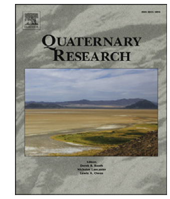
Quaternary Research xxx (2016) 1–11

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: http://www.journals.elsevier.com/quaternary-research



The extent of middle Pleistocene ice cap in the coastal Dinaric Mountains of Croatia

Tihomir Marjanac [a, *], Ljerka Marjanac [b]

[a] University of Zagreb, Faculty of Science, Department of Geology, Horvatovac 102a, 10000 Zagreb, Croatia
[b] Croatian Academy of Sciences and Arts, Institute of Quaternary Paleontology and Geology, Ante Kovačića 5, 10000 Zagreb, Croatia

A R T I C L E I N F O

Article history:
Received 28 August 2015
Available online xxx

Keywords:
Dinarides
Krk Island
Rab Island
Velebit Mt.
Pleistocene glaciation
Erratic blocks
Tills
Depositional processes
Glaciogenic sediments

A B S T R A C T

Solitary limestone blocks and groups of blocks occur on Risnjak and Velebit Mountains and on the northern Adriatic islands of Krk and Rab. Previous researchers have interpreted some of these as a) erratic blocks, b) corrosional remnants, or c) rock-falls. We have studied their mode of occurrence and composition, and revised previous interpretations of their origin in the light of transport mechanism and depositional processes. After analyzing the context of the block positions and the physical processes responsible for their emplacement, and taking into account their sedimentological context (their association with glaciogenic sediments), we herein propose a glacial origin for most of these blocks. However, some blocks are indeed shaped by sub-soil corrosion, as evidenced by their structure. The interpreted erratic blocks on the inner northern Adriatic Sea islands document the presence of middle Pleistocene glaciation of Dinaric Mountains though not its maximal extent, which is still unclear as the ice terminus was in the area that is inundated by postglacial rise of Adriatic Sea. The reconstructed ice cap area, which extended along the coastal mountains from Risnjak Mt. to south Velebit Mt. and across the range from Lika Polje to Rab Island, is conservatively estimated to be 5400 km^2.

Introduction

The extent of Pleistocene glaciation in SE Europe has been a controversial issue since the early 20th century and continues to be, primarily due to the lack of apparent geomorphological evidence of glacial processes and products that were sought by some researchers. This is an important issue because the full extent of the Pleistocene ice cover in Europe and its climatic consequences remain unclear. Glaciation in the Mediterranean region recently became a research target; current data show that the mountains and some islands were glaciated (Hughes et al., 2006a). Herein we document the conservative extent of the ice cap in the NE part of the Adriatic Sea coast, which reached ca. 100 m below the modern sea level and spread from the coastal Velebit Mountain to some inner Adriatic islands.

The early proponents of glaciation of the coastal Velebit Mt. (part of the Dinaric mountain range (a.k.a. Dinarides)) (Fig. 1) were inspired by geomorphological evidence, but their interpretation was not accepted by the geological community (Marjanac and Marjanac, 2004). The first convincing geomorphological evidence of glaciation of the Velebit Mt. was provided by Nikler (1973), and the first radiometric dating of glaciogenic sediments was provided by Marjanac (2012).

Velebit Mt. has been studied for the geomorphological evidence of Pleistocene glaciation by various authors (see references in Marjanac, 2012). The study of Pleistocene glaciation was also conducted on the islands of Krk, Rab and Pag (Marjanac and Marjanac, 2004; Marjanac, 2012), which face Velebit Channel.

However, there is abundant sedimentological evidence of glaciogenic origin of coarse-grained clastic deposits along the coastal Dinarides, such as tills/tillites along Velebit Channel and Novigrad Sea coasts (Marjanac and Marjanac, 2004; Marjanac, 2012). Their approximate chronostratigraphy was established upon results of the U-series dating of calcite cements in tills (Marjanac, 2012); thus the Dinaric glaciation ice expansion happened during middle Pleistocene. The paleobotanical study of middle Pleistocene paleoclimate in coastal part of Velebit Mt. and Velebit Channel revealed mean annual temperatures of 2.89–5.51°C (depending on the research method) and annual precipitation of 679 mm (Blazic et al., 2013). This contribution aims to help reconstruct the extent of

* Corresponding author.
E-mail addresses: marjanac@geol.pmf.hr (T. Marjanac), ljerka@hazu.hr (L. Marjanac).

http://dx.doi.org/10.1016/j.yqres.2016.03.006
0033-5894/

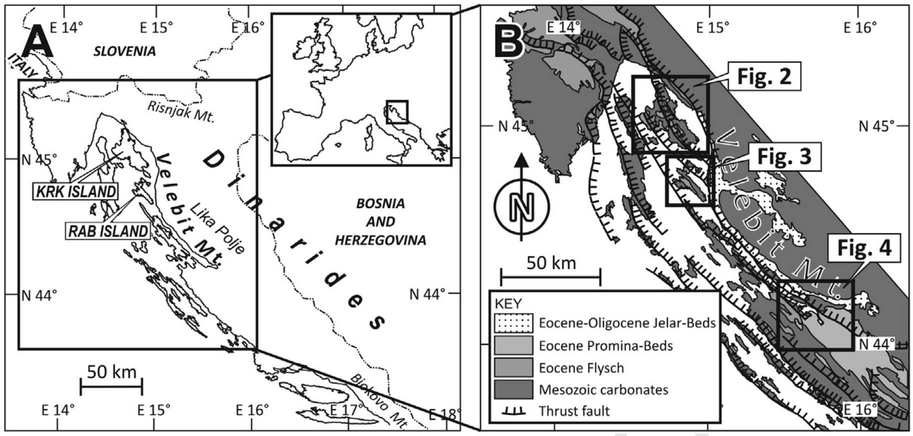


Figure 1. A) Location map of the study area in the Croatian Dinarides. B) Geological map of the study area, simplified after Oluić et al. (1972).

glaciation and paleoclimatic conditions during middle Pleistocene in SE Europe.

The field study of Pleistocene sediments in the northern part of coastal Dinarides revealed a large number of solitary (erratic) limestone blocks at different positions in modern topography, some resting on mogote summits and mountain slopes and in valleys. The majority of erratic blocks in the study area were unrecognized as glacial products by previous authors, except the few on the Risnjak Mt. (Bognar and Prugovečki, 1997), northern Velebit Mt. (Bognar et al., 1991a, 1991b) and southern Velebit Mt. (Belij, 1985a, 1995b), which they attributed the late Pleistocene age but without discussing their lithological difference with the bedrock. Many of these blocks are located where there is no nearby higher topography from which they might have been emplaced by rock-fall.

Historically, the first account of the glaciogenic origin of erratic blocks (then called "great Stones") in the valley of Chamonix was provided by Martel (1744, p. 349). De Saussure (1779) called them "blocs adventifs" and speculated that they were transported by water. The term "blocs erratique" was coined by Fortis (1802, p. 391), whereas Agassiz (1838) and von Charpentier (1841) attributed them to the glacial transport. The erratic blocks are currently considered to be one of several major diagnostic features that document the extent of ancient glaciations, and their recognition may help to understand extreme climates of the past.

Herein we describe several large blocks (over 1 m^3 in volume) recognized in Croatian coastal Dinarides, and we present arguments for their glacial origin versus the alternative interpretations (rockfalls, corrosional remnants) proposed in the local literature. We use the term "erratic blocks" for blocks that are lithologically/stratigraphically different from the bedrock, and also for those that do not differ from the bedrock but were apparently transported from some distant sources.

Study areas and geological setting of erratic blocks

The study areas are located in coastal part of the Croatian Dinarides and the North Adriatic islands of Krk and Rab (Fig. 1). The Dinarides strike NW–SE for 645 km along the eastern Adriatic Sea and comprise NW–SE striking elongated mountain chains that are divided by deep valleys, usually referred to as karst poljes.

Dinarides are predominantly built of Mesozoic carbonates with restricted occurrences of Carboniferous clastics and Permian carbonates and clastics, which are locally exposed in tectonic or erosional "windows" (Herak, 1997). The Cenozoic deposits in the study area are represented by Eocene limestones attributed to so-called Foraminiferal Limestones, and clastics attributed to the Eocene flysch and Eocene-Oligocene molasse (Marjanac and Ćosović, 2000), which occur along the eastern Adriatic Sea coast and at some inland localities. The Eocene limestones occur only in coastal parts of the Dinarides, including many of the eastern Adriatic Sea islands, but nowhere on the coastal Velebit Mt. (Mamužić et al., 1969; Šušnjar et al., 1970; Grimani et al., 1973; Mamužić and Milan, 1973). The Dinaric strike (NW–SE) of geological structures influenced the development of modern topography.

Dinarides are typical karst area (Herak, 1972) with the whole spectrum of karst forms present in the study area. The age of karstification is currently unknown, except for the subterranean karst in Slovenia, whose sediments were dated as over 5 Ma old (Zupan Hajna et al., 2010). The occurrence of paleo-karstified blocks in the Velika Paklenica cemented till (dated as over 350 ka old; Marjanac, 2012) indicates that karstification of the Velebit Mt. commenced well before the middle Pleistocene glaciation. Furlani et al. (2009) reported modern limestone corrosion as surface lowering rate for the "Classical" Karst and inland Istrian karst of 9 and 18 μm/yr, respectively.

Krk Island

Baščanska Draga valley on Krk Island (Fig. 2) is a structurally faulted syncline comprising early to middle Eocene Foraminiferal Limestones overlain by middle Eocene "Transitional" Limestones (or "beds") with "Flysch" in the syncline core (Mamužić et al., 1969; Mamužić and Milan, 1973). Patches of polymict to monomict breccia of presumed late Eocene to early Oligocene age disconformably overlay Cretaceous limestones (Mamužić et al., 1969; Šušnjar et al., 1970). The youngest deposits on Krk Island are Quaternary clastic sediments (breccias, sand, gravel) (Mamužić et al., 1969; Šušnjar et al., 1970); however, those exposed in the Baščanska Draga valley were reinterpreted as glaciogenic deposits (Marjanac and Marjanac, 2004; Marjanac, 2012).

Rab Island

Rab Island comprises two anticlines with Cenomanian-Turonian limestones in the cores and two synclines with Eocene clastics in their cores (Mamužić, 1962; Mamužić et al., 1969) (Fig. 3). The "main" anticline forms the 410-m-high island ridge Kamenjak, whereas the anticline on the Kalifront Peninsula is eroded, forming a low plateau dissected by numerous gorges. The Rab synclines are built of Eocene Foraminiferal Limestones and "Transitional" Beds and clastics, which are referred to as "flysch" (Mamužić, 1962; Mamužić et al., 1969). The Rab Island also hosts thin polymict

Please cite this article in press as: Marjanac, T., Marjanac, L., The extent of middle Pleistocene ice cap in the coastal Dinaric Mountains of Croatia, Quaternary Research (2016), http://dx.doi.org/10.1016/j.yqres.2016.03.006

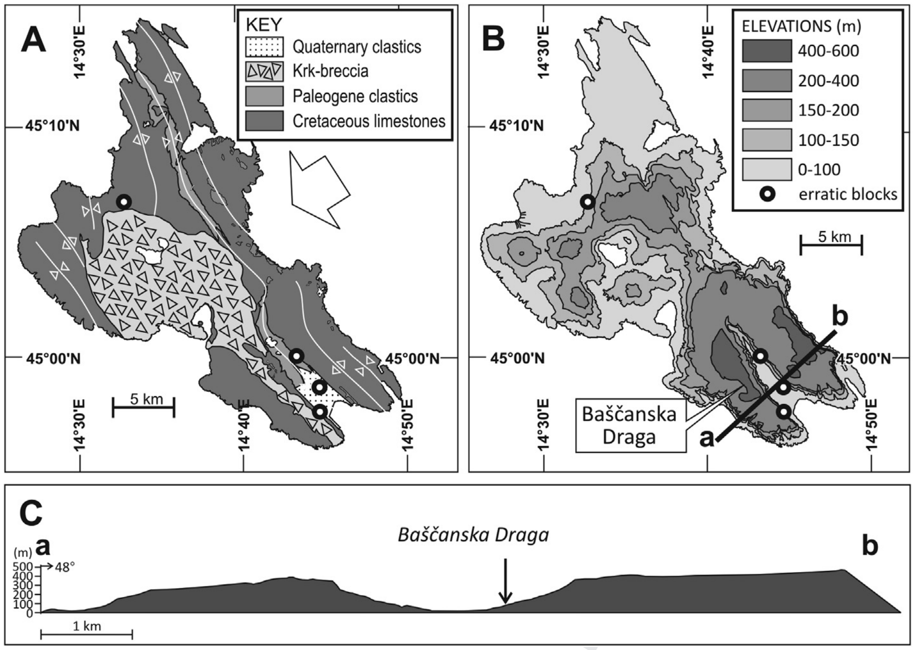


Figure 2. A) Geological map of the Krk Island, simplified after Šušnjar et al. (1970) and Marjanac et al. (2003) with the positions of erratic blocks. Arrow indicates presumed glacier flow direction. Eocene limestones occur in a narrow zone along the syncline. The age of the Krk-breccia is determined only as post-Eocene and it compositionally differs from the Jelar-breccia of the Velebit Mountain coastal slopes. B) Topography of Krk Island and position of erratic blocks illustrated in Fig. 5. C) Topographic profile (a– b) across the Baščanska Draga valley. Arrow marks position of erratic blocks. No vertical exaggeration.

breccia of presumed Paleogene and Neogene age, which patchily occurs on the Kamenjak anticline. The youngest deposits on Rab Island are Quaternary sands, which occur on the Kalifront peninsula and locally on the Kamenjak anticline (Mamužić, 1962; Mamužić et al., 1969; Mamužić and Milan, 1973).

Velebit Mt.

The oldest sediments of the central Velebit Mt. are Permian conglomerates, black limestones and dolomites, which are overlain by Triassic and Jurassic carbonates and clastics (Sokač et al., 1974), whereas on the southern Velebit Mt. the oldest rocks are Permian

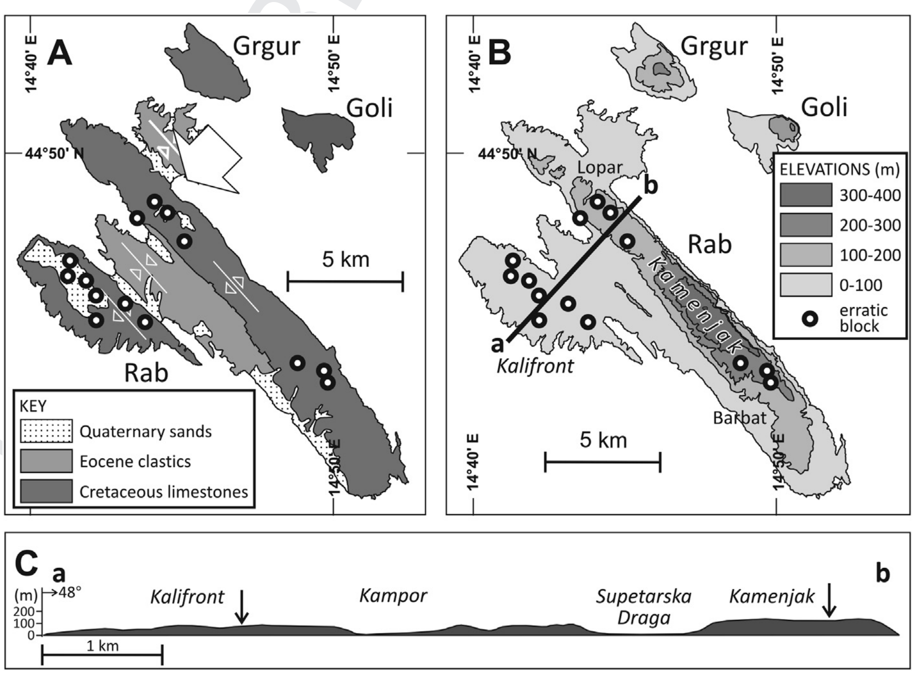


Figure 3. A) Geological map of Rab Island, simplified after Mamužić et al. (1969) with the positions of erratic blocks. Patches of Paleogene-Neogene breccia are not marked on the map because of their small size. Arrow indicates presumed glacier flow direction. B) Topography of the Rab Island and positions of the erratic blocks. C) Topographic profile Kalifront-Kamenjak (a– b). Arrows mark positions of the erratic blocks. No vertical exaggeration.

conglomerates and siltstones, which occur in the upper reaches of the Velika Paklenica gorge (Ivanović et al., 1973; Šušnjar et al., 1973) and are overlain by Lower Triassic sandstones. The youngest pre-Quaternary sediments on Velebit Mt. are polymict breccia, usually referred to as Jelar Breccia (Bahun, 1974) attributed Paleogene and Neogene (Mamužić et al., 1969; Ivanović et al., 1973), Eocene-Oligocene (Sokač et al., 1974), and middle to late Paleogene (Majcen et al., 1970; Mamužić et al., 1970) age, respectively (Fig. 4).

Other areas

Several large erratic blocks were also found during field reconnaissance in the Ravni Kotari area (Supplementary Table 2, Supplementary Fig. 4) where they lay on top of the Medviđa hill.

Bognar and Prugovečki (1997) reported erratic blocks on Risnjak Mt. at 925 m asl., whereas several others were also found during our field reconnaissance in other parts of the mountain (Supplementary Table 2, Supplementary Fig. 5). Bognar et al. (1991a, 1991b) also reported erratic blocks on the northern Velebit Mt. at 1000 m asl., whereas Velić et al. (2011) illustrated erratic blocks on the central Velebit Mt. at ca. 1300 m asl.

Research methods

The research was primarily field-based and involved detailed geological and lithofacial mapping of Pleistocene deposits on Krk and Rab islands and southern Velebit Mt., an area of ca. 60 km^2. Large outcrops in coastal cliffs and sand pits on Krk Island and in road-cuts of the Velika Paklenica canyon were mapped at 1:200 scale. The sections with thickness over 5 m and lithological variability were sedimentologically logged at the scale 1:50. Elsewhere, only point-observations of individual blocks, groups of blocks, and sediments were recorded. We have registered and mapped to date 88 blocks and groups of blocks (Supplementary Table 2). The size of largest solitary blocks was measured on aerial images, some were trigonometrically measured in the field, and some smaller blocks were measured by measuring tape. The provenance and age of individual blocks was determined by the study of their microfacies and biota in thin sections. The age of the host sediment of some blocks (till), was determined by the U-series dating of secondary sparry calcite which was precipitated in its intergranular voids, since this method had previously yielded good results in dating tills and tillites of Montenegro and Greece (Hughes et al., 2006a, 2006b, 2010, 2011). The dating of ten samples was performed at the UK Natural Environment Research Council (NERC) Open University Uranium-series Facility. For detailed facies description of the studied sections reported in this paper, logs and dating results, see Marjanac (2012).

Results

Krk Island

Krk Island erratic blocks (Supplementary Table 2, Supplementary Fig. 1) (Fig. 2) occur in the lower part (ca. 46–92 m asl) of the Baščanska Draga valley (Marjanac and Marjanac, 1994; Marjanac, 2012). They are angular, and the largest one attains 8 m across (Fig. 5). The blocks are composed of middle Eocene Foraminiferal Limestone and “Transitional” Limestone. They directly lay on compacted diamict, which is composed of sub-rounded to medium rounded cobble-to boulder-size limestone debris in a matrix of clayey fine sand (Fig. 5 B), and partly on loose cobbles. Their bases are flat and polished, with parallel shallow grooves (Fig. 5 D). The bedrock is made of middle to late Eocene “Flysch” clastics which occur along the entire valley, but are unexposed at this location.

We interpret these blocks as glacial erratics due to their allochthonous position in the field, lithological difference from the footwall rocks, and sedimentological evidence of glacial environments (kame-terrace and glaciofluvial sediments) in the Baščanska Draga valley (Marjanac, 2012). They may have been transported from Krk Island itself, because their lithology corresponds to the

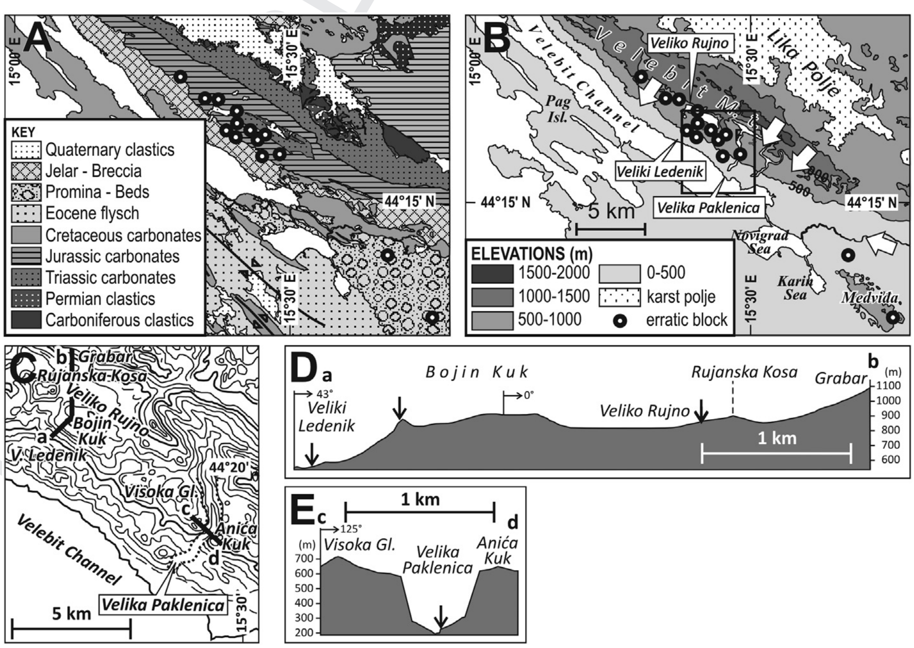


Figure 4. A) Geological map of the Southern Velebit Mt. Simplified after Majcen et al. (1970), Ivanović et al. (1973), Šušnjar et al. (1973) and Sokač et al. (1974) with the positions of erratic blocks. B) Topography of the southern Velebit Mt. and the position of erratic blocks. The Rujanska Kosa ridge strikes diagonally across the central part of the Veliko Rujno valley, but cannot be labeled in this map scale. Arrows indicate glacier flow direction. C) Detailed topographic map of the Veliko Rujno – Velika Paklenica area and topographic profiles in panels D and E. D) Topographic profile Veliki Ledenik – Grabar (a–b). E) Topographic profile across the Velika Paklenica canyon (c–d). Arrows mark positions of erratic blocks. No vertical exaggeration.

Please cite this article in press as: Marjanac, T., Marjanac, L., The extent of middle Pleistocene ice cap in the coastal Dinaric Mountains of Croatia, Quaternary Research (2016), http://dx.doi.org/10.1016/j.yqres.2016.03.006

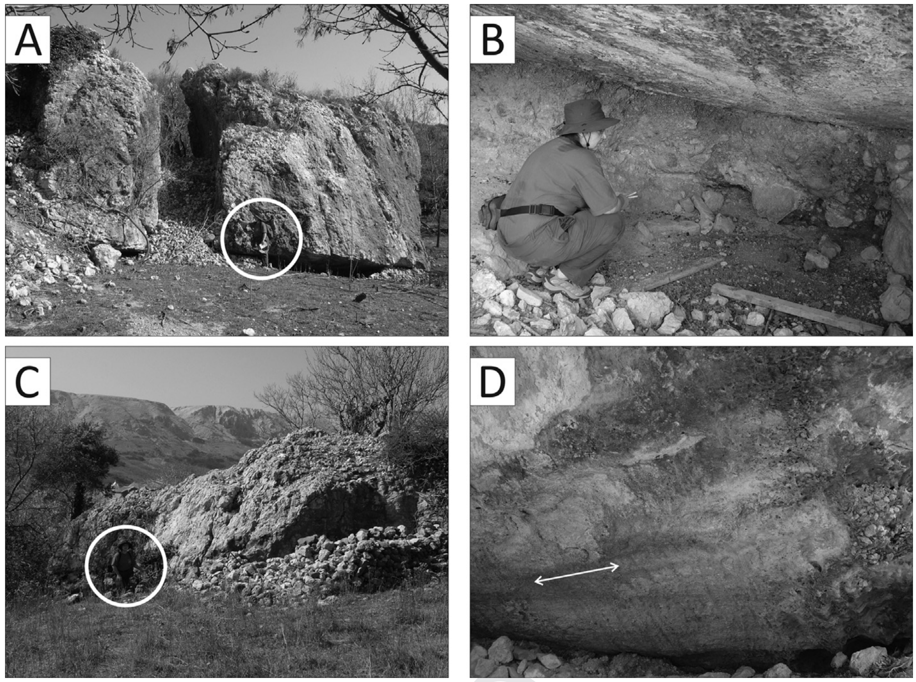


Figure 5. Erratic blocks in the Baščanska Draga valley. A) The blocks are standing 3 m apart, and probably represent two parts of a single block. The larger block has volume of 240 m^3. Both blocks are made of Lutetian Foraminiferal limestone. Loose gravel in the gap between and around the blocks, is partly washed-out diamict and partly recent rubble. See person in circle for scale. B) The larger block with polished bottom surface sits on a diamict composed of cobble-size subangular to subrounded debris in clayey fine sand matrix with compaction and traction textures visible in the underlying diamict. C) The block of Lutetian "Transitional" limestones sits on mostly loose angular debris. D) The bottom surface of the block in Fig. C has long shallow grooves (arrow) which are cross-cut by perpendicular younger set of narrow grooves, indicating transport along the valley strike. The width of the scene is ca. 2 m.

local geological structure, and their nearest source may be exposed several kilometers upvalley.

Rab Island

The erratic blocks occur at several locations on the island (Supplementary Table 2, Supplementary Fig. 2) (Fig. 3 B); on northern part of the Kamenjak ridge near the Lopar village (Fig. 6 A, B) at 99–117 m asl, on the Kalifront peninsula (Fig. 6 C) at 34–88 m asl, and near Barbat village (Fig. 6 D) at 139–250 m asl These erratic blocks are usually located just few tens of meters below the highest ground in the local topography. The Lopar blocks (Fig. 6 A, B) occur on a topographic high, 270 m from and 13 m below the highest local elevation. The Kalifront blocks (Fig. 6 C) are located on a low, flat peninsula ca. 5 km from the Kamenjak ridge. The Kalifront peninsula is separated from that ridge by 700–800 m wide valleys of Kampor and Supetarska Draga with valley bottoms at 8 m and 15 m asl respectively. A 75 m high hill separates the two valleys (Fig. 3 C). The Barbat blocks (Fig. 6 D) lay on a topographic high, 80 m below 330 m high hill on the island crest at the distance of 800 m. These topographic conditions make mass-flows and rockfalls unlikely mechanisms of block transport.

Rab Island erratic blocks (Fig. 6) are usually rounded and karstified, particularly at the Lopar and Kalifront localities. The Lopar blocks are up to 5 m across, the Kalifront blocks are 1.5–10 m across, and the Barbat blocks are 1–6 m across, although the smallest clasts are of decimeter size.

The erratic blocks are most numerous on the Kalifront peninsula where Mamužić (1962) and Mamužić et al. (1969) mapped the core of an anticline composed of Cenomanian-Turonian Rudistid limestones with dolomite interbeds (Fig. 3 A). The Kalifront blocks usually occur in piles (herein referred to as "groups") which form NE–SW striking linear ridges 5–12 m high, up to 50 m wide and few hundred meters long, and divided by ca. 50 m wide flat areas filled with clay-rich quartz sand. Some blocks are encased in that sand, whose origin seems to post-date the emplacement of blocks. The direct contact of erratic blocks with the underlying Cretaceous limestones is unexposed, but a road-cut exposure at the northern coast of the peninsula reveals that the blocks are encased in matrix-rich till with rounded and striated pebbles and boulders.

The majority of Kalifront erratic blocks are composed of massive Cretaceous limestones and subordinately of breccia of an unknown age. The analyzed limestone blocks are mudstones to wackestones (biomicrites) with abundant pelagic foraminifers of early and late Cretaceous age. The limestone blocks are of various ages; Aptian, Turonian, Turonian-Campanian, and Eocene (Lutetian). The facies of blocks as well as their ages differ from the underlying Rudistid limestones of Turonian age.

The Barbat blocks are also partly encased in matrix-rich till that sharply overlies afossiliferous calcareous polymict breccia (locally referred to as the Rab-breccia) of post-Eocene age. The till is coarse-grained and comprises striated pebbles and cobbles. Some blocks at this locality are composed of Cretaceous stromatolitic limestone, which also locally occurs on the Rab Island.

The blocks are interpreted as erratics because of their allochthonous mode of occurrence, and stratigraphical and lithological difference with the bedrock (Turonian Rudistid limestones and post-Eocene breccia). Rab Island blocks of late Cretaceous pelagic limestones match coeval limestones on the islands of St. Grgur and Goli (Mamužić et al., 1969), which are located 12 km northeastward (Fig. 1).

Velebit Mt.

Solitary blocks on the southern Velebit Mt. occur at various altitudes, from 65 m to 1026 m asl (supplementary Table 2,

Please cite this article in press as: Marjanac, T., Marjanac, L., The extent of middle Pleistocene ice cap in the coastal Dinaric Mountains of Croatia, Quaternary Research (2016), http://dx.doi.org/10.1016/j.yqres.2016.03.006

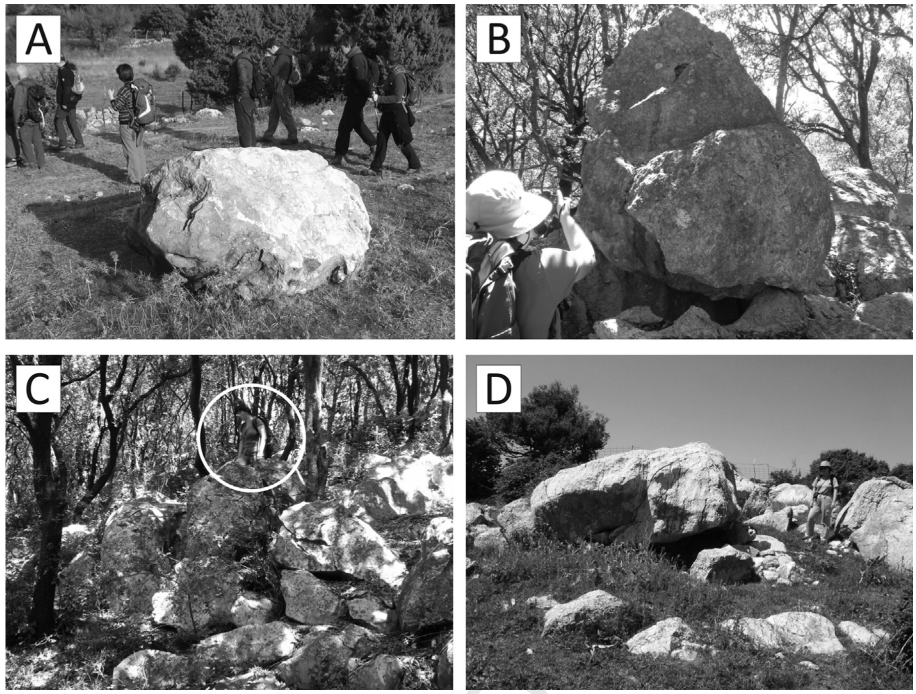


Figure 6. Erratic blocks on the Rab Island. A) Solitary block of Cretaceous limestone on the flat top of a hill near the Lopar village. B) Upper part of 6-m-high block pile located 650 m SW from the block in A). All piled blocks are karstified Cretaceous limestones. C) Group of blocks of Cretaceous limestones in the Kalifront woods is ca. 5 m high, 54 m wide and a few hundred meters long; pile strikes NE–SW. Individual blocks are up to 3 m across, see person in circle for scale. D) One of the Cretaceous limestone blocks on a hill above the Barbat village. The lower surface of the block is striated.

supplementary Fig. 3) (Fig. 4), and at different positions in the topography: some on the mountain slope, some in valleys, and some on tops of mogote. These blocks were interpreted as corrosional remnants by Poljak (1929) but as glacial erratics by Belij (1985a, 1985b), and they are herein referred to as erratics after our preferred interpretation of their origin.

A number of erratic blocks occur on the Rujanska Kosa ridge (>900 m high) (Fig. 4 C, D), which is a medial moraine (Marjanac and Marjanac, 2004; Marjanac, 2012). It comprises matrix-rich till with striated, commonly bullet-shaped cobbles and boulders, and its surface is covered by rounded cobbles and small boulders of a younger washed-out subglacial till (Marjanac, 2012). The erratic blocks sit scattered on both (Fig. 7 A).

The erratic blocks on Bojin Kuk mogote (Fig. 4 C, D) rest on the bedded limestones and dolomitic limestones of Late Jurassic age and locally over Eocene-Oligocene Jelar-Breccia which are both intensively tectonized and corroded (Perica and Marjanac, 2009). One block with volume of ca. 84 m^3 rests on karstified bedrock, partly sitting on several ball-size clasts at the contact on the very edge of the topographic ridge at 850 m asl facing the Adriatic Sea (Fig. 7 B). It does not differ lithologically from the surrounding mogotes, so its transport distance cannot be estimated. A number of inaccessible blocks are also considered as erratics due to their clear offset position and lack of conformity with the bedrock, as well absence of high topography for their source area (Fig. 7 C).

Several large erratic blocks occur scattered on a small plateau (ca. 557 m asl) above the abandoned village of Veliki Ledenik (Fig. 4 C, D). These angular blocks are made of massive, bituminous limestone of Late Jurassic age, cross-cut by fissures and covered with modern karren, and their estimated volume is 200 m^3 and 790 m^3, respectively (Fig. 7 D). The blocks lay on cobble and small boulder-size debris over Eocene-Oligocene Jelar-Breccia, 300–500 m away from western slope (35°) of the Bojin Kuk mogote, while the distance from its possible source on the northern mountain ridge (Fig. 4 A) is several kilometers.

Large blocks also occur below the Anića Kuk mogote at ca. 200 m asl (Fig. 4 C, E) in the Velika Paklenica canyon, which is cut through the Eocene-Oligocene Jelar-Breccia (Sokač et al., 1974). Some blocks are free-standing, some rest over partly cemented till, whereas the others are embedded in till (Fig. 8) which Marjanac (2012) identified as the "mega-diamict facies". The block in Fig. 8 is ca. 34 m wide and its volume is ca. 4896 m^3; the bottom surface is polished, with glacial grooves and striations. This block is located at a distance of ca. 200 m from the steep rock face (75°) of the Anića Kuk mogote.

The majority of Velebit Mt. blocks are apparently of the local lithological composition, and the distance of transport cannot be precisely estimated because the same lithologies are widespread on the Velebit Mt. However, smaller debris made of Triassic and Permian fine-grained clastics, which are common in glacigenic sediments of the Velika Paklenica canyon indicate transport from the sources located in the upper reaches of the Velika Paklenica gorge for a minimum distance of 5–6 km (Sokač et al., 1974).

Chronostratigraphy of glaciogenic sediments

Chronostratigraphy of glaciogenic deposits on Velebit Mt. has been a matter of debate for many years and still is, due to lack of chronostratigraphical data. The biostratigraphical data from Quaternary deposits in Dinarides are scarce and restricted to cave deposits, which makes correlation with other sediments very difficult.

The biostratigraphical data relevant for the study region are revealed from lacustrine ostracods, which document the middle Pleistocene age "Mindelian" glaciation and the "Mindelian/Rissian" interglacial (Malez and Sokač, 1969).

The uranium-series dating of the secondary calcite cements found in tills provided minimum ages of the host sediments, from 110 ka to over 350 ka (Marjanac, 2012), and are consistent with the ages of glaciogenic sediments in Montenegro (Hughes et al., 2011) and Greece (Hughes, 2004; Hughes et al., 2007). Glacial deposition probably occurred during both Skamnelian and Vlasian Stages

Please cite this article in press as: Marjanac, T., Marjanac, L., The extent of middle Pleistocene ice cap in the coastal Dinaric Mountains of Croatia, Quaternary Research (2016), http://dx.doi.org/10.1016/j.yqres.2016.03.006

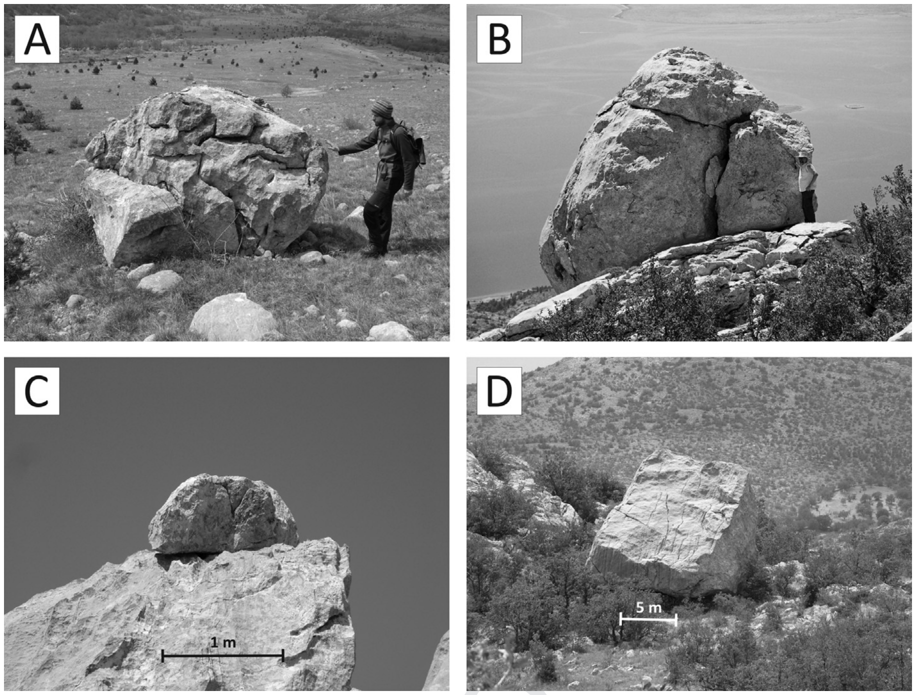


Figure 7. Erratic blocks on the southern Velebit Mt. A) One of several erratic blocks on southern slope of the Rujanska Kosa moraine ridge. The block rests on well rounded cobbles and small boulders interpreted as washed-out lodgment till. B) Erratic block on the Bojin Kuk crest rests over several cobble-size clasts, which overlie karstified bedrock with 40-cm-deep grikes. C) Erratic block on the top of a mogote near Bojin Kuk rests on karstified bedrock. Its clear offset position indicates glacial emplacement. D) Erratic block with volume of ca. 790 m^3 above the Veliki Ledenik village is made of massive tectonically fractured Jurassic limestone. The block short edge is ca. 7 m long. It overlies limestone cobbles on a gentle slope built of Jelar-breccia.

(Pindus chronostratigraphy), which correlate with Marine Isotope Stages (MIS) 12 to 6 (Hughes et al., 2006b), and perhaps during even earlier cold stages. The U-series minimum ages and allomorpho-lithostratigraphic approach to the studied glaciogenic sediments and related erratic blocks enabled preliminary regional correlation of tills (Marjanac, 2012). Therefore, based on scientific knowledge currently available, the studied tills and erratics of the NW Dinarides described in this paper are attributed to the middle Pleistocene.

Discussion

Transport and depositional processes

Solitary large blocks in mountain valleys, like in the Velika Paklenica canyon, are commonly interpreted as: 1) rockfalls that originated from nearby steep mountain faces (Bognar and Blazek, 1985; Bognar, 1994), 2) corrosional remnants only ostensibly detached from their lithological bedrock on hill tops and mogotes (Poljak, 1929), or 3) glacial erratic blocks (Belij, 1985a, 1985b; Marjanac, 2012).

Rockfalls, mode of occurrence and characteristics

Rockfalls usually involve (a) collapse of a single block of rock from the rock face (rockfall s. str.), which, after colliding with the slope base, shatters and transforms into (b) a cohesionless mass flow of loose debris, similar to rock avalanches (Evans and Hungr, 1993).

a) Rockfalls *sensu stricto* are simple gravitational falls of individual blocks (Evans and Hungr, 1993), which commonly create a crater at the point of impact (De Saussure, 1779, p. 168; Evans and

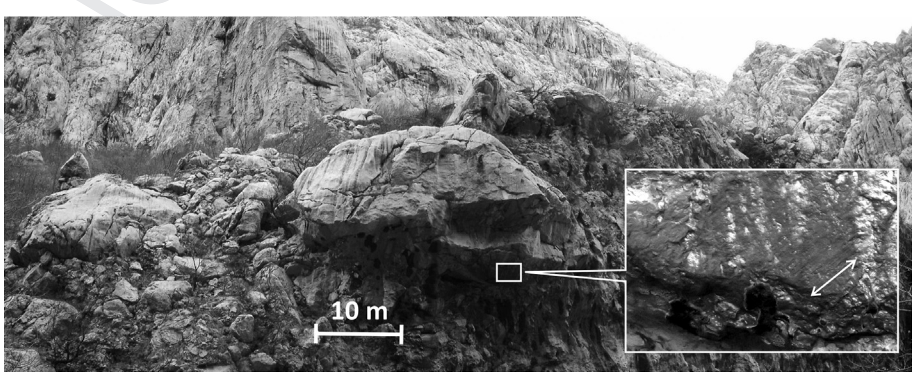


Figure 8. Large erratic block in the Velika Paklenica canyon, partly embedded in till ("mega-diamict facies" of Marjanac, 2012). The block is 34 m wide, and its bottom surface is grooved and striated (see insert), which indicates long-valley transport.

Hungr, 1993), or shatter marks if they impact solid rock base. Large blocks may continue to roll downslope for some distance before coming to final rest (Evans and Hungr, 1993; Dorren, 2003). The resultant deposit is composed of angular rock fragments with shallow grooves and bounce marks, which may not survive long exposure.

b) Cohesionless mass flows are rock avalanches and *sturzstroms* (Hsü, 1975), where individual rock fragments follow individual ballistic trajectories without significant intergranular collisions. The initial ballistic fly stage (i), when the airborne debris follows ballistic trajectories (already illustrated by Heim in 1932, Hsü, 1975) is followed by mass flow stage (ii) when debris travels as a turbulent mass flow. Intergranular collisions transmit dispersive pressure (Lowe, 1976) which maintains the flow and can produce a large volume of shattered debris. Rock avalanches may come to rest rather abruptly, creating a debris lobe morphologically similar to glaciers (Fauque and Strecker, 1988). A large volume of rock dust is ejected from the flow and become airborne, and will eventually settle above the rock avalanche sediment. Large blocks do not travel far from the source (Evans and Hungr, 1993; Dorren, 2003), and the transport may be of the order of several tens to several hundreds of meters, only exceptionally more (Hsü, 1975). The rockfall debris has local provenance with little variation in lithological composition.

The studied blocks do not share characteristics of rockfalls (Table 1) because: a) neither the impact crater, clastic ejecta, nor compressed sediments were observed anywhere below the erratic blocks. On the contrary, the blocks commonly rest on smaller clasts, even on their sharp points or over karren (Figs. 6 B and 7 C); b) the blocks have more-or-less well preserved old rillen karren (grikes) at the surface that would be crushed if the block had rolled for a hundred meters or more; c) cobbles and small boulders underlying some blocks are sharp-edged, indicating negligible movement of the overlying block; and d) some blocks are encased in coarse till (Fig. 8).

Corrosional remnants, mode of occurrence and characteristics

Poljak (1929) referred to some erratic-looking blocks on the southern Velebit Mt. as "squat-stones" (Fig. 9) and hypothesized that they were formed by the weathering of thin interbeds, which was more efficient compared to the weathering of massive breccia that shaped large blocks standing on small pedestals. However, remnants of these thin interbeds have not been observed below any of the studied erratic blocks in the same area of the southern Velebit Mt., but instead the studied blocks overlie karstified surfaces (e.g. Figs. 6 B and 7 C), or small cobble-to ball-sized clasts.

Figure 9. "Squat stones" on tops of mogote in Bojin Kuk area. Some more easily accessible blocks are indeed corrosional remnants. Though they resemble erratic blocks, they do not lie on rock debris but lie conformably on the bedrock.

Some limestone blocks on the southern Velebit Mt. are indeed selectively corroded; they appear to be erratic from a distance, but are still attached to the underlying bedrock with no finer debris, which typically supports rock-fall blocks and glacial erratics. Being weathered, they are usually rounded to semi-rounded, unlike rockfall debris and erratics (Fig. 9).

Semi-rounded limestone boulders may be also produced by subsoil corrosion, which is a consequence of leaching by humic acids in vegetated soil (Slabe and Liu, 2009; Zseni, 2009). The resultant blocks and boulders are characterized by smooth corroded surface, but also by tubes and channels in all orientations, which document percolation of the acidic soil waters. However, after exhumation the blocks are subjected to subaerial weathering, which superimpose younger grikes over the old surface. Stratigraphically, these blocks correspond to the underlying stratigraphic unit. None of the studied blocks exhibit the above properties. Consequently, the occurrence of the majority of solitary blocks in the study area may be better explained by other processes.

Glacial erratics, mode of occurrence and characteristics

Since Agassiz's time it is well known that glaciers transport the debris subglacially, englacially and supraglacially. As discussed by

Table 1
Major characteristics of blocks vs. mode of their origin

	Rockfall	Corrosional remnants	Erratic blocks
Block position	At the cliff base	On mogote summits and flanks	On mogote summits, on flanks, in valley bottoms or flat land
Block size	Any	Any	Any
Block shape	Angular, shattered	Rounded	Angular or rounded
Block groups	In groups, debris cones or lobes	Solitary	Solitary or grouped in block piles and ridges
Block lithology vs. bedrock	Semi-autochthonous or autochthonous	Autochthonous	Semi-autochthonous or allochthonous
Block surface features (karren)	May be locally preserved but also eroded in transport, superimposed with younger karren	Superimposed with younger karren	May be preserved or partly preserved, eroded, superimposed with younger karren
Relation to bedrock	Resides on crushed debris	Attached, subsoil corroded blocks detached from bedrock	Lay on rounded smaller debris and/or karstified bedrock
Associations	Matrix-free angular debris, fine clastic ejecta, rock dust	None	Tills/tillites, but also may directly lie on bedrock
Amount of transport	Local, gravitational	Not transported	Transported for shorter or larger distance
Transport agent and process	Gravity, free fall	None	Glacier ice, supraglacial, englacial, subglacial

Agassiz (1838), supraglacial debris can be readily differentiated from subglacial by the degree of rounding, the former being angular and the latter well rounded. The detachment mechanism that provides supraglacial debris is essentially the same as for rockfalls (Dorren, 2003), whereas subglacial debris is entrained in the ice flow by plucking at the base (Benn and Evans, 2010). Supraglacial debris is transported passively, whereas the subglacial transport involves intensive shearing and shaping of clasts (Benn and Evans, 2010), with the lodgement till characterized by rounded, polished and striated debris.

The studied blocks share characteristics of both supraglacially and subglacially transported debris. The angular and subangular blocks on Krk Island (Fig. 5), Rab Island (Fig. 6 B, C), Bojin Kuk (Fig. 7 B) and Veliki Ledenik (Fig. 7 D) were most likely transported supraglacially. The rounded to subrounded blocks on Rab Island (Fig. 5 A, D), Rujanska Kosa (Fig. 7 A) and in the Velika Paklenica canyon (Fig. 8) were transported subglacially, as indicated by their shape and position in the till matrix. As thawing is gradual, the supraglacial blocks gently settle onto the underlying lodgement till (Agassiz, 1838; von Charpentier, 1841; Lyell, 1863) and maintain the position they had during the transport, some remaining vertical.

Lithologically and stratigraphically, glacial erratic boulders and directly underlying lodgement till can vary significantly, the basal debris usually being transported for a shorter distance. The ice-melt water may wash out all fine-grained debris, creating a network of open space beneath erratic blocks.

The Velika Paklenica erratic blocks (Fig. 8) previously interpreted as rock falls (Bognar and Blazek, 1986; Bognar, 1994) are reinterpreted as glaciogenic deposits (Marjanac, 2012) because of their till "matrix". Other blocks are located too far from steep mountain or mogote slopes (e.g., on Rab Island, Fig. 6 A, C, D; and near Veliki Ledenik village on southern Velebit Mt., Fig. 7 D) to account for gravitational transport, and some even rest on the hill/mogote tops (e.g., on Rujanska Kosa, Fig. 7 A; and the Bojin Kuk mogote, B, C).

The emplacement of erratic blocks on the top of 900-m-high Rujanska Kosa moraine ridge (Fig. 7 A) obviously post-dated deposition of till, and the blocks could not be brought to their present position by any other process but ice transport. The same applies to the erratic block on the edge of 820-m-high Bojin Kuk mogote ridge (Fig. 7 B).

The studied blocks have various degree of karstification, with the Rab Island blocks being more karstified than the blocks on Velebit Mt. This difference is probably a consequence of their setting. The blocks in the Kalifront woods on Rab Island were subjected to leaching by humic acids, whereas the blocks on Velebit Mt. are located at exposed positions on the mountain slope and mogote tops where leaching could be caused only by meteoric water. Although also karstified, most of the studied blocks on Velebit Mt. appear fresh. It is not known for how long the blocks were exposed to weathering, but lichens cover their complete surface, including grikes, which suggests thousands of years for such extensive surface colonization. That also suggests that most of grikes are today moribund. The modern chemical weathering rate of exposed limestones as reported by Furlani et al. (2009) is so high (9–18 μm/yr) that all blocks smaller than 3 m across should have been completely dissolved since the middle Pleistocene. Their good preservation may be attributed to several possible causes; one being burial under thick soil (or sediment) cover, but that would induce subsoil corrosion which is also very effective and creates easily visible traces which have not been observed on the studied blocks. The second cause may be much slower Pleistocene weathering rate than those reported by Furlani et al. (2009) because of significantly lower middle Pleistocene mean annual temperature and precipitation (reported by Blazic et al., 2013), which must have retarded chemical processes.

Rationale

Differentiation of rockfall from glacial erratics essentially depends on characteristics of the underlying debris (Table 1): till in the case of glaciogenic deposit, and crushed rocks in the case of rockfalls. Differentiation of corrosional remnants from erratic blocks essentially depends on the difference in age and lithology between blocks and bedrock, which are coeval in the case of corrosional product, but diachronous in the case of glaciogenic debris. The difference between lithology of blocks and bedrock is usually diagnostic for their transport and provenance, although that largely depends on the geological composition and lithological/stratigraphical heterogeneity of the mountain range.

The extent of middle Pleistocene Dinaric ice cap

The inner island channels in the Northern Adriatic were formed as valleys due to sea-level fall in the order of −112 m (Šegota, 1968, 1982; Benac and Šegota, 1990), −139 m (Rohling et al., 1998), −150 m (Van Straaten, 1970), or even −262 m (Rabineau et al., 2006). They were loci of clastic deposition in late Pleistocene (Benac et al., 1995; Juračić et al., 1999). The blocks on the islands of Krk and Rab were transported by glaciers that descended from the present Velebit Mt., crossed the 50–100 m deep and 5–12 km wide valley that forms the modern Velebit Channel, and climbed at least to 300 m asl on the island counterslope.

The erratic blocks mark approximately the maximal extent of the Pleistocene ice cover in the external Dinarides. However the glacier terminus during the maximal extent of the Pleistocene glaciers must have been seaward from the Krk, Rab and Pag islands (Fig. 10), since terminal moraines have not been found on the islands.

The high positions of erratic blocks on some hilltops (the Bojin Kuk mogote) document that the whole area, including the lower mountain tops, was covered by an ice cap, probably with only a few nunataks that are today difficult to recognize. The aerial distance from the northernmost recognized erratic block to the southernmost one (across the flow line) is over 180 km, and the width of the ice-covered area (along the flow line) is at least 30 km (from the

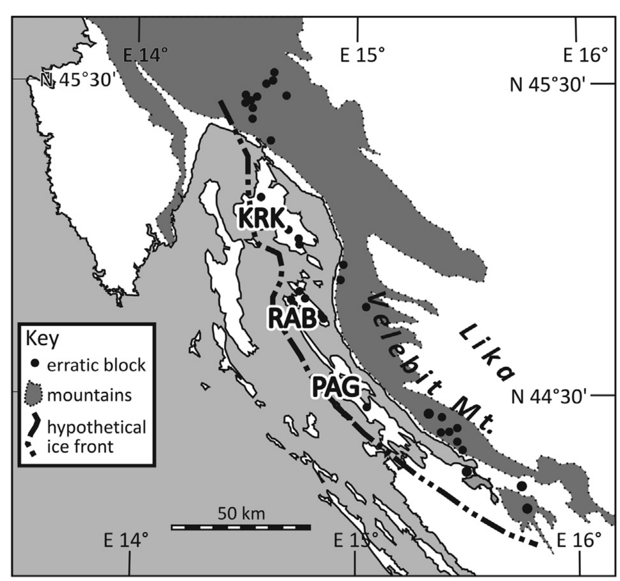


Figure 10. Reconstruction of the SW margin of the proposed Dinaric ice cap, based on occurrences of glaciogenic sediments and erratic blocks (not all observed erratic blocks are marked). The NW ice-cap margin is uncertain due to lack of research.

Please cite this article in press as: Marjanac, T., Marjanac, L., The extent of middle Pleistocene ice cap in the coastal Dinaric Mountains of Croatia, Quaternary Research (2016), http://dx.doi.org/10.1016/j.yqres.2016.03.006

island of Rab to the northeastern margin of the Velebit Mt.), which gives the proposed ice cap approximate minimum area of 5400 km^2 (Fig. 10). This is three times larger than area of the ice cap in Montenegro (1647 km^2, Hughes et al., 2011). It must be noted, however, that the present study did not take into account the glaciated area of Biokovo Mt., which is located 140 km southeastward from the southern Velebit Mt. (Fig. 1 A) and was reported by Roglić (1931). If Biokovo Mt. was glaciated approximately to the same extent as was Velebit Mt., it would contribute to the area of ice cover by an additional ca. 320 km^2.

At this stage of research we are uncertain about the eastern margin of the ice cap. Our preliminary data show that Lika Polje was also glaciated, but more research is needed to establish the NE boundary of the ice cap.

Close association of the studied erratic blocks with tills of the middle Pleistocene age (Marjanac, 2012) and their identical aerial distribution suggests that the reconstructed ice cap must have been also of the middle Pleistocene age.

Regional consequences

Pleistocene glaciation of the peri-Mediterranean area has been studied for over a century. Reviews of glaciated areas are presented by Messerli (1967), Ehlers and Gibbard (2004), Hughes et al. (2006a) and Hughes and Woodward (2008), who illustrated glaciation in limited areas of the Dinaric Mts. in particular, and elsewhere in the region (such as Greece).

Hughes et al. (2010, 2011) studied glaciation in Montenegro and recognized at least three cold stages that correlate with Marine Isotope Stages (MIS) 12, 6, and 5d-2. We have also recognized physical evidence of at least two (possibly three) glacial episodes in the coastal mountains of Croatia, but their chronostratigraphy is not established yet due to lack of isotopic datings (Marjanac, 2012).

Glaciation in the eastern Adriatic was apparently more extensive than in other peri-Mediterranean areas (Marjanac et al., 1990; Marjanac and Marjanac, 2004; Marjanac, 2012) (Fig. 10). The formation of such an extensive ice cap in the middle Pleistocene was certainly caused by significant climate deterioration whose proportions require further study. The presence of such large ice mass must have had profound influence on the climate in southern Europe, as discussed previously by Hughes et al. (2007).

Conclusion

The recognition of ancient rockfalls and erratic blocks is essential for the correct interpretation of Quaternary climate in the central Europe. We have studied a number of solitary blocks and groups of blocks that occur scattered throughout the study area along the eastern Adriatic coastal Velebit Mt. and the islands of Krk and Rab, and we have revised the interpretation of their origin proposed by previous researchers. After analyzing the context of studied individual blocks and groups of blocks, we regard the rockfall hypothesis for them as physically invalid. Rockfalls have also been recognized in the study area, and we have proposed a set of criteria to differentiate them from glaciogenic blocks. Some of the studied blocks are shaped by subsoil corrosion, and such are recognized as corrosional blocks, whereas the origin of inaccessible "squat stones" on the mogote tops could not be proven. However, the majority of the studied solitary blocks on the northern Adriatic islands of Krk and Rab as well as on Risnjak and Velebit Mts. are interpreted to be of glaciogenic origin, given their allochthonous position in the field and lithological as well as stratigraphical difference from the underlying bedrock.

These erratic blocks on the internal northern Adriatic islands document the extent of the middle Pleistocene glaciation of the Dinaric Mts. although not its maximal extent, which remains unclear because the ice terminus was in the area currently inundated by the postglacial sea-level rise. The distribution of erratic blocks and glaciogenic sediments in the studied part of the Dinaric mountain range, namely on Risnjak and Velebit Mountains, their foothills and northern Adriatic internal islands, indicates a minimum area of the ice cap of 5400 km^2.

Acknowledgments

This study was part of the research projects 1-09-084 and 119-303 funded by the Croatian Ministry of Science and Technology, and projects 0119-401 and 119-0000000-1164 funded by the Ministry of Science, Education and Sport. For introduction to some Platak and Risnjak Mt. sites with erratic blocks we are grateful to Marko Randić of the Public Institution Priroda, and for valuable discussions in the field we are grateful to Prof. Dražen Perica (University of Zadar), Prof. Phil Hughes (University of Manchester), Prof. Wojtek Nemec (University of Bergen), and Prof. Stanislaw Leszczyński (University of Krakow). Thanks also go to our student companions Ana Marija Tomša, Ivana Adžić, Luka Blažić, Tomislav Valenčak, Marina Čalogović and Dragana Šolaja for their help during many field campaigns. We also thank Prof. Philip Gibbard, Prof. Julien Moreau and two anonymous reviewers for their constructive criticism which helped us to clarify our ideas and greatly improve the manuscript. English was kindly corrected by Dr. Richard Wrigley.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.yqres.2016.03.006.

References

Agassiz, M.L., 1838. Upon glaciers, moraines, and erratic blocks. Edinburgh Philosophical Journal 24, 364–383.
Bahun, S., 1974. Tektogeneza Velebita i postanak Jelar-naslaga. Geološki vjesnik 27, 35–51.
Belij, S., 1985a. Glacijalni i periglacijalni reljef južnog Velebita. Posebna izdanja Srpskog geografskog društva 61, 5–68.
Belij, S., 1985b. Glacijalni reljef južnog Velebita. Geografski glasnik 47, 71–85.
Benac, Č., Šegota, T., 1990. Potopljena ris-virmska abrazijska terasa u podmorju ispred Rijeke, Hrvatska. Geološki vjesnik 43, 43–52.
Benac, Č., Senjanović, P., Čerina, P., 1995. Podmorski istraživački radovi u projektu "110 kV otočne veze", 1st Croatian Geological Congress. Proceedings. Institute of Geology, Croatian Geological Society, Zagreb, Croatia, pp. 75–79.
Benn, D.I., Evans, D.J.A., 2010. Glaciers and Glaciation, second ed. Hodder Education, London.
Blazic, L., Adzic, I., Marjanac, T., Marjanac, Lj, 2013. Ice advance into forested lake environment, evidence of rapid climate change. Case study of Middle Pleistocene Dinaric Mts. foreland, Croatia. In: Davos Atmosphere and Cryoshpere Assembly DACA-13; Symposium A1.1: from Explaining the Pleistocene to Projecting the Anthropocene, Session A1.1c Reconstructing and Understanding the Pleistocene. Abstract 176.
Bognar, A., 1994. Morfogeneza područja bazena porječja Velike i Male Paklenice, pp. 33–42. Paklenički zbornik 1, National Park Paklenica, Starigrad-Paklenica, Croatia.
Bognar, A., Blazek, I., 1986. Geomorfološka karta područja Velike Paklenice, 1: 25.000. Acta Carsologica 14–15, 199–206.
Bognar, A., Prugovečki, I., 1997. Glaciation traces in the area of the Risnjak Mountain Massif. Geologia Croatica 50 (2), 269–278.
Bognar, A., Faivre, S., Pavelić, J., 1991a. Tragovi oledbe na Sjevernom Velebitu. Geografski glasnik 53, 27–39.
Bognar, A., Faivre, S., Pavelić, J., 1991b. Glacijacija sjevernog Velebita. Senjski zbornik 18, 181–196. Gradski muzej Senj – Senjsko muzejsko društvo, Senj.
De Saussure, H.-B., 1779. Voyages dans les Alpes. Précédes d'un essai sur l'historie naturelle des environs de Geneve 1. Samuel Fauche, Neuchatel, Switzerland.
Dorren, L.K.A., 2003. A review of rockfall mechanics and modeling approaches. Progress in Physical Geography 27, 69–87.
Ehlers, J., Gibbard, P.L., 2004. Quaternary Glaciations – Extent and Chronology. Developments in Quaternary Science 2a. Elsevier B.V., Amsterdam, The Netherlands.
Evans, S.G., Hungr, O., 1993. The assessment of rockfall hazard at the base of talus slopes. Canadian Geotechnical Journal 30, 620–636.

Please cite this article in press as: Marjanac, T., Marjanac, L., The extent of middle Pleistocene ice cap in the coastal Dinaric Mountains of Croatia, Quaternary Research (2016), http://dx.doi.org/10.1016/j.yqres.2016.03.006

Fauque, L., Strecker, M.R., 1988. Large rock avalanche deposits (sturzströme, sturzstroms) at Sierra Aconquija, northern Sierras Pampeanas, Argentina. Eclogae Geologicae Helvetiae 81, 579–592.

Fortis, A., 1802. Mémoires pour servir a l'historie naturelle et principalement a l'oryctographie de l'Italie, et de pays adjacens 1. J.J. Fuchs, Paris, France.

Furlani, S., Cucchi, F., Forti, P., Rossi, A., 2009. Comparison between coastal and inland Karst limestone lowering rates in the northeastern Adriatic Region (Italy and Croatia). Geomorphology 104, 73–81.

Grimani, I., Šušnjar, M., Bukovac, J., Milan, A., Nikler, L., Crnolatac, I., Šikić, D., Blašković, I., 1973. Osnovna geološka karta SFRJ 1:100.000, Tumač za list Crikvenica L 33-102. Institut za geološka istraživanja Zagreb, Savezni geološki zavod Beograd, pp. 5–41.

Herak, M., 1972. Karst of Yugoslavia. In: Herak, M., Stringfield, V.T. (Eds.), Karst: Important Karst Regions of the Northern Hemisphere. Elsevier Publ. Co., Amsterdam, pp. 25–83.

Herak, M., 1997. Croatia. In: Moores, E.M., Fairbridge, R.W. (Eds.), Encyclopedia of European and Asian Regional Geology. Chapman & Hall, London, U.K, pp. 155–160.

Hsü, K.J., 1975. Catastrophic debris streams (sturzstroms) generated by rockfalls. Geological Society of America Bulletin 86, 129–140.

Hughes, P.D., 2004. Quaternary Glaciation in the Pindus Mountains, Northwest Greece (Ph.D. thesis). Darwin College, University of Cambridge, U.K. http://www.qpg.geog.cam.ac.uk/people/hughes/Hughes%202004.pdf.

Hughes, P.D., Woodward, J.C., 2008. Timing of glaciation in the Mediterranean mountains during the last cold stage. Journal of Quaternary Science 23, 575–588.

Hughes, P.D., Woodward, J.C., Gibbard, P.L., 2006a. Quaternary glacial history of the Mediterranean mountains. Progress in Physical Geography 30, 334–364.

Hughes, P.D., Woodward, J.C., Gibbard, P.L., Macklin, M.G., Gilmour, M.A., Smith, G.R., 2006b. The glacial history of the Pindus Mountains, Greece. Journal of Geology 114, 413–434.

Hughes, P.D., Woodward, J.C., Gibbard, P.L., 2007. Middle Pleistocene cold stage climates in the Mediterranean: new evidence from the glacial record. Earth and Planetary Science Letters 253, 50–56.

Hughes, P.D., Woodward, J.C., van Calsteren, P.C., Thomas, L.E., Adamson, K.R., 2010. Pleistocene ice caps on the coastal mountains of the Adriatic Sea. Quaternary Science Reviews 29, 3690–3708.

Hughes, P.D., Woodward, J.C., van Calsteren, P.C., Thomas, L.E., 2011. The glacial history of the Dinaric Alps, Montenegro. Quaternary Science Reviews 30, 3393–3412.

Ivanović, A., Sakač, K., Marković, S., Sokač, B., Šušnjar, M., Nikler, L., Šušnjara, A., 1973. Osnovna geološka karta SFRJ 1:100.000, List Obrovac. L 33-140. Institut za geološka istraživnja Zagreb, Savezni geološki zavod, Beograd.

Juračić, M., Benac, Č., Crmarić, R., 1999. Seabed and surface sediment map of the Kvarner Region, Adriatic Sea, Croatia (lithological map, 1:500.000). Geologia Croatica 52, 131–140.

Lowe, D.R., 1976. Grain flow and grain flow deposits. Journal of Sedimentary Petrology 46, 188–199.

Lyell, Ch, 1863. Geological Evidence of the antiquity of Man with Remarks on Theories of the Origin of Species by variation. John Murray, London.

Majcen, ž., Korolija, B., Sokač, B., Nikler, L., 1970. Osnovna geološka karta SFRJ 1: 100.000, List Zadar L 33-139. Institut za geološka Istraživanja Zagreb, Savezni geološki zavod, Beograd.

Malez, M., Sokač, A., 1969. O starosti slatkovodnih naslaga Erveničkog i žegarskog polja. III simpozij Dinarske asocijacije. Proceedings 1. Institut za geološka istraživanja, Zagreb, Croatia, pp. 81–93.

Mamužić, P., 1962. Novija geološka istraživanja otoka Raba. Geološki vjesnik 15, 121–141.

Mamužić, P., Milan, A., 1973. Osnovna geološka karta SFRJ 1:100.000, Tumač za list Rab L33-144. Institut za geološka Istraživanja Zagreb, Savezni geološki zavod, Beograd, pp. 5–39.

Mamužić, P., Milan, A., Korolija, B., Borović, I., Majcen, ž, 1969. Osnovna geološka karta SFRJ 1:100.000, List Rab L 33-114. Institut za geološka Istraživanja Zagreb, Savezni geološki zavod, Beograd.

Mamužić, P., Sokač, B., Velić, I., 1970. Osnovna geološka karta SFRJ 1:100.000, List Silba, L 33-126. Institut za geološka Istraživanja Zagreb, Savezni geološki zavod, Beograd.

Marjanac, Lj, 2012. Pleistocene glacial and Periglacial Sediments of Kvarner, Northern Dalmatia and Southern Velebit Mt. – Evidence of Dinaric Glaciation (Ph.D. thesis). University of Zagreb, Croatia. https://bib.irb.hr/datoteka/586790.MARJANAC_LJ_DISSERTATION.Bullzip.pdf.

Marjanac, T., Ćosović, V., 2000. Tertiary depositional history of Eastern Adriatic Realm. In: Pamić, J., Tomljenović, B. (Eds.), Outline of the Geology of the Dinarides and South Tisia with Field Guidebook. Guidebook Pancardi 2000, vol. 37. Vijesti Hrvatskoga geološkog društva, pp. 93–103.

Marjanac, Lj, Marjanac, T., 2004. Glacial history of Croatian Adriatic and coastal Dinarides. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations – Extent and Chronology. Developments in Quaternary Science 2a. Elsevier B.V., Amsterdam, The Netherlands, pp. 19–26.

Marjanac, T., Marjanac, Lj, Oreški, E., 1990. Glacijalni i periglacijalni sedimenti u Novigradskom moru. Geološki vjesnik 43, 35–42.

Marjanac, T., Tomša, A.M., Marjanac, Lj, 2003. Krk-breccia, possible Impact-crater fill, Island of Krk in Eastern Adriatic Sea (Croatia). In: Dypvik, H., Burchell, M., Claeys, P. (Eds.), Cratering in Marine Environments and on Ice. Impact Studies. Springer, Berlin, pp. 115–134.

Martel, P., 1744. An account of journey to the glaciers in Savoy. In: Mathews, C.E. (Ed.), 1900, The Annales of Mont Blanc. L.C. Page and co., Boston, U.S.A, pp. 341–356.

Messerli, B., 1967. Die eiszeitliche und die gegenwartige Vertgletscherung im Mittelemeerraum. Geographica Helvetica 22, 105–228.

Nikler, L., 1973. Nov prilog poznavanju oledbe Velebita. Geološki vjesnik 25, 109–112.

Oluić, M., Grandić, S., Haček, M., Hanich, M., 1972. Tektonska građa vanjskih Dinarida Jugoslavije. Nafta 23 (1–2), 3–16.

Perica, D., Marjanac, T., 2009. Types of karren and their genesis on the Velebit Mountain. In: Gines, A., Knez, M., Slabe, T., Dreybrodt, W. (Eds.), Karst Rock Features. Karren Sculpturing, pp. 259–274. Carsologica 9, Založba ZRC, Postojna – Ljubljana, Slovenia.

Poljak, J., 1929. Geomorfološki oblici krednih kršnika Velebita. Vijesti geološkog zavoda u Zagrebu 3, 53–85.

Rabineau, M., Berné, S., Olivet, J.L., Aslanian, D., Guillocheau, F., Joseph, Ph, 2006. Paleo sea level reconsidered from direct observation of paleoshoreline position during Glacial Maxima (for the last 500.000 yr). Earth and Planetary Science Letters 252, 119–137.

Roglić, J., 1931. Glacijalni tragovi na Biokovu. Posebna izdanja srpskog geografskog društva 10, 49–51.

Rohling, E.J., Fenton, M., Jorissen, F.J., Bertrand, P., Ganssen, G., Caulet, J.P., 1998. Magnitudes of sea level lowstands of the past 500.000 years. Nature 394, 162–165.

Šegota, T., 1968. Morska razina u holocenu i mlađem dijelu wurma. Geografski glasnik 30, 15–39.

Šegota, T., 1982. Razina mora i vertikalno gibanje dna Jadranskog mora od ris-virmskog interglacijala do danas. Geološki vjesnik 35, 93–109.

Slabe, T., Liu, H., 2009. Significant subsoil rock forms. In: Gines, A., Knez, M., Slabe, T., Dreybrodt, W. (Eds.), Karst Rock Features: Karren Sculpturing, pp. 123–137. Carsologica 9, Založba ZRC, Postojna – Ljubljana, Slovenia.

Sokač, B., Nikler, L., Velić, I., Mamužić, P., 1974. Osnovna geološka karta SFRJ 1: 100.000, List Gospić, L 33 127. Institut za geološka Istraživanja Zagreb, Savezni geološki zavod, Beograd.

Šušnjar, M., Bukovac, J., Nikler, L., Crnolatac, I., Milan, A., Šikić, D., Grimani, I., Vulić, ž, Blašković, I., 1970. Osnovna geološka karta SFRJ 1:100.000, List Crikvenica L 33-102. Institut za geološka istraživanja Zagreb, Savezni geološki zavod Beograd.

Šušnjar, M., Sokač, B., Bahun, S., Bukovac, J., Nikler, L., Ivanović, A., 1973. Osnovna geološka karta SFRJ 1:100.000, List Udbina, L 33-128. Inst. Geol. Istraž. Zagreb, Savezni geol. zavod, Beograd.

Van Straaten, L.M.J.U., 1970. Holocene and Late Pleistocene sedimentation in the Adriatic Sea. Geologisches Rundschau 60, 106–131.

Velić, J., Velić, I., Kljajo, D., 2011. Sedimentary bodies, forms and occurrences in the Tudorevo and Mirevo glacial deposits of northern Velebit (Croatia). Geologia Croatica 64, 1–16.

von Charpentier, J., 1841. Essai sur les glaciers et sur le terrain erratique du bassi du Rhône. Imprimerie et librarie de Marc Ducloux, Lausanne.

Zseni, A., 2009. Subsoil shaping. Carsologica 9, Založba ZRC, Postojna – Ljubljana, Slovenia. In: Gines, A., Knez, M., Slabe, T., Dreybrodt, W. (Eds.), Karst Rock Features: Karren Sculpturing, pp. 103–121.

Zupan Hajna, N., Mihevc, A., Pruner, P., Bosák, P., 2010. Palaeomagnetic research on karst sediments in Slovenia. International Journal of Speleology 39 (2), 47–60.

Please cite this article in press as: Marjanac, T., Marjanac, L., The extent of middle Pleistocene ice cap in the coastal Dinaric Mountains of Croatia, Quaternary Research (2016), http://dx.doi.org/10.1016/j.yqres.2016.03.006