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Review scientific paper

A geological overview of glacial accumulation and erosional occurrences on the Velebit and the Biokovo Mts., Croatia

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Abstract

Numerous accumulation and erosional forms originating from the activity of small valley glaciers or cirque glaciers occur on the highest mountains in Croatia: Velebit (1757 m) and Biokovo (1762 m). They were produced during the Upper Pleistocene, in the Würm glacial stage of the Alpine classification.
Accumulation forms comprise ground, terminal and recessional moraines, drumlins, eskers, glacial erratics and glaciofluvial and glaciolacustrine sediments. Single ridge eskers are often associated with areas of kame and kettle topography. Among erosional occurrences roche moutonnée (sheepback rocks), U-shaped valleys ranging in size from meso-macro, arêtes, hanging valleys, meso-sized cirques, kettles, and striations were noted. In the Croatian Dinarides, such forms mainly occur at an altitude between 900 and 1400 meters. During the early to middle Würm glacial maximum, the snow line was above 900 m, perhaps even above 1000 m altitude, and sea levels were 120 meters lower than at present day. Considering the features of the present relief, the ice cover was probably 200 to 300 m thick. Features of drumlins, eskers and kettles point to warm-based glaciers. The drumlins are small – up to 100 meters long and 50 meters wide, with the most common long axis ranging orientation from 130°-310°. The near total absence of platy clasts, as well as their stratigraphic affiliation, largely reflects features of source rocks.

Keywords

glacial records, Würm, situmetry, stratigraphy of till clasts, Mt. Velebit, Mt. Biokovo, Dinarides, Croatia

1. Introduction

Discussions in Croatian literature about glaciation in the mountains Velebit and Biokovo took place throughout the entire 20th century, mainly among geomorphologists (**Hranilović, 1901**; **Gavazzi, 1903a, 1903b**; **Roglić, 1931)**. However, the first to describe moraine deposits on Mt Velebit was a geologist, precisely **Nikler (1973),** who identified glacial sediments on the Southern Velebit localities Oglavinovac, Javornik and Ribnička Vrata as parts of the Rujno moraine and depicted the presumed boundaries of the glacier. Later, on the Basic Geological Maps 1:100 000 and Explanatory notes for Otočac (**Velić et al., 1974**; **Sokač et al., 1976**) and Gospić sheets (**Sokač et al., 1974**; **Sokač et al., 1976**) on Velebit Mt. and Imotski sheet(**Raić et al., 1977**; **Raić & Papeš, 1978**) on Biokovo Mt., traces of glaciation are only generally and roughly stated. This is in accordance with the opinion of senior geoscientists (**Schubert, 1909**; **Roglić, 1931**) on Pleistocene glaciations in the Croatian Dinarides.

The Rujno glacier existed on altitudes between 1300 and 1400 meters above sea level and eventually descended to 920 meters (**Nikler, 1973**). This indicates a relatively wide geographic distribution of Pleistocene glaciations on Velebit Mt. Later research has confirmed these findings, thus **Belij (1985)** wrote on the glacial relief of Southern Velebit and illustrated its icebound top ranging from Kozjak ridge in the northwest towards Dušice Plane in the southeast. According to some authors, Middle Pleistocene glacial and periglacial deposits even extend to the present day's coast in the Novigrad Sea and Karin Sea, as well as on the islands of Krk and Pag and elsewhere on recent altitudes ranging from 75 to 300 m (**Marjanac et al., 1990**; **Marjanac & Marjanac, 2004**). Based on geomorphological traces of glaciation, e.g. exaration morphological features and forms of sediment accumulations, **Bognar et al. (1991a, b)**, **Bognar et al. (1997)** and **Bognar & Faivre (2006)** presume that Northern and Central Velebit were affected by glaciation at altitudes above 1300 m. **Hughes et al. (2011)** stressed

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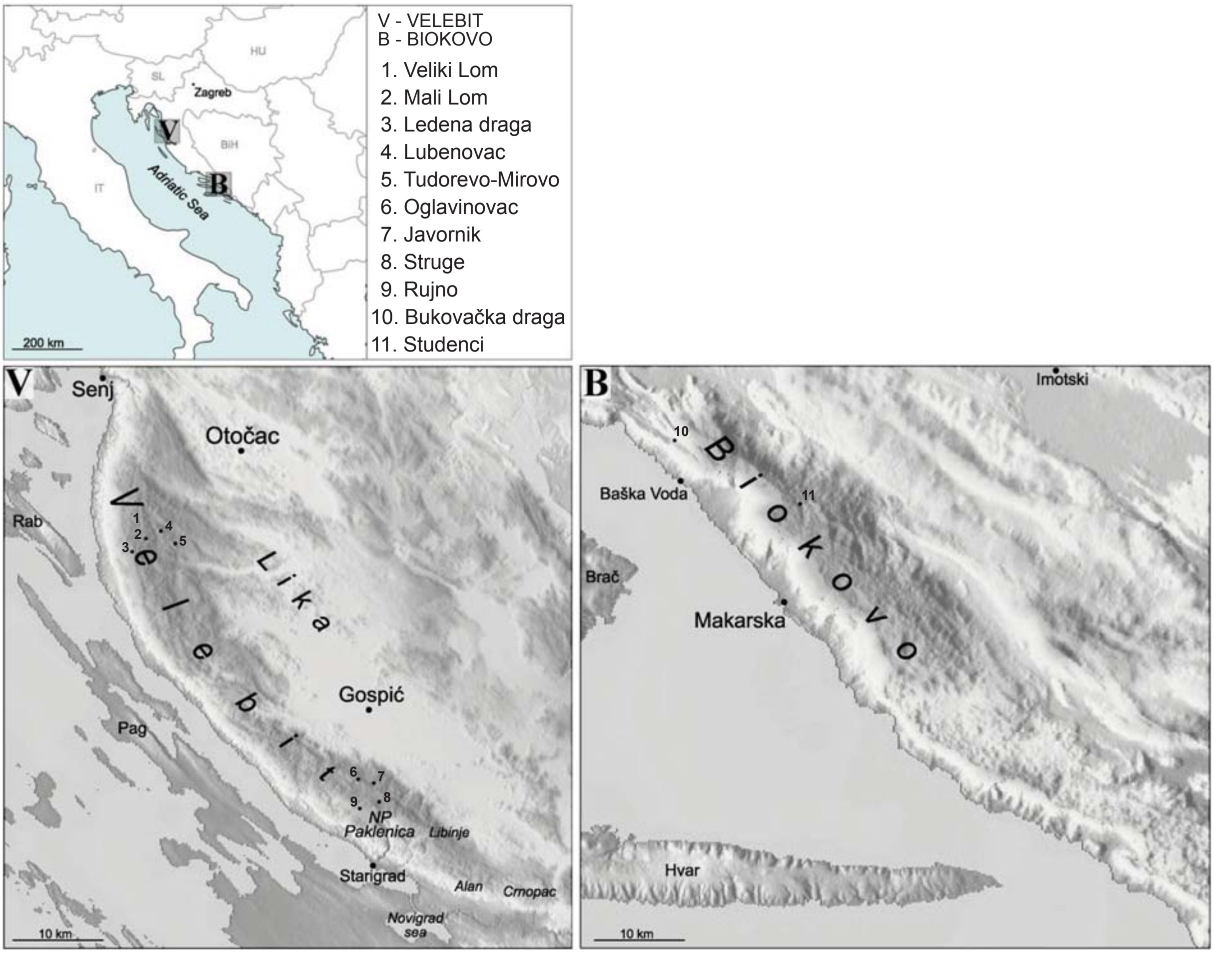

Figure 1: Situation map. V: Velebit Mt., B: Biokovo Mt.

that "the Balkan ice caps are likely to have rivalled in size the ice masses over Pyrenees and were certainly amongst the largest ice masses of the Mediterranean mountains".

During the research for preparation of the Geological guides of the Northern Velebit National Park (**Velić & Velić, 2009**), Paklenica National Park (**Velić et al., 2014**) and Nature Park Biokovo (**Velić & Velić, 2016**) a series of occurrences relating to glaciation were observed, which have not yet been the subject of detailed analysis and publishing in Croatian geological literature, or were partially published (**Velić et al., 2010**; **Velić et al., 2011**; **Protrka et al., 2011**; **Velić et al., 2013**). Therefore it is clear that geological exploration of traces of glaciation on Mts. Velebit and Biokovo has intensified over the last less than a decade, contributing to new findings such as presented in this article. It is important to note that the degree of research, findings and interpretation of data varies for the eleven localities described in this article. Many of these are inaccessible by roads and can only be reached by mountain tracks, undertaking steep climbs or simply "by azimuth". Apart from the relatively well investigated, such as the Alan glacier of the valley type in Tudorevo and Mirovo in Northern Velebit (see **Figure 1 V**) and Bukovačka Draga and Studenac on Mt. Biokovo (see **Figure 1 B**), some localities containing glacial sediments were merely registered and are scheduled for detailed investigation, those being primarily Oglavinovac, Javornik and Struge in the Southern Velebit.

Recently, Slovenian geomorphologists published articles on glaciofluvial relief on North Velebit Mt. (**Stepišnik, 2015**) and on pleistocene glaciation of the Biokovo Mt. (Žebre **et al., 2013**).

2. 2. Study area and geological setting

The Velebit and Biokovo Mts. are amongst the highest mountains in the Croatian part of the Karst Dinarides. Geomorphologically and climatologically, they represent the boundary between the Continental and Mediterranean Croatia. Mt. Velebit forms a natural boundary between continental and Mediterranean climatic regions. In its peak areas, two different climate zones, the maritime and the continental, collide causing unpredictable weather patterns. The average snowy winter lasts longer than seven months. In the valleys and dolines (sinkholes) snow lingers much longer, and the so-called snow-holes retain snow throughout the whole year. Mt. Biokovo is also never ice-free in the deepest dolines (sinkholes), ice pits and ice caves. At altitudes above 1200 m, there are no summer months without frost occurrences. In the higher parts of Mt. Biokovo (regularly above 800 m), precipitation throughout the cooler seasons (from late autumn to early spring) is mostly in the form of snow. Here snow preserves regularly until the beginning of the summer. This is in accordance with the results of the studies conducted on Mt. Durmitor, located 150 km away from Mt. Biokovo (**Gachev et al., 2016**), where on altitudes above 1910 m a number of small but permanent firn-ice patches, which can be classified as small glaciers, can be found.

Geological composition and structural framework have greatly influenced the formation of relief suitable to the genesis of glaciers and its traces. The geological structure of both of these mountains is composed of scaly structures formed by reverse faulting of the original anticlines (see **Figure 2**). They were formed by several structural mechanisms, as evidenced by the morphology of their slopes – the northeastern slope being steepened on Velebit Mt. as opposed to the steep southwestern slope on Biokovo Mt.

Velebit Mt. was uplifted by the reverse faulting of northeastern vergencies. As the result of such tectonic movements, Northern Velebit is recently a large faulted anticline with Middle Triassic deposits in its core, and Jurassic and Cretaceous deposits in its limbs. In contrast, Southern Velebit is composed of the reversely elevated southwestern limb of an anticline. Its Late Carboniferous and Permian clastic-carbonate deposits are reversely uplifted above the Triassic-Jurassic deposits of Ličko Polje. Thus is the northeastern limb of the Southern Velebit anticline was cut off and eroded. In the southwestern limb, a continuous Middle Permian to Middle Jurassic sedimentary sequence appear, concordantly from the base to the highest peaks above 1700 m. Higher parts and the topmost peaks of the Mt. Velebit are composed of Jurassic carbonates, apart from the northern parts (Rožanski and Hajdučki Kukovi) and southeastern parts (Crnopac), which are composed of unique Oligocene-Miocene tectogenic limestone breccias, known as Velebit breccia (**Velić & Velić, 2009**).The breccia were formed during the uplift of Mt. Velebit in the most active fault zones within the Jurassic and Cretaceous carbonates, along the horizontal faults. The Velebit breccia on Mt. Velebit and Lika Region are a unique phenomenon in the world (**Velić & Velić, 2009**; **Velić et al., 2014**).

Biokovo Mt. was uplifted by reverse faulting and thrusting of southwestern vergencies. Its scaly structures resulted from the subduction of the Paleogene limestones and Flysch deposits below the Upper Cretaceous and Middle Jurassic carbonates. Thus its seaward slope, which is pronouncedly steep, contains two thrust sheets – a lower sheet, with the Upper Cretaceous Kotišina deposits (carbonate breccia. and calcarenites), overlying Eocene flysch deposits, and a higher (upper) sheet, with the Middle and Upper Jurassic limestones, whose sharp edge comprises peaks ranging from 1400 to 1600 meters in height, located only 3 to 4 km away from the sea.

Development of glaciation on Velebit Mt. was partly influenced by the relief with relatively large valleys (snow-dolines), reflecting the structure and composition of the substrate and results with karstification during the Middle and Late Pleistocene. Low temperatures were very important in this process - the average annual temperature was -2°C during the Würm Glacial Maximum, which is 10 to 12°C lower than recently (**Šegota, 1966**), as well as the abundant rainfall in uppermost Würm. According to the calculations presented by **Bognar et al. (1991a,b)**, **Perica & Orešić (1999)** and **Bognar & Faivre (2006),** the total average precipitation was 4662 mm, which was enough to create large snow accumulations and regional glaciations. The snow line was at about 1300 m, and the estimated thickness of ice was 200 m (**Bognar et al., 1991a, b**).

Glacial deposits on the Northern Velebit Mt. (see **Figure 2 A**) were created and deposited by the movement of small valley glaciers over the Jurassic carbonates and Velebit carbonate brecciaIn Veliki and Mali Lom valleys (see **Figure 2 A, VL, ML**) they are overly Upper Jurassic limestones and dolomites and Velebit breccia., but in Ledena Draga (=Cold Valley; **Figure 2 A, LD**) they are overly Middle Jurassic and Upper Jurassic carbonate rocks. In the Lubenovac Valley (see **Figure 2 A, LU**) bedrocks are of the Upper Jurassic age. The Tudorevo-Mirovo Glacier (see **Figure 2 A, TM**) was moving across the Lower Jurassic and Middle Jurassic carbonates on which its glacial sediments recently lay.

In Southern Velebit Mt. (see **Figure 2.B**), at the Oglavinovac (see **Figure 2 B, OG**) and Javornik (see **Figure 2 B, JA**) cirques, moraine deposits overly Lower and Middle Jurassic carbonates. Out of these cirques the glacier moved through the U-valley Ribnička Vrata toward the Rujno Plane (see **Figure 2 B, RU**). There, moraine sediments were deposited over the Upper Triassic dolomites and Jurassic limestones. Eastwardly, on the mountain valley and Pass of Struge (see **Figure 2 B, ST**), glacial sediments overly Middle Jurassic and Upper Jurassic carbonates.

Glacial deposits from Bukovačka Draga at Biokovo Mt. (see **Figure 2 C, BD**) overly the Upper Cretaceous Kotišina carbonates and Eocene Flysch deposits. In the Studenci karst depression (see **Figure 2 C, SC**), glacial deposits were deposited over the Lower Cretaceous limestones of Aptian age. Valleys, on which sedimentary bodies of glacial origin and erosional forms were identified (from the North towards the South) are:

1. Veliki Lom (mark VL; **Figure 1 V, Figure 2 A**)
2. Mali Lom (mark ML; **Figure 1 V, Figure 2 A**)
3. Ledena Draga (mark LD; **Figure 1 V, Figure 2 A**)
4. Lubenovac (mark LU; **Figure 1 V, Figure 2 A**)
5. Tudorevo and Mirovo (mark TM; **Figure 1 V, Figure 2 A**)
6. Oglavinovac (mark OG; **Figure 1 V, Figure 2 B**)
7. Javornik (mark JA; **Figure 1 V, Figure 2 B**)

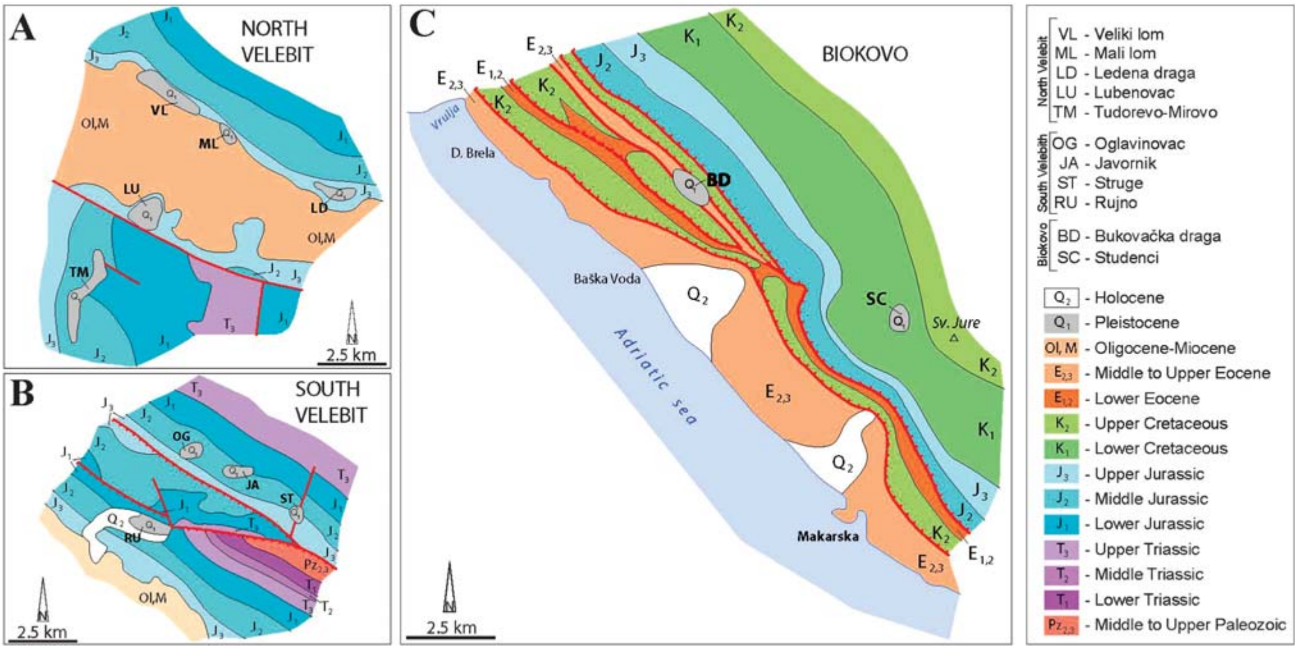

Figure 2: Geological maps with the occurrences of glacial deposits. A: Northern Velebit Mt., B: Southern Velebit Mt., C: Biokovo Mt.

8. Struge (mark ST; **Figure 1 V, Figure 2 B**)
9. Rujno (mark RU; **Figure 1 V, Figure 2 B**)
10. Bukovačka Draga (mark BD; **Figure 1 B, Figure 2 C**)
11. Studenci (mark SC; **Figure 1 B, Figure 2 C**).

3. Materials and methods

Research was predominantly realized by the field investigations, with initial observations and determination of geomorphological occurrences which indicated glacial conditions, as illustrated by panoramic photographs of the Mirovo (see **Figure 3 A**), Struge (see **Figure 3 B**) and Rujno (see **Figure 3 C**) localities. Accumulation forms were located by GPS (coordinates), their depths, widths and heights were measured, their "peaks" were positioned and the direction of form axes were determined – mainly numerous drumlins and several eskers. Afterwards, a detailed analysis of till was done by collecting a representative number of fragments/clasts of various sizes from all the bodies (situmetry, **Schreiner, 1992**), measuring of three perpendicular dimensions of the clasts, determination of petrographic composition and stratigraphic ages of fragments and cobbles. A limited number of samples, granulometry was performed in a laboratory. Values were calculated in the cabinet, which, on the basis of Zingg diagram (**Zingg, 1935**), were the base for the determination of clast sizes. Stratigraphic ages were statistically processed, and presented in histograms. Data on clast sizes were used for correlation within three groups of localities (Northern Velebit Mt., Southern Velebit Mt., Biokovo Mt.), and for the precise identification of the source area of glaciers. Due to the firm knowledge of the geological composition, stratigraphy and structures of the Mts. Velebit and Biokovo, based on the stratigraphic determination of a large number of clasts, it was possible to reliably determine the ciques, travel routes and travel distances of the glaciers. In further presentation, the review of glacial occurrences and research results, are described from the North (from the Velebit Mt.) towards the South (to the Biokovo Mt.).

4. Results

During the Late Pleistocene (Würm) glaciation, numerous glaciers existed on Velebit Mt. According to the available and gathered data, two areas are distinguished: Northern Velebit Mt. and Southern Velebit Mt. In chapters 4.1. to 4.5. Northern Velebit Mt. area, and in chapters 4.6. to 4.9. Southern Velebit Mt. area are described.

4.1. Veliki Lom

Veliki Lom (see **Figure 1 V, Figure 2 A**) contains a ground moraine (see **Figure 4 A**), drumlins (see **Figure 4 B, 4 C**) and kettles (see **Figure 4 D**). This drumlin field is situated at 1300 meters above sea level. The largest drumlin (see **Figure 4 C**) stretches about 100 m along its longer axis striking 120°-200° (130°-310°). Two excavations were done here (see **Figure 4 E**) up to depths of 90 cm. Below the 20 cm thick black-brownish soil lies a light-coloured fine-grained gravel/sand 40 cm thick, and below it, clasts of different sizes, including blocks, appear. Deposits are poorly sorted, and clasts are differently rounded, ranging from sharp-edged to relatively well-rounded. Based on the results of situmetry for 133

Figure 3: A: Glacial deposits of a "drumlin field" on Mirovo Valley, Northern Velebit Mt., B: Glacial deposits of Struge Pass, Southern Velebit Mt., C: Glacial deposits of Veliko Rujno Plane, Southern Velebit Mt.

clasts, they are mostly spherical, discoidal and spindle shaped (see **Figure 4 F**). By age/lithology they are mostly clasts of the Oligocene-Miocene Velebit breccia. and to the Upper Jurassic gray limestones. The diameter of the kettle is 7 m.

4.2. Mali Lom

In Mali Lom (see **Figures. 1 V, 2 A**), at the altitude of 1230 meters, a flattened drumlin field is found, containing a ground moraine, with several smaller drumlins (see **Figure 5 A**), kettles (see **Figure 5 B**) and eskers. Clasts in the drumlin are predominantly Jurassic mudstones (77 %), the majority of which (62 %) are of the Middle and Upper Jurassic ages, and the rest are the Upper Cretaceous clasts (8 %) (see **Figure 5 C**) and various shapes of Oligocene-Miocene Velebit breccia. (15 %) (see **Figure 5 D**). They originate from the Middle and Upper Jurassic limestones of the nearby Mali Rajinac Mount. The bedrock is the Upper Jurassic limestone. The strike of the largest drumlin is 310^0-130^0, the lengths of their two perpendicular axes are 91 m and 50 m respectively, and the height (thickness) is about 5 m. As it was covered with the soil and the grass, details of its composition were determined after the excavation. The longer axis of the largest esker has a strike of 300^0-120^0. Its average width is 15 m, and it is 60 m long.

4.3. Ledena Draga

Ledena Draga (see **Figures. 1 V, 2 A**) lies at 1050 meters altitude. A "field" of glacial accumulations is situated within a deep forest with several small drumlins. They are 40 x 90 m in size, with strikes 60°-240° and 135°-315°, respectively (see **Figure 6 A**). Clasts of the Upper and Middle Jurassic limestones predominate in the composition (56 % and 23 % respectively, **Figure 6 C**). The lengths of the three axes were measured at 127 clasts and the grain shape diagram was produced. Platy forms are the rarest, while the spherical forms are the most common (see **Figure 6 B**).

4.4. Lubenovac

Lubenovac locality (see **Figures. 1 V, 2 A**) includes two valleys – Veliki Lubenovac Valley and Mali Lubenovac Valley. Veliki Lubenovac lies at an altitude of 1350 meters. It is by shape a cirque, with the clusters of till laying in elongated, decametric, tongue-like shapes lain

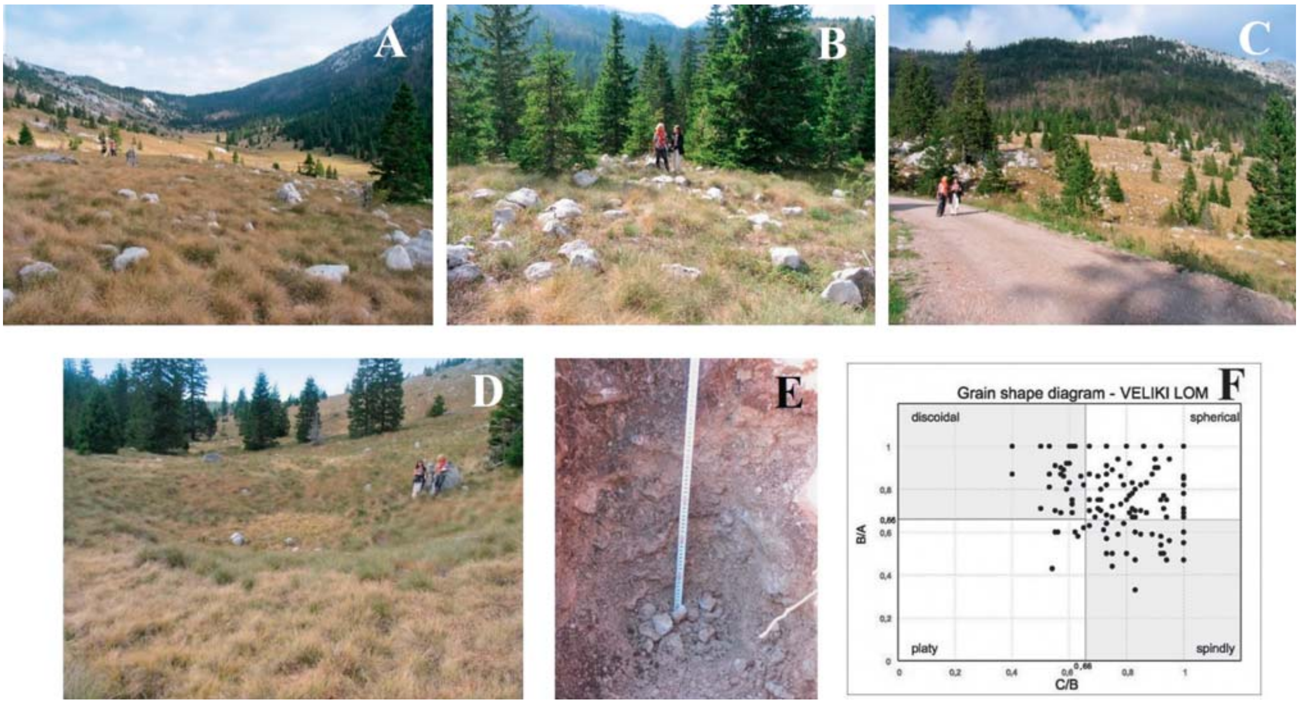

Figure 4: Veliki Lom Valley, Northern Velebit Mt. A: ground moraine with the erratics, B, C: drumlins, D: kettle, E: burrow in the ground moraine till, F: grain shape diagram of the till clasts.

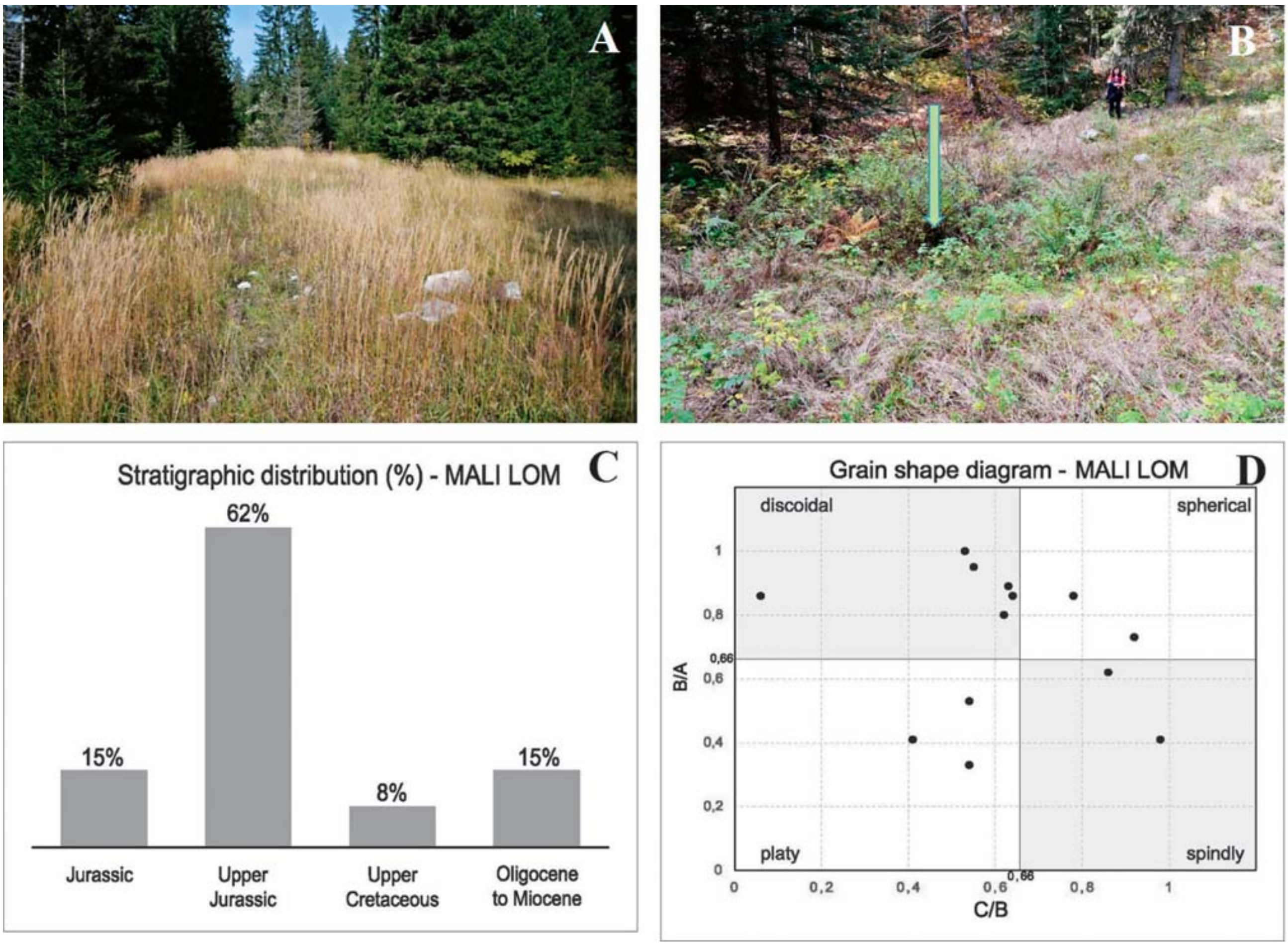

Figure 5: Mali Lom Valley, Northern Velebit Mt. A: drumlin with erratics, B: kettle, C: histogram of the stratigraphic age distribution of the clasts, D: grain shape diagram of the till clasts.

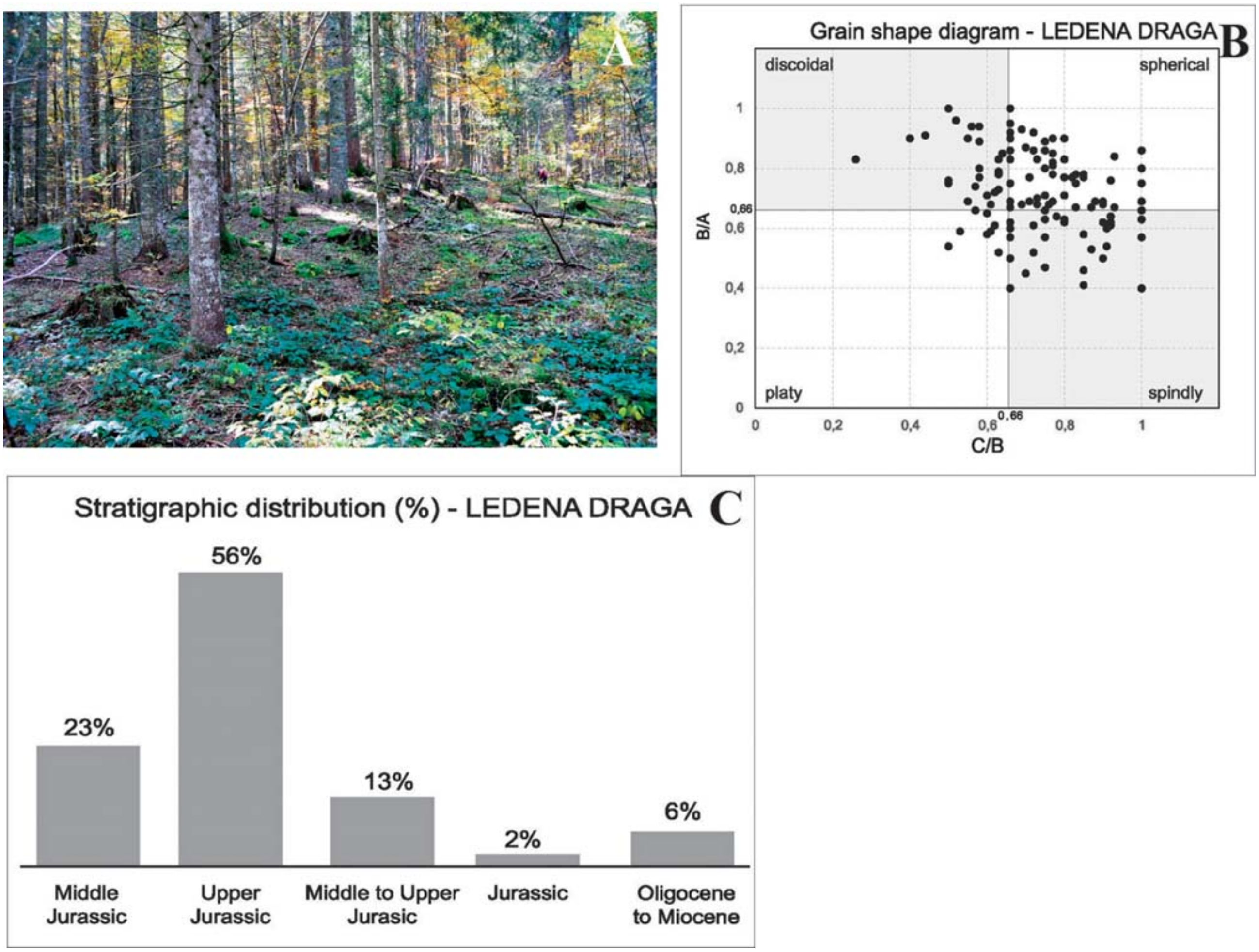

Figure 6: Ledena Draga Valley, Northern Velebit Mt. A: drumlin, B: grain shape diagram of the till clasts, C: histogram for the stratigraphic age distribution of the clasts.

one over another alongside its edges (see **Figure 7 A**). Glacial deposits are represented by a ground moraine, i.e. till, with partially rounded clasts of the Jurassic limestones and Oligocene-Miocene Velebit breccia, ranging in size between 0.5 and 20 cm (see **Figure 7 B**). Numerous kettles are present, especially in Mali Lubenovac, as well as erratic blocks (see **Figure 7 C**). Most notable is the drumlin that lies between 1300 and 1315 meters of altitude in Veliki Lubenovac, which is 15 m thick 100 m long, and about 30 m wide (see **Figure 7 D**). It is composed of the fragments from Velebit breccia. Its longer axis has a strike 130°-310°. Erratic blocks, composed mainly of Velebit breccia, are scattered around. The results of the measurement of 25 clasts shows that they are predominantly of spherical and discoidal forms, with some being spindly and none as platy form (see **Figure 7 E**). In Mali Lubenovac, at an altitude of 1280 meters, a 200 m long and about 50 m wide esker is located with the direction of strike towards 350°.

4.5. Mirovo and Tudorevo

The best investigated features near Alan are at a small valley glacier in Mirovo (**Bognar et al., 1991a, b**; **Velić et al., 2011**). It lies between 1330 and 1400 meters altitude (see **Figures. 1 V, 2 A, 3 A**). The area of Mirovo, due to the appearance of numerous drumlins, represents a true drumlin field (see **Figures. 3 A, 8 A**). It contains an accumulation of forms and shapes, such as a ground moraine (see **Figure 8 B**), a terminal (see **Figure 8 C**) and a recessional (stadial) moraine (see **Figure 8 D**), about 100 m long and 6 m high drumlins (see **Figures 8 A, 8 C, 8 D, 8 E**) with strikes 100°-280° and 130°-310°, 200 m long and 50 m wide esker (see **Figure 8 F**) with the strike direction 350°, erratic blocks (see **Figure 8 E**), and kettles as the erosional forms (see **Figure 8 C**) as well.

Granulometric composition of the till is heterogeneous (see **Figure 9 D**), yet of uniform lithological composition. It is composed exclusively of debris from the Lower Jurassic and Middle Jurassic carbonates, mostly limestones, ranging from the sand-sized grains to blocks as large as 1m^3 (**Velić & Velić, 2009**).

The Middle Jurassic clasts compose approximately 83 % of the total till mass, with the remaining 17 % belong to the Lower Jurassic clasts (see **Figures. 9 A, 9 B**). All shapes are represented, most of them being discoidal (see **Figure 9 C**).

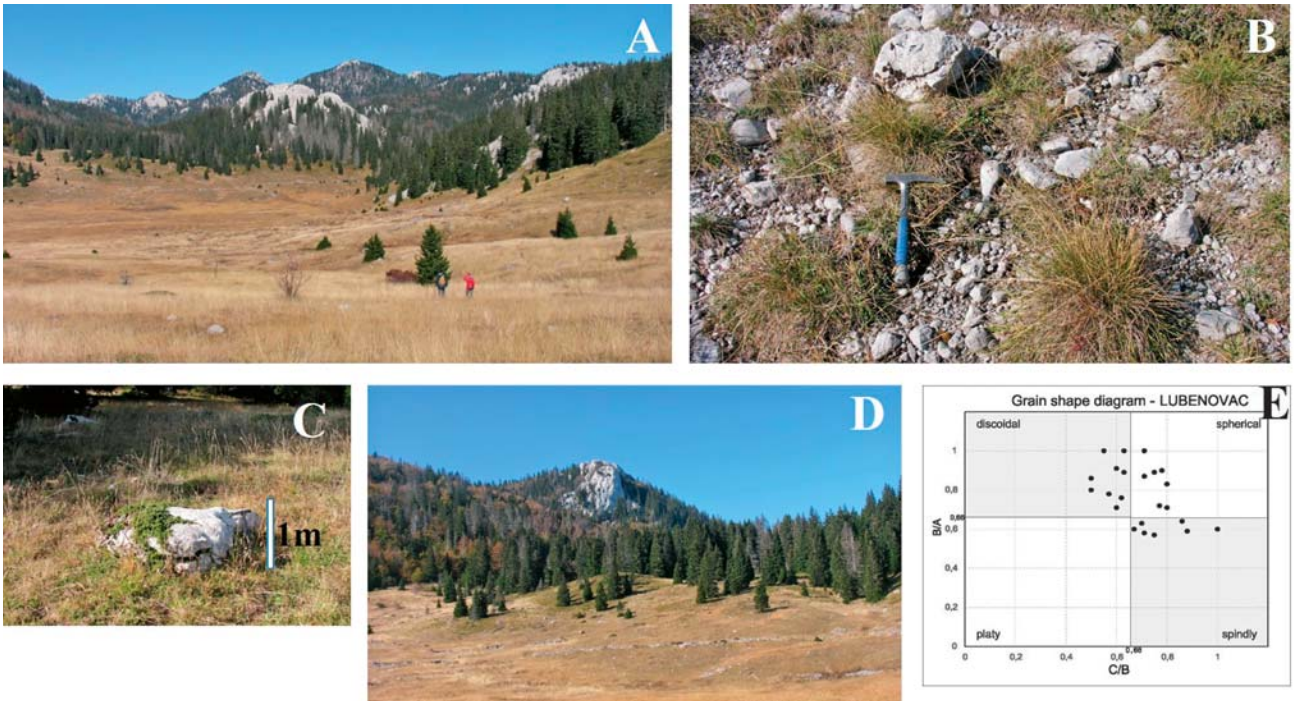

Figure 7: Cirque of the Veliki Lubenovac Valley, Northern Velebit Mt. A: till accumulations on the cirque slopes, B: till composed from the clasts of the Upper Jurassic limestones and the Oligocene-Miocene carbonate Velebit breccia., C: drumlin with an erratic; D: drumlin, E: grain shape diagram of the till clasts – mainly spheroidal and discoidal, and subordinated spindly clasts.

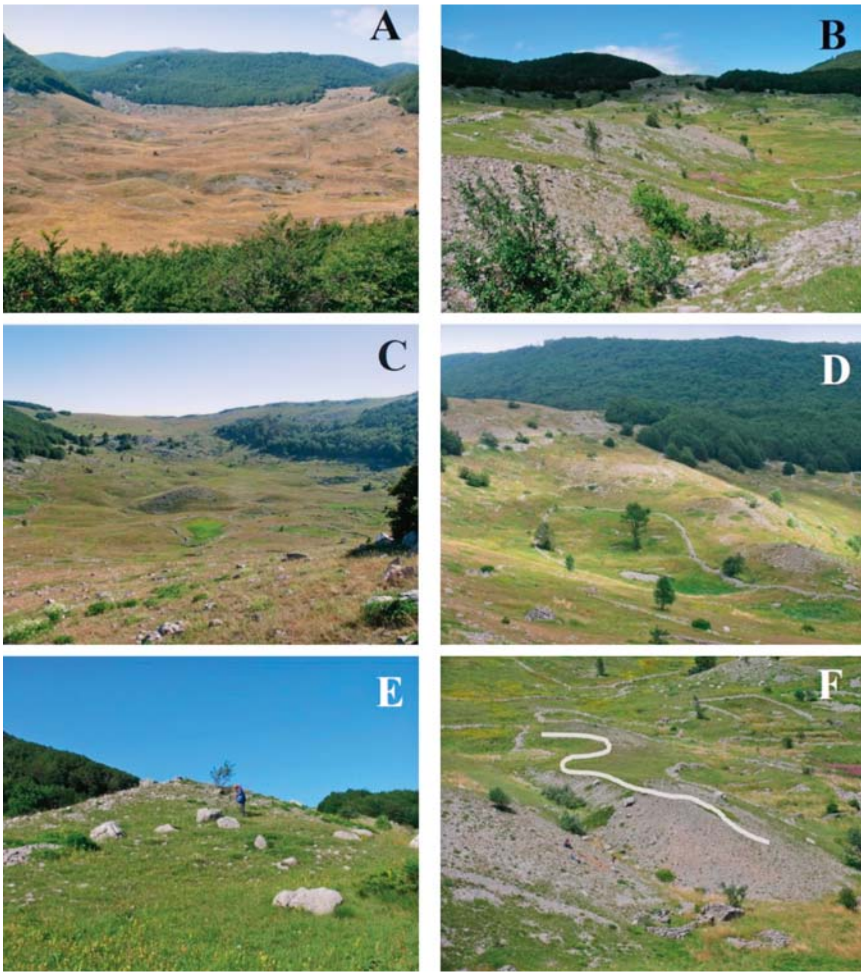

Figure 8: The Mirovo Valley, Northern Velebit Mt. A: drumlins and recessional moraine (top right), B: ground moraine, C: drumlins, kettles and the terminal moraine, D: small drumlins and the recessional moraine (top left), E: erratics on the small drumlin, F: esker.

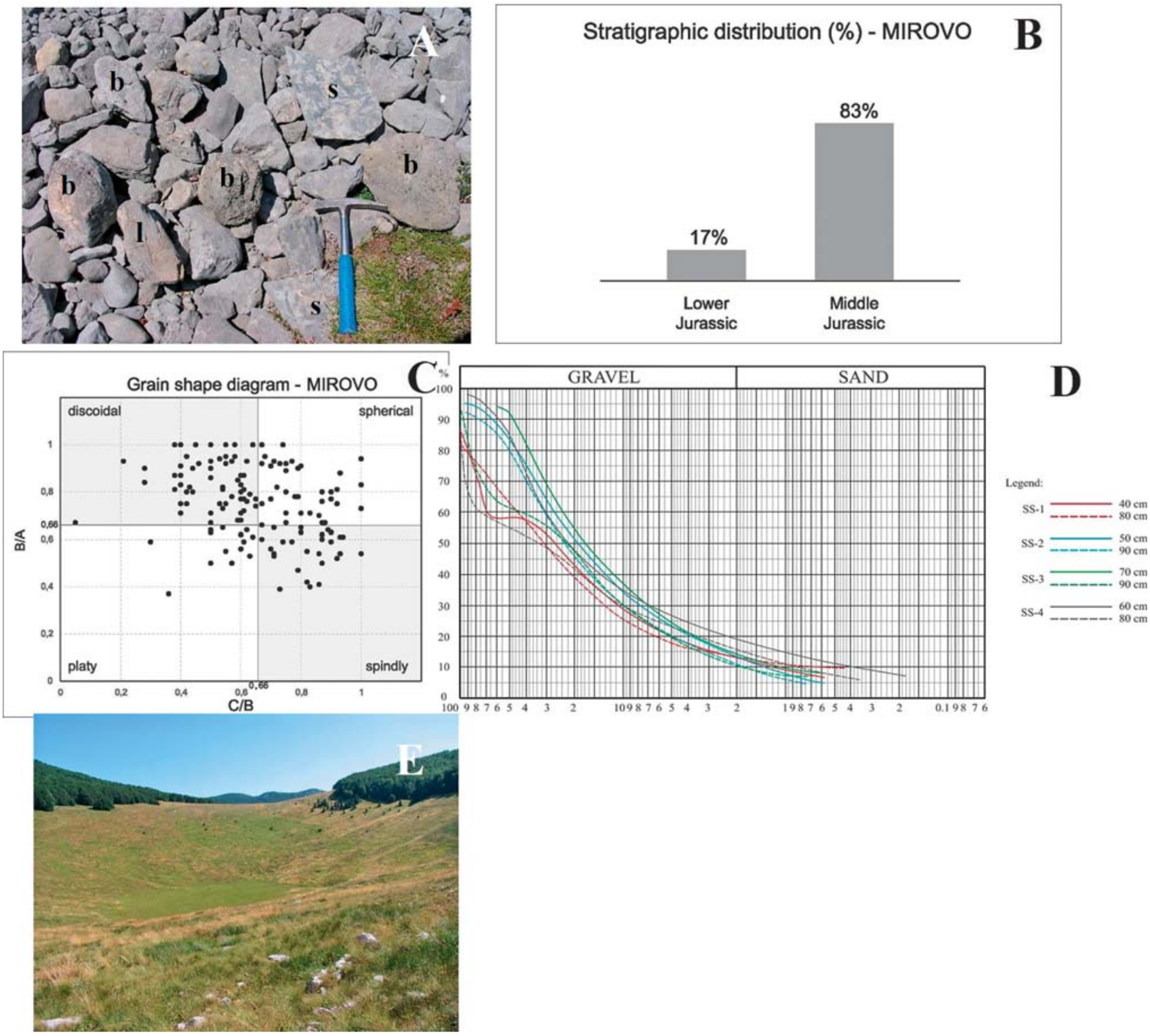

Figure 9: Mirovo valley, Northern Velebit Mt. A: clasts of the terminal moraine – Lower Jurassic Lithiotid floatstone (l), Brachiopod floatstone (b), Spotty bioturbated limestone (s), and predominantly Middle Jurassic mudstones, B: histogram for the stratigraphic age distribution of the till clasts, C: grain shape diagram of the till clasts, D: granulometric diagram of the sand and gravel distribution in till from burrows (SS-1 to SS-4), E: Tudorevo Cirque Valley, Northern Velebit Mt.

Glacial deposits can also be found in the Tudorevo karst depression (see **Figure 9 E**), located N-NE from Mirovo. The till is represented by clasts similar to those in Mirovo. Tudorevo was a cirque valley, from which ice moved cca 3.5 km towards theS-SW through Mirovo Valley into the Baričević Dolac Valley, where the terminal moraine was deposited.

The Mirovo and Tudorevo glacier was named as Alan Glacier by **Bognar et al. (1991a, b)**.

4.6. Oglavinovac

Oglavinovac.Valley (see **Figures 1 V, 2 B**) lies at 1250 meters altitude. Middle Jurassic limestones are at the base, and the middle part of the valley is a typical cirque (see **Figure 10 A**). Its till is composed from the fragments of the Lower Jurassic and the Middle Jurassic limestones (see **Figure 10 B**). The Middle Jurassic clasts predominate, but the Lower Jurassic, Pliensbachian Lithiotid Limestones (see **Figure 10 C**) and Toarcian Spotty Limestones (see **Figure 10 D**) originated from the slopes N-NE of Oglavinovac at a distance up to 2 km were also observed. A detailed investigation is in progress.

4.7. Javornik

Javornik Valley (see **Figures. 1 V, 2 B**) lies on the Lower and Middle Jurassic carbonates at 1300 m altitude. In its western part there is a cirque (see **Figure 11 A, 11 B**), and towards the east there is a drumlin field (see **Figures 11 B, 11 C**) as well as several kettles (see **Figure 11 D**) and erratic blocks are located. The till is composed of the Lower Jurassic and Middle Jurassic

Figure 10: Oglavinovac Valley, Southern Velebit. A: cirque, B: till, C: a clast of the Pliensbachian Lithiotid rudstone, D: a clast of the Toarcian bioturbated Spotty limestone.

clasts, originating from the nearby slopes of this karst depression. Similar to the Oglavinovac Valley glacial deposits, detailed investigation of glacial occurrences on the Javornik Valley is in progress as well.

4.8. Struge

Struge Pass (see **Figures 1 V, 2 B, 3 B**) is a locality hitherto undescribed, but recently its glacial accumulation and erosional occurrences are under detailed investigation (see **Figures 12 A, 12 B, 12 C**). These can be found between 1350 and 1390 meters altitude. The till is extremely poorly sorted (see **Figure 12 D**) and it is mainly composed of the Middle Jurassic clasts and subordinately of Upper Jurassic clasts.

A small cirque, with the clusters of till laying in elongated, decametric, tongue-like shapes lain one over another alongside its edges could be recognized (see **Figure 12 A)** as well as drumlins (see **Figure 12 B)** and erratics **(see Figure 12 C**).

4.9. Rujno

Rujno is a karst Plane in Southern Velebit Mt. comprising Veliko Rujno in the eastern part, and Malo Rujno in the western part of the Plane. The first glacial deposits ever described in Southern Velebit were found at the locality of Veliko Rujno, where they form the Rujanska Kosa Ridge, at altitudes between 800 and 950 meters (see **Figures 1 V, 2 B, 3 C**). They were described by **Nikler (1973)**, who defined them as a lateral moraine, a large, over 1.5 km long, and 150 m high body. Our research redefined Rujanska Kosa Ridge as a large drumlin (see **Figure 13 A**), with smaller drumlins of 90^{o}-270^{o} strikes, positioned alongside its flanks (see **Figure 13 B, 13 C**), as well as eskers and numerous erratic blocks (see **Figure 13 A**) of several Jurassic stratigraphic units. In **Figure 13 C** a strongly pronounced U- valley can be seen. Altogether 155 clasts from till (see **Figure 13 D**) of the largest drumlin were analysed. The results are shown in the **Figure 14**. Platy clasts are subordinated (see **Figure 14 A**) and the Upper Jurassic and Middle Jurassic clasts predominate (see **Figure 14 B**). Several clasts of the Upper Triassic age were also found. Highly significant are the findings of cca 5 % of the Upper Jurassic clasts, because they undoubtedly prove their previously-mentioned origins from the Oglavinovac and Javornik Cirques (OG and JA on **Figure 2 B**). Glaciolacustrine

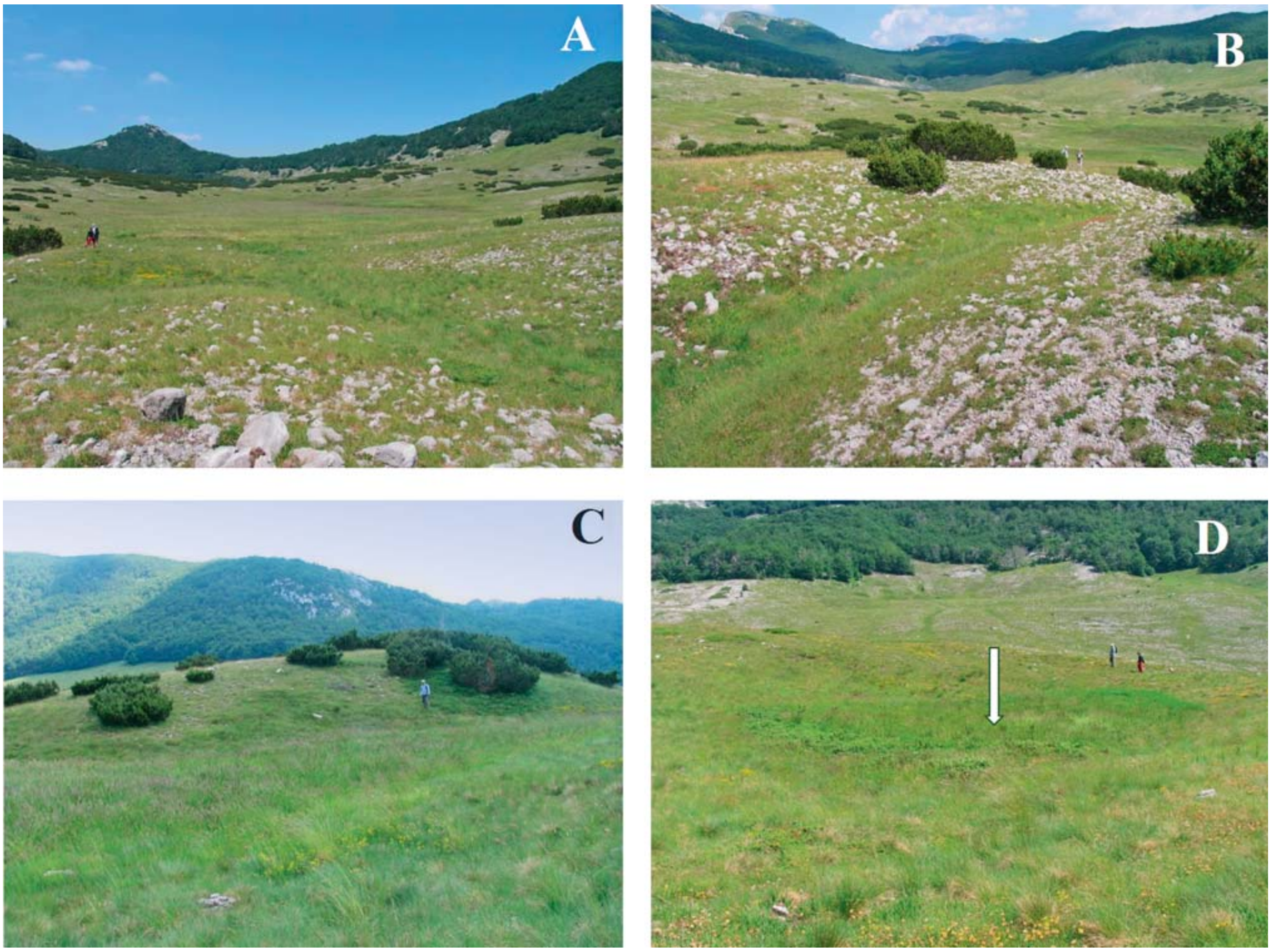

Figure 11: Javornik Valley, Southern Velebit Mt. A: cirque, B: drumlins, C: the largest drumlin, D: kettle (arrow).

deposits are also present in the Veliko Rujno Plane (see **Figure 14 C**). They are composed of silt and fine-grained sand, with sporadic occurrences of larger (up to 15 cm) clasts. The till of Rujanska Kosa Ridge and nearby drumlins had been redeposited in the beginning of the Holocene, as glaciofluvial deposits at Malo Rujno Plane.

On Biokovo Mt., two localities were relatively thoroughly processed, despite being hard to reach. They are located in the northwestern part of Biokovo Mt. (see **Figures 1 B, 2 C**).

4.10. Bukovačka Draga

In the northwestern part of the Biokovo Mt., in the Bukovačka Draga Valley (BD in **Figures. 1 B and 2 C**), on altitudes between 1030 to 1200 m, between the Bukovac Mountain hut and the Bukovac Pass, occurrences relating to the Würm glaciation were thoroughly investigated in the field. A panoramic view shows the U-shape of the Valley, as well as arêtes rising on its SW side. These were formed by the erosion and abrasion caused by a local small valley glacier (see **Figure 15 A**). Several drumlins between 3 and 5 m thick, were identified. The northern drumlin (see **Figure 15 B**), near the Mountain hut, is 61 m long and 27 m wide, with a strike of 330°–150°. The middle drumlin is 71 m long, 26 m wide and has the same strike as the previous one. The southern drumlin (see **Figure 15 C**) is smaller: it is only 12 m long and10 m wide, showing the same strike as well. On the highest point, at 1180 meters, a 40 m long and 12 m wide drumlin is located, (see **Figure 15 D)** with a strike 165°-345°

Glacial sediment in drumlins contain till (see **Figure 16 A**) formed from sharp-edged to semi-rounded chipped debris and fragments of Middle Jurassic and Upper Cretaceous limestones originated from Bukovačka Draga bedrock. From each drumlin, several dozen rock fragments were measured and their stratigraphic age and rock type was determined as well (see **Figure 16 B**). Various types of the Middle Jurassic limestones prevail (above 75 %), and the Upper Cretaceous Kotišina clasts are subordinated (up to 25 %). The share of the fragments from the Kotišina breccia. and calcarenites increases from the North towards the South: out of 6 % in the northern drumlin, over 19 % in the middle and up to 25 % in the southern one. The trend in the share of the Middle Jurassic clasts is quite opposite: from 94 % in the northern drumlin, the share decreases to 75 % in the southern one. According to the grain shape diagram,

Figure 12: Struge Pass, Southern Velebit Mt. A: ground moraine and drumlins, B: drumlins, C: erratics, D: till.

spindly and discoidal clasts prevail (see **Figure 16 C**). This occurrence is interpreted as a consequence of glacier movement through the Bukovačka Draga Valley, where the bedrock of the glacier was of different stratigraphic units. The immediate bedrock is composed mostly of the Kotišina deposits, which, due to the small thicknesses of drumlins, outcrop at numerous locations, displaying so-called "sheepback rocks" or "roche moutonn**ée" (**see **Figure 15 E**). In the higher part of the northeastern slope of Bukovačka Draga Valley, the glacier additionally encompassed the Middle Jurassic carbonates – mostly micritic limestones and carbonate breccia. On the top of the Valley bedrocks are Maastrichtian Kotišina deposits and Eocene Flysch.

4.11. Studenci

In the karst depression Studenci, north of the mountain hut Lokva, at an altitude of 1350 m, a small valley is laid out containing remains of glacial accumulation forms (SC in **Figures. 1 B and 2 C**). Very highly pronounced erosional forms are situated alongside its flanks and in the north, with an extension into a U-shaped valley (see **Figure 17 A**). This locality was first cartographically presented by **Raić et al. (1977)** and **Raić & Papeš (1978)**. The bottom of the valley is covered with moraine deposits (see **Figure 17 A**). In the eastern part, several small drumlins appear (see **Figure 17 B**). Till comprises fragments ranging from 0.5 cm long to erratic blocks of 2 m (see **Figure 17 C**). On the surface, there are fragments between 20 and 30 cm, and below them is debris from 0.5 up to 5 cm in size. These are very small drumlins; sized 60 x 35 m and 37 x 22 m respectively, with the longer axis strike at 350°-170°. Based on the analysis of the shapes for 40 clasts, those of discoidal and spherical shape prevail (see **Figure 17 D**). Several kettles were noted (see **Figure 17 A**). In the northern part of the valley "sheepback rocks" or "roche moutonnée" on the Lower Cretaceous limestones age were discovered (see **Figure 17 E**).

5. Discussion

Based on the analysis and interpretation of gathered data, as well as the results of former exploration of the Velebit and Biokovo Mts. (see **Figure 1**) numerous accumulation and erosional forms caused by the activity of small valley glaciers and cirque glaciers are described. According to the published data (**Nikler, 1973; Bognar et al., 1991a, b; Bognar et al., 1997; Bognar & Pru-**

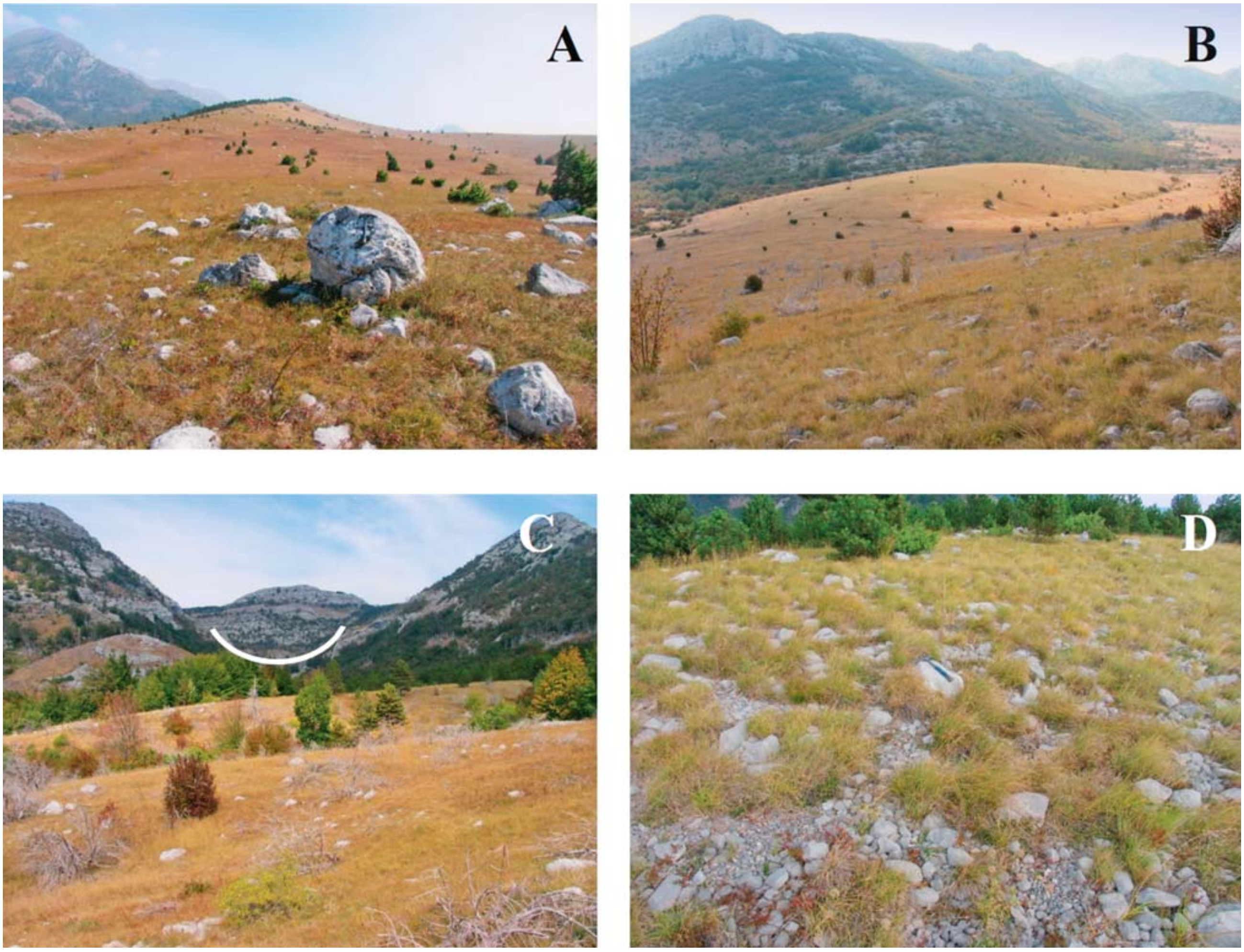

Figure 13: Veliko Rujno Plane, Southern Velebit Mt. A: drumlin of the Rujanska Kosa Ridge with erratics, B: drumlin south of the Rujanska Kosa Ridge, C: drumlins below the Ribnička Vrata – glacial "U" valley; a northward view from the Rujanska Kosa Ridge, D: till of the Rujanska Kosa Ridge.

govečki, 1997; Belij, 1985; Marjanac & Marjanac, 2004) due to glacial occurrences in the Croatian part of the Karst Dinarides, these were placed in the Upper Pleistocene, according to the Alpine temporal classification in the Würm period.

Both the shape of drumlins in Lubenovac and the strike of its longer axis at 130°-310°, indicate that the direction of glacier movement was at 130°, towards the Lika Region. Mirovo and Tuderevo were completely investigated and represent a unique model case containing more or less all occurrences formed by the influence of glacier. The strikes of the drumlins, eskers and the glacial U-valley, as well as the terminal and recessional moraines, indicate movement of the glacier from the Northeast towards the Southwest and the South, generally in the direction of 210^0, from Tudorevo and Mirovo Valleys towards the Baričević Dolac depression. Alongside this route, fragments, boulders and blocks were deposited on a several kilometre long trail, the furthest of these Lower Jurassic Toarcian Spotty limestones up to 3,5 km, from the north part of Tudorevo Valley to the terminal moraine on Bilo Ridge and Pliensbachian Lithiotid limestone, more than 2 km from Dundović Mirovo Valley to Bilo Ridge as well. The relations between the sedimentary bodies, such as the position of the recessional moraine on the older drumlin and ground moraine, the fact that the younger drumlin lies over the older one in Mirovo and the formation of younger cirques in Tudorevo, all indicate for the multiphase thaw and freeze events of the Alan Glacier.

Since the beginning of the final phase of glacier melting, drumlins and an eskers were formed on the ground moraine, and inside the moraine itself kettles were hollowed out with ice blocks. Along with the advanced melting and retreat of the ice sheet from Mirovo towards Tudorevo, on the weakly permeable ground moraine of Mirovo and terminal moraine of Bilo Ridge serving as a dam, it is assumed that a glacier lake existed in Mirovo (**Velić et al., 2011**), like for the Central Velebit proposed **Bočić et al., 2012**. As water gradually leaked from the lake, and ground moraine deposits eroded all the way to the Middle Jurassic karstified carbonate base, all the wa-

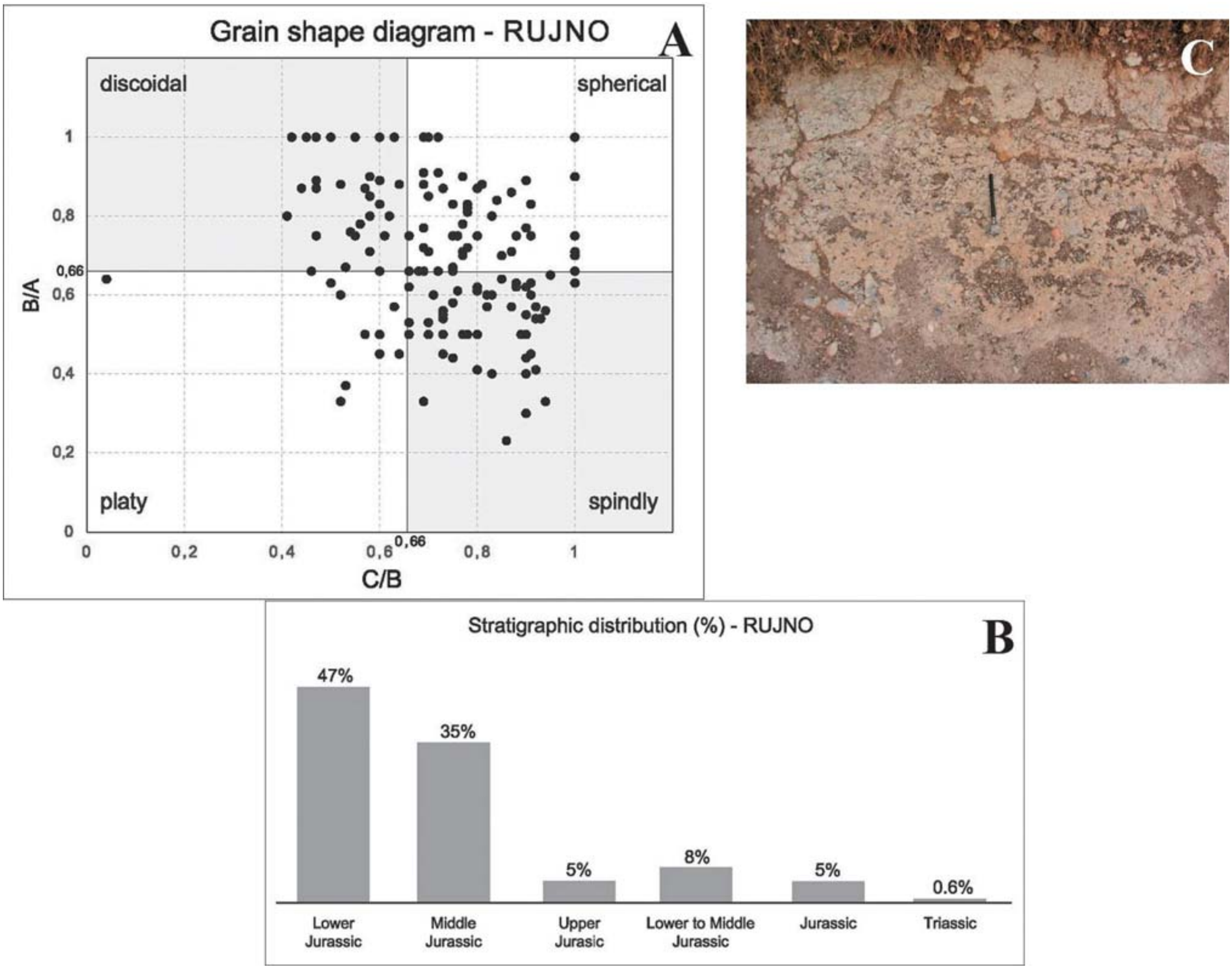

Figure 14: Veliko Rujno Plane, Southern Velebit Mt. A: grain shape diagram of till clasts at the Rujanska Kosa Ridge drumlin, B: histogram for the stratigraphic age distribution of the till clasts at the Rujanska Kosa Ridge drumlin, C: glaciolacustrine deposits of the Veliko Rujno Plane.

ter had drained out and the recent relief of Mirovo was formed. At the same time, in Tudorevo a glacier still existed, and its activity created a recessional moraine at the Mirovo/Tudorevo Pass, but similarly as in Mirovo itself, it was melted at the very beginning of the Holocene.

Till in The Oglavinovac and Javornik Cirques is composed of the Lower Jurassic and Middle Jurassic limestone clasts, originating from the nearby slopes of these karst depressions. Till on the Struge locality is composed mainly of the Middle Jurassic clasts and subordinately of the Upper Jurassic clasts. Drumlin orientation (see **Figure 12 A, 12 B**) points to the movement of the glaciers towards the N-NE.

The orientations, relationships and superposition of drumlins as well as their different sizes on the Veliko Rujno Plane point to multiple melting and glacier formation phases at the same site. The glacier source was in the cirques Oglavinovac (1250 m) and Javornik (1300 m), and it moved through the U-valley Ribnička vrata (see **Figure 13 C**) towards the Veliko Rujno Plane (830 m to 900 m), which is a distance of approx. 5 km. Terminal moraine is missing, probably being eroded, and the material redeposited into glaciolacustrine and glaciofluvial deposits today present on the Malo Rujno Plane (**Sokač et al., 1974**., **Velić et al., 2014**).

The share of Upper Cretaceous fragments in the till of Bukovačka Draga on the Biokovo Mt. increases from the north towards the south, or the share of Middle Jurassic clasts decrease (see **Figure 16 B**). This occurrence is interpreted as a consequence of glacier movement through the Bukovačka Draga Valley, following the lithological and stratigraphic changes of the bedrock units in the Valley. The immediate bedrocks are Kotišina breccia and calcarenites. The glacier was moving from the Southeast towards the Northwest, descending along a relatively steep slope towards the lower valleys of Korito and Bukva, South of the church of St. Nicholas. At the Studenci locality, the direction of movement is most likely northwards. Namely, the Studenci locality is at an altitude of 1330 m, the southern edge of the valley is

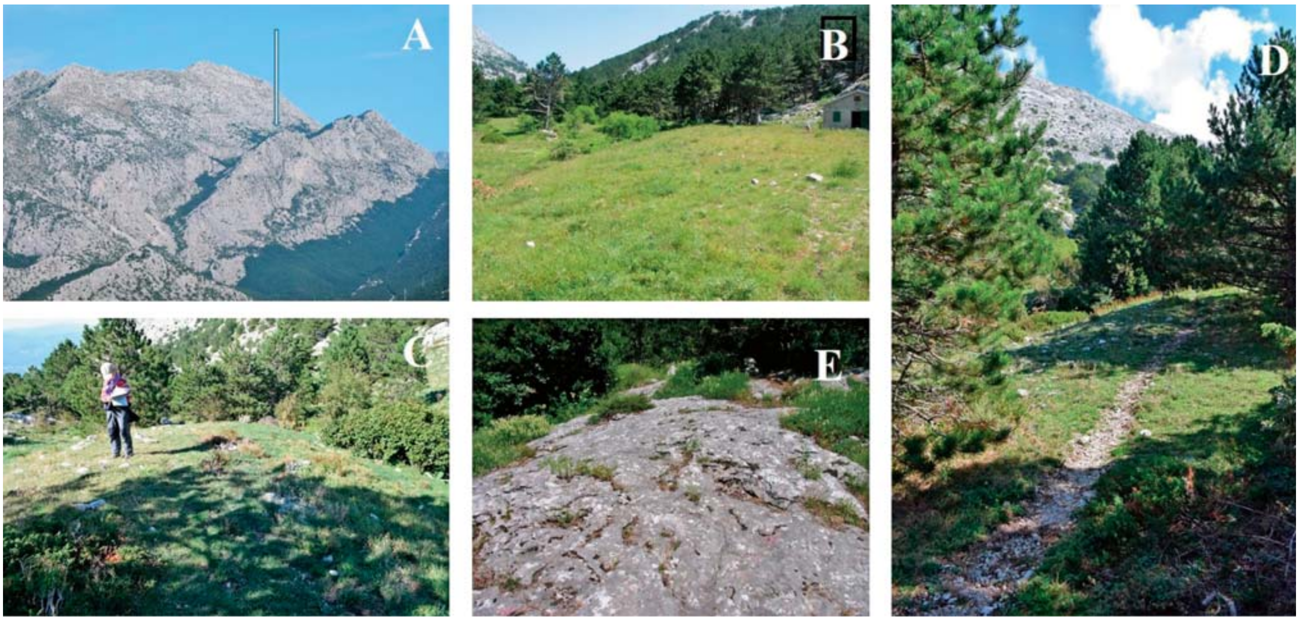

Figure 15: Bukovačka Draga Valley, Biokovo Mt. A: "U" valley of the Bukovačka Draga and arete of the Bukovac Ridge (arrow), B: Northern drumlin, C: Southern drumlin, D: the highest drumlin, E: "sheepback rocks" or "roche moutonnée".

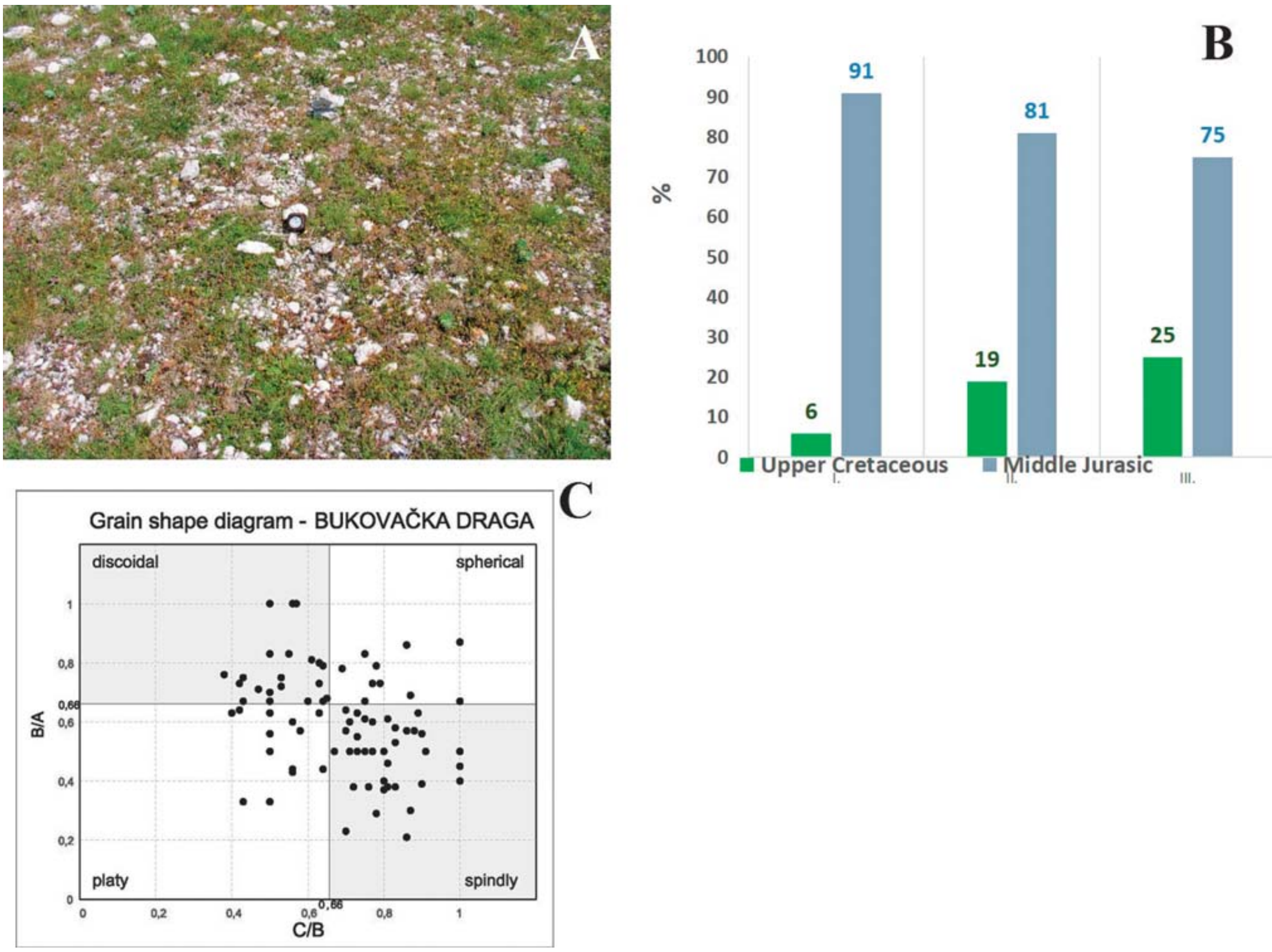

Figure 16: Bukovačka Draga Valley, Biokovo Mt. A: till of the Northern drumlin, B: histogram of clasts stratigraphy in till of the I.-northern drumlin, II.-middle drumlin, III.-southern drumlin, C: grain shape diagram of the till clasts of the drumlins.

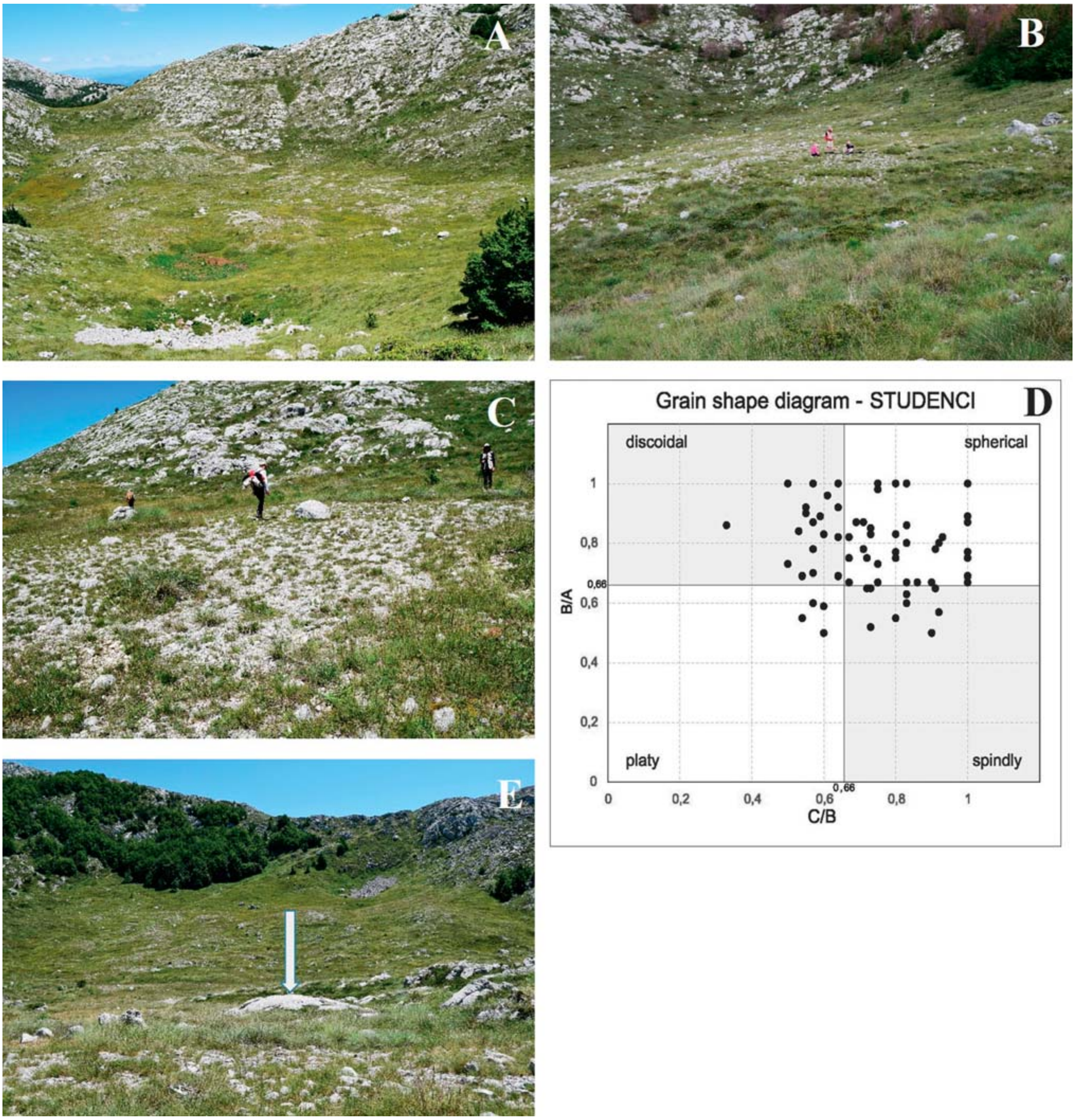

Figure 17: The Studenci Valley, Biokovo Mt. A: Panoramic northward view of the Studenci "U" valley with drumlins, kettles and roche moutonnée, B: drumlins in the eastern part of the valley, C: till and erratics, D: grain shape diagram of till clasts, E: southward view of the valley: showing sheepback rocks or roche moutonnée (arrow) in the Aptian limestones.

situated at 1425 m, and the northern edge at 1365 m. A number of smaller depressions and sinkholes in the north are located at altitudes between 1260 m and 1300 m.

Observed glacial occurrences on Velebit Mt. are found above an altitude of 1050 meters, except on the Rujno locality, which is situated at 850 m to 920 m. On Biokovo Mt., glacial occurrences are situated above 1200 meters. The glaciation range for Croatian Dinarides is approximately from 900 to 1400 meters altitude.

Therefore, during the glacial maximum ranging from Early to Middle Würm, the snow boundary (glacial bodies) was definitely above contemporary 900 or 1000 meters at the time. Since the sea level in the Northern Adriatic in Croatia in Pleistocene, during glacial times, was up to about 120 m lower than today, and a significant part of the Adriatic was land (**Mikulčić Pavlaković et al., 2011**), glaciers were formed at a contemporary range of approximately 1000 do 1100 metres above sea level. **Surić et al. (2014)** pointed out that "in spite of very favourable coastal features, late Pleistocene-Holocene relative sea-level changes along the eastern Adriatic coast are still not completely resolved, mostly due to

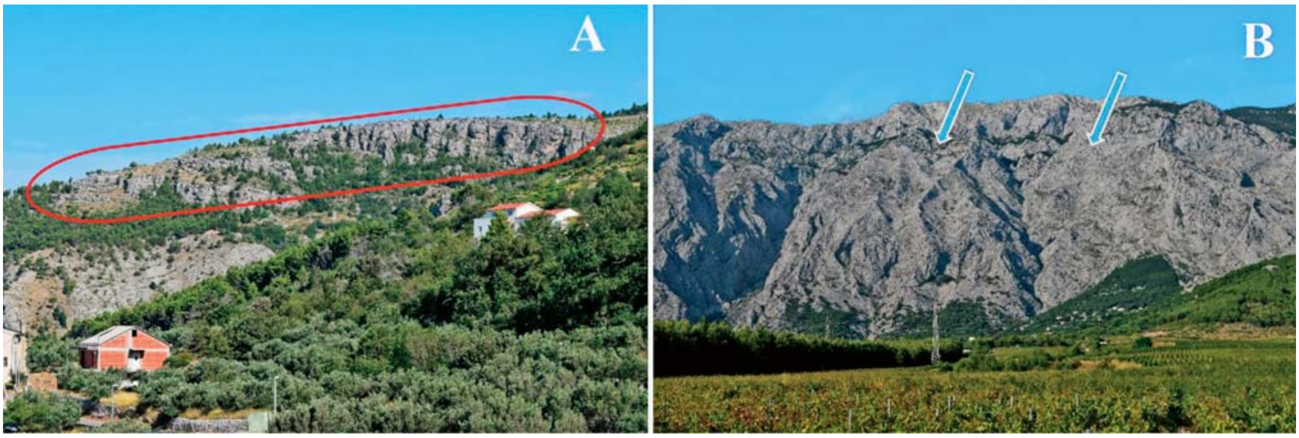

Figure 18: SW slope of the Biokovo Mt. A: Glaciofluvial fan of the Upper Pleistocene-Lower Holocene breccia (within red ellipse) of the Brdo Ridge, B: icefall flutes above the Bast Village (arrows).

the intensive and complicated regional and local neotectonics".

However, **Marjanac & Marjanac (2004)** considered the existence of glacial deposits on very low-altitudes in the coastal Dinaric Alps in comparison with the rest of the Mediterranean. The authors found evidence of lowland glaciation along the Adriatic coast ambiguous, similar to **Hughes et al. (2006)**. Considering the height of the influence zone on the formation of recent relief (especially arêtes on Biokovo Mt.), ice thickness has been estimated at 200 to 300 m. According to the data on contemporary altitudes of numerous cirques, the most intense generation of glacial bodies occurred above contemporary altitudes of 1200 m.

By the features of drumlins, eskers and kettles, the glaciers in the investigated areas can be classified as warm-based glaciers (**Bennett & Glasser, 2003**). This is in agreement with the paleoclimatic features presented in the paper **Perica & Orešić (1999)**. It is presumed that the mean temperature was lower than contemporary by about 10° C. The cooling occurred gradually, and the optimal conditions occurred prior to (approximately) 70000 years. In the first phase, the climate was cool and humid, at the end very cold and arid, and the maximum cooling occurred 25000-18000 years ago (**Perica & Orešić, 1999)**. The summers were relatively warm due to the influence of the sea which suited the forming of warm-based glaciers.

Furthermore, exploring the Quaternary sediments of the island of Susak located 60 km to the west of Velebit Mt., **Wacha et al. (2011)** and **Mikulčić Pavlaković et al. (2011)** concluded that loess and loess derivatives represent a very detailed record correlating to the Marine Isotope Stage MIS 3, precisely the major part of the aeolian deposits, including the tephra layers, correlates to MIS 3 – MIS 5 interval. Cooler MIS 4 began 74000 years ago, the age which can be correlated with results of **Perica & Orešić (1999)** who estimated the timing of optimal conditions at 70000 years.

Investigations of loess sediments of Vukovar and its surroundings, approximately 300 km E-SE from Velebit Mt., show that the loess/palaeosol sequence has a very detailed record correlating with MIS 2-MIS 6, and MIS 4-MIS 5 respectively (**Galović et al., 2011; Wacha & Frechen, 2011; Banak et al., 2016**). Thus, the paleoclimatologic picture of glacial and periglacial areas of Croatia during the Upper Pleistocene is completed, as well as its influence on glaciations of Velebit and Biokovo Mts.

The near absence of platy clasts greatly reflects the features of source rocks. Rocks lacking lamination and of thin stratification, such as Mesozoic and Cenozoic limestones in Velebit and Biokovo Mts. by abrasion and transport produce clasts of spherical, discoid and spindly forms. Spherical forms indicate longer transport and a higher energy of transporting medium (**Zingg, 1935; Tišljar, 1994**). Thus, it was possible to determine clast sources and the directions and lengths of movement of particular glaciers. Movement was relatively short – a few kilometers towards the direction of topographically lower regions. Due to the amount of spherical clasts, the longest transport could be ascribed to tills in Ledena Draga and Veliki Lom (Velebit Mt.) and Studenci (Biokovo Mt.). On other localities, discoid forms predominate, indicating relatively shorter transport routes.

Glaciofluvial deposits are most widely distributed on Malo Rujno Plane, and were also identified on Alan Pass and Krasno village in Northern Velebit Mt. (**Sokač et al., 1974**, **Velić et al., 1974, Stepišnik, 2015**) as well as on Libinje on Southern Velebit Mt.

Several curiosities should also be mentioned. At two localities on very steep seaward slopes of Biokovo Mt. sediment bodies 1 x 1.5 km in size, resembling fans, were formed (see **Figure 18 A**). The authors consider them as products of icefall during the melting. Furthermore, on the same side of Biokovo Mt., well developed flutes 75 to 200 m were identified, with a height of about 850 m (see **Figure 18 B**), reaching from the base to the peaks of its peripherals, also produced as a consequence of the relatively rapid melting of large quantities of ice from the peaks of Biokovo Mt. and icefalls, precisely water and clast falls alongside a steep slope. Investigation of the glaciolacustrine deposits of Mts. Velebit and Biokovo should be vital for the more precise determination of conditions and timeframe of glaciation and its end.

6. Conclusions

Numerous accumulation and erosional occurrences of glacial deposits can be found in the coastal Dinarides in Croatia, on Velebit and Biokovo Mts., originating from the activity of small valley and cirque glaciers. They are situated on altitudes of approximately 900 to 1400 meters.

The snow boundary was at least at 900 meters above sea level. That corresponds to contemporary 1000 meters, as the sea level was 120 meters lower at the time of glaciation (the Würm glacial).

Ice thickness was estimated at 200 to 300 m, and the most intense generation of glacial bodies occurred above contemporary altitudes of 1200 m. Drumlins, eskers and kettles point to *warm-based glaciers*.

Lengths of their movements were from 2 to 6 km, and directions of movement alongside the continental and seaward slopes of Velebit and Biokovo Mts.

On the seaward slopes no glacial features were found at altitudes below 900 meters above sea level. Investigated forms are remains of the final (Würm) glaciation in the Late Pleistocene.

Among the accumulation forms ground, terminal and recessional moraines, drumlins, eskers, erratic blocks and glaciofluvial and glaciolacustrine deposits were determined.

Eskers are of the single ridge variety, which are often associated with areas of kame and kettle topography.

Among the erosional forms sheepback rocks (roche moutonnée), U-shaped valleys of meso-macro sizes, arêtes, hanging valleys, icefall flutes, meso-sized cirques, kettles and striations were defined.

Predominant quantity of discoidal types of clasts reflects the relatively shorter lengths of glacier flow. However, due to the topographical features of the Mts. Velebit and Biokovo, it would be valuable to investigate other prospective sites containing not only glacial but proglacial and periglacial features as well.

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SAŽETAK

Geološki pregled glacijalnih naslaga i erozijskih pojava na planinama Velebitu i Biokovu, Hrvatska

Brojne su pojave naslaga i erozije podrijetlom iz aktivnosti u malim ledenjačkim dolinama ili cirkovima, a koje su postojale na najvišim hrvatskim planinama – Velebitu (1757 m) i Biokovu (1762 m). Takve pojave nastale su tijekom gornjega pleistocena, u virmu (dobu prema alpskoj klasifikaciji). Akumulacijski oblici obuhvaćaju površinske, terminalne i recesijske morene, drumline, eskere, glacijalne prekide te glacijalno-riječne i glacijalno-jezerske taložine. Pojedinačni ledenjački talozi, grebeni tipa eskera, često su udruženi s topografskim oblicima, tj. područjima kama (brežuljaka) i kotlića (udubina). Također se pojavljuju i oblici *roche moutonnée*, tj. oblici stijena nastali prolaskom ledenjaka, te doline U-oblika koje variraju od mezoveličina do makroveličina. Zatim su opažene *arête*, uski grebeni koji dijele dvije doline, urezane doline, mezocirkovi, ledenjačke udubine te pojave strija. Unutar hrvatskih Dinarida takve pojave opažene su na visinama od 900 do 1400 metara. Tijekom ranoga do srednjega virma, u vrijeme ledenjačkoga maksimuma, snježna granica nalazila se iznad 900, a možda i 1000 metara, dok je morska razina bila 120 metara niža od današnje. Promatrajući današnji reljef, zaključeno je kako je ledeni pokrivač bio vjerojatne debljine 200 – 300 metara. Pojave poput drumlina, eskera i kotlića upućuju na ledenjake iznad ili blizu točke topljenja leda uz podlogu (engl. *warm-based*). Drumlini su mali, dimenzija do 100 m dužine i 50 m širine, dok im duža os uglavnom ima orijentaciju 130° – 310°. Gotovo potpuno nedostaju ravni klasti što, uz njihovu stratigrafsku pripadnost, upućuje na svojstva ishodišnih stijena.

Ključne riječi:
dokazi oledbi, virm, situmetrija, stratigrafija nesortiranih klasta, Velebit, Biokovo, Dinaridi, Hrvatska

Author(s) contribution

Josipa Velić: leader of the field investigations on all presented localities; analysed, synthesized and interpreted field and laboratory data; wrote the most of text of the article. **Ivo Velić**: participated in field investigations on all localities; determined stratigraphic age of clasts of till, erratics and bedrocks; wrote a part of text on stratigraphy and tectonics of the all localities; made geological sketch maps of all localities with positions of glacial deposits. **Dubravka Kljajo:** participated in field investigations on the North Velebit Mt., especially in analysing of lithology of glacial sediments in burrows, and dimension of clasts. **Ksenija Protrka**: participated in field investigations on the Biokovo Mt., in analysing of lithology of glacial sediments, measured dimensions of clasts, orientations and size of drumlins; collected published data on the Biokovo Mt. glaciation. **Hrvoje Škrabić**: participated in field investigations on the Biokovo Mt., in analysing of lithology of glacial sediments, measured dimensions of till clasts, erratics and drumlins. **Zlatko Špoljar**: gathered till clasts for situmetry, measured „a/b/c“ axes of clasts for graphics of grain shape diagrams.