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

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ABSTRACT

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) rockfalls. 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

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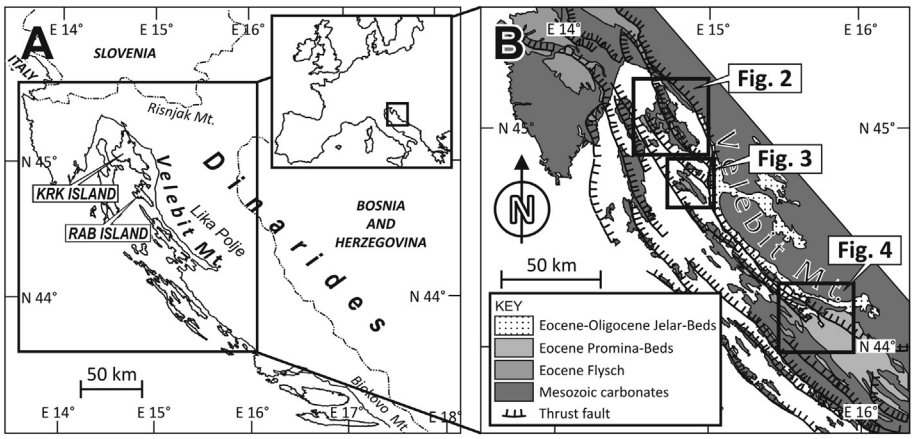


**Figure 1.** A) Location map of the study area in the Croatian Dinarides. B) Geological map of the study area, simplified after Oluić et al. (1972).

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,b), 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 rockfall.

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