Last glacial maximum deglaciation of the Southern Velebit Mt. (Croatia): insights from cosmogenic ^{36}Cl dating of Rujanska Kosa

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ORIGINAL PAPER

Last glacial maximum deglaciation of the Southern Velebit Mt. (Croatia): insights from cosmogenic ^{36}Cl dating of Rujanska Kosa

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Abstract
Although several types of glacial landforms and deposits were described from different parts of the Croatian Dinarides, up to date there are no quantitative glacial chronological data. Here we present the first cosmogenic ^{36}Cl glacial chronology from the Southern Velebit Mt. from a moraine complex known as the Rujanska Kosa. We sampled four limestone boulders and used 20 mm ka^{-1} erosion corrected ages, as the study area is composed of well-karstified carbonate deposits and located in one of the highest precipitation regions of Europe. The inner Rujanska Kosa ridge yielded an age of 20.7 ± 2.2 ka for the retreat of glaciers in that part of Velebit Mt. A slightly older age was measured from the outer ridge on the left-lateral part of the Rujanska Kosa, which dates back to 22.7 ± 2.7 ka ago. Whilst the ages between inner and outer ridges overlap within error, we can place an age difference between the two moraines to be between 0 and 6.9 ka, supported by the geomorphic evidence that the latter is older. Although we could not perform any geomorphological work higher up in the Rujno paleo-ice field due to the remnant minefields, our results may indicate a Late Pleistocene (i.e. la st glacial maximum) retreat of ice from the Southern Velebit Mt. Despite the small number of valid samples, acquired age data on glacial landforms in Southern Velebit Mt. are in accordance with ages from several other Mediterranean mountain ranges.

Keywords Cosmogenic dating · Moraine · LGM · Rujanska Kosa · Velebit Mt. · Croatia

Introduction

Knowing the timing of deglaciation of past mountain glaciers is key to understand the paleoclimate and environmental changes. It is also important for the cultural changes and adaptation of mountain-dwellers. The most trusted paleoclimate archives of quaternary (known as the *Ice-Age* in popular terminology) are obtained from glaciers. There is a robust connection between glacier mass balance changes and the changes in climate. Glaciers quickly respond to changes in climate by changing their mass balance, and thus their sizes (Oerlemans 2005). Recent studies on the glacial landform dating by quantitative methods (i.e. terrestrial in situ cosmogenic exposure dating, OSL, U-series dating and radiocarbon dating) greatly improved our knowledge of Late Pleistocene and Holocene glaciations of the Mediterranean mountains (Hughes et al. 2013), whereas the age of glacial deposits was earlier assessed solely by relative methods, including stratigraphic relationships, degree of weathering/oxidation and soil/vegetation development.

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Although several researchers have studied glacial history in the Dinarides (Hughes et al. 2010, 2011), quantitative glacio-chronological studies from the Croatian Dinarides are absent, especially for the Late Pleistocene (Hughes and Woodward 2017). The first studies date back to 1899 by the studies of Albercht Penck's journey (Marjanac and Marjanac 2004). Later, Hranilović (1901), Gavazzi (1903) and Schubert (1909) identified glacial stages on the Velebit Mt. Cvijić (1917), in his seminal work, described the glaciations of the southern parts of the Dinarides at the beginning of the twentieth century. Belij (1985) made a more complex geomorphological study at the same location, and reconstructed the flow directions and extent of the corresponding paleo-valley glaciers. Faivre (1991) and Bognar et al. (1991) provided evidence of glaciations in the Central and Northern Velebit Mt. Marjanac and Marjanac (2004) listed 15 key sections for the glacial history of the Croatian Adriatic coastal area (in the Hrvatsko Primorje and Northern Dalmatia) and islands of Krk and Pag.

The erratic deposits identified by Marjanac and Marjanac (2016) within the coastal zone and on some islands in the Adriatic document the presence of Middle Pleistocene glaciation of Dinaric Mountains. The coarse-grained glaciogenic clastic deposits along the costal zone, such as tills/tillites along Velebit Channel and Novigrad Sea coasts (Marjanac and Marjanac 2004; Marjanac 2012) were dated using U-series dating of calcite cements in tills (Marjanac 2012), indicating glacial extent in the region during Middle Pleistocene. However, the maximal ice extent is still unclear as the glacial termini were in the area that was inundated by postglacial sea-level rise (Marjanac and Marjanac 2016).

In the Southern Velebit Mt., the first description of the glacial deposits in the area of the Velika Paklenica Canyon was made by Milojević (1922). Nikler (1973) described a well-preserved "terminal" moraine ridge, named as Rujanska Kosa Moraine (Fig. 1), located at ~ 920 m above sea level (a.s.l.) on a plateau adjacent to the Velika Paklenica Canyon. The moraine was later re-interpreted as a medial moraine of supposedly extensive Middle Pleistocene glaciation (Marjanac and Marjanac 2016). Krklec et al. (2015) implemented diagenesis of carbonate till within this moraine and emphasized the importance of geochronological and paleoclimatological interpretations in carbonate regions.

The glacial landforms on Southern Velebit Mt. were mapped and their lithostratigraphy described in detail (Nikler 1973; Marjanac and Marjanac 2004, 2016; Marjanac 2012; Krklec et al. 2015; Velić et al. 2017; Marjanac et al. 2018). However, because these glacial deposits on Southern

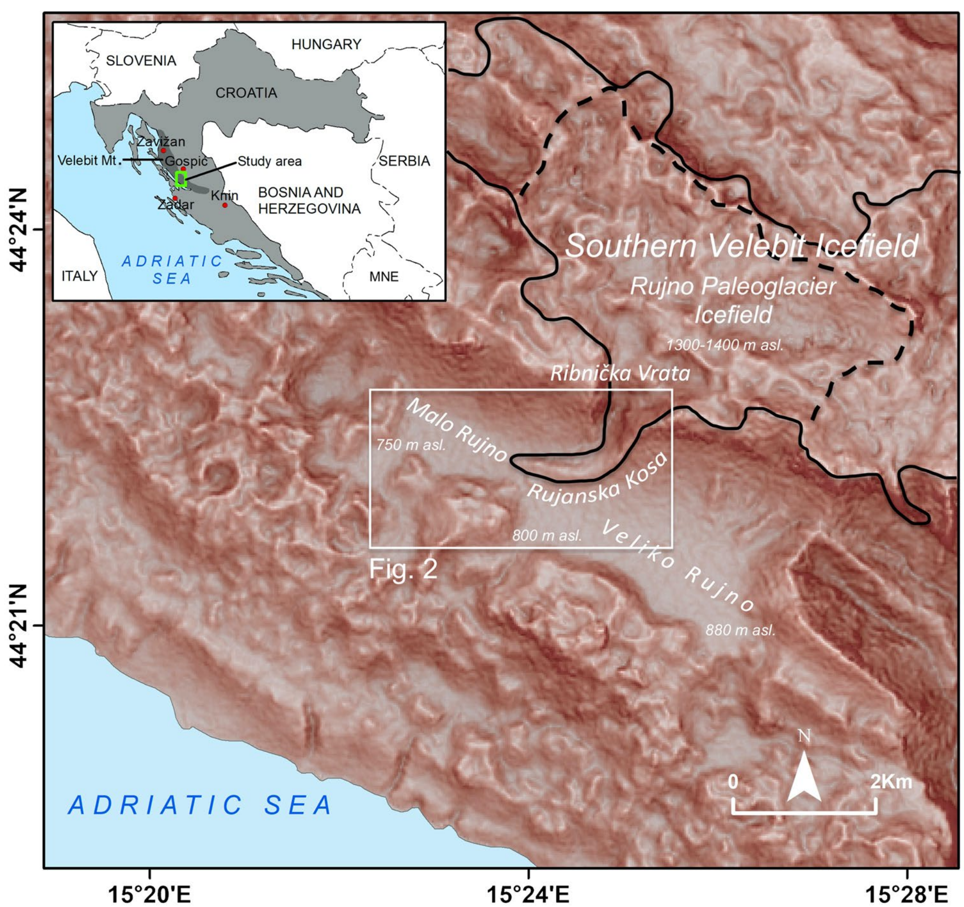

Fig. 1 Location and red relief image map of the study area. Red dots in the inset are weather stations used in this study. Dark gray zone inside Croatia is the Velebit Mt. Paleoglacier icefield areas were adapted from Krklec et al. (2015)

Velebit Mt. have not been dated numerically, the exact timing of glaciations is still unknown, which precludes paleoclimatic interpretation based on the glacial records. Additional issue here represents minefield areas that remained in a close proximity of the moraine as a reminder of the last armed conflict in Croatia (1991–1995) what makes key study areas fairly inaccessible. In this study, we examined the timing (from the age of landforms) of the Rujanska Kosa moraine on the Southern Velebit Mt. using the cosmogenic ^{36}Cl exposure dating method. Results presented here are the first numerical dating results of a moraine in the Southern Velebit Mt. area, and largely in the Velebit Mt., Croatia.

Study area

The Dinarides are located along the eastern Adriatic coast and comprise NW–SE oriented 645 km long fold-and-thrust orogenic belt formed due to collision of Adria Microplate and European foreland (Schmid et al. 2008). It is dissected by elongated lowlands hosting karst poljes (Nicod 2003) (Fig. 1). The External Dinarides, as their coastal part, are predominantly built of Mesozoic carbonates with restricted occurrences of Carboniferous, Permian, Eocene and Miocene clastic and carbonate sedimentary rocks (Vlahović et al. 2005). The Velebit Mt. is composed of a sedimentary sequence several thousand meters in thickness ranging from Carboniferous to Paleogene age, with the final tectonic uplift during the late Eocene–Oligocene and subsequent isostatic uplift during Oligo-Miocene (Vlahović et al. 2005; Środoń et al. 2018).

The Southern Velebit area is a section of the Velebit Mt. positioned in-between mountain passes of Baške Oštarije (boundary towards Central Velebit) and Mali Alan (boundary towards SE Velebit). It occupies the highest peaks of the whole mountain range reaching elevations up to 1757 m a.s.l. at Vaganski vrh. The study area is positioned within SW section of the highest plateau located ~ 10 km NW from Starigrad.

This research focuses on glacial geology and geomorphology of the Rujno Plateau (44.37° N, 15.40° E) positioned on the SW slopes of the Southern Velebit Mt. at ~ 750–880 m a.s.l. (Fig. 1). The whole plateau is ~ 5 km long and ~ 1 km wide, and is predominantly elongated in NW–SE direction. The plateau is surrounded by the highlands to the NE (> 1000 m a.s.l.) and placed around well-karstified rocks hosting deeply entrenched canyons to all other directions.

The Rujno Plateau is divided into two geomorphic domains: Veliko Rujno (meaning *Big Rujno*, 800–880 m a.s.l.) to the SE, and Malo Rujno (meaning *Little Rujno*, 750–800 m a.s.l.) to the NW (Figs. 1, 2). In between, there is a morphological barrier called the Rujanska Kosa moraine ridge (800–980 m a.s.l.), which was first recognized by Nikler ((1973); Fig. 3).

The climate of the study area has mountain characteristics. The mean annual precipitation was 1983 mm for the period 1971–2000 for the Zavižan meteorological station (1594 m a.s.l, 44°49′ N, 14°59′ E), 60 km NW of the study area (Zaninović et al. 2008). However, according to gridded climatology (Zaninović et al. 2008; Perčec Tadić 2010), the precipitation amount in Southern Velebit is higher with respect to Northern Velebit; the highest peaks annually receive more than 3000 mm for the same period. The summer precipitation is only about 18% of the annual precipitation of the region. Most of the precipitation (~ 60%) falls during the fall (Sep, Oct, Nov) and winter months (Dec, Jan, Feb). During the same period (1971–2000), the mean annual temperature at the Zavižan station was 3.8 °C, with mean minimal temperature of the warmest and coolest months being 12.5 °C (July) and − 4.0 °C (February), respectively.

Equilibrium Line Altitude (ELA) for the Last glaciation was estimated between 1217 and 1300 m a.s.l. by Höfer's

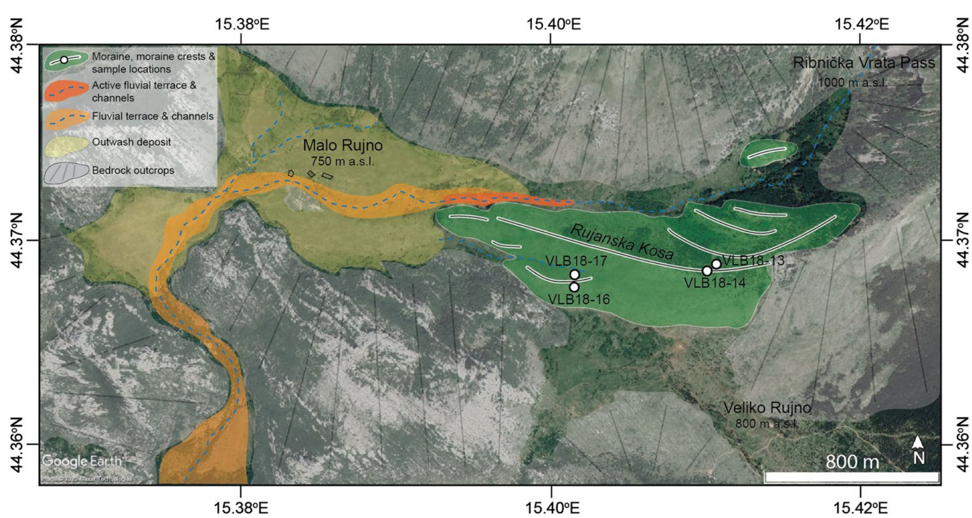

Fig. 2 Detailed geomorphology map of the study area. (adapted from Krklec et al. 2015)

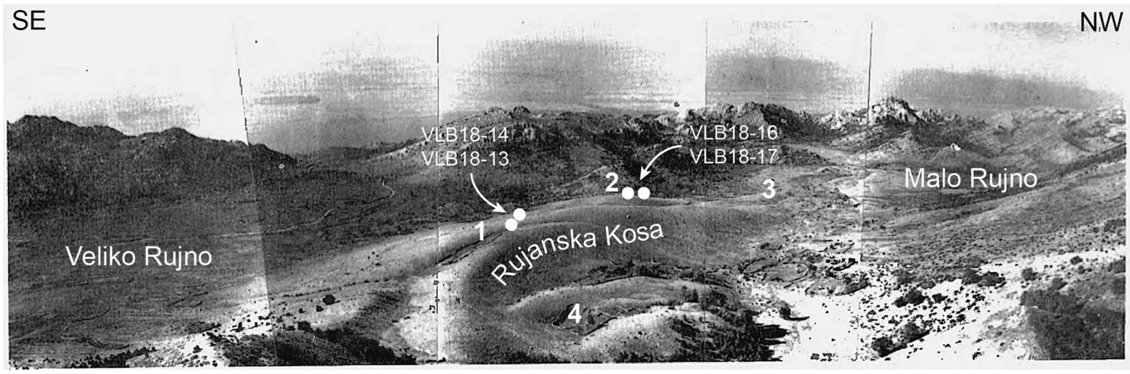

Fig. 3 Rujanska Kosa moraine complex as photographed by Sokač in 1970 and presented in Nikler (1973), with added labels and sample locations, looking to SW towards the Adriatic Sea. 1: main left-lateral moraine crest, 2: outer left-lateral moraine crest, 3: ground moraine and 4: possible small terminal moraine; 3 and 4 were interpreted by Marjanac (2012)

method (von Höfer Heimhalt 1879) on the Southern Velebit Mt. (Belij 1985; Bognar and Faivre 2006). The Northern Velebit had a higher ELA of ~ 1400–1500 m a.s.l. during the Last glaciation (Bauer 1934–1935). There is no recent glacier in the region.

Methods

Fieldwork and mapping

We carried out a fieldwork in 2018 for mapping of the main moraine complex and sample collection. For that purpose, maps produced by Nikler (1973), Marjanac (2012) and Krklec et al. (2015) were also adapted. Satellite images from Google Earth and digital elevation models (DEM) from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) Global DEM (Slater et al. 2011) were also used to prepare base maps. DEM data were converted to hypsometric colored DEM, hill-shade and slope rasters to produce Red Relief Image Map (Fig. 1). Topographic openness, which represents surface concavities and convexities observed from a given Zenith (Yokoyama et al. 2002; Chiba et al. 2007), was computed by SAGA 7.1. software and added to the multi-layered illumination-free images in ArcMap to produce the Red Relief Image Map (Fig. 1).

Cosmogenic surface dating

Cosmogenic ^{36}Cl can be used to date timing of retreat of glaciers in carbonate lithologies. Secondary neutrons and muons are mostly responsible for in situ production of ^{36}Cl via spallation and muon-induced reactions of ^{40}Ca, ^{39}K, and thermal neutron capture reactions of ^{35}Cl, on or near the rock surfaces (Gosse and Phillips 2001; Dunai 2010). Since the production rates of ^{36}Cl via these reactions are known (e.g., Borchers et al. 2016; Marrero et al. 2016a; Phillips et al. 2016), their measured concentrations in rocks can be used to calculate how long these rocks have been exposed at the surface. Spatial and temporal dependency of total ^{36}Cl production can be calculated by the exact location of the sampled site (mainly latitude, elevation and depth) and by the time-dependent change of total production mechanism of the nuclide of interest, respectively.

We collected rock samples from the central-top of the moraine boulders located on the crests of the Rujanska Kosa moraines. About half a kilogram of rocks was plucked by hammer and chisel. The thickness of the samples was recorded along with the shielding angles due to the surrounding topography (Table 1). Sample locations were determined with a handheld-GPS unit with a nominal horizontal accuracy of ± 5 m. The boulders were selected according to their positions on the crest. They were sampled based on their appearance, size and preservation. The biggest and the most stable boulders with strong roots into the moraine matrix were preferred. Sample locations, attributes and local corrections to production rates are shown in Table 1.

Sample preparation

Sample preparation was done at the ITU/Kozmo-Lab (Istanbul Technical University, Turkey) (http://www.kozmo-lab.itu.edu.tr/en) according to the procedures described in Sarıkaya (2009) and Schimmelpfennig et al. (2009). Rock samples were first crushed and ground to the size fraction of 0.25–1 mm. After leaching samples with milli-Q and dilute nitric acid (10%) to remove any meteoric chlorine, Cl was liberated from the rock matrix by dissolving the sample with 400 ml 65% HNO_3 in HDPE bottles. A mixture of natural NaCl (Merc Emsure) and ^{35}Cl (~ 95.28%) enriched Aldrich carrier (Na^{35}Cl) was added to the samples

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

	Sample ID	Latitude (WGS84) °N (DD)	Longitude (WGS84) °E (DD)	Elevation (m)	Boulder dimensions ($L \times W \times H$) (m)	Sample thickness (cm)	Topography correction factor (−)
1	VLB18-13	44.3692	15.4089	944	2.2 × 1.1 × 0.9	4	0.9940
2	VLB18-14	44.3690	15.4085	953	1 × 0.9 × 0.6	2	0.9940
3	VLB18-16	44.3680	15.4013	851	1.1 × 1 × 0.6	2	0.9966
4	VLB18-17	44.3683	15.4013	860	2.5 × 1 × 0.5	3	0.9966

before total dissolution, and chlorine was precipitated by addition of $AgNO_3$. Sulfur (including any ^{36}S isobar) was removed from the samples by two consecutive precipitations as $BaSO_4$ (Mechernich et al. 2019). The chlorine isotopic ratios of the samples were measured with 6 MV SIRIUS Tandem Accelerator in the Australian Nuclear Science and Technology Organization (ANSTO), Sydney, Australia (Wilcken et al. 2017).

The primary and secondary AMS standards are Purdue Z93-0005 ($^{36}Cl/Cl$: 1.2 ± 10^{-12} with natural $^{37}Cl/^{35}Cl$ ratio) and KN supplied by Kunihiko Nishiizumi (1.6 ± 10^{-12} and 5.0 ± 10^{-13}, $^{36}Cl/Cl$ ratios), respectively (Wilcken et al. 2013). The decay constant of $2.303 \pm 0.016 \times 10^{-6}$ year^{-1} used corresponds to a ^{36}Cl half-life of 3.014×10^5 years. The analytical uncertainties include counting statistics, machine stability, and blank correction. Total Cl was determined by the isotope dilution method (Wilcken et al. 2013). The natural chlorine concentrations are low with an average of 29.4 ppm. Major and selected trace element concentrations of all samples were measured at the Activation Laboratories, Inc., Ontario, Canada (Table 2). CaO concentrations of the samples are 55.2%, in average, while K_2O concentrations are below the detection limits (< 0.01%). Rock density of the samples was assumed to be 2.6 g cm^{-3} for all samples. All other required data (e.g., carrier data, mass dissolved, chlorine isotope ratios, procedural blank ratios, etc.) to recalculate the natural ^{36}Cl concentrations were given in the Supplementary Table (Table S1, Appendix 1).

Production rates

We used the ^{36}Cl production rates reported in Marrero et al. (2016a) [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}, which uses CRONUS-Earth production rates (Borchers et al. 2016; Marrero et al. 2016b; Phillips et al. 2016). They were scaled following the time-dependent Lifton–Sato–Dunai method (also called "LSD" or "SF" scaling) (Lifton et al. 2014) and Lal-Stone time-independent method (also called "ST" scaling) (Lal 1991; Stone 2000) for comparison (Table 3). Spallation and negative muon capture reactions by ^{40}Ca are responsible for 92–96% of total ^{36}Cl production, while lesser contribution is from slow neutron capture reactions by ^{35}Cl (4–8%), and almost no contributions from ^{39}K (~ 0.05%). All essential information including the carrier data, Cl isotope ratios, blank concentrations and scaling factors to reproduce resultant ages is given in the Supplementary Table (Table S1, Appendix 1).

Snow correction

Snow correction for spallation reactions was applied to all samples based on climate data in the Climate Atlas of Croatia (Zaninović et al. 2008). We presented two scenarios for the snow correction. For the maximum amount of snow correction, we used the monthly maximum snow thickness data between 1971 and 2000 on the Zavižan weather station (1594 m a.s.l. on the Northern Velebit, ~ 60 km NW and 700 m higher in altitude than our study area). The average snow correction factor is 0.86, and it produced the maximum ages of the moraines. Secondly, we projected the monthly maximum snow thickness data of the nearby weather stations to the sample altitudes. We used four stations including the Zavižan along with Zadar (5 m a.s.l.), Knin (234 m a.s.l.) and Gospić (564 m a.s.l.) stations (Fig. 1, Table 4). The average snow correction factor is then 0.95, and it produced the minimum ages of the moraines.

Exposure age calculations

The exposure ages of the samples were calculated by the CRONUS Web Calculator version 2.0 (http://www.cronuscalculators.nmt.edu) (Marrero et al. 2016b). All ages have corrections for thickness and topographic shielding. 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 age of moraines represents 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.

Table 2 Whole rock chemistry and ^{36}Cl measurements of the samples

	Sample ID	Major elements											Trace elements					^{36}Cl (measured) (10^4 atoms g^{-1} rock)
		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)	Sm (ppm)	Gd (ppm)	U (ppm)	Th (ppm)	Cl (ppm)	
1	VLB18-13	0.02	55.38	0.04	< 0.01	0.52	< 0.01	< 0.01	< 0.01	0.12	< 0.01	43.9	< 0.05	< 0.05	3.00	< 0.2	18.2 ± 0.6	54.202 ± 2.155
2	VLB18-14	< 0.01	55.23	0.07	< 0.01	0.47	< 0.01	< 0.01	< 0.01	0.16	< 0.01	44.0	< 0.05	< 0.05	2.00	< 0.2	29.9 ± 0.9	70.583 ± 2.859
3	VLB18-16	0.05	54.93	0.05	< 0.01	0.54	< 0.01	< 0.01	0.02	0.33	< 0.01	44.0	< 0.05	< 0.05	1.50	< 0.2	40.5 ± 1.3	72.980 ± 2.806
4	VLB18-17	0.08	55.12	0.06	< 0.01	0.45	< 0.01	< 0.01	< 0.01	0.21	< 0.01	44.0	< 0.05	0.09	0.80	< 0.2	29.0 ± 0.8	51.529 ± 2.028

Results

We collected four samples from the multi-crested Rujanska Kosa moraine (Fig. 4 and Appendix 2). Two samples (VLB18-13 and VLB18-14) were collected from the crest of the largest and best developed main moraine ridge (Fig. 5). They were 40 m away from each other. This moraine ridge appears at 970 m a.s.l. and after ~ 1.5 km it terminates at 800 m a.s.l. It rises up to ~ 100 m above its base. It has a curvy shape towards its terminal part (Figs. 1, 3). Apart from the main ridge, we also collected two more samples (VLB18-16 and VLB18-17) on the outer left-lateral part of the main ridge (Fig. 5). This second ridge is ~ 500 m long, 160 m wide and has a low-rolled ridge, ~ 20 m high from its base.

Two samples from the main ridge of the Rujanska Kosa moraine yielded ^{36}Cl ages of 15.7 ± 1.7 ka (VLB18-13) and 20.7 ± 2.2 ka (VLB18-14). Boulders from the outer ridge gave ages of 22.7 ± 2.7 ka (VLB18-16) and 15.8 ± 1.6 ka (VLB18-17) (Table 3). These ages were calculated based on the minimum snow correction factors (i.e. maximum estimated snow thickness from the Zavižan station). Thinner snow depths, estimated from interpolation of weather station's data, yield 10% younger ages (range from 14.0 ± 1.4 to 19.9 ± 2.1 ka). On the other hand, reported ages were calculated using the Lifton/Sato flux, time-dependent (SF) scaling schema. Lal/Stone time-dependent (ST) scaling produces 4% older ages (Table 3).

We reported both zero-erosion and erosion corrected boulder ages (20 and 40 mm ka^{-1} of bedrock weathering assumed) (Table 3) and preferred to use the 20 mm ka^{-1} erosion corrected ages, because the study area is located in one of the high-precipitation regions of Europe, and the denudation rate of similar lithologies with similar precipitation rates range from 20 to 40 mm ka^{-1} (Thomas et al. 2018).

Although we have a small data set, none of the measured ages is more than twice the standard deviation away from the mean of the surface exposure ages (Table 3); therefore, no statistical outliers can be identified. It is likely that the exhumation of the boulders may have an influence on the distribution of the ages. Assuming that inheritance is not a relevant process due to the position and characteristics of the moraine, then the oldest ages from each ridge are likely to best estimate the true depositional age of the moraines.

The oldest age from the main Rujanska Kosa moraine is 20.7 ± 2.2 ka, and the oldest age from the outer ridge on the left-lateral part is 22.7 ± 2.7 ka, indicating a Last Glacial Maximum retreat of the Rujanska Kosa moraine complex. On the other hand, ages calculated with different scaling schemes (Lifton/Sato flux, time-dependent and

Table 3 Cosmogenic surface exposure ages of the samples based on different erosion rates, snow corrections and scaling schemas

Sample ID	Scaling	Erosion uncorrected (0 mm ka^{-1})	Erosion corrected (20 mm ka^{-1})	Erosion corrected (40 mm ka^{-1})	Landform age (ka)[a]
		Corrected with maximum snow thickness data on Zavižan station			
VLB18-13	SF (Lifton/Sato flux, time-dependent)	13.0 ± 1.1	15.7 ± 1.7	23.1 ± 4.1	21.7 ± 1.4
VLB18-14		16.7 ± 1.4	20.7 ± 2.2	42.0 ± 16.0	
VLB18-16		18.4 ± 1.5	22.7 ± 2.7	59.0 ± 35.0	
VLB18-17		13.5 ± 1.2	15.8 ± 1.6	22.9 ± 4.3	
VLB18-13	ST (Lal/Stone time independent)	13.3 ± 1.4	16.2 ± 2.1	21.4 ± 3.8	23.0 ± 1.4
VLB18-14		17.2 ± 1.8	22.0 ± 3.0	39.0 ± 13.0	
VLB18-16		19.0 ± 1.9	24.0 ± 3.5	50.0 ± 25.0	
VLB18-17		13.7 ± 1.4	16.0 ± 2.0	21.1 ± 3.7	
		Corrected with interpolated maximum snow thickness using four stations at different altitudes			
VLB18-13	SF (Lifton/Sato flux, time-dependent)	12.0 ± 1.0	14.2 ± 1.5	20.0 ± 3.0	19.5 ± 0.6
VLB18-14		15.3 ± 1.3	19.0 ± 2.0	31.1 ± 9.3	
VLB18-16		16.7 ± 1.4	19.9 ± 2.1	40.0 ± 10.0	
VLB18-17		12.0 ± 1.0	14.0 ± 1.4	19.0 ± 3.0	
VLB18-13	ST (Lal/Stone time independent)	12.2 ± 1.2	14.6 ± 1.8	18.1 ± 2.8	20.1 ± 1.1
VLB18-14		15.8 ± 1.6	19.3 ± 2.6	28.7 ± 6.8	
VLB18-16		17.1 ± 1.7	20.8 ± 2.8	32.8 ± 9.1	
VLB18-17		12.4 ± 1.2	14.3 ± 1.7	17.3 ± 2.6	

[a]Landform age is based on arithmetic average of maximum erosion corrected (20 mm ka^{-1}) ages of sampled surfaces

Table 4 Monthly maximum snow thicknesses (cm) for the 1971–2000 (from Zaninović et al. 2008)

Station	Elev. (m, asl)	Months											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Zadar	5	15	13	5	0	0	0	0	0	0	0	1	19
Knin	234	32	24	7	0	0	0	0	0	0	0	5	40
Gospić	564	82	117	58	62	10	0	0	0	0	9	95	91
Zavižan	1594	230	287	320	298	272	106	3	5	18	87	122	167

Lal/Stone time-dependent) and different snow correction scenarios (maximum/minimum snow thicknesses) are also presented in Table 3.

Discussion

Uncertainties related to cosmogenic ^{36}Cl nuclide dating

Several types of uncertainties, such as analytical, production rate, geological and geomorphological uncertainties, should be taken into account when interpreting exposure ages. The geological and geomorphological uncertainties can be sometimes important especially in carbonate-dominated areas principally related to chemical dissolution, moraine degradation, reworking and exhumation of boulders, prior-exposure (inheritance), and shielding by vegetation and/or snow cover. Except the inheritance issue, all of the above-mentioned complications underestimate the true age of the landform. The inheritance refers to the retention of remnant cosmogenic nuclides from a previous episode of exposure (Gosse and Phillips 2001). For example, a rock sampled on a moraine crest may contain some residual cosmogenic nuclide inherited from a time when the rock was exposed on a cliff face prior to deposition by a glacier. However, it is shown that the moraine boulders have little inheritance due to the excessive erosional features of glaciers (Schmidt et al. 2011), and relatively short transport distances compared to fluvial sediments. The clustering of ages gives strong indication that inheritance is small for our samples.

On the other hand, carbonate rocks in moraines are subject to diagenetic processes such as chemical dissolution or cementation (Boggs 2009; Krklec et al. 2015). Rainwater is sub-saturated in carbonate minerals, and the solution gets more acidic after passing through soils. Chemical

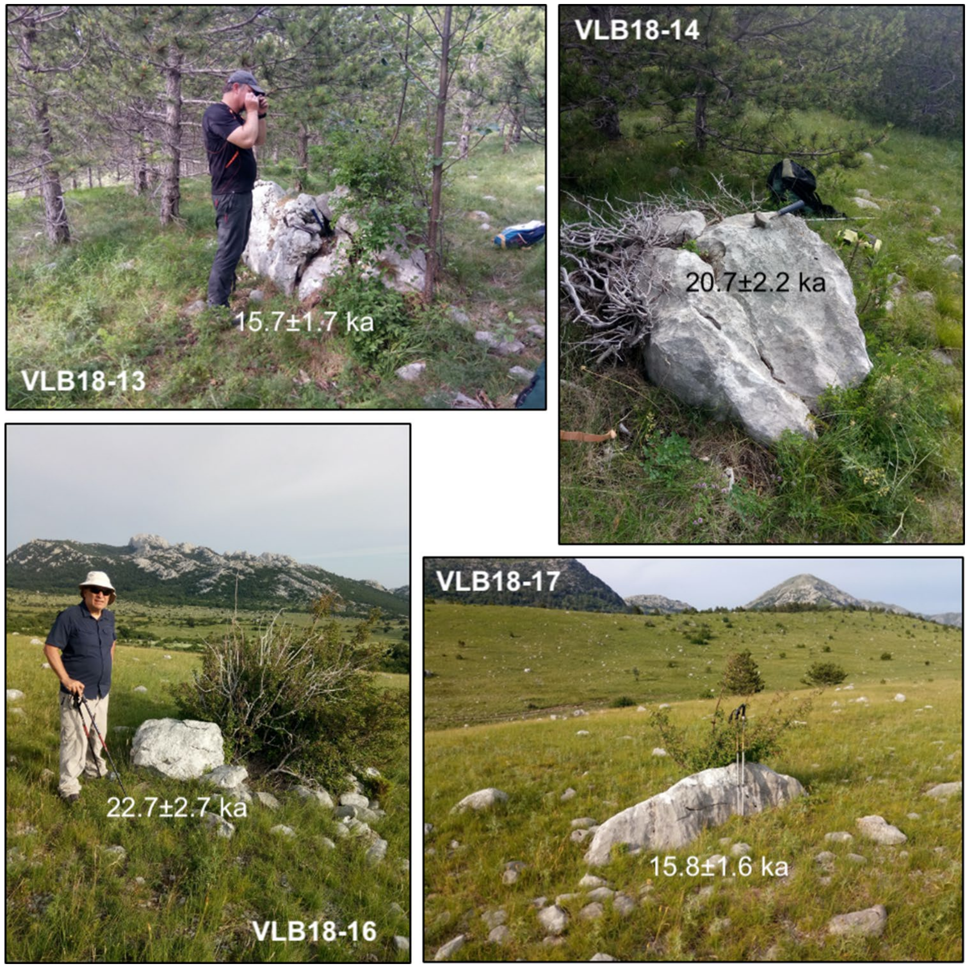

Fig. 4 Field photographs of the sampled boulders with cosmogenic exposure ages

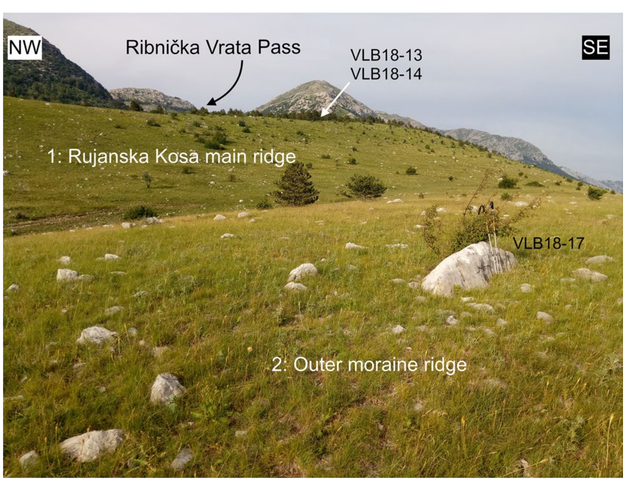

Fig. 5 View of the Rujanska Kosa moraine complex with sample locations. 1: main left-lateral moraine of the Rujanska Kosa, 2: outer left-lateral moraine ridge

dissolution takes place on deposited glacial sediments, and consequently, the dissolution of carbonate re-precipitated between sediments could impact the preservation of till, and thus moraine landforms. Glacial striations and other small erosive features are diagnostic evidence for the extent of glaciers in regions that lack other indicators (Reading 1996; Glasser and Bennett 2004). Our samples show little evidence of glacial striations, however, couple of cm-deep solution groves and karrens may indicate significant chemical dissolution. 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} (Žebre et al. 2019). 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 of Bosnia and Herzegovina, Žebre et al. (2019) applied denudation rate of 40 mm ka^{-1} even though previous studies in the Balkans did not apply denudation corrections in cosmogenic dating (e.g. Pope et al. 2015) or used rather low rates like 5 mm ka^{-1} (e.g., Gromig et al. 2018; Styllas et al. 2018). Here, we decided to use 20 mm ka^{-1} as the denudation rate of moraine boulders, because the precipitation rates are not much different from those in the central-eastern Dinarides of Bosnia and Herzegovina. However, for the sake of comparison we also provided the exposure ages calculated by a higher erosion rate (i.e. 40 mm ka^{-1}; Table 3).

Another uncertainty arises during the interpretation of a moraine landform age from the dated boulders in deciding whether to take the oldest boulder age within a cluster or weighted average age of boulders after the exclusion of outliers (e.g., Putkonen and Swanson 2003; Heyman et al. 2011; Applegate et al. 2012; Çiner et al. 2017; D'Arcy et al. 2019). In this study, we used the oldest boulder age as the age of the landform, assuming that the erosion of boulders in karstic terrains and degradation of moraines in humid environments are the two most important factors that influence the age. We refer the readers to Žebre et al. (2019) for further discussion related to this issue, especially focused on the climatic conditions specific to the Dinaric Mountains. Detailed discussions on moraine boulder age interpretations are also described in Palacios et al. (2019), and in the Appendix of D'Arcy et al. (2019).

Interpretation of the Velebit Mountain glaciation

Several authors (Nikler 1973; Belij 1985; Marjanac and Marjanac 2004; Krklec et al. 2015; Velić et al. 2017) studying former glaciations in the Southern Velebit area agree that this part of the Velebit Mt. was covered by an icefield sometime during the Late Quaternary with several outlet glaciers flowing down from the highlands (Fig. 2). Our study is focused on the chronology of the Rujanska Kosa terminal moraine that was deposited by an outlet glacier flowing down from the Rujno icefield, whose accumulation area was estimated at 19.5 km^2 (Krklec et al. 2015). Although some previous studies (Marjanac and Marjanac 2004) suggest this moraine could be a medial moraine of a larger glacier, most of the studies (Nikler 1973; Belij 1985; Krklec et al. 2015), including ours, support the initial interpretation of Nikler (1973) that this is a terminal moraine. The morphostratigraphical evidence for that was recently presented by Krklec et al. (2015), who interpreted that the sediment building the main moraine ridge has characteristics of a melt-out till deposited in a supraglacial environment, while the outer ridge is mainly composed of a lodgement till deposited at the base of a glacier. The latter is covered only by a thin layer of a supraglacial deposit and its location proximal to the moraine crest suggests that this outer moraine has been subject to a substantial post-glacial degradation, estimated to at least 3 m by Krklec et al. (2015). Considerably smoother crest morphology of this moraine with respect to the crest of the main moraine ridge further supports such interpretation.

Žebre et al. (2019) estimated the degradation rate of lateral moraines in the Velež and Crvanj mountains (Bosnia and Herzegovina) to be of the order of 20 m since the Lateglacial. Although a substantial difference exists in the intensity of degradation among different types of moraines, we assume that the moraine degradation of a minimum 3 m is a very conservative estimation. Thus, our ages should be taken as the minimum ages of moraine stability.

In our study, we went further to support the morphostratigraphy with absolute dating. The cosmogenic age of the main Rujanska Kosa moraine was calculated to 20.7 ± 2.2 ka, while the outer ridge on the left-lateral part yielded 22.7 ± 2.7 ka. The two ages of this multi-crested lateral moraine confirm the assumption of the majority of previous studies that suggested the Last Glacial Maximum age for this moraine. Both morphostratigraphy and absolute dating have confirmed that the outer ridge is older than the main ridge. The absolute dating suggests this age difference to be of the ~ 2 ka order. However, the difference in morphostratigraphy between the two ridges indicates a more pronounced degradation of the outer ridge, which can have a great influence on the age of samples because of the exhumation of boulders caused by erosion of the moraine, resulting in cosmogenic ages being younger than the true depositional ages. It is therefore very likely that the true age of the outer ridge is older than the one yielded by exposure dating.

According to the existing glacial geological, geomorphological and chronological evidence, we can only make a very rough estimation of the extent of the icefield covering the Southern Velebit Mt. during the Last Glacial Maximum. The area covered by the icefield is estimated to be at least 50 km^2 (Krklec et al. 2015). This reconstruction is based on the assumption that all the lowest moraines surrounding the mountain were deposited at the same time as the Rujanska Kosa moraine. Nevertheless, more chronological data are needed in the future for an improved empirical reconstruction and its validation with numerically modelled simulations of former glaciers in this area.

Selected glacial chronologies from the Mediterranean Mountains

Several studies have documented geomorphological evidence of former glaciations in the Dinaric Mountains (e.g. Milivojević et al. 2008; Žebre et al. 2013, 2016; Žebre and Stepišnik 2014, 2016), but only few presented chronological evidences, supported by absolute dating methods. Our glacial chronological data from the Southern Velebit Mt. are in good agreement with the cosmogenic nuclide dating data from other parts of the Balkan Peninsula. LGM glaciations have been reported from the Rila Mountain in Bulgaria (23.5–14.4 ka; 0 mm ka^{-1} erosion rate; ^{10}Be exposure dating; Kuhlemann et al. 2013), Šar Planina Mt. in North Macedonia (19.4 ± 3.2 to 12.4 ± 1.7 ka; 10 mm ka^{-1} erosion rate; ^{10}Be exposure dating; Kuhlemann et al. 2009), Čvrsnica Mt. in Bosnia and Herzegovina (22.7 ± 3.8 ka; 40 mm ka^{-1} erosion rate; ^{36}Cl exposure dating; Çiner et al., 2019) and Mount Chelmos in Greece (22.9 ± 1.6 to 21.2 ± 1.6 ka; 0 mm ka^{-1} erosion rate; ^{36}Cl exposure dating; Pope et al., 2015). Relatively large LGM icefields and/or valley glaciers several kilometers long have been reported from the Rila Mt., Šar Planina Mt. and Čvrsnica Mt., which is in good agreement with our results and suggest that majority of well-preserved glacial features reaching the lowest altitudes within individual mountain range present a record of the last major glaciation, dating to LGM. Large LGM icefields and several kilometers long valley glaciers have also been reported from Durmitor Massive in Montenegro (Hughes et al. 2011). The Late Pleistocene (probably LGM) glaciers in the Durmitor that were merged together with glaciers occupying Moračke Planine, have extensive ice-fields and outlet glaciers reaching 5–6 km in length (Hughes et al. 2011). Elevations of their terminal moraines are higher than the Rujanska Kosa in Croatia (reaching down to < 1500 m a.s.l.). This might be a result of enhanced continental climate effect due to altered position of coastline during the LGM. The same holds true for the Eastern Mediterranean (Sarıkaya and Çiner 2017), where the maximum extent of Last Glaciation occurred during the LGM in wetter southwest Turkish coastal mountains (Sarıkaya et al. 2008; Bayrakdar et al. 2017), while interior (Sarıkaya et al. 2009) and northwestern Anatolia (Akçar et al. 2017; Reber et al. 2014) experienced more drier conditions than today (Sarıkaya et al. 2014).

Conclusion

Our results are the first cosmogenic surface exposure dating data from the Southern Velebit Mt. of Croatia. Four glacial boulders from a well-preserved "terminal" moraine complex, named Rujanska Kosa moraine were dated by in situ cosmogenic ^{36}Cl. The inner Rujanska Kosa ridge yielded an age of 20.7 ± 2.2 ka for the retreat of glaciers. A slightly older age was measured from the outer and more subdued crest on the left-lateral part of the main ridge and dates back to 22.7 ± 2.7 ka ago. Due to the geological and geomorphological uncertainties our ages should be considered as the minimum retreat ages of glaciers from the Southern Velebit Mt. Results presented here are in accordance with other mountains in Dinaric mountain chain, Balkan Peninsula and Anatolia.

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Compliance with ethical standards

Conflict of interest The authors declare no competing financial interests.

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