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**Abstract**

This study presents the first cosmogenic 36Cl surface exposure data from a moraine in the Former Yugoslav Republic of Macedonia (FYROM). Five limestone boulders from a terminal moraine in the Galicica Mountains (40.94°N, 20.83°E, 2050 m a.s.l.) were used for cosmogenic 36Cl surface exposure dating. The 36Cl concentrations from the five boulders are identical within their measurement uncertainties ruling out major effects of inheritance, erosion, or snow cover. The calculated ages are very consistent ranging from 11.3 to 12.8 ka (mean 12 ka) after applying a Ca-spallation production rate of 56 at g-1 a-1 (LSD scaling) and correction for 5 mm ka-1 carbonate weathering and 2 % snow shielding. The applied corrections for weathering and snow shielding cause a shift to older ages in the order of magnitude of ca. 5 % on average, making the production rate the main impact on exposure ages. The ages point to a moraine formation during the Younger Dryas period, consistent with the timing of the last deglaciation in the Galicica Mountains derived from previous geomorphological studies in the area. The formation of a glacier was likely favoured by several topoclimatic factors, accounting for additional snow input. This interpretation is in line with regional studies on glaciation chronologies from Šara Range (FYROM/Republic of Kosovo), Retezat Mountains (Romania), Mount Orjen (Montenegro) and Durmitor (Montenegro). Lake sediment analyses of lakes Prespa (Republic of Albania/ FYROM/Greece), Maliq (Republic of Albania) and Dojran (FYROM/Greece) indicate that cold conditions promoted the formation of a local cirque glacier. However, studies of sediment records of the adjacent lakes Ohrid (Republic of Albania/FYROM) and Prespa do not indicate the presence of a proximal glaciation. An explanation might be a combination of the small size of the cirque glacier, generating only small amounts of debris, and the karstic bedrock, which hampers fluvial transport and acts by its aquifer system as a natural sediment trap, as the fluvial transport of the sediments to the lakes is absorbed by the karst system.



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| **Keywords** | Galicica Mountains; Chlorine-36 (36Cl); Cosmogenic surface exposure dating; Younger Dryas; Balkan Peninsula; Moraine |



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To the editor of
Quaternary International

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To whom it may concern,

We conducted a study in the Galicica Mountains (Former Yugoslav Republic of Macedonia) on a terminal moraine of Younger Dryas age using cosmogenic 36-Chlorine surface exposure dating. The data has been set in context to other Balkan deglaciation chronologies. Also paleoclimate reconstructions derived from nearby lake records were evaluated concerning a possible imprint of a local glaciation on the sedimentation pattern of the lake on the one hand, and if the climate reconstructions reveal favourable climate during the time of a local glaciation on the other hand.

We are confident that Quaternary International would be an excellent journal to publish this data since it would stand in line with similar publications (e.g. Reuther et al., 2007, Makos et al., 2013, Kuhlemann et al., 2013). This study contributes to the reconstruction of glaciations on the Balkan Peninsula.

Thank you in advance for considering to publish our research.

Best regards

Raphael Gromig

# Quaternary International

We the authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.
We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.
We understand that the Corresponding Author is the sole contact for the Editorial process. He/She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Sincerely,

On behalf of all authors

**Evidence for a Younger Dryas deglaciation in the Galicica Mountains (FYROM) from cosmogenic 36-Chlorine**

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## Abstract

This study presents the first cosmogenic $^{36}Cl$ surface exposure data from a moraine in the Former Yugoslav Republic of Macedonia (FYROM). Five limestone boulders from a terminal moraine in the Galicica Mountains (40.94°N, 20.83°E, 2050 m a.s.l.) were used for cosmogenic $^{36}Cl$ surface exposure dating. The $^{36}Cl$ concentrations from the five boulders are identical within their measurement uncertainties ruling out major effects of inheritance, erosion, or snow cover. The calculated ages are very consistent ranging from 11.3 to 12.8 ka (mean 12 ka) after applying a Ca-spallation production rate of 56 at $g^{-1}$ $a^{-1}$ (LSD scaling) and correction for 5 mm $ka^{-1}$ carbonate weathering and 2 % snow shielding. The applied corrections for weathering and snow shielding cause a shift to older ages in the order of magnitude of ca. 5 % on average, making the production rate the main impact on exposure ages. The ages point to a moraine formation during the Younger Dryas period, consistent with the timing of the last deglaciation in the Galicica Mountains derived from previous geomorphological studies in the area. The formation of a glacier was likely favoured by several topoclimatic factors, accounting for additional snow input. This interpretation is in line with regional studies on glaciation chronologies from Šara Range (FYROM/Republic of Kosovo), Retezat Mountains (Romania), Mount Orjen (Montenegro) and Durmitor (Montenegro). Lake sediment analyses of lakes Prespa (Republic of Albania/FYROM/Greece), Maliq (Republic of Albania) and Dojran (FYROM/Greece) indicate that cold conditions promoted the formation of a local cirque glacier. However, studies of sediment records of the adjacent lakes Ohrid (Republic of Albania/FYROM) and Prespa do not indicate the presence of a proximal glaciation. An explanation might be a combination of the small size of the cirque glacier, generating only small amounts of debris, and the karstic bedrock, which hampers fluvial transport and acts by its aquifer system as a natural sediment trap, as the fluvial transport of the sediments to the lakes is absorbed by the karst system.

**Keywords:** Galicica Mountains, Chlorine-36 ($^{36}Cl$), Cosmogenic surface exposure dating, Younger Dryas, Balkan Peninsula, Moraine

## 1 Introduction

The glaciation history on the Balkan Peninsula is subject of research since the late 19th century (Hughes et al., 2011 and references therein). It is of particular interest since glacier reconstructions provide a valuable tool to contribute to Quaternary paleoclimate reconstructions. The southerly latitude position of these former glaciers on the Balkan Peninsula made them especially sensitive to climatic changes, i.e. they react faster with glacier retreat or advance if there are even minor shifts in the climatic conditions (Hughes and Woodward, 2008; Sarıkaya et al., 2014). Several glaciations occurred and are documented on the Balkan Peninsula since the Mid Pleistocene. To date, numerous glacial studies in the Balkan Mountains have been carried out, for example in the Durmitor Massif, Mount Orjen and Mount Lovćen in Montenegro (Hughes, 2010; Hughes et al., 2011; Žebre and Stepišnik, 2014), Mount Prokletije in the Albanian Alps (e.g. Milivojević et al., 2008), the Rila Mountains in Bulgaria (e.g. Kuhlemann et al., 2013), or Mount Tymphi and Mount Smolikas in northern Greece (Hughes et al., 2003; Hughes et al., 2006a; 2007b, c.f. Fig. 6). In most regions, the glaciation during the Marine Isotope Stage (MIS) 12 (Skamnellian Stage, ca. 478 – 424 ka BP) (Lisiecki and Raymo, 2005) is considered to represent the maximum glacier advances (e.g. Hughes et al., 2010; Hughes et al., 2011; Adamson et al., 2014). However, a precise dating of glacial features, such as of moraines, is lacking in most studies. One reason for the fragmentary age control is that many of the investigated areas are composed of limestone, where age determination is limited to U-series dating of secondary carbonate cements on moraines, which does not necessarily date the actual formation of a moraine but the precipitation of the calcitic cement (Hughes et al., 2013). In some areas, where quartz-bearing rocks are common, cosmogenic $^{10}Be$ surface exposure dating was conducted (e.g. Reuther et al., 2007; Kuhlemann et al., 2013).

Studies in the Former Yugoslav Republic of Macedonia (FYROM, in the following referred to as Macedonia) are very rare, which is surprising, as Macedonia is situated in a central position of the Balkan Peninsula. The Šara Mountain Range at the border of Macedonia and the Republic of Kosovo was studied by Kuhlemann et al. (2009). In the Galicica Mountains, which separate Lakes Ohrid and Prespa, a precise mapping of geomorphological features allowed a reconstruction of the expansion of local cirque glaciers (Ribolini et al., 2011).

We now present the first cosmogenic $^{36}Cl$ exposure ages of a glacial moraine in the Galicica Mountains. The results are set in context with the reconstructed deglaciation history of the Balkan Peninsula in order to improve the understanding of the regional climate history. The results are also compared to other sediment records from nearby lakes in order to test if the results are in line with the paleoclimatic interpretation.

## 2 Location, Regional Geology and Climate of the Galicica Mountains

The Galicica Mountain Range is situated in the southern Balkan region (Fig. 1) and is mostly belonging to the Republic of Macedonia. The highest peak is Magaro with a maximum elevation of 2255 m above sea level (a.s.l.). The mountain range is framed by the Ohrid graben with Lake Ohrid (693 m a.s.l.) to the west and the Prespa graben with Lake Prespa (849 m a.s.l.) to the east. Towards the south, the Galicica Mountain Range extends into the Republic of Albania, where it is named Mali i Thatë Mountains, with the highest peak being Kota with an elevation of 2265 m a.s.l. (Watzin et al., 2002; Bordon et al., 2009; Hoffmann et al., 2010).

The Galicica Mountains are a horst structure, which is intersected by a E-W striking normal fault, creating a wind gap extending from Lake Prespa to Ohrid (Hoffmann et al., 2010). The Galicica Mountains are mainly composed of Triassic and subordinated Early Jurassic (Hoffmann et al., 2010) unfossiliferous limestones and locally dolomites (Wagner et al., 2008; Ribolini et al., 2011). The limestones are strongly karstified, rugged and broken (Wagner et al., 2008). Isolated clastic sedimentary rocks of Triassic age occur occasionally (Vogel et al., 2010b). However, the area studied here in more detail, located ca. 2 km south of the wind gap (Fig. 1, further described below) is entirely composed of Triassic limestone. The cirque is approx. 400 m wide. The headwall is partly very steep, producing large slope debris surfaces. Rockfalls, generating large boulders debris, are also active today, forming a belt of large blocks at the base of talus fan (Ribolini et al., 2011).

The large scale climate in Macedonia is controlled by the proximity to the Aegean Sea in the south-east and the Adriatic Sea in the west. Additionally, the surrounding mountains have a crucial influence on the regional climate, which shows characteristics of Mediterranean as well as continental influences (Watzin et al., 2002; Leng et al., 2013). At higher altitudes, montane climate predominates, with higher daily temperature differences compared to the areas in close proximity of lakes Ohrid and Prespa, that buffer daily temperature variations (Watzin et al., 2002). The climate at lakes Ohrid and Prespa for the period between 1961 and 1990 is recorded by several weather stations at altitudes below 1020 m a.s.l.. Present day weather stations at higher altitudes unfortunately do not exist. The Ohrid meteorological station (760 m a.s.l., near the city of Ohrid) recorded an annual average temperature of 11.1° C, whereas Resen meteorological station (881 m a.s.l.) at Lake Prespa recorded a mean annual temperature of 9.5°C (Popovska and Bonacci, 2007). Applying a thermal lapse rate of 0.6 °C 100 $m^{-1}$ to the average annual temperature of Ohrid meteorological station leads to an annual average temperature of ca. 3.4 °C at the altitude of the sampled moraine sequence, which is situated at 2010 – 2050 m a.s.l. (ca. 2.5 °C based on the Prespa meteorological station). The climate in the Lake Prespa watershed is considered to exhibit more temperature variations compared to the Lake Ohrid watershed, as Lake Ohrid, which has a water volume 15 times larger than Lake Prespa, acts as a strong thermal buffer (Popovska and Bonacci, 2007). The precipitation data recorded between 1961 and 1990 reveals an annual average precipitation of 907 mm in Lake Ohrid watershed and 795 mm in Lake Prespa watershed (Popovska and Bonacci, 2007). After 1990 no continuous climate record is published. Snowfall in the mountains is assumed to exceed 1 m annually and to last until late spring (Hollis and Stevenson, 1997).

In total four moraine sequences were mapped in detail by Ribolini et al. (2011), and range in altitudes from 1780 to 2050 m a.s.l. (Fig. 2). The studied moraine is located in the southern of two cirques. The lower moraines (G1-3 sequences) are less well shaped and lack material suitable for exposure dating. Ice moulted rocks occur and are partly covered by fluvio-glacial deposits. Dating with other methods, i.e. radiocarbon dating, was also not possible, as a 4-m deep borehole in the sediments dammed by the G3 moraine did not deliver datable material and it was not possible to get deep enough, for a rough dating of the G3.

In contrast, at 2010 – 2060 m a.s.l. a series of well preserved nested moraines forms the G4-moraine sequence (Fig. 2), which is considered to have built up in the course of the same glaciation phase (Ribolini et al., 2011). The largest moraine ridge was sampled for cosmogenic $^{36}$Cl dating on carbonates (Fig. 3). The distance of the G4 moraine to the headwall of the cirque is approx. 400 m and thus most likely not affected by rockfalls from the headwall, also due to the elevated position. The moraine is mainly composed of limestone blocks, pebbles and coarse gravel. Depressions between the ridges originated from glacier retreat stages. Karst dissolution and permafrost creep may have intensified deformation of the original topography of some ridges (Ribolini et al., 2011).

## 3 36Cl dating method

36Cl dating has successfully been applied to reconstruct glacial chronologies in several areas (e.g. Phillips et al., 1997; Makos et al., 2013; Sarıkaya et al., 2014).

With known production rates, the built up of cosmogenic nuclides can be converted into ages, which reflects the time, when the dated material was first exposed to secondary cosmic rays. For this application, the surface exposure ages mark the point of a glacier retreat when fresh rock is deposited in terminal moraines, which then start to accumulate cosmogenic nuclides.

### *3.1 Sample collection*

Five limestone boulders in or near crest-position of the well-defined terminal moraine G4 were sampled for $^{36}$Cl exposure dating (Fig. 3). Today, the moraine exhibits a crest height of approx. 14 m with reference to the base of the uphill side of the moraine and shows implications of only moderate degradation since deposition. Boulders were chosen based on their size, their plausibility to be in stable position and their post-depositional preservation. The samples themself were collected at the upper surfaces of each boulder with a hammer and chisel (Fig. 4). Horizon angles were measured in the field using an inclinometer in 20° intervals in order to correct for topographic shielding.

*3.2. Sample preparation*

The samples were treated mechanically and chemically at the laboratory facilities of the Institute of Geology and Mineralogy at the University of Cologne, Germany, following mainly the chemistry protocol of (Stone et al., 1996). The weathered rock surface and any contaminations like recrystallized calcite or lichen were mechanically removed using a hand held rotary tool with a diamond bit. This is relevant as they can contain a relevant amount $^{35}Cl$, which acts as a target element to produce $^{36}Cl$ by thermal neutrons. Subsequently, the boulders were crushed and sieved and the 250 – 500 µm grain size fraction was treated with 30 % $H_2O_2$ at 40° C for 96 hours in order to remove any residual organic matter. Each aliquot was rinsed and leached twice in 0.3 M $HNO_3$ until ~13% of material was removed in order to eliminate any meteoric $^{36}Cl$. Afterwards the samples were spiked with a known amount of isotopically enriched stable chloride carrier to allow simultaneous determination of the natural chlorine and $^{36}Cl$ (Desilets et al., 2006 and references therein). After adding the carrier and some excess $AgNO_3$ to avoid degassing, ~22 g of each sample were dissolved using MilliQ water and subsequent careful addition of 2 M $HNO_3$. As sulphur displays a major issue for Accelerator Mass Spectrometer (AMS) $^{36}Cl$ measurement, because $^{36}S$ it is an isobar of $^{36}Cl$, it was removed by extraction of crystallized $BaSO_4$ after addition of $Ba(NO_3)_2$. Finally, the precipitated and dried AgCl powder was pressed into AMS cathodes and measured at the CologneAMS facility (Klein et al., 2011). To track any chlorine contamination in the chemistry process, a chemistry blank is coupled with each series and measured in the same AMS run.

*3.3. Sample Measurements (AMS; Actlabs, ICP-OES)*

To ensure the accuracy and precision of the AMS measurement, the AMS was calibrated and normalized to three standards with different concentrations ($^{36}Cl/Cl$: 5.000 x $10^{-13}$, 1.600 x $10^{-12}$, and 1.000 x $10^{-11}$) from the NIST SRM 4843 material (Sharma et al., 1990). Additionally, we prepared four pure spike blanks (Oak Ridge National Laboratory batch 150301, NaCl enriched with $^{35}Cl$), and five blanks with the $^{35}Cl/^{37}Cl$ natural ratio of 3.127 (four Standard Reference Material 975 and a commercial NaCl purchased from VWR company).

Major and trace element contents of bulk non-leached sample material were measured by fusion inductively coupled plasma and fusion mass spectrometry at Actlabs, Canada (Table

1), in order to calculate the sample specific production rate of $^{36}Cl$. These analyses were only performed for RG14/001 and RG14/005 since the limestone is very homogeneous, the catchment is small and the natural chlorine content of the sample is very low. The measurement of the two samples, therefore, can be considered as representative. In addition, an aliquot of each dissolved sample was analyzed on the ICP-OES at the Institute of Geology and Mineralogy in Cologne to reveal the composition of the target AMS-measured fraction (Table 1). The concentration of $^{36}Cl$ and natural chlorine was measured via AMS at the CologneAMS facility (Table 2).

## 4 Results

### *4.1 Sample chemistry*

Major as well as minor element concentrations point to a relatively pure limestone (Table 1). For samples RG14/002, RG14/003 and RG14/004, values from the measurement of RG14/001 were taken. Applying the value of RG14/005 instead of RG14/001 was tested and the effect was minor i.e. in the range of ca. 1%. Elements, which can have a crucial influence on the formation of $^{36}Cl$ via the thermal neutron pathway are consistently very low. Also K, Fe and Ti, on which $^{36}Cl$ can be produced spallogenically, are low. Radiogenic production of $^{36}Cl$ can also be excluded, as Uranium and Thorium, which can act as a neutron source once they decay (Bierman et al., 1995), were below detection limit in the sampled rocks.

**Table 1: Chemical composition of samples. Values below detection limit are marked with "<".**

| | Major elements | | | | | | | | | | | Trace elements | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample ID | $SiO_2$ (wt-%) | $TiO_2$ (wt-%) | $Al_2O_3$ (wt-%) | $Fe_2O_3$ (wt-%) | MnO (wt-%) | MgO (wt-%) | CaO (wt-%) | $Na_2O$ (wt-%) | $K_2O$ (wt-%) | $P_2O_5$ (wt-%) | $CO_2$ (LOI) (wt-%) | Cl ppm | B ppm | Sm ppm | Gd ppm | U ppm | Th ppm |
| RG14/001 - 004 | 0.71 | 0.003 | 0.28 | 0.04 | 0.003 | 0.4 | 54.92 | 0.09 | 0.05 | 0.03 | 42.56 | 23.6 | < 0.5 | <0.1 | 0.1 | 0.3 | 0.2 |
| RG14/005 | 0.19 | 0.01 | 0.5 | 0.04 | 0 | 0.48 | 53.29 | 0 | 0 | 0.02 | 40.02 | 35.2 | 30 | 0.1 | < 0.1 | < 0.1 | < 0.1 |

*4.2 Cl and $^{36}$Cl concentrations*

Stable chlorine concentrations of the samples are consistently low ranging from 16 ± 1 to 34 ± 2 µg $g^{-1}$, indicating that the thermal neutron production of $^{36}$Cl has only a minor contribution to the total production. Blank corrections were obtained from subtracting the number of Cl and $^{36}$Cl atoms in the blank from the respective atoms in the samples, which resulted in a decrease of the uncorrected $^{36}$Cl concentration by 1.2 - 1.4%. The measured $^{36}$Cl concentrations are very consistent, ranging from 1.07($10^6$) at $g^{-1}$ to 1.21($10^6$) at $g^{-1}$. This reflects a high precision of the measurement and a low geological variability (Table 2).

**Table 2: Sample specific characteristics. A bulk density of 2.6 g cm$^{-3}$ is assumed for all samples.**

| Sample ID | Latitude °N (DD) | Longitude °E (DD) | Altitude m.a.s.l. | thickness of sample cm | Topographic shielding factor | 36Cl conc. (atoms g-1) | 35Cl/37Cl | 36Cl/37Cl | Prod. Rate (atoms g-1 a-1) | calc. Age° with 0 mm ka-1 erosion | calc. Age* with 5 mm ka-1 erosion | calc. Age° with 10 mm ka-1 erosion | calc. Age° with 5 mm ka-1 erosion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RG 14/001 | 40.937333 | 20.825389 | 2051 | 2 | 0.964 | 1.07E+06 | 9.231 | 6.981E-12 | 86.26 | 10.75 ± 1.11 | 11.28 ± 1.28 | 11.39 ± 1.39 | 10.78 ± 1.21 |
| RG 14/002 | 40.937417 | 20.825472 | 2050 | 3 | 0.964 | 1.19E+06 | 7.726 | 6.015E-12 | 87.83 | 11.77 ± 1.08 | 12.25 ± 1.17 | 11.32 ± 1.26 | 11.79 ± 1.20 |
| RG 14/003 | 40.937583 | 20.825500 | 2048 | 2 | 0.964 | 1.13E+06 | 8.239 | 6.4E-12 | 87.28 | 11.24 ± 1.18 | 11.74 ± 1.23 | 11.81 ± 1.08 | 11.26 ± 1.09 |
| RG 14/004 | 40.937694 | 20.825361 | 2040 | 2 | 0.967 | 1.10E+06 | 10.555 | 9.138E-12 | 84.80 | 11.26 ±1.13 | 11.90 ± 1.29 | 12.09 ± 1.41 | 11.30 ± 1.29 |
| RG 14/005 | 40.937889 | 20.825056 | 2048 | 6 | 0.969 | 1.21E+06 | 7.623 | 6.151E-12 | 86.29 | 12.18 ± 1.23 | 12.79 ± 1.42 | 13.01 ± 1.31 | 12.21 ± 1.06 |
| Blank B3 | - | - | - | - | - | | 19.452 | 2.70E-13 | | - | - | - | - |

^ total sample specific contemporary depth average production rate

* corrected for snow shielding (2%)

° no snow correction applied

*4.3 $^{36}Cl$ ages*

Exposure ages of the sampled boulders were computed based on the measured Cl isotope ratios. For the calculations, we used cosmogenic $^{36}Cl$ production rates of 56 ± 4.1 at $^{36}Cl$(g Ca)$^{-1}$ a$^{-1}$ for Ca spallation (Marrero et al., 2016), which is the main production pathway, accounting for ca. 90-94 % of $^{36}Cl$ production. K spallation production rates of 155 ± 11 at $^{36}Cl$ (g K)$^{-1}$ yr$^{-1}$ (Marrero et al., 2016) were used, but the impact of this production pathway is low due to the low K content in the samples. Used thermal neutron production rate is 759 ± 180 neutrons (g air)$^{-1}$ a$^{-1}$ (Marrero et al., 2016). Also production via thermal neutron capture is minor as the stable Cl content of the samples is low (Table 2), ranging from ca. 5-7.5 %. Production of $^{36}Cl$ via muons is also subordinated, accounting for ca. 2.5 % of the total production. These production rates are scaled to sea level and high geomagnetic latitude. In order to account for site-specific variations in the atmospheric secondary cosmic-ray flux scaling factors of Lifton et al. (2014) were applied. The surface exposure ages were calculated from the measured $^{36}Cl$ concentrations using the CRONUScalc (Cosmic-Ray Produced Nuclide Systematics on Earth) (accessed October 2016) calculator with the software Matlab® (R2016a, MathWorks®). The calculation allows for corrections for e.g. shielding, which can be due to topographic shielding and snow cover, and erosion. Topographic shielding correction factors as well as the sample-specific attenuation length were determined using the CRONUS calculator. The exposure ages range between 10.8 ka and 12.2 ka, with a mean age of 11.4 ka and a median of 11.3 ka (Table 2) without corrections for erosion and no snow shielding and using of 56 ± 4.1 at $^{36}Cl$(g Ca)$^{-1}$ a$^{-1}$ for spallation. Correction factors are individually discussed in chapter 5.1.

## 5 Discussion

*5.1 36Cl age calculation uncertainties*

The results of the timing of the moraine formation depend on different input parameters used for the age calculations, such as erosion, snow shielding, inheritance, and production rates. A proper discussion of these input parameters is needed to evaluate the robustness of the dating results. Major corrections and assumptions were defined by the following aspects:

(i) **Erosion**: Field observations did not indicate significant erosion of the upper boulder surfaces itself (especially chemical weathering due to dissolution of limestone). However, below the G4 moraine series, limestone surfaces exhibit weathering channels carving several centimeters deep into the rock surface, suggesting dissolution of carbonatic rock surfaces due to precipitation. Chemical weathering of limestone can cause erosion rates of up to 10 mm ka$^{-1}$, according to observations of Ivy-Ochs et al. (2009). A dissolution rate in this magnitude is in accordance with field experiments of (Plan, 2005). Experiments with micro-erosion meters also confirm limestone dissolution rates in the same order of magnitude or even higher (Stephenson and Finlayson, 2009 and references therein). We think that 10 mm $ka^{-1}$ represents a maximum possible erosion rate. However, we propose a lower erosion rate/limestone dissolution rate of 5 mm $ka^{-1}$ since field observations do not suggest any higher limestone dissolution rates on the boulders itself.

(ii) **Snow Shielding:** The combination of Mediterranean as well as continental climate in the region (Watzin et al., 2002), leads to substantial snow cover in the Galicica Mountains in winter (Hollis and Stevenson, 1997). Hence, ignoring the effect of snow could lead to an underestimation of the surface exposure ages. Correction for snow shielding is difficult to assess for several reasons:

i) Climate data from locations with similar altitudes as the sampling site are not available
ii) Climatic conditions likely changed throughout the Holocene
iii) The effect of elevation of boulders on moraine crest is unclear
iv) Topography-related effects on snow accumulation unclear
v) The effect of snow shielding is not completely understood yet

A potential reduction of the production of the target element due to snow cover (Gosse and Phillips, 2001) was partly disproved by Dunai et al. (2014). A hydrogen rich cover, such as from snow, can significantly increase the production rate of certain nuclides (e.g. $^{36}Cl$). However, since the concentration of $^{35}Cl$ is consistently low throughout all five samples, the reinforcing effect of a snow cover is very limited. Hence, we assume that snow cover has a net attenuating effect of the production of $^{36}Cl$. Based on the available literature (Hollis and Stevenson, 1997), we suggest a snow cover of 0.3 m for an average duration of 4 months per year with a density of 0.3 g $(cm^3)^{-1}$, leading to an age correction of approx. 2%, using the equation of Gosse and Phillips (2001).

(iii) **Inheritance**: The exposure ages are very consistent with only minor differences within the analytical uncertainties of the $^{36}Cl$ concentrations. The present debris fans indicate a high supply of new rock material, which leads to a continuous renewal of the cliff surface. According to Putkonen and Swanson (2003) the chance of dating boulders with significant prior exposure is extremely low in settings, where erosion at the source rock delivering rock debris is high. Relatively high temperature differences between day and night cycles as well as frost shattering during winter season might be the driving mechanisms for relatively high physical weathering. Inheritance can thus be ruled out.

(iv) **Production rates**: The amount of studies determining $^{36}Cl$ production rates is still limited and the published rates scatter significantly, particularly for Ca spallation and the muonic contribution. We used production rates recently published by Marrero et al. (2016) for which one out of three calibrations sites are on the same latitude as our study site and the published production rates are scaled to scaling factors of Lifton et al. (2014), to calculate the exposure ages. Since the geographical position of the Galicica Mountains is very close to the sampling sites for production rate studies of Schimmelpfennig et al. (2011), we also tested these production rates, which are in the order of ca. 20-25 % lower for Ca spallation and ca. 2-17 % for K spallation (depending on scaling model, respectively) than those of Marrero et al. (2016), respectively, in order to calculate ages.

The uncorrected ages (Table 2) can be regarded as minimum ages. Applying an erosion rate of 5 mm $ka^{-1}$ does not have any significant impact on the ages but should also not be ignored (Fig. 5). An applied erosion of 10 mm $ka^{-1}$ shows a more significant effect towards older ages in the order of 0.5 - 0.8 ka. We do not suggest that such a relatively high erosion rate applies to the sampled boulders in this particular geological setting, we rather want to illustrate, that erosion as one of the major correction factors has only a minor influence in such young samples. The incorporation of snow shielding (2%) has an impact on the ages to the same degree than the applied maximum erosion rate. In contrast to erosion and snow shielding, the selection of Ca spallation production rates plays a crucial role regarding the impact on the surface exposure ages. Applying the Ca spallation production rate of Schimmelpfennig et al. (2011) yields significantly older ages, ranging from 13.9 to 15.5 ka (uncorrected for erosion). These ages are consistently younger than the time frame assessed for the global last glacial maximum (LGM, 26.5 ka to 19 ka, Clark et al., 2009), even when applying an erosion rate of 10 mm $ka^{-1}$ and consequently, a moraine formation in the course of a deglaciation after the LGM can be excluded. These ages, however, would correspond to the Older Dryas period, but as a consequence, no evidence for a Younger Dryas moraine would then be evident. We favour the recently determined Ca spallation rate of Marrero et al. (2016) and think that the Ca spallation rate of Schimmelpfennig et al. (2011) indicate maximum ages and rather overestimate the surface exposure ages.
In this study because the $^{36}Cl$ concentrations and the calculated ages cluster very closely, we can rule out a significant impact of moraine degradation and assume a permanent exposition of the boulders, which reflect the actual deposition of the moraine. Consequently, only chemical weathering due to precipitation needs to be taken in to account. Hence, the calculated ages range from 11.3 to 12.8 ka (mean 12 ka) after correction for 5 mm $ka^{-1}$ erosion, snow cover and topographic shielding. In this case the glacier advance forming this moraine was centered in the Younger Dryas cold period. The sampled moraine is part of a series of nested moraines located in the cirque. Taking the stratigraphical order into account the sampled moraine is the second oldest one of the G4 moraine sequence. Thus, the moraine likely represents a stage of the glacier stagnation after the maximum advance has already occurred.

*5.2 Galicica moraine ages*

Since the dated moraine is only one part of the G4 moraine series, the deglaciation after the Younger Dryas glacier advance was likely interrupted by stagnations, leading to the multicrested shape of the G4 moraine series.

Assuming that the G4 moraine sequence was formed in the course of the Younger Dryas period, the G3 moraine, which is situated on an altitude of ca. 1930 m a.s.l. was likely formed at either the Oldest Dryas period (ca. 17.5 – 14.5 ka BP), LGM or MIS 6 (ca. 190 – 130 ka BP). Also a moraine formation at the Older Dryas can be possible. Moreover it can be stated, that no glacier advances during the entire Holocene took place, due to a lack of geomorphological evidence.

*5.3 Comparison to glaciation timing of other Balkan Mountain Ranges*

Studies dating glacial retreats are very sparse on the Balkan Peninsula. However, findings in other formerly glaciated areas are in good agreement with the results of this study. The most proximal dated site to the Galicica Mountains is the Šara Range, which is situated at the border of the Republic of Macedonia and the Republic of Kosovo. Kuhlemann et al. (2009) sampled a series of moraines at altitudes between 1355 m a.s.l. and 2300 m a.s.l. for $^{10}$Be surface exposure dating. The lowest moraine yielded ages of 19.4 ± 3.2 ka (1402 m a.s.l., N-facing cirque) , 16.1 ± 2.3 and 12.4 ± 1.7 ka (1398 m a.s.l. and 1355 m a.s.l., respectively, same moraine ridge, NE-facing cirque) and 14.4 ± 2.1 (1776 m a.s.l., S-facing cirque) including corrections for erosion (10 mm ka$^{-1}$), respectively. The inconsistency of the ages is explained by dislocation of some of the sampled boulders. However, the oldest age points to a moraine formation in the course of the LGM, whereas the others could potentially represent recessional moraines (Hughes et al., 2013). At higher altitudes (2020 – 2300 m a.s.l.) moraines were ascribed to the Younger Dryas, with ages from 11.9 ± 1.7 to 14.7 ± 2.1 ka, with the same corrections applied for erosion. The higher altitude of certain Younger Dryas moraines compared to the G4 moraine is not surprising, since there is a precipitation gradient on the Balkan Peninsula, which decreases from west to east (Kuhlemann et al., 2009).

In the Retezat Mountains in Romania, Reuther et al. (2007) investigated glacial features and dated N-facing moraines using cosmogenic $^{10}$Be for surface exposure dating. They identified a Late Glacial glaciation phase clustering around 16.1 ± 0.5 ka, implying that the local LGM was delayed by several thousand years compared to the global LGM, but coinciding with the Oldest Dryas (Heinrich-event H1 ca. 16.8 ca ka BP). However, they also identified a moraine ascribed to the Younger Dryas with $^{10}$Be ages of 11.4 ± 1.3 ka and 13.6 ± 1.5 ka (corrected for 5 mm ka$^{-1}$ erosion, uplift and snow cover). The boulders sampled for dating were not deposited on the moraine ridge, but directly above and below the moraine, representing the time frame of the moraine built-up, which is in good agreement with our results.

Kuhlemann et al. (2013) dated moraines in the Rila Mountains (Bulgaria) using cosmogenic $^{10}Be$. They identified two glacial stages during which moraines were formed. Similar as in the Šara Mountains, the glacier retreats were asynchroneous with the LGM, with moraines dating at the beginning (24 – 23 ka BP) and the termination of the LGM (18 – 16 ka BP). Moraines documenting a glacier retreat at the Oldest Dryas and the Younger Dryas are not dated but suggested based on stratigraphical relationship of geomorphological findings, respectively.

A number of studies exist from Montenegro. Studies of Hughes et al. (2010) on Mt. Orjen revealed the presence of Younger Dryas moraines based on U-Series dating of secondary carbonates in moraines. These moraines are situated approx. 500 m lower than the G4 moraine in the Galicica Mountains. The differences in altitudes can be due to different local topoclimatic factors and much higher precipitation in Montenegro (today ca. 5000 – 6000 mm $a^{-1}$), which may have led to a much thicker sow cover and a lower equilibrium line altitude (ELA).

Also for the Durmitor Massif in Montenegro Younger Dryas moraines are reported by Hughes et al. (2011). Hughes et al. (2006a, 2007b) argue that maximum glacier advances in the Pindus mountains in Greece likely occurred between 30 and 25 ka, based on climate modelling of the pollen record of Lake Ioannina, which would be in agreement with the assumption of Kuhlemann et al. (2013) of dryness during the LGM. However, also evidence for a glacier readvance is reported for the Pindus Mountains (Hughes et al., 2006b).

For Mt. Prokletije at the border to Albania, Milivojević et al. (2008) hypothesize, based on detailed geomorphological mapping, calculation of ELAs and comparison of those to other Mediterranean mountains that the last of a total of three glacier advances occurred during the Younger Dryas. At Mount Lovćen moraine sequences are believed to be of older origin than Younger Dryas, most likely of LGM age (Žebre and Stepišnik, 2014). Precise correlation is not possible due to a lack of a dating of the geomorphological evidence.

The lack of evidence for Younger Dryas glaciation in certain areas might have different causes. Topoclimatic factors, such as regional temperature and precipitation can play a key role for the formation of a glacier. Additional snow availability can be promoted by avalanching, and wind blown snow into a cirque. The latter is likely in the Galicica Mountain range from the plateau topping the cirque. Hughes (2009) proposes that avalanching in front of steep cliffs and snow drift can increase the snow accumulation by a factor of two as shown for present day glaciers at Mount Prokletije (Albania/Montenegro). Moreover, the orientation of the cirque can promote glacier activity. A N-E oriented cirque enables a better shading, which can lead to less ablation due to direct solar radiation (Evans, 1977; Hughes et al., 2006a). This feature is in particular common for glaciations younger than MIS 12 (Hughes et al., 2007a). Also the geology may play a significant role in glacier formation. In the Galicica Mountains, the karstic bedrock may have led to a formation of initial depressions, which then acted as a snow-trap and promoted the accumulation of snow. Also the relatively light color of limestone and, hence, relatively high albedo may have set favourable conditions for a glacier growth (Hughes et al., 2006a). Taken together, these factors can explain the formation of a glacier due to only a modest increase of the local ELA, which was calculated to 2130 m a.s.l with respect to the ELA for the G2-3 glacial phase, (calculated to ca. 2000 m a.s.l.) (Ribolini et al., 2011). This is significantly lower than the calculated ELA (2300 m a.s.l.) for the Šara Mountain range for the Younger Dryas.(Kuhlemann et al., 2009).

*5.4 The Younger Dryas in the sedimentary records of lakes Ohrid, Prespa, Maliq, and Dojran*

It is likely that the dated moraine was formed during a more windy or wet period of the Younger Dryas.

Nearby paleoclimate records reveal a sharp transition from the relatively warm and humid Bølling/Allerød interstadial to the Younger Dryas period (Bordon et al., 2009; Lézine et al., 2010; Panagiotopoulos et al., 2013). Adrop of the mean annual temperature of around 10°C is reconstructed at Lake Maliq (Bordon et al., 2009), and lakes Ohrid and Prespa record (Fig. 1) the last occurrence of ice rafted debris during the Younger Dryas (Vogel et al., 2010a; Aufgebauer et al., 2012). However, the Younger Dryas does not seem to have had constant cold and dry conditions. Bordon et al. (2009) subdivide the Younger Dryas into three periods according to best modern analogue technique using pollen assemblages: whilst 12.8– 12.2 and 11.9 – 11.3 cal ka BP are interpreted as cold and dry, the intermediary interval was slightly warmer and more humid. A paleoclimate record from Lake Prespa indicates rather dry conditions between 13.2 and 12.6 cal ka BP, which were followed by wetter conditions between 12.6 and 11.5 cal ka BP during the overall cold Younger Dryas (Aufgebauer et al., 2012). This is in line with a shift in pollen assemblages, where a decrease in Artemisia and Chenopodiacaea is correlated with an increase in tree taxa (Panagiotopoulos et al., 2013), and with a shift in the diatom assemblages, which suggest increased moisture availability after 12.3 ka BP (Cvetkoska et al., 2014). These findings are also in agreement with those from Lake Dojran, located ca. 160 km to the east of the Galicica Mountains (Fig. 6). Lake Dojran records an extreme lake level low-stand between 12.5 and 12.1 cal ka BP and a subsequent higher lake level during the second part of the Younger Dryas period until 11.5 cal ka BP (Francke et al., 2013). The different climate conditions in the course of the Younger Dryas are not recorded in Lake Ohrid, as its much larger water volume may have buffered some climatic shifts. However, Vogel et al. (2010a) postulate enhanced aeolian supply and a stronger wind activity during the Younger Dryas period in the surroundings of

Lake Ohrid, which potentially promote snow accumulation in the glacier cirque of the Galicica Mountains.

Taking into account the errors of the respective age information for the lacustrine successions as well as for the cosmogenic nuclides, an unambiguous alignment of the G4 moraine formation and the existence of a cirque glacier to one of the described more humid periods during the Younger Dryas is not possible.

*5.5 Imprints of glacial erosion on lakes Ohrid and Prespa?*

Glacial activity usually enhances erosional processes that increase the amount of debris, which is eventually transported into a sedimentary basin such as lakes Ohrid and Prespa. Rather high supply of debris to the lakes would therefore be expected at the onset of the deglaciation (Ballantyne, 2002) and would lead to an increase in the sedimentation rate of both lakes during the Younger Dryas. However, the sediment cores from lakes Prespa (Aufgebauer et al., 2012) and Ohrid (Vogel et al., 2010b) indicate relatively constant sedimentation rates prior, during and after the Younger Dryas. Moreover, increased erosion and transport from Galicica Mountain bedrock should increase the amount of detrital calcite in the sediments of lakes Ohrid and Prespa. However, total inorganic carbon (TIC) is low during the Younger Dryas and isotope investigations on the carbonates in the Lake Ohrid sediments have revealed the formation of calcite is predominantly bound to authigenic precipitation and siderite is formed diagenetically (Lacey et al., 2016).

The lack of a significant imprint of the reconstructed glaciation in the Galicica Mountains during the Younger Dryas on the sediments of lakes Ohrid and Prespa might have three different reasons. Firtsly, the limited number of age control points constraining the time period of the Younger Dryas in the sediment cores Co1202 (Ohrid) (Vogel et al., 2010a) and Co1215 (Prespa) (Aufgebauer et al., 2012) is probably not sufficient to record variations in the sedimentation rates on centennial time scales. Moreover, the regional geological setting with the strongly karstified Galicica Mountain range may have buffered increased erosion and sediment transport to the lakes. River runoff to lake Ohrid only accounts for ca. 25% of the total inflow today (Wagner et al., 2010). Popovska and Bonacci (2007)report that 40 % of the water discharging into Lake Ohrid at St. Naum at its south eastern shore close to the investigated moraine is fed by karstic water derived from Lake Prespa. The remaining 60 % of the inflow at St. Naum originate from direct precipitation over the Galicica Mountains, which, however, drains directly into the karst system (Popovska and Bonacci, 2007). As a result, only small rivers and creeks feed lakes Ohrid and Prespa today, and the majority of water and sediments formed by the Galicica glacier may not have reached the lakes via surficial pathways.

Similar processes were observed at Mount Orjen in Montenegro where glacier-derived headwater became uncoupled from the depositional basin due to the formation of a subterranean karst system (Adamson et al., 2014).

A third explanation for the lack of a significant change in the sedimentation patterns of the lakes during the Younger Dryas is that the glacial erosion was relatively restricted. This seems plausible taking the small distance between the slopes of the cirque and the dated moraine, as well as the high distances to the shoreline of the recovered lacustrine sediment successions in lakes Ohrid and Prespa.

## 6 Conclusions

Five boulders from a terminal moraine in the Galicica Mountains were dated using cosmogenic $^{36}$Cl surface exposure dating on limestones in Macedonia. The ages indicate a moraine formation in the course of the Younger Dryas period based on surface exposure ages centering at ca. 12 ka (corrected for 5 mm ka$^{-1}$ erosion and snow shielding). Corrections for erosion and snow cover have only a minor effect on the age calculation. The calculated exposure ages are in good agreement with several studies on deglaciation chronology from the Balkan Peninsula. The timing of the formation of the glacier is in line with sediment based paleoclimate reconstructions of the adjacent Lakes Prespa and Maliq as well as Lake Dojran located ca. 160 km east of the Galicica Mountains, all of which point to increased moisture availability along with cold temperatures and increased wind activity from ca. 12.5 – 12.1 ka BP onwards.

On the other hand, the dated glacial event did not leave a significant imprint in the sediments of the adjacent lakes Ohrid and Prespa, probably due to insufficient age control points to constrain centennial variations in the sedimentation rates, the strong karstification of the Galicica Mountains and decoupling of erosional transport from the sedimentary basins and the restricted erosional force of the local glacier.

The results of this study display an important contribution to improve the glacial chronology of the Balkan Peninsula and emphasize the necessity of analysing different archives of paleoclimate information.

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Figure 1: A) Overview map with Macedonia highlighted B) Overview map with locations of the Galicica Mountains, Lake Ohrid, Lake Prespa and Lake Maliq, Asterisks mark the City of Ohrid and Resen, respectively, where climate stations are situated C) Digital surface model (DSM) of the cirque with the G4 moraine series. The model was created using structure-from-motion photogrammetry with the software Agisoft Photoscan. (please print as colored image)

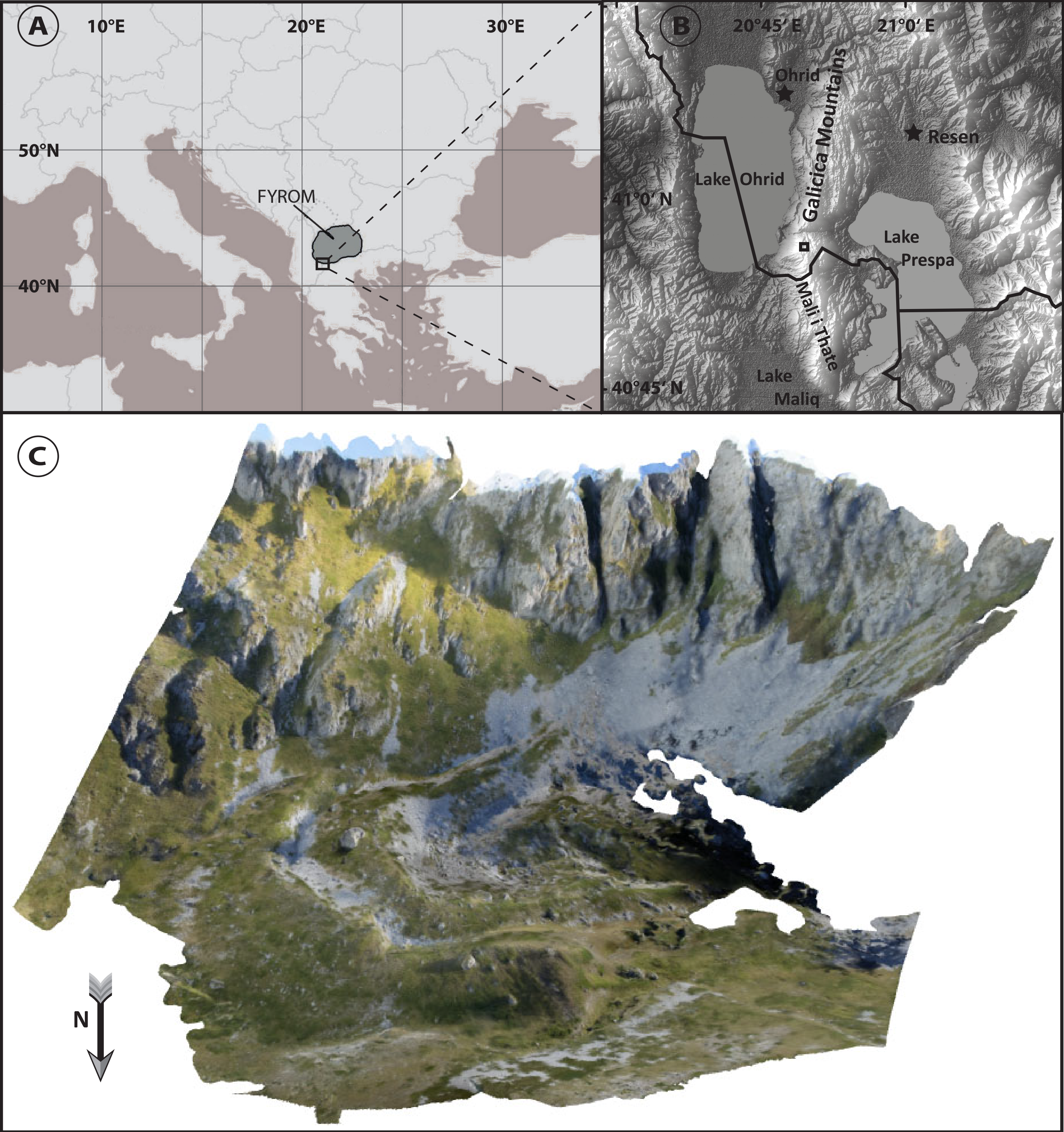
Figure 2: Geomorphological overview map of the two cirques beneath Magaro Mountain. Sampled moraine is highlighted in detail map (modified after Ribolini et al., 2011). (please print as colored image)

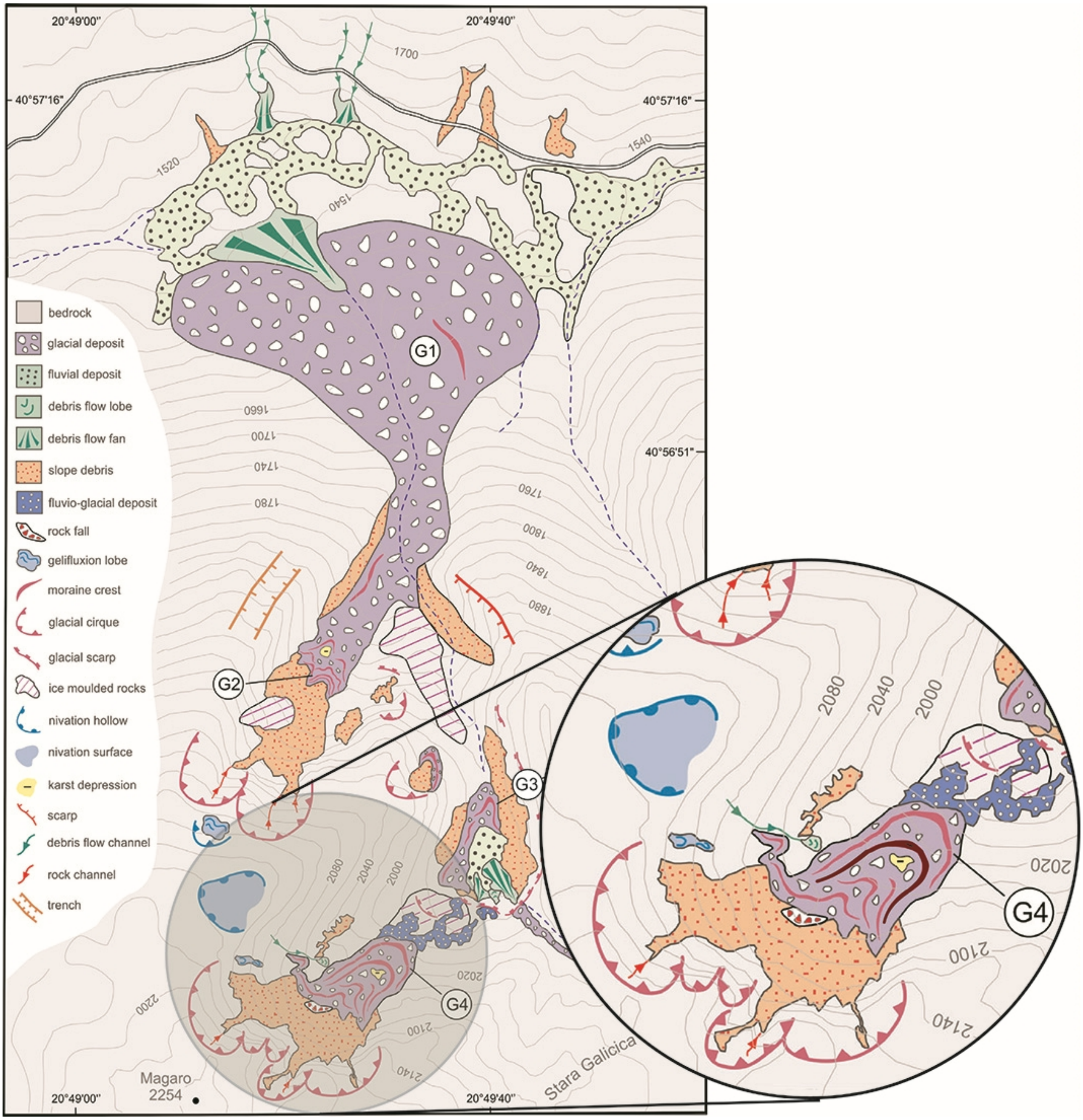
Figure 3: Panorama picture of the sampled moraine. Arrows indicate position of sampled boulders. Picture is taken in downvalley direction, i.e. picture shows inner side of the moraine. (please print as colored image)

Figure 4: Sampled boulders on the moraine crest. Arrows point to exact sampling position on each boulder. Hammer for scale. (please print as colored image)

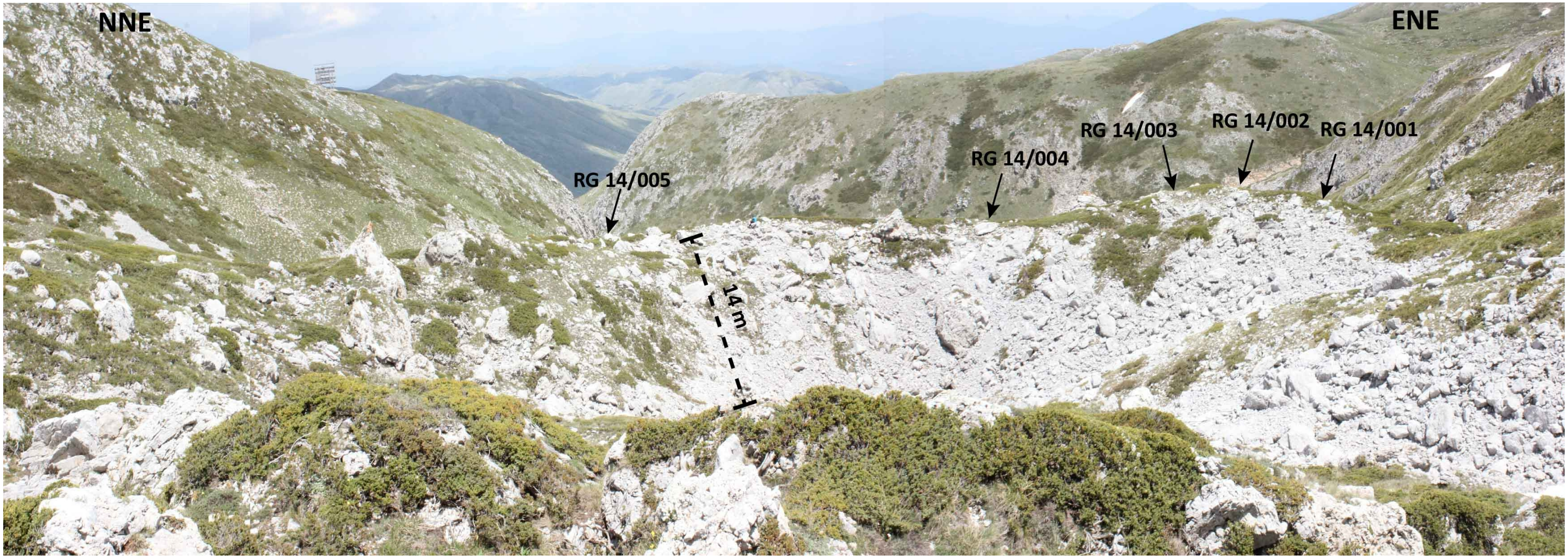
Figure 5: Probability density plots showing the calculated ages. The dashed box reflects the period of the Younger Dryas, blue area the Last Glacial Maximum. Black lines represent normal distribution of the single ages, red line displays cumulative relative probability. Corrections for erosion and snow cover are given in the diagrams, respectively. Thick arrows indicate significant impact of the applied correction on the exposure ages, while thin arrow indicates only minor impact. We used a production rate of $^{36}Cl$ from Ca spallation of 56 at $g^{-1}$ $a^{-1}$ (Marrero et al., 2016) and LSD scaling. (please print as colored image)

Figure 6: Overview map with locations of studied glaciers on the Balkan Peninsula: 1) Durmitor Massif 2) Mt. Orjen 3) Mt. Lovćen 4) Mt. Prokletije 5) Rila Mts. 6) Mt. Tymphi 7) Mt Smolikas 8) Galicica Mts. 9) Šara Mts. Lake Dojran is marked with the red asterisk. Authors corresponding to the Study areas are noted in the text. (please print as colored image)


A
10°E
20°E
30°E
50°N
40°N
FYROM
B
20°45′ E
21°0′ E
Ohrid
Resen
Galicica Mountains
Lake Ohrid
41°0′ N
Lake
Prespa
Mali i Thate
Lake
Maliq
40°45′ N
C
N



20°49'00"
20°49'40"
40°57'16"
40°56'51"
1700
1520
1540
1660
1740
1780
1760
1800
1840
1880
2080
2040
2000
2020
2100
2140
2200
G1
G2
G3
G4
Magaro
2254
Stara Galicica
bedrock
glacial deposit
fluvial deposit
debris flow lobe
debris flow fan
slope debris
fluvio-glacial deposit
rock fall
gelifluxion lobe
moraine crest
glacial cirque
glacial scarp
ice moulded rocks
nivation hollow
nivation surface
karst depression
scarp
debris flow channel
rock channel
trench


NNE
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RG 14/005
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RG 14/002
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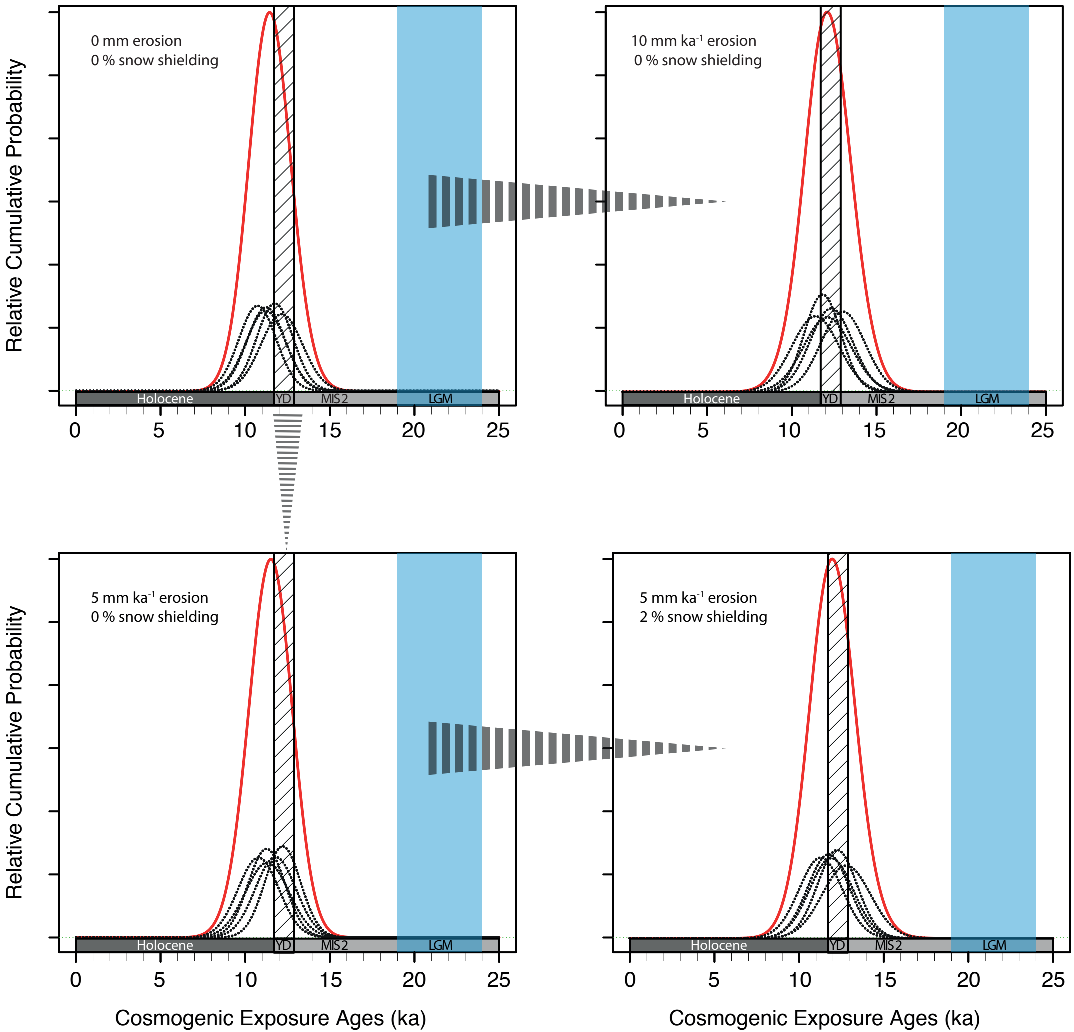
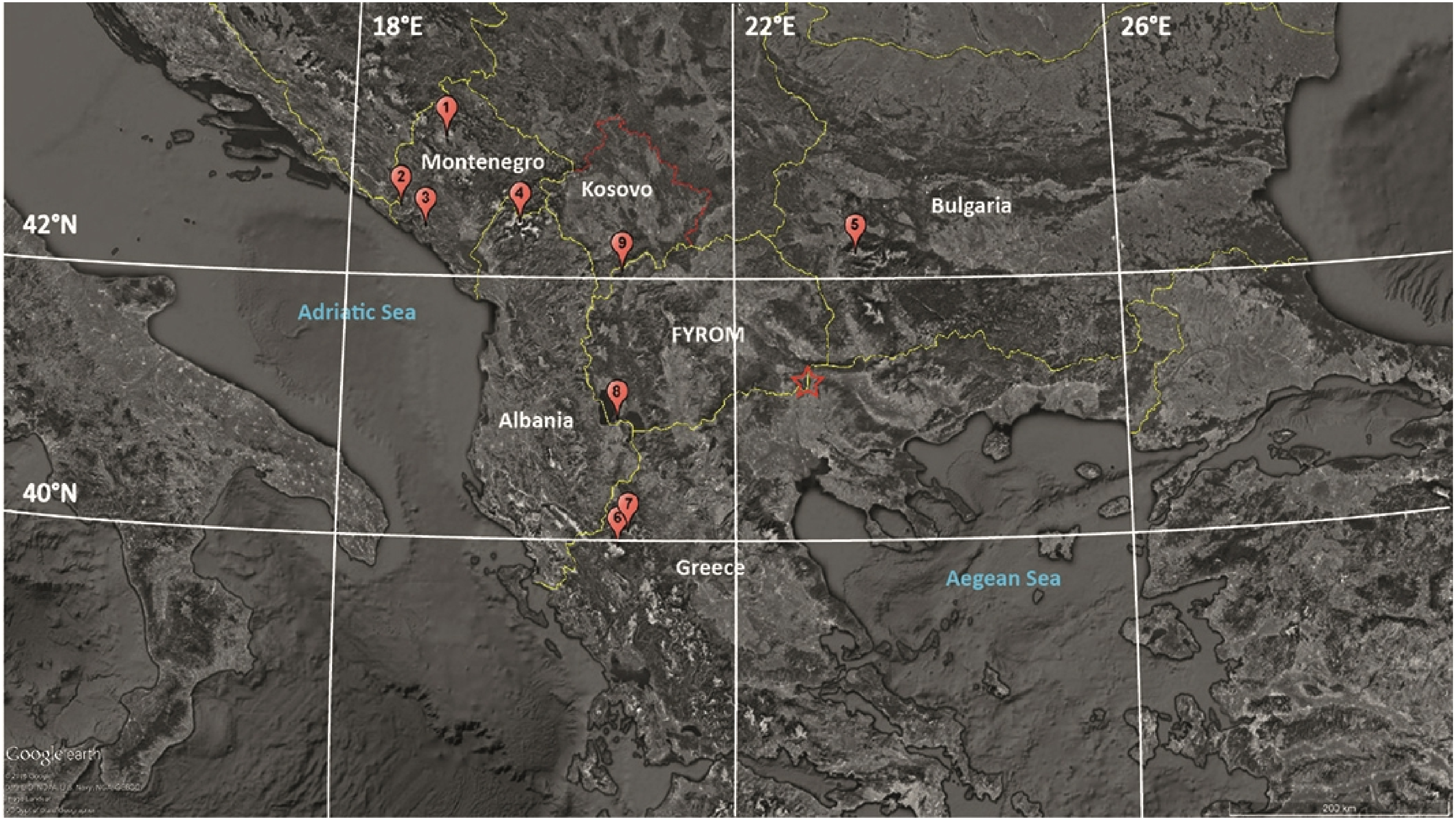


0 mm erosion
0 % snow shielding
10 mm ka-1 erosion
0 % snow shielding
5 mm ka-1 erosion
0 % snow shielding
5 mm ka-1 erosion
2 % snow shielding
Relative Cumulative Probability
Holocene
YD
MIS 2
LGM
0
5
10
15
20
25
Cosmogenic Exposure Ages (ka)



18°E
22°E
26°E
42°N
40°N
Montenegro
Kosovo
Bulgaria
Adriatic Sea
FYROM
Albania
Greece
Aegean Sea
1
2
3
4
5
6
7
8
9
Google earth
200 km