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Last glacial geomorphologic records in Mt Chelmos, North Peloponnesus, Greece

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Abstract: This study deals with the analysis of the glacial processes that have affected the relief of Mt Chelmos in northern Peloponnesus, Greece during middle and Late Pleistocene. The goal was to compile a combined geomorphological-geological map of the study area which would enable the chronological stratification of the glacial landforms cropping up on Mt. Chelmos. Chronological stratification was further aided by optically stimulated luminescence (OSL) dating. The map served as the basis upon which the reconstruction and discussion on the phases of the Middle-Late Quaternary paleoclimatic history of Mt. Chelmos have been made. A sophisticated semi-automated method was first used to analyze the Digital Elevation Model (DEM), combined with Aster, Quickbird and ALOS imagery in order to identify glacial and periglacial, as well as karstic features. Then, these features along with other non-recognizable features from the remote-sensing images were documented in the field. In this way, several glacial landforms were identified, such as moraines and cirques, indicating extended glaciation phases during the middle and Late Pleistocene. Additionally, a ground moraine located at an altitude of 1900-2050 m, within the Spanolakos glacial valley, was dated using the OSL-dating method. The resulting ages indicate a phase of glacier advance/stabilization during MIS-5b (89-86 ka), which is in consistence with pollen-record evidence from Greece and the Mediterranean.

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Introduction

Greece represents one of the few areas in the Mediterranean where the full progression from pioneer to advanced research phases has taken place and the glacial sequence in northwest Greece (Mount Tymphi) is currently one of the best dated of all Mediterranean mountains (Woodward et al. 2004; Hughes et al. 2006a, b; Woodward and Hughes 2011). The chronostratigraphy of the Pindus Mountains has been defined by Hughes et al. (2006c) and stratigraphic results from glacial and periglacial units on Mount Tymphi have been correlated with cold stage intervals recorded in the pollen stratigraphy at the nearby Lake Pamvotis, Ioannina (Tzedakis 1994; Tzedakis et al. 2002). The Ioannina sequence was then used as a parastratotype to define a glacial chronostratigraphy for the Pindus Mountains, allowing for correlations with the marine isotope record. Three main glacial stages have been identified (Hughes et al. 2006a):

- the Skamnellian Stage (MIS12; ca. 480-430 ka),
- the Vlasian Stage (MIS 6; 190-130 ka), and
- the Tymphian Stage (MIS 5d-2; 110-11.7 ka).

For the first two stages there is clear evidence from U-series dating of well-preserved glacial deposits (Woodward et al. 2004; Woodward and Hughes 2011). However, for the Tymphian Stage the evidence has been limited to rock glaciers and small moraines in high altitudes which have been attributed to the last cold stage but lacks any radiometric dating (Hughes 2004; Hughes et al. 2006a, d). The presence of such small glaciers during the Tymphian Stage at high altitudes combined with the presence of many rock glaciers has been linked to arid and cold climate conditions during this period, including the global Last Glacial Maximum (LGM) (Hughes et al. 2003). Still, the lack of further evidence from this glacial phase constitutes an important gap in the current glacial chronostratigraphy of the Pindus Mountains. Similarly, about 15 km to the northeast of Mount Tymphi on Mount Smolikas (2637 m), well-developed moraines have been mapped at elevations above the floors of the highest cirques on Mount Tymphi (Hughes 2004). These glacial landforms postdate the youngest moraines on Mount Tymphi (Tymphian Stage MIS 5d-2), and it has been argued that they might be Younger Dryas in age (Woodward and Hughes 2011) although this has not been confirmed by radiometric dating (Hughes et al. 2006d).

Recent field observations throughout the mountains of central Greece (Leontartitis and Pavlopoulos, unpublished data) demonstrate that the glaciation extent has been underestimated in several locations. In particular, it has been claimed that evidence of glaciation is present only in mountains that exceed 2200 m in altitude (Woodward and Hughes 2011). However, in Evritania (e.g. Mt Chelidona, Mt Kaliakouda, South Agrafa) as well as in Thessaly (Agrafa - also mentioned by Hunt and Sugden 1964), several glacial landforms such as glacial cirques and well-preserved extensive moraine complexes have been confirmed for the first time, following some minor reports from the pioneer geographer Mistardis (1937a). In many occasions, these mountains do not exceed 2000 m. Moreover, evidence for extensive glaciation phases has also been found in the mountains of southern central Greece. These findings confirm the early reports for Mt Parnassus (Mistardis 1937a; Pechoux 1970), Mt Giona and Mt Vardousia (Mistardis 1937a). Dating of the glacial landforms found in the above-mentioned, once-glaciated mountains is of great importance for understanding the missing links between Northern Greece and Peloponnesus. These links can finally contribute to the clarification of striking contradictions emerging from both areas.

In the mountains of Peloponnesus (e.g. Taygetos, Chelmos, Erymanthos) several researchers have identified glacial landforms (Philippson 1892; Maull 1921; Mistardis 1937a,b,c, 1946; Mastronuzzi et al. 1994; Pope et al. 2017). The first studies on Mt Chelmos report cirques, moraines, perched boulders and ice-moulded bedrock which are generally attributed to Quaternary glaciers (Philippson 1892; Maull 1921; Mistardis 1937a,b,c, 1946), while Mastronuzzi et al. (1994) date them to Late Pleistocene age. However, the geochronology and the palaeoclimatic context of this glacial evidence have been only partly explored so far. In particular, the only systematic study that has been conducted on Mt Chelmos is by Pope et al. (2017). Their results (based on cosmogenic-^{36}Cl dating of glacial boulders) showed that quite extensive moraine complexes are the result of glacier advance/stabilization during two phases in Late Pleistocene, at 40-30 ka and 13-10 ka respectively, and a glacial retreat phase during 23-21 ka.

The first glacial advance stage suggests that the local Late Pleistocene Last Glacial Maximum (LGM) predates the global LGM during 23-21 ka and is in accordance with evidence from other mountains across the Mediterranean (Pope et al. 2017), namely northern Spain (Serrano et al. 2012a, b), the Italian Apennines (Federici et al. 2012) and Turkey (Sarikaya et al. 2014) opening up a new perspective on the study of the Tymphian Stage. Practically, as the latitude difference of the two mountains (Mt Chelmos and north Pindus/Mt Tymphi) is relatively small, any differences in the extent of glaciations should mainly be attributed to precipitation differences rather than temperature differences, implying a relatively wet climate in southern Greece during these periods. This kind of information is very useful for circulation models and generally for the reconstruction of the palaeo-climate of the eastern Mediterranean. However, at this stage it is not possible to compare the findings from the two mountains as the glacial record of Mt Tymphi lacks chronological constraints for the period between MIS-5d and MIS-2 (Tymphian Stage and Younger Dryas).

The stage of glacier retreat (23-21 ka) in Mt Chelmos, around the global LGM (22-20 ka), is consistent with evidence of dry conditions around the LGM from northern Greece (Pope et al. 2017), as mentioned above. Finally, the last glacial advance phase (13-10 ka) probably corresponds to the Younger Dryas (12.9-11.7 ka), being consistent with evidence from Montenegro (Hughes et al. 2010, 2011) and the Italian Maritime Alps (Federici et al. 2012). This is of great significance since there is no obvious agreement on the severity of the climatic deterioration during the Younger Dryas in the eastern Mediterranean (Hughes et al. 2003; Pope et al. 2017). According to some researchers, the Younger Dryas event is scantly represented in the eastern Mediterranean pollen records and cannot be perceived as a sudden deterioration of climatic conditions (Bottema 1995; Lawson et al. 2004). On the other hand, there are authors claiming that the Younger Dryas is characterized by cold and arid conditions, as seen from sea–land correlations of pollen records in the eastern Mediterranean (Rossignol-Strick 1995).

The goal of this paper is to further study the glacial history of Mt Chelmos in an effort to complete the chronostratigraphical framework of Quaternary glaciation phases in the mountains of Greece. With this intention, we compiled a combined geomorphological-geological map that enables the chronological stratification of the glacial sedimentary units that have already been identified and dated on Mt Chelmos. Additionally, new evidence on the glacial history of Mt Chelmos is presented through relative and numerical (OSL - Optically Stimulated Luminescence) dating. Finally, the geomorphological map serves as the basis upon which the reconstruction/correlation and discussion on the phases of the Middle-Late Quaternary palaeoclimatic history of Mt. Chelmos can be made.

1 Materials and Methods

1.1 Study area

The study area includes the southwestern part of Mt Chelmos, which includes the Loussoi polje (Figure 1). Mt Chelmos is located in northern Peloponnesus and its peak rises to 2355 m, favoring the accumulation of snow which does not melt until late summer. The distance from the coastline is only 25 km, reflecting the intense tectonic uplift that governs the Corinthian Gulf. The rates of uplift vary from 0.3 mm/y in Corinth (Armijo et al. 1996) to 2.9-3.5 mm/y near Aigion (Pirazzoli et al. 2004), showing that Mt Chelmos is situated within the most tectonically active area of Greece.

Mt Chelmos is composed of two geological units mainly. The first (Upper Unit) corresponds to the Olonos-Pindos Unit, which consists of pelagic limestones and radiolarites of Mesozoic age and Tertiary clastic sequences (flysch). The second Unit corresponds to the Gavrovo-Tripolis Unit, mainly consisted of Upper Triassic-Upper Eocene carbonate formations. The two geological zones bear similar geological/lithological properties but differ as to the geological age. The presence of carbonate formations (highly soluble in water), the supply of water from melting ice, the precipitation and the influence of tectonism, have led to significant karstic processes on Chelmos. As a result, notable karstic landforms can be observed in the study area, such as a polje, karstic sinkholes, dolines, caves, karstic springs etc.

Likewise, sedimentary formations (northern part) of later age can be seen. The most recently deposited sediments (Pleistocene-Holocene age) can be found in the north-western part (gravels) and in the central part of the area depicted in Figure 1. These types of sediments are mainly transported and deposited by surface runoff along with gravitational processes.

Finally, several glacial landforms can be distinguished within the study area. As the aim of this study was to provide further evidence on the glaciation history of Mt, a moraine within the Spanolakos glacial valley, which drains the northwestern flank of Mt Chelmos to the polje of Ano Loussoi, was selected as the most representative high-altitude glacial feature to be dated. The moraine is denoted by a red arc in Figure 1. This clear arcuate termino-lateral moraine has also been identified by Mastronuzzi et al. (1994) and Pope et al. (2017) and, although it

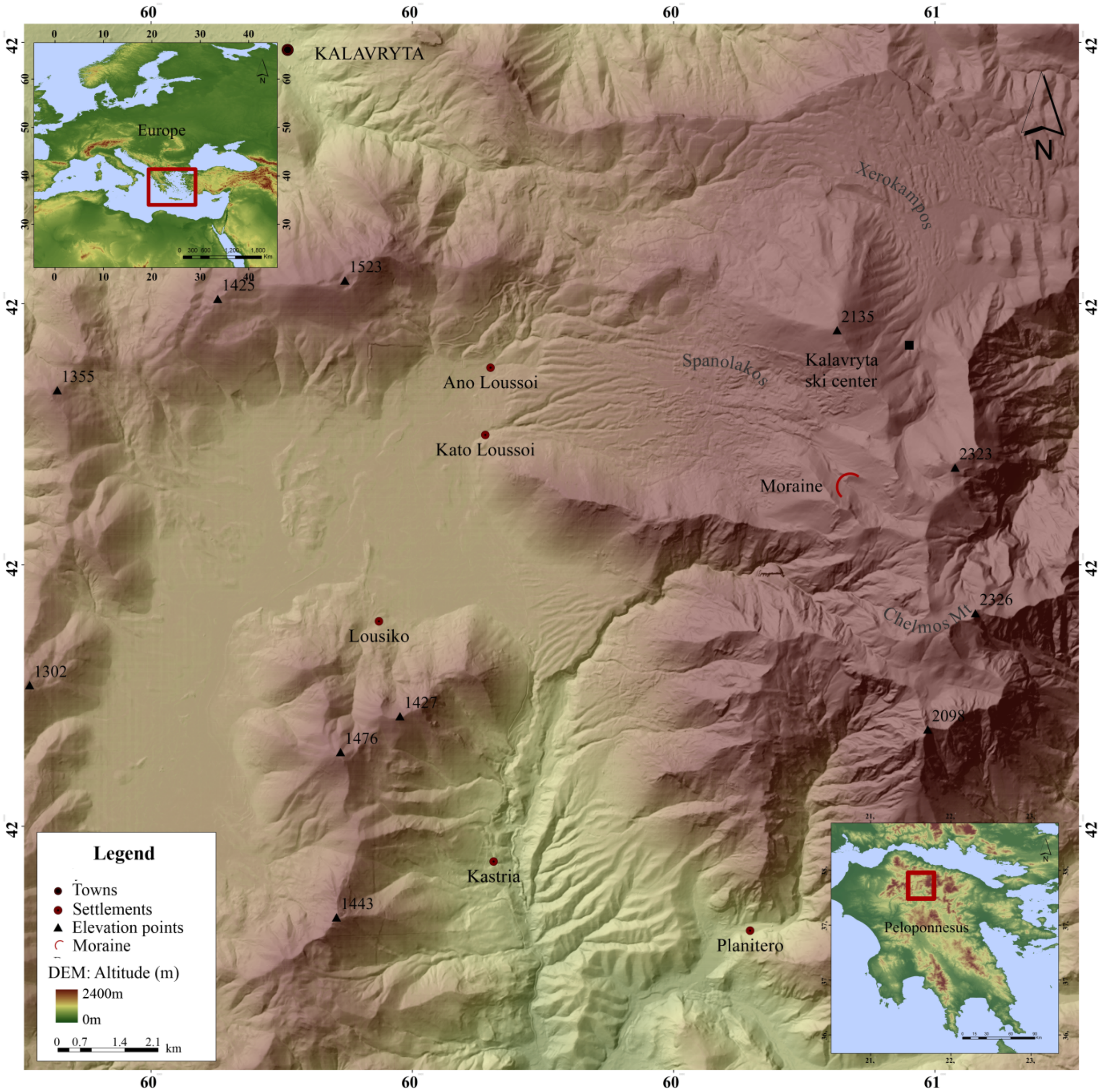


Figure 1 Location map of the study area. The red arc denotes the sampled moraine.

has never been dated, it has been correlated by Pope et al. (2017) with other dated units on grounds of altitude. Its formation has therefore been attributed to a glacial advance/stabilization phase during 40-30 ka. In the framework of this study, it was decided to collect samples from this moraine and date them in order to test the above-mentioned assumptions.

1.2 Topographic data

Research was initiated by collecting raster maps and satellite imagery. The raster maps included the large scale (1/5000) topographic sheets of Loussoi and the surrounding area, by the Hellenic Military Geographical Service, as well as the medium scale (1/50,000) geological map from the Institute of Geology and Mineral Exploration. The topographic maps provided the 4-meter contours. In the areas where the slope was less than 15° the 4 m and the 2 m contours were digitized in order to enrich the Digital Elevation Model (DEM) provided by the National Cadastre (cell size 5m). Cirques, moraines and glacial valleys have first been detected from the observation of the high-accuracy orthophoto and the DEM. During the fieldwork these landforms have been spotted, recorded and mapped with GPS.

The second stage of the geomorphological mapping involved the collection of data in situ.

During the fieldwork many landforms, as well as a number of topographical and geological features, which were not apparent or recognizable on the maps and images of the study area, were documented. Finally, during the fieldwork four (4) samples from a glacial moraine (Figure 1) were collected and dated by OSL (see section 1.5 for details). The obtained results were proved to be very useful for further defining the glaciation phases of Mt Chelmos during the Tymphian Stage (MIS 5d-2).

1.3 Remote sensing data

Remote sensing data included large scale aerial photos by the National Cadastre, Quickbird satellite images, ALOS imagery and Google Earth imagery, which were used to enhance the DEM. These combined with orthophotos) provided significant information on the glacial, periglacial and karstic features within the study area and contributed towards creating a representative geomorphological map.

1.3.1 Advanced Land Observing Satellite (ALOS)

Almost all environmental and geological studies need quite accurate elevation data with global coverage. The increased need for elevation data has simultaneously accelerated the development of algorithms for automatic Digital Surface Model (DSM) extraction (Toutin 2001, 2004). As described in Nikolakopoulos et al. (2006) the along-track stereo-data acquisition is superior as it reduces radiometric image variations (refractive effects, sun illumination, temporal changes) and thus increases the correlation success rate in any image matching. The vertical accuracy of ALOS PRISM DSM created with photogrammetric techniques has been assessed in many studies worldwide (Takaku et al. 2007, 2008; Maruya and Ohyama 2007, 2008; Gruen and Wolff 2007; Lamsal et al. 2011) and for the Greek territory especially (Nikolakopoulos and Vaiopoulos 2011; Nikolakopoulos 2013). In general the vertical accuracy of ALOS DSM ranges between 2 and 3 meters and thus ALOS DSM is characterized as one of the most accurate sources for elevation data.

1.3.2 PRISM data Processing

The automatic DSM creation from ALOS PRISM stereopair is described in detail in Nikolakopoulos et al. (2010). A PRISM data set acquired in 2008 over Chelmos Mountain (provided freely by The European Space Agency) was used in this study. A stereo pair (Nadir and Forward) with a base to height ratios (B/H, where base to height ratio is the distance on the ground between the centers of overlapping photos, divided by aircraft or satellite altitude) of 0.45 was processed using Leica Photogrammetry Suite (LPS). Twenty-five ground control points and more than forty tie points were used. A DSM with a pixel size of 7.5 m was created and no further processing (editing) was performed. The vertical accuracy of the DSM from PRISM data was controlled using 145 ground control points very well spread around the study area. The RMS error was calculated at 7.7 m an acceptable according to the sensor specifications and the steep relief. A final orthophoto with 2.5 m spatial resolution was created and used in the suite of this study with the respective DSM.

1.4 Semi-automated geomorphological mapping

Basic criteria for the identification of the landforms were slope and lithology. Specifically, according to Van Asselen et al. (2006) topographic gradients greater than 35 degrees were treated as cliffs (alpine formations) while in case these gradients were within a buffer zone of 20m from streams they were treated as down-cut erosion. Finally topographic gradients between 5 and 35 degrees were treated as deposit cones and debris (post alpine deposits).

Cliffs were identified on the basis of topographic gradient; were treated as cliffs. The areas that were marked by the automated process were verified by remote sensing images (ALOS orthophoto, Google Earth) and fieldwork.

The shapes of the valleys, down-cutting erosion and gorges were identified by the combined study of the topographic maps, the slope map and fieldwork, while landforms like caves, were mainly identified through literature and fieldwork.

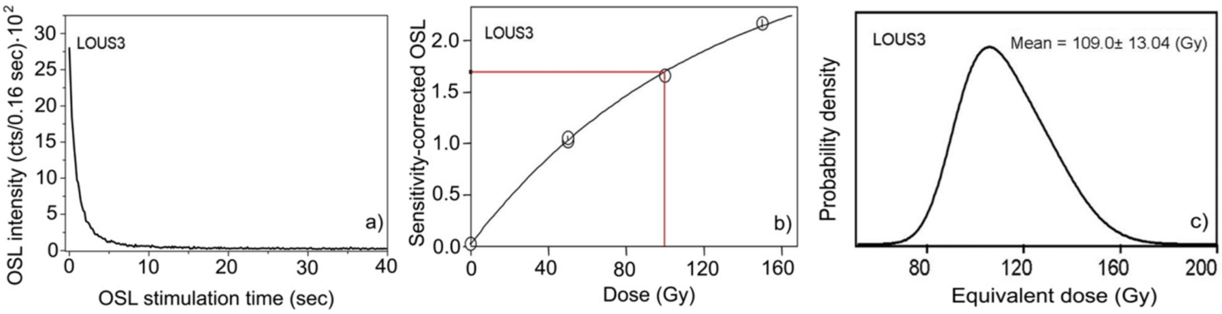
1.5 Optically stimulated luminescence (OSL) dating of moraine deposits

Four samples from glacial deposits (LOUS1, LOUS3, LOUS4, NEW-LOUS6) were collected from the lower part of the moraine described in section 1.1 (Figure 2). Samples LOUS1 and LOUS3 were taken from cohesive sand and fine gravels at a depth of 50cm from the exposed surface in order to ensure they were undisturbed. Samples LOUS4, and NEW-LOUS6, on the other hand, were taken from cemented material (tillites). All samples were subsequently submitted for OSL dating at 'Demokritos' OSL dating laboratory (Athens, Greece) in 2011.

Two of the samples (LOUS1, LOUS3) were collected in aluminum tubes while the other two (LOUS4, NEW-LOUS6) were extracted as blocks. The latter ones had to be carved under controlled illumination conditions (subdued ~580 nm light) in order to obtain their light-safe interior prior to chemical treatment. All the above samples underwent standard chemical and mechanical treatment (e.g. Athanassas et al. 2012) to isolate quartz grains. Initial steps involved HCl (10% concentration) and H_2O_2 (20% concentration). Remaining sediment residue was found to be fine-grained and clay-rich and, therefore, a "fine-grain" dating approach was followed. The material underwent grain-size fractionation through suspension, isolating the 4-11 μm particle-size fraction. The isolated fraction was then submitted to hexafluorosilicic acid (H_2SiF_6, 40% concentration) for several days to dissolve the feldspathic content and purify the fine-grained quartz. Retained fine-grain quartz was then divided into sub-samples (aliquots) and was mounted on stainless disks (1 cm in diameter) to produce "large aliquots".

(a) (b)

Figure 2 (A) The dated arcuate termino-lateral moraine in the Spanolakos valley (1900-2050 m). Photos by Kosmas Pavlopoulos – 2009. (B) Arrow points at the sample spot in the lower part of Spanolakos moraine.



(A) (B) (C)

Figure 3 (A) Typical optically stimulated luminescence (OSL) decay curve; (B) Growth curve and bottom; (C) Equivalent dose distribution. All figures for the LOUS3 moraine sample.

Luminescence measurements were carried out using a RISØ-TL/OSL-15 reader. Equivalent dose measurements were carried out running the "post-infrared OSL" (pIR-OSL) protocol by Banerjee et al. (2001) on multiple aliquots (~20 aliquots/sample), generating in this way a number of individual equivalent doses per sample. Specifically, measurement of natural infrared stimulated luminescence (IRSL) and OSL signals were succeeded by the measurement of the IRSL and OSL responses to a series of regenerated laboratory irradiations, all normalized by the IRSL and OSL response to a constant laboratory dose respectively, known as the "test dose" (Murray and Wintle 2000).

OSL stimulation induced explicit decay curves for samples LOUS1, LOUS3 (Figure 3A) but poor signal-to-noise ratios for LOUS4, NEW-LOUS6. Therefore only samples LOUS1, LOUS3 were considered for further analysis. Dose rate estimation involved measurements of the sample's radioelement content in U, Th and K by means of ICP-MS combined with *in situ* γ-spectrometry. Concentrations of U and Th (in ppm) and K (in % by weight) were then converted to dose rate units by taking into account conversion factors published by Adamiec and Aitken (1998). The dose rate values were further corrected for moisture content, grain-size attenuation and cosmic-ray contribution. The dose rate for samples LOUS1 and LOUS3 was finally estimated to be 0.79 ±0.1 Gy/ka. OSL ages were subsequently calculated at 89±9 ka and 86±7 ka respectively.

1.6 Geomorphological map composition

The geographical entities were classified according to their characteristics following the rules of cartographic generalization, abstraction and simplification (Gustavsson 2006). Specifically, discrete levels of information were generated concerning topographical, hydrographical, geological and geomorphological features. Lithology, tectonics, and geomorphology is generally in accordance with most geological and geomorphological maps (Pavlopoulos et al. 2009). In general, the aim was to create a final geomorphological map, which along with its legend is self-explanatory (see Figure 4). Since the contours are displayed with light shades of grey, indication of the relief inclinations was essential as an additional feature of the morphology, in order to improve the map clarity.

2 Results

2.1 Geomorphology of study area

The landscape of the study area is characterized by karstic, fluvial and glacial landforms. The most significant karstic landform is situated at the center of the map and can be described as a smooth relief (low inclination) area. It has been formed by the dissolution of limestone, and it is characterized as a polje (Tsoflias 1973; Koutsi and Stournaras 2011).

The Ano-Loussoi polje is mainly infilled by alluvial deposits-sediments transported by the fluvial and glacio-fluvial processes. These torrents are nourished by the melting of the seasonal ice and snow during spring/summer, as well as by rainwater during winter, to form the main stream of the polje known by the local toponym as "Mana Stream" (Koutsi and Stournaras 2011). The stream actually drains the whole area through two karstic sinkholes within the polje. Moreover, the presence

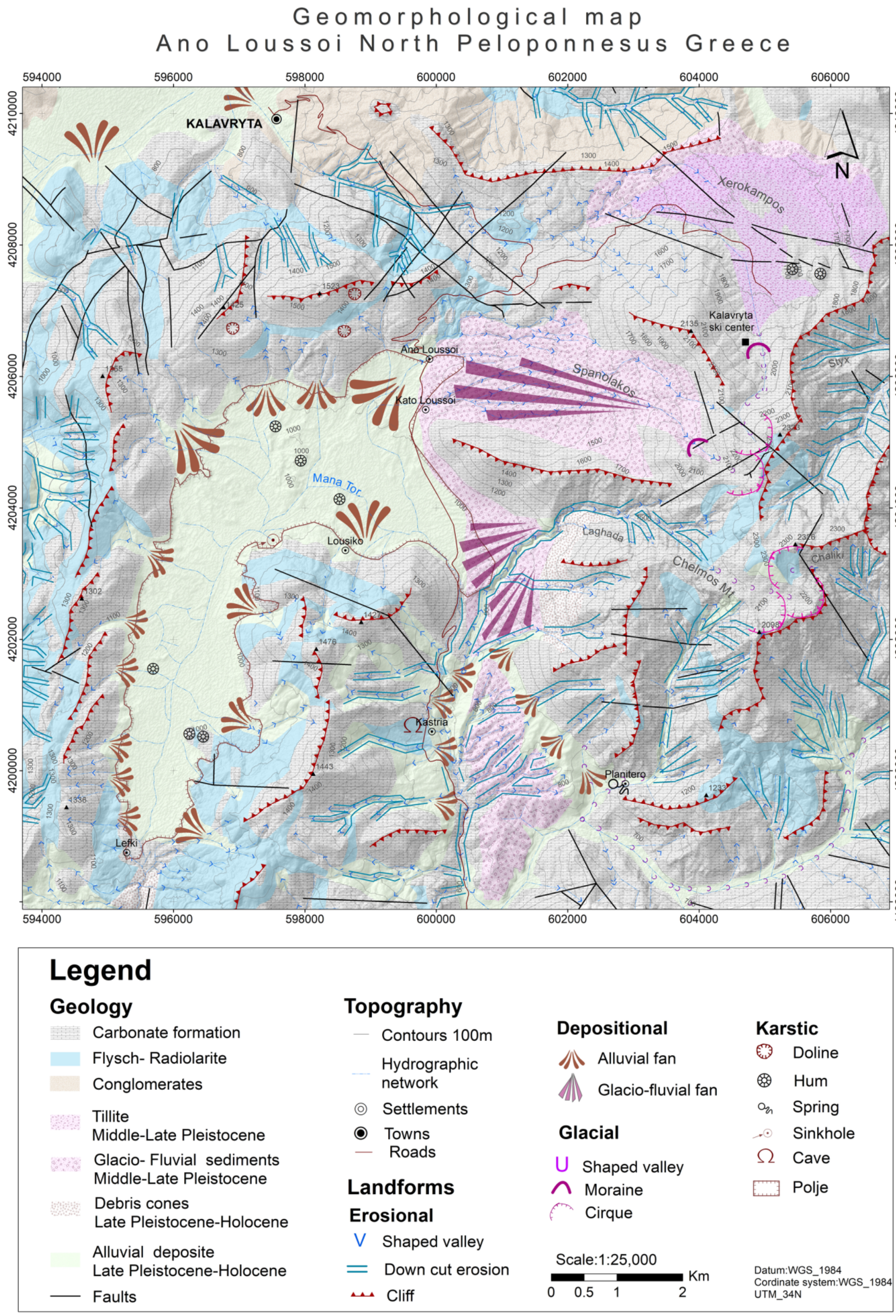


Figure 4 Geomorphological map of the study area: geology and landforms.

of the karstic springs in Planitero village and the presence of sinkholes in the western part of Loussiko village (located in the center of the map) provide additional evidence about the intense karstic processes.

2.2 Glacial and glacio-fluvial features

Glacial landforms can be found mainly in the northern-eastern part of the study area in altitudes between 1500-2200 m. Cirques are situated on the higher part of Mt Chelmos, in the eastern part of the geomorphological map (Figure 4), at altitudes between 2000 m and 2200 m and have also been reported by Mastronuzzi et al. (1994) and Pope et al. (2017). Most interestingly, on Mt Chelmos there is a number of glacial valleys reported also in the studies of other researchers (Philippson 1892; Maull 1921; Mistardis 1937 b, c, 1946; Mastronuzzi et al. 1994; Pope et al. 2017). Within the study area of the present paper the most interesting examples are the valleys of Spanolakos, the valley of Xerokambos where the Kalavryta ski resort is located and the valley of Laghada in the central part of the study area (Figure 5). For reasons of consistency, the three Stratigraphic Units defined by Pope et al. (2017) have been used to correlate the different glacial features, depositions and sedimentary units. These Stratigraphic Units along with the attributed ages are summarized in Table 1.

2.2.1 Spanolakos Valley

The glacial origin of the Spanolakos valley (2145-1300 m) has also been recognized by Pope et al. (2017), distinguishing three main glacial features attributed to three distinct stratigraphical units. A well preserved cirque at 2145 m marks the head of the valley (Figure 4) along with large boulders and an indistinct moraine (Stratigraphical Unit 1). The most interesting glacial feature however is a very clear arcuate termino-lateral moraine, as it has been characterized by Mastronuzzi et al. (1994) and Pope et al. (2017), at an altitude of 1900-2050 m. Although it has never been dated, this moraine has also been correlated by Pope et al. (2017) with the Kato Kambos unit on grounds of altitude. Its formation has therefore been attributed to a glacial advance/stabilisation phase at 40-30 ka (Stratigraphical Unit 2) like the Xerokambos moraine at 1850 m. However the samples collected from the same moraine were dated with the OSL method and yielded an age of 89-86 ka.

The lower part of the Spanolakos valley (1900-1200 m) lies within the area below the sampled glacial moraine and is characterized by thick accumulations of gravels and sand interbeds. This sediment unit was firstly identified by Pope et al. (2017) and has been associated with glacial activity in the Middle Pleistocene (Stratigraphical Unit 1), based on the vast expanse of glaciation and the respective geochronological framework of North Pindus in Greece (Hughes et al. 2006a). Between

Figure 5 Detail of the diamicton tillite unit below the ski resort car park at ca. 1650 m. Photo by Aris Leontaritis – 2016.

Table 1 Updated Glacial Stratigraphic units of Mt Chelmos (1: OSL Dating, 2: ^{36}Cl dating).

Stratigraphic Unit/Glacier Phase		Altitude range of glacial features	Age	MIS - Glacial stage
Current study	Pope et al. (2017)			
1 / I	1 / I	950-1450 m	N/A–Middle Pleistocene age (correlation with northern Greece and Montenegro)	MIS 12 – Skamnellian Stage or MIS 6 – Vlasian Stage
2a / IIa	-	1850-2050 m	89-86 ka [1]	MIS 5b - Tymphian Stage
2b / IIb	2 / II	1600-2100 m	40-30 ka [2]	MIS 3 - Tymphian Stage
2c - Advance or Retreat Phase?	Retreat Phase	2200 m	23-21 ka [2]	MIS 2 – Global LGM - Tymphian Stage
3 / III	3 / III	2100 m	13-10 ka [2]	MIS 2 - Younger Dryas

1700 m and 1900 m cemented gravels and sands are topped by numerous large perched boulders and this range of heights has been noted as the approximate down-valley extent of the largest former glacier limit in this valley (Pope et al. 2017). In the same study, the range between 1700-1200 m where larger boulders are absent was interpreted as a stacked sequence of glacio-fluvial fans.

This unit of glacial sediments can be seen in Figure 4 along with the Laghada valley unit discussed next. These units are clearly distinguished from those derived from erosional and depositional processes. Due to erosional processes V-shaped valleys and down cut erosion are formed by the action of the hydrographic network. The alluvial fans are present mainly in the western part of the study area, where most of the torrents deriving from the neighboring mountains end up in the polje of Loussoi, forming a continuous line of alluvial fans. A direct result of the above alluvial and glacial sediment flows was the extensive deposition inside, and in the boundaries, of the polje, filling it with sediments. These sediments are cohesive and they are reported in the geological maps as "Kato Soudena" formation.

2.2.2 Xerokambos Valley

This valley drains the northern flanks of Mt Chelmos. Its glacial origin is easily distinguishable and several glacier landforms, like a glacial cirque (Figure 4) and scattered perched boulders at the head of the valley at ca. 2200 m (Stratigraphical Unit 3 - Pope et al. 2017) as well as a terminal moraine at ca. 1850 m, have been identified (Philippson 1892; Mistardis 1937b,c, 1946; Mastronuzzi et al. 1994; Pope et al. 2017). The moraine has not been dated but it has been correlated by Pope et al. (2017) with the Kato Kambos unit on grounds of altitude. Its formation has therefore been attributed to a glacial advance/stabilisation phase during 40-30 ka (Stratigraphical Unit 2). However, given the new evidence from the dating of a termino-lateral moraine in the Spanolakos valley at a similar altitude (1900-2050 m) this moraine could also be correlated with a newly defined glacial advance/stabilization phase at 89-86 ka. The central part of the moraine at 1850 m has been destroyed by ski-resort earthworks in 1985. However, Mistardis (1937b, 1946) describes it as a quite high and very clear arcuate terminal moraine, blocking entirely the valley. Mistardis names it "Loutsa", which means seasonal lake in Greek, and indeed Philippson (1892) states that a seasonal lake was present there. Later on, in 1937, Mistardis (1937b, 1946) observed that the modern river channel at that time had cut down deeply the moraine, and as a result it was draining the hollow area behind the moraine, preventing the accumulation of water. Downstream from the moraine there was found a fluvial fan of fine, well-sorted deposits. Moreover Mistardis in the same studies remarked that the flat bottom of the hollow implied a lacustrine origin. The former lake bottom was plane and rich in fine sediments while scattered large-size perched boulders were found. The breakage of this moraine-dammed lake in Xerokambos valley between years 1896 and 1937 could be linked with tremendous floods in Peloponnesus at the beginning of the 20th century (Diakakis et al. 2011) and the creation of the nearby Tsivlos lake by a huge landslide on 24th March 1913 (Stavropoulou et al. 2003). Finally, Mistardis (1937b, 1946) reports another smaller moraine at ca. 2000 m, partly blocking the valley which however has not been confirmed by any other researchers. Some remnants of these glacial deposits can indeed be observed, flanking the ski run above the upper building of the ski resort.

At the lower part of the valley (1650-1700 m), the construction of the ski resort runs, buildings and car park has destroyed much of the evidence. The scattered surviving glacial features (mainly sub-rounded boulders and thin diamicton deposits) have been interpreted by Pope et al. (2017) as the probable furthest extent of former glaciers during Middle Pleistocene (Stratigraphical Unit 1).

However, further evidence at lower altitudes within the valley indicates further glacial/periglacial processes. Specifically, there has been identified a well-preserved cemented diamicton tillite unit (Figure 4), just below the car park at ca. 1650 m (Figure 5). The upper-altitude tillites consist of poorly sorted cemented sub-rounded rocks, boulders and gravels and can be spotted on the ground surface.. The unit's valley limits downwards are not clear but the cemented gravels, probably of glacio-fluvial origin extend down to 1200 m at the western part of the

Xerokambos valley (Valvousi valley). This unit has also been reported by Tsoflias (1973), and was characterized as cemented conglomerates. At lower altitudes (<1500 m), it mainly consists of gravels which are also exposed by the main road from Kalavryta to the ski resort. However, at this stage, the absence of clear evidence for the glacial limits makes rather difficult the determination of the extent of the largest former glacier in Xerokambos valley.

2.2.3 Laghada valley

This valley neighbours the Spanolakkos valley in the south and drains the western flanks of Mt Chelmos, including the basins of Strogilolaka (northern branch of Laghada valley) and Kato Kambos (southern branch of Laghada valley).

The Kato Kambos valley (2280-2250 m) has clearly glacial origins and is headed by a very well-developed cirque at 2280 m (Maull 1921; Mistardis 1937c; Pope et al. 2017). Its upper part is a glacio-karst cirque basin where cirque moraines have been identified at ca. 2140 m and perched boulders have been dated with ^{36}Cl by Pope et al. (2017). The results indicated a glacial advance/stabilisation phase at 13-10 ka characterized as Stratigraphical Unit 3. Further down the valley, between 2050 m and 2140 m another latero-frontal moraine has similarly been identified and perched boulders at ca. 2120 m have been dated by cosmogenic ^{36}Cl by (Pope et al. 2017). The results indicated a glacial advance/stabilisation phase at 40-30 ka characterized as Stratigraphical Unit 2. Glacial boulders can be found down to 2050 m perched just above the steep and steeply incised upper Laghada valley which has been interpreted as the down-valley glacial limit of this unit (Pope et al. 2017). Occasional boulders can also been seen further down until the point where Kato Kambos Valley converges on the southern fork of the Stogilolaka valley, but no further deposits have been preserved due to the steepness of the valley.

Similarly, within the Strogilolaka valley (2100-1900 m) there is abundant glacial evidence, like glacial boulders lying on top of diamicton ridges, but deposits have been poorly preserved due to modern stream activity (Pope et al. 2017). In any case, the limits of Stratigraphical Unit 1 have not been yet identified within the Laghada valley, which ends up right on the southern edge of the Loussoi polje.

The lower part of the Laghada valley, stretching from 1000 to 2000 m, is very steep at middle altitudes (1400-2000 m) and deeply eroded by surface runoff for its entire stretch (V shaped - Figure 4). At around 1000 m it reaches the polje of Loussoi where extended alluvial deposits similar to the ones found in the lower Spanolakos valley above the settlement of Loussoi can be seen (Figure 4). This area is characterized by thick accumulations of gravels and sands, superficially (<5 m in thickness) cemented in places (zone a in Figure 6). Interestingly, this sediment unit expands over the southern edge of the polje, where it has been exposed both by the modern Laghada river channel on its eastern side and by the modern river channel draining the polje on its western side. The latter vertical section is about 40 m deep and can be seen in Figure 6. As it can also be observed by this photo, the material at the upper part (zones a

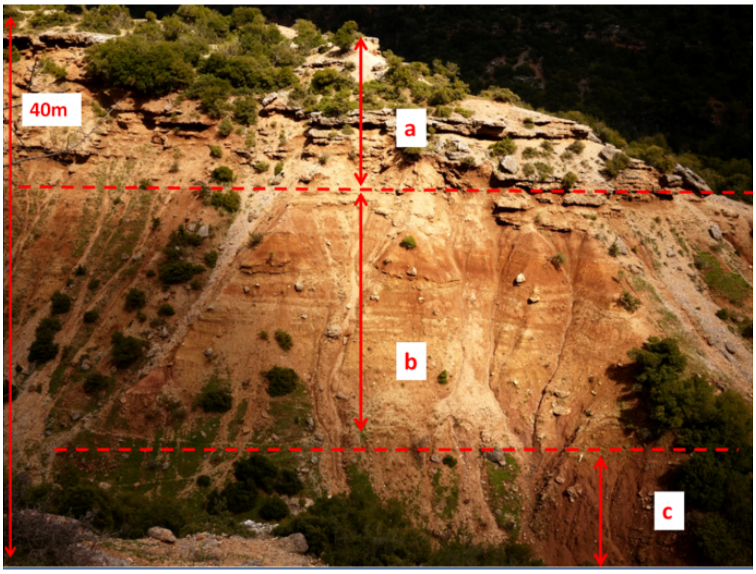


Figure 6 The Laghada alluvial fan at ca. 950 m. The lower part of this fan (zone c) is characterised by sub-rounded rock and boulder deposits. These are likely to be glacial in origin, either moraines or high-energy glaciofluvial deposits emanating from a glacier front that was a short distance up-valley at the apex of the fan in the Laghada gorge. The boulders present in stratified sands (zones a and b) are consistent with a glacio-fluvial origin. Photo by Aris Leontaritis – 2016.

and b in Figure 6) is stratified forming a stacked sequence of gravel and sand accumulations, resembling the Spanolakos unit. It could therefore be characterized as a sequence of glacio-fluvial fans. The large sub-rounded boulders (>2 m in diameter) present in stratified sands (zones a and b) are consistent with a glacio-fluvial origin. However, the lower part of the unit (zone c in Figure 6) is a non-stratified diamicton with sub-rounded gravels, rocks and sub-rounded rocks (ca. 0.5-1m in diameter). A more detailed depiction of the unsorted material in zone c can be seen in Figure 7. These lower parts of the Laghada sedimentary unit could be interpreted as a former moraine which have then been eroded and subsequently mixed-with/covered-by later glacio-fluvial fans during more recent glaciation-deglaciation stages. Alternatively, they could be high-energy glaciofluvial deposits emanating from a glacier front that was a short distance up-valley at the apex of the fan in the Laghada gorge.

Moreover, the southern part of the Laghada sedimentary unit remains unburied by the later glacio-fluvial sequences, forming a ridge (Figure 8). As it can be seen from the photo, there are large limestone sub-rounded boulders exposed on its surface, similar to the ones found in the buried diamicton zone describe above. From a stratigraphical point of view, the buried diamicton zone is in the same position as the ridge. This evidence indicates that this ridge could be a former moraine created by the most extensive glacier in the Laghada valley.

This sedimentary unit could thus be interpreted as the approximate down-valley extent of the largest glacier in this valley. In this case, it can be correlated with the diamicton deposits identified by Pope et al. (2017) at the lower parts of Chaliki valley (1300 m) and the Styx valley (1200 m) in the Neraidorachi area, at the southern and eastern flanks of Mt Chelmos respectively. Conclusively these deposits could be correlated with Stratigraphical Unit 1 and be attributed a Middle-Pleistocene age. However, considering the fact that the boulders in the middle-zones sediments of this unit are in stratified sands deposits and mixed with sands and gravels, as well as that the diamicton unit is highly eroded then it might also be likely that they are high-energy glaciofluvial deposits associated with a glacier front which was in the Laghada gorges immediately upwards. In this case this sediment unit could be interpreted as proximal glacio-fluvial deposits associated with a glacier front that existed nearby

(A) (B)

Figure 7 The diamicton lower part of the Laghada sedimentary unit (zone c in Figure 4) topped by clearly stratified sand layers (zone b in Figure 4). Possibly a glacial moraine eroded and buried by later glacio-fluvial deposits. Photos by Aris Leontaritis – 2017. (A) shows the lowest part of zone c close to the riverbed while (B) provides a wider picture of this zone.

Figure 8 The southern un-buried part of the moraine ridge. Top: looking north. Bottom: looking southeast. The large sub-rounded boulders exposed on the ridge surface are solid limestone boulders rather than blocks of cemented gravels that are found elsewhere on the surface of the northern part of the Laghada sedimentary unit. These ridges are in terms of strata position in consistence with the respective diamicton deposits shown in zone c of Figure 6. Photos by Aris Leontaritis – 2017.

in the valley and these have since been buried by later alluvial fan deposits.

3 Discussion and Conclusions

3.1 Correlation of the glacial and glacio-fluvial features on Mt Chelmos

In this section, the glacial features that were identified and presented in this study are summarized along with the findings of other researchers in an effort to correlate them with each other and lead to a better understanding of the glaciation history of Mt Chelmos. The different Stratigraphic units and the correlated glacial stages are summarized in In this part, the glacial features that were identified and presented in this study are summarized along with the findings of other researchers in an effort to correlate them with each other and lead to a better understanding of the glaciation history of Mt Chelmos. The different Stratigraphic units and the correlated glacial stages are summarized in Table 1.

The lowest glacial sediments/deposits identified are the eroded/buried moraines at the lower Laghada valley (down to ca. 950 m). They have been interpreted as the down-valley limits of these glaciers and correlated with the respective sediments of Stratigraphic Unit 1, identified by Pope et al. (2017) in the Chaliki valley in the south (down to ca. 1300 m) and the lower Styx valley in the north-east (down to ca. 1150 m). These new findings, complement our knowledge of

Stratigraphic Unit 1 and redefine the boundaries of glacier Phase I as defined in the work of Pope et al. (2017). Based on correlations with evidence from northern Greece and Montenegro this largest glaciation was Middle Pleistocene in age, during Skamnellian Stage/MIS 12 and Vlasian Stage/MIS 6 (Pope et al. 2017).

However, the most significant evidence came from the OSL dating of the termino-lateral moraine at an altitude of 1900-2050 m in the Spanolakos valley. This moraine had initially been correlated by Pope et al. (2017) with the Kato Kambos unit on grounds of altitude. Its formation had therefore been attributed to a glacial advance/stabilisation phase at 40-30 ka (Stratigraphical Unit 2) like the Xerokambos moraine at 1850 m. However, the new OSL dating of samples from the foot of the moraine yielded ages of 89-86 ka, indicating that this could be another glacier advance/stabilization phase. Considering that this phase is part of the complex Tymphian Stage (MIS 5d-2) it has been categorized as Stratigraphic Unit 2a and the respective glacier phase as IIa. Given the morphostratigraphical similarity, in-valley position headed by a clear cirque of quasi identical orientation (N-NW) and altitude, the Xerokambos moraine at 1850 m could also be correlated with Stratigraphic Unit 2a.

The formerly defined Stratigraphic Unit 2 and glacier phase II (Pope et al. 2017), correlated with the Kato Kambos unit and a glacier advance/stabilization phase at 40-30 ka is denoted as Stratigraphic Unit 2b in Table 1, corresponding to glacier Phase IIb. The other moraine in the Xerokambos valley, identified by Mistardis (1937b, 1946) at 2000 m has been almost completely destroyed by ski-run earthworks but could either be correlated with Stratigraphic unit 2b or interpreted as a recessional moraine after gacier phase IIa.

Finally, Stratigraphic Unit 3 and glacier phase III remain as defined by Pope et al. (2017).

Evidence of a very similar glacial sequence to the one recorded in Mt Chelmos has been identified in the Pyrenees. Peña et al. (2004) applied OSL to date glacio-fluvial deposits in the Gallego Valley in the western part of the mountain range. They were able to differentiate between three phases of glacier advance/stabilization, at ca. 155.8 ka (Sabiñánigo phase – MIS 6), 85 ka (Aurín phase – MIS 5b) and 35.7 ka (Senegüe phase – MIS 3) which correlate very well with glacier Phases I, IIa and IIb as defined in Table 1.

3.2 Glacial evidence and history of Mt Chelmos

In this study, further evidence for the most extensive glaciation phase has been presented. Based on correlations with evidence from northern Greece and Montenegro this largest glaciation was Middle Pleistocene in age, during Skamnellian Stage/MIS 12 and/or Vlasian Stage/MIS 6 (Pope et al. 2017). These new findings complete the model proposed by Pope et al. (2017) and re-define the respective down-valley limits of glaciers during this period.

Most importantly, new significant evidence from the OSL dating of moraine depositions at an altitude of 1900-2050 m in the Spanolakos valley could indicate another phase in glacial evolution. Specifically, although different evidence has indicated a possible glaciation phase in the mountains of Greece during this period (MIS 5b), this is the first time that evidence is supported by dating results. The issue of glacial activity in the Mediterranean during the cold sub-stages of MIS 5 (5d and 5b) has been characterized by Woodward et al. (2004) as an intriguing one and it was acknowledged that further work was required to confirm this. Macklin et al. (2002), widely reviewed Middle and Late Pleistocene river behavior in the Mediterranean and identified major periods of valley-floor sedimentation during MIS 6 and most notably at the 5b/5a boundary.

The extensive dating program on Mt Tymphi in northern Greece provided some unclear evidence for the glaciation phases during the Tymphian Stage (Late Pleistocene - MIS 5d-2). The separation of Late and Middle Pleistocene glacial units was achieved by detailed mapping and by applying U-series dating methods to date secondary calcite cements in glacial deposits on Mount Tymphi (Woodward et al. 2004; Hughes et al. 2006b). However, radiometric ages have only been obtained from the Middle Pleistocene moraines because no secondary calcites were found in younger moraines. There was just one case, in Vrichos member, where a single calcrete sample from a lateral moraine at 1750 m yielded a uranium series age of 80.45±15.10 ka, indicating that this moraine system had a minimum age of creation during MIS 5b-4 (Woodward et al. 2004). However, evidence from morphologically similar nearby moraines showed two generations of calcite growth (131.25±19.25 ka and 81.70±12.90 ka). In this case, the older of the two ages provided the minimum age of the latter moraine complex, suggesting a related glacial phase during MIS 6. Accordingly, the moraine of Vrichos member has also been correlated with this unit. Tymphian stage deposits on the other hand, are clearly younger than those of the Vlasian stage based on stratigraphical position and soil PDI data (Hughes et al. 2006a), and are limited to rock glaciers and small moraines in high altitudes (>2000 m). It is possible, that multiple episodes of glacial activity had occurred during the Tymphian stage, with only the last of these being recorded in the glacial stratigraphical record (Hughes et al. 2006a, e).

Nevertheless, some further insights into the timing of Late Pleistocene glaciation were inferred from radiometric dates obtained from fluvial sediments deposited by the Voidomatis River, which drains the southern slopes of Mount Tymphi (Hughes and Woodward 2008). As mentioned by Woodward et al. (2004), the uranium-series method was used successfully to develop a chrono-stratigraphic framework for the coarse-grained alluvial units at lower elevations in the Voidomatis River basin (Macklin et al. 1998; Hamlin et al. 2000) providing ages that were in good agreement with other methods such as ESR, TL (Lewin et al. 1991) and radiocarbon (Woodward et al. 2001). Macklin et al. (1998) and Hamlin et al. (2000) recognized at least four separate alluvial units. Secondary carbonates within three of them, yielded maximum uranium ages of 113 ka, 80 ka and 25 ka correlating with deposition during MIS 6, MIS 5b and MIS 2 (closely to the LGM at 22-20 ka) respectively. The presence of silt-rich, fine-grained, limestone-derived material has been attributed to glacial crushing and abrasion (Woodward et al. 1992). The uranium-series ages thus strongly suggest that large glaciers and active moraine complexes were present in the headwaters of this river system during these periods (Woodward et al. 2004)

Further evidence, supporting the established glaciation history of Greece during MIS 6, MIS 3, MIS 5b and MIS 2 comes from the work of Hughes et al. (2006e). In this work the authors made an effort to identify the intervals with the most favorable conditions for glacier formation - in terms of temperatures and precipitation - during the late Vlasian Stage (MIS 6) and the Tymphian Stage (MIS 5d - 2) in Northern Greece. The most useful insight came from the study of the high resolution pollen record from the nearby lacustrine sediment core of Ioannina – I284 sequence (Tzedakis et al. 2002, 2004). It is noted that according to Hughes et al. (2006e), major variations in arboreal pollen frequencies in the Ioannina - I284 sequence over millennial time scales, closely match variations in Mediterranean sea surface temperatures (Cacho et al. 1991) as well as isotope records of marine sediments in North Atlantic (Shackleton et al. 2000) and the Greenland ice sheet (Grootes and Stuiver 1997). The drawn conclusions of the above mentioned study, can thus be used in a broader perspective, and are good indicators of glacial activity also for the more southern Mt Chelmos.

The identification of those intervals was based on the fact that precipitation strongly controls the mass balance of glaciers (Ohmura et al. 1992) while o moisture supply and temperatures strongly affect vegetation populations. In this context, major stadials are characterized by low total arboreal pollen frequencies related with arid and cold climatic conditions. However, reduced precipitation during these stadials would have inhibited glacier build-up and would have forced the retreat of pre-existing glaciers (Hughes et al. 2003). Such intervals have been recognized close to the Heinrich Event 2 (24 ka – Hemming 2004) and the LGM (22-20 ka) between 23 and 24 ka and towards the end of the Vlasian stage (MIS 6 / 190-130 ka) at ca. 133 ka (age limit of pollen record). Concerning the latter interval during MIS 6 though, Hughes et al. (2006a) argue that the maximum extent of glaciers during the Vlasian Stage might have occurred in an interval of cold, yet more moist conditions, prior to the pollen record limit at 133 ka. As for the former interval close to the LGM, it could be correlated with the glacial phase of Mt Chelmos at 23-21 ka (see Table 1) recognized by Pope et al. (2017) as a retreat phase. Cold and arid conditions during the LGM would most likely have caused glacial retreat on Mt Chelmos.

Another type of favorable intervals for glacier formation is characterized by large differences between total arboreal pollen frequencies and arboreal frequencies excluding the tolerant of cold-conditions Pinus and Juniperus species, reflecting to moist yet cold conditions (Hughes et al. 2006e). Such intervals are recognized between 31 and 35 ka BP, 37 and 39 ka BP and finally 83 and 88 ka BP. These periods seem to be strongly related to the Mt Chelmos glacier phases IIb (MIS 3 / 40-30 ka) and IIa (MIS 5b / 89-86 ka) respectively (see Table 1). The latter is also well in agreement with the alluvial unit deposited during MIS 5b (maximum uranium series age of 80 ka) in the Voidomatis basin. However, further pollen record evidence for MIS 5b, are contradictory, in terms of moisture supply, with the Ioannina- I284 sequence. The arboreal pollen record of the Tenaghi Philippon sequence in northeast Greece (Wijmstra 1969; Wijmstra and Smit 1976; Tzedakis et al. 2006) as well as the arboreal pollen record obtained from the sediment sequence of borehole K93 of drained Lake Kopais in central Greece (Tzedakis 1999), ca. 90 km to the northeast of Mt Chelmos, show a clear depression below 20% in arboreal pollen frequencies, implying clearly stadial and arid conditions during MIS 5b. Especially in Lake Kopais, it is striking the extent of aridity as suggested by the significant expansion of *chenopods* and *Artemisia* (Tzedakis 1999).

At a global level, the time interval 84-89 ka BP is representative of stadial conditions of the early part of the MIS-5 interglacial (at the end of cold stadial MIS 5b). This is shortly after both global temperatures and atmospheric concentrations of CO_2 have fallen significantly and the Laurentide ice sheet has expanded to a significant size, but before the Fennoscandian ice sheet could have a major influence on climate (Hoogakker et al. 2016). The pollen-based biomization for 84 ka BP (MIS 5b) clearly reflects the warmer and wetter conditions with more CO_2 available than at the LGM (21 ka BP), especially in Europe, with the majority of sites showing highest affinity scores for the temperate forest biomes. Sites in other parts of the world show similar affinity scores to those at the LGM, although there are not many sites and it is less clear whether they reflect widespread climatic conditions (Hoogakker et al. 2016). On the other hand, according to the evaluation of the GISP2 ice core as to the variability in the North Atlantic at the millennial-scale, the ages of cooling events during MIS-5 were dated to 85.20–86.00 and 103.55–103.80 ka BP respectively (Rohling et al. 2003), and are in agreement with the Spanolakos moraine deposition OSL dating.

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