Ice Caves in Greece

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CHAPTER

ICE CAVES IN GREECE

18

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CHAPTER OUTLINE

18.1 INTRODUCTION

Over 70% of Greece's territory consists of carbonate rocks (limestone, dolomite and marble). This almost uniform geological composition of the bedrock, in combination with the very active tectonic regime and the climatic setting of the broader region of the east Mediterranean, favors cave development (Pennos and Lauritzen, 2013). The exact number of caves is still unknown since there is no official archive. However, there is an estimate of more than 10,000 caves and rock shelters, and almost 10% of them occur only in a small part of the Lefka Ori mountains on Crete(Adamopoulos, 2013).

Despite the common belief that Greece lacks permanent ice deposits, a plethora of ice bearing caves have been reported from different parts of Greece (e.g., SPELEO, 2017). Most of these caves are located in high altitudes (>1500 m) and are vertically developed. This setting (i.e., high altitude, verticality) favors the seasonal accumulation of snow, since solar radiation does not reach the deeper parts of the vertical shafts. These perennial ice bodies are preserved inside the host caves when the cold winter air sinks in, displacing the warm air that is pushed out through the pit as described by Perşoiu and Onac (2012). These ice deposits depict a characteristic layering that reflects their depositional history and therefore are ideal for palaeoclimatic reconstructions (Perşoiu and Onac, 2012).

In this chapter, we introduce four high-altitude ice caves that experience different patterns of precipitation and temperature related to the major atmospheric circulation patterns and trajectories of the Eastern Mediterranean. We present the survey of each cave and characteristic photos from the ice deposits.

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Furthermore, we host a literature review of the climate of Greece in relation to the large-scale atmospheric circulation in the area.

We believe that this short chapter about the *Greek Ice Caves* will introduce the existence of the ice bodies to the scientific community and will motivate researchers from different disciplines to work on them.

18.2 SETTING

18.2.1 GEOLOGICAL SETTING

The Greek peninsula shows a complex geological history, but a relatively homogenous lithological composition, as it consists mainly of carbonate rocks (marble, limestone and dolomite). In general, the northern and northeast part of the country consists of Paleozoic marbles and metamorphic rocks that are part of the old continental crust, and in the periphery of which the closing of the Tethys Sea took place during the Alpine orogenesis. In contrast, the rest of the Greek mainland, as well as most of the islands (apart from those that belong to the Hellenic arc and demonstrate considerable volcanic activity), are mainly built up of Mesozoic limestones and igneous rock formations. The carboniferous sediments represent shallow and deep marine deposits from the Tethys Sea. Overall, the general structure of Greece is characterized by a series of stacked nappes, with a composite thickness of ~5–10 km, consisting of the upper crust that was detached from the present subducted continental and oceanic lithosphere of the Adriatic-African Plate (Jolivet and Brun, 2010; van Hinsbergen et al., 2010; van Hinsbergen et al., 2005). These nappes (or “mega-units”) were thrusted and stacked in an east-to-west direction since the Cretaceous (Faccenna et al., 2003; Jolivet and Brun, 2010; van Hinsbergen et al., 2005) and form a shortened representation of the paleogeographical distribution of continental ribbons and deep basins that existed in the western Neo-Tethys (e.g., Dercourt et al., 1986; Mountrakis, 2010; Stampfli and Hochard, 2009).

The Aegean Sea and its surrounding areas belong to the active continental boundary of the Alpine-Himalayan belt (Fig. 18.1) and are subjected to large-scale active deformation that stems from the subduction of the eastern Mediterranean lithosphere under the Aegean Sea, along the Hellenic Arc (Papazachos and Comninakis, 1971). Consequently, the majority of continental and coastal parts of Greece share common characteristics of back-arc extensional tectonics, expressed by the presence of a strong deformational pattern, volcanic activity, and the development of fault bounded grabens, lying in accordance with the dominant N-S extensional stress field. However, as illustrated in Fig. 18.1, the northern part of Greece is additionally influenced by a subsidiary right-lateral shear because of its coexistence with the North Aegean Trough, a dextral strike-slip structure (McKenzie, 1972).

18.2.2 THE CLIMATE OF GREECE

Located on the southern part of Balkan Peninsula, the general climatic characteristics of Greek climate correspond to “Mediterranean Climate,” with wet mild winters and dry warm summers. However, this simplistic description holds truth only for a few low-lying coastal areas and for the majority of Aegean islands. Here a specific focus is given on the basic statistics of reconstructed precipitation and temperature, since they are the most important climatic variables for the formation of glacial and periglacial features, such as ice formation in caves.

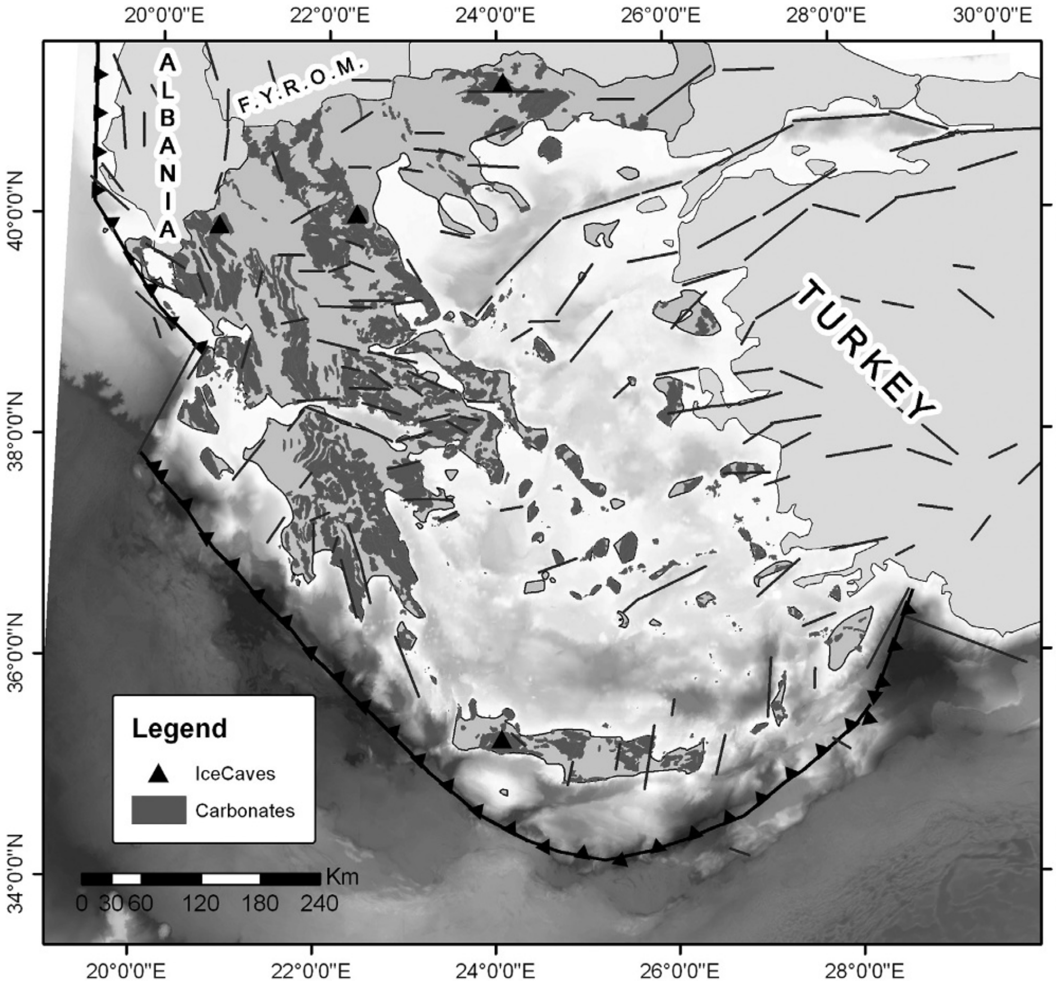

FIG. 18.1

Reference map of the broader Aegean region where the carbonate rocks, the selected Ice caves, the main tectonic lines, and the bathymetry are shown. Fault lines are extracted from Papazachos et al. (2001).

Most of the precipitation in Greece occurs during the winter and early spring (December–March), while summer precipitation occurs as convective, and often intense, rainfalls (Feidas et al., 2007; Xoplaki et al., 2000). The patterns of winter precipitation over Greece are influenced by its complicated coastline and mountainous relief. Despite the large spatio-temporal variability of winter precipitation, a significant fraction (30%) is explained by large-scale atmospheric circulation (Xoplaki et al., 2004).

18.2.2.1 The climate of Greece in relation to large-scale atmospheric circulation

Xoplaki et al. (2000) and Quadrelli et al. (2001) defined the main 500 hPa patterns connected to winter precipitation over Greece and concluded that the North Atlantic Oscillation (NAO) plays a major role in controlling precipitation over the Mediterranean region including Greece. Winters with mild temperatures and high amounts of precipitation in Greece are linked to negative phases of NAO (Bartzokas et al., 2003), whereas low winter temperatures, and a lack of precipitation over the north, northwestern parts of Greece, are associated with an enhanced frequency of northern and/or northeast continental dry and cold airflow over the area, driven by the Siberian High (Maheras et al., 1999; Xoplaki et al., 2000). This last pattern (pattern C in Fig. 18.2) originates over the Siberian Plateau and often causes precipitation and snowfall in the eastern part of Greece, including Falakro Mountain, with considerably higher amounts accumulating in the down-water direction on the south-east shores of the Aegean Sea and in many occasions on the island of Crete, including the Lefka Ori in Crete (Fig. 18.2).

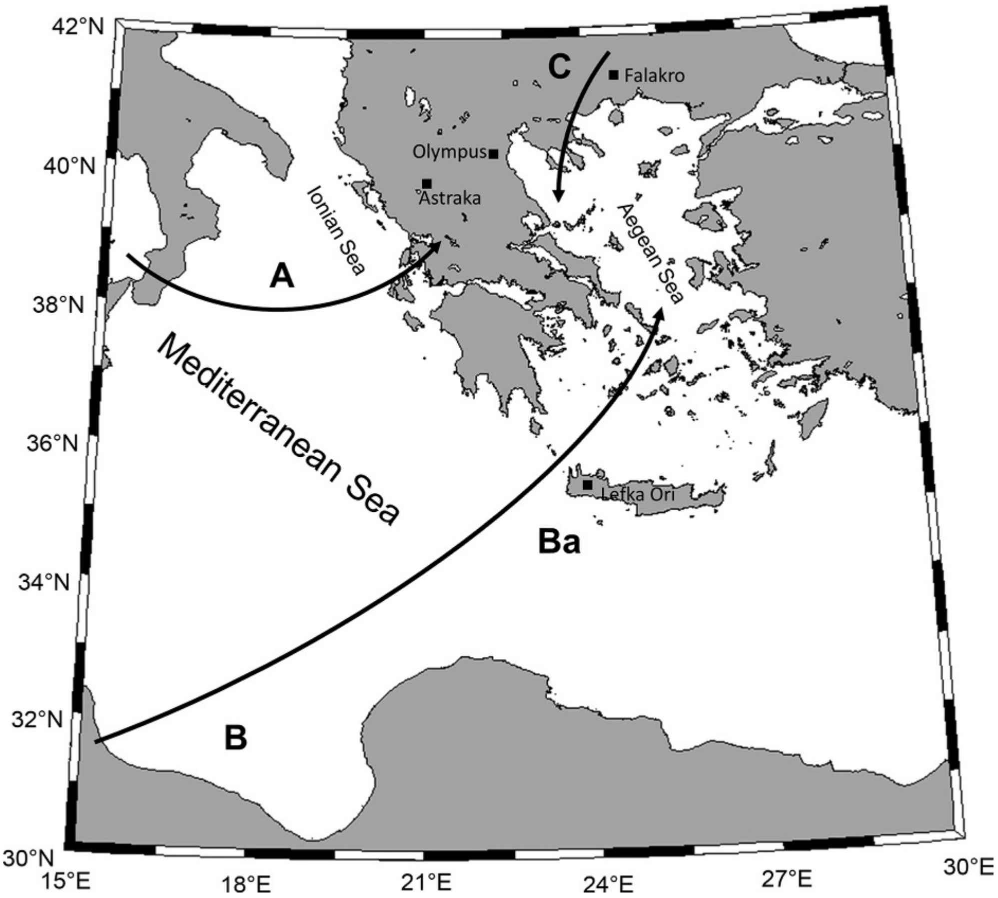

FIG. 18.2

Location of the selected mountain ranges/massifs with respective ice-caves presented in this chapter, in relation to the major patterns and trajectories of the dominant large-scale atmospheric circulation patterns that exert major controls on winter precipitation and temperature along north Aegean Sea. The movement of North Atlantic Oscillation (NAO) induced cyclonic depressions over the northwestern Mediterranean (A), cyclonic depressions generated along the lee side of the Atlas Mountains (B), and offshore western Crete (Ba), while the general direction of cold wind outbreaks of Arctic origin due to intensification of Siberian High (C) are related to low air, sea surface temperatures, and reduced precipitation in north and west Greece.

Winter NAO-driven depressions originate in the Atlantic, near the Straits of Gibraltar, and track northeastwards, barely crossing the Adriatic, with high rainfall limited to the western Greece, including the Tymfi Mountain, but with significant influence extending further east, reaching the west ramparts of Mount Olympus (Styllas et al., 2015) and, to a lesser extent, at the north-eastern part (Fig. 18.2). As these frontal depressions approach Greece from the west, they cause southwest winds (pattern A, Fig. 18.2) over the Ionian and Aegean Seas and force maritime air to move eastwards. Precipitation totals decrease south of this mean track, partly because of surface retardation due to land-air effects, and partly because the depressions decay rapidly by the time they reach eastern Greece (Flocas and Giles, 1991). In the above mechanisms of winter precipitation, the influence of the warm Aegean Sea should also be mentioned. The variability in winter cyclonic routes over Greece may be found in the complex topography of the region that yields significant monthly variations (Alpert et al., 1990).

The complex land-sea interactions, orographic precipitation variations, and frequent cold invasions of polar origin along the north coast of Mediterranean Basin, are the main causes of local cyclogenesis in specific regions, the most important of which are the Gulf of Genoa, the Atlas Mountains lee area, Southern Italy, the Central Mediterranean/southern Ionian Sea, the Cyprus region, and the Black Sea (e.g., Bartzokas et al., 2003; Feidas et al., 2007; Fotiadi et al., 1999; Prezerakos and Flocas, 1997; Trigo et al., 1999). Central Mediterranean cyclogenesis has considerable effects on the overall wetness of western Crete (Lefka Ori, pattern Ba in Fig. 18.2), but mild temperatures do not always ensue nivation and the formation and/or preservation of ice in Lefka Ori.

18.2.3 CAVES IN GREECE

More than 10,000 caves are known in Greece (SPELEO, 2017). The majority of them are vertical pits with depths ranging from a few meters up to 1200 m (Adamopoulos, 2005). Pennos and Lauritzen (2013) point out that this fact is related to the intense tectonic regime of the area that results in the fracturing of the bedrock in the accentuated topography. The high tectonic activity is responsible for the continuous lowering of the phreatic zone, creating a high vadose zone in which the vertical caves occurred (most vertically developed caves of the world are essentially vadose). Here, we present four characteristic shafts that are influenced from the different atmospheric circulation patterns and present thick ice deposits (Fig. 18.2).

18.2.4 SELECTED ICE CAVES

18.2.4.1 Chionotrypa cave, Falakro Mountain

The northernmost cave in Greece is *Chionotrypa* (Fig. 18.3) in Falakro Mountain. This ice cave is located 18.2 km northwest from Drama city in Eastern Macedonia, N. Greece, in the vicinity of the Falakro Ski Center, at an elevation of 2080 m. The cave presents a 111 m vertical expansion, and it is formed in the compact dolomitized marbles of the Rhodope Massif by vadose water circulation. The entrance of the cave is a spectacular collapsed doline 65 m in diameter.

The ice inside the cave is formed at the bottom of the collapsed doline (Fig. 18.3A) and penetrates further inside the cave. The vertical height of the ice sheet is almost 30 m (Fig. 18.3C). The formation of the ice is due to snow accumulation and compaction during winter months (Fig. 18.3B). Ice movement is suspected by Lazaridis and Makrostergios (2014) due to shearing in some speleothems at the lowest part of the cave.

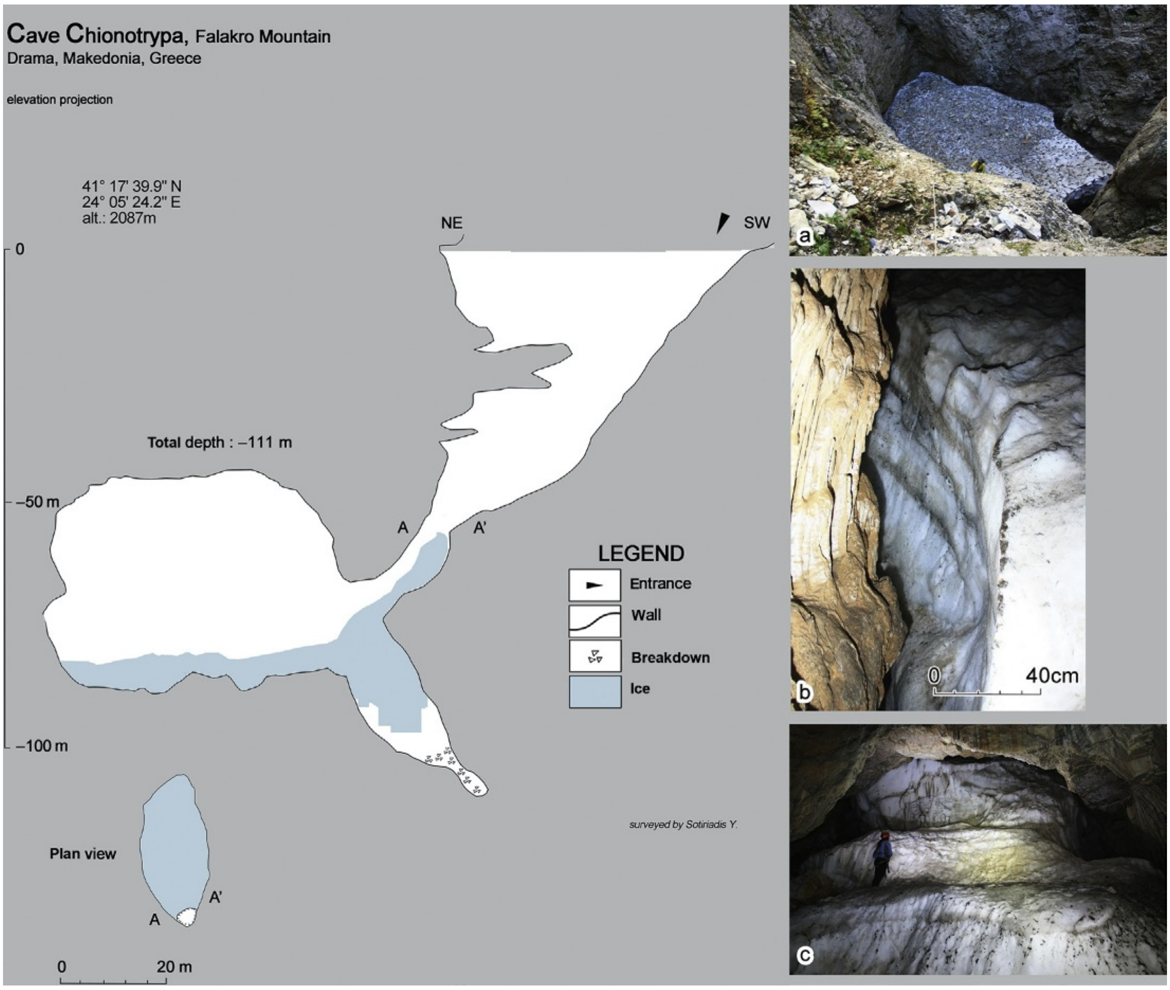

FIG. 18.3

Chionotrypa cave survey. Inlet (A) view of the ice from the surface, note that caver is 10 m above the ice. Inlet (B) shows organic layers inside the ice deposit where in (C) the ice thickness is shown.

18.2.4.2 Chionotrypa cave, Mount Olympus

On Mount Olympus is found another "*Chionotrypa*" cave. The name "*Chionotrypa*" means "snow hole," and it is the name that locals have given to these ice-bearing pits all over the country. The cave has developed along tectonic discontinuities in Jurassic bedded limestones of the Gavrovo Zone in the Olympus tectonic window (Godfriaux, 1968). Its entrance lies in a slope with eastern orientation facing the Aegean Sea at 2560 m elevation and has an elliptical shape of 6.6 × 8 m, the total depth of the cave is 26 m (Fig. 18.4A). The cave holds a large ice deposit that is generated due to the high amounts of snow that cover the area during the winter time, resulting in characteristic layering (Fig. 18.4B). The ice thickness fluctuates due to rising air temperature during the summer months. The minimum thickness is observed during the early autumn months (~20 m), where during winter it expands up to 25 m (Vaxevanopoulos, 2011). Smaller ice bearing pits in the adjacent area of Chionotrypa cave are also known (Vaxevanopoulos, 2011).

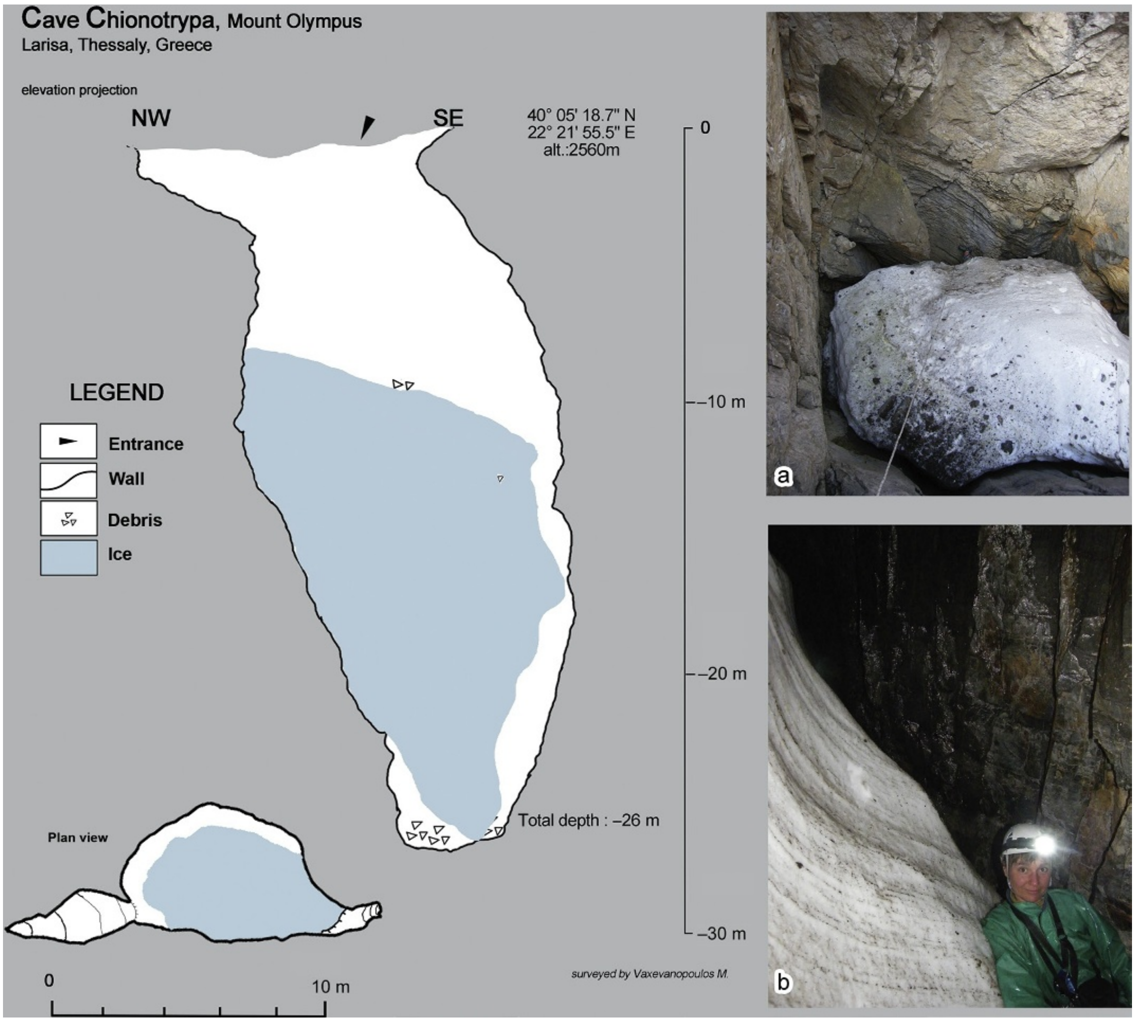

FIG. 18.4

Mount Olympus Chionotrypa cave survey. Inlet (A) view of the ice body as seen from above, and (B) organic layering at the bottom of the ice.

18.2.4.3 Provatina cave, Tymfi Mountain

Provatina cave, probably the most iconic Greek cave, constitutes a vertical pit with total depth of 407 m (Fig. 18.5). The cave is located 35.5 km north of Ioannina city at the Tymfi Mountain, W. Greece. It was first explored in 1968 by a British army expedition (Adamopoulos, 2005). The cave has developed on the edge of Tymfi Mountain's limestone bedding plane. It is formed along big vertical tectonic discontinuities of Jurassic to Upper Cretaceous limestone. The ice deposit is located at the middle part of the cave at a depth of 180 m (Fig. 18.5B) and has a mean thickness of 15 m. The ice is a mixture of snow, during winter months, and vadose waters that infiltrate the cave. The cave temperature, in combination with the position of the ice that makes it unreachable by the sun's rays, is the key factor for its preservation.

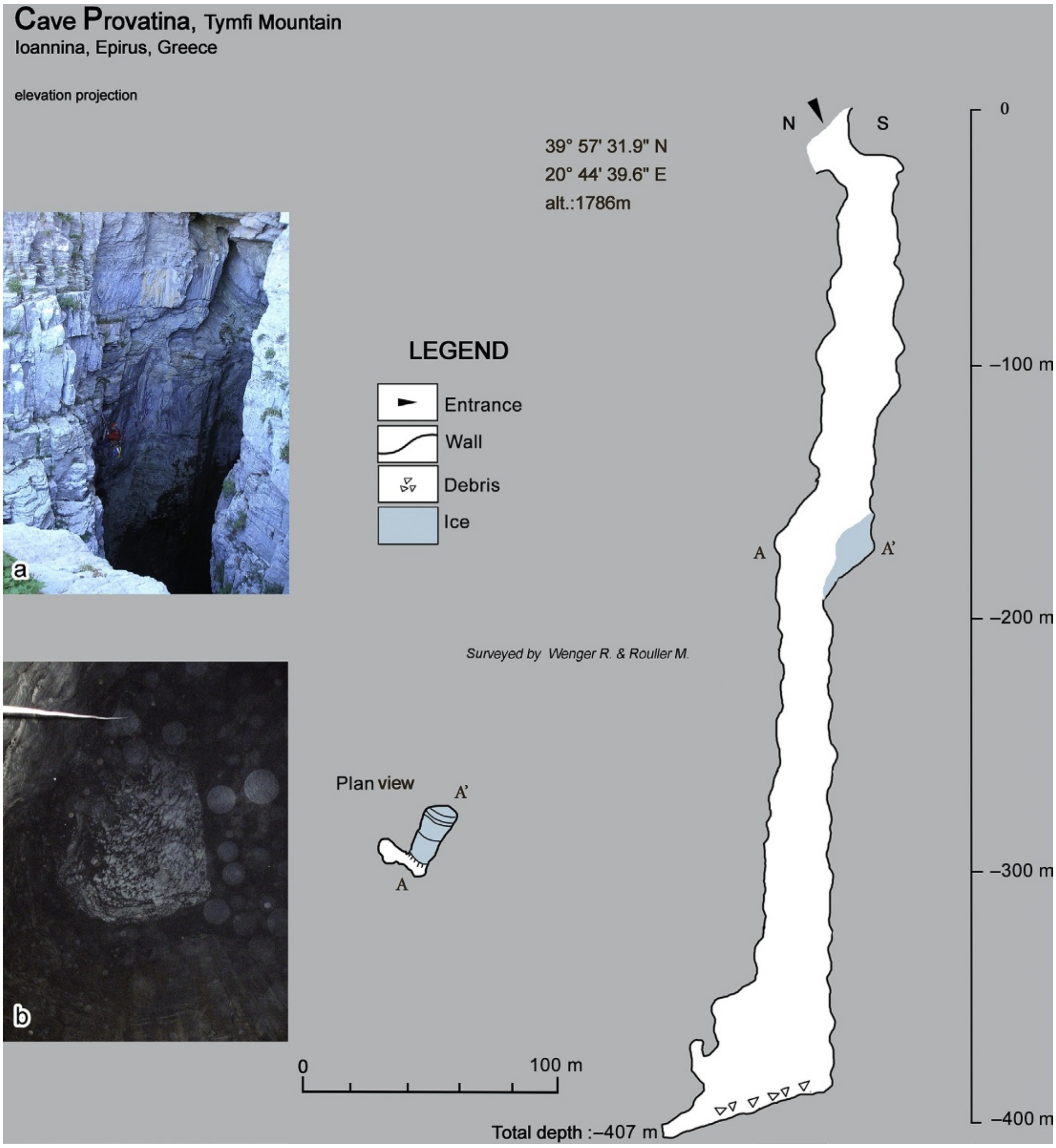

FIG. 18.5

Provatina cave survey (Graglia et al., 1982). Inlet (A) the entrance of the cave (see caver for scale) and (B) the ice deposit as seen from 80 m above (rope for scale).

18.2.4.4 Skud cave, Lefka Ori mountain range

The southernmost cave presented here is *Skud* cave. The cave is located at the Lefka Ori mountain range in the western part of Crete. The area presents the highest density of caves per square meter globally (Adamopoulos, 2005). According to Adamopoulos (*pers. comm.*) more than 100 caves and rock-shelters in the area host ice deposits throughout the year, potentially ranking them as the southernmost European Ice Caves. *Skud* (SPELEO, 2017) cave is a 46 m vertical pit that hosts a 15 m ice deposit (Fig. 18.6). The cave entrance is found at a 1915 m elevation facing toward the north. The ice is formed due to snow accumulation and compaction during the winter months, and it is preserved throughout the year because of the cave depth and entrance orientation which prevent the sun's rays from reaching the ice body (Fig. 18.6B).

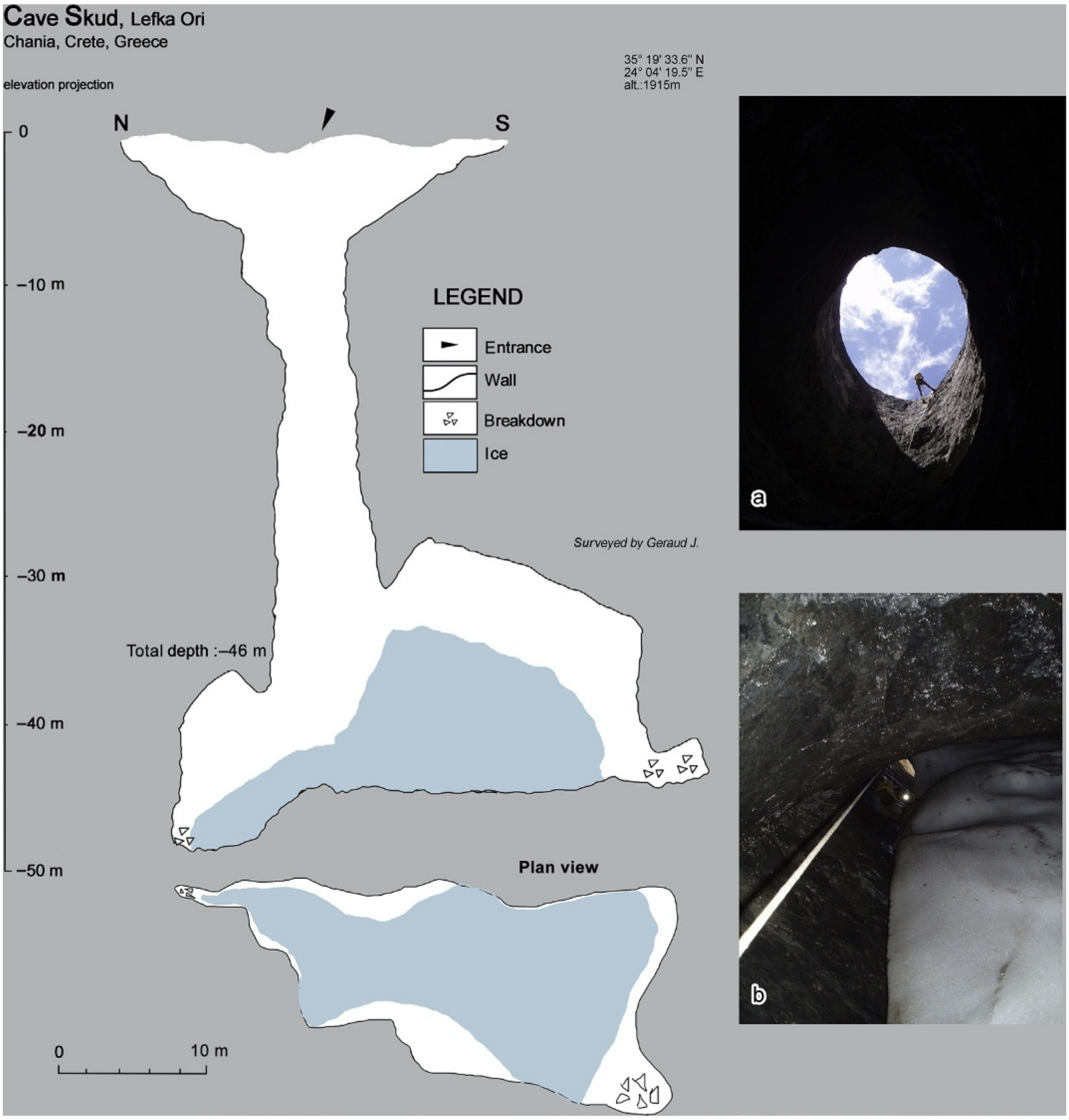

FIG. 18.6

Skud cave survey (Maire, 1982). Inlet (A) view of the entrance from the bottom of the cave, (B) the lower parts of the ice.

18.2.5 CLIMATIC CONDITIONS IN THE VICINITY OF FALAKRO, OLYMPUS, TYMFI, AND LEFKA ORI MOUNTAINS

To depict the general climatic characteristics of each separate area, data from the Climate Research Unit (CRU) gridded climatology (precipitation and temperature) are utilized. More specific, the CRU TS3.23 grid cells have been utilized (Harris et al., 2014), centered at 41.25°N, 24.25°E for Falakro Mountain, at 40.25°N, 22.25°E for Mount Olympus, at 39.75°N, 20.75°E for Tymfi Mountain, and at 35.25°N, 24.25°E for Lefka Ori, respectively. The reconstructed data spans 114 years of observations from 1901 to 2014 (Harris et al., 2014).

Average monthly variations of precipitation show a different pattern. The distribution of monthly precipitation in Falakro and Olympus is bimodal, with peaks in December and May, in contrast to Tymfi and Lefka Ori, which show a unimodal distribution where maximum precipitation occurs in December–January (Fig. 18.7).

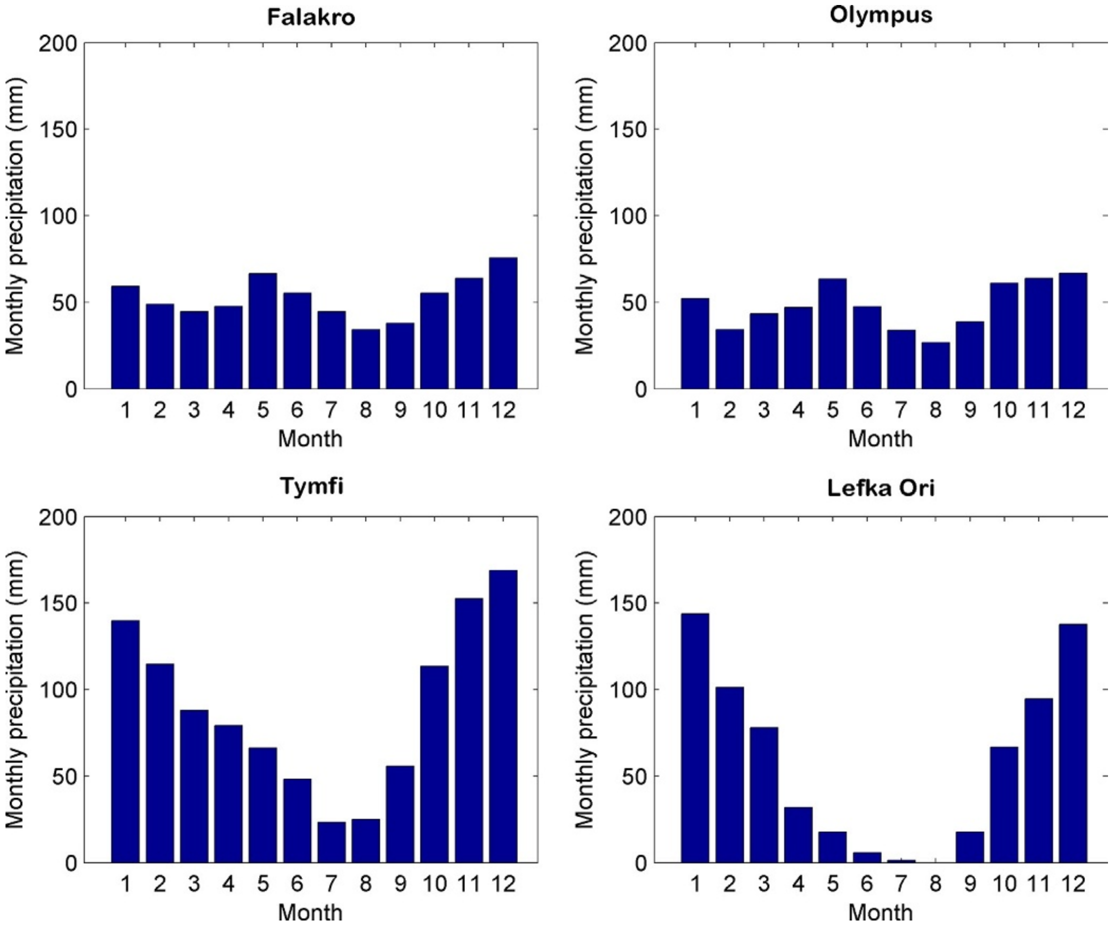

FIG. 18.7

Monthly distribution charts of precipitation for the four selected locations.

Summer precipitation in Falakro and Olympus is higher in comparison to Tymfi and Lefka Ori, the latter exhibiting precipitation values close to zero for July and August. Overall, Tymfi and Lefka Ori are characterized by wetter conditions, as average annual precipitation for the selected grid cells is approximately 1100 mm for Tymfi and 700 mm for Lefka Ori, while Falakro and Olympus are 630 mm and 580 mm, respectively. It has to be noted that the actual values in the locations of the ice caves are expected to be higher due to orographic effects.

In terms of temperature, Falakro and Olympus are characterized by colder winters. Tymfi, on the other hand, is slightly warmer, while Lefka Ori in Crete demonstrates mild temperatures (Fig. 18.8), with considerably warmer summers, so that the formation and preservation of ice in Lefka Ori requires exceptionally colder conditions in relation to the last century.

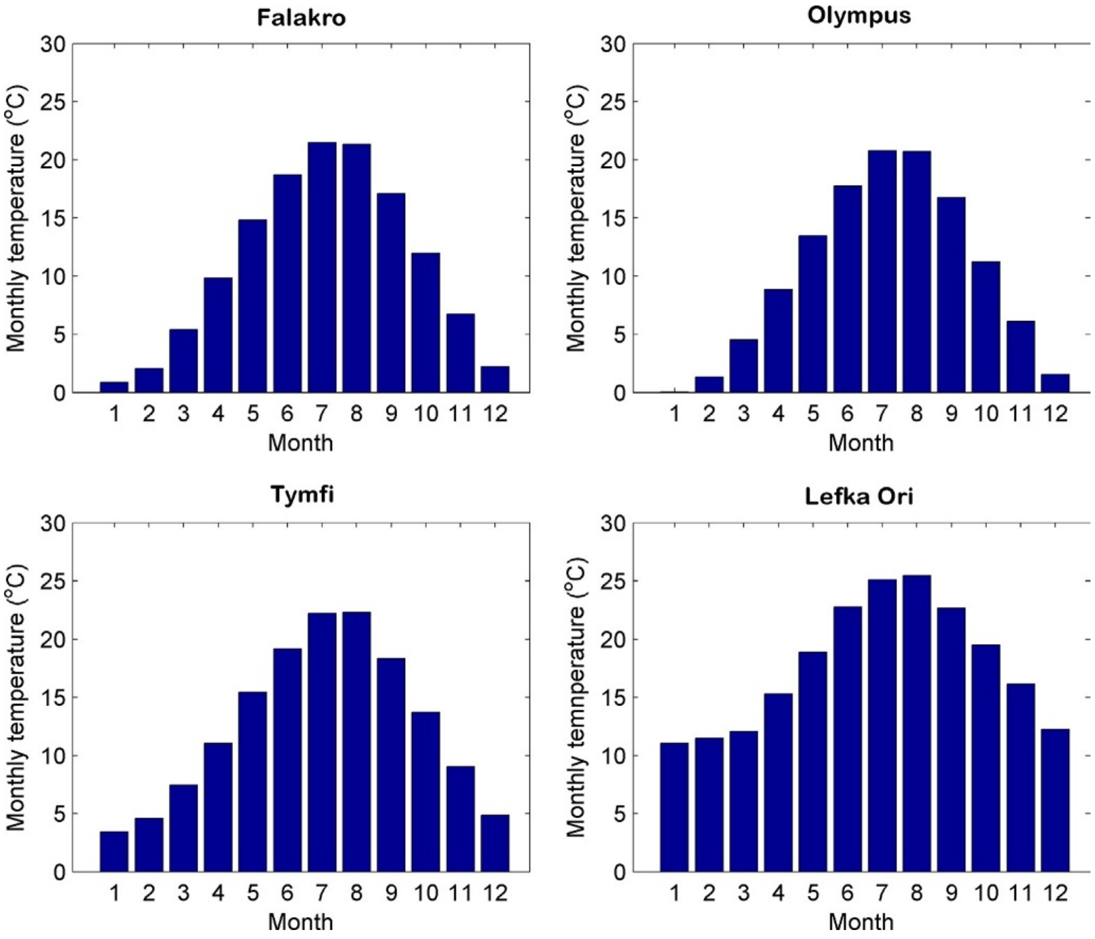

FIG. 18.8

Monthly distribution charts of temperature for the four selected locations.

The variable climatological conditions of the ice caves presented here are important in terms of their past evolution. Unraveling the information stored in these underground ice bodies may be very useful in reconstructing the contrasting patterns of previous large-scale atmospheric circulation patterns over the southern Balkans. We believe that the knowledge of the recent climatic conditions, and their relation to large-scale atmospheric variability along the selected key-sites where ice caves exist (Falakro Mountain, Mount Olympus, Tymfi Mountain and Lefka Ori), has important implications on the past (Holocene) evolution of these localities, as abrupt changes in atmospheric teleconnection patterns recorded from other proxies (i.e., pollen records, fluvial deposits and glacial variability) are expected to exert strong controls on the evolution of ice deposits as well.

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