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First ^{36}Cl cosmogenic moraine geochronology of the Dinaric mountain karst: Velež and Crvanj Mountains of Bosnia and Herzegovina

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Abstract

This article presents the first attempt to date moraines in the Dinaric mountain karst using cosmogenic ^{36}Cl surface exposure dating technique. Twenty samples were collected from moraine boulders from two sets of the lowest and largest lateral moraines on the Velež (1965 m asl) and Crvanj mountains (1920 m asl) in Bosnia and Herzegovina. The dated lateral-terminal moraine complexes, spanning elevations from ~980 to 1350 m asl, are up to 2.7 km long and rise more than 100 m above the valley floor. The moraine boulders yielded ^{36}Cl ages spanning from Oldest Dryas for Velež (14.9 ± 1.1 ka) to Younger Dryas for Crvanj (11.9 ± 0.9 ka), considering the average age of the two oldest samples from each lateral moraine as the most representative time of moraine emplacement. The dated moraines mark the largest extent of glaciers in both study areas, which have been reconstructed to ~ 28 km^2 for Velež and ~24 km^2 for Crvanj, having a mean equilibrium line altitude at 1388 m and 1541 m, respectively. Under modern precipitation values, which account for ~2000 mm, the temperature depression between 8 and 10 °C is required to sustain the palaeoglaciers with reconstructed equilibrium line altitudes. Glaciers of similar size with such low equilibrium line altitudes during the Lateglacial have not been reported until now for the Balkan Peninsula. It is very likely that the boulder ages reflect complex exhumation and denudation histories, which at this point do not allow obtaining more precise moraine chronologies for the study areas. Nevertheless, this article delivers new data on the extent and timing of Quaternary glaciations in the Mediterranean mountains, where records of glacier fluctuations seem to be asynchronous amongst different areas. It is clear that dating moraines with cosmogenic ^{36}Cl surface exposure dating in carbonate lithologies in areas of high precipitation like the Dinaric karst, remains challenging.

Keywords: Quaternary; Glaciation; Dinaric Karst; Cosmogenic Surface Exposure Dating; Equilibrium Line Altitude; Palaeoclimate

1. Introduction

The Dinaric Mountains is more than 650 km long mountain chain flanking the eastern Adriatic coast. It is characterised by a karst landscape with high-elevated plateaux, reaching the highest elevations in the central-southern belt (Čvrsnica – 2228 m asl (above sea level), Maglič - 2386 m asl, Durmitor – 2522 m asl, Prokletije - 2694 m asl). The highest parts of the Dinaric Mountains were glaciated during Pleistocene (Cvijić, 1899) and even today few small glacial remnants still exist in the Durmitor and Prokletije mountains (Gachev et al., 2016). Hence, this area is characterised by a combination of karst and glacial landscape (Telbisz et al., 2019; Žebre and Stepišnik, 2015).

Pioneer studies on past glaciations in the Dinaric Mountains were conducted at the end of the 19th century, focusing on the area of Montenegro and Bosnia and Herzegovina (e.g. Cvijić, 1899; Grund, 1902; Penck, 1900). Extensive monographs and scientific papers from that time hold detailed descriptions of glacial landforms and even reasonably precise geomorphological maps. In the 20th century the research on palaeoglaciations continued also in other Dinaric areas (e.g. Habič, 1968; Liedtke, 1962; Riđanović, 1966; Šifrer, 1959) with several interruptions owing to wars and political instabilities. These turbulent past events have left a great impact also on the recent state of knowledge on past glaciations in the Dinaric Mountains since majority of areas still remain undated (e.g. Krklec et al., 2015; Milivojević, 2007; Milivojević et al., 2008; Petrović, 2014) and without any detailed sedimentological and stratigraphic research. Nevertheless, it is not only the landmine contamination that prevents more detailed studies, but also dating glacial deposits in carbonate areas, with high precipitation gradients and hence important denudation rates (Levenson et al., 2017 and references therein), is still very challenging.

A number of techniques can be applied to date moraines and outwash deposits in carbonate environments, including U-series, luminescence, radiocarbon (^{14}C) and TCN (terrestrial cosmogenic nuclide) dating. U-series dating can be used to date secondary carbonates that are found cementing moraines and the practical range of this technique is ~350 ka (Hughes et al., 2013). The method relies on several assumptions and criteria, where special care should be taken to ensure that samples are from distinct crystal horizons and show no evidence of re-crystallisation and open-system behaviour (Smart, 1991). Although the U-series method can provide only the age of the cement growth, therefore lacking the precision needed to constrain the timing of moraine deposition, it was found to be useful for bracketing moraines within certain glacial cycles in some of the Mediterranean mountains (Hughes et al., 2011, 2010, 2006). Luminescence dating is often used to date outwash sands and the upper age limit may extend up to 500 ka (Wallinga and Cunningham, 2015), but the method is hardly applicable to carbonate environments owing to the lack of quartz and feldspars in deposits (Krklec et al., 2015). Nevertheless, the method was successfully applied to some of the carbonate-dominated landscapes in the Mediterranean, where smaller amounts of quartz were present in outwash due to the limited exposures of non-carbonate bedrock in the glaciated catchments (Bavec et al., 2004; Lewin et al., 1991). Although radiocarbon dating has a limited chronological range (<50 ka) (Hughes et al., 2013), it has been shown to be a very robust method for dating Last Glacial Maximum (LGM) moraines (e.g. Monegato et al., 2007) or other Late Pleistocene glacial sequences even in limestone-dominated environments (e.g. Nieuwendam et al., 2016; Ruiz-Fernández et al., 2016). However, in karstic terrains, this technique is commonly restricted either by material availability in moraine matrix or by the hard-water error when applying the technique in moraine-dammed lakes or bogs. Cosmogenic surface exposure dating with ^{36}Cl is an established method for dating moraines (Dunai, 2010; Gosse and Phillips, 2001) and has been successfully applied in carbonate environments elsewhere (e.g. Gromig et al., 2018; Pope et al., 2015; Sarıkaya et al., 2014; Styllas et al., 2018). However, karst denudation rates limit the ^{36}Cl exposure dating technique to be applied on carbonate lithologies that are exposed to extremely wet environmental conditions, if they are older than ~40 ka (Hughes and Woodward, 2017).

Despite several methodological and physical obstacles such as landmines, it is important to obtain as much data as possible on the glacial extent and chronology from the Dinaric Mountains and wider Balkan area in order to better understand the temporally (a)synchronous maximum phase of glaciation in the Mediterranean (Hughes and Woodward, 2017) and the past and present changes in atmospheric circulation influencing the Mediterranean region. The coastal Dinaric Mountains receive one of the highest precipitation amount in Europe today (Crkvice weather station - MAP (mean annual precipitation) ~ 5000 mm) and this seemed to be true also for the cold stage climates since according to the present state of knowledge one of the lowest equilibrium line altitudes (ELAs) in the Mediterranean were located in this area, showing a strong west-east gradient associated with westerlies (Hughes and Woodward, 2017). The Balkan area is also considered one of key areas for assessing the environmental and population history of Europe since it has been argued that this region served as a Lateglacial refugium for humans, animals and plants (Pilaar Birch and Vander Linden, 2018).

Although geomorphological evidence for palaeoglaciations in some of the Bosnia and Herzegovina Mountains has already been recognized in the 19th century (Cvijić, 1899), Bosnia and Herzegovina is considered as one of the main black spots in the Dinaric Mountains from the glacial chronological point of view, as there are no quantitative age data and detailed sedimentary analyses until today. In this paper we focus on the glacial chronology of the Velež and Crvanj mountains. Velež Mountain was recognized as glaciated for the first time by Grund (1902, 1910) in the early 20th century. In this very exact and advanced study for his time, considering the available topographic maps and other field instruments, Grund presented the geomorphological map of the northern side of Velež, including a detailed description of glacial features. He also estimated the snow line for the north-facing palaeoglaciers to be between 1350-1500 m asl. This area has been long time forgotten until 2015, when the glaciokarst phenomena were studied by Žebre and Stepišnik (2015). On the contrary, the Crvanj Mountain has never been studied before from a palaeoglaciological point of view. Therefore, the aims of our research are (a) to present the geomorphological and sedimentological evidence for glaciation on the Velež and Crvanj mountains, (b) to constrain the timing of the largest recognized glacier extent on Velež and Crvanj by applying the cosmogenic ^{36}Cl surface exposure dating technique for the first time in the Dinaric Mountains, (c) to reconstruct palaeoglacier dimensions and related palaeo-ELAs, and (d) to critically evaluate a relevance of the obtained cosmogenic ages in the light of regional geomorphological and climate context.

2. Regional setting, geology and climate

The Velež and Crvanj mountains (43° 15'–43° 30' N and 17° 55'–18° 20' E) are located in the central Dinaric Mountains in southern Bosnia and Herzegovina between the Mostar basin to the west and Nevesinjsko polje to the south (Figure 1). The central mountain crest of Velež reaching elevations above 1700 m asl is approximately 12 km long and oriented in a NW-SE direction. The highest peak is Botin with 1965 m asl. On the other hand, the Crvanj Mountain has a plateau shape top with the highest elevations in its western part, where the peak of Zimomor reaches 1920 m asl.

The Velež Mountain is an overthrust of the Cretaceous shallow water carbonates over the Tertiary and Cretaceous sedimentary rocks (Hrvatović, 2005). The north-facing slopes, where majority of the research took place, are predominantly composed of Cretaceous limestone and dolostone. The Crvanj Mountain exhibits very similar geological features. Central part of the mountain is an overthrust of Triassic and Jurassic dolostones, with beds of limestone containing chert, overlying Jurassic and Cretaceous limestone (OGK, 1981, OGK, 1970). Owing to the prevalence of carbonate lithology, a well-developed karst aquifer functions within both areas. Subsurface drainage is oriented towards springs at the Nevesinjsko polje and other deep-entrenched valleys around the mountain, thus the vadose zone reaches depths of at least few hundred metres.

The study area is situated in a transition zone between the Mediterranean and continental climate, having characteristics of a warm temperate climate, fully humid, with cool summers (Cfc) according to the Köppen-Geiger climate classification (Kottek et al., 2006). Precipitation is well distributed throughout the year owing to the moisture coming from the Adriatic Sea (west) and the effect of orography. At Nevesinje (891 m asl), MAP over the period 1961-1990 was 1795 mm (Data courtesy

Federal Hydrometeorological Institute, Sarajevo), while MAP at higher elevations is likely to be higher; it was estimated to be up to 2000 mm (Vojnogeografski institut, 1969). The mean annual air temperature (MAAT) at Nevesinje is 8.6 °C with the warmest month being July (18 °C) and the coldest January (-0.9 °C).

Figure 1: (a) Study area and the topography of Mediterranean region after the mountain belts from Kapos et al. (2000) and (b) a close up of the southern Bosnia and Herzegovina. The study areas of the Velež and Crvanj mountains are located between Mostar basin to the west and Nevesinjsko polje to the south.

3. Methods

3.1 Geomorphological mapping

Field geomorphological mapping was carried out between 2012 and 2015. Topographic maps in a scale of 1:25.000 were used for mapping, while basic geological maps in a scale of 1:100.000 (OGK, 1981, OGK, 1970) were useful for giving a general support on the geological setting of the study area. With the exception of the northwestern area of Velež and northern part of Crvanj that are situated close or in the minefields (http://www.bhmac.org), the rest of the study area was examined in detail although the north-facing slopes of Velež below 1400 m asl are densely forested and therefore not easy to map. The interpretation of the spatially documented landforms on the field was supported by the sedimentological description of some outcrops, commonly exposed as road cuts or abandoned gravel pits. Standard field procedures (e.g. sedimentary structures, colour, clast size, distribution and roundness) and lithofacies codes following Evans and Benn (2004) were used for sediment description.

3.2 Cosmogenic nuclide dating

Cosmogenic ^{36}Cl surface exposure dating was used to infer the depositional ages of the moraines in the Velež and Crvanj mountains. The length of time that the boulder has been exposed on the moraine surfaces can be estimated by this method (Davis and Schaeffer, 1955; Dunai, 2010) via cosmogenically produced isotopes such as ^{36}Cl, ^{10}Be and ^{26}Al. Here, we used the ^{36}Cl because all lithologies, especially the carbonates, are suitable for the production mechanism of ^{36}Cl.

Dating with ^{36}Cl depends on the interactions between cosmic rays and nuclides in rocks. When rocks are exposed at or near surface, cosmic ray particles, which are secondary fast neutrons, thermal neutrons and negative slow muons start to bombard and interact with three main nuclides (^{40}Ca, ^{39}K and ^{35}Cl) to cause formation of cosmogenic ^{36}Cl. Therefore, measured ^{36}Cl concentrations in rocks can be used to quantify the time-length of boulder exposition (Gosse and Phillips, 2001; Owen et al., 2001).

3.2.1 Sample collection and chemical preparation

We collected 20 samples for cosmogenic ^{36}Cl dating from the top of the boulders on the crest of the moraines. The boulders were selected according to their positions on the crest, stability, size and preservation indicators; such imbedded large enough boulders on moraine crests were preferred. We concentrated on the largest moraines that were reasonably away from the minefields; hence safe enough to accomplish the fieldwork. We sampled on both right and left lateral moraines, targeting same number of samples from each lateral moraine. Only the largest glacial boulders with a stable position on the moraine crests have been taken into account. A hammer and chisel were used to take samples from upper few centimetres of the boulders and thicknesses of the samples were recorded (Table 1). Shielding of surrounding topography was measured by inclinometer from the horizon at each sample location (Gosse and Phillips, 2001). Sample locations were recorded by a hand-held GPS. Elevations data are also based on the GPS measurements except for BU samples, which are from topographic maps.

The rock samples were prepared at Istanbul Technical University (ITU) Kozmo-Lab (http://www.kozmo-lab.itu.edu.tr/en) according to procedures described in Sarıkaya (2009). First, samples were crushed and sieved to appropriate grain size (0.25-1 mm). Then they were leached with deionized water and 10% HNO_3 to remove secondary carbonates, dust and organic particles. Spiked (^{35}Cl enriched) samples were digested with excess amount of 2 M HNO3 in 500 ml HDPE bottles (Sarıkaya et al., 2014; Schlagenhauf et al., 2010). ~10 ml of 0.1 M AgNO3 solution was added before the digestion to precipitate AgCl. Later, isobar ^{36}S was removed from the solution by repeated precipitation of $BaSO_4$ with addition of $Ba(NO_3)$ and re-acidifying with concentrated HNO_3. Final precipitates of AgCl were sent to the ANSTO, Accelerated Mass Spectrometer (AMS) in Sydney, Australia for isotope ratio measurements given in Supplementary Table S1.

Major element concentrations were determined with inductively coupled plasma emission spectrometry (ICP-ES) and trace element concentrations with inductively coupled plasma mass spectrometry (ICP-MS) at the Acme Lab (ActLabs Inc., Ontario Canada) to provide the total element concentrations (Table 2). Total Cl was calculated by isotope dilution method (Desilets et al., 2006; Ivy-Ochs et al., 2004) after AMS analysis (Table 2).

3.2.2 Determination of ^{36}Cl ages

The CRONUS Web Calculator version 2.0 (http://www.cronuscalculators.nmt.edu) (Marrero et al., 2016a) was used to calculate sample ages. Cosmogenic ^{36}Cl production rates of Marrero et al. (2016b) [56.3 ± 4.6 atoms ^{36}Cl (g Ca)-1 a-1 for Ca spallation, 153 ± 12 atoms ^{36}Cl (g K)-1 a-1 for K spallation and 743 ± 179 fast neutrons (g air)-1 a-1] were used using the time-dependent Lifton-Sato-Dunai scaling (also called “LSD” or “SF” scaling) (Lifton et al., 2014). We used 190 µ g-1 a-1 for slow negative muon stopping rate at land surface at sea-level high-latitude (Heisinger et al., 2002). Lower Ca spallation production rates suggested by Stone et al. (1996) or Schimmelpfennig et al. (2011) will make our ages 7-10% older. Spallation and negative muon capture reactions are responsible for the main production of ^{36}Cl (>95% for Mt. Velež samples and ~60% for Mt. Crvanj samples), with lesser contributions from thermal neutron capture reactions by ^{35}Cl (5% for Mt. Velež samples and 40% for Mt. Crvanj samples). The chemical data (Table 2) and all other essential information including the ^{36}Cl concentrations and scaling factors to reproduce resultant ages is given in Table 3 and Supplementary Table S1.

All surface exposure ages include corrections for thickness and topographic shielding. We reported both zero-erosion and erosion corrected boulder ages (from 10 to 60 mm ka^{-1} of bedrock weathering assumed) and preferred to use the 40 mm ka^{-1} erosion corrected age, because the study area is located in one of the highest precipitation regions of Europe, and boulder surfaces show up to several cm deep solution grooves. Snow correction factor for spallation reactions of 0.9539 was applied to all samples based on snowpack of 25, 100, 100, 100, 50, 25 cm of snow on Nov, Dec, Jan, Feb, Mar and Apr on top of boulders. Snow thicknesses were estimated based on meteorological data from the Nevesinje weather station (Data courtesy Federal Hydrometeorological Institute, Sarajevo).

Table 1: Sample locations, attributes and local corrections to production rates.

Table 2: Geochemical and isotopic analytical data.

3.3 Glacier and climate reconstruction

3.3.1 Glacier geometry

A digitized geomorphological map of glacial features together with 20 m digital elevation model was used in the glacier geometry reconstruction. The glacier's extent was established using the field geomorphological evidence such as trimlines and lateral-frontal moraines. Then, the reconstruction was carried out by producing theoretical glacier surface profiles using the Profiler v.2 spreadsheet developed by Benn and Hulton (2010). We have largely followed the procedure presented in Žebre and Stepišnik (2014), which is based on similar principles as the newly developed semi-automated GlaRe GIS tool (Pellitero et al., 2016). Software ArcGIS 10.3.1 and a predefined *Topo to Raster* interpolation method was used for calculating the ice surface with 50 m contour intervals.

3.3.2 Equilibrium Line Altitudes (ELA)

The equilibrium line altitude (ELA) of the reconstructed palaeoglaciers was determined by applying the area altitude balance-ratio method (AABR) (Osmaston, 2005). The accumulation-area ratio (AAR) method, which is the most widely used approach for the palaeo-ELA reconstruction, is becoming increasingly replaced by the AABR method, which is also more reliable, provided that the correct balance ratio is applied (Rea, 2009). The principle of the AABR method is that the total annual accumulation above the ELA exactly balances the total annual ablation below the ELA under equilibrium conditions (Benn and Gemmell, 1997). The advantage of this method is that explicitly accounts for both glacier hypsometry and mass balance gradients (Benn and Gemmell, 1997). The method gives the best results for the clean glaciers (Benn and Lehmkuhl, 2000) where most of them will have the balance ratio between 1.5 and 3.5 (Osmaston, 2005). A representative balance ratio for maritime mid-latitude glaciers is 1.9 ± 0.81 (Rea, 2009), which we applied for calculating the ELA of palaeoglaciers on the Velež and Crvanj mountains. A GIS tool developed by Pellitero et al. (2015) was used to facilitate the ELA calculations of individual valley, cirque and outlet glaciers. The latter were separated by subdividing the ice field into sectors of individual glacier entities (Cowton et al., 2009; Hughes et al., 2010). The local ELA of an individual mountain is represented as a mean ELA of the entire group of glaciers. The ELA of each glacier was also estimated with the AAR method using a ratio of 0.6, which is believed to be representative of valley and cirque glaciers (Benn and Evans, 1998; Nesje and Dahl, 2000; Porter, 1977). This allowed crosschecking the ELA results calculated with the AABR method.

3.3.3 Temperature-melt simulations

For a better understanding of the relationship between glaciers and climate as well as an additional consideration of the age-dating results, we used a simple degree-day model (Brugger, 2006; Hughes, 2008), which calculates the amount of accumulation required to sustain glaciers. The inputs required for the model are mean annual temperature range and mean annual temperature. The latter is distributed over a sine curve to produce daily temperature means using the following equation (Brugger, 2006):

$$T_d = A_y sin(2\pi d/\lambda - \phi) + T_a$$

where T_d is the mean daily air temperature, A_y is the amplitude of the yearly temperature (½ of the annual temperature range), d the day of the year (1–365), λ is the period (365 days), ϕ is the phase angle (taken as 1.93 radians to reflect the fact that January is the coolest month) and T_a is the mean annual air temperature.

The annual accumulation required at the ELA to balance melting is equal to the sum of daily snowmelt, using a degree-day factor (Hughes et al., 2010). In our study we used the mean degree-day factor for snow of 4.1 mm day^{-1}°K^{-1}, which is representative of most glaciers and also in accordance with values reported in the literature (e.g. Braithwaite, 2008; Braithwaite et al., 2006). Snowmelt at the palaeo-ELAs on the Velež and Crvanj mountains was then reconstructed under different temperature regimes, using the climate data from Nevesinje (891 m asl) for the period 1961-1990. Mean annual temperature at this station was depressed by 4-15 °C in 1 °C intervals and then extrapolated to the mean palaeo-ELAs on Velež and Crvanj using the modern environmental lapse rate of 0.65 °C/100 m. The model was run using two different mean annual temperature ranges: the modern one (18.9 °C) and 150% of the modern range (28.35 °C). The latter reflects the possibility that palaeoclimate might have been more continental, since the sea level in the Adriatic basin was approximately 115 m lower at 20 ka, 100 m lower at 16 ka, and 60 m lower at 12 ka (Lambeck et al., 2011). Nevertheless, the above-described procedure allowed obtaining a range of temperature-accumulation predictions and better understanding of the palaeoclimate needed to sustain glaciers in the study areas.

4. Results

4.1 Glacial geomorphology

4.1.1 Velež Mountain

The palaeoglacial landscape of the Velež Mountain (Figure 2a), with an emphasis on the glaciokarst features, was previously mapped by Žebre and Stepišnik (2015). The south-facing slopes exhibit minor glacier remodelling of the surface with only three cirques present below the highest peak Botin (1965 m asl). The cirque`s floors are situated between 1620 and 1790 m asl. A thin cover of glacial deposits is present on the cirque rims, while no glacial traces can be observed in lower elevations. On the contrary, the north-facing slopes are steep cliffs characterized by a series of cirques (Figures 3a and 3b) and extensive glacial deposition down to 950 m asl. Cirque floors on the northern side of Velež are situated much lower in elevation (between 1400 and 1500 m asl) from those on the south. Below cirques are polished limestone pavements and arêtes in between individual glacial valleys. Less than 5 km from the main mountain crest lateral-terminal moraine complexes occur at an elevation between 1300 and 1200 m.

We mapped 5 large lateral moraine pairs that are up to 2.7 km long and rise more than 100 m above the valley floor. Other two smaller moraine complexes are 1.1 km long and no more than 50 m high (Figure 2a). Moraines extend down to a minimum altitude of 940 m asl, where they are coupled with outwash fans. Breach-lobe moraines, formed by the glacier cutting through the main lateral moraines, are present on the external parts of some lateral-terminal moraine complexes, which are believed to be deposited by moraine-dammed glaciers, typical for the karst areas (Žebre and Stepišnik, 2015). Moraines occur also approximately 1 km up-valley of the outermost limits of glaciation and some 100 m higher. They are much smaller, indicating an evident shrinkage of glaciers especially in ice thickness. In most valleys of the Velež Mountain, left- and right-lateral moraine couples are common (Figure 2a). We did not recognize more than two clear sets of lateral moraines. The third set is usually present only on the rim of some cirques.

Lateral moraines are composed of a diamicton (Dmm) characterized by a sandy-silty matrix and subangular to subrounded cobble-to boulder sized clasts of Cretaceous limestone and dolostone. Common boulders of ~1 m in diameter are scattered along the moraine crests, although those up to 3 m can be also found (i.e. sample BU16-06). Further down moraines two larger areas of outwash deposition are present below 1000 m asl. The meltwaters from the glacial valleys west of the peak Botin were directed towards the Donje Zijemlje karst depression (Figure 3c), while those from the valleys east of the highest peak were running off towards Nevesinjsko polje. However, a bifurcation of meltwaters below glaciers in the karst underground system is not excluded. Outwash fans are slightly inclined, from 1.5° in the proximal zones to only 0.5° in the distal zones. They consist of horizontally bedded, clast-supported gravels with rare sandy lenses (Gh). The clasts are subrounded to rounded Cretaceous limestone and dolostone. Average size of the clasts is from 1 to 7 cm, attaining a maximum of 17 cm.

Figure 2: (a) Geomorphological map of glacial landforms on the Velež Mountain. (b) Samples for ^{36}Cl cosmogenic nuclide dating were collected from the Budijevača lateral-terminal moraine complex. The samples ID`s along with the ages (ka) corrected for 40 mm ka^{-1} of erosion are presented in (b).

Figure 3: (a) Steep north-facing slopes of the Velež Mountain showing a series of cirques in the upper parts and moraines entirely covered by forest below them. (b) The easternmost cirque on the Velež Mountain, which hosted a small valley glacier during the maximum glacial phase. (c) The westernmost outwash fan filling the floor of Donje Zijemlje karst depression.

4.1.2 Crvanj Mountain

The western slopes of the Crvanj Mountain (Figure 4a) were remodelled by limited extent of a cirque-type glaciation. A complex of three cirques (Figure 5a) with northwestern exposition are present below the highest peak Zimomor (1920 m asl). The cirque floors are situated at an elevation span of 1430-1480 m asl. Up to 10 m high moraine ridges are located inside and below the cirques between 1400 and 1500 m asl. Three km long, deeply entrenched gully starts below glacial deposits and terminates in the apex of the large outwash fan, covering the northern part of Nevesinjsko Polje.

Central part of the mountain is a wide-ranging plateau, having surface slightly sloping eastwards. Major part of the plateau area is made of dolostone that appears to be glacially moulded, showing rounded hills slightly elongated in the direction of glacier flow, and few dolines and polished pavements. Only limited patches of glacial till can be found on the plateau, whereas on the eastern and southern slopes of Crvanj glacial till appears in the form of large lateral moraines. The northern sector of the mountain, where glacial deposits are also to be expected, has not been examined on the field due to the presence of minefields. Since the area is completely overgrown by a forest, it was neither possible to confirm the presence of moraines by means of remote sensing data.

A pair of lateral moraines and minor recessional moraines on the south-facing slopes extend between 1180 and 1400 m asl. In between the main lateral moraines, a gully is carved in bedrock, and after approximately 3 km of length it terminates in the outwash fan on Nevesinjsko Polje. The largest moraines that were also sampled (Figure 4b), are present on the eastern slopes of Crvanj at an elevation range of ~1000-1350 m asl. Lateral moraines are no more than 1.5 km long and rise up to 150 m above the terminal moraine depression, where a lake is present (Figure 5b).

Till building these lateral moraines appears as a diamicton (Dmm) with sandy-silty matrix and angular to subrounded clasts (Figure 5c). The lithology is more diverse as in the case of the Velež moraines. Limestone and dolostone clasts show greater roundness compared to sandstone clasts (Figure 5d), which are often striated. Gravel- to boulder sized clasts prevail within examined outcrops, while scarce boulders, not exceeding 1.5 m in height, can be observed on the crests of moraines. Outwash deposits in the Crvanj area have not been examined in detail due to a lack of outcrops.

Figure 4: (a) Geomorphological map of glacial landforms on the Crvanj Mountain. (b) Samples for ^{36}Cl cosmogenic nuclide dating were collected from the Jezero left and right lateral moraines. The samples ID`s along with the ages (ka) corrected for 40 mm ka^{-1} of erosion are presented in (b).

Figure 5: (a) Northern cirque below the highest peak of the Crvanj Mountain. (b) The sampled left and right lateral moraine with a lake in between and (c) glacial till exposed in a road cut (d) with striated sandstone clasts.

4.2 ^{36}Cl exposure ages

We collected a total of 20 glacial boulder samples from Velež and Crvanj mountains for ^{36}Cl cosmogenic nuclide dating purposes (Table 1). The sampled moraines belong to a group of the lowest moraines in both study areas and therefore mark the largest extent of palaeoglaciers that can be recognised on the basis of geomorphological evidence.

Denudation rates of carbonate rocks can be very high and are believed to increase with increasing MAP (Levenson et al., 2017; Ryb et al., 2014). The data from several carbonate terrains around the world show denudation rates of the order of 40 (± 20) mm ka^{-1} for areas with mean annual precipitation similar to that of Nevesinje (Levenson et al., 2017), while similar denudation rates (30-60 mm ka^{-1}) were recently measured also in the Mediterranean karst (SE France) (Thomas et al., 2018) independently of the precipitation amount. Thus, 40 mm ka^{-1} was used as the most representative erosion rate for the correction of all sample ages in this study.

Reported age uncertainties were given at the 1-sigma level (i.e., one standard deviation), which include both the analytical and production rate errors. The cosmogenic ages of boulders, and thus the age of moraines represent the beginning of glacier retreat i.e., change in the equilibrium conditions of the glacier mass, or stationing of the glacier on a terminal point.

4.2.1 Velež Mountain glacial chronology

Ten samples (Figure 6) were collected from the crest of one of the largest and best developed lateral-terminal moraine complexes on the Velež Mountain, located in the Budijevača Valley (Figures 2b, 7a and 7b). The sampled lateral-terminal moraine complex on Velež appears at 1300 m asl and after 2.7 km terminates at 980 m asl. It rises up to 130 m above the lake, which is located in between the moraine complex. The lithology of all boulders that were collected from this moraine complex is limestone, showing high concentrations of CaO (~55%) and very low K_2O and Cl (12.9-37.5 ppm), thus the main production mechanism (>95%) is spallation of Ca (Table 2, and supplementary Table S1).

Five boulders from the right lateral moraine of Budijevača Valley yielded ^{36}Cl ages of 14.1 ± 1.8 ka (BU16-01), 7.8 ± 0.9 ka (BU16-02), 10.9 ± 1.4 ka (BU16-03), 8.8 ± 1.1 ka (BU16-04) and 9.0 ± 1.0 ka (BU16-05). Boulders from the left lateral moraine gave ages of 15.7 ± 2.1 ka (BU16-06), 9.0 ± 1.0 ka (BU16-07), 6.3 ± 0.6 ka (BU16-08), 10.7 ± 1.3 ka (BU16-09) and 11.5 ± 1.4 ka (BU16-10) (Table 3).

Figure 6: Photos of the sampled boulders and their cosmogenic ages based on 40 mm ka-1 bedrock erosion rates on the Velež Mountain.

None of the measured ages is more than twice the standard deviation away from the mean of the surface exposure ages in a data set (Figure 8); therefore, no statistical outliers can be identified. However, the biggest and tallest two boulders (BU16-01, BU16-06) gave the oldest ages (14.1 ± 1.8 ka and 15.7 ± 2.1 ka, respectively) among the group of samples taken from this moraine complex, which indicates the exhumation caused by erosion of the moraines is likely to have a great influence on the age of samples. Assuming that inheritance is not a relevant process due to the position and characteristics of the moraine, then the oldest ages are likely to best estimate the true depositional age.

Therefore, the oldest two samples representing the best estimate of the age of the landform, give ages of 14.1 ± 1.8 ka (BU16-01) for the right lateral moraine and 15.7 ± 2.1 (BU16-06) for the left lateral moraine. These average ages of 14.9 ± 1.1 ka indicate the Oldest Dryas glaciation in the Velež Mountain.

Figure 7: (a) GoogleEarth image and (b) an aerial photo of the Budijevača lateral-terminal moraine complex. Sampling locations are marked with yellow points in (a), white dotted lines in (b) are moraine crests and blue arrowed line is the direction of the glacier flow. Note the height (130 m) of the moraine in (b).

Figure 8: Cosmogenic ^{36}Cl ages of the boulders from right- (RL) and left-lateral (LL) moraines of (a) Mt. Velež and (b) Mt. Crvanj. Upper panels show the individual sample ages with 1-sigma uncertainties, and the lower panels show the probably density functions (PDF) of the samples. Average age of the oldest two samples (indicated by thick black PDF curves) from both data sets were shown and assigned to the age of the landforms.

4.2.2 Crvanj Mountain glacial chronology

We also collected 10 samples (Figure 9) from a pair of lateral moraines on the western slopes of the Crvanj Mountain (Figure 4b). The sampled pair of lateral moraines stretches between 1350 and 1120 m asl and stands approximately 150 m above the lake area. Boulders are of different carbonate lithologies with prevailing seven dolostone and three limestone boulders. Dolostone samples

(samples from CR16-01 to CR16-06 and sample CR16-08) have lower concentrations of CaO (26.51-43.59%), but much higher concentrations of Cl (155.7-450.0 ppm) compared to limestone samples (samples CR16-07, 09 and 10) (Table 2), which make the low energy neutron capture reactions via ^{35}Cl an important part of the production mechanism of ^{36}Cl (about 40% of total ^{36}Cl production) (supplementary Table S1).

Six boulders were collected from the left lateral moraine that yield ages of 8.2 ± 1.6 ka (CR16-01), 9.2 ± 1.6 ka (CR16-02), 4.2 ± 1.0 ka (CR16-03), 8.4 ± 1.5 ka (CR16-04), 11.3 ± 2.5 ka (CR16-05) and 7.0 ± 1.2 ka (CR16-06) (Table 3). The samples taken from the right lateral moraine yielded slightly younger ages, i.e. 7.0 ± 0.7 ka (CR16-07), 8.5 ± 1.4 ka (CR16-08), 8.3 ± 1.0 ka (CR16-09) and 12.4 ± 1.6 ka (CR16-10).

Even in this data set the statistical outliers do not appear (Figure 8) and the largest and at the same time the tallest boulder (CR16-05) gave the oldest age. We applied the same approach as for Velež and chose the oldest sample from each lateral moraine as the most representative time of moraine emplacement. The oldest two samples yielded ages of 11.3 ± 2.5 ka (CR16-05) for the left lateral moraine and 12.4 ± 1.6 ka (CR16-10) for the right lateral moraine. The average age of two samples (11.9 ± 0.8 ka) indicate the Younger Dryas stadial event in the Crvanj Mountain.

Table 3: Cosmogenic ^{36}Cl inventories, production rates, ages of boulders considering different erosion rates and ages of glacial landforms using 40 mm ka^{-1} of erosion in the Velež and Crvanj mountains.

Figure 9: Photos of the sampled boulders and their cosmogenic ages on the Crvanj Mountain.

4.3 Palaeoglacier geometry

On the basis of additional field observations, we revised the palaeoglacier extent and ELA estimation for the Velež Mountain, which have been previously presented by Žebre and Stepišnik (2015a).

However, the reconstruction of glaciers and ELAs on the Crvanj Mountain is presented for the first time in this paper.

Geomorphological evidence indicates that during the maximum phase of glaciation the Velež glaciers covered an area of approximately 28.2 km^2 (Figure 10a). The north-facing glaciers, to some extent described already by Grund (1910, 1902), initiated in cirques, moved down the valleys and terminated in the karst depressions north of the mountain. Eight km-wide and up to 210-m-thick system of 7 interconnected valley glaciers, with a number of nunataks protruding above the ice (Figure 10b and 10c), was situated below the cirque complex. Only two valley glaciers on the north-facing slopes, the eastern- and westernmost ones, were disconnected from this uniform ice mass. The lengths of the north-facing glaciers were between 1.5 and 5 km. The westernmost valley glacier was the lowest glacier in the study area, which terminated at an altitude of 940 m asl. According to the calculations made by Profiler v.2 (Benn and Hulton, 2010) the thicknesses of the ice below the cirques were between 130 and 210 m. On the south-facing slopes below the highest peak Botin, only two small cirque glaciers existed, covering an overall area of less than 1 km^2.

Figure 10: (a) Palaeoglacier geometry with 50 m glacier contour lines, (b) glacier extent with longitudinal profiles used in glacier reconstruction, and (c) the modelled ice thickness of the Velež glaciers. Numbers in (b) indicate separate valley and cirque glaciers used for the ELA calculations. For the geomorphology and sampling locations refer to Figure 2a.

The Crvanj Mountain hosted a small ice field and two cirque glaciers with an overall area of 23.9 km^2 during the maximum phase of glaciation (Figure 11a). Four outlet glaciers, heading towards N, E and S directions (Figure 11b), drained the ice field. The outlet glaciers were between 2 and 3.5 km long and up to 1.5 km wide. They ended at elevations between 900 and 1200 m. The northern outlet glacier might have reached lower altitudes, but owing to landmines in that area we were not able to make the geomorphological investigation. The greatest ice thickness was calculated on the plateau area, reaching approximately 200 m (Figure 11c). The two cirque glaciers formed on the northwest-facing slopes and covered an area of 1.4 km^2.

Figure 11: (a) Palaeoglacier geometry with 50 m glacier contour lines, (b) glacier extent with longitudinal profiles used in glacier reconstruction, and (c) the modelled ice thickness of the Crvanj ice field. Numbers in (b) indicate separate outlet and cirque glaciers used for the ELA calculations. For the geomorphology and sampling locations refer to Figure 4a.

4.4 Palaeo-equilibrium line altitudes

The mean ELA of palaeoglaciers on the Velež Mountain was calculated to 1388 m (σ=186) using the BR ratio of 1.9 ± 0.81 (Rea, 2009) (Table 4). While the mean ELA of the north-facing valley glaciers was 1292 m, on the south-facing slopes where only two cirque glaciers formed, the ELA was 434 m higher. Applying the same BR ratio, the mean palaeo-ELA on the Crvanj Mountain was found at 1541 m (σ=46) (Table 4). The ELA of the ice field with pertaining outlet glaciers was calculated to 1476 m, while the ELA of cirque glaciers was 104 m higher. Northeast oriented glaciers had in general lower ELAs, which is reasonable owing to differences in solar radiation and temperatures between north and south facing slopes. However, the NE-SW difference in ELA is approximately 8-times higher on Velež (NE-SW ELA difference=434 m) compared to Crvanj (NE-SW ELA difference=52 m), which can be explained by different morpho-climatological conditions. The morphology of the Velež Mountain with steep north-facing slopes allowed the formation of valley glaciers, where the accumulation was likely dominated by windblown deposition and avalanches. These two mechanisms were not as pronounced on the Crvanj Mountain due to the ice field type glaciation and consequently the local ELA differences were relatively small.

To crosscheck the ELA calculations using the AABR method, we also applied the AAR method using the ratio of 0.6 (Benn and Evans, 1998; Nesje and Dahl, 2000; Porter, 1977), which is the most widely accepted, but not necessarily one of the most accurate methods (and ratios) for the palaeo-ELA calculations (e.g. Kern and László, 2010). The results differ insignificantly, since the mean ELA for the Velež Mountain is calculated to 1392 m and for the Crvanj Mountain to 1596 m. Taking into account the ELAs calculated with the AABR method, the Velež Mountain ELA is 153 m lower than the ELA on the Crvanj Mountain and 204 m lower in the case of AAR method.

Table 4: The estimated palaeoELAs (in metres) for all reconstructed palaeoglaciers on the Velež and Crvanj mountains (see Figure 10b and 11b for the location of each glacier). The applied method is area altitude balance ratio (AABR) with a ratio of 1.9 ± 0.81, which is representative for mid-latitude maritime glaciers according to empirically derived results by Rea (2009).

4.5 Degree-day model outputs

Because snowmelt equals snow accumulation at the ELA under equilibrium conditions, our melt predictions using a simple degree-day model show the amount of accumulation required to sustain the reconstructed glaciers (Table 5). Hypothesizing the existence of glaciers with the reconstructed ELAs on the Velež and Crvanj mountains in the recent climate, the annual accumulation required to offset melting would need to be 9304 and 8295 mm of water equivalent, respectively. Further hypothesizing the accumulation on palaeoglaciers was similar to the modern MAP at Nevesinje and the modern annual temperature range was same as today, then the temperature depression between 9 and 10 °C for Velež and between 8 and 9 °C for Crvanj is required to sustain the palaeoglaciers with reconstructed ELAs. This is a very rough estimation because annual accumulation on glacier approximates winter and not annual precipitation, excluding local inputs from avalanching and wind-blown snow. The Velež glaciers on the north-facing slopes were likely influenced by the aforementioned local inputs, which makes the melt predictions further overestimated. If assuming higher annual temperature range because of possibly more continental climate during glacial stages, even higher accumulation is required to balance melting.

Table 5: The degree-day model outputs for the Velež and Crvanj palaeoglaciers based on the reconstructed mean ELAs for each mountain (ELA Velež =1388 m, ELA Crvanj=1541 m) and modern climate data from Nevesinje (891 m asl) (mean annual temperature=8.6 °C, mean annual temperature range=18.9 °C, MAP=1795 mm) for the period 1961-1990 (Data courtesy Federal Hydrometeorological Institute, Sarajevo).

5. Discussion

5.1 ^{36}Cl cosmogenic nuclide dating uncertainties

Apart from analytical and production rate uncertainties, geological uncertainties also have to be considered when interpreting exposure ages. The latter often overshadow the first two and are principally subject to prior-exposure (inheritance), reworking and exhumation of boulders on moraines and erosion rates. Influence of vegetation and snow cover as well as tectonic movements and other geomorphological processes can also play an important role in the interpretation of exposure ages. Below, we discuss in detail the most relevant uncertainties for our study area.

5.1.1 Moraine degradation and exhumation of boulders

Although moraines in karst areas dating to Last Glaciation but also to older Pleistocene glaciations (e.g. Hughes et al., 2011, 2010) are believed to be well-preserved because of the absence or minimal fluvial reworking, they nevertheless degrade due to karst denudation and the topography is getting smoother over time. Moraine crest lowering is more pronounced in its early stage, within the first few thousands of years after the moraine deposition, when majority of large boulders are exhumed (Putkonen and Swanson, 2003). However, there is a substantial difference in the intensity of degradation among different types of moraines. Moraines with broad and flat crests, such as hummocky moraines, will degrade less than for example lateral moraines with sharp crests and steep slopes (Applegate et al., 2010; Putkonen and Swanson, 2003). In our case, the dated lateral moraines exhibit smooth crest morphology and few large boulders are present on their crests. This indicates that their post-glacial evolution has been influenced by a relatively marked degradation. Several studies highlighted the problems related to the degradation of moraines and consequently the boulder exhumation, resulting in cosmogenic ages that are inconsistent with the stratigraphic order of moraines (e.g. Hughes et al., 2018; Palacios et al., 2019; Roy et al., 2017; Schaefer et al., 2008). The influence of exhumation is particularly evident when trying to date moraine boulders older than Late Pleistocene (Hughes et al., 2018). According to the moraine degradation model (Applegate et al., 2010; Putkonen and Swanson, 2003), our dated moraines are supposed to degrade in the order of ~20 m since Lateglacial. Our exposure ages likely reflect a range of ages when the active degradation of the surface took place, and therefore in high precipitation regions we prefer to consider the oldest age within a group as the best estimation of the true depositional age. Without erosion corrections, these figures are 10.5 ± 0.9 ka for the Velež, and 15.6 ± 2.3 ka for the Crvanj mountains. The oldest age in both cases is represented by the tallest and overall largest boulder within the group of samples, which further demonstrates that the exhumation of boulders is one of the main geological uncertainties to be considered while interpreting exposure ages in similar environments. This is in accordance with the analysis of a large dataset of glacial boulders, confirming that tall boulders, most likely with minimum post-glacial shielding, yield higher quality exposure ages (Heyman et al., 2016).

5.1.2 Inheritance

The inheritance is the initial nuclide concentration that is already in the rock before the beginning of the final exposure (Ivy-Ochs and Schaller, 2009). Therefore, one of the most important assumptions of the cosmogenic surface exposure dating is that the inheritance is negligible or could be determined (Schmidt et al., 2011). Several studies related to moraine boulder inheritance indicate that the glacier scouring of the bedrock is a very efficient mechanism in removing the pre-existing cosmogenic component (e.g. Applegate et al., 2012, 2010; Davis et al., 1999; Dortch et al., 2013; Hallet and Putkonen, 1994; Heyman et al., 2011). Several studies carried out on the moraine boulders in the Taurus Mountain Range of Turkey since 2008 were compiled by Çiner et al. (2017) (their figure 11), who concluded that out of 183 limestone samples, only 6 boulders (3.3%) were outliers attributed to inheritance; the authors hence assumed this figure close to negligible. Although few cases where inheritance is reported from moraine boulders (e.g. Dortch et al., 2013), we believe that given the high erosion rates of the boulders, mainly due to high precipitation in our study area, any inheritance related to prior exposure would have been zeroed. We therefore neglected inheritance as a factor in our age calculations.

5.1.3 Karst denudation rate

In karst terrains, both chemical denudation and mechanical erosion processes operate and the total karst denudation rate is the sum of both processes (Ford and Williams, 2007). Chemical denudation rates established within karst vary due to runoff of precipitates, temperature and partial pressure of carbon dioxide in surrounding atmospheres (Gunn, 2004). The chemical denudation rates are regularly calculated through monitoring of dissolved mater content in karst springs (Ford and Williams, 2007; Veress, 2009). Those values are non-relevant for determining karst denudation rates on exposed carbonate bedrock (e.g. karren, glacial boulders), since there is no effect of enhanced dissolution in epikarst subsoil environments. Relevant methods for exposed carbonate surfaces include continual in-situ measurements by means of micro-erosion meter (Cucchi et al., 1995; Furlani et al., 2009; Veress, 2009). However, these are only relevant for the recent climatic conditions. Results from the northern part of the Dinaric Mountains highlight significant differences, which are the result of lithological control coupled with climatic setting (Furlani et al., 2009). There are differences between dolomites and calcarenites (~10 mm ka^{-1}) and micritic limestones (~40 mm ka^{-1}) (Cucchi et al., 1995; Furlani et al., 2009). Substantial differentiations in denudation rates are a consequence of climatic setting and even small climatic variations (Mediterranean and sub-alpine climate) can yield double denudation rates (Furlani et al., 2009). There is a shortage of detail monitoring of micro-erosion meter denudation rates in high Dinaric environments. Available data from the nearby Julian Alps on micritic limestones show average denudation rate of ~40 mm ka^{-1} with considerable increases (up to ~100 mm ka^{-1}) within depressions with thicker snow cover (Kunaver, 1979). Those results correspond, in the order of magnitude, with other values obtained with the same method in similar environments (Forti, 1984; Pulina, 1974). Furthermore, recently applied measurements of ^{36}Cl concentrations for establishing denudation rates in different karst terrains around the world (Levenson et al., 2017) and in SE France (Thomas et al., 2018) show denudation rates in the order of 40±20 mm ka^{-1}. According to Thomas et al. (2018) there is no clear connection between climatic spatial gradients and denudation rates; the latter are rather influenced by the surface inclination. On the Velež and Crvanj mountains we deducted denudation rate at 40 mm ka^{-1} even though previous researchers in the Balkans did not apply denudation corrections in cosmogenic dating (Pope et al., 2015) or used rather low rates as 5 mm ka^{-1} (e.g. Gromig et al., 2018; Styllas et al., 2018) (Table 6).

Table 6: A list of different dating methods applied to glacial landforms in the Balkan Peninsula. Note that calculations of ^{36}Cl cosmogenic exposure ages from Mount Chelmos and Mount Olympus are based on the production rates from Stone et al. (1996) and Schimmelpfennig et al. (2011), respectively. For comparison, two boulder-ages from Mount Chelmos (CH10 (11.03 ± 0.9 ka), CH11 (8.76 ± 0.70 ka)) (Pope et al., 2015) and two boulder-ages from Mount Olympus (TZ03 (12.44 ± 1.07 ka), MK12 (12.37 ± 1.07 ka)) (Styllas et al., 2018) were recalculated using the production rates of Marrero et al. (2016b). The two ages from Mount Olympus were also corrected for snow and erosion, using the same values as in the paper of Styllas et al. (2018). The recalculated ages are 13-14% younger for Mount Chelmos and 23-24% younger for Mount Olympus with respect to the

published ages. ^{14}C ages from Snežnik were recalculated according to the IntCal13 calibration (Reimer et al., 2013). Recalculated ages are marked with asterisk.

5.1.4 Shielding

Post-depositional processes such as shielding by snow, vegetation, sediment and soil can reduce nuclide concentrations on boulders, resulting in underestimation of landform ages. Although most studies on moraines indicate that snow cover is a second-order process (~10% or less) (Schildgen et al., 2005), a relatively thick snow cover might have been present in our study area because of high precipitation potentials. As Velež and Crvanj mountains are geographically close, we assumed identical snow shielding acting on the sampled boulders. We estimated a snowpack of 25, 100, 100, 100, 50, 25 cm of snow on Nov, Dec, Jan, Feb, Mar and Apr on top of boulders and calculated that the total effect of snow correction of our samples to be around 4.9% (i.e. snow correction make the ages 4.9% older). Doubling the snowpack data would add another 5.4% in average.

Another shielding factor might be related to vegetation. The presence of forest increases boulder instability in matrix-rich moraines. Trees, soil and leaf litter decrease the cosmic rays reaching the rock by only a few percent (Kubik et al., 1998). However, as trees grow or fall even large boulders can be toppled (cf. Cerling and Craig, 1994). Assuming that dense trees covered the study areas, as we see today, one would need to consider the shielding due to the vegetation during the exposure time of the boulders.

5.2 Interpretation of ^{36}Cl cosmogenic nuclide dating results from the Velež and Crvanj mountains

After taking into account all relevant cosmogenic nuclide dating uncertainties for both study areas, the most probable age of the dated moraines is Lateglacial, spanning from Oldest Dryas for Velež (14.9 ± 1.1 ka) to Younger Dryas for Crvanj (11.9 ± 0.9 ka). These are still to be considered as minimum ages. To better understand a relevance of the obtained ages, these have been put into the geomorphological and climate context.

According to the geomorphological evidence, the dated moraines mark the largest extent of glaciers in both study areas. These have been estimated to approximately 28 km^2 for Velež and 24 km^2 for Crvanj using field evidence combined with the glacier flow-line model. The ELAs have been calculated to 1388 m for Velež and 1541 m for Crvanj by applying the AABR method. Glaciers of similar size with so low ELAs during Younger or Oldest Dryas have not been reported until now for the Balkan Peninsula; they have been recorded only in the form of cirque glaciers (e.g. Gromig et al., 2018; Hughes et al., 2011, 2010; Kuhlemann et al., 2009; Pope et al., 2015; Ribolini et al., 2011, 2018; Styllas et al., 2018). Smaller moraines that are present at higher altitudes compared to the dated moraines in our study area (Figures 2 and 4) are in better agreement with the above-cited Lateglacial moraines and their corresponding ELAs. We would also assume that the dated moraines on both mountains pertain to the same glacial period, because they mark the largest extent of glaciers in their respective areas, which were of similar size. These local differences in ages might result from different denudation rates between dolostone and limestone lithologies, the first being dominant in the Crvanj area and the last in the Velež area (supplementary Table S1). Moreover, it would be unrealistic to assume that all LGM moraines would have been washed away or entirely degraded, also because moraines in karst environments generally tend to be better preserved compared to moraines in the typical alpine environments, where slope and fluvial processes are much more intense. Thus, it is difficult to justify the Lateglacial age of the reconstructed glaciers on Velež and Crvanj from the geomorphological context.

Temperature depressions between 8 and 10 °C are required to sustain the reconstructed glaciers with pertaining ELAs according to the degree-day model simulations (Table 5) if considering the accumulation on palaeoglaciers was similar or less than the modern MAP. This is in accordance with the reconstructed LGM temperature drop inferred from pollen for northern Greece and central Italy

(Peyron et al., 1998) as well as from ELAs for the Central Dinaric Mountains (Kuhlemann et al., 2008). Though some of the reported temperature depressions for the Oldest and Younger Dryas in the Balkan Peninsula are even more pronounced from those at LGM, like for example pollen inferred 10-14°C drop in temperature for Oldest Dryas and around 10°C for Younger Dryas in the Lake Maliq in Albania (Bordon et al., 2009). This is highly unlikely, also because no such drop in temperature has been confirmed elsewhere in the Mediterranean, while the Younger Dryas temperature depression inferred from the distribution of relict rock glaciers in the SE European Alps has been estimated to 3-4°C (Frauenfelder et al., 2001). MAAT depression of 4°C for Velež and Crvanj would result in 4807-5601 mm of water equivalent (w.e.) of annual melt at ELA, which is unrealistic. However, a drop in temperature of 5-6°C, which would result in 4064-4807 mm w.e. of snow accumulation required to balance melting at the ELAs of the reconstructed glaciers (Table 5), might be reasonable. The modern glaciers in the Pacific Coast Range with maritime climate (e.g. South Cascade glacier) having very high winter mass balance (~2000-4000 mm w.e.) and MAAT at the ELA close to or even above 0°C (Krimmel, 2001; Ohmura et al., 1992; WGMS, 2016), are good modern analogues to our reconstructed glaciers. Nevertheless, having glaciers in the Velež and Crvanj mountains with similar winter mass balance as today in the Pacific Coast Range would require substantially higher MAP than today.

The boulder ages reflect complex exhumation and denudation history, which at this point do not allow obtaining more precise moraine chronologies for the Velež and Crvanj mountains. Future work is needed to better understand the exhumation and denudation processes and their influence on the cosmogenic exposure dating approach in a karst landscape like the Dinaric Mountains. Both study areas as well as the entire country of Bosnia and Herzegovina lack any previous knowledge on the timing of glaciations, which makes the correlation of the age data very difficult. This is however a new dataset and presents a relevant contribution towards better understanding of the glacial chronologies in the Dinaric Mountains.

5.3 Glacial chronologies in the Balkans and elsewhere in the Mediterranean

Although the mountains in the Dinarides and elsewhere in the Balkan Peninsula exhibit large areas of glacially modified landscape, they are still poorly represented by age data, which makes a robust comparison with the Velež and Crvanj data rather difficult. The closest area with established glacial chronologies are mountains of Montenegro (Hughes et al., 2011, 2010) (Table 6, Figure 12), where Younger Dryas has been recorded only in the form of cirque glaciers, having ELA at 1465 m on the coastal Orjen Mountain. More distant Balkan areas with existent glacial chronologies, but still relevant for comparison with the Velež and Crvanj mountains, are the Šar Planina and Galičica mountains in the Former Yugoslav Republic of Macedonia (FYROM), and Mount Chelmos and Mount Olympus in Greece. The glacier advance in the course of Younger Dryas on the aforementioned mountains is also reported as cirque glaciations, with ELAs of 2300-2400 m on the Šar Planina Mountains (Kuhlemann et al., 2009), 2130 m on the Galičica Mountain (Gromig et al., 2018; Ribolini et al., 2011) and 2114 m on Mount Chelmos (Pope et al., 2015). ELA for Mount Olympus was estimated to 2200-2600 m for the LG1-3 Lateglacial phase, which corresponds to Younger Dryas period after the recalculation of the ages using the same production rates as those applied to our moraine boulders (Table 6). All the above-mentioned published ELAs have been recalculated (supplementary Table S2) to the same ELA method, and hence they are entirely comparable. The Younger Dryas advances in other Mediterranean mountains have been confirmed in the High Atlas (Hughes et al., 2018), Taurus Mountains (Sarıkaya and Çiner, 2017), Iberian Peninsula (Palacios et al., 2016) and Maritime Alps (Federici et al., 2017). While the Younger Dryas glaciers where restricted to cirque areas in the High Atlas, Taurus Mountains and majority of Iberia, they reached the size of short valley glaciers in the Central Pyrenees (García-Ruiz et al., 2016) and Maritime Alps (Federici et al., 2017). Nevertheless, the magnitude of glaciation on the Crvanj Mountain is outstanding when compared with other Younger Dryas glaciers in the Balkan Peninsula and elsewhere in the Mediterranean.

Glaciers in the Balkan Peninsula dated to the Oldest Dryas were as well small in extent, with ELAs between 2200 and 2350 m on the Šar Planina Mountains (Kuhlemann et al., 2009), 2250 m on Mount Pelister (Ribolini et al., 2018), and at 2000 m on the Galičica Mountain (Ribolini et al., 2011). The Oldest Dryas advance on Orjen has not been recognized by Hughes et al. (2010), but from the minimum ages provided by U-series dating that show early Holocene ages (Table 6), these can be interpreted in terms of Younger Dryas (as interpreted by Hughes et al. (2010) or Oldest Dryas glaciation with ELA at 1465 m. The calculated ELA for Velež is extremely low (1388 m) when compared with the aforementioned ELAs, even after recalculating all the published ELAs (supplementary Table S2). The Oldest Dryas advance in the Eastern Mediterranean has been recognized on Dedegöl Mountains, where moraines were dated to between 16.4 ± 0.7 ka and 12.0 ± 1.0 ka (Köse et al., 2018), while Mt. Akdağ (14–17 ka), Mt. Sandıras (13–20 ka) and Erciyes Volcano (14–17.5 ka) show similar Lateglacial chronologies (Sarıkaya and Çiner, 2017). Similar ages have also been reported from other Mediterranean mountains (Federici et al., 2011; Palacios et al., 2016).

Several marine and continental proxies from the Adriatic Sea (e.g. Combourieu-Nebout et al., 2013; Favaretto et al., 2008; Rossignol-Strick, 1995) and Balkan region (e.g. Aufgebauer et al., 2012; Bordon et al., 2009; Vogel et al., 2010), respectively, indicate that the Younger Dryas and Oldest Dryas were cold events. However, the relative amount and source of moisture is still a matter of debate. While some argue for cold and dry glacier advance during Lateglacial (Ribolini et al., 2018; Styllas et al., 2018), others suggest the climate at that time was humid (Hughes et al., 2011, 2010; Pope et al., 2015). Thus, understanding palaeo-precipitation sources is of major importance for understanding the zonal partitioning of glacier behaviour in the Balkan Peninsula. Pope et al. (2015) suggested that the moisture bearing atmospheric systems delivering winter precipitation in the west central Balkan Peninsula were different from those influencing southern Greece, the first being influenced by cyclogenesis in the northern Adriatic (Hughes et al., 2010) whereas the latter likely received winter precipitation from a western or southern source. The position of the polar jet stream is a key factor in controlling precipitation pattern in the Mediterranean as well in the Balkan Peninsula. A general idea of the southern shift of the polar jet stream during LGM, which brought a southward shift of the North Atlantic storm tracks to about 40°N (Hofer et al., 2012; Laîné et al., 2009), is well supported by atmospheric circulation models, but how the local synoptic circulation was acting in the Mediterranean area is still debatable. Recent findings suggest a southerly moisture transport across the southern Mediterranean and then approaching the Alps from southward direction (Luetscher et al., 2015), which is consistent with the idea of the moisture bearing atmospheric systems delivering high precipitation amount, mainly during spring and autumn, to the west central Balkans. While this precipitation pattern was suggested for the LGM, it might hold true also for the Younger Dryas and Oldest Dryas events, likely for a shorter period and not as intense as during LGM, but still supporting the idea, to some extent, of a relatively large ice masses on Velež and Crvanj during that time. Moreover, the Adriatic coast during LGM and Oldest Dryas was much further south with respect to the Younger Dryas (Figure 13a). This suggests that during Younger Dryas greater amount of moisture was available in the low-level jet, which is the main source for the orographic precipitation in the Dinaric Mountains. Even if temperatures at that time were not as low as during LGM, the available moisture might have been higher.

It is also worth noting the role of the orographic barrier of the Dinaric Mountains in capturing (today, and most likely also in the past) most of the humidity from the Adriatic Sea air masses, leaving the inland part of the Balkans relatively dry (Hughes et al., 2010). This effect is reflected in a strong west-east gradient in ELA, which was suggested for the last cold stage glaciers in Montenegro and Greece by Hughes et al. (2011, 2010, 2006). A rise in ELA of 100 m for every 15 km inland was calculated for the Montenegrin glaciers by the same authors. Similar pattern of the inland ELA rise can be recognized also for the Younger Dryas and Oldest Dryas glaciers in the part of the Balkan Peninsula facing the Adriatic Sea (Figure 12b and 12c), which suggests the west-east gradient in ELA was characteristic throughout the Late Pleistocene. We estimated a rise in the ELA of 94 m during the Younger Dryas and 77 m for the Oldest Dryas for every 15 km inland. Very low ELAs in our study areas seem to be shifted further inland (Figures 12b and 12c). This pattern might be related to the fact that the first orographic barriers in the Neretva catchment are located more than 50 km from the Adriatic coast and that specific topoclimatic conditions controlled the ELA depression. This might be the reason why the Oldest Dryas ELA on Velež would have been lower than the ELA on Orjen, since the modern MAP on Orjen is more than twice as high as on Velež.

On some of the massifs in the Iberian Peninsula the glaciers between 17.5 and 14.5 ka deposited moraines that are spatially close to the LGM moraines (Palacios et al., 2016), which seem to be the case also for some of the Turkish Mountains (e.g. Sarıkaya et al., 2014, 2009). However, in the Velež and Crvanj mountains we did not find any geomorphological evidence that would imply larger glacier extent, but closely spaced to the one we dated. It might be true that these large lateral-terminal moraine complexes are products of several glacial stages, as has been already suggested by Žebre and Stepišnik (2015a), which would imply that the glaciers on Velež and Crvanj reached their Late Pleistocene maximum extents well after the global LGM. This is in agreement to some extent with the ages obtained in the Šar Planina Mountain (Kuhlemann et al., 2009) and Montenegrin Mountains (Hughes et al., 2011, 2010), where the moraines indicative for the local LGM were dated to the period following the global LGM. The cosmogenic ages from terminal moraines in the Rila Mountain (Kuhlemann et al., 2013) indicate that the local LGM extent occurred in two phases, i.e. prior and after the global LGM. In contrast with the records in FYROM and Montenegro, the Late Pleistocene glacier maximum on Mount Chelmos was dated to 40-30 ka and thus predates the global LGM (Pope et al., 2015) (Table 6). While a relatively large LGM glaciation is reported from the Rila Mountains (Kuhlemann et al., 2013), with 29 valley glaciers covering an area of 430 km^2 and having ELAs between 2150 and 2290 m, from the Šar Planina Mountains with valley glaciers several km long having ELAs between 1900 and 2300 m (Kuhlemann et al., 2009), and from Montenegro with several smaller valley and cirque glaciers with a total area of 56 km^2 and ELAs between 1456 and 1952 m (Hughes et al., 2011, 2010), much smaller glaciation in the form of cirque and small valley glaciers has been recognized on Mount Chelmos (Pope et al., 2015), covering less than 5 km^2 in total, with the mean ELA of 1986 m.

The evidence for older, Middle Pleistocene glaciations, when the glaciers in Montenegro, Greece and Croatia would have reached their maximum extent (Table 6), is missing in our study areas. It is obvious from several studies that the timing of glaciations not only varied across the Mediterranean mountains (Hughes and Woodward, 2017), but also on a regional scale across the Balkan Peninsula. Although our findings seem to match to a considerable extent to the results from the Balkan Peninsula and some other Mediterranean mountains, more research is needed in Bosnia and Herzegovina and in the Dinaric Mountains in general to better understand the climatic controls on glaciations and the asynchrony of glacier fluctuations amongst different areas. The focus of future research should be on moraine build-up during several glacial stages and possible age conflicts between different dating methods, as recently pointed out also by Rodríguez-Rodríguez et al. (2018).

Figure 12: (a) All locations in the Balkan Peninsula where moraines/outwash have been dated so far. Base layer of mountain belts is from https://ilias.unibe.ch/goto.php?target=file_1049915, based on the mountain definition by Kapos et al. (2000). Bathymetric data is from the European Marine Observation and Data Network (http://www.emodnet.eu/), while the sea level data for LGM, Oldest Dryas and Younger Dryas is from Lambeck et al. (2011). ELA as a function of the distance from the Adriatic Sea for (b) Younger Dryas and (b) Oldest Dryas. Only areas with absolute age data are taken into account.

6. Conclusions

The Velež and Crvanj mountains in the Dinaric mountain karst in Bosnia and Herzegovina were extensively glaciated during the Late Pleistocene despite their low altitude (<2000 m asl). During the most extensive glaciation total glacier area was 28.2 km^2 on the Velež Mountain and 23.9 km^2 on the Crvanj Mountain. High karst plateaux were covered by ice fields reaching thicknesses up to 200 m. Valley and outlet glaciers reached as far down as ~900 m asl, where large lateral-terminal moraine complexes were deposited. Twenty glacial boulders from the largest two moraine complexes were sampled and dated using cosmogenic ^{36}Cl surface exposure dating. The obtained ages correspond to the Lateglacial advances, namely the Younger Dryas on Crvanj and the Oldest Dryas on Velež, although the age difference in the maximum glacier extent between the two mountains might result from different denudation rates. However, the magnitude of glaciation along with the equilibrium line altitude and degree day model simulations are exceptional in terms of the Lateglacial evidence in the Balkan Peninsula. A possible explanation for that might be an increased moisture supply during Lateglacial due to larger extent of the Adriatic Sea with respect to LGM along with specific topoclimatic conditions controlling the ELA depression. This paper presents the first attempt to date moraines in the Dinaric mountain karst using cosmogenic ^{36}Cl surface exposure dating and is thus an important contribution towards a better understanding of the timing of glaciations in the Dinaric Mountains. However, dating moraines in this type of karst with high precipitation amounts remains problematic owing mainly to unknown denudation rates and the magnitude of moraine degradation.

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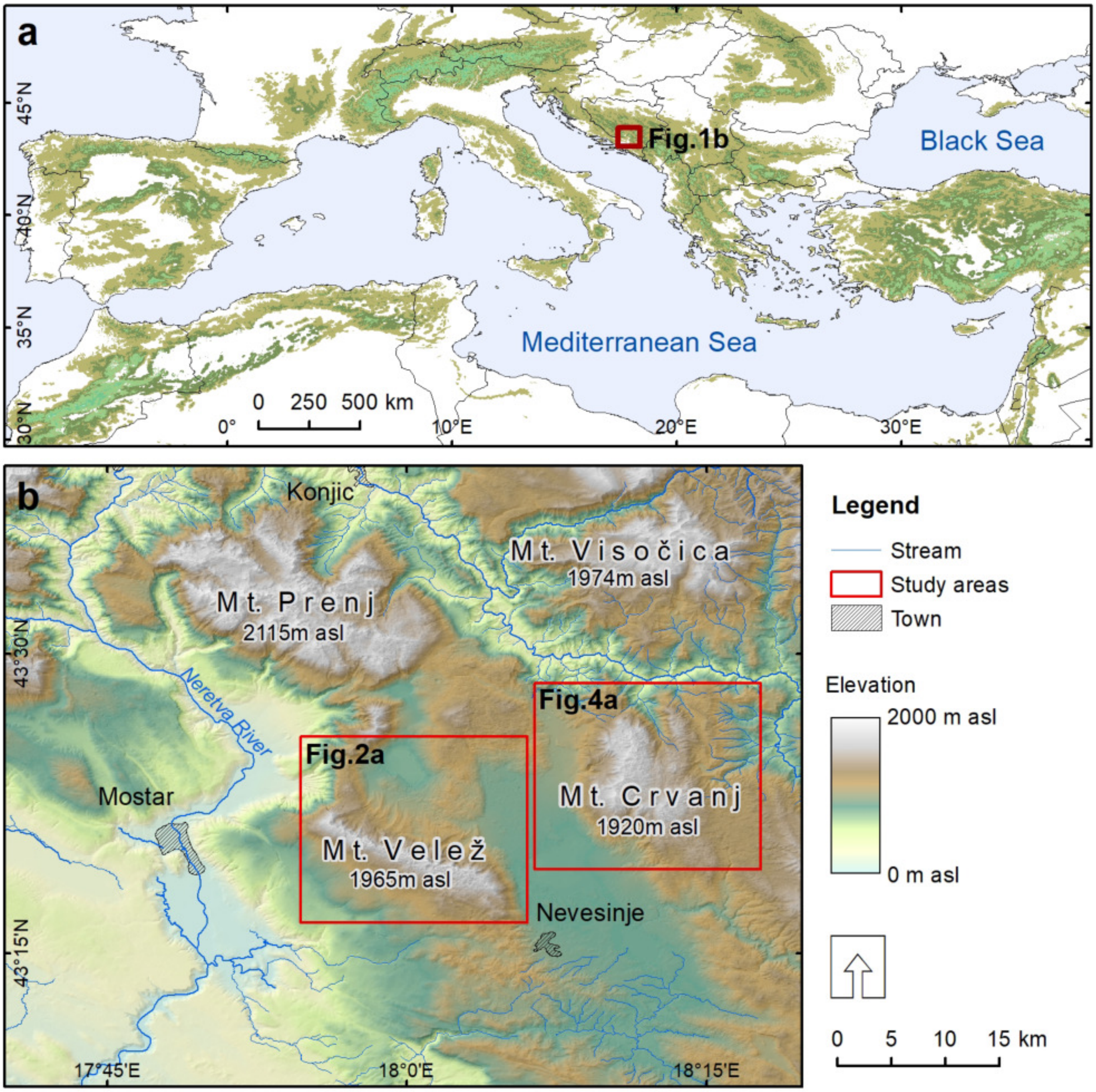
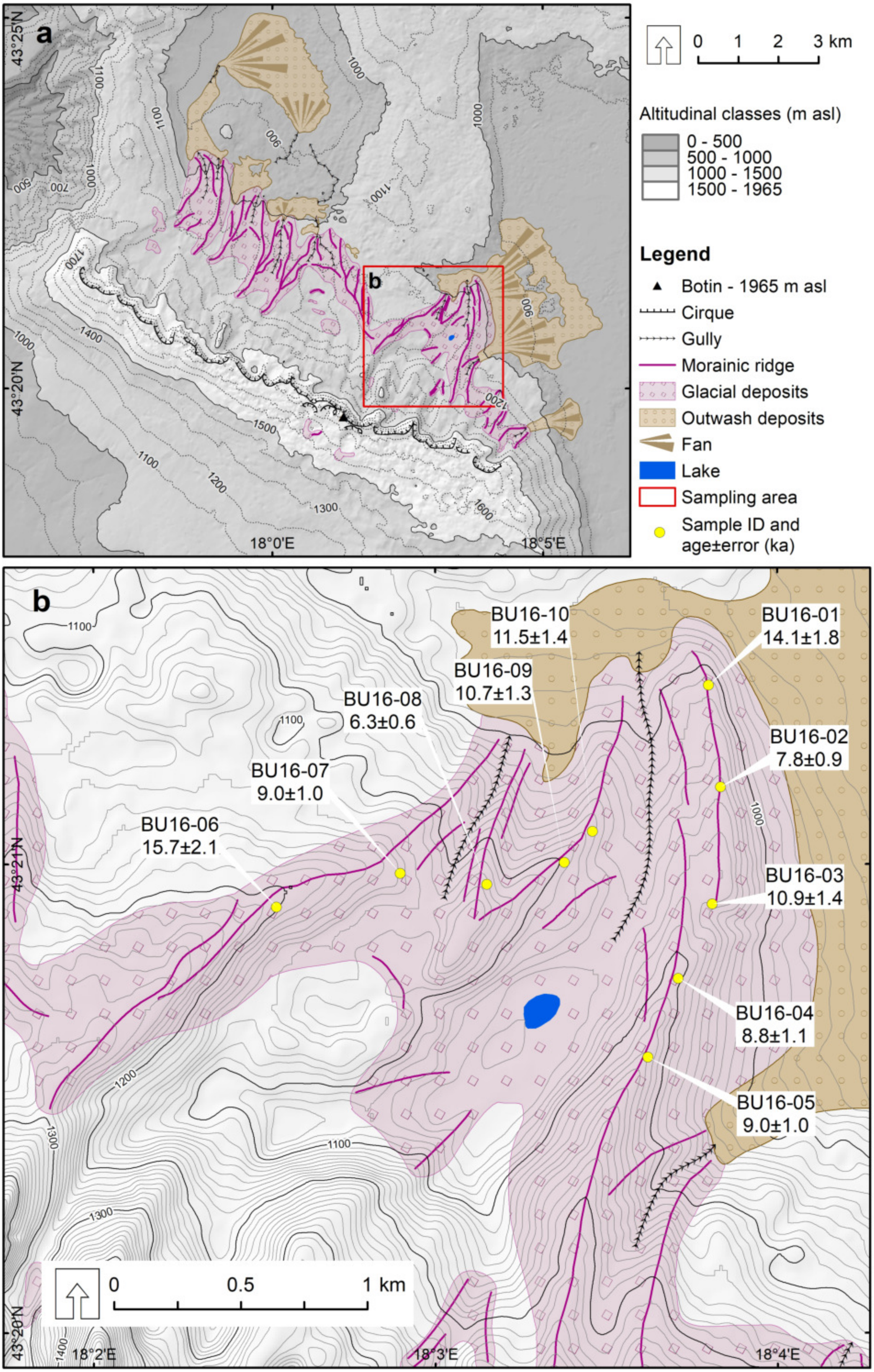
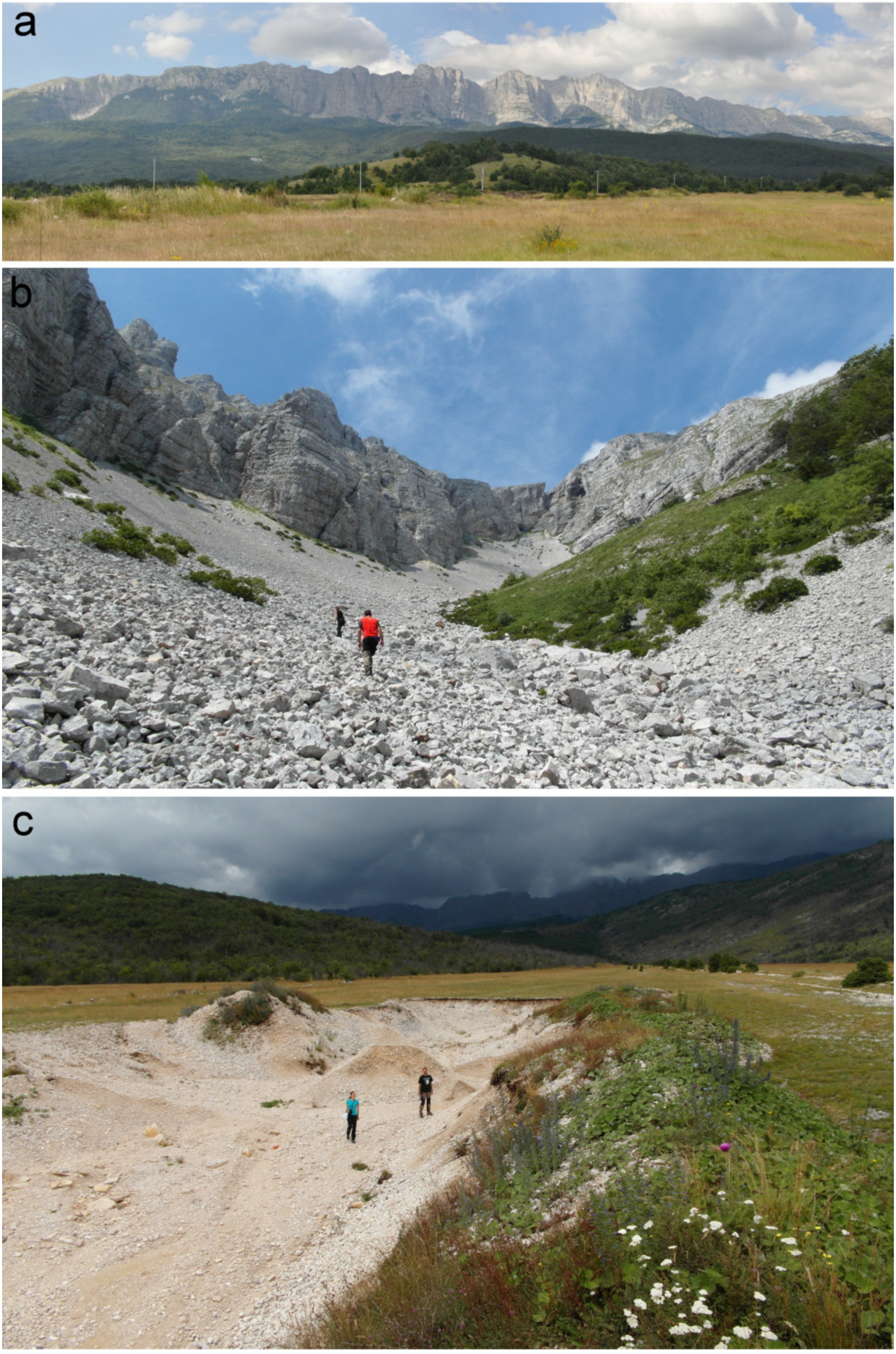
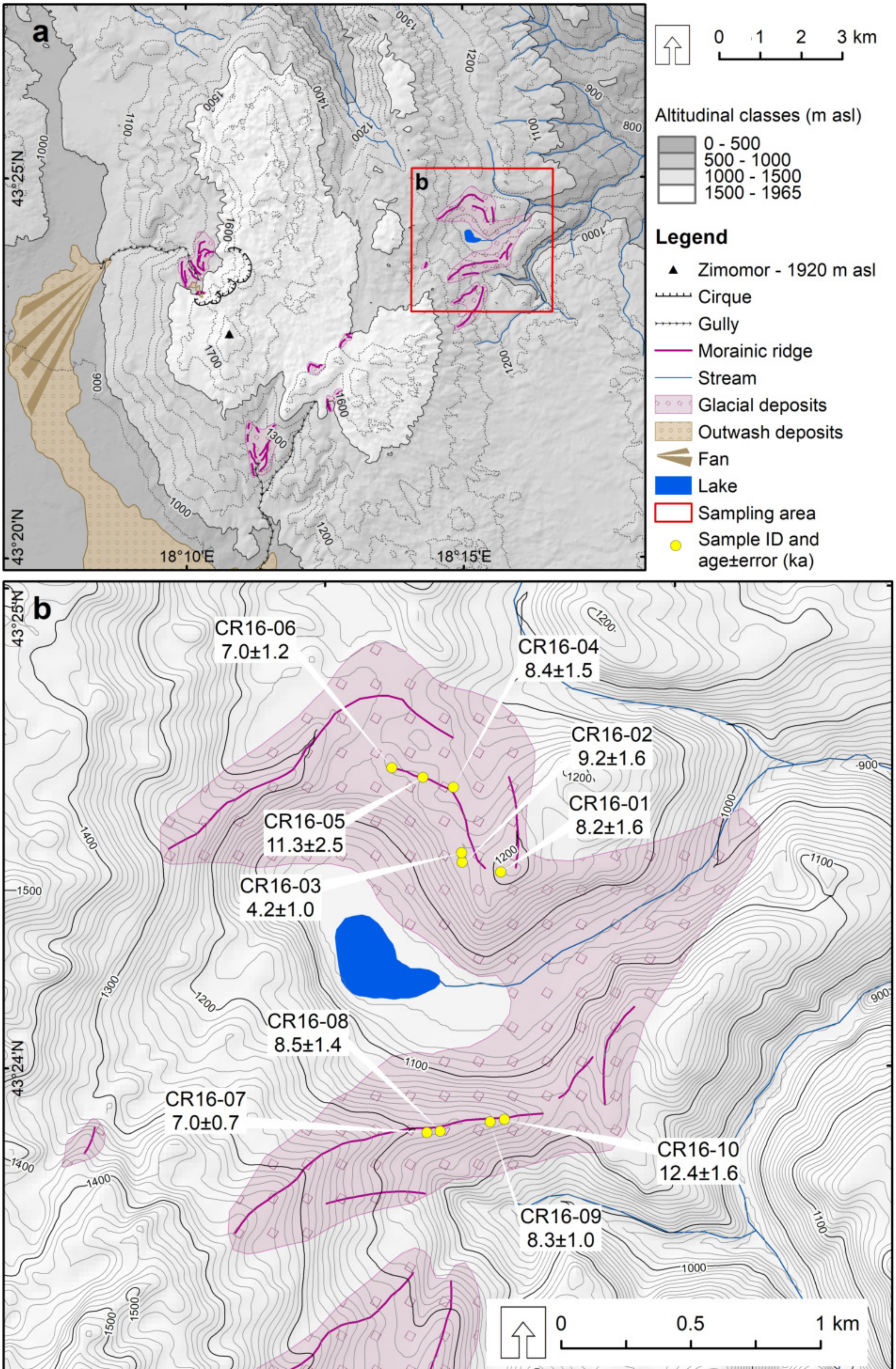
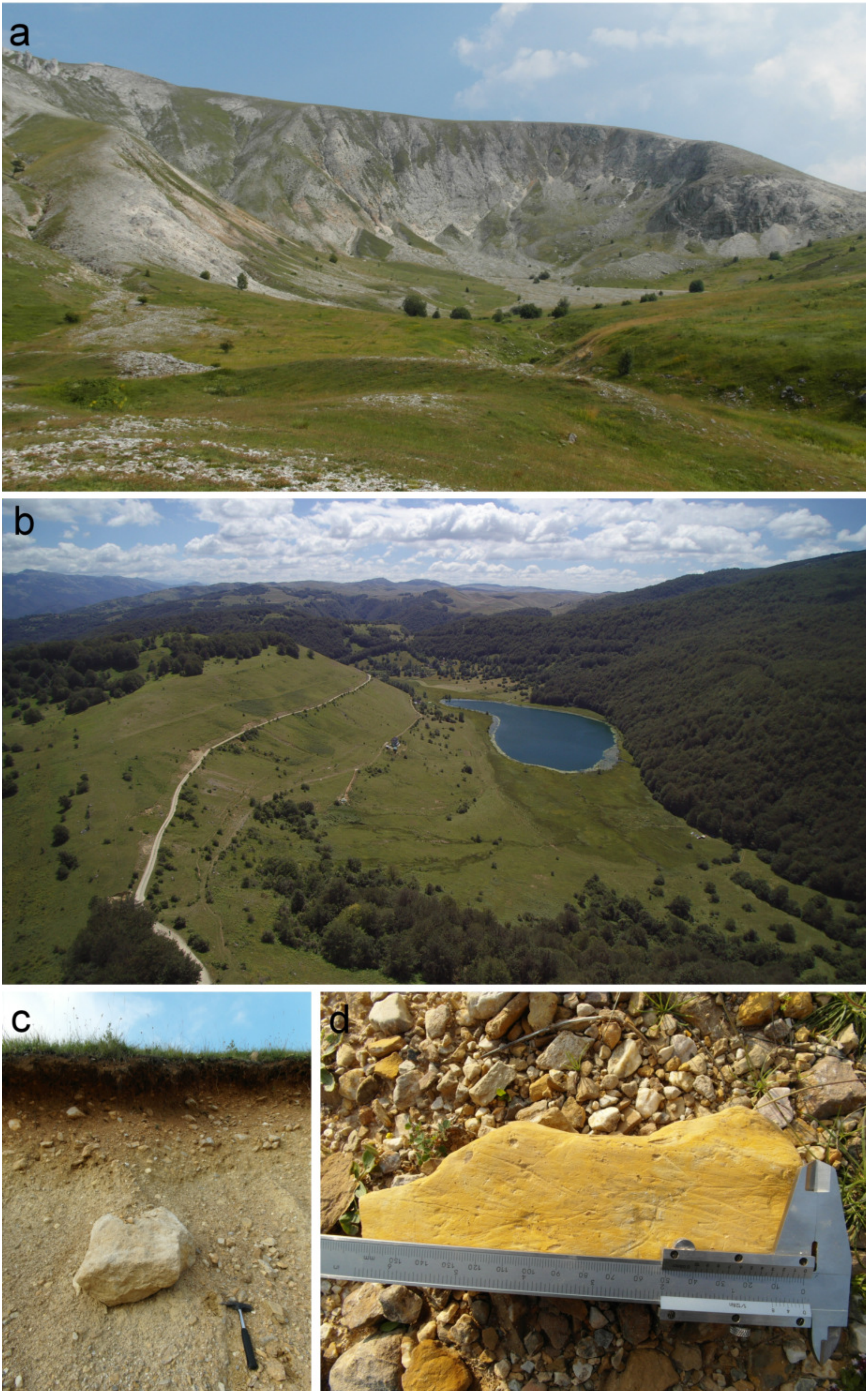

a
45°N
40°N
35°N
30°N
0°
10°E
20°E
30°E
Fig.1b
Black Sea
Mediterranean Sea
0 250 500 km
b
Konjic
Mt. Visočica
1974m asl
Mt. Prenj
2115m asl
43°30'N
Neretva River
Fig.4a
Fig.2a
Mostar
Mt. Crvanj
1920m asl
Mt. Velež
1965m asl
Nevesinje
43°15'N
17°45'E
18°0'E
18°15'E
Legend
Stream
Study areas
Town
Elevation
2000 m asl
0 m asl
0 5 10 15 km

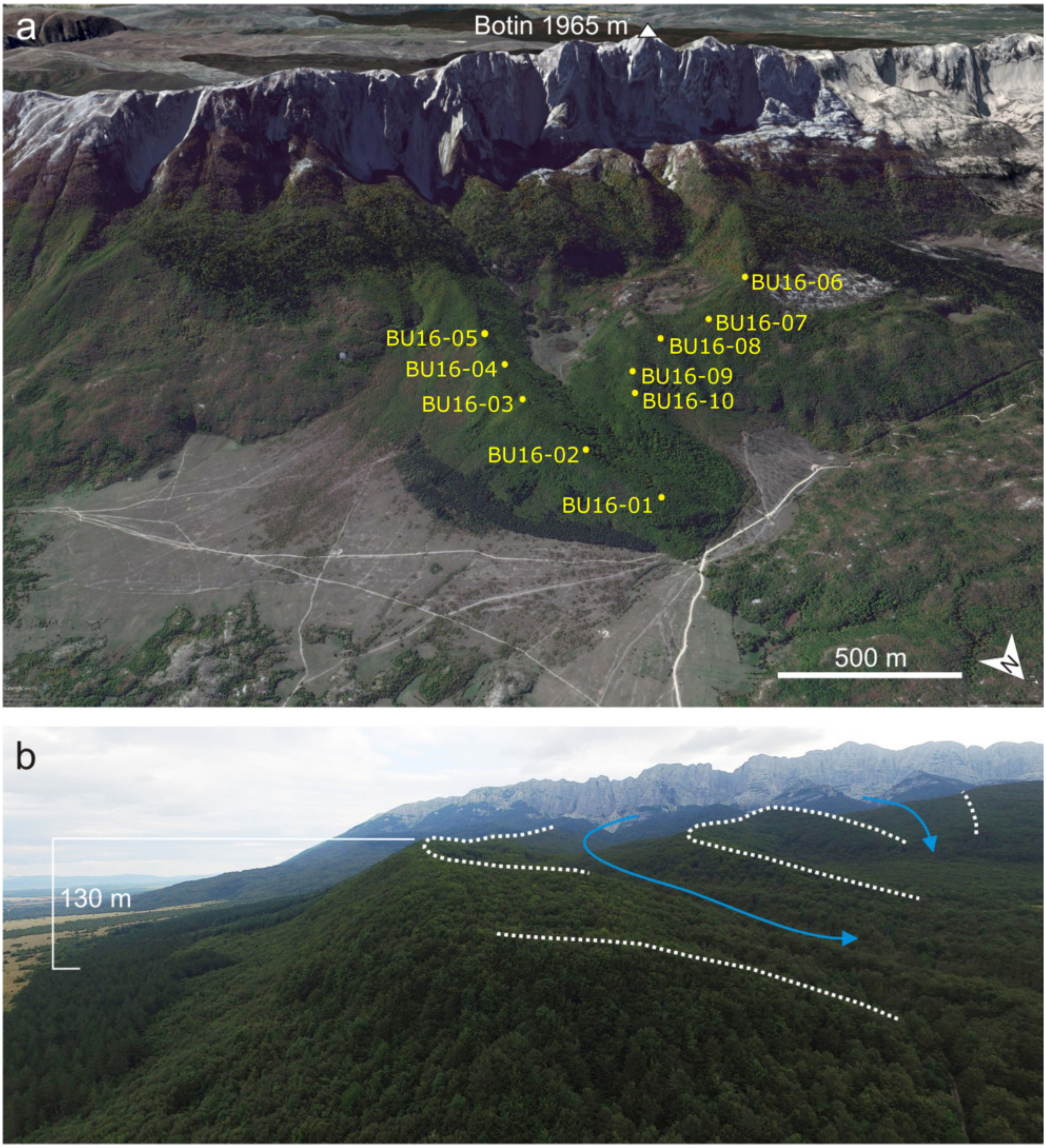

a
43°25'N
43°20'N
18°0'E
18°5'E
0 1 2 3 km
Altitudinal classes (m asl)
0 - 500
500 - 1000
1000 - 1500
1500 - 1965
Legend
Botin - 1965 m asl
Cirque
Gully
Morainic ridge
Glacial deposits
Outwash deposits
Fan
Lake
Sampling area
Sample ID and
age±error (ka)
b
BU16-10
11.5±1.4
BU16-09
10.7±1.3
BU16-08
6.3±0.6
BU16-07
9.0±1.0
BU16-06
15.7±2.1
BU16-01
14.1±1.8
BU16-02
7.8±0.9
BU16-03
10.9±1.4
BU16-04
8.8±1.1
BU16-05
9.0±1.0
43°21'N
43°20'N
18°2'E
18°3'E
18°4'E
0 0.5 1 km

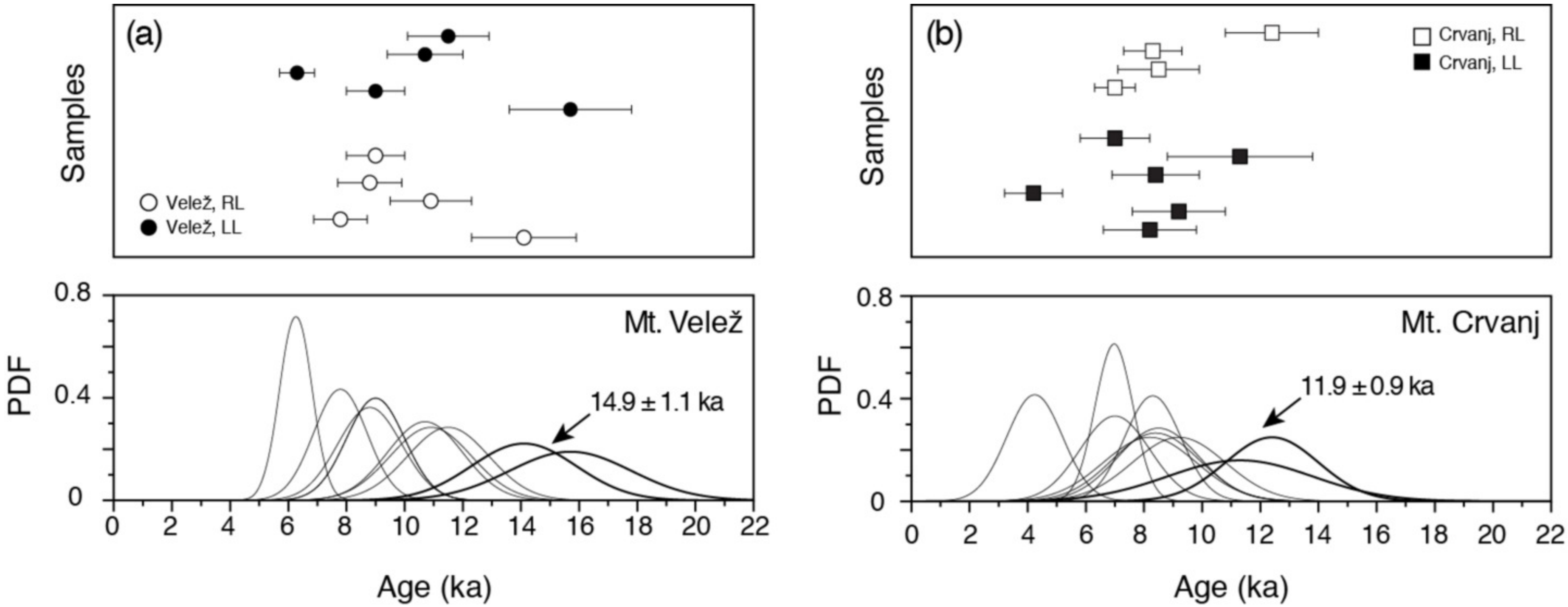

a
b
c


a
b
0 1 2 3 km
Altitudinal classes (m asl)
0 - 500
500 - 1000
1000 - 1500
1500 - 1965
Legend
Zimomor - 1920 m asl
Cirque
Gully
Morainic ridge
Stream
Glacial deposits
Outwash deposits
Fan
Lake
Sampling area
Sample ID and age±error (ka)
43°25'N
43°20'N
18°10'E
18°15'E
18°16'E
43°24'N
CR16-06
7.0±1.2
CR16-04
8.4±1.5
CR16-02
9.2±1.6
CR16-01
8.2±1.6
CR16-05
11.3±2.5
CR16-03
4.2±1.0
CR16-08
8.5±1.4
CR16-07
7.0±0.7
CR16-10
12.4±1.6
CR16-09
8.3±1.0
0 0.5 1 km

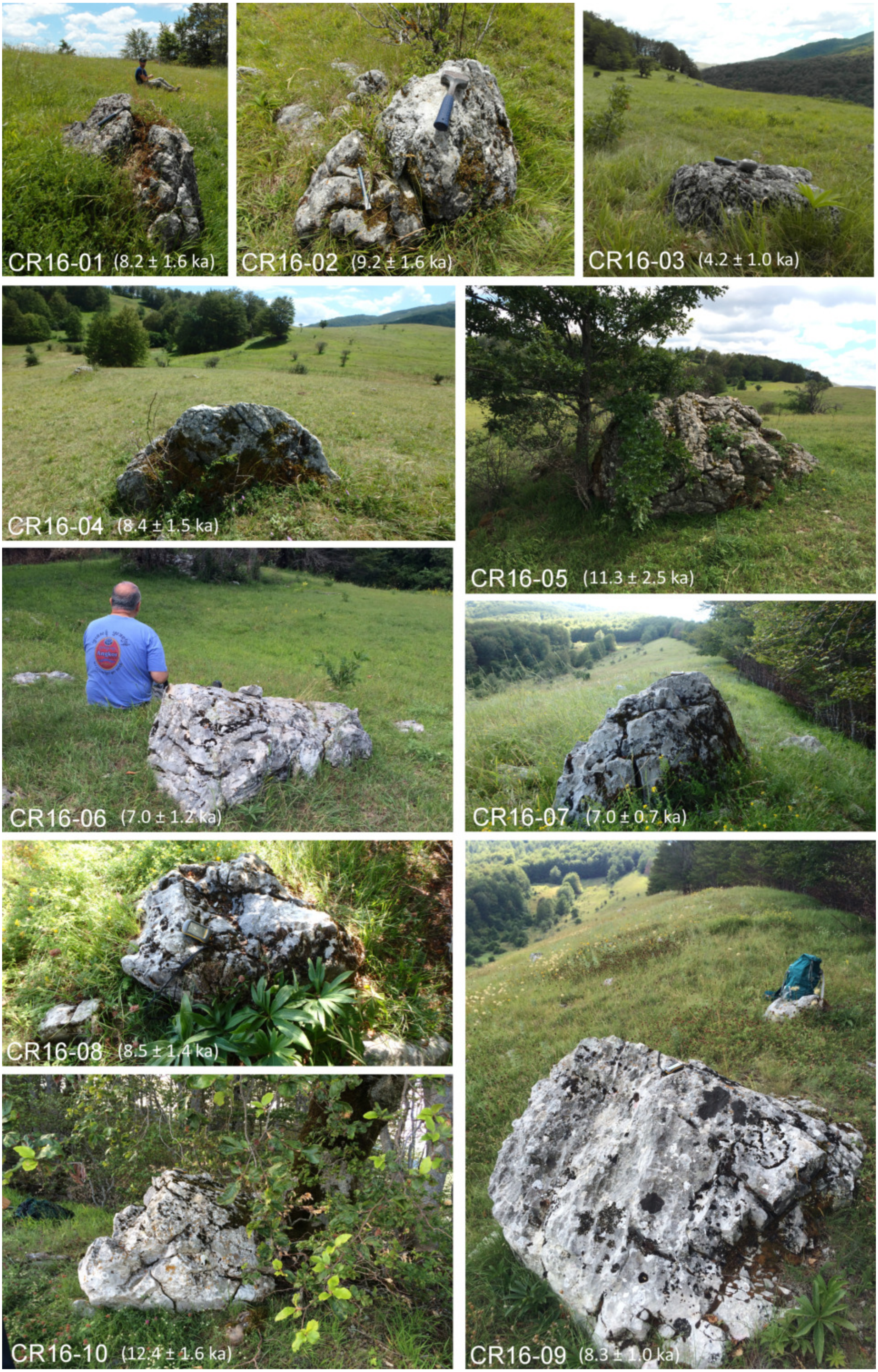

a
b
c
d

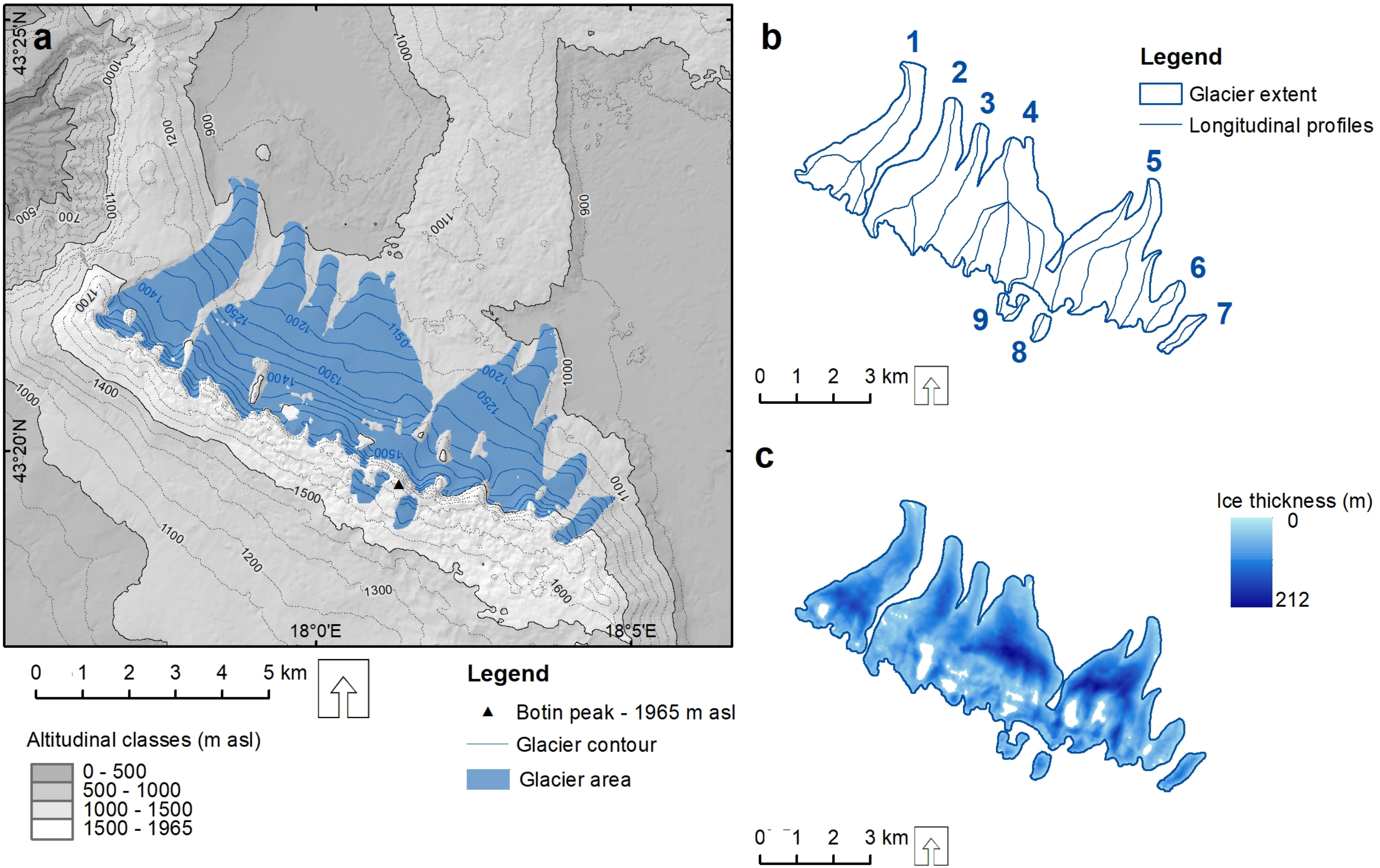

BU16-01 (14.1 ± 1.8 ka)
BU16-02 (7.8 ± 0.9 ka)
BU16-03 (10.9 ± 1.4 ka)
BU16-04 (8.8 ± 1.1 ka)
BU16-05 (9.0 ± 1.0 ka)
BU16-06 (15.7 ± 2.1 ka)
BU16-07 (9.0 ± 1.0 ka)
BU16-08 (6.3 ± 0.6 ka)
BU16-09 (10.7 ± 1.3 ka)
BU16-10 (11.5 ± 1.4 ka)

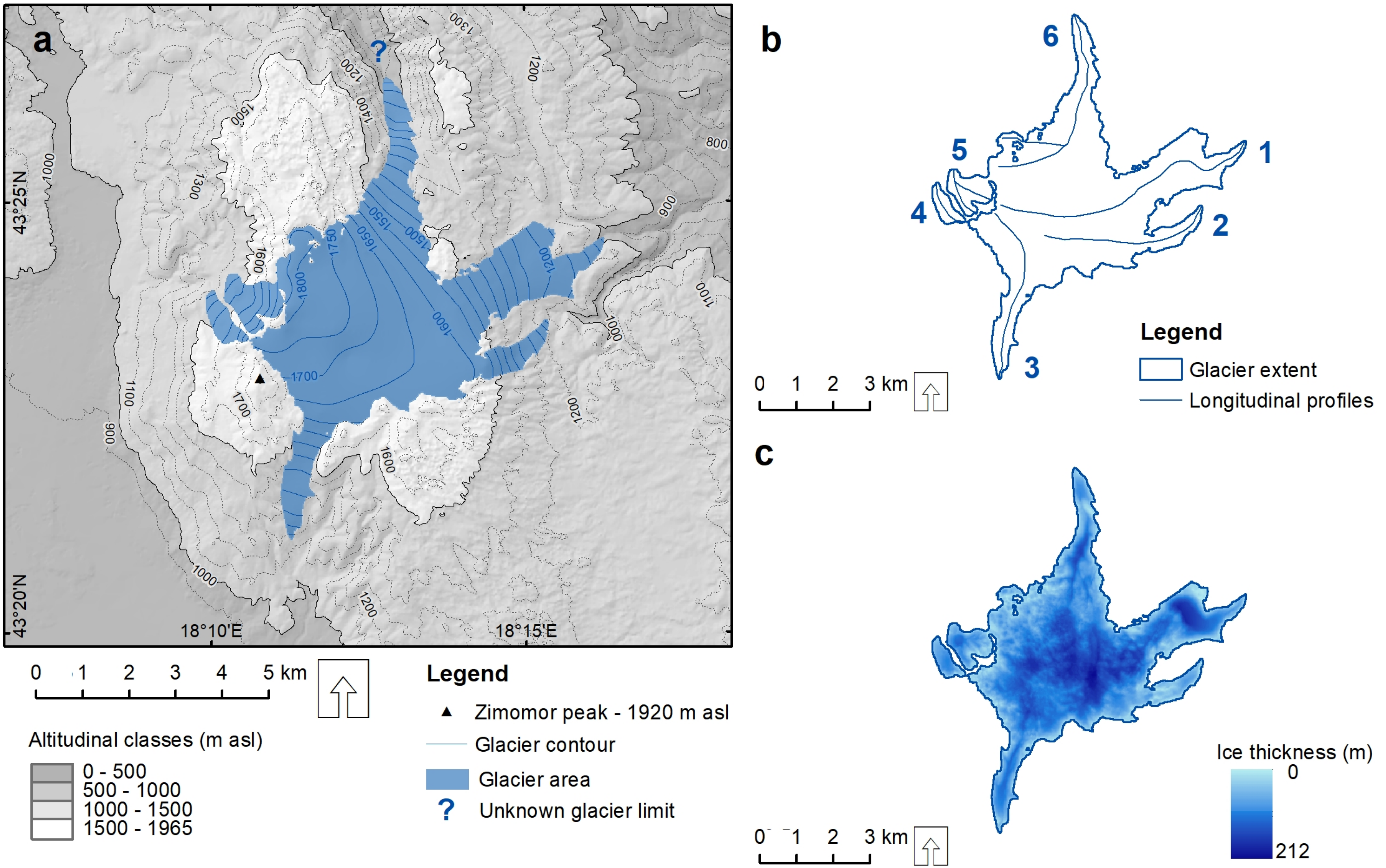

a
Botin 1965 m
BU16-06
BU16-07
BU16-08
BU16-05
BU16-04
BU16-09
BU16-10
BU16-03
BU16-02
BU16-01
500 m
N
b
130 m



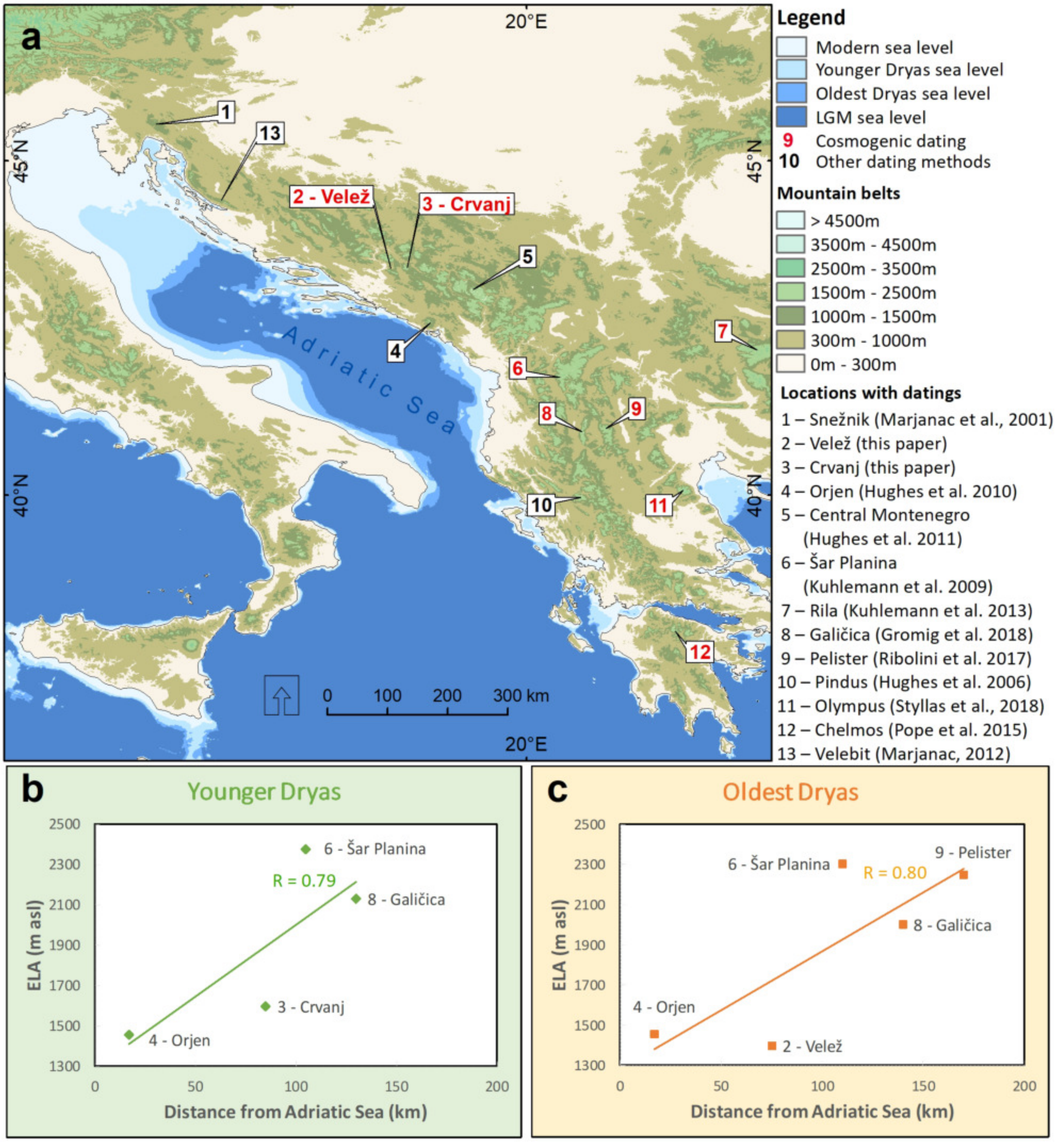
(a)
Samples
Velež, RL
Velež, LL
PDF
Mt. Velež
14.9 ± 1.1 ka
Age (ka)
(b)
Crvanj, RL
Crvanj, LL
Mt. Crvanj
11.9 ± 0.9 ka


CR16-01 (8.2 ± 1.6 ka)
CR16-02 (9.2 ± 1.6 ka)
CR16-03 (4.2 ± 1.0 ka)
CR16-04 (8.4 ± 1.5 ka)
CR16-05 (11.3 ± 2.5 ka)
CR16-06 (7.0 ± 1.2 ka)
CR16-07 (7.0 ± 0.7 ka)
CR16-08 (8.5 ± 1.4 ka)
CR16-09 (8.3 ± 1.0 ka)
CR16-10 (12.4 ± 1.6 ka)


a
43°25'N
43°20'N
18°0'E
18°5'E
0 1 2 3 4 5 km
Altitudinal classes (m asl)
0 - 500
500 - 1000
1000 - 1500
1500 - 1965
Legend
Botin peak - 1965 m asl
Glacier contour
Glacier area
b
1
2
3
4
5
6
7
8
9
Legend
Glacier extent
Longitudinal profiles
0 1 2 3 km
c
Ice thickness (m)
0
212
0 1 2 3 km



a
b
c
?
43°25'N
43°20'N
18°10'E
18°15'E
0 1 2 3 4 5 km
Legend
Zimomor peak - 1920 m asl
Glacier contour
Glacier area
Unknown glacier limit
Altitudinal classes (m asl)
0 - 500
500 - 1000
1000 - 1500
1500 - 1965
1
2
3
4
5
6
0 1 2 3 km
Legend
Glacier extent
Longitudinal profiles
Ice thickness (m)
0
212
0 1 2 3 km


a
20°E
45°N
40°N
Adriatic Sea
1
13
2 - Velež
3 - Crvanj
4
5
6
7
8
9
10
11
12
0 100 200 300 km
Legend
Modern sea level
Younger Dryas sea level
Oldest Dryas sea level
LGM sea level
9 Cosmogenic dating
10 Other dating methods
Mountain belts
> 4500m
3500m - 4500m
2500m - 3500m
1500m - 2500m
1000m - 1500m
300m - 1000m
0m - 300m
Locations with datings
1 – Snežnik (Marjanac et al., 2001)
2 – Velež (this paper)
3 – Crvanj (this paper)
4 – Orjen (Hughes et al. 2010)
5 – Central Montenegro (Hughes et al. 2011)
6 – Šar Planina (Kuhlemann et al. 2009)
7 – Rila (Kuhlemann et al. 2013)
8 – Galičica (Gromig et al. 2018)
9 – Pelister (Ribolini et al. 2017)
10 – Pindus (Hughes et al. 2006)
11 – Olympus (Styllas et al., 2018)
12 – Chelmos (Pope et al. 2015)
13 – Velebit (Marjanac, 2012)
b
Younger Dryas
ELA (m asl)
Distance from Adriatic Sea (km)
6 - Šar Planina
8 - Galičica
3 - Crvanj
4 - Orjen
R = 0.79
c
Oldest Dryas
ELA (m asl)
Distance from Adriatic Sea (km)
6 - Šar Planina
9 - Pelister
8 - Galičica
4 - Orjen
2 - Velež
R = 0.80

	Sample ID	Latitude (WGS84)	Longitude (WGS84)	Elevation	Boulder dimensions (LxWxH)	Sample thickness	Topography correction factor
		°N (DD)	°E (DD)	(m, asl)	(m)	(cm)	
1	BU16-01	43.3565	18.0583	1010	2x2.5x1.6	3	0.9986
2	BU16-02	43.3529	18.0589	1055	1x1x0.5	3	0.9970
3	BU16-03	43.3487	18.0585	1070	1.5x0.8x0.6	3	0.9990
4	BU16-04	43.3461	18.0568	1105	1.5x1.5x0.6	2.5	0.9982
5	BU16-05	43.3433	18.0553	1130	2x1.8x1.2	3	0.9971
6	BU16-06	43.3486	18.0372	1200	2.4x3x1.5	2	0.9983
7	BU16-07	43.3498	18.0433	1145	1.5x1x0.6	2	0.9897
8	BU16-08	43.3494	18.0475	1130	1.5x0.8x0.4	2	0.9886
9	BU16-09	43.3502	18.0513	1095	1x0.8x0.5	4	0.9915
10	BU16-10	43.3513	18.0526	1075	1x0.5x0.45	2	0.9939
11	CR16-01	43.4069	18.2533	1208	1x2.5x1	3	0.9956
12	CR16-02	43.4072	18.2515	1180	0.9x0.4x0.6	3	0.9927
13	CR16-03	43.4076	18.2514	1180	1x1.5x0.2	3	0.9946
14	CR16-04	43.4098	18.2510	1170	1.7x1.2x0.6	3	0.9935
15	CR16-05	43.4102	18.2496	1170	3x4x1.5	3	0.9947
16	CR16-06	43.4105	18.2481	1175	1.5x1.8x0.5	3	0.9925
17	CR16-07	43.3979	18.2497	1187	1x1.5x1	4	0.9824
18	CR16-08	43.3979	18.2504	1202	1x1x0.4	4	0.9866
19	CR16-09	43.3982	18.2527	1187	2.5x2x1.5	4	0.9960
20	CR16-10	43.3983	18.2534	1187	1.4x1x1	3	0.9960

	Sample ID	Major elements											Trace elements				
		Al_2O_3 (wt. %)	CaO (wt. %)	Fe_2O_3 (wt. %)	K_2O (wt. %)	MgO (wt. %)	MnO (wt. %)	Na_2O (wt. %)	P_2O_5 (wt. %)	SiO_2 (wt. %)	TiO_2 (wt. %)	CO_2 (LOI) (wt. %)	Sm (ppm)	Gd (ppm)	U (ppm)	Th (ppm)	Cl (ppm)
1	BU16-01	0.02	54.87	0.04	0.01	0.79	0.01	0.02	0.01	0.38	0.01	43.80	0.05	0.05	2.30	0.20	20.8 ± 1.9
2	BU16-02	0.11	54.72	0.11	0.03	0.89	0.01	0.03	0.01	0.42	0.01	43.60	0.05	0.05	1.70	0.20	37.5 ± 3.4
3	BU16-03	0.29	54.17	0.12	0.09	0.69	0.01	0.01	0.01	0.96	0.01	43.60	0.13	0.19	2.60	0.20	25.6 ± 2.3
4	BU16-04	0.02	55.21	0.04	0.01	0.55	0.01	0.01	0.01	0.43	0.01	43.70	0.05	0.05	1.60	0.20	12.9 ± 1.2
5	BU16-05	0.01	54.28	0.04	0.01	1.55	0.01	0.01	0.01	0.19	0.01	43.90	0.05	0.05	0.70	0.20	22.9 ± 2.1
6	BU16-06	0.01	55.65	0.04	0.01	0.47	0.01	0.01	0.01	0.18	0.01	43.60	0.05	0.05	1.50	0.20	18.6 ± 1.7
7	BU16-07	0.04	53.66	0.04	0.01	2.14	0.01	0.02	0.01	0.33	0.01	43.70	0.05	0.05	2.10	0.20	27.2 ± 2.5
8	BU16-08	0.01	55.06	0.04	0.01	0.50	0.01	0.03	0.01	0.24	0.01	44.10	0.05	0.05	1.50	0.20	21.7 ± 2.0
9	BU16-09	0.03	54.59	0.04	0.01	0.74	0.01	0.02	0.01	0.44	0.01	44.10	0.05	0.05	1.10	0.20	19.5 ± 1.8
10	BU16-10	0.02	54.82	0.04	0.01	0.68	0.01	0.02	0.01	0.25	0.01	44.10	0.05	0.06	2.10	0.20	20.5 ± 1.9
11	CR16-01	0.37	34.16	0.15	0.13	17.48	0.01	0.04	0.06	1.11	0.02	46.10	1.20	1.46	3.10	0.40	410.7 ± 37.1
12	CR16-02	0.98	26.51	0.34	0.36	15.25	0.01	0.04	0.07	17.28	0.05	38.80	1.03	1.04	1.40	1.00	139.3 ± 12.6
13	CR16-03	0.16	32.27	0.19	0.06	19.21	0.01	0.03	0.02	0.65	0.01	47.10	0.33	0.59	1.20	0.20	450.0 ± 40.3
14	CR16-04	0.29	32.69	0.14	0.12	18.68	0.01	0.05	0.06	1.00	0.02	46.60	0.79	1.00	4.80	0.30	283.5 ± 25.4
15	CR16-05	0.58	30.49	0.29	0.20	17.45	0.01	0.04	0.02	6.57	0.03	44.00	0.54	0.55	0.80	0.50	279.5 ± 25.1
16	CR16-06	0.44	32.24	0.19	0.16	18.38	0.01	0.04	0.05	2.21	0.03	45.90	0.49	0.59	3.60	0.40	340.3 ± 30.6
17	CR16-07	0.15	54.28	0.08	0.06	0.76	0.01	0.02	0.03	0.65	0.01	43.90	0.41	0.52	0.80	0.20	61.4 ± 5.6
18	CR16-08	0.11	43.59	0.14	0.04	9.79	0.01	0.02	0.06	0.52	0.01	45.50	0.29	0.30	0.50	0.20	155.7 ± 14.1
19	CR16-09	0.08	54.02	0.07	0.03	1.10	0.01	0.02	0.05	0.42	0.01	44.20	0.58	0.76	0.80	0.20	31.8 ± 2.9
20	CR16-10	0.04	54.39	0.04	0.02	0.93	0.01	0.02	0.03	0.38	0.01	44.10	0.26	0.32	0.50	0.20	63.8 ± 5.8

Sample ID	Landform	^{36}Cl (measured)	Contemporary depth average total production rate	SURFACE EXPOSURE AGES: erosion not corrected (0 mm ka^{-1})	erosion corrected (20 mm ka^{-1})	erosion corrected (40 mm ka^{-1})	erosion corrected (60 mm ka^{-1})	Landform age calculated using erosion correction of 40 mm ka-1
		(10^4 atoms g^{-1} rock)	(atoms g^{-1} rock a^{-1})	(ka)	(ka)	(ka)	(ka)	(ka)
Mt. Velež								
BU16-01	Budijevača, right lateral moraine	46.53 ± 1.54	41.8	9.9 ± 0.9	11.3 ± 1.1	**14.1 ± 1.8**	21.0 ± 5.0	
BU16-02	Budijevača, right lateral moraine	34.46 ± 1.77	44.8	6.8 ± 0.6	7.1 ± 0.7	7.8 ± 0.9	9.0 ± 1.3	
BU16-03	Budijevača, right lateral moraine	41.84 ± 1.39	44.0	8.4 ± 0.7	9.2 ± 0.9	10.9 ± 1.4	14.1 ± 2.3	**14.1±1.8**
BU16-04	Budijevača, right lateral moraine	35.17 ± 1.37	44.7	7.0 ± 0.6	7.7 ± 0.7	8.8 ± 1.1	10.9 ± 1.6	
BU16-05	Budijevača, right lateral moraine	37.57 ± 1.17	45.7	7.3 ± 0.6	7.9 ± 0.7	9.0 ± 1.0	11.0 ± 1.8	
BU16-06	Budijevača, left lateral moraine	58.24 ± 1.71	49.3	10.5 ± 0.9	12.2 ± 1.2	**15.7 ± 2.1**	27.5 ± 8.6	
BU16-07	Budijevača, left lateral moraine	39.59 ± 1.32	46.0	7.6 ± 0.6	8.1 ± 0.7	9.0 ± 1.0	11.4 ± 1.8	
BU16-08	Budijevača, left lateral moraine	28.09 ± 1.22	46.0	5.5 ± 0.5	5.8 ± 0.5	6.3 ± 0.6	7.0 ± 0.8	**15.7±2.1**
BU16-09	Budijevača, left lateral moraine	40.27 ± 1.36	43.9	8.1 ± 0.7	9.0 ± 0.9	10.7 ± 1.3	13.9 ± 2.2	
BU16-10	Budijevača, left lateral moraine	42.79 ± 1.68	44.0	8.6 ± 0.8	9.6 ± 1.0	11.5 ± 1.4	15.3 ± 2.7	
Mt. Crvanj								
CR16-01	Crvanj, lateral above the lake	116.95 ± 3.61	75.8	12.0 ± 1.8	8.5 ± 1.4	8.2 ± 1.6	8.6 ± 2.1	
CR16-02	Crvanj, lateral above the lake	52.69 ± 1.67	38.9	11.5 ± 1.4	9.2 ± 1.4	9.2 ± 1.6	10.2 ± 2.3	
CR16-03	Crvanj, lateral above the lake	61.30 ± 9.51	78.7	6.1 ± 1.3	5.0 ± 1.0	4.2 ± 1.0	4.7 ± 1.0	**11.3±2.5**
CR16-04	Crvanj, lateral above the lake	97.27 ± 3.24	59.4	12.0 ± 1.7	8.7 ± 1.5	8.4 ± 1.5	8.9 ± 2.2	
CR16-05	Crvanj, lateral above the lake	105.07 ± 3.69	57.8	15.6 ± 2.3	11.2 ± 1.8	**11.3 ± 2.5**	13.0 ± 4.1	
CR16-06	Crvanj, lateral above the lake	92.05 ± 2.82	66.0	10.2 ± 1.6	7.4 ± 1.1	7.0 ± 1.2	7.1 ± 1.5	
CR16-07	Crvanj, right lateral moraine	37.34 ± 1.37	51.4	6.4 ± 0.5	6.6 ± 0.6	7.0 ± 0.7	8.0 ± 1.0	
CR16-08	Crvanj, right lateral moraine	59.78 ± 1.82	55.2	9.5 ± 1.1	8.3 ± 1.1	8.5 ± 1.4	9.4 ± 1.9	**12.4±1.6**
CR16-09	Crvanj, right lateral moraine	38.21 ± 1.31	48.4	7.0 ± 0.6	7.5 ± 0.6	8.3 ± 1.0	9.9 ± 1.5	
CR16-10	Crvanj, right lateral moraine	60.16 ± 1.87	52.4	10.2 ± 0.8	11.0 ± 1.0	**12.4 ± 1.6**	16.5 ± 3.4	

Velež

	AABR 1.9±0.81
Glacier 1	1287 (+ 40 / -20)
Glacier 2	1271 (+ 40 / -20)
Glacier 3	1216 (+ 30 / -10)
Glacier 4	1284 (+ 30 / -20)
Glacier 5	1265 (+ 30 / -20)
Glacier 6	1327 (+ 20 / -20)
Glacier 7	1393 (+ 30 / -10)
Glacier 8	1724 (+ 10 / -10)
Glacier 9	1728 (+ 10 / -10)
Mean	**1388** (σ 186)

Crvanj

	AABR 1.9±0.81
Glacier 1	1468 (+ 60 / -30)
Glacier 2	1577 (+ 30 / -20)
Glacier 3	1541 (+ 40 / -20)
Glacier 4	1553 (+ 20 / 0)
Glacier 5	1607 (+ 20 / -10)
Glacier 6	1500 (+ 50 / -30)
Mean	**1541** (σ 46)

Velež

Temperature depression (ºC)	*Mean annual temperature at ELA (ºC)*	Annual melt (mm w.e.)	
		Annual Range = 18.9 ºC	*150% Annual Range = 28.35 ºC*
0	5.4	9304	11295
4	1.4	5601	7837
5	0.4	4807	7058
6	-0.6	4064	6313
7	-1.6	3371	5601
8	-2.6	2729	4923
9	**-3.6**	**2140**	4280
10	**-4.6**	**1605**	3671
11	-5.6	1128	3098
12	-6.6	714	2561
13	-7.6	372	2063
14	-8.6	115	1604
15	-9.6	0	1188

Crvanj

Temperature depression (ºC)	*Mean annual temperature at ELA (ºC)*	Annual melt (mm w.e.)	
		Annual Range = 18.9 ºC	*150% Annual Range = 28.35 ºC*
0	4.4	8295	10378
4	0.4	4807	7058
5	-0.6	4064	6313
6	-1.6	3371	5601
7	-2.6	2729	4923
8	**-3.6**	**2140**	4280
9	**-4.6**	**1605**	3671
10	-5.6	1128	3098
11	-6.6	714	2561
12	-7.6	372	2063
13	-8.6	115	1604
14	-9.6	0	1188
15	-10.6	0	817

Mountain	Dating method	Age	Erosion rate	Number of samples	Reference
Snežnik (Croatia)	14C	LGM (*18.7 ±1.0 cal kyr BP)	/	1 (animal bone in outwash fan)	Marjanac et al., 2001
Pindus (Greece)	U-series	MIS 12 (>350 to 71 ka), MIS 6 (131.3 to 80.5 ka)	/	28 from at least 11 landforms (calcite cement from moraines and alluvial deposits)	Hughes et al., 2006; Woodward et al., 2004
Šar Planina (FYROM)	10Be cosmogenic exposure dating	LGM (19.4 ± 3.2 to 12.4 ± 1.7 ka), Oldest Dryas (14.7 ± 2.1 ka) Younger Dryas (12.7 ± 1.9 ka)	10 mm/ka	8 from at least 6 landforms (moraine and rock glacier boulders)	Kuhlemann et al., 2009
Orjen (Montenegro)	U-series	MIS 12 (>350 to 324.0 ka), MIS 6 (124.6 to 102.4 ka), MIS 5d-2 (17.3 to 12.5 ka), Younger Dryas (9.6 to 8.0 ka)	/	12 from 7 landforms (calcite cement from moraines)	Hughes et al., 2010
Central Montenegro	U-series	MIS 12 (>350 ka; 396.6 to 38.8 ka), MIS 8 or 10 (231.9 to 58.8 ka), MIS 6 (120.2 to 88.1 ka) MIS 2 (13.4 ka), Younger Dryas (10.9 to 2.2 ka)	/	19 from 11 landforms (calcite cement from moraines)	Hughes et al., 2011
Velebit (Croatia)	U-series	MIS 12-6 (>350 to 61.5 ka)	/	9 from at least 6 landforms (calcite cement from moraines, paleocaverns, former ice wedges)	Marjanac, 2012; Marjanac&Marjanac, 2016
Rila (Bulgaria)	10Be cosmogenic exposure dating	LGM (23.5 to 14.4 ka)	0 mm/ka	10 from at least 6 landforms (moraine boulders)	Kuhlemann et al., 2013
Chelmos (Greece)	**36Cl cosmogenic exposure dating**	MIS 3 (39.9 ± 3.0 to 30.4 ± 2.2 ka), LGM (22.9 ±1.6 to 21.2 ± 1.6 ka), Younger Dryas (*CH10=12.6 ± 0.9, *CH11=10.2 ± 0.7 ka)	0 mm/ka	7 from 4 different landforms (moraine boulders)	Pope et al., 2015
Galičica (FYROM)	**36Cl cosmogenic exposure dating**	Younger Dryas (12.8 ± 1.4 to 11.3 ± 1.3 ka)	5 mm/ka	5 from 1 landform (moraine boulders)	Gromig et al., 2018
Pelister (FYROM)	10Be cosmogenic exposure dating	Oldest Dryas (15.56 ± 0.85 to 15.03 ± 0.85 ka)	0 mm/ka	3 from 1 landform (moraine boulders)	Ribolini et al., 2017
Olympus (Greece)	**36Cl cosmogenic exposure dating**	Lateglacial (3 phases: 15.5 ± 2.0 ka (*TZ03=16.35 ± 1.15 ka, *MK12=16.22 ± 1.13 ka), 13.5 ± 2.0 ka, 12.5 ± 1.5 ka), Holocene (3 phases: 9.6 ± 1.1 ka, 2.5 ± 0.3 ka, 0.64 ± 0.08ka)	5 mm/ka	20 from 11 landforms (moraine boulders, bedrock)	Styllas et al., 2018