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LATE PLEISTOCENE GLACIATIONS AND PALEOCLIMATE OF TURKEY

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ABSTRACT

Glaciers respond quickly to climatic changes and thus they are considered to be very accurate indicators of changes in atmospheric conditions. Similarly, the extent of past glaciers gives valuable insights into paleoclimatic changes. For this purpose, we reviewed the paleo-glaciated mountains where cosmogenic surface exposure dating was applied in Turkey. We also evaluated the paleoclimatic results obtained from these studies to provide a regional overview. Twenty-seven mountains in Turkey are high enough to support Quaternary valley glaciers or ice caps. The timing of glaciations was reported mainly by cosmogenic dating of moraines. We re-evaluated the dated sites and recalculated some of the published cosmogenic ages using the up-to-date production rates. The oldest geochronological records reported from the region belong to the glaciations before the globally defined Last Glacial Maximum (LGM). These glaciers developed probably during the beginning of the last glaciation (MIS 4; 71 ka ago) and stopped advancing at the end of the MIS 3 (at 29-35 ka ago). Later, glaciers expanded and reached to their most extensive locations during MIS 2 (after 29 ka ago). They reached maximum extents between 21.5 ka ago and 18.5 ka ago. This local-LGM was synchronous with the global-LGM. After the LGM, the glaciers started to retreat to less extensive positions and deposited their moraines ~16 ka ago during the Late Glacial. The Younger Dryas (~12 ka ago) advances were also reported from a limited number of mountains. Rare Early Holocene glaciations were dated to 8.5 ka in the interior regions. Late Holocene (1-4 ka ago) and Little Ice Age (between 1300-1850 AD) advances were also observed. We reconstructed the paleoclimate using glacier modeling together with paleoclimate proxy data from several regions. The results show that LGM climate was 8-11°C colder than today and moisture levels were 1.5 to 2 times in SW Turkey, somewhat similar to modern values in central parts and 30 % drier in the NE. The Late Glacial was colder by 4.5-6.4°C based on up to 50 % wetter conditions. The Early Holocene was 2.1-4.9°C colder and up to twice as wet as today, while the Late Holocene was 2.4-3°C colder and its precipitation amounts approached to similar conditions as today.

1. Introduction

Studies researching glaciers in Turkey have increased in recent years. Currently due to climatic changes our glacial assets are reducing daily and examining records of the past quantitatively will allow more reliable climatic predictions to be made for the future. As stated in the latest report by the Intergovernmental Panel on Climate Change (IPCC) on 27 September 2013, global climate change is a truth beyond doubt. According to the same report, the mean surface temperature of Earth has increased by 0.89°C since 1901 and this increase has caused a significant reduction in global snow and ice cover. Accordingly, each year global glacier volume reduce by 259 billion tons each year. The yearly ice loss from Greenland glaciers is 97 billion tons while the

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loss in Antarctica has reached 121 billion tons (IPCC, 2013).

In Turkey the situation is no different. According to Sarıkaya (2012), the Mount Ağrı Ice Cap's surface area, the largest glacier in Turkey, has reduced by 29 % in the last 35 years (1976-2011). According to the latest study by Yavaşlı et al. (2015), the areal distribution of glaciers in Turkey had reduced in the last 41 years from 25 km^2 to 11.2 km^2. These and similar studies to date reveal the truth of climate change, but in the past how often and by how much did climate change? What was the distribution of glaciers in Turkey? What geographical and climatic relationships exist between paleo- and present glaciers? Have similar climatic changes as today happened in the past? If it is considered that past changes happened without the effect of humans, how much does natural change contribute to the climate changes today? To answer these and similar questions, it is necessary to research paleo-glacial records. This study is a review of the distribution and timing of glaciers developed during Quaternary ice ages in Turkey (Figure 1). Additionally, findings obtained about paleoclimatic conditions during these ice ages are presented.

Studies on quantitative glacial research and dating of paleo-glaciers in Turkey in recent years have shown that Turkey experienced significant glacial advances in the Late Pleistocene (126-11.6 ka) and partially in the Holocene (last 11.7 ka) (Sarıkaya et al., 2011). Previous studies were done only based on relative location and sizes (Erinç, 1951; Doğu et al., 1993; Çiner, 2003; 2004), but now can be completed in a more sensitive manner with quantitative dating studies to determine advance and retreat times of glaciers. This study brings recent studies in Turkey into a more general view and presents regional implications of glacial timing and paleoclimate.

2. Quaternary Glaciers and Ice Ages

Glaciers and climate have a direct relationship and they react very quickly to ongoing climatic changes (Oerlemans, 2001). The most reliable records of the climatic changes in the Pleistocene, called the Ice Age, come from glaciers. Climate change dominating the Quaternary (last 2.58 Ma) is the most important factor in the creation of glacial periods. Periodic changes in the orbit of Earth affect the intensity of sunlight reaching the earth and as a result Earth's climate. These changes, called Milankovitch cycles, cause glaciers to advance in cold climate conditions and retreat in relatively warmer periods.

It is thought that in the Quaternary period at least 21 glacial periods developed, each numbered by their Marine Isotope Stages (MIS). Of these glacial periods in the last 900 ka, four have reached large scales globally. These are, from the oldest to most recent, MIS 16, MIS 12, MIS 10-6-8 and MIS 4-2 glacial periods (Gibbard and Cohen, 2008).

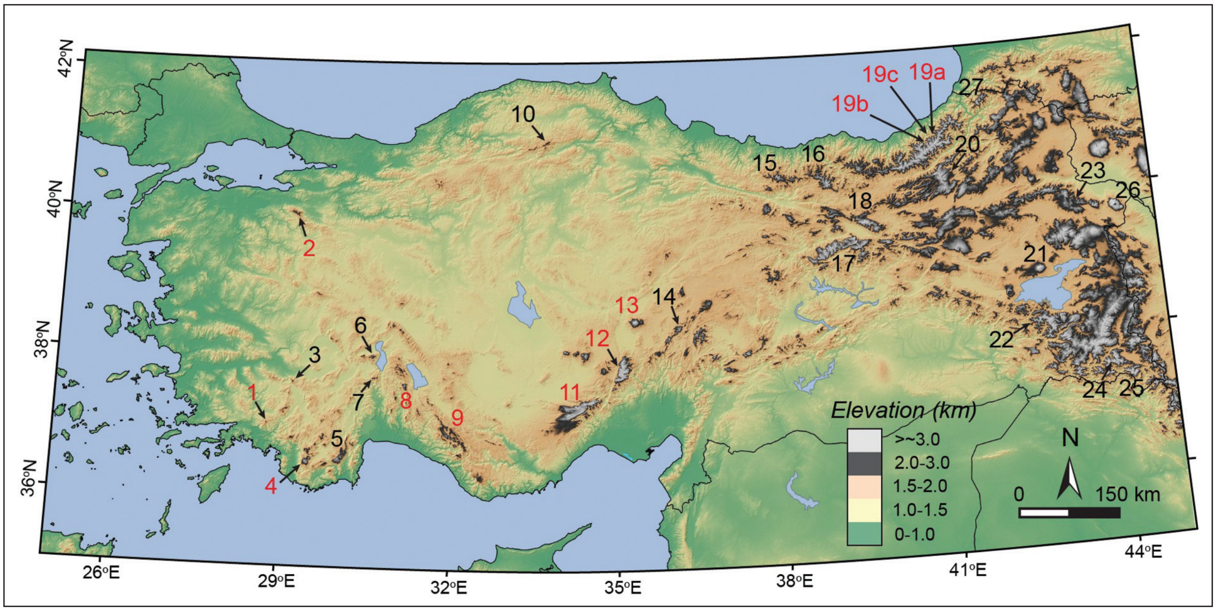

Figure 1- Distribution of glaciers in Turkey in the Late Pleistocene. Areas in red indicate cosmogenic dating areas.

In European glacial stratigraphy the MIS 16, called the Günz, ended about 610 ka ago (Termination 7) while the Mindel ice age (MIS 12) ended 424 ka ago (Termination 5). The Riss ice age (MIS 10, 8 and 6) (Penultimate glaciation) ended 130 ka ago in the period called Termination 2. The closest ice age to the present day includes MIS 4-2 and is called the Würm (or Last Ice Age) in European Alpine stratigraphy (Rose, 2007).

MIS-4 occurred between 71 ka and 57 ka (Würm I), while MIS-2 occurred from 29 ka to 14 ka ago (Würm II). Within the MIS-2 the glaciation reached maximum size from 19-23 ka (mean 21 ka) (Mix et al., 2001) which is known as the Last Glacial Maximum (LGM). During the LGM glaciers reached largest sizes in Europe, North America and many central and high latitude regions, covering one third of the continents.

We also observed the evidences of LGM, in Turkey. The traces of the latest glaciation goes back to about 14 ka years ago (Late Glacial). In this period where temperatures began to approach current conditions, some part of the world entered a rapid and short cold stadial. This period, called the Last Henrich Period (H0), is also known as the Younger Dryas (12.0-11.7 ka) named after an Alpine tundra flower Dryas octopetala. The Younger Dryas was mainly felt in northern Europe and temperatures in Greenland dropped by 12-18^{o}C compared to the present. The reason for this is given as large glaciers melting after the LGM disrupted oceanic currents in the North Atlantic Ocean and blocked heat transfer from equatorial regions (Alley et al., 1993). With the end of the Younger Dryas period, climatic conditions similar to the present developed and the Holocene (from 11.7 ka to the present) began (Mayewski et al., 2004).

3. Method: Cosmogenic Surface Exposure Dating

The pionering on suggest cosmogenic surface exposure dating methods to date landforms appeared in the 1950s (Davis and Schaffer, 1955), however the practical application started with advances in Accelerator Mass Spectrometry (AMS) in the 1980s (Zreda et al., 1991). This method is accepted as the beginning of a new era in Quaternary studies as due to this method any surface protected by certain conditions can be dated. For a review of this method, papers by Cerling and Craig (1994), Zreda and Phillips (2000), Gosse and Phillips (2001), Cockburn and Summerfield (2004), and Dunai (2010) are useful.

Cosmic rays that form the cosmogenic isotopes on land surface occur in the universe due to supernova explosions and radioactive radiation from the sun. These rays have a very high energy and speed and hit Earth from all directions (Dunai, 2010). The rays initially react with atmospheric elements, then reach the surface and enter reactions with lithospheric elements in rock surfaces and form new isotopes in the first 2-3 meters of the rock. These are called cosmogenic isotopes (for example: ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{3}He, ^{21}Ne, etc.) (Dunai, 2010). If the production rate of these new isotopes within the rock is known (Schimmelpfennig et al., 2011; Marrero, 2012), and when the concentration of cosmogenic isotopes are measured, then it is possible to determine how long these rocks have been exposed at the surface. The main landforms that this method can be applied to are moraines, alluvial fans, river terraces, fault planes and volcanic surfaces.

The first applications in the literature was to glacial deposits. Moraines form as a result of glacial deposits, (Figure 2a). New surfaces are also formed by glacial erosion of bedrock (Figure 2b). These surfaces can be dated by this method. Moraines are exposed to cosmic rays from the moment the glacier starts to retreat and it is assumed that the deposited material has not been exposed to cosmic rays previously, thus the minimum age of deposition of the moraine is calculated as the beginning of glacial retreat (Zreda and Phillips, 2000). In Turkey by measurement of ^{36}Cl and ^{10}Be cosmogenic isotopes on moraines, the chronology of Quaternary glaciation has been revealed in detail and paleoclimate interpretations have been made (Akçar et al., 2007; 2008; Sarıkaya et al., 2008; 2009; Sarıkaya, 2009; Zahno et al., 2009; 2010; Zreda et al., 2011; Sarıkaya et al., 2014; Çiner et al., 2015; Akçar et al., 2015; Çiner and Sarıkaya, 2015).

4. Distribution and Chronology of Glaciers

The first studies on glaciation of Anatolia began at the end of the 1800s and beginning of the 1900s by some European voyagers (Ainsworth, 1842; Palgrave, 1872; Maunsell, 1901). Later with the contribution of Turkish researchers, glacier studies increased (Erinç, 1944; 1949*a*; 1949*b*; İzbırak, 1951; Erinç, 1951; 1952; 1953; Doğu et al., 1993; 1999). In the last 15 years the application of cosmogenic surface exposure dating to Turkish glacial deposits has given a new dimension to Quaternary studies. Moraines, previously only dated by qualitative methods such as relative relations, degree of erosion,

Figure 2- Sample collection for cosmogenic age dating: a) above blocks (Bolkar Mountains, Alagöl Valley); b) whaleback on bedrock (Aladağlar, Körmenlik Valley).

and development of soil and plant cover, began to be dated quantitatively by cosmogenic methods (Akçar et al., 2007; 2008; Sarıkaya et al., 2008; 2009; Sarıkaya, 2009; Zahno et al., 2009; 2010; Zreda et al., 2011; Sarıkaya et al., 2014; 2015; Çiner et al., 2015; Çiner and Sarıkaya, 2015).

Turkey's Late Pleistocene glaciers developed on high mountains in Anatolia; the Taurus and Eastern Black Sea Mountains, and along with individual volcanoes. According to Kurter's (1991) classification, Turkey's glacial regions can be divided in three regions. These are (1) the Taurus Mountains extending parallel to the Mediterranean coast to the southeastern most part of Turkey, (2) the Eastern Black Sea Mountains extending along Turkey's Black Sea coast and (3) scattered and isolated high mountains and volcanoes in Anatolia (Table 1). This study focuses on dating studies of old glacial deposits within Turkey which have rapidly increased in recent years. Readers may benefit from Çiner (2003; 2004), Sarıkaya et al. (2011), Sarıkaya and Tekeli (2014) and Yavaşlı et al., (2015) for studies of Turkey's current and paleo-glacial inventories.

4.1. Taurus Mountains

The Taurus Mountains contain widespread glaciers and glacial areas that can explain the paleoclimate of the Eastern Mediterranean. This mountain range can be divided into roughly three areas; (1) Western Taurus, (2) Central Taurus and (3) Eastern Taurus (Sarıkaya et al., 2011). The mean elevation of the Taurus Mountains increases from west to east. Turkey's largest current glaciers are in the Eastern Taurus, concentrated in the region close to the Turkey-Iraq-Iran border (Sarıkaya and Tekeli, 2014). However, as there are no studies on the quantitative age of glaciers in this region yet, this study will mainly focus on the Western and Central Taurus Mountains.

4.1.1. Western Taurus

In the Western Taurus, there are eight mountains with signs of Late Pleistocene glaciers. The peaks of these mountains are generally at 3000 m or a little higher. The westernmost one is Mount Sandıras (37.1^{o}N, 28.8^{o}E; 2295 m) located very close to the Mediterranean (Figure 1). Mount Sandıras presents very important information about the LGM and later glaciations with the most important evidence in the form of moraines deposited in three north-facing valleys and cirques. The largest glacier on Mount Sandıras reached a maximum length of 1.5 km from its cirque and deposited terminal moraines at an elevation of 1900 m. Sarıkaya et al. (2008) published cosmogenic ^{36}Cl surface exposure dates of nine samples belonging to four moraine ridges in two different valleys. According to re-calculations using current ^{36}Cl isotope production rates (Marrero, 2012), the most widespread glaciation appears to have begun to retreat at 22.9 ± 3.3 ka in the Kartal Lake Valley. Other moraines in the same valley show that the glacier advanced slightly and/or remained stable for several thousand years at 20.6 ± 3.1 ka. Another valley northwest of Kartal Lake Valley was found to have moraines deposited at 16.4 ± 3.2 ka and 17.2 ± 3.2 ka. The glaciers on Mount Sandıras, are smaller than in other regions. After the glaciers on Mount Sandıras reached their maximum extent at the LGM, there were some small advances and/or stabilizations in the Late Glacial period before the disappearance at the onset of Holocene.

Table 1- List of Late Pleistocene glaciers in Turkey

#	Mountain Name	Peak Elev. (m)	Lat. (DD°N)	Long. (DD°E)	LGM* Snowline (m)	Present Snowline (m)	Source
1	Sandıras Mt.	2295	37,0814	28,8380	2000	3000-3500	Sarıkaya et al. (2008)
2	Uludağ	2543	40,0706	29,2215	2400	3500	Zahno et al. (2010); Akçar et al. (2014)
3	Honaz Mt.	2571	37,6791	29,2850	2500-2600	3600	Erinç (1955; 1957); Messerli (1967)
4	Akdağ	3016	36,5439	29,5674	2518	3500	Sarıkaya et al. (2014)
5	Beydağ	3086	36,5684	30,1017	2500-2650	3600	Louis (1944); Messerli (1967)
6	Barla Mt.	2800	38,0531	30,7022	2400-2500	3750	Louis (1944); Ardos (1977)
7	Davraz Mt.	2637	37,7571	30,7317	2400-2500	3750	Louis (1944); Messerli (1967)
8	Dedegöl Mts.	2992	37,6437	31,2835	2350-2400	3300-3500	Zahno et al. (2009)
9	Geyikdağ	2850	36,8075	32,2021	2500	3400	Çiner et al. (2015)
10	Ilgaz Mt.	2587	41,0342	33,6545	?	4300	Louis (1944)
11	Bolkar Mts.	3524	37,3862	34,6087	2650	3450-3700	Çiner and Sarıkaya (2015)
12	Aladağlar	3756	37,8366	35,1453	2700	3450	Zreda et al. (2011)
13	Erciyes Mt.	3917	38,5318	35,4469	2700	3550	Sarıkaya et al. (2009)
14	Soğanlı Mts.	3075	38,4084	36,2119	2610	3550	Ege and Tonbul (2005)
15	Karagöl Mt.	3107	40,5101	38,1928	2600-2700	3500	Planhol and Bilgin (1961)
16	Karadağ	3331	40,3793	39,0710	2600-2850	3500	Gürgen (2001)
17	Mercan Mts.	3368	39,4934	39,1669	2750	3600-3700	Bilgin (1972)
18	Esence Mts.	3477	39,7836	39,7548	2750	3600-3700	Akkan and Tuncel (1993)
19a	Kavron V.	3932	40,8354	41,1614	2300-2500	3100-3200	Akçar et al. (2007)
19b	andrçenik V.	3907	40,7220	40,8924	2300-2500	3100-3200	Akçar et al. (2008)
19c	Başyayla V.	3425	40,7814	41,0104	2300-2500	3100-3200	Reber et al. (2014)
20	Mescid Mt.	3239	40,3273	41,1673	2750	3600-3700	Yalçınlar (1951)
21	Süphan Mt.	4058	38,9309	42,8326	3200	3700-4000	Kesici (2005)
22	Kavuşşahap Mts.	3503	38,2146	42,8563	?	3400	Doğu (2009)
23	Balık Lake	2804	39,7766	43,5274	?	4300	Birman (1968)
24	Buzul Mts.	4135	37,4877	44,0012	2100-2800	3600	Erinç (1952)
25	İkiyaka Mts.	3794	37,3105	44,2502	2600	3600	Bobek (1940)
26	Ağrı Mt.	5137	39,7018	44,2983	3000	4300	Sarıkaya (2012)
27	Karçal Mts.	3415	41,3472	41,9830	?	3400	Gürgen and Yeşilyurt (2012)

LGM: Last Glacial Maximum

Another glacial region in the Western Taurus is Akdağ (36.54ºN, 29.57ºE; 3016 m) (Figure 1). Located 90 km southeast of Mount Sandıras, Akdağ contains first pre-LGM glaciers dated up to today. Forty-one moraine blocks in three valleys north of Akdağ have been dated using the cosmogenic ^{36}Cl method (Sarıkaya et al., 2014) (Figures 3 and 4a,b). The glaciers attained a length of up to 6 km reaching a height of 2000 m above sea level. Before the LGM, about 35.1 ± 2.5 ka before the present, the glaciers reached an elevation of 2150 m (Sarıkaya et al., 2014). At the LGM the glaciers reached their largest extent 21.7 ± 1.2 ka before the present (height of 2050 m above sea level). Later about 15.1 ± 0.9 ka in the Late Glacial period, the glaciers retreated slightly and remained stable for a short time. Similar OSL ages (17.7 ± 4.4 ka) have been obtained by Bayrakdar (2012) for glacial deposits on Akdağ.

The Dedegöl Mountains are another glacial area about 300 km east of Mount Sandıras (37.37ºN, 31.19ºE; 2992 m) (Figure 1). The glacial sediments in this region have been dated with ^{10}Be and ^{26}Al isotopes (Zahno et al., 2009). The Muslu Valley on the eastern side of the mountains has two lateral moraines extending to an elevation of 1400 m which were dated by Zahno et al. (2009). Glaciers were determined to have developed before the LGM (>29.6 ± 1.9 ka; recalculated by Reber et al., 2014), at the LGM (21.5 ± 1.5 ka) and in the Late Glacial period (15.2 ± 1.1 ka).

The most widespread hummocky moraines in Turkey are observed in the Namaras and Susam Valleys on Geyikdağ (36.53ºN, 32.10ºE; 2877 m) (Figures 1 and 4c,d). In addition to hummocky moraines there are lateral and terminal moraines (Çiner et al., 1999; 2015). These hummocky moraines are formed on the piedmont at an elevation of 2350-2650 m as a result of melting glaciers. Thirty-four block-scale rock samples from moraines in the Namaras and Susam Valleys were dated with the cosmogenic ^{36}Cl method. The obtained ages indicate three phases of regression during the Late Pleistocene (Çiner et al., 2015). The oldest and most extensive regression was at 18.0 ± 1.1 ka, toward the end of the

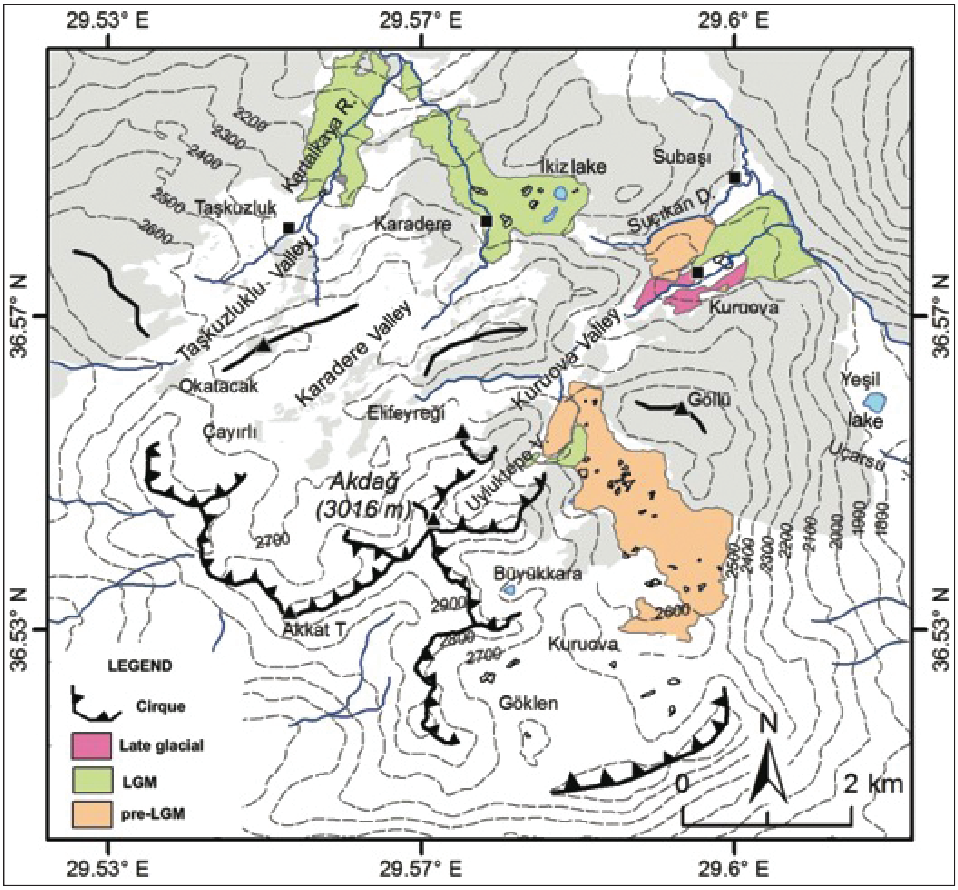

Figure 3- Akdağ glacial geomorphological and deposition map. Adapted from Sarıkaya et al. (2014).

Figure 4- a) Appearance of terminal moraine in Akdağ Taşkuzluklu Valley (scale: car); b) Terminal moraine and dried glacial lake in background in Akdağ Kuruova Valley (scale: blue hut); c) section of hummocky moraine in Geyikdağ Namaras Valley. Undifferentiated sediment layers of varying sizes from fine sand to block size. The soil and plant development on the surface of the moraine gives an idea of the age; d) Hummocky moraines in Geyikdağ Namaras Valley. The entrance to Susam Valley is seen in the background; e) Black-coloured volcanic erratics deposited on limestone bedrock in Karagöl Valley in the Bolkar Mountains (block size 2 m); f) Right and left lateral moraines in Karagöl Valley in Bolkar Mountains near Meydan Plateau (scale: incomplete hotel construction on left lateral moraine).

LGM. The Late Glacial lateral moraines were deposited at 14.0 ± 2.7 ka, while the terminal moraine in Susam Valley was formed at 13.4 ± 1.5 ka. The hummocky moraines in Susam Valley appear to have occurred along 5 km showing that the ice retreat occurred very rapidly (14.0 ± 1.3 ka). Moraines confirming the Younger Dryas in Geyikdağ were deposited near the exit of the Susam Valley about 11.6 ± 1.3 ka.

Though there are no quantitative age data, on other mountains in the Western Taurus Mountains it is possible to find evidence of Late Pleistocene glaciation in regions such as Beydağ (36.57ºN, 30.10ºE; 3086 m) (Louis, 1944; Messerli, 1967), Mount Barla (38.05ºN, 30.70ºE; 2800 m) (Ardos, 1977), Mount Honaz (37.68ºN, 29.29ºE; 2571 m) (Yalçınlar, 1954; Erinç, 1955; 1957) and Mount Davraz (37.76ºN, 30.73ºE; 2637 m) (Monod, 1977; Atalay; 1987) (Figure 1).

The snow line in the Western Taurus during the LGM varied from 2000 m to 2600 m. In other areas apart from Mount Sandıras, the LGM permanent snow line was above 2000 m (Figure 5). The reason for this is probably that in the ice ages the mountain was exposed to humid air currents due to its proximity to the Mediterranean (Doğu et al., 1993; Sarıkaya et al., 2008). In the Western Taurus Mountains the modern snow line varies from 3400 m to 3700 m. This indicates that there has been a 1100-1500 m increase in the height of the snow line since the LGM.

4.1.2. Central Taurus

The Central Taurus Mountains are in the south of Turkey and contain three glacial regions (Figure 1). These are the Bolkar Mountains, Aladağlar and Soğanlı Mountains.

The Bolkar Mountains are 200 km east of Geyikdağ (37.39ºN, 34.61ºE; 3524 m) (Figure 1). Çiner and Sarıkaya (2015) in a study of two north-facing valleys and one south-facing valley in the Bolkar Mountains using thirty ^{36}Cl samples dated terminal and lateral moraines and bedrock eroded by glaciers and erratic block samples (Figure 4e,f). The northern Karagöl and Alagöl Valleys and southern Elmalı Valley contain many lateral and terminal moraines. Accordingly, four glaciations were defined that developed before the LGM (46.0 ± 7.0 ka) (Çiner and Sarıkaya, 2015). The glaciers in the Bolkar Mountains reached their maximum size at 18.9 ± 3.3 ka. In this situation the length of the glaciers from the cirque is estimated to have reached 5.5 km. Late Glacial moraines are thought to have formed between 15.2 ± 1.6 and 12.6 ± 2.3 ka. The most recent glacial remains in the Bolkar Mountains are recorded in the Early Holocene. Holocene moraines were dated at 9.0 ± 0.9 ka in Karagöl Valley and 8.5 ± 1.8 ka in Elmalı Valley. At the exit of the Alagöl Valley, outwash plain formation ended before 8.4 ± 1.0 ka.

In Aladağlar (37.48ºN, 37.09ºE, 3575 m), there are indications of paleo-glacial activity. Zreda et al. (2011) carried out cosmogenic ^{36}Cl dating on a U-shaped glacial valley, Hacer Valley, in the east of the

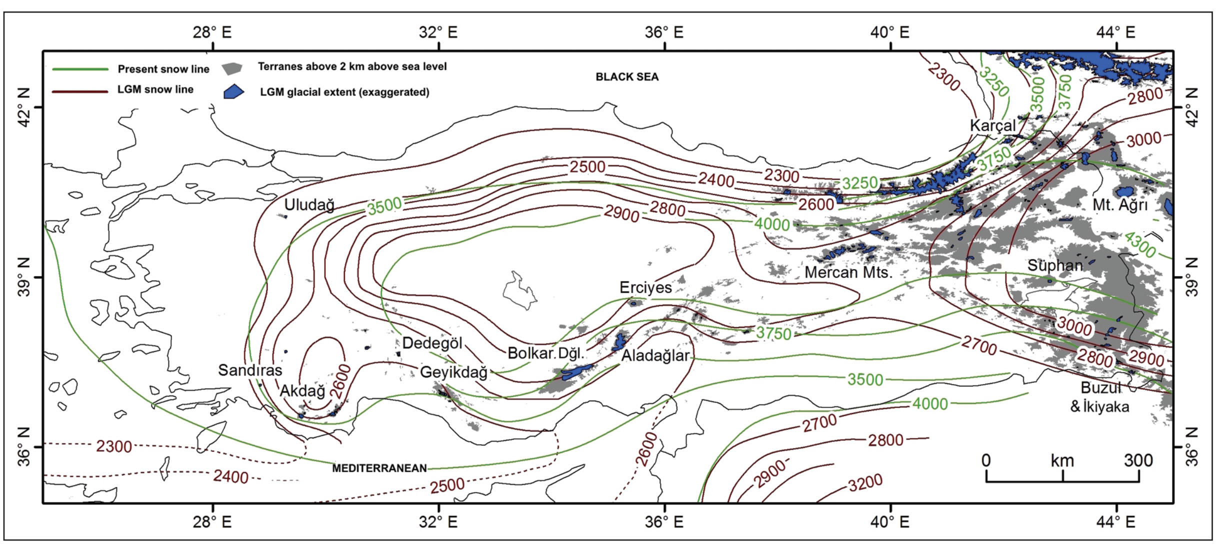

Figure 5- Map showing LGM and current snow limits (adapted from Messerli, 1967). Blue areas show enhanced Late Pleistocene glacial distribution.

Aladağlar. They revealed that at the Late Pleistocene-Holocene boundary, the glaciers retreated rapidly. Several moraine ridges were identified at an elevation of 1100 m in the Hacer Valley (valley entrance) and at Yedigöller Plateau at 3100 m elevation (Figure 6a). It is thought that there was an ice sheet completely covering the Yedigöller Plateau just below the peaks. Using new cosmogenic production rates developed by Marrero (2012), the ages of 22 samples were recalculated (Sarıkaya and Çiner, 2015). The age intervals were determined as 14.0 ± 1.5 ka for the valley floor and 11.5 ± 1.3 ka for the plateau. This shows that at the end of the Late Glacial there was a glacier extending 15 km and after the Younger Dryas there was rapid melting. Other glacial valleys in the Aladağlar indicate glaciers from much older periods. In the north and northwest sections of the Yedigöller Plateau (about 1850-2100 m) there are several valleys with terminal and lateral moraines. These contain evidence that glaciation developped in MIS 3 or MIS 4 periods based on studies in the valleys near Ecemiş Fault (Sarıkaya et al., 2015).

Mount Soğanlı is located in the Tahtalı Mountains, another glacial region of the Central Taurus. There are signs of glaciation in areas close to the peak of Mount Soğanlı (Ege and Tonbul, 2005). In the northwest of Dökülgen Valley, glacial deposits have been identified at 2250 m elevation. Hummocky moraines and terminal moraines on Mount Soğanlı have been dated relatively, indicating that there may have been effective glaciation in the Pleistocene (Ege and Tonbul, 2005).

In the Central Taurus the elevation of the snow line in the LGM varied from 2600 to 2700 m (Messerli, 1967). Currently the snow line is between 3400 and 3600 m (Figure 5). This shows that the permanent snow line has risen by 800-900 m since the LGM.

4.1.3. Southeast Taurus

Containing Turkey's largest current glaciers (Erinç, 1953; Sarıkaya and Tekeli, 2014), the Southeast Taurus Mountains contain Late Pleistocene

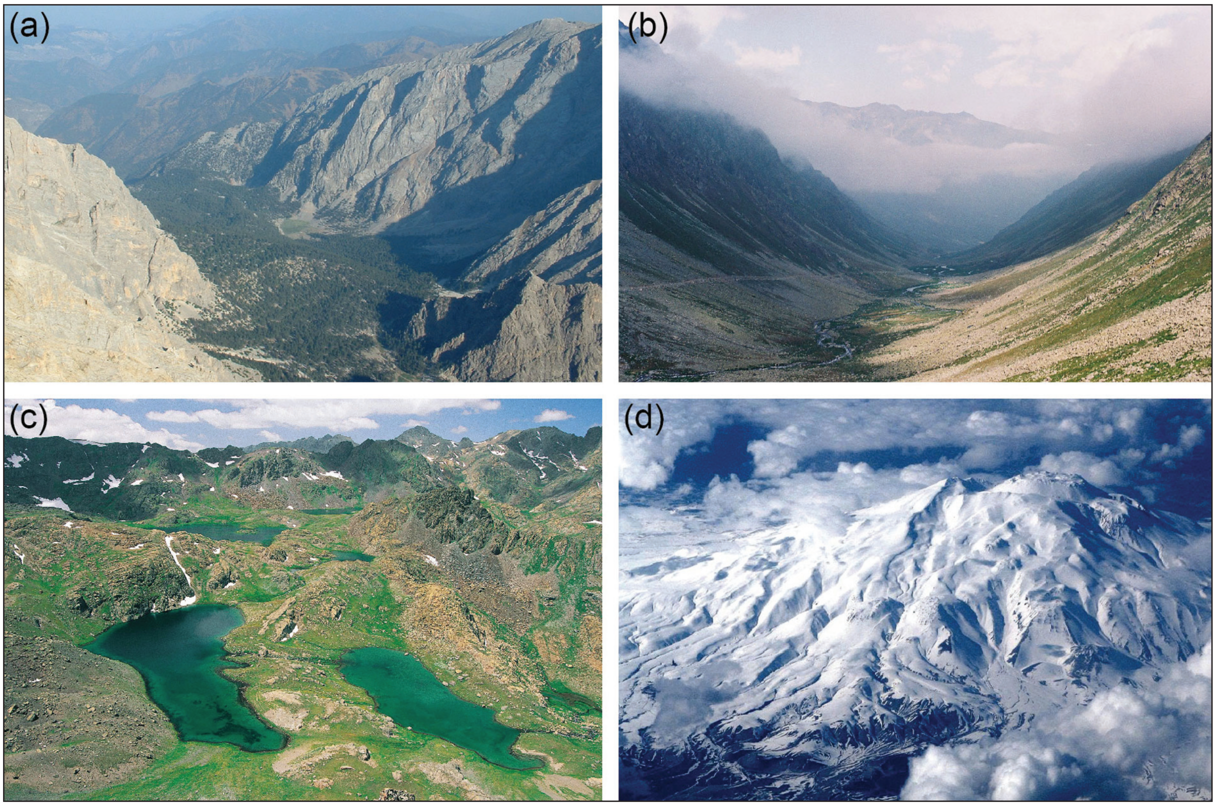

Figure 6- a) View from Aladağlar Hacer Valley to Yedigöller Plateau. Looking approximately east, with valley depth of 1500 m (Photograph: Serdar Bayarı); b) U-shaped valley caused by glacial erosion in the Kavron Valley of the Eastern Black Sea Mountains (Photograph: Naki Akçar); c) Glacial lakes in the upper portion of the Salacur Çoruh Valley. It is possible to find similar lakes on many mountains in Anatolia (Photograph: Hakan Gün, Atlas Magazine); d) Süphan Volcano 4058 m elevation (Photograph: Anonymous).

glaciers in three important areas (Figure 1). These are Mount Buzul and Mount İkiyaka within the borders of Hakkari and Kavuşşahap Mountains south of Lake Van. Studies by Bobek (1940) and Erinç (1953) found that on Mount Buzul and Mount İkiyaka, glaciers extended to an elevation of 1600 m in the Late Pleistocene (Würm) reaching lengths of 9-10 km. It is possible to see moraines belonging to these glaciers in the Zap Suyu Valley and other neighboring valleys (Erinç, 1953; Wright, 1962). To date no quantitative age data have been obtained in this region.

4.2. Eastern Black Sea Mountains

With mountain ridges running parallel to the coast of the Eastern Black Sea, they contain widespread signs of paleo-glacial activity (Figure 1). The majority of these mountains contain well-developed U-shaped glacial valleys and cirques in places close to 3000-4000 m above sea level (Figure 6b). The Eastern Black Sea Mountains rise as they move east and form a physiographic barrier between the Black Sea and the Eastern Anatolian plateau. The climate in the Eastern Black Sea Mountains is affected by mobile mid-latitude cyclones and associated frontal systems along with the high pressure system in Siberia. As a result air masses from the Black Sea produce orographic rainfall year round along the Black Sea coastal strip and the northern-facing slopes of the Eastern Black Sea Mountains (Akçar et al., 2007).

The Kaçkar Mountains, located in the highest section of the Eastern Black Sea Mountains, have had cosmogenic ^{10}Be dating completed on a typical glacial valley extending north, the Kavron Valley (Akçar et al., 2007). Accordingly moraines deposited at 27.3 ± 1.7 ka were identified in this valley, with the LGM glaciation ending at 19.8 ± 1.4 ka. Moraines belonging to the Late Glacial in the region were dated to 17.0 ± 1.1 ka, while the Younger Dryas in the region was dated to 12.8 ± 1.0 ka. Similar results were obtained for the nearby Verçenik Valley (Akçar et al., 2008). Here LGM glaciers developed at 27.5 ± 1.8 ka and ended before 20.3 ± 1.4 ka. Additionally in the Verçenik Valley moraines from 17.2 ± 1.2 ka were identified (Akçar et al., 2007). According to the latest study by Reber et al. (2014) in Başyayla Valley, glaciers developed from 57.0 ± 3.5 ka before the LGM. It has been determined that the local LGM occurred much earlier than the global LGM around 41.5 ± 2.5 ka. Additional glacial advances were identified between 32 ka and 21 ka. Lastly Late Glacial period moraines were dated to 17.0 ± 1.0 ka.

Although the elevation is low, there are terminal and hummocky moraines of Late Pleistocene age on Karadağ (40.38ºN, 39.07ºE; 3331 m) and Mount Karagöl (40.51ºN, 38.19ºE; 3107 m) in the Gümüşhane and Giresun Mountains (Çiner, 2004). Though there are large U-shaped valleys and many landforms related to glaciation in Bulut-Altıparmak and Soğanlı Mountains in the Eastern Black Sea, no quantitative data has been obtained (Gürgen, 2003). In addition to these, the Karçal Mountains (41.35ºN, 41.98ºE; 3415 m) on the Turkish-Georgian border have well-preserved glaciers, glacial landforms and rock glaciers (Gürgen and Yeşilyurt, 2012).

The current permanent snow line in the Eastern Black Sea Mountains is 3500-3550 m (Erinç, 1952) to the south and between 3100-3200 m on north-facing slopes (Figure 5). This difference is probably due to the effects of moist air coming from the Black Sea (Erinç, 1952). The LGM permanent snow line was 2600-2700 m to the south, varying between 2300-2500 m to the north.

4.3. Other Mountains in Anatolia

The Erciyes Volcano, in the Central Anatolia Volcanic Province, is another mountain that was glaciated in the Late Pleistocene (38.53ºN, 35.45ºE; 3917 m) (Figure 1). Glaciers on the north of the mountain extended to elevations of 2150 m reaching lengths of 6 km. A total of 44 samples (Sarıkaya et al., 2009) taken from two valleys, the north-facing Aksu Valley and the Üçker Valley, were dated with ^{36}Cl surface exposure dating and glacial periods at 24.4 ± 3.4 ka (LGM), 15.7 ± 1.9 ka (Late Glacial) and 10.5 ± 1.3 ka (Early Holocene) were revealed. The latest advance occurred at 4.2 ± 0.6 ka (Sarıkaya et al., 2009). The elevation of the LGM permanent snow line was calculated as 2700 m on the north slope (Sarıkaya et al., 2009), and 3000 m on the south slope (Messerli, 1967) (Figure 5). Today the permanent snow line on Erciyes is 3550 m (Sarıkaya et al., 2009). Presently there is a small glacier on the north ridge of the mountain (around 260 m long), however since 1902 there has been a horizontal melting rate of 4.2 m (Sarıkaya and Tekeli, 2014). If the melting continues at this rate, it is assumed that the Erciyes glacier will completely disappear by the year 2070 (Sarıkaya et al., 2009).

According to the first studies on Late Pleistocene glaciation on Mount Ağrı, Turkey's highest mountain, the LGM permanent snow line was around 3000 m. where an ice cap of 100 km^2 would have covered the summit of the mountain. To date although intense moraine deposits have not been found in the valleys around the mountain, Birman (1968) mentioned some paleo-glacial traces on the mountain's south-facing slopes. Blumenthal (1958) attributed the reason for not observing moraines on Mount Ağrı to the lack of sufficient slope to produce moraines or support intense valley glaciation and volcanic activity developing later. Currently the peak of Mount Ağrı is covered by Turkey's largest ice cap. The results of a study by Sarıkaya (2011) using satellite imagery found that in 2011 the ice cap covered an area of 5.66 km^2 and determined that the area had reduced by 29% between 1976-2011. A similar study was completed by Yavaşlı et al. (2015) and the area of the ice cap was identified as 5.34 km^2 in 2013.

In the Marmara region the only glaciated mountain is Uludağ (40.04°N, 29.13°E; 2542 m) ski resort and according to dating studies on Kovuk Valley (Zahno et al., 2010) and the Karagöl Valley (Akçar et al., 2014) to the east, LGM glaciers developed in the ski resort valley at 24.6 ± 1.5 ka and the melting of these glaciers was completed before 18.6 ± 1.3 ka (Zahno et al., 2010). Other valleys east of Uludağ developed LGM glaciers at similar times. For example in Karagöl Valley, the LGM glaciers began to develop before 20.4 ± 1.2 ka and ended before 18.6 ± 1.2 ka. In Kovuk Valley the last melting of LGM glaciers occurred at 18.1 ± 1.7 ka before the present. On Uludağ the Late Glacial period moraines are encountered at 15 ka. The only Younger Dryas moraines in the region are from 11.6 ± 0.7 ka located within the ski resort.

Another volcanic mountain in the eastern Turkey, Mount Süphan (38.56°N, 42.50°E; 4058 m) had an ice cap in the LGM period and it is estimated that the ice descended to 2650-2700 m on the north side of the mountain and 2950-3000 m on the south side (Kesici, 2005) (Figure 6d). These observations, indicating 1.5-2 km long glaciers, have not been quantitatively studied. On Mount Süphan the LGM permanent snow line was 3100 m, while the current permanent snow line is around 4000 m (Figure 5).

Traces of glaciation are found on many individual mountains in Anatolia (Figures 1 and 6d). One of these is the Mercan Mountains (39.49°N, 39.17°E; 3368 m) located to the south of Erzincan. Detailed mapping in this region by Bilgin (1972) identified that the region was covered with an intense glacial network and the glaciers descended to 1650 m elevation (Atalay, 1987). The Esence Mountains (39.78°N, 39.75°E) at 3477 m elevation had well-developed Late Pleistocene glaciers. Lateral moraines formed by valley glaciers reaching 9 km length from the cirques (Yalçınlar, 1951; Atalay, 1987). It is thought that the LGM permanent snow line was around 2750 m (Figure 5). Lastly in other regions in Anatolia, like Mount Ilgaz (41.03°N, 33.65°E; 2587 m) (Louis, 1944) and Lake Balık (39.78°N, 43.53°E; 2804 m) (Birman, 1968), there are indications on the Late Pleistocene glacial presence.

5. Interpretation and Discussion

Cosmogenic isotope application in recent years in Turkey have produced significant developments in the glacial chronology of Turkey in the Late Pleistocene. Data currently obtained allow the possibility to gain a general view of the distribution and timing of Anatolian glaciers (Figure 7).

When all studies since the year 2000 are reviewed, sampling was completed generally on blocks forming moraines, bedrock eroded by glaciers, erratic blocks and outwash plain deposits and to date a total of 365 samples appear to have been collected (Table 2). These studies generally focus on the Taurus and Eastern Black Sea Mountains and in a total of 27 glacial regions 9 have been dated (Table 3). All these studies have been completed by our group and the Swiss-based study group led by Dr. Naki Akçar. Generally, studies have used ^{36}Cl, ^{10}Be and ^{26}Al isotopes with a total of 48 samples excluded from the calculations for various reasons. Among these reasons are primary isotopes in blocks yielding true ages are much older, or presenting younger ages due to the effect of erosion or overturning. Generally mean ages were calculated from geomorphologic surfaces with multiple samples in these studies and in summary it was revealed that glaciers were active in five separate time slices in the Late Pleistocene. These are pre-LGM, LGM, Late Glacial, Younger Dryas and Holocene period glaciations (Figure 7).

The majority of the paleo-glacial formations in Turkey began to develop much before the LGM (about 29-35 ka) and probably reached their maximum size by the LGM period (21 ka). Some of these began to develop much earlier than this (during MIS 4) and it is thought they partially retreated before the global LGM (at the end of MIS 3, 29 ka).

During the LGM glaciers advanced once more (21.5-18.5 ka) and reached their maximum size. This

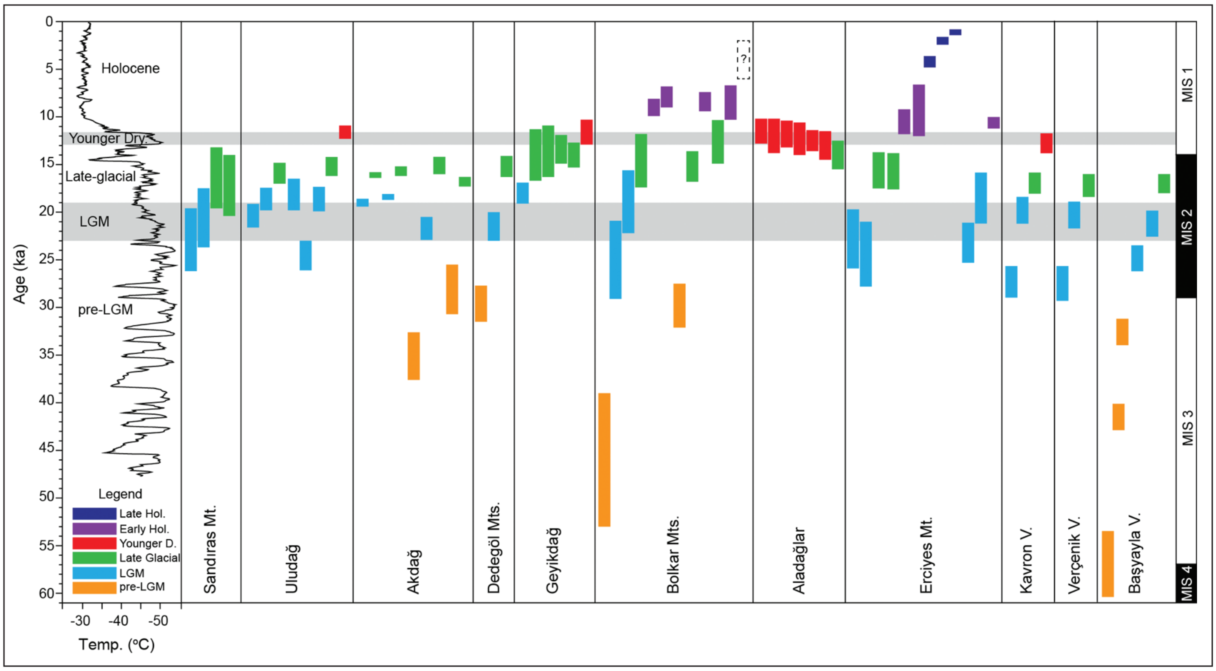

Figure 7- Correlation of glacial chronology from cosmogenic dating of mountains in Turkey. Temperatures from Greenland GISP 2 ice cores on the left (Alley, 2000), MIS series on the right. Colour coded lines give the moraine age intervals from original publications. For details see the original publications given in table 2. Horizontal grey lines show time intervals for global-LGM (Last Glacial Maximum) (19-23 ka) (Mix et al., 2001) and the Younger Dryas (11.7-12.9 ka) (Broecker et al., 2010) (Adapted from Sarıkaya and Çiner, 2015).

period was the beginning of the retreat of glaciers in Turkey. Later glaciers began to decrease in size and sometimes remained stable producing Late Glacial moraines (about 16 ka). Though shorter than the LGM and Late Glacial, in the Younger Dryas (around 12 ka) glacial advances occurred in some regions. Early Holocene glaciation developed in an extraordinary manner in the interior regions of Turkey around 8.5 ka. Lastly the precursor to current glaciers in the Late Holocene (1-4 ka) and Little Ice Age advances covered much smaller areas than paleo-glaciations and were only effective in certain regions. This paper will discuss some implications of these chronological results.

5.1. Why Are Glaciation Signs not Observed Everywhere Before The LGM?

The glacial advance in Turkey's mountains began before the global LGM. For example, the moraines in Kuruova Valley on Akdağ were dated to 35.1 ± 2.5 ka. In the upper parts of Kuruova Valley, moraines protected since before the LGM to the present have been dated to 28.1 ± 2.6 ka. The protected high topographic location of these moraines prevented their destruction by more intense glacial advances that developed in later periods.

However, in the Western Taurus on Mount Dedegöl the glacial advance was determined to have occurred 29.6 ± 1.9 ka ago (Zahno et al., 2009). Similarly in the Bolkar Mountains, a glacial advance has been revealed before the LGM (Çiner and Sarıkaya, 2015). In the Karagöl and Alagöl Valleys, the ground moraines and ground-lateral moraines were dated to 46.0 ± 7.0 ka and 29.8 ± 2.3 ka, respectively.

The glacial ages in other regions before the LGM are in agreement. Generally younger moraines are more common than old moraines from pre-LGM. This shows that the pre-LGM moraines were covered by larger and more effective LGM glaciers or were completely removed and destroyed in many areas. In all regions only four mountains were observed to have traces of glaciation from pre-LGM (Figure 7). The lack of frequent glacial traces from pre-LGM in Turkey can be explained by a broader and stronger glaciation (LGM glaciation) that developed in a later period.

Table 2- List of regions with cosmogenic age control for the Late Pleistocene. Statistics from cosmogenic samples according to isotopes, sample types and ages are given.

#	Mountain Name	Isotope	Number of samples (n=363)	Used samples (n=315)	Outliers (n=48)	Glacial ages (n=315)*	Sample types (n=363)	Source
1	Sandıras Mt.	^{36}Cl	12	10	2	LGM=6, LG=4	12 moraine blocks	Sarıkaya et al. (2008)
2	Uludağ	$^{10}Be/^{26}Al$	30	23	7	LGM=5, LG=12, YD=6	23 moraine blocks, 7 bedrock	Zahno et al. (2010)
2	Uludağ	^{10}Be	42	40	2	LGM=23, LG=17	41 moraine blocks, 1 bedrock	Akçar et al. (2014)
4	Akdağ	^{36}Cl	41	33	8	pre-LGM=8, LGM=18, LG=7	41 moraine blocks	Sarıkaya et al. (2014)
8	Dedegöl Mts.	$^{10}Be/^{26}Al$	25	19	6	pre-LGM=4, LGM=3, LG=12	6 bedrock, 19 moraine blocks	Zahno et al. (2009)
9	Geyikdağ	^{36}Cl	34	28	6	LGM=9, LG=16, YD=3	34 moraine blocks	Çiner et al. (2015)
11	Bolkar Mts.	^{36}Cl	30	22	8	pre-LGM=5, LGM=2, LG=5, EH=10	1 bedrock, 3 outwash boulder, 26 moraine blocks	Çiner and Sarıkaya (2015)
12	Aladağlar	^{36}Cl	22	22	0	LG=3, YD=19	2 bedrock, 20 moraine blocks	Zreda et al. (2011)
13	Erciyes Mt.	^{36}Cl	44	37	7	LGM=11, LG=6, EH=12, LH=8	5 outwash boulder, 39 moraine blocks	Sarıkaya et al. (2009)
19a	Kavron V.	^{10}Be	22	21	1	LGM=14, LG=5, YD=2	18 moraine blocks, 4 bedrock	Akçar et al. (2007)
19b	Verçenik V.	^{10}Be	19	19	0	LGM=4, LG=12, YD=3	10 moraine blocks, 9 bedrock	Akçar et al. (2008)
19c	Başyayla V.	$^{10}Be/^{26}Al$	42	41	1	pre-LGM=11, LGM=20, LG=10	41 moraine blocks, 1 bedrock	Reber et al. (2014)

Table 3- Summary of results of cosmogenic surface dating of mountains in Turkey.

#	Mountain name	Valley	Moraine	Age (ka)	Source
1	Sandıras Mt.	Kartal Lake Valley	LGM	22.9 ± 3.3	Sarıkaya et al. (2008)*
			LGM	20.6 ± 3.1	
		NW Valley	Late Glacial	16.4 ± 3.2	
			Late Glacial	17.2 ± 3.2	
2	Uludağ	Karagöl Valley	LGM	20.4 ± 1.2	Akçar et al. (2014)**
			LGM	18.6 ± 1.2	
			Late Glacial	15.9 ± 1.1	
		Kovuk Valley	LGM	18.1 ± 1.7	Zahno et al. (2010)**
		Ski Valley	LGM	24.6 ± 1.5	Zahno et al. (2010)**
			LGM	18.6 ± 1.3	
			Late Glacial	15.2 ± 1.0	
			Younger Dryas	11.6 ± 0.7	
4	Akdağ	Taşkuzluklu Valley	LGM	19.0 ± 0.4	Sarıkaya et al. (2014)
			Late Glacial	16.1 ± 0.3	
		Karadere Valley	LGM	18.4 ± 0.3	
			Late Glacial	15.7 ± 0.5	
		Lower Kuruova Valley	pre-LGM	35.1 ± 2.5	
			LGM	21.7 ± 1.2	
			Late Glacial	15.1 ± 0.9	
		Upper Kuruova Valley	pre-LGM	28.1 ± 2.6	
			Late Glacial	16.8 ± 0.5	
8	Dedegöl Mts.	Muslu Valley	pre-LGM	29.6 ± 1.9	Zahno et al. (2009)**
			LGM	21.5 ± 1.5	
			Late Glacial	15.2 ± 1.1	
9	Geyikdağ	Namaras Valley	LGM	18.0 ± 1.1	Çiner et al. (2015)
			Late Glacial	14.0 ± 2.7	
			Late Glacial	13.6 ± 2.7	
		Susam Valley	Late Glacial	13.4 ± 1.5	
			Late Glacial	14.0 ± 1.3	
			Younger Dryas	11.6 ± 1.3	
11	Bolkar Mts.	Karagöl Valley	pre-LGM	46.0 ± 7.0	Çiner and Sarıkaya (2015)
			LGM	25.0 ± 4.1	
			LGM	18.9 ± 3.3	
			Late Glacial	14.6 ± 2.8	
			Early Holocene	9.0 ± 0.9	
			Early Holocene	7.9 ± 1.1	
		Alagöl Valley	pre-LGM	29.8 ± 2.3	
			Late Glacial	15.2 ± 1.6	
			Early Holocene	8.4 ± 1.0	
		Elmalı Valley	Late Glacial	12.6 ± 2.3	
			Early Holocene	8.5 ± 1.8	
			?	4.0 ± 2.0	
12	Aladağlar	Hacer Valley	Younger Dryas	11.5 ± 1.3	Zreda et al. (2011)*
			Younger Dryas	12.0 ± 1.8	
			Younger Dryas	11.8 ± 1.4	
			Younger Dryas	12.3 ± 1.7	
			Younger Dryas	12.5 ± 1.1	
			Younger Dryas	13.0 ± 1.5	
			Late Glacial	14.0 ± 1.5	
13	Erciyes Mt.	Aksu Valley	LGM	22.8 ± 3.1	Sarıkaya et al. (2009)*
			LGM	24.4 ± 3.4	
			Late Glacial	15.6 ± 1.9	
			Late Glacial	15.7 ± 1.9	
			Early Holocene	10.5 ± 1.3	
			Early Holocene	9.3 ± 2.7	
			Late Holocene	4.2 ± 0.6	
			Late Holocene	2.0 ± 0.4	
			Late Holocene	1.1 ± 0.3	
		Üçker Valley	LGM	23.2 ± 2.1	
			LGM	18.5 ± 2.7	
			Early Holocene	10.6 ± 0.6	
19	Eastern Blacksea Mts.	19a) Kavron Valley	LGM	27.3 ± 1.7	Akçar et al. (2007)**
			LGM	19.8 ± 1.4	
			Late Glacial	17.0 ± 1.1	
			Younger Dryas	12.8 ± 1.0	
		19b) andrçenik Valley	LGM	27.5 ± 1.8	Akçar et al. (2008)**
			LGM	20.3 ± 1.4	
			Late Glacial	17.2 ± 1.2	
		19c) Başyayla Valley	pre-LGM	57.0 ± 3.5	Reber et al. (2014)
			pre-LGM	41.5 ± 1.4	
			pre-LGM	32.6 ± 1.3	
			LGM	24.8 ± 1.4	
			LGM	21.2 ± 1.3	
			Late Glacial	17.0 ± 1.0	

* Re-calculated by Sarıkaya and Çiner (2015)

** Re-calculated by Reber et al. (2014)

5.2. Widespread LGM Glaciation In Anatolia

Latest research has shown that there is good age control on local LGM glaciation on nearly all of Turkey's mountains. The chronologies we have to date show that LGM glaciation developed in Kartal Lake Valley on Mount Sandıras (17.5-26 ka; Sarıkaya et al., 2008), on Akdağ (18-23 ka; Sarıkaya et al., 2014), in Muslu Valley on Mount Dedegöl (20-23 ka; Zahno et al., 2009), in Namaras Valley on Geyikdağ (17-19 ka Çiner et al., 2015), in the Bolkar Mountains (16-29 ka; Çiner and Sarıkaya, 2015), on Erciyes Volcano (16-28 ka; Sarıkaya et al., 2009), on Uludağ (24-18 ka; Zahno et al., 2010) and in the Kaçkar Mountains (27-21 ka; Akçar et al., 2014; Reber et al., 2014). In general the LGM glacial advance began before 30 ka (initial stage of MIS 2) and reached its maximum extend before 21.5 ka. As glaciation in this period was more severe, the mountains in Turkey have more common traces of LGM glaciation compared to other periods.

The LGM dates obtained from Turkey are in accordance with LGM moraine ages from other mountains in Eastern Europe (Hughes et al., 2006; Woodward et al., 2008) and the European Alps (Hughes and Woodward, 2008). More, the dates obtained from Turkish mountains are contemporaneous with the lowest sea level during MIS 2 (120-135 m below current sea level) (Martinson et al., 1987; Yokoyama et al., 2000) and also with the ice cores, marine isotope series and global LGM (19-23 ka).

5.3. Glacial Retreat In The Late Glacial

After the LGM the glacial retreat on some mountains in Turkey continued until 18.5 ka. In this period glaciers in some regions retreated by a certain amount or remained stable for several thousands of years. Though there is little information on the amount of retreat, small valley or cirque glaciers continued to exist in upper valley systems. The duration of retreat of larger ice masses naturally took longer. For example, during the LGM on Geyikdağ the glaciers on the piedmont advanced as far as Namaras Valley. These glaciers remained under thick debris cover, slowing their reaction to changing climatic conditions (Çiner et al., 2015). As a result the glaciers on Geyikdağ began to fully retreat much later than the LGM (18.0 ± 1.0 ka). Similar situations existed for glaciers on Mount Dedegöl (14-16 ka), Akdağ (14-17 ka) and Mount Sandıras (13-20 ka).

Further east the Late Glacial retreat on Erciyes Volcano began before 14-17.5 ka. In the northeast Black Sea Mountains, in the Kavron, Verçenik and Başyayla Valleys, the Late Glacial retreat began slightly earlier compared to the mountains in the Eastern Mediterranean. This situation may be related to early warming of the Black Sea region. For example in Kavron Valley, Late Glacial moraines were deposited before 17.0 ± 1.1 ka. In Verçenik and Başyayla Valleys, dates have been determined before 17.2 ± 1.2 ka and 17.0 ± 1.0 ka, respectively.

In general the Late Glacial period on Turkey's mountains can be dated to before 16 ka. However, compared to previous advances, these glaciers were much smaller and less widely distributed.

5.4. Sparse Glaciation In The Younger Dryas

The glacial advance in the Younger Dryas (11.7-12.9 ka) (Broecker et al., 2010) has a scattered distribution in Turkey. This may be due to a lack of sufficient age data or it may be due to Younger Dryas glaciers truly developing in a sparse manner in Turkey. Glacial traces in this period are only encountered in 4 regions (Figure 7). The glacier in Hacer Valley in the east of Aladağlar is a good example of Younger Dryas glaciation. The age of a series of moraines in this 15 km valley on the mountain has been determined as the Late Pleistocene-Holocene transition (Zreda et al., 2011). However, the results of new calculations by us using current ^{36}Cl production rates have revealed that the ages of these moraines may be Younger Dryas (Sarıkaya and Çiner, 2015).

There are indications of the Younger Dryas advance on Geyikdağ. However Younger Dryas advance on other mountains in Turkey, especially in the southwest of Turkey, appears to be insufficient. The reason for the scattered distribution of Younger Dryas advance in the Taurus Mountains may be related to special climatic effects in the region.

In northeast Anatolia, Akçar et al. (2008) consider that glacial advance in the Kavron Valley very likely occurred during the Younger Dryas (12.8 ± 1.0 ka). In fact, there are traces of similar Younger Dryas glacial chronology in the mountains of southern Europe (Hughes et al., 2006). Similar Younger Dryas glacial chronologies are found in the French Maritime Alps (Federici et al., 2008), the Apennine Mountains in Italy (Giraudi and Frezzotti, 1997) and in Montenegro (Hughes and Woodward, 2008).

5.5. Rare Holocene Glaciation

In Turkey after the Late Glacial and Younger Dryas, glaciers became even smaller. When the Holocene started, glaciers were only observed on high mountains like the Bolkar Mountains and Erciyes. Samples obtained by Çiner and Sarıkaya (2015) from erratic blocks found on limestone and lateral moraines in the Karagöl Valley in the Bolkar Mountains have confirmed the presence of moraines deposited in the Early Holocene period. During the cold period in the Early Holocene on Erciyes Volcano a small glacial advance period may have been experienced. The presence of glaciers has been determined in Aksu Valley at 10.5 ± 1.3 ka and in Üçker Valley at 10.6 ± 0.6 ka on Erciyes.

Similarly in Eastern Europe, Hughes and Woodward (2008) obtained dates of 10.6 ± 0.2 ka and 9.6 ± 0.8 ka on the Durimitor Massif in Montenegro from a U-series of secondary calcite from two well-described terminal moraines. However, it is not clear yet whether the glaciers in southern and central Anatolia, along with those in Montenegro, are part of a broad region of Early Holocene glaciation or represent a limited area.

Late Holocene and Little Ice Age moraines have only been determined on Erciyes Volcano. Samples from this region have been dated to around 1-4 ka before present. In the Aksu Valley on Erciyes Volcano, terminal moraines at 3000 m elevation have been dated to 4.2 ± 0.6 ka and 1.1 ± 0.3 ka.

Similarly, Late Holocene glaciers have been described in the Apennine Mountains in Italy (around 4.3 ± 0.1 ka, 2.8 ± 0.03 ka and 1.3 ± 0.03 ka) (Giraudi, 2004), in the French Maritime Alps (Federici and Stefanini, 2001) and high cirques on Mount Olympus in Greece (Smith et al., 1997). However, fresh-looking moraines near the peaks of Erciyes Volcano and Aladağlar may possibly belong to the Little Ice Age. Late Holocene and Little Ice Age moraines have been observed also in the Kaçkar Mountains (Akçar et al., 2007; 2008).

5.6. Recent Glaciers

Though small, recent glaciers are observed on several mountains in Turkey. The most important of these is the ice cap on Mount Ağrı. The other important region of southeast Anatolia houses nearly 2/3 of active glaciers in the country (Çiner, 2003; 2004). The presence of glaciers reaching several hundreds of meter is known from the Kaçkar and Taurus Mountains. However, these glaciers are retreating and are on the brink of disappearing. The majority are covered with debris. In the Aladağlar (Gürgen et al., 2010) and Bolkar Mountains (Erinç, 1952; Çalışkan et al., 2014) several glaciers covered with debris have been determined. Before Turkey's current glaciers completely disappear emphasis should be given to scientific studies to record them.

6. Paleoclimate Interpretations From Glacial Studies

To identify climatic conditions in glacial periods, the temperature and precipitation conditions that form glaciers can be modeled. Using physical glacier models (Zweck and Huybrechts, 2005; Sarıkaya, 2009), climatic modeling of the LGM and later has been completed for a variety of regions in Turkey. For these models to work, it is necessary to know the current precipitation and temperature values and topographic conditions in the regions. Changing current climatic conditions by certain amounts creates glaciers in glacial valleys. Comparing the glacial distribution obtained from model results with glacial distribution limits observed in the field (elevations of terminal moraines, lateral moraines, etc.), an attempt could be made to estimate the climatic conditions forming glaciers.

In this context, glacier modeling analysis completed by our group (Sarıkaya et al., 2009; 2014) has shown that the largest glaciers in the LGM formed in an environment 8-11^{o}C colder than today (Sarıkaya et al., 2014). The precipitation conditions in that period were calculated to be 1.5-2 times higher than today for the southwestern Anatolian coast (Mount Sandıras and Akdağ), while central and interior regions (for example Erciyes) were similar to today and northern sections (Kaçkar Mountains) had 30% less precipitation than today (Sarıkaya et al., 2014).

Other proxy data obtained from Turkey and surroundings show that in the LGM the Eastern Mediterranean really had a colder climate than today (Roberts, 1983; Bar-Matthews et al., 1999; Robinson, 2006). However, there is still continuing controversy on the humidity levels in the region (Prentice et al., 1992; Rowe et al., 2012). This situation is due to inconsistency between paleobotanic evidence in the LGM indicating semi-arid climatic values with geomorphologic evidence (Roberts, 1983) belonging to relatively high paleo-lake levels. Additionally, the almost complete disappearance of woody trees (Van Zeist et al., 1975) in the glacial period supports the opinion of a widespread cold and steppe-like climate (Elenga et al., 2000). Different scenarios have been proposed to explain these inconsistencies (Tzedakis, 2007).

Contrary to paleo-precipitation in the west of the Mediterranean region being greater than today, in the interior, north and east, the formation of drier conditions show that the paleoclimate of Turkey had a different situation in terms of atmospheric conditions, compared to today. The strengthened Siberian High, especially due to the effect of large glacial areas in higher latitudes (Scandinavian Ice Shield) and other atmospheric causes, broadening in area over the central sections of Anatolia would have prevented the frontal systems originating over the Atlantic Ocean from penetrating as far as the north and east regions of Anatolia. The subtropical high pressure belt of these systems retreating to the south, together with a more southerly trajectory (above the Mediterranean), would have moved toward the east. This situation would have caused frontal systems with more humidity and energy to meet with the cold Siberian High over the southwest of Anatolia and caused more severe precipitation episodes in this region. In cold periods jet streams and polar fronts moving to more southerly latitudes would have increased the efficacy of polar winds in Turkey and as precipitation increased in coastal areas as a result of this, the interior would have experienced less humid conditions. It is known from a variety of studies that expected climatic changes in the future (in the form of global warming) will have the opposite effect to the theory described above. Global warming will move the subtropical belt northward, thus frontal systems bringing rain to Turkey will follow a more northerly trajectory and precipitation will reduce in the south but increase in the north (Giorgi and Lionello, 2008; Şen et al., 2011; Yücel et al., 2014, Önol et al., 2014).

Model data from the Late Glacial period show that in this period mountains in the interior of Anatolia (like Erciyes) had a climate colder by about 4.5 °C to 6.4ºC and 50% more humidity (Sarıkaya et al., 2009). In the Early Holocene meanwhile, it is thought that the climate was between 2.1 °C and 4.9 °C colder than today and had up to twice the precipitation (Sarıkaya et al., 2009). In the Late Holocene period although precipitation conditions may have approached current levels, the temperature is still assumed to be between 2.4 °C and 3 °C colder than today.

Quantitative data obtained from glacial chronology over the last 15 years has changed our view of glaciers in Turkey and allowed the possibility to make very important and reliable interpretations about paleoclimate. In Turkey, with more studies than in many European countries in terms of quantitative data, the next step is to interpret the data on a broader regional scale. A better understanding of paleoclimatic conditions is a sine qua non condition to allow us to be more prepared for climate changes which are currently occurring and likely to cause significant problems in the future.

7. Conclusions

- A clear geochronology of Late Pleistocene glaciation in Turkish Mountains has been revealed by cosmogenic surface exposure dating published in recent years.
- Late Pleistocene glaciers were observed in 27 regions in Turkey. Of these to date only 9 have had cosmogenic surface exposure dating studies completed.
- Determining the lower limit for ice accumulation for Late Pleistocene glaciers, the LGM permanent snow line varied from 2000-2900 m elevation on mountains in Turkey. Due to continental conditions in central and western sections, the permanent snow line increased.
- Glaciers on mountains in Turkey generally developed in north-facing cirques or on plateaus at the peaks of mountains (generally above 3000 m). The majority of glaciers were a few km long in the form of valley or piedmont glaciers flowing to lower elevations of 1900-2200 m.
- The oldest paleo-glacial advance known developed much before the LGM in global terms (71 ka, at the beginning of MIS 4) and ended at the end of MIS 3 (29-35 ka).
- Later (29 ka) the glaciers advanced again and during MIS 2 (21.5-18.5 ka) and reached their maximum extent. In many regions these precise results, define the local-LGM for Turkish mountains and are in accordance with the global LGM.
- After the LGM, the glaciers began to retreat. This retreat commenced several thousand years later in some regions. The Late Glacial period, dated to around 16 ka, deposited moraines on many mountains in Turkey.

- The glaciers of the Younger Dryas (12 ka) have a scattered spatial distribution. As shown by undated moraines, the reason for this may be different reactions of Younger Dryas glaciers in different regions.
- The extraordinary Early Holocene glaciation (8.5 ka) is only observed in the central regions of Turkey.
- The Late Holocene (1-4 ka) and Little Ice Age glaciations, predecessors of current glaciers, rarely developed near the peaks of high-elevation mountains.
- Glacier models reveal that the LGM climate was 8-11^{o}C colder than today, with 1.5-2 times higher precipitation in southwest Anatolia, with similar precipitation to today in central and interior sections while the northeast was 30% drier than today.
- Glacier models belonging to later periods show that in the Late Glacial the climate was 4.5-6.4^{o}C colder than today and 50% more humid; in the Early Holocene it was 2.1-4.9^{o}C colder with twice as much precipitation while in the Late Holocene precipitation conditions approached those of today however temperature was still 2.4-3^{o}C colder than today.

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