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Sedimentary bodies, forms and occurrences in the Tudorevo and Mirovo glacial deposits of northern Velebit (Croatia)

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ABSTRACT

A small glacier of cirque-valley type existed during the Late Pleistocene Würm Glacial in the Tudorevo and Mirovo karst valleys of Northern Velebit. Its source was in Tudorevo, and it moved through Dundović Mirovo and Bilensko Mirovo to Baričević Dolac, shaping U-valleys around 4 km in length. After melting, glacial deposits remained, composed of chaotic and unsorted till, composed of carbonate sand, debris and sub-rounded clasts, cobbles and blocks of predominantly Middle Jurassic and subordinately Lower Jurassic carbonate rocks. In Dundović Mirovo and Bilensko Mirovo, where the largest masses of glacial deposits occur, terminal and recessional moraines can be found over the ground moraine, as well as some other features, mostly drumlins (drumlin field), eskers, erratic blocks, kettle holes and striations. Some erratics have been transported for more than 4 km from their primary outcrops, e.g. clasts of Lower Jurassic Toarcian Spotty limestone. A terminal moraine was deposited between Bilensko Mirovo and Baričević Dolac, perpendicular to the glaciated U-valley and it forms the Bilo hill, the northern and southern foothills of which are composed partly of glaciofluvial deposits. Between Tudorevo and Mirovo, a recessional moraine occurs above the ground moraine. The glacier was subject to polyphase melting and freezing, and the youngest freezing events may be related to cirques in Tudorevo. During melting events, glacier lakes are supposed to have existed, initially in the Baričević Dolac, later in Mirovo area and finally in Tudorevo. These discharged into the karst underground by percolation through till and by erosion to the karstified underlying Middle Jurassic carbonates.

Keywords: Tudorevo–Mirovo glacier, till, moraines, drumlins, esker, kettle holes, erratics, glaciolacustrine deposits, glaciofluvial deposits, Late Pleistocene, Northern Velebit, Croatia

1. INTRODUCTION

Although discussions on glaciation in Velebit Mt. were led (almost throughout the entire 20th century) by mostly geomorphologists, glacial deposits have been described for the first time at Velebit Mt. by a geologist. The first description was made in Southern Velebit, where at Oglavinovac, Javornik, Ribnička Vrata and Rujno localities NIKLER (1973) described the boundaries of glaciers, as well as moraine at Rujno. That confirmed the opinion of former geoscientists (e.g. HRANILOVIĆ, 1901; GAVAZZI, 1903a, b; SCHUBERT, 1909) on Pleistocene glaciations in Croatian Dinarides.

The Ribnik–Rujno glacier existed in the area between 1300 and 1400 m a.s.l., and descended all the way to 920 m a.s.l. (NIKLER, 1973), indicating significant spreading of Pleistocene glaciation at Velebit Mt. This was confirmed by later investigations, e.g. BELIJ (1985) who reported on the glacial relief of Southern Velebit, and illustrated its glaciated apical part from Southern Velebit Kozjak in the southwest, to Dušice in the southeast. There are also suggestions that Middle Pleistocene moraines may be found at the coast in Novigradsko More (MARJANAC et al., 1990). BOGNAR et al. (1991, 1997) have determined that Northern and Central Velebit were glaciated at heights above 1300 m a.s.l. BOGNAR et al. (1991) have, in their description of morphological indicators of glaciations in the northern Velebit area, including exaggerated? morphological elements and accumulated deposits, also covered the study area of Tudorevo and Mirovo, where they described glacial deposits of the Late Pleistocene Alan glacier.

However, most of the cited authors investigated and described Velebit Mt. glaciations from the geomorphological point of view. Only NIKLER (1973) briefly mentioned the composition and origin of glacial deposits.

During investigations for the geological guide-book of the Northern Velebit National Park (VELIĆ & VELIĆ, 2009), many features that have not previously been reported in Croatian geological literature have been found in tills of the Tudorevo and Mirovo. In the guide-book, glacial deposits were marked for the first time on the geological map of the area.

The main goal of the investigation presented here was to determine the basic geological properties of the area characterized by glacial deposition, e.g. the stratigraphy of bedrocks and clasts within the til, as well as the shapes of glacial sedimentary bodies. On the basis of this investigation it was possible to estimate the volume, length and orientation of glacier movements. Investigation of the Würmian and recent climate, and their correlation, together with the influences of postglacial corrosion, etc. were beyond the scope of the investigation.

Tudorevo (approximately 2 km long), and Mirovo (1.5 km long), are karst valleys in Northern Velebit (Fig. 1), located between 1300 and 1450 m a.s.l. In the higher part they are wider, approximately 1 km. Mirovo is composed of two smaller valleys, Dundović Mirovo in the NE and Bilensko Mirovo in the SW (Fig. 1).

2. LITHOLOGY OF THE GLACIAL DEPOSITS

Three lithofacies units have been defined within the glacial deposits of Tudorevo and Mirovo: till, glaciofluvial deposits and glaciolacustrine sands and clays. Till is the most common, and may be found in all parts of the study area, while glaciofluvial deposits are observed in the foothills of the Bilo terminal moraine, together with relics of glaciolacustrine deposits assumed in Tudorevo and Mirovo.

2.1. Till

Tills have been widespread in central and southern parts of Tudorevo, in Dundović Mirovo, Bilensko Mirovo and at Bilo hill. Some tills can also be found in the western part of the Bilenski Padež. Till represents loose clastic sediment of highly variable grain size distribution, because it is completely chaotic and unsorted (Figs. 2, 4, 10, 16, 19, 21 and 22). It is composed of debris and clasts of carbonate rocks over which, and along which, the glacier moved. Clast sizes vary from millimetre, centimetre, and decimetre to metric dimensions i.e. from coarse sands, gravels, cobbles to boulders and blocks. They are mostly poorly rounded, and some show preserved striation formed by friction with ice or with other rock clasts.

Clast size measurements used for the statistical analysis showed their great variability, so in sampling site SS–1 within a thickness of 1 metre 60% of clasts were below 10 cm, and 40% of 10–25 cm in size. In SS–2, SS–3 and SS–4 the percentage of clasts below 10 cm was about 30%. To illustrate this, data from a till in the top layer of a recessional moraine (RM, SS–1; Fig. 3) between the Tudorevo and Dundović Mirovo and in drumlin till (D–13, SS–4; Fig. 3) in the Bilensko Mirovo are presented.

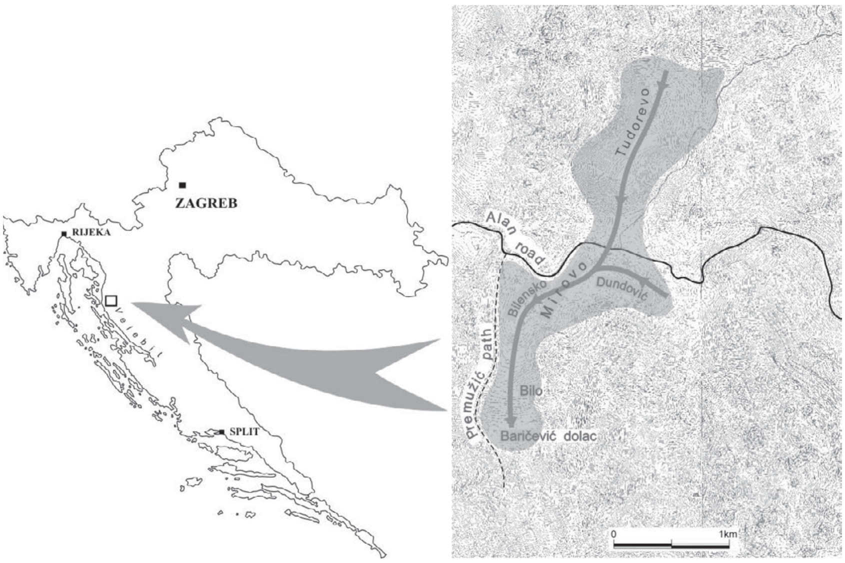

Figure 1: Location map showing the distribution of the Tudorevo–Mirovo glacier (light greyish) and direction of its movement (gray).

Figure 2: Chaotic and unsorted till of recessional moraine cropping out on the Alan road, northern slope of Dundović Mirovo.

Sampling site–1 **(SS–1)**

Geographic location: recessional moraine on the ridge between Tudorevo and Mirovo, north of the Alan Road, orientation 130–310° (Fig. 3).

Moraine dimensions: length 143 m, width 61 m.

Description: till of the recessional moraine (RM) mainly overlies till of the ground moraine (GM) and drumlin till (D–1; Fig. 3), the eastern part overlies thick Middle Jurassic limestone layers dipping 266/30 (Fig. 4). Striation oriented 145–325° is visible. Till is composed of debris, smaller clasts, cobbles, boulders and blocks of Aalenian–Bajocian limestones, mostly mudstones, interspersed with interbeds of oncoids up to 1 cm in diameter and lenses of intraclastic wackestones with rounded intraclasts. Clasts of Toarcian bioturbated Spotty limestones rarely occur, while clasts of typical fine-crystalline Toarcian brown dolomite are common.

Samples from SS–1 trench

Clasts are mostly cobbles (size in cm and age):

23x23x17, ab; 11x10x8, ab; 20x20x10, ab; 11x9x6,5, ab; 9x12x5, to, dol; 9x10x4, to; 19x24x12, ab; 9x10x4, to; 14x13x10, ab, dol; 13x15x5, ab; 12x12x8, ab; 12x8x7, ab; 12,5x10x6, ab; 10x13x9, ab; 10x18x7, ab;13x12x16, ab; 17x14x15, to; 11x20x9, ab; 25x10x17, ab; 12x17x10, q; 9x8x6, ab; 6x10x7, ab; 9x10x4,5, ab; 11,5x10x4, ab; 10,5x10x5,5, ab; 17x9x10, ab; 15x16x15, to; 23x11x12, ab; 20x13x19, ab; 9x13x10, ab.; 11x10x8, ab; 20x17x10, ab; 11x12x8, ab; 11x11x7, ab; 15x16x15, to; 18x14x11, ab; 14x15x10, ab; 20x16x7, to; 9x24x12, ab; 15x14x7, ab; 7x13x6, b; 15x11x11, ab; 7,5x13x8, ab; 7x10x8, ab; 21x15x12, ab; 13x12x9, ab;

(Legend: to – Toarcian; a – Aalenian; b – Bajocian; q – quaternary, calcite; dol – dolomite)

The remaining 60% of the total excavated mass are clasts of smaller dimensions in the ranges from 8x9x3 cm to 0.7x1x3 cm and smaller.

Sampling site–4 **(SS–4)**

Geographic location: drumlin D–13 in the southern part of the Bilensko Mirovo (Figs. 3, 8, 20 and 23).

Drumlin dimensions: length 71 m along the 100–280° orientation, width 64.50 m (NE–SW).

Description: drumlin D–13 overlies older drumlin D–12. Till is composed of unsorted, poorly rounded clasts of mm to dm size. Only one erratic block has been noticed on top of the drumlin. Predominant clasts are of Lower Jurassic limestones, others are Aalenian–Bajocian in age. Among the identified clasts are those of lithiotid, brachiopod and dark muddy limestones of Pliensbachian age, as well as Spotty limestones and dolomites of Toarcian age. Aalenian–Bajocian limestone clasts are gray to dark gray mudstones.

Samples were taken from SS–4 trench at the depths from 50 cm to 90 cm.

Clasts from the trench are mostly cobbles, rarely boulders (size in cm and age):

15x25x30, prob. ab; 12x13x8, to; 14x9x8, p; 30x24, prob. ab; 13x10x6, p; 10x7.5x3, p; 17x7x6, p; 15x6x5, ab; 10x12x6, ab; 15x12x9, to; 16x10x9 p; 20x13x7, p; 14x10x5, prob. ab; 10x5.5x3, p; 9x6.5x4, p; 13x7x5, to.

(Legend: p – Pliensbachian; to – Toarcian; a – Aalenian; b – Bajocian)

Smaller clasts (gravels to pebbles) of sizes from 3x2.5x1, to 0.5x0.5x0.4 comprise 25–30 wt. % of the excavated material.

For the abovementioned clasts which were not taken for granulometric analysis, three values of their size were measured – the largest, medium and minimum. Parameters needed for the determination of their shape were also calculated (after ZINGG, 1935). Nearly 50% of clasts have a discoid shape (in three trenches – SS–1, SS–2 and SS–3) or spheroidal shape (trench SS–4).

According to their stratigraphic origin, clasts of Middle Jurassic carbonates predominate, which is understandable considering that the glacial 'U' valley is mostly cut into these deposits. They comprise about 85–90% of the till in the Bilensko Mirovo, and 40–50% in northern Tudorevo. Remaining clasts are derived from Lower Jurassic rocks: Pliensbachian Lithiotis limestones and Toarcian Spotty limestones. An interesting situation has been noticed in the trench SS–4 where it was determined that the total mass of till clasts larger than 10 cm is 70%, and among them 70% of the clasts are derived from Lower Jurassic deposits of eastern part of Dundović Mirovo (Fig. 3).

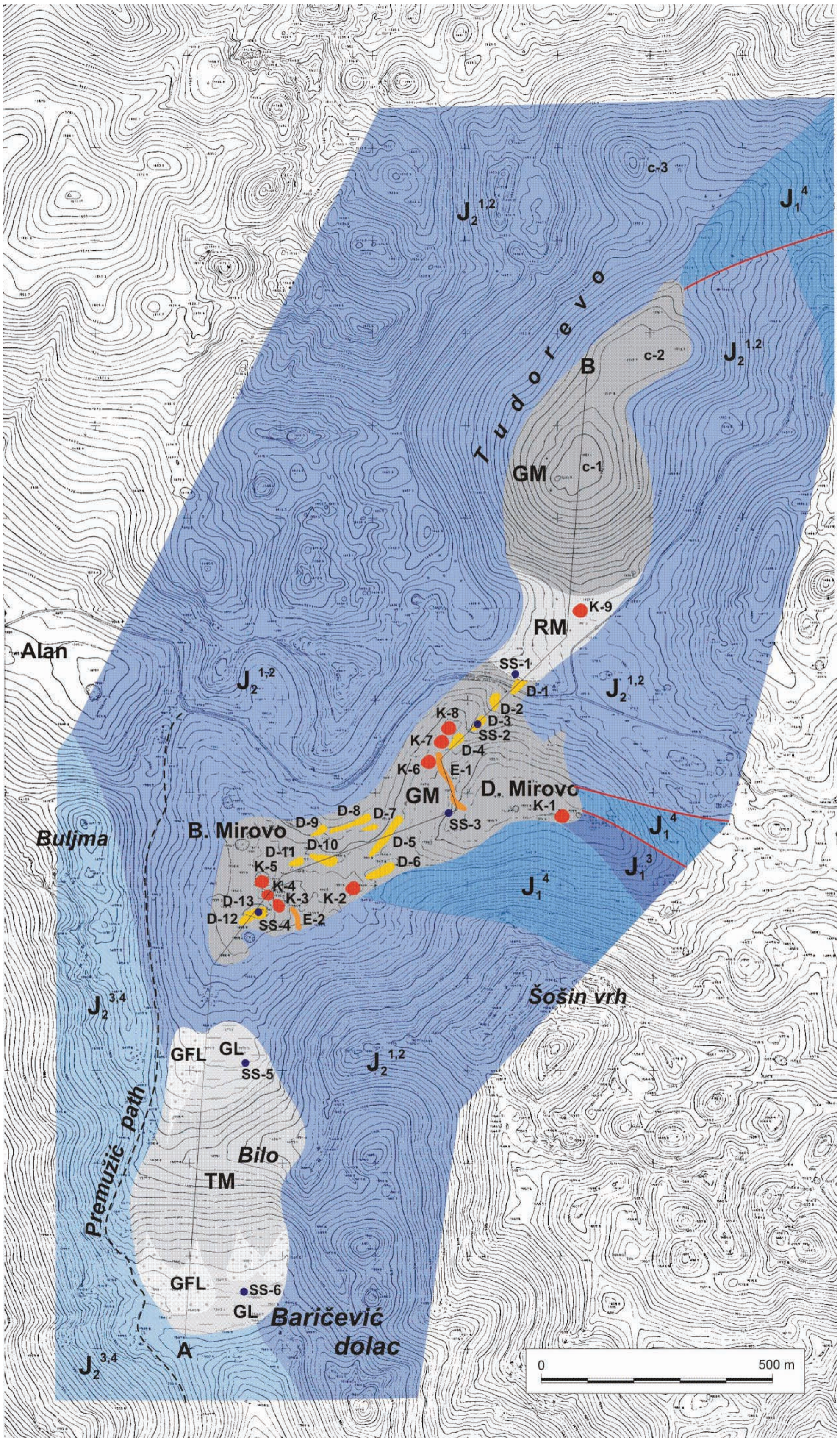

Figure 3: Geological sketch-map of the Tudorevo–Mirovo area showing the distribution of the glacial deposits with main sedimentary bodies and stratigraphic age of their basement and neighbouring rocks. Legend: J_1^3 – Pliensbachian Lithiotis limestones; J_1^4 – Toarcian bioturbated Spotty limestones and dolomites; $J_2^{1,2}$ – Aalenian–Bajocian limestones and dolomites; J_2^3 – Bathonian limestones; GM – ground moraine; TM – terminal moraine; RM – recessional moraine; D–1 to D–13 – drumlins; E–1, E–2 – eskers; K–1 to K–9 – kettle holes; GL – glaciolacustrine deposits; GFL – glaciofluvial deposits; SS–1 to SS–6 – sampling sites; A–B – geological profile.

Besides these carbonate clasts, the till contains small amounts of carbonate silt and clay.

Granulometric analysis (Fig. 5) was performed on eight samples from which, as mentioned above, large clasts were removed. The following values/coefficients were obtained:

- median (Md) mean grain size is 18–32 mm;
- sorting (So) all samples were poorly sorted, which is one of the fundamental features of till;
- the skewness coefficient (Sk) in relation to the median larger grains prevail in all samples except in sample SS–3 from 80–90 cm depth, and all samples are designated as gravel.

2.2. Glaciofluvial deposits

Glaciofluvial deposits have been determined in the lower parts of the Bilo terminal moraine – in the northern part towards Bilensko Mirovo and in the southern foothills in Baričević Dolac (Figs. 3, 6 and 7). They are composed of material redeposited from the till. Generally, glaciofluvial deposits are composed of subrounded clasts and pebbles which are smaller and better sorted than those found in till (Fig. 6). They were formed by erosion of glacial deposits, in which erosional channels can be found at present in both sides of the terminal moraine, and depositional fans have also been found in the Baričević Dolac (Figs. 3 and 7).

It is possible that glaciofluvial deposits could also be found in some parts of the Tudorevo and Mirovo. In neighbouring areas they have been found in the vicinity of a mountaineering hut at Alan, and also 2 km west in the Dundović Pod (MAMUŽIĆ et al., 1969).

2.3. Glaciolacustrine deposits

It is assumed that sand and clay deposits may represent the relics of glacial lakes which were formed during glacier melting. Such conditions may have existed in the lowermost parts of Tudorevo, Dundović and Bilensko Mirovo, as well as on both sides of the Bilo terminal moraine in Bilensko Mirovo and Baričević Dolac. In all these localities glacial deposits are covered by humus and dense mountain grass vegetation, and are only sporadically exposed. However, some outcrops, especially on the northern and southern slopes of Bilo hill – indicate the existence of probably short-lived small lakes. These heavily vegetated areas are characterized by temporary shallow streams (Fig. 7) and abandoned gardens, indicating probably thicker humus and underlying deposits. Such underlying deposits have been investigated by digging approximately 1 m deep trenches, in which silt–clayey deposits with some sand have been found. The thickness and sediment type indicate probable deposition from stagnant water – shallow lakes and swamps, formed in the last phase of glacier melting.

Figure 4: Geological boundary and geomorphological contrast between Middle Jurassic (Aalenian–Bajocian) carbonate bedrock (right) and till (left); Alan road.

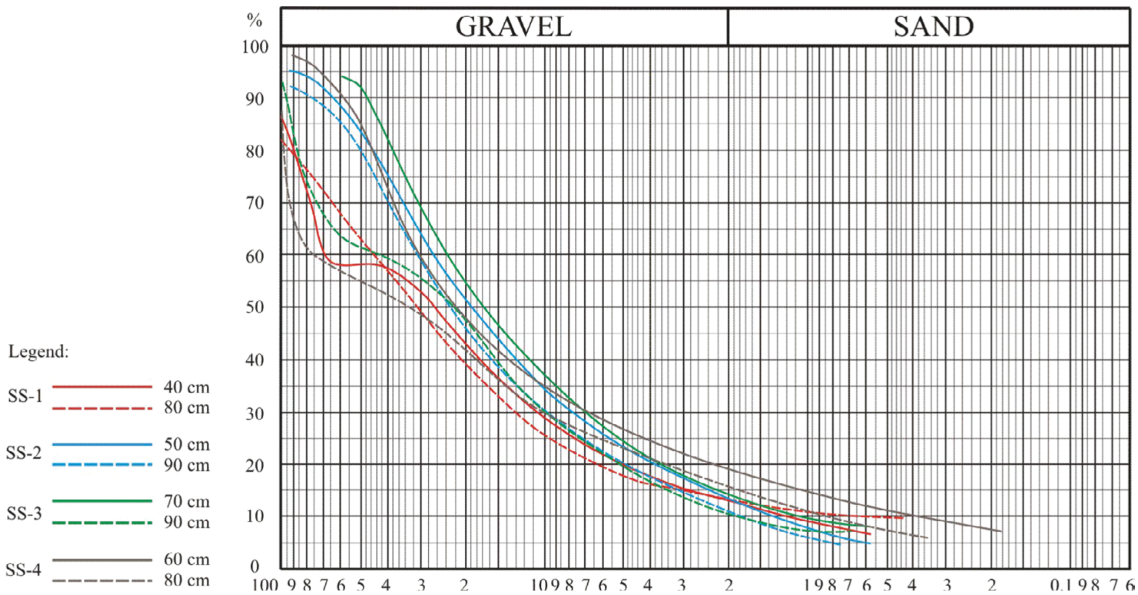

Figure 5: Granulometric diagram of till from sampling sites SS–1 to SS–4 (for location see Fig. 3)

Figure 6: Glaciofluvial deposits (GFL in Fig. 3) on the northern slope of the terminal moraine (TM in Fig. 3); southern part of Bilensko Mirovo.

3. SEDIMENTARY BODIES AND FORMS OF THE GLACIAL DEPOSITS

The erosive action and melting of the Tudorevo–Mirovo glacier resulted in formation of glacial deposits of varied morphology, including drumlins, eskers, kettles and erratic blocks, as well as ground moraine, terminal moraine and recessional moraine, including some specific structures including striations.

3.1. Drumlins

Drumlins (D) occur from the ridge between the Tudorevo and Dundović Mirovo to the southwest part of Bilensko Mirovo (Figs. 3, 9 and 20). In this area of glacial deposits, drumlins are the most common and most numerous forms, so the area of Mirovo may be called a drumlin field.

Drumlins are especially well morphologically expressed at the moraine ridge on the western slope of the Dundović Mirovo as well as in Bilensko Mirovo (Figs. 8 and 9). According to their dimensions these are small drumlins, since their average length is below 100 m, width 25–65 m, and height 5–15 m (see in BENNETT & GLASSER, 2009). The largest drumlins are observed at the pass between Dundović and Bilensko Mirovo – approximately 250x60 m in size (Fig. 3, drumlins D–5 and D–8).

Lithological composition of the drumlin till was described in the previous section. It is interesting that the till, is in all forms, moraines, drumlins and eskers, of uniform lithology, composed of clasts, boulders and blocks of Jurassic carbonates.

3.2. Eskers

Two eskers (E) occur; a larger one on the western slopes of the Dundović Mirovo (E–1; Figs. 3, 10a, 10b and 23), and a smaller one in Bilensko Mirovo (E–2; Figs. 3 and 20). E–1 is separated from the underlying moraines towards the west by a narrow gully (Fig. 10a). Its orientation is NNW–SSE (340–160°). It is 117 m long and on average, about 30 m wide. The highest elevation of the esker is 1337 m a.s.l., measured at its top, and the lowest is 1319 m a.s.l. at its terminus in the Dundović Mirovo, where it ends abruptly by the steep slope (Fig. 10a).

The lithological composition of till in the esker is the same as in the previously described drumlins. In the terminal frontal part, several erratic blocks have been observed (Fig. 16). Clasts are mostly composed of older Middle Jurassic limestones (Aalenian–Bajocian), but there are some clasts of Spotty limestones and dolomite of the Lower Jurassic (Toarcian).

3.3. Kettle holes

Kettle holes or kettles (K) occur in several places in the recessional moraine, i.e. on the Tudorevo–Mirovo ridge and in Mirovo (Figs. 3, 9, 11 and 23). Here, the lithological com-

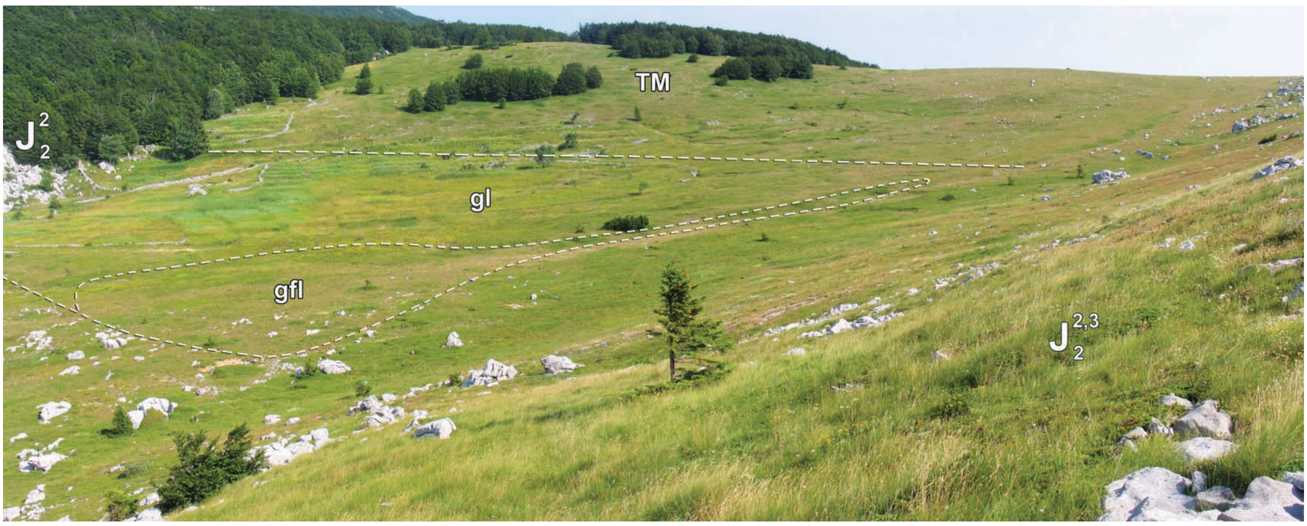

Figure 7: Northern slope of the terminal moraine (TM) in the southern part of the Bilensko Mirovo with glaciofluvial deposits (GFL) and, probably, glaciolacustrine (GL) deposits below Holocene cover.

position of till is visible, which is similar to that of the till of surrounding drumlins and ground moraines. Their bases are covered with humus; diameters are 5–20 m and depths 3–7 m.

3.4. Cobbles, boulders and erratic blocks

Boulders and erratic blocks often occur on the surface of glacial deposits, especially along the road from the Tudorevo–Mirovo pass through Mirovo and on the Bilo. They are an important source of data for the reconstruction of glacier size and extent of glacier movement.

Cobbles (ca. 10–30 cm), and *boulders* (ca. 30–50 cm) are most commonly found in walls and fences of the former arable land and pastures (e. g. Figs. 10, 11, 12 and 20). They originated from Jurassic carbonates, almost exclusively limestones. Their shape is variable – blocky, prismatic, tetrahedral and ellipsoidal, and they are frequently and characteristically poorly rounded (Figs. 12 and 13). They are mostly composed of Middle Jurassic limestones, mainly Bajocian and Aalenian mudstones, which underlie the glacial deposits. Poorly represented, (but very important for the palaeogeographic interpretation), are Lower Jurassic limestones – lithiotid (Figs. 13 and 22) and brachiopod floatstones (Figs. 14 and 22) of Pliensbachian, and typical, unevenly dolomitized Spotty Limestones of Toarcian age (Figs. 13 and 22). Similar to the Middle Jurassic ones, Lower Jurassic clasts are also subrounded, but their shape is often platy as a result of their originally thinner bedding.

Erratic blocks are scattered in and over various parts and forms of glacial deposits. They are most common on drumlins (Fig. 15) and eskers (Fig. 16), but some also occur in ground and terminal moraines. Their dimensions vary from small (35x60x25 cm) to medium (90x60x50 cm) and large (130x96x110 cm). They originate mainly from the middle Jurassic mudstones, and less frequently form Lower Jurassic Lithiotis floatstones, including the largest erratic block in these sediments found on the top of the terminal moraine on Bilo hill (Fig. 17).

3.5. Striations

Striations in the form of scratches and shallow grooves (2–8 mm deep) occur at several places in Mirovo, and were observed on the clasts, blocks and primary outcrops of Aalenian–Bajocian limestones (Fig. 18). They show the orientation of the local ice drift, not the direction of glacier movement. This was observed by measurements at the Tudorevo–Mirovo pass where scratches are oriented 325–145°, nearly perpendicular to the direction of movement of glaciers, which was towards 190°. Similarly, in the western part of the Bilensko Mirovo scratches are oriented 80–260°, and the movement of the glacier was to the south – 180°.

3.6. Ground moraine

Remains of ground moraine (GM) were observed in Tudorevo, Dundović and Bilensko Mirovo (Figs. 3, 10a, 19, 20 and 23), where they represent till, underlying drumlins and eskers.

Figure 8: Drumlin (D–13 in Figs. 3 and 23) in Bilensko Mirovo.

Lithological composition of ground moraine till is similar to that of drumlins and eskers. In the western part of Dundović Mirovo in trench SS–3 (Fig. 3), the composition of these deposits was investigated and clast sizes measured. Till is composed of unsorted, poorly rounded clasts of mm to dm size, rarely even erratic blocks. Clasts of older Middle Jurassic limestones are very common, mostly Aalenian–Bajocian in age, but there are also, in places even frequent, clasts of Lower Jurassic Lithiotis limestones (with variable amounts of brachiopods) and of Spotty limestones and dolomites (Figs. 12–14). Clasts below 10 cm in size comprise about 30% of the total mass of the ground moraine till.

3.7. Terminal moraine

Terminal moraine (TM) was found on the Bilo Hill, the ridge between Bilensko Mirovo and in Baričević Dolac (Figs. 3, 7, 20, 21 and 23). It is a classical example of the terminus and also the frontal moraine of a valley type glacier, where moraine was deposited transverse to the narrow U-valley (Figs. 3, 20 and 21), which is only some 350 m wide.

Till of the terminal moraine on Bilo Hill is lithologically similar to other parts of such sediments in Tudorevo and Mi-

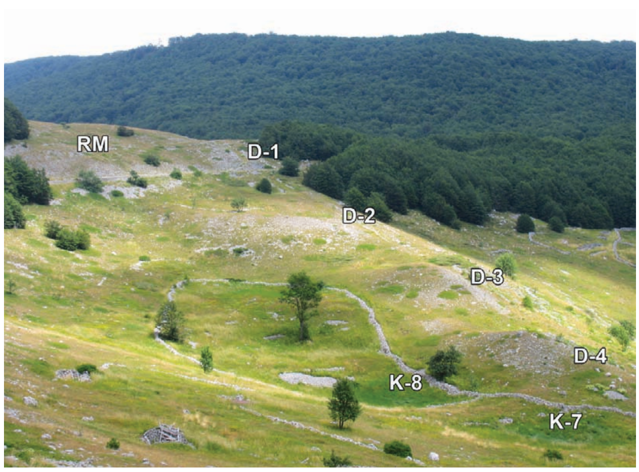

Figure 9: Recessional moraine (RM) and drumlin field (drumlins D–1 to D–4 and kettle holes K–7 to K–8 in Figs. 3 and 23) in Dundović Mirovo.

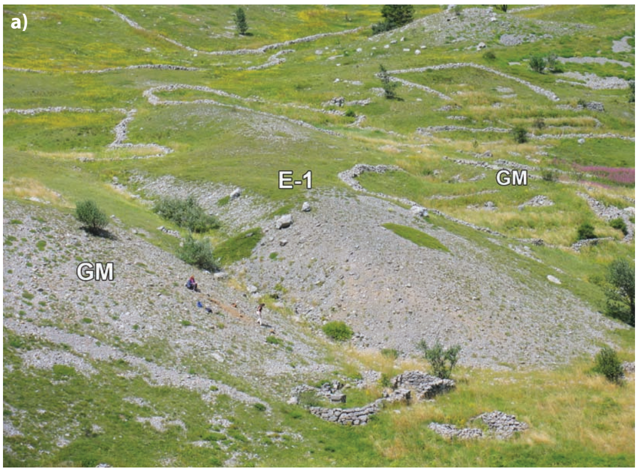

Figure 10: Esker (E–1 in Figs. 3 and 23) in Dundović Mirovo: 10a – norththward view (GM = ground morraine); 10b – southward view

rovo, since it is unsorted, chaotic sediment composed of clasts, boulders and blocks of Jurassic carbonates mixed with similar mm-sized debris and carbonate silt. Clasts are slightly rounded, and mostly originate from the surrounding Middle Jurassic limestones and partly of the Lower Jurassic limestone and dolomite (Fig. 22). Particularly notable, as already mentioned, is an erratic block of Pliensbachian Lithiotis limestone, found at the top of Bilo Hill, i.e. at the highest part of the terminal moraine (Fig. 17).

The thickness of terminal moraine till is estimated at more than 100 m, since only hypsometric difference from the base to the top of the moraine, on the southern slope, is more than 80 m.

3.8. Recessional moraine

Recessional moraine (RM) was determined on the ridge between Tudorevo and Mirovo, above the Alan Road. Its lithological characteristics and dimensions are described in the description of the SS–1 trench. This is probably the youngest form in the glacial deposits of the Tudorevo–Mirovo glacier as testified by its superposition, since it lies on an older drumlin and ground moraine. BOGNAR et al. (1991) already stated that this is moraine, considering it as the younger frontal moraine of up to 100 m height, up to the base of Bilensko Mirovo, so it also includes the drumlin field in Dundović Mirovo. However, all glacial deposits below the recessional moraine, i.e. south of the Alan road in Dundović and Bilensko Mirovo, belong to the ground moraine and drumlin field (Figs. 3, 9 and 23).

4. GEOLOGICAL CHARACTERISTICS OF THE TUDOREVO–MIROVO GLACIER AREA

According to the geological and geomorphological characteristics of the Tudorevo and Mirovo karst valleys, and the recent position of glacial deposits, it is possible to reconstruct the size and spread of the glacier which represented their source. The most important factors for such a reconstruction are geological ones, especially the geological composition of rocks underlying glacial deposits and rocks forming the flanks of the valleys through which the glacier was moving, as well as the stratigraphic composition of clasts within glacial deposits.

4.1. Geological composition of glacial deposits footwall

Glacial deposits of Tudorevo and Mirovo mostly overlie Middle Jurassic carbonate rocks (VELIĆ & VELIĆ, 2009; Figs. 3 and 23). Only in the far eastern part of the Dundović Mirovo and the northern part of Tudorevo, do glacial deposits overlie Lower Jurassic carbonates.

Boundaries between the underlying rocks and glacial deposits are clearly visible, both lithologically and morphologically (Fig. 3). Limestones are karstified solid and bedded rocks, which provide strong relief, while glacial and periglacial deposits, mostly non-lithified till, form gentle relief morphologies, and are mostly covered by mountain grasses (e.g. Figs. 4 and 20).

4.1.1. Lower Jurassic carbonates

Lower Jurassic deposits occur in the immediate vicinity or below glacial deposits in the eastern part of the Dundović Mirovo and northern part of Tudorevo. They are represented by two typical Lower Jurassic lithostratigraphic units: Lithiotis limestones and Spotty limestones.

Lithiotis limestones crop out in the far eastern part of Dundović Mirovo in a gully which ascends towards the Veliki Alan Pass in the ESE. Towards the north they are in tectonic contact with Spotty limestones, and towards the SW, on the slopes of Šošin Vrh, they are covered by them in normal superposition (Fig. 3).

Carbonate deposits of this lithostratigraphic unit are well-bedded dark grey, in places even black wackestones, rarely packstones and grainstones alternating with bioclastic floatstones and lithiotid and brachiopod coquinas. The most common allochems include pellets, oncolized intraclasts and bioclasts of bivalves, gastropods, brachiopods (which are very frequent in the younger-most part of the Lithiotis limestones), foraminifera and calcareous algae. Beds are 10–80 cm thick, mostly 40–60 cm.

Lithiotis limestones are Pliensbachian in age – among the index fossils a benthic foraminiferal assemblage including the most important species, *Orbitopsella praecursor* GÜMBEL is especially important in addition to the lithiotid bivalves.

Spotty limestones underlie glacial deposits at three localities. They form the NE slopes of Tudorevo and the eastern part of Dundović Mirovo, whereas to the NE they are tectonically seized between Aalenian limestones (on the northern slopes of the valley) and Pliensbachian Lithiotis limestones (in the central part of the valley). The biggest outcrop of Spotty limestones crops out south of Dundović Mirovo, where on the northern slope of Šošin Vrh they normally overlie Lithiotis limestones (Fig. 3).

Lithologically they are composed of alternations of dark muddy and fine-grained bioturbated and ooid limestones. They are well- to thin-bedded (mostly 20–30 cm), in places thick-bedded (up to 80 cm), and usually appear irregularly thin-bedded if weathered.

Spotty limestones were deposited during the Toarcian in somewhat deeper environments than those of the underlying and overlying deposits. This change was caused by synsedimentary tectonic activity in the Peri-mediterranean area and the influence of the oceanic anoxic event.

Figure 12: Poorly rounded limestone clasts (mostly cobbles), predominantly of Aalenian–Bajocian age, within a stone wall on the esker in Dundović Mirovo; hammer length 33 cm.

Figure 13: Boulders of Pliensbachian Lithiotis limestones (left) and Toarcian Spotty limestones (right) in ground moraine in Bilensko Mirovo; hammer length 33 cm.

4.1.2. Middle Jurassic carbonates

The strike of the Tudorevo and Mirovo karst valleys is almost parallel to the strike of the Jurassic stratigraphic units, i.e. NE–SW and N–S (Figs. 1 and 3). Therefore glacial deposits mostly overlie Middle Jurassic rocks – Aalenian–Bajocian in Tudorevo and at Bilo Hill, Aalenian–Bajocian and Bathonian limestones.

Figure 11: Kettles (K–4, K–5 in Fig. 3) in Bilensko Mirovo.

Although these rocks are of a wide stratigraphic range (Aalenian–Bathonian) they are quite monotonous. Middle Jurassic rocks are composed mostly of grey and dark-grey thick-bedded (40–200 cm), in places massive mudstones, with rare beds of skeletal and bioclastic wackestones and packstones, very rarely grainstones, and interbeds of browngreyish late-diagenetic coarse-crystalline dolomites.

Stratigraphic subdivision is complicated by the monotonous succession of similar facies and relatively poor fossil contents. Division of Aalenian and Bajocian limestones is especially problematic, and this can only be undertaken by very careful sampling and analysis. In the Aalenian limestones of the Tudorevo and Mirovo, the foraminifer *Bosniella croatica* (GUŠIĆ) was determined, which is in Bajocian

Figure 14: Part of a Pliensbachian brachiopod floatstone cobble in ground moraine of Bilensko Mirovo; scale 5 cm.

Figure 15: Erratic blocks originated from Pliensbachian Lithiotis limestones as well as from Aalenian–Bajocian limestones in drumlin (D–3 in Figs. 3 and 23) of Dundović Mirovo.

limestones accompanied by the foraminifer *Pseudoeggerella elongata* SEPTFONTAINE and the dasyclad algae *Selliporella donzellii* SARTONI & CRESCENTI. Bathonian limestones may be more easily recognized, since they contain a rich assemblage of typical Bathonian index fossils including *Paleopfenderina salernitana* (SARTONI & CRESCENTI), *Satorina apuliensis* FUORCADE & CHOROWICZ, *Orbitammina elliptica* (D'ARCHIAC), etc.

Middle Jurassic carbonates were deposited in somewhat shallower environments than Toarcian Spotty limestones, but probably deeper than Pliensbachian Lithiotis limestones, mostly in spacious, protected lagoons.

4.2. Origin and distribution of clasts in till

Till of the Tudorevo, Mirovo and Bilo is composed of clasts, boulders and blocks of Lower Jurassic Lithiotis limestones of Pliensbachian age, and Spotty limestones and dolomites of Toarcian age, as well as Middle Jurassic, mostly Aalenian and Bajocian limestones, which are accompanied by Bathonian limestones in the terminal moraine. It is important to stress that these deposits do not contain Upper Jurassic clasts.

Figure 24 shows the distribution of clasts according to their stratigraphy. It is obvious that the most common clasts are those originating from Aalenian–Bajocian carbonates, which is not unsurprising since these rocks compose most of the bedrock beneath the glacial deposits (Fig. 3). Their compositional proportion may be estimated as from 60% in the northern part of Tudorevo to approximately 85% in Mirovo. Clasts of Spotty limestones may be found in till of all glacial deposits, from the northern part of Tudorevo to the terminal moraine in Baričević Dolac. Their origin is geologically clear, since Spotty limestones represent the bedrock of the SW part of Tudorevo and the eastern and southern parts of the Dundović Mirovo (Fig. 3).

However, data on the distribution of Lithiotis limestones (Fig. 24) are especially interesting. They have not been found at Tudorevo, only at Mirovo and in the terminal moraine of Bilo. This information, in addition to the fact that there are no Upper Jurassic clasts in the investigated till deposits, is very important for the interpretation of glacier movement, which will be discussed in the next section.

5. ORIGIN, DIMENSIONS AND MOVEMENT OF THE GLACIER

In order to enable easier understanding of this section it is important to discuss some possible terminological confusion. BOGNAR et al. (1991) described Alan glacier with a source area in Lubenovac and a terminal moraine in Bilensko Mirovo. The Tudorevo–Mirovo glacier described in this paper had its source area in Tudorevo and terminal moraine in Baričević Dolac (Fig. 1). It is clear that these are two different names for the same glacier, but with different supposed sources and glacier paths. A new name was proposed here because (i) no evidence was found that the glacier had a connection with Lubenovac, and (ii) to enable differentiation of the geological approach in this paper with the geomorphological approach applied by BOGNAR et al. (1991).

Figure 16: Erratic blocks in esker (E–1 in Fig. 3; Figs. 10 and 23) of Dundović Mirovo composed of Aalenian–Bajocian limestones; hammer length 33 cm.

Figure 17: Erratic block originated from Pliensbachian Lithiotis limestones on the top of the terminal moraine at the Bilo hill; hammer length 33 cm.

Figure 18: Striations in Bajocian limestones; western slope of Bilensko Mirovo; scale 5 cm.

Concerning the stratigraphy of clasts and boulders, as well as the recent geomorphology of Tudorevo and Mirovo, it is very probable that the studied glacier was composed of two glacial tongues – the main one, which originated in the cirques of Tudorevo and a lateral one which originated in the eastern part of Dundović Mirovo. Both tongues joined into one glacier in the central part of the Dundović Mirovo.

Along its way from the source in Tudorevo to Mirovo and Baričević Dolac, the glacier eroded the underlying and surrounding rocks, and crushed them into blocks, boulders and clasts, dragging them and transporting them several kilometres from their source. Material was crushed and rounded during transport, and phases of thawing resulted in deposition as till in drumlins and eskers, as ground, terminal and recessional moraines. A glacial tongue in the eastern Dundović Mirovo abraded Pliensbachian Lithiotis limestones (with frequent brachiopods) and Toarcian Spotty limestones, and transported their fragments to the Dundović Mirovo where it united with the main glacial tongue coming from Tudorevo. These fragments were transported to the terminal moraine in Baričević Dolac, a distance of some 2.5 km from the source rocks.

5.1. Previous investigations

BOGNAR et al. (1991) determined the direction of movement of the glacier from Lubenovac towards the southwest to Mirovo, which was predisposed by the pre-Würmian morphology of this part of Velebit. The authors named it as the Alan glacier. In addition to the main glacier source in Lubenovac large amounts of the ice mass moved by three glaciers, or glacial tongues, towards the southeast into the valley of Kosinjski Bakovac – one through Vranjkova Draga, a second through Kozjanska Draga, and the third through Jurekovačka and Begova Draga. The authors described the movement of the glacier from Veliki Lubenovac to Tudorevo and over the ridge between Tudorevo and Mirovo to Dundović Mirovo and Bilensko Mirovo where they marked the terminal moraine. However, the terminus of the glacier was still further away, more than 1 km south in Baričević Dolac.

During the latest investigation, presented here, the connection between glacial deposits, i.e. glaciers in Lubenovac and Tudorevo has not been proven by geological methods. If such a connection existed, i.e. if the glacier originated in Lubenovac then clasts of Lithiotis limestones should occur, in Tudorevo but are missing, since these rocks crop out in the valley between Grebalište and Vučjak, through which the glacier should have passed. Clasts of Upper Jurassic strata are also missing, and these form Lubenovac and the neighbouring area, so should also have been transported to Tudorevo, or even to Mirovo.

On the basis of analysis of the present relief it seems more probable that the glacier was moving from the northern part of Tudorevo (approximately 1350 m a.s.l.) towards Lubenovac (ca. 1260 m a.s.l.) than vice versa. Geological evidence could be discovered by future investigation of the glacial deposits of Lubenovac. BOGNAR et al. (1991) indicated that terminal moraine of the Alan glacier should be located in the Bilensko Mirovo, which is a typical drumlin field, although it is located more than 1 km southwards at Bilo, between Bilensko Mirovo and Baričević Dolac (Figs. 3, 20, 21, 22 and 23).

Figure 19: Till of ground moraine; western Dundović Mirovo.

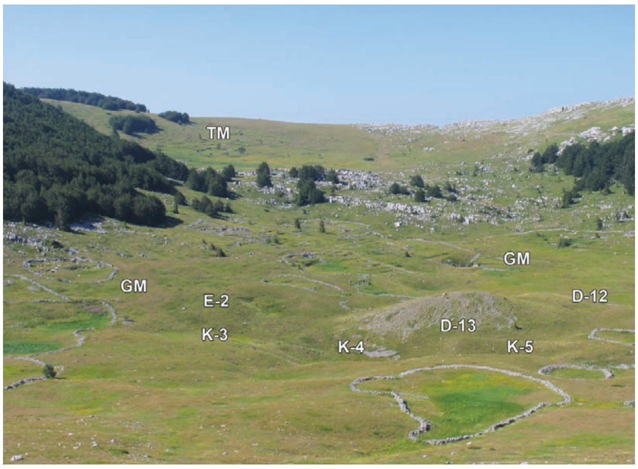

Figure 20: Terminal moraine (TM) at the Bilo hill (back of the photo), ground moraine (GM, with drumlins D–12 and D–13, esker E–2 and kettle holes K–3 to K–5) and karstified carbonate bedrock (of the Upper Bajocian age) between them; southward view from Bilensko Mirovo.

Views presented by BOGNAR et al. (1991) are based solely on geomorphological studies, while geological investigations presented in this paper do not confirm such glacier movement. In contrast, geological data collected in tills of Tudorevo and Mirovo did not confirm any connection with Upper Jurassic deposits of Lubenovac. Therefore the studied glacier was named the Tudorevo–Mirovo glacier.

5.2. Origin

Basic characteristics of the northern Velebit valley glaciers were described by BOGNAR et al. (1991). Generally, the authors claimed that numerous glacial tongues were directed from the surrounding hills towards the bigger valleys, forming several km-sized glaciers.

This statement also describes the Tudorevo–Mirovo glacier very well. It originated from Tudorevo as a combination of cirque-type and valley-type glaciers. Today three cirques may be morphologically recognized in Tudorevo: northern, central, and southern, which is morphologically the most typical and biggest (Fig. 25). Glacial tongues from neighbouring hills were moving towards Tudorevo, the biggest and hypsometrically lowest valley (southern cirque at ca. 1300 m a.s.l., northern cirque at 1350 m a.s.l.), where they formed three smaller cirque glaciers, which were united into a single glacier by further accumulation of ice. On reaching a thickness of ~100 m and with sufficient kinetic energy, the glacier moved across the pass south of Tudorevo and spilled into Dundović Mirovo, where it united with a much shorter glacial tongue that originated from the eastern part of the Dundović Mirovo.

In this way, the united glacier, containing a huge ice mass, became a typical valley-type glacier which gouged a typical ‘U’-shaped glacier valley along its path through Dundović and Bilensko Mirovo.

5.3. Volume and movement

The Tudorevo–Mirovo glacier was a typical cirque-valley glacier of varying width – from about 250 m at the bottom to probably more than 500 m, and in some places up to 1,000 m in its apical part, as wide as present glacial valleys, e.g. Tudorevo, through which it moved. During maximum glaciation, the glacier was about 4 km long, and therefore it was a relatively small, local glacier. At that time it covered Tudorevo, Dundović Mirovo and Bilensko Mirovo, reaching Baričević Dolac where it deposited a terminal moraine, the current Bilo hill.

The length of the transport of this material was determined on the basis of current distance of clasts in glacial deposits from their primary outcrops and beds. The most reliable deposits are clasts, boulders and blocks of Lower Jurassic Lithiotis limestones of Pliensbachian age and Spotty limestones and dolomites of Toarcian age. In order to determine the spreading and movement of the glacier, strati-

Figure 21: Landscape of glacial ‘U’ valley in the Dundović and Bilensko Mirovo; in background terminal moraine (TM) at the Bilo hill.

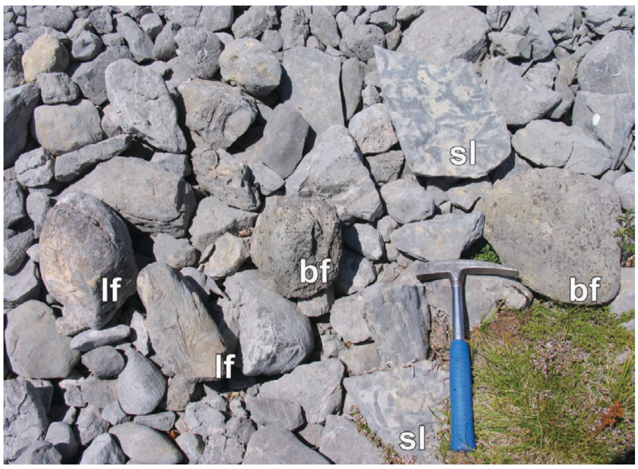

Figure 22: Till of the terminal moraine (southern slope of the Bilo hill) with clasts, cobbles and boulders of Lower Jurassic Pliensbachian Lithiotis limestones including lithiotid floatstones (lf) brachiopod floatstones (bf), Toarcian bioturbated Spotty limestones (sl), and predominantly of Middle Jurassic limestones; hammer length 33 cm.

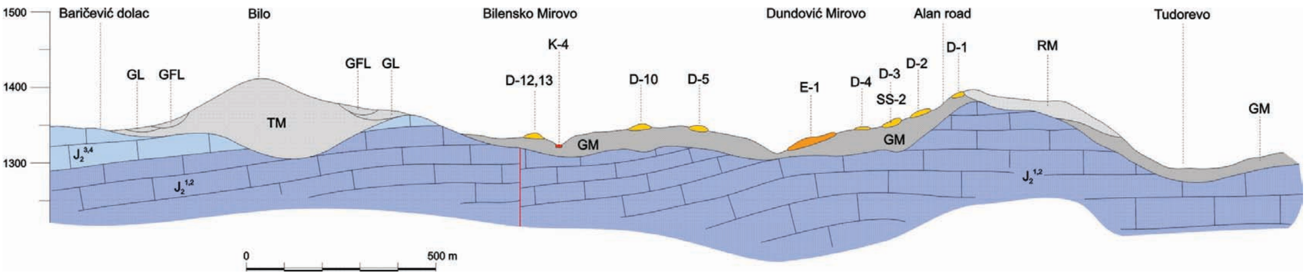

Figure 23: Geological profile Baričević dolac–Tudorevo (profile line A–B on Fig. 3). Legend: $J_2^{1,2}$ = Aalenian–Bajocian limestones, sporadically intercalations of latediagenetic dolomite; J_2^3 = Bathonian limestones; GM = ground morraine, TM = terminal morraine; RM = recessional morraine; D–1 to D–13 = drumlins; E–1 = esker; K–4 = kettle hole; GL = glaciolacustrine deposits; GFL = glaciofluvial deposits.

graphic analysis of more than 2000 clasts of Jurassic rocks from Tudorevo, Mirovo and Bilo was performed. Dimensions of the studied clasts were from 1 cm to erratic blocks of more than 2 m^3.

In Dundović and Bilensko Mirovo, clasts were transported from their source rocks for at least 2 km. The most distant ones occur at Bilo, including the aforementioned large erratic block (approximately 2 m^3 in volume) of Pliensbachian Lithiotis limestones (Fig. 17), which was transported from primary outcrops in the easternmost part of the Dundović Mirovo (Fig. 3). The same locality was the source of Pliensbachian Lithiotis limestones with frequent brachipods (indicating the younger-most level of this lithostratigraphic unit) for the entire Mirovo (Fig. 14) and terminal moraine of Bilo (Fig. 22). Transport of Toarcian Spotty limestones clasts and boulders (Figs. 13, 22 and 23) was even longer, up to 4 km, since they could have originated not only from the Dundović Mirovo, but also from the northern part of the Tudorevo (Figs. 3 and 24).

The origin of the glacier in Tudorevo, instead of Lubenovac, is confirmed by analysis of till clasts in Tudorevo, but also in Mirovo and in the Bilo terminal moraine. In till from all the aforementioned localities, no clasts of Upper Jurassic limestones have yet been discovered, and Lubenovac and neighbouring area north of the Bakovac fault are completely composed of such rocks. In addition, according to recent hypsometric relationships, in order to start the glacier from Lubenovac towards Tudorevo, ice in the Lubenovac cirque had to reach a thickness between 200 and 300 m. This is supported by the contour lines of recent elevation: the base of the Lubenovac is at an altitude of 1255 m a.s.l., and rises towards Tudorevo at 1445 m a.s.l., so ice not only must have infilled the Lubenovac cirque but must also have exceeded the height of the ridge, thus gaining kinetic energy to initiate its movement towards Tudorevo.

A similar situation occurs in Tudorevo where the base of the southernmost cirque is at an altitude of 1291 m a.s.l. In order for the glacier from Tudorevo to cross the ridge on its way to Mirovo, where present primary layers of the Aalenian–Bajocian limestones occur at an altitude of 1390 m a.s.l., the thickness of the ice had to be more than 100 m. It was probably even up to 200 m, which is not surprising, because the glacier was also enriched by ice arising from the cirques of Tudorevo, and from the surrounding hills and valleys.

The direction of movement of the glacier is indicated by shapes and orientations of the drumlins and eskers, since their long axes are parallel with the direction of movement. In plan view, the narrow end of the drumlin ellipsoid determines the direction of movement of the glaciers, and also in the longitudinal profile their more gentle slopes. In the Tudorevo–Mirovo glacier drumlins are best expressed in Mirovo. On the northern slopes of Dundović Mirovo, from Alan Road to the bottom of the valley, there are several drumlins

Figure 24: Distribution of bedrock clasts (pebbles, cobbles, boulders, blocks) in morraine deposits. Legend: 1 = clasts originated from Toarcian Spotted, bioturbated limestones/dolomites and Aalenian–Bajocian limestones (in terminal morraine of Bathonian limestones too); 2 = clasts originated from Pliensbachian Lithiotis and brachiopod limestones.

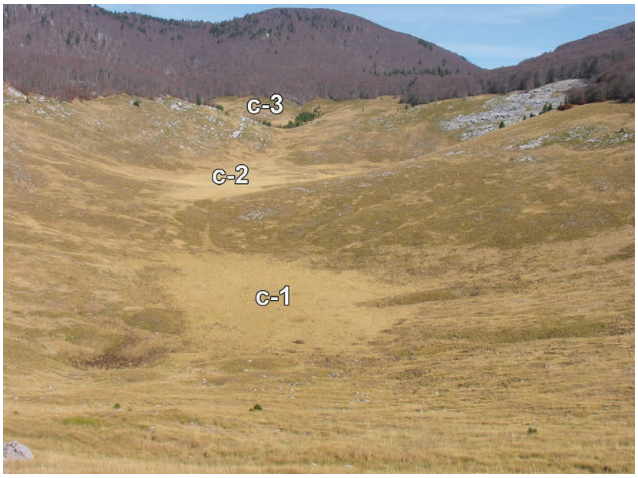

Figure 25: Landscape of the Tudorevo valley (northward view) with three cirques: c-1 (South Tudorevo), c-2 (Central Tudorevo), c-3 (North Tudorevo).

and one esker which narrows, indicating the direction of movement of the glacier, towards the southwest – direction D = 225° (Figs. 1 and 3). This direction deviates from the general orientation of the esker, south–southeast, D = 160°, which is logical, because till of the esker was deposited by streams that flowed below or within the ice toward the bottom of the Dundović Mirovo (Fig. 3). On the ridge between the Dundović and Bilensko Mirovo, longer axes of the drumlins and therefore the direction of movement are rotated mostly to the southwest, D = 240°, and in Bilensko Mirovo also to the west–northwest, D = 280° (Fig. 3, drumlins D–10 and D–13). These individual differences are due to local topography, which influenced the direction of the movement of ice and streams during the deposition of drumlins.

From the Bilensko Mirovo, the main part of the glacier, from which glacial deposits accumulated, moved to the south to Baričević Dolac. However, it is possible that part of the ice mass moved west across the ridge between Bilensko Mirovo and the Alan valley, and over the Buljma ridge (elevation 1400 to 1450 m a.s.l.), but data on this are currently unavailable, because this area has not yet been the subject of a detailed geological survey.

The southern end of the Bilensko Mirovo, where the glacial 'U' valley is best expressed (Figs. 3, 20 and 21), exposes Upper Bajocian–Lower Bathonian carbonates underlying the glacial deposits. Going further south, after 250 m, glacial deposits occur again, building up the ridge (Bilo hill) between Bilensko Mirovo and Baričević Dolac (Fig. 3). These are the remnants of the terminal moraine of the glacier. Its extreme southern boundary was probably in the Baričević Dolac (Figs. 1, 3 and 23) at an altitude between 1330 and 1290 m a.s.l., because at lower elevations no remnants of glacial deposits have been observed. If these data are compared with the starting point of the glacier in Tudorevo, they indicate a maximum length of, approximately 4 km (Fig. 1).

It is assumed that the Tudorevo–Mirovo glacier had several phases of melting and re-freezing, as indicated by several factors. In Bilensko Mirovo, drumlin D–13 (Fig. 8) lies obliquely across an older drumlin D–12 (Figs. 3 and 20). Recessional moraine between the Tudorevo and Dundović Mirovo overlies older ground moraine and drumlin D–1 (Figs. 3 and 9). This recessional moraine can be assumed to be not only a stadial moraine but also a a terminal moraine of the Tudorevo part of the glacier during a shorter stadial, when in Mirovo ice had already completely melted.

Melting occurred in a direction opposite to the movement of glacier, i.e. from the southwest from Bilensko Mirovo to the northeast to Tudorevo. In the early stages of melting, when ground moraine, drumlins and eskers were created, glacial lakes/marsh were formed on both sides of the terminal moraine, because of the large amounts of water. It was also the time of occurrence of kettle holes which were carved in the till of the ground moraine by ice boulders and blocks in the lowermost part of the glacier. Water escaped (due to draining from the lake and erosion of till of the ground moraine) into the underlying karstified Middle Jurassic carbonates.

Smaller, decametre-sized fans of glaciofluvial material were formed by erosion of till of the Bilo terminal moraine on the lower part of its slopes (Figs. 3, 6 and 7), which was partially deposited within the aforementioned lakes. Such glaciofluvial material may also probably occur in some parts of Mirovo and Tudorevo.

At the same time, the glacier still existed in Tudorevo, resulting in accumulation of the recessional moraine deposited at the pass from Tudorevo to Mirovo. However, warming in the Early Holocene also melted that part of the glacier, and large amounts of water produced by melting ice eroded the eastern, thinnest part of the recessional moraine in the vicinity of the crossing of the Alan road with the road to Lubenovac, where the bedrock crops out – the primary outcrops of Aalenian–Bajocian limestones.

The local climate conditions, large amounts of snow precipitation, temperatures below zero for 10 months of the year (BOGNAR et al., 1991 – p. 35, Table 2) and suitable relief were the most important factors in the development of a series of glaciers on northern Velebit. The Tudorevo–Mirovo area had all the conditions for the development of a valley-type glacier. These conditions are in part upheld up today, because even with the average annual snow precipitation, large snow drifts form at the pass between Tudorevo and Mirovo. During the winter months snow freezes, and in the spring thaws slowly so that the Alan road is only passable from June.

According to BOGNAR et al. (1991) Alan's youngest glacier was of Würmian age. That is its most probable age, although geological work on the glacial deposits of Tudorevo and Mirovo neither confirmed nor denied this. Research in this regard is still pending.

6. CONCLUSIONS

During the younger Pleistocene, probably Würmian glaciation in the Northern Velebit several glaciers were formed, among them the Tudorevo–Mirovo cirque/valley-type glacier. Its starting point was in Tudorevo and it extended to the southwest through the karst valleys of Dundović Mirovo and

Bilensko Mirovo to Baričević Dolac along a distance of about 4 km. The glacier formed a typical U-shaped valley, with an average width of ~500 m, best expressed today in Mirovo.

The action and melting of the glacier formed glacial deposits particularly well preserved in Tudorevo and Mirovo with many typical relief forms. They were deposited over Lower and Middle Jurassic carbonates ranging in age from Pliensbachian to older Bathonian.

Glacial deposits are composed of chaotic and unsorted till of heterogeneous particle size, but uniform lithological composition, represented only by the clasts of Lower and Middle Jurassic carbonates, mainly limestones. Grain-size is very variable, from sand to various blocks even greater than 2 m^3 in volume. Middle Jurassic clasts make up from about 60% of the total mass of till in NE Tudorevo to 85% in Mirovo.

Many forms of moraine have been identified, described and illustrated: ground moraine, terminal moraine and recessional (stadial) moraine, drumlins, eskers, erratic blocks, kettle holes and striation. The area of Mirovo, due to the numerous drumlins, represents a drumlin field. Recessional moraine, drumlins, drumlin field, eskers and kettles were recognized and described for the first time in the area of the Velebit Mt., but also in Croatia.

Orientation of the drumlins, eskers and glacial ‘U’ valleys, as well as the terminal and recessional moraines indicate movement of the glacier from the northeast to the southwest and south, i.e. from the Tudorevo through Mirovo to Baričević Dolac. In Dundović Mirovo, the glacier was accompanied by a smaller glacial tongue, the source of which was in the far eastern part of the Dundović Mirovo.

Along its 4 km length from the area composed of bioturbated Toarcian Spotty limestones in the NE part of Tudorevo, the glacier moved mostly through Middle Jurassic carbonates of the Tudorevo and Mirovo, as well as through Pliensbachian Lithiotis limestones of Dundović Mirovo to its terminus in Baričević Dolac. It transported clasts, boulders and blocks for several kilometres (longest transport is recorded for clasts of Toarcian Spotty limestones – 4 km and for Pliensbachian Lithiotis limestones clasts – more than 2 km).

Relationships between the sedimentary bodies, such as the position of recessional moraine on older drumlin and ground moraines, or the case that a younger drumlin overlies an older one in Bilensko Mirovo, indicate multiphase dissolution and refreezing of the Tudorevo–Mirovo glacier.

Since the beginning of the final stage of glacier melting, drumlins and eskers were formed on the ground moraine, and within the moraine ice blocks carved kettles. Advancing melting and retreat of ice from the Mirovo towards Tudorevo formed glacial lakes with glaciolacustrine sedimentation on the low permeable ground moraine of Mirovo and terminal moraine of Bilo.

Gradual percolation of water from the lakes, and erosion of the underlying sediments of ground moraine to the underlying karstified Middle Jurassic carbonate rocks caused draining of water and formation of the recent relief of Mirovo. At that time, a glacier still existed at Tudorevo resulting in a recessional moraine at the pass to Mirovo, but this, (similar to the one in Mirovo), melted at the very beginning of the Holocene.

Erosion of till, formed glaciofluvial deposits, and their fans were found in the lower parts of ravines on the slope of the Bilo terminal moraine.

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