework based on widely used geosite assessment criteria, including scientific value, rarity, integrity, educational significance, accessibility, and vulnerability. Rather than applying a numerical scoring system, these criteria were evaluated descriptively based on field observations and geological context in order to highlight the specific characteristics of the Ice Cave lava tube within the Mount Ağrı volcanic system. First, the Ice Cave has high scientific value, as it provides direct evidence of lava tube formation within a well-documented Quaternary stratovolcano system. Based on field relationships and regional geological mapping, the host basaltic lava flow is interpreted as part of the late-stage volcanic activity of Mount Ağrı during the Quaternary period (Yılmaz et al., 1998; Hepşen, 2009). Second, in terms of rarity, lava tubes are uncommon in Türkiye compared to karst caves (e.g., Kıranşan and Şengün, 2017), and the Ice Cave represents the first systematically surveyed lava tube developed within Mount Ağrı volcanism. Third, the integrity of the cave is high, as original volcanic features such as smooth wall surfaces, remnant flow linings, and drained lava marks are well preserved, indicating minimal post-emplacement alteration.

In addition, the Ice Cave has significant educational value, as its clear volcanic morphology and relatively easy access make it suitable for geoscience education, field training, and public outreach activities. Accessibility is another important criterion, as the cave is located approximately 37 km from Doğubayazıt and can be reached via paved roads without the need for intrusive infrastructure. However, like many young volcanic caves, the Ice Cave is mechanically fragile and particularly vulnerable as it is located within the seismically active region of Eastern Anatolia. The tectonically active nature of the region (Ercan et al., 1990; Yılmaz et al., 1998) emphasizes the importance of appropriate conservation measures. This vulnerability highlights the need for appropriate conservation and management strategies to ensure long-term preservation.

Ice Cave Lava Tube also exhibits significant potential for sustainable geotourism. Its proximity to Doğubayazıt, accessibility via paved roads, and suitability for guided visits without the need for intrusive infrastructure make it an attractive natural geosite. However, any future geotourism development should prioritize conservation measures to protect the cave's structural integrity, microclimate, and biological use. Recommended management strategies include limiting daily visitor numbers to reduce physical degradation of cave walls and floors, restricting access to guided tours only to prevent uncontrolled exploration, and implementing periodic structural monitoring to assess roof stability in this seismically active region. These visitor management measures could be implemented through controlled access systems coordinated by local authorities and relevant conservation institutions. The establishment of a designated entrance point, guided visitation programs, and basic monitoring of visitor numbers would allow sustainable use of the site while minimizing potential impacts on the cave environment. In addition, interpretive

signage located outside the cave entrance may be used to explain volcanic processes, lava tube formation, and microclimatic phenomena without introducing intrusive infrastructure inside the cave. Conservation planning should also consider the potential ecological role of the cave as a wildlife shelter. Visitor management strategies should therefore aim to minimize disturbance to fauna that may use the cave as a temporary refuge. In this context, the Ice Cave represents not only a valuable geological monument but also a key element of the volcanic geodiversity of Mount Ağrı and its surroundings.

GENİŞLETİLMİŞ ÖZET

Lav tünelleri, bazaltik lav akıntıları içerisinde volkanik aktivite sırasında gelişen ve oluşum mekanizmaları, morfolojik özellikleri ve jeolojik bağlamları bakımından karstik mağaralardan belirgin biçimde ayrılan doğal boşluklardır. Bu yapılar, yüksek sıcaklıkta ve düşük viskoziteli lavların yüzeyde hızla soğuyarak bir kabuk oluşturması ve alttaki lavın akışını sürdürmesi sonucunda meydana gelmektedir. Lav akışının sona ermesiyle birlikte, lavın boşalttığı kanallar boyunca lav tünelleri oluşmakta ve bu yapılar volkanik alanların önemli jeomorfolojik unsurları arasında yer almaktadır. Dünya genelinde lav tünelleri özellikle aktif veya yakın jeolojik geçmişe sahip volkanik kuşaklarda yaygın olarak gözlenirken, Türkiye’de bu tür oluşumlar karstik mağaralara kıyasla daha az sayıda çalışılmıştır. Bu durum, volkanik alanlardaki lav tünellerinin hem bilimsel hem de jeolojik miras açısından yeterince belgelenmemiş olmasından kaynaklanmaktadır.

Türkiye, genç volkanizma ürünlerinin geniş alanlar kapladığı bir jeolojik yapıya sahip olmasına rağmen, lav tünellerine yönelik sistematik çalışmalar sınırlıdır. Doğu Anadolu Bölgesi’nde yer alan Ağrı Dağı (Mount Ağrı), Kuvaterner yaşlı stratovolkanik yapısı, geniş bazaltik lav örtüleri ve

genç volkanik morfolojisi ile lav tüneli oluşumuna elverişli alanlardan biridir. Ancak bugüne kadar Ağrı Dağı volkanizması içerisinde gelişmiş lav tünelleri detaylı biçimde belgelenmemiştir. Bu çalışma, Ağrı Dağı volkanik alanı içerisinde yer alan Buz Mağarası Lav Tüneli’nin ilk kez detaylı olarak ölçülmesi, haritalanması ve çok yönlü değerlendirilmesi amacıyla gerçekleştirilmiştir.

Buz Mağarası Lav Tüneli’nin, Doğu Anadolu Bölgesi’nde, Türkiye–İran sınırına yakın bir konumda yer alan Ağrı Dağı’nın kuzey eteklerinde, Kuvaterner yaşlı genç bazaltik lav akıntıları içerisinde gelişmiştir. İnceleme alanı, geç evre bazaltik volkanizmanın ürünleriyle karakterize olup, akışkan lavların topoğrafik çukurluklar ve eski akarsu yatakları boyunca ilerlemesi sonucu lav tünellerinin gelişimine uygun koşullar sunmaktadır. Arazi çalışmaları kapsamında lav tünelinin plan ve kesitleri çıkarılmış, iç morfolojisi ayrıntılı biçimde belgelenmiş ve mikroklimatik özellikleri ölçülmüştür. Jeolojik veriler, lav tünelinin, yüzeyde hızla soğuyarak kabuk oluşturan akışkan bazaltik lavların altında, alttaki lavın akmaya devam etmesi sonucu geliştiğini göstermektedir.

Mağara girişi, lav tünelinin tavan kısmının yer yer çökmesiyle oluşmuş bir çökme dolini (collapse doline) niteliğindedir. Bu morfolojik özellik, lav tünelinin yüzeyle olan ilişkisini açık biçimde ortaya koymakta ve tünelin gelişim sürecine dair önemli ipuçları sunmaktadır. Yapılan ölçümler sonucunda lav tünelinin toplam uzunluğu 101 m olarak belirlenmiş, yarı yatay–yatay gelişimli bir geometriye sahip olduğu ortaya konmuştur. Tünel içerisinde tavan yüksekliği ve genişlik değişkenlik göstermekte olup, bazı kesimlerde blok düşmeleri ve tavan çökmesine bağlı birikimler gözlenmektedir.

Buz Mağarası Lav Tüneli’nin dikkat çekici özelliklerinden biri, tünel (tüp) içerisinde gelişen mikroklimatik koşullardır. Yapılan ölçümler, yaz aylarında mağara girişinde yaklaşık 13 °C

olan sıcaklığın mağara iç kesimlerinde 2–4 °C aralığına düştüğünü ve yüksek nem koşullarının hâkim olduğunu göstermiştir. Kış döneminde gerçekleştirilen ölçümlerde ise mağara (tüp; tünel) girişinde sıcaklık yaklaşık –2 °C, mağara iç kesimlerinde ise –4 ile –6 °C arasında değişmektedir. Bu mikroklimatik ortam, mağara tabanı ve duvarlarında buz birikimlerinin yanı sıra buz sarkıt ve diktlerinin oluşmasına olanak sağlamaktadır. Gaz ölçümleri (O_2 , H_2S , CH_4) herhangi bir tehlikeli gaz birikimine işaret etmemiştir.

Biyolojik gözlemler, Buz Mağarası Lav Tüneli'nin yalnızca jeolojik değil, aynı zamanda ekolojik açıdan da önemli bir doğal yapı olduğunu ortaya koymuştur. Mağara girişinde ve yakın çevresinde büyük memelilere ve kuşlara ait biyolojik izler tespit edilmiş, mağaranın özellikle sert iklim koşullarında geçici barınak olarak kullanıldığı belirlenmiştir.

Jeolojik miras açısından değerlendirildiğinde, Buz Mağarası; genç volkanizma ürünü olması, nadirliği, iyi korunmuş morfolojik özellikleri ve bilimsel araştırmalara açık yapısı nedeniyle yüksek jeolojik miras potansiyeline sahiptir. UNESCO tarafından tanımlanan jeolojik miras kriterleri ve Maden Tetkik ve Arama Genel Müdürlüğü (MTA) tarafından benimsenen Korunması Gereken Tabiat Varlıkları kriterleri çerçevesinde değerlendirildiğinde, Buz Mağarası bilimsel değer, nadirlik, bütünlük, eğitimsel önem, erişilebilirlik ve kırılabilirlik gibi temel ölçütleri karşılamaktadır. Özellikle Ağrı Dağı gibi hem bilimsel hem de kültürel açıdan önemli bir volkanik merkez içerisinde yer alması, bu lav tünelinin jeoturizm ve eğitim amaçlı kullanım potansiyelini önemli ölçüde artırmaktadır.

Sonuç olarak bu çalışma, Ağrı Dağı volkanik alanı içerisinde sistematik olarak ölçümü ve haritalaması yapılmış ilk lav tüneline belgeleyerek Türkiye'de lav tünellerine yönelik sınırlı literatüre önemli bir katkı sunmaktadır. Elde edilen


veriler; benzer volkanik alanlarda yer alan lav tünellerinin belirlenmesi, korunması ve jeolojik miras kapsamında değerlendirilmesi açısından önemli bir metodolojik temel oluşturmaktadır. Gelecekte yapılacak detaylı çalışmalar, Ağrı Dağı ve çevresindeki diğer potansiyel lav tünellerinin ortaya konmasına, bu yapıların korunmasına ve Türkiye'nin jeolojik miras envanterinin geliştirilmesine katkı sağlayacaktır.


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