Aladağlar Mountain Range: A Landscape-Shaped by the Interplay of Glacial, Karstic, and Fluvial Erosion

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Abstract

The Aladağlar Mountain Range (AMR) is a large massif mainly composed of carbonate rocks hosting beautiful examples of glacial, karstic, and fluvial erosion. Extreme variations in climate and topography as well as the multitude of diverse geochemical conditions since the early Paleocene allowed development of huge hypogenic and epigenic karst systems. The interplay between the surface and karst drainage systems resulted in an attractive fluvial morphology with large karst springs, travertine bridges, gorges, and valleys. All of the karst valleys spreading from the heights of the AMR-hosted valley glaciers that once flowed down to 1100 m elevation. With its diverse landscape, the AMR is a promising land for tourists, backpackers, trekkers, and mountaineers. Large hanging karst springs, long rafting routes along gorges, travertine bridges, U-shaped glacial valleys and lakes, and challenging peaks are the major landscape attractions.

Keywords

Aladağlar Mountain Range • Glacio-karst
Quaternary glaciation • Hanging karst spring
Travertine bridge

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22.1 Introduction

Aladağlar Mountain Range (AMR) is a large (~1000 km^2) carbonate massif located in south-central Anatolia (37°75′ N, 35°20′ E; Fig. 22.1). It is part of the Taurus Mountains Range, a mountain belt belonging to Alp-Himalaya Orogeny. The elevation in the AMR ranges from 400 m a.s.l. to above 3750 m a.s.l., which makes the AMR one of the deepest karst systems in the world. It is surrounded by the left-lateral Ecemiş Fault corridor on the west, Zamantı River on the east, Erciyes Volcano on the north, and Karsantı Tertiary Basin on the south. The AMR hosts large lead and zinc carbonate deposits and provides great pastures for nomadic shepherds.

With its rugged topography and number of challenging peaks, the AMR is a favorite area for international trekkers and mountaineers (Fig. 22.2). The AMR hosts several national parks because of its pristine and unique vegetation and spectacular landscapes like hanged karst springs, natural travertine bridges, "superkarst" landforms (i.e., a very rugged and naked limestone topography shaped by numerous karrens and dissolution dolines with a complex network of conduits and shafts), glacially scoured highlands, rock glaciers, glacial valleys, and moraines. While glacial and periglacial climates dominated the massif during most of the Pleistocene, a mild Mediterranean and a semi-arid continental climate currently prevails in the southern and northern parts, respectively (Oliva et al. 2018).

22.2 General Setting

22.2.1 Geology and Geomorphological Evolution of AMR

The geology of the AMR is characterized by the presence of five carbonate nappes, which have been thrusted onto each other during the late Cretaceous period due to the closure of

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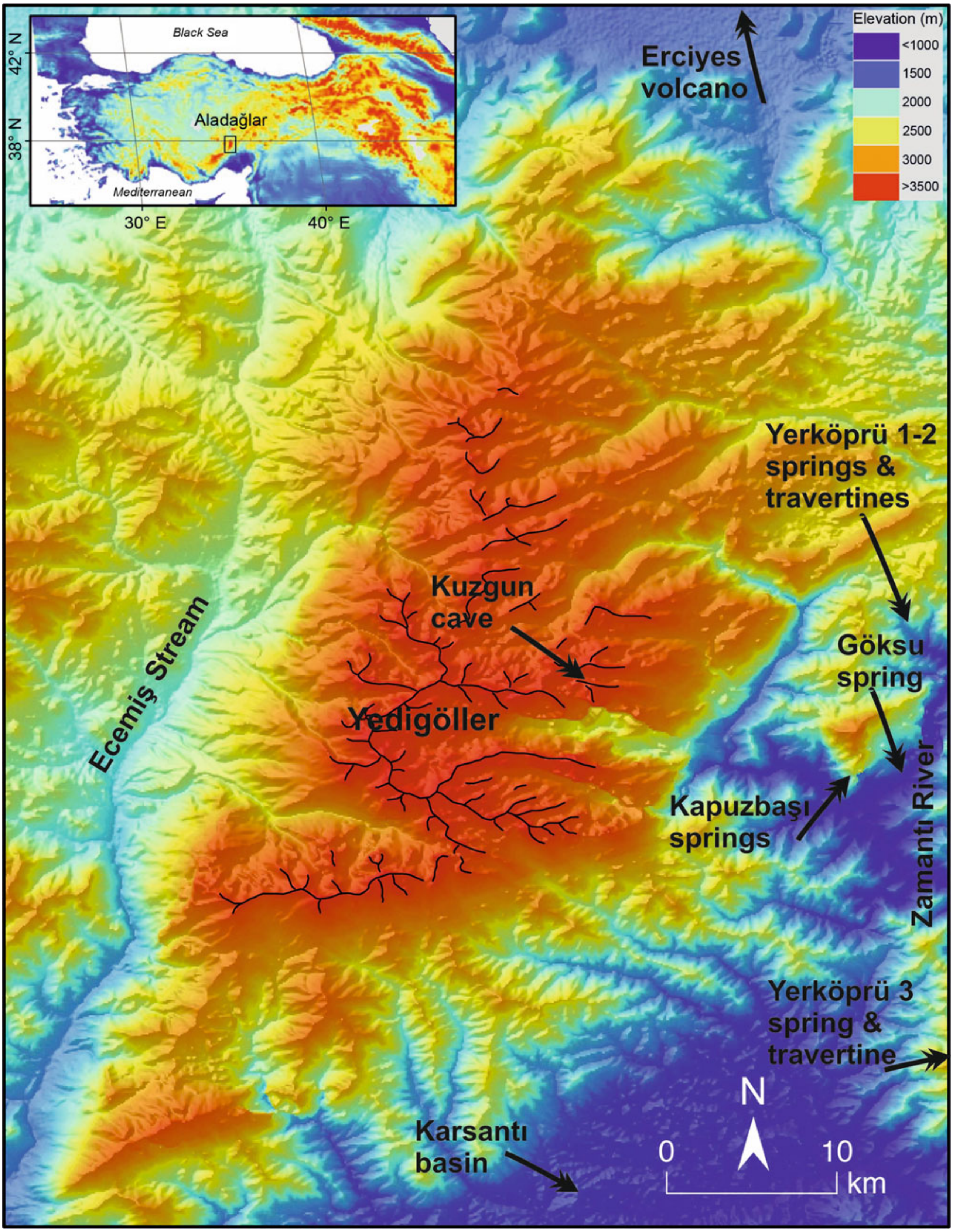

Fig. 22.1 Location of Aladağlar Mountain Range (AMR) in Turkey. Locations of the sites mentioned in text are shown on the digital elevation model of the AMR

Fig. 22.2 The aerial view shows western mountain flank and numerous peaks at the highlands (photo courtesy of Turgut Tarhan)

the northern branch of Neo-Tethys Ocean (Tekeli et al. 1984; Özgül 1984). This process resulted in stacking of five separate but compositionally similar stratigraphic sequences —once spread side-by-side in a 1500-km-wide epicontinental sea—into the roughly 30-km-wide AMR. These nappe sequences include deposits aged from Ordovician to late Cretaceous. While detrital and volcanic rocks are also observed, carbonate rocks are the dominant lithology in each nappe unit. Quiet conditions of the epicontinental sea terminated in the late Cretaceous with the beginning of ocean closure process. First, detrital deposits including marl, mudstone, siltstone, and sandstone along with the slump deposits, olistostroms, blocks of carbonate and ophiolite rocks cover the carbonate sequences. Then, these sequences moved as independent nappe units which thrusted onto each other to form the core of the AMR. Finally, a more than 1 km thick ophiolite nappe covered the AMR until the initiation of its exhumation around the early Paleocene (Tekeli et al. 1984).

During the early Paleocene–late Eocene period (65–50 Ma), hydrothermal activity and hypogenic karstification associated with nearby granitic rock formation resulted in the development of sulfidic lead-zinc deposits and open hydrothermal cavities in the AMR. Based on observations of the nature of sedimentation in the surrounding basins to the south and west, it is understood that the AMR started to emerge above sea level (e.g., 250 m) during that period. At the end of the early Eocene, rapid uplift became dominant until the end of Oligocene (50–25 Ma). During this period, the maximum elevation was probably around 1000 m a.s.l. and a tropical to sub-tropical climate favored epigenic karst development as the ophiolite cover over the stacked nappes was gradually removed. It is assumed that the initially sulfidic lead-zinc deposits have been converted to their carbonate counterparts because of the infiltration of oxygen-rich groundwater recharge from precipitation. The maximum elevation of the AMR rose from ~1000 m to ~3000 m during the period between early Oligocene and middle Miocene when seawater intruded the surrounding basins due to enhanced subsidence resulted from increased erosion in the AMR (Jaffey and Robertson 2001, 2004). Probably because of the ever-increasing elevation of Anatolian micro-continent since the closure of the Neo-Tethys, the climate changed from tropical/sub-tropical marine to semi-arid continental that resulted in reduced precipitation input over the AMR. As the elevation increased, the mean annual temperature was reduced at the highlands where a poor, steppe type vegetation cover started to become dominant. These environmental changes slowed down the epigenic karst development in the AMR from early Oligocene to early Miocene (25–15 Ma).

Though with slower rates, uplift of the AMR continued from early Miocene to recent with an increase in maximum elevation from ~3200 m to ~3500 m. Such land rise accompanied with cooler climate conditions reduced intensity of epigenic karst development until early Quaternary (last 2 Ma). Glacial conditions interrupted by interglacial paucities were dominant during the Pleistocene (~2 Ma to 10 ka). The AMR has been affected strongly by the Quaternary glaciations (Çiner 2004; Spreitzer 1957, 1971; Zreda et al. 2004). In the central part of the highlands, the Yedigöller Plateau has been covered by a thick ice cap from where the tributary glacial valleys were fed. Valley glaciers extended down to 1500 m on the western and 1100 m on the eastern flanks of the AMR (Sarıkaya et al. 2011; Sarıkaya and Çiner 2015, 2017; Zreda et al. 2011). Such extensive glacier formations along with the thawing and freezing in the periglacial zones resulted in the complete destruction of epikarstic landscapes formed before that time. Today, large glacial valleys extending from Yedigöller Plateau, cirques hosting permanent or temporal lakes, glacially scoured surfaces, roches moutonnées, saddles, outwash deposits, and large moraine sets constitute the major evidences of Pleistocene glaciations. Rock glaciers and kettle holes are the remnants of the last glacial activity of the Last Glacial Maximum (LGM) between ~20 ka and 10 ka ago.

The effect of Pleistocene glaciations on epikarst of the AMR is amazing. Widespread formation of numerous decapitated shafts shows how immense the power of glacial scouring over the epikarst zone was (Klimchouk et al. 2006). Similarly, large number of unwalled cave occurrences observed along the walls of glacial valleys provides evidence on dissection by glacial erosion of pre-formed cave systems.

Termination of the last glacial period has made strong reflections on the landscape of the AMR. Among those, the most prominent are the hanged karst springs, travertine bridges and a "superkarst" landscape. The superkarst zone, which is the rejuvenation of epikarst at the mountain flank, is developed along the timber line (i.e., 1800 m a.s.l.) at the south and southwest of the AMR where Mediterranean-type climate with wet-mild winters and hot-dry summers dominate. Here, pre-conditions for epikarst development were enhanced by periglacial processes and epikarst has been recovered during the Holocene (i.e., last 10 ka) due to favorable climate conditions.

Both the hanged karst springs and travertine bridges are located about 10–30 m above the present stream level at respective sites. Moreover, there are other karst springs which are not hanged on the wall of gorges but are still above the level of stream they discharge to. Such an elevation difference apparently resulted from the difference between erosive powers of surface (i.e., fluvial) and subsurface (i.e., karstic groundwater) flow systems in the AMR. Under common circumstances where surface and subsurface erosion rates are at a comparable level, karst springs and the travertine deposits associated with them are located at the elevation of a neighboring stream. However, when the recharge to groundwater system is locked fully or partly in the ice phase but precipitation feeding the streams at lower elevations is in the form of rainfall, fluvial erosion is much faster than groundwater erosion. The result is that groundwater outflow and deposits associated with them are located above the stream level. Another process that favors the formation of elevated/hanged springs and travertine bridges is the glacio-isostatic rebound of the AMR. With an assumed ice cap thickness of 400 m, the AMR might have experienced an isostatic rebound of 100 m since LGM.

22.2.2 Hydrogeological Characteristics

The AMR has a much higher elevation compared to the surrounding valleys and plains. Therefore, the groundwater recharge supplied by precipitation is transmitted to karst springs located along the flanks of the AMR. While there are karst springs along the northern, western, and southern margins of the AMR, the most prominent discharge of the karst system occurs through a number of karst springs located along the Zamantı River or its tributaries in the east where the AMR has a lower boundary elevation compared to the other sides. The karst aquifer system of the AMR acts like a sponge which has a very high absorbance capacity of the recharge fallen on it. Even the most torrential rainfalls fallen on snow cover do not generate substantial surface flows over the karst terrain. Notable floods occur only on detrital-dominant lithological units like ophiolite or ophiolite mélange where infiltration is limited. The high seepage capability of karst formations is due to extensive development of conduit system throughout their historical development. High hydraulic gradient imposed by the substantial elevation difference of main recharge and discharge zones is another factor that eases absorbing the recharge events.

The long-term mean annual discharge of karst springs into the Zamantı River through a number of karst springs is about 1 billion cubic meters. Almost all of this discharge is accounted by Yerköprü 1, 2, 3, Göksu and Kapuzbaşı springs. Yerköprü in Turkish means earthen bridge, which refers to travertine bridges formed by these springs (Bayarı 2002). Yerköprü 1, 2, 3, Göksu, and Kapuzbaşı (hanged) springs account for the 46%, 31%, and 15% of the total karst groundwater discharge into the Zamantı River, respectively. The mean residence times of groundwater discharging from these springs were found to be around 20 years based on numerical modeling studies that rely on environmental tracer observations (Özyurt and Bayarı 2005).

22.3 Geomorphological Landscapes

22.3.1 Glacially Scoured Highlands, Yedigöller Plateau

Extensive development of karst landscape in the AMR appears to have slowed down since early Miocene (15 Ma) when the mean elevation reached 1750 m a.s.l. Since then, the mean elevation steadily rose to 2000 m a.s.l. It is thought that sparse vegetation above 1750 m a.s.l. was the primary factor that slowed the karst development in the highlands. Following the humid Pliocene period, dramatic change in climate during the Pleistocene resulted in glacial conditions in the AMR. According to field observations, valley glaciers fed by an ice cap nested in Yedigöller Plateau extended down to 1500 m a.s.l. on the western and about 1100 m a.s.l. on the eastern flanks of the AMR. Continuous melting of ice at the foot of glaciers on the western flank resulted in the formation of a large sandur deposit by alluvial fans extending over the Ecemiş Fault (Sarıkaya et al. 2015a, b; Yıldırım et al. 2016). These well-preserved alluvial fans are located along a ~20 km long, NNE trending linear valley on the western front of the AMR (Fig. 22.3). Recently, they have been dated using the ^{36}Cl surface exposure dating methods (Sarıkaya et al. 2015a, b). The oldest alluvial fan surface was formed by 136.0 ± 23.4 ka ago. The incision of the younger Emli Fan surfaces occurred by 97.0 ± 13.8 ka and created an erosional surface around 81.2 ± 13.2 ka ago. After that time, glacial outwash sediments were deposited during the Last Glacial (Sarıkaya et al. 2015a, b).

Today, the highlands including the Yedigöller Plateau are comprised of bedrock surfaces completely devoid of epikarst zone. Freezing and thawing in the periglacial zone during the glacial periods or in the highlands during the interglacial periods followed by the glacial scouring at the bottom, sides and foot of the glaciers devastated the entire epikarst zone developed until Pleistocene (Fig. 22.4).

The highlands of the AMR abound with glacio-karstic landscape elements like permanent and perennial lakes (tarns) nested in overdeepened cirques or over bedrock cavities, arêtes, cols, pyramidal hills, saddles, roches moutonnées, kettle lakes (holes), unwalled caves, and decapitated shafts (Bayarı et al. 2003; Klimchouk et al. 2006). A seven-year-long survey conducted in 2000–2008 by an international team of cavers discovered about 250 caves in and around the Yedigöller Plateau. Many of these caves are in the form of decapitated shafts partly filled by debris scoured from the epikarst zone by the Pleistocene glaciers. The AMR is rich in spectacular glacial landscapes like pyramidal hills and saddles (Fig. 22.5).

While the Pleistocene glaciation terminated about 10 ka ago, rock glaciers and/or debris-covered glaciers are still observed at southern part of the Yedigöller Plateau and at the higher part of the Emli Valley where insolation does not reach effectively (Fig. 22.6). These glaciers are currently melting, probably because of the recent climate changes. Melting of large ice blocks within clay-to-boulder-sized debris results in the formation of ice caves with running streams inside or kettle holes which are meter-to-decameter-sized lakes nested in ice blocks (Fig. 22.6).

22.3.2 Glacial Valleys and Moraines; Hacer Valley

Pleistocene glaciation has led to the formation of long valley glaciers, mainly originating from the ice cap in the Yedigöller Plateau. Among all, the most prominent was the glacier of Hacer Valley on the eastern part of the AMR

Fig. 22.3 View of the AMR and alluvial fans developed along the Ecemiş Fault. Demirkazık Peak and Yalak River are on the left side of the photo. Emli Valley is located on the right side of the picture. Please note that the alluvial fan surfaces were cut by the Ecemiş River, which runs to the south (right)

Fig. 22.4 Early summer view of Yedigöller Plateau (looking west). The elevation ranges from 3000 m a.s.l. to 3750 m a.s.l. The highland has been completely scoured by Pleistocene glaciers, which removed the epikarst zone, leaving only decapitated cave shafts filled by glacial debris. This highland is thought to have hosted an ice cap during the peak periods of glaciations

(Fig. 22.7). This glacier originated from the ice cap in the Yedigöller Plateau and extended down to 1100 m a.s.l. elevation through a 14-km valley which is now the major trekking route within the Hacer National Park. In the lower part of the valley, there are a number of terminal moraines followed by glacial outwash deposits. Surface exposure dates obtained from the cosmogenic chlorine-36 content of moraines and glacially eroded bedrock surfaces revealed an extensive glaciation during the transition of Pleistocene to Holocene (Zreda et al. 2011).

Valley glaciers have been set up in valleys that had been formed during the Pleistocene by the interplay of fluvial and karst erosion processes. Many of such valleys appear to have formed by the gradual collapse of underground karst rivers that connected sinkholes to karst springs. Such underground rivers turned into gorges due to the continuing roof collapses as the underground drainage network grew larger. Then, these gorges turned into V-shaped valleys by continuing fluvial and karst erosion. These V-shaped valleys turned out to become U-shaped valleys due to glaciers flowing through them.

Valley glaciers scoured and filled out all karst features once existing in these valleys. Furthermore, loss of the huge pressure exerted by glaciers on the walls of valley, due to ice melting, caused wall expansion that resulted in further destruction of karst shafts and their exposure in the canyon walls.

22.3.3 Deep Cave Systems; Kuzgun Cave

The AMR has a more than 2000-m-deep unsaturated zone in which there is vast potential for vertical cave development. However, extensive glacial scouring during the Pleistocene (~last 2.6 Ma) devastated the epikarst and filled in almost all karst shafts extending into the depths of the karst system. Substantial effort has been spent for several years by an international team of cavers to find access to deep cave systems that should exist in such a thick unsaturated karst zone (Klimchouk et al. 2006). Eventually, a narrow crack, which hid itself from glacial debris inflow in the shadow of a roche moutonnée, led way to such a deep system, the Kuzgun Cave (Fig. 22.8). Entrance of the cave is located at 2800 m a.s.l. and after 4 years of efforts, the cavers penetrated in the main branch to a depth corresponding to ~1400 m a.s.l. While further penetration has been stopped due to a risky boulder choke zone, there is still another 300 m of penetration potential before the local saturated zone is reached.

Observations inside the Kuzgun Cave provided striking evidences on the historical evolution of the karst in the AMR. Morphology of high- and narrow-inclined passages ("meanders") connecting separate shafts indicates their formation in the vadose zone and supports the idea that the entire system uplifted very fast after the early Oligocene. Vadose invasion shafts and connecting meanders cut across pre-formed voids of different origin, particularly hypogenic hydrothermal cavities lined with a crust of columnar calcite crystals and partly filled with clay containing large spherical concretions. The hypogenic karst development probably took place during the early stage of exhumation of the carbonate massif through the early Paleocene–late Eocene period (65–50 Ma). In sediment fill of other intercepted cavities, marine fossils of Miocene age were identified, indicating that sediments of Miocene age were once present

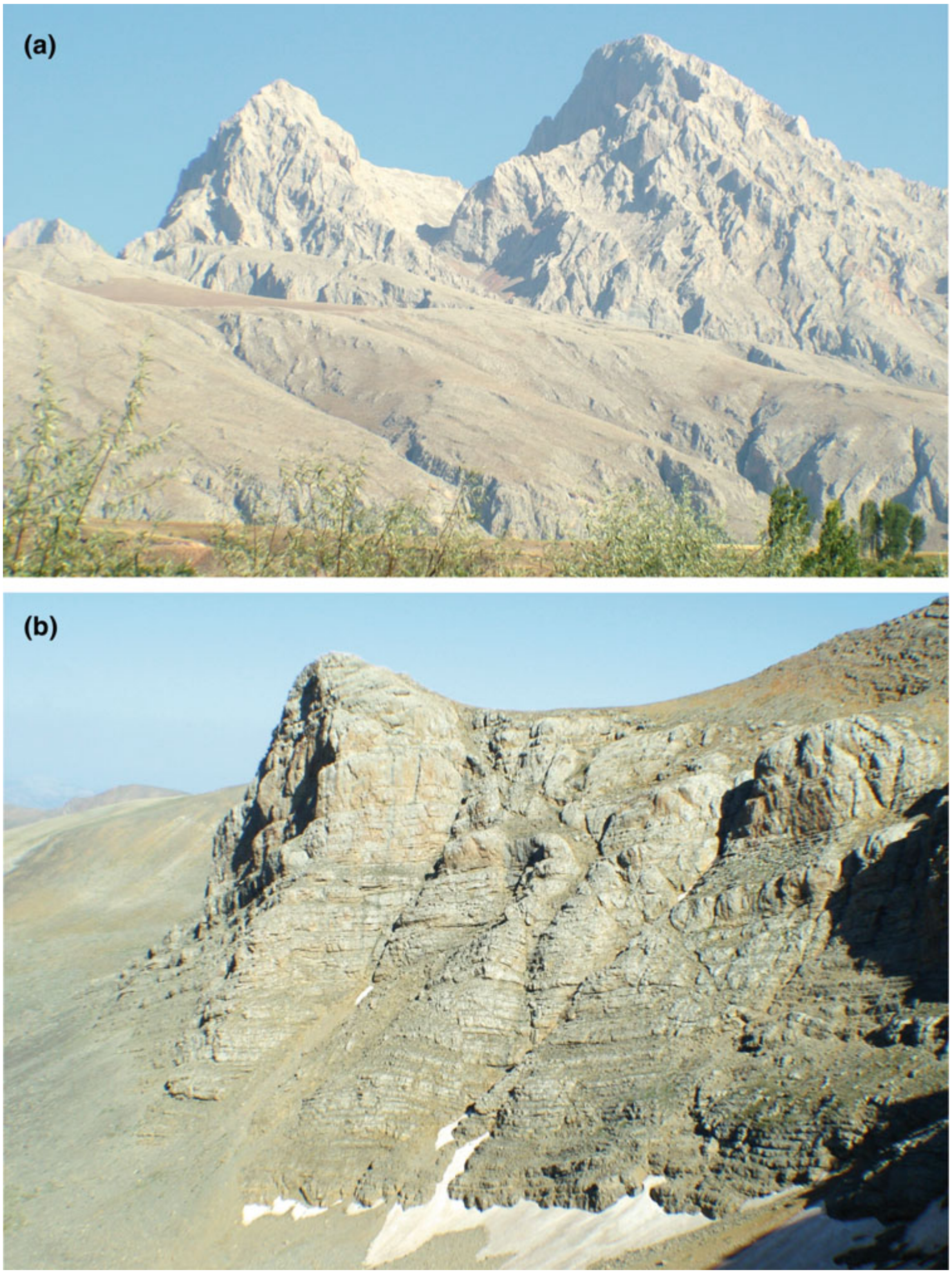

Fig. 22.5 **a** Pyramidal peaks shaped by glacial erosion in western AMR (left). Pyramidal peaks are common in the AMR. **b** Saddles (large-scale roches moutonnées) formed by the differential erosion of bedrock due to spatial velocity difference of overlying glacier are also common in the AMR (Körmenlik Valley, NW of AMR, right)

in a catchment area of the conduit system. Some parts of the Kuzgun Cave contain a multiplicity of unusual secondary mineral formations waiting to be thoroughly studied.

Considering the large number of decapitated shafts discovered in and around the Yedigöller Plateau, it is understood that the AMR hosts an unsaturated zone with extreme conduit development. This argument is also supported by the fact that even the most torrential storms do not generate any surface flow over the carbonate terrain of the AMR.

22.3.4 Ulupınar “Superkarst” Zone

One of the remarkable landscapes in the AMR is the “superkarst” (a kind of polygonal karst) extending along the tree line on the southeastern and southern parts of the massif (Fig. 22.9). The “superkarst” belt is characterized by numerous densely packed dolines and deep fissure-type karren (e.g., Öztürk et al. 2018). Because of the high density of dolines, the surface has gained a honeycomb-like

Fig. 22.6 Rock glaciers as mixture of ice and boulder to clay-sized debris still exist above 3300 m a.s.l. in the Yedigöller Plateau. Kettle Holes are encountered frequently in the AMR. They are formed by rapid melting of large ice blocks in rock glaciers

structure. The regions with "superkarst" formation are open to Mediterranean Sea where abundant precipitation is supplied year-round. Lightning storms lasting all night are common events during the summer time.

The valleys of the Zamantı River and its tributaries opening southward provide easy access paths to air masses to reach at these parts of the AMR. The superkarst belt corresponds to an area where periglacial conditions have been dominant during the Pleistocene glaciations. Hence, physical weathering and fracturing of the near-surface zone were intense in this belt because of frequent freezing and thawing. Active dissolution in favorable climatic conditions since the LGM caused rejuvenation of the epikarst development and the formation of the "superkarst" landscape at the periglacial zone during the glacial periods.

22.3.5 Kapuzbaşı Hanged Springs

The spectacular Kapuzbaşı hanged karst springs pours from the steep right bank of the Kapuz Gorge which is located about 10 km east of the AMR (Fig. 22.10). There are seven major groundwater discharges four of which pour directly onto the stream which is also fed by spring water except during the snowmelt season. The springs are located about 15–30 m above the stream level. The site is a part of the Aladağlar National Park. The groundwater discharging through these springs is fed mainly from snowmelt in the Yedigöller Plateau. Because of the fast infiltration and lack of dissolved soil carbon dioxide, the recharge water has limited capacity to dissolve carbonate minerals before they pour out from the Kapuzbaşı springs. Hence, the specific conductance of a spring's water is around 120 microS/cm. The temperature of water (9 °C) is similar to the mean temperature at the time of snowmelt season (usually April–May). Numerical modeling studies based on long-term environmental tritium observations revealed a mean residence time of 20 years for these springs. In other words, it takes 20 years in average for snowmelt to reach these springs (Özyurt and Bayarı 2005).

22.3.6 Yerköprü Travertine Bridges

Another noteworthy set of landscapes in the AMR is the Yerköprü travertines located at three distinct locations along the Zamantı River. These travertines are formed by karst springs that are fed from the highlands of the AMR (Bayarı 2002; Fig. 22.11). Two of these bridges (Yerköprü 1 and 2) are located upstream from the Zamantı River at 700 m a.s.l, and the third one is located on the downstream part of Zamantı River at 400 m a.s.l. (Yerköprü 3). Temperature of the groundwater forming the travertine bridges increases from 13.5 °C at Yerköprü 1 to 14.5 °C at Yerköprü 3. Similarly, the specific conductance of Ca-HCO_3-type groundwater increases from 450 microS/cm at Yerköprü 1 to 500 microS/cm at Yerköprü 3 (Bayarı and Günay 1995; Özyurt and Bayarı 2008). Similar to the Kapuzbaşı springs, the mean residence time of groundwater discharging from these springs is about 20 years.

The width of the stream covered by the travertine bridges is about 15 m whereas the bridges are located about 10 m above the low level of the stream. Currently, the stream water erodes the bridges while they are still being built by the

Fig. 22.7 **a** Down-looking view of 14-km-long U-shaped Hacer Glacier Valley on the eastern part of the AMR (looking east from ~3000 m a.s.l.). Green zone is the pine forest spreading below 1800 m a.s.l. The pine forest covers several terminal moraines beyond which tarns are nested. **b** an erratic block left on the moraines upon melting of the glacier. The weight of the erratic is estimated to be 170 tons. Note the human scale at the bottom-left of erratic boulder

Fig. 22.8 **a** The profile of Kuzgun Cave (above); **b** the downside view of one of the large shafts in this cave (below, note the human scale at central right)

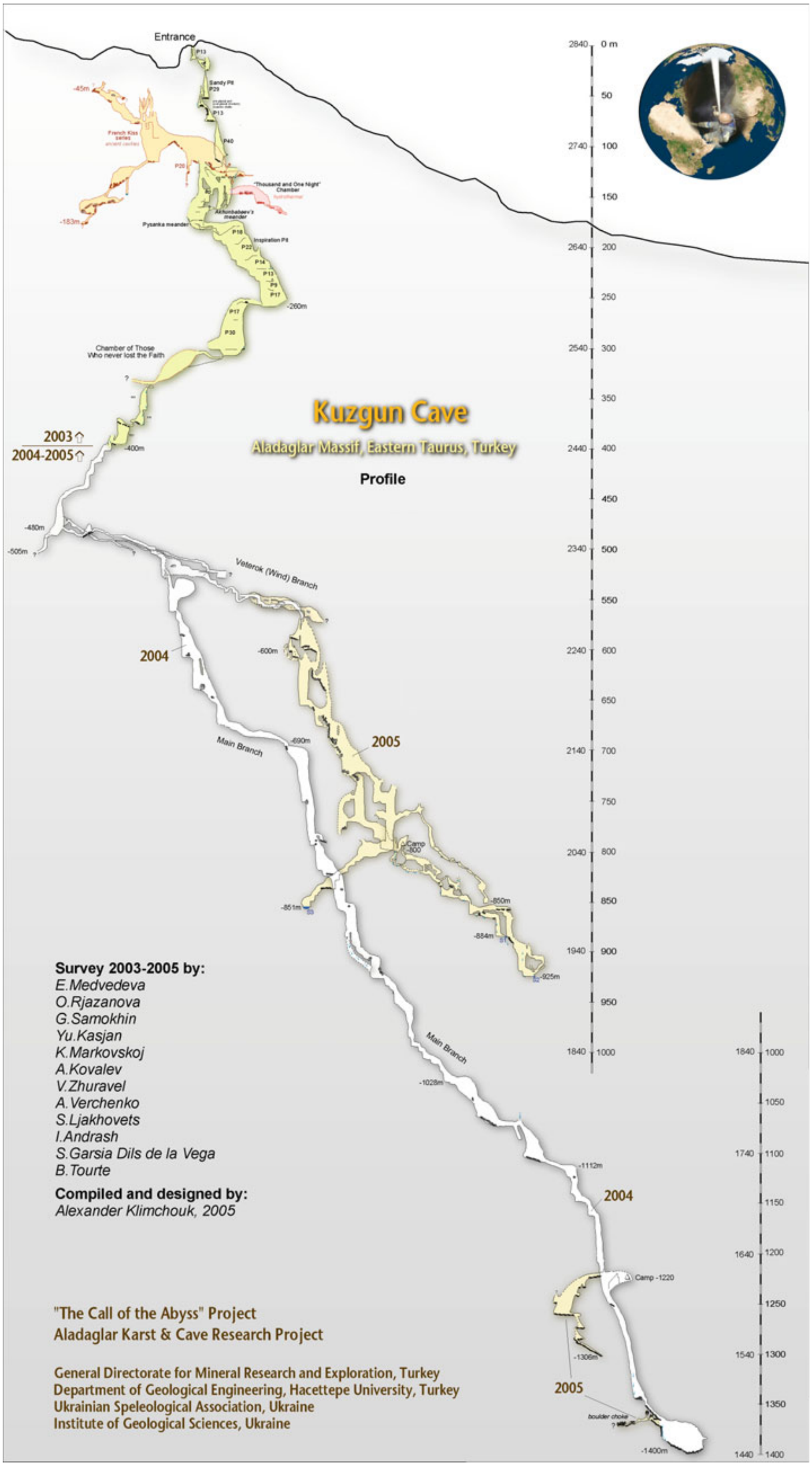

Fig. 22.8 (continued)

Fig. 22.9 “Superkarst” belt is located along the eastern flank of AMR where Mediterranean-type climate dominates. Favorable climate conditions result in extreme dissolution of carbonate rocks. As a consequence, a long and thick belt of epikarst has developed. Superkarst zone has been probably located in the periglacial zone during the glacial periods

associated karst springs. Calculations show that bridge formation by lateral travertine build-up is possible considering stream width and the height of springs from the stream (Bayarı 2002). However, there is evidence that trunks and bushes carried by the stream might have provided a basement for the travertine bridge development if they got trapped.

Almost all of the groundwater discharge from the AMR is supplied by karst springs located along the including Yerköprü 1, 2, and 3. However, travertine bridge formation is observed only in Yerköprü springs because the groundwater is super-saturated with respect to calcite only in these springs.

Fig. 22.10 Kapuzbaşı hanged karst springs pouring from about 30 m above the stream formed as a result of competition between the fluvial and karst erosion rates during the glacial periods (photograph Attila Çiner)

Fig. 22.11 Yerköprü 3 Travertine bridge located at 400 m a.s.l. on Zamantı River (looking from upstream). The travertine bridge measures 20 m across the stream and ~10 m wide

22.4 Conclusions

The Aladağlar Mountain Range of south-central Turkey is probably one of the most outstanding regions on Earth in terms of a unique collage of spectacular glacial, karstic, and glacio-karstic landforms. Long-lasting research on the processes that shaped these landforms has shed light on the morphogenetic evolution of the AMR. However, there are still many issues to be resolved in the future like the extent of deep cave systems and the wealth of information about paleo-environments they contain. Furthermore, there is an ever-increasing pressure over the natural stability of this region. Raising the quality of existing backcountry roads will eventually cause an increase in tourist population and construction of hydropower structures over Zamantı River threatens aesthetic values of the karst springs and the travertine bridges.

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