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DIG - 2nd Workshop on DInaric Glaciation:
Early/Middle Pleistocene glaciations of NE Mediterranean - filling the gaps in reconstructing its geological history and climate change.
Focus on glacial-interglacial transitions (sediments and processes)

WORKSHOP FIELD GUIDEBOOK

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Location map

1 - Velika Paklenica
2 - Novigrad Sea - Nozret
3 - Novigrad Sea
4 - Karin
5 - Ždrilo
6 - Obrovac (optional)

INTRODUCTION

Dinaric Mountains (aka Dinarides, or Dinaric Aps) (DA) are 645 km long mountain range which strikes from Southern Calcareous Alps (SCA) along the eastern Adriatic Sea to the Albanids (AA). Across the strike, Dinarides extend from the Adriatic Sea (AS) coast to the Pannonian Basin (PB) (Fig. 1). The focus of our study was coastal part of Dinarides, namely the Velebit Mt.

Although being less than 2000 m high, Penck (1900) stated that the coastal Dinaric mountains in Croatia were glaciated, and the idea was supported by local researchers Hranilovic (1901) and Gavazzi (1903 a, b) who reported geomorphological evidence of glaciation of the Velebit Mt. The mountains in Montenegro were studied by Cvijic (1900, 1917), Gregory (1915) and Milojevic (1922) who all reported evidence of glaciation of the studied mountains. Milojevic (1922) also reported on glacial and fluvioglacial sediments on the Velebit Mt. in Croatia. However, Gorjanovic (1902) and Poljak (1947) rejected their arguments, and claimed that the Velebit Mt. has never been glaciated. The first definitive evidence of glaciation of the coastal part of the Dinaric Mts. was presented by Nikler (1973) who described well preserved ‘terminal’ moraine ridge on the south Velebit Mt.

Previous authors (Belij, 1985; Bognar et al., 1991; Bognar and Prugovecki, 1997; Bognar and Faivre, 2006; Velic J. et al., 2011) held that the Dinaric Mts. were affected only by Late Pleistocene glaciation (Würm). However, Marjanac T. et al. (1990) recognized two major cool epochs divided by a warm period, which were tentatively recognized as glacial and interglacial epochs, and attributed these climatic stages to the Middle Pleistocene.

Pleistocene biostratigraphic record in Dinaric Mts. is rather poor. The fossil fauna is restricted to vertebrates found in cave deposits, and was attributed to interglacial (Villafranch, Günz/Mindel) and glacial (Günz, Mindel) periods (Malez, 1969; Kastmüller, 1989). Mollusc fauna is rare, and the Late Pleistocene (Würm) interstadial gastropod Striata fauna in paleosols on the Krk Island (Marjanac Lj. et al., 1992/93) is an exception. Pleistocene lacustrine sediments locally comprise cold-climate ostracods of Middle Pleistocene age (Malez and A. Sokac, 1969). The only accounts of Pleistocene flora in Dinaric Mts., apart from palynomorphs studied in offshore boreholes (Šercelj, 1969) are provided by Adžic (2012) and Adžic et al. (2012) who described fossil leaves from varved lacustrine sediments of Ždrilo and Seline Sections of the South Velebit Lake.

Detailed study of glacigenic and periglacial sediments (Marjanac Lj., 2012) revealed complex depositional history of the Middle Pleistocene sediments which documented at least three cold stages, tentatively attributed to Mindel and Riss equivalents, or equivalents of the Skamnelian and Vlasian stages of Greece (Hughes et al., 2007). U-series dating of secondary calcite precipitated in intergranular spaces of oldest moraines yielded minimal age of > 350 ka (Marjanac Lj., 2012).

The study of glacigenic sediments along the eastern Adriatic Sea coast revealed that the south Velebit Channel and inland Novigrad and Karin Seas hosted proglacial lakes, which are herein referred to as South Velebit Lake, Novigrad Sea Lake and Karin Sea Lake, respectively (Fig. 2). Their lacustrine sediments were overrun at a later stage by glaciers which descended from the Velebit and Dinara Mt. areas (Marjanac T. et al., 1990; Marjanac Lj. and Marjanac T., 2006, 2012). The Ždrilo Section sediments of the South Velebit Lake are varved (Adžic et al., 2012) and document changes in climate by variations in thickness of clay (winter) and silt (spring-autumn) layers and fossil flora (Adžic, 2012; Adžic et al., 2012). Proximal part of this lake in the Seline Section provides evidence of climate-driven lake level fluctuations (Marjanac T. and Marjanac Lj., 2002) which most probably pre-dated the studied distal lacustrine sediments of the Ždrilo Section.

Paleoclimate of South Velebit Mt. was studied by Bognar et al. (1991) who reconstructed Pleistocene mean annual temperature (MAT) of 1,1 EC and annual precipitation of 895 mm, and Perica and Orešic (1999) who interpreted Pleistocene MAT of 2,2 EC and paleoprecipitation of 831 mm. Their reconstruction was based on interpolation of meteorological data (Bognar et al., 1991), and suffered from the lack of dating. The study of fossil leaves found in proglacial lake sediments of the Ždrilo section (Adžic, 2012) allowed reconstruction of paleoclimate parameters in broadly the same area as referred by Perica and Orešic (1999), and the MAT was in range from 3,89 ± 2,72 EC to 5,51 ± 2,86 EC, whereas the paleoprecipitation was 679 mm.

GEOLOGY OF THE AREA

The Dinaric Alps strike NW-SE and comprise elongated mountain chains with crests just over 1500 m high (the highest peak is on Dinara Mt., 1831 m), which are divided by fairly deep valleys, usually referred to as karst poljes. Geomorphology of Dinaric Alps is described in more detail by Bongar (2006).

The Dinaric Alps are a massif which originated from Adriatic-Dinaric carbonate platform (Vlahovic et al., 2002, 2005). The oldest lithology are clastics and carbonates of Carboniferous and Permian age, which are exposed in Lika, just below the Velebit Mt., and Permian clastics and carbonates in restricted outcrops on central Velebit Mt. and in the Velika Paklenica gorge (Sokac B. et al., 1974). The largest part of the Velebit Mt. is built of Mesozoic carbonate rocks, which are on its seaward slope overlain by Cenozoic breccia (Majcen et al., 1970; Ivanovic et al., 1973; Šušnjar et al., 1973; Sokac B. et al., 1974), commonly referred to as Jelar-Breccia (Bahun, 1974) or less commonly as Jelar-Formation (Herak and Bahun 1979). The south Velebit Mt. and the Velebit Channel northern coast are built of Cenomanian to Turonian limestones, and Jelar-Breccia (Ivanovic et al., 1973). The southern Velebit Channel coast and the Novigrad and Karin Sea coasts are built of Senonian limestones, Eocene Flysch and Eocene-Oligocene conglomerates of the Promina Fm. (Ivanovic et al., 1973).

Good marker lithologies suitable for provenance studies of coarse debris are variegated conglomerates and yellowish siltstones of the Permian age, and purple micaceous sandstones of the Werfenian (Lower Triassic, Scythian) age which crop out in exhumed anticline cores on the Central and Southern Velebit Mt. (Majcen et al., 1970; Ivanovic et al., 1973; Šušnjar et al., 1973; Sokac B. et al., 1974).

DATING OF PLEISTOCENE GLACIGENIC SEDIMENTS

The studied glacigenic sediments were dated by U-series dating at the NERC Open University U-series Facility, obtained through the collaborative research project "*Timing of extensive ice cap glaciation in the northeast Adriatic mountains, Croatia: implications for moisture supply and cyclogenesis in the Mediterranean basin"* conducted by Ph. Hughes (University of Manchester) and financially supported by the UK Natural Environment Research Council (NERC Grant 2009).

The dated material was sparry calcite precipitated in intergranular voids in moraines. Yielded ages are minimum ages of the host glacigenic sediment, which means that deposition of those sediments could have occured much earlier in different periods. Calcite cements of the same host sediment can also be precipitated different periods. Therefore, dating results based on 10 samples enabled only approximate chronostratigraphy of the studied glacigenic sediments.

The oldest age of > 350 ka BP was obtained on samples of secondary calcite from the Paklenica Member moraines in Velika Paklenica Canyon, and the age of 339,4 ± 61,4 ka BP on samples from the Paklenica Mbr. at the Ždrilo Section. This age of calcite coinsides with Termination IV at 337 ka, while the older age of calcite could coinside with Termination V at 424 ka or MIS 11. Thereafter, we assume that the host sediment age corresponds to the Mindel glacial (Alpine chronostratigraphy) or Skamnellian stage (Pindus chronostratigraphy), MIS 12 respectively or older (Marjanac Lj., 2012). This age correlates well with dating of oldest and most extensive glacial deposits in Montenegro which are attributed to Middle Pleistocene (MIS 12), 480-430 ka BP (Hughes et al., 2011). It also correlates well to dating of moraines on the Pindus Mt. in Greece, which yielded the age of 474-427 ka BP (Hughes et al., 2007).

Younger ages of 159,7 ± 8,2 ka BP and 74,7 ± 1,8 ka BP were also obtained on samples from the moraines of Velika Paklenica, which probably represent later stages of calcate precipitation in voids. However, the age of 159,7 ± 8,2 ka preceed Termination II at 130 ka, though the age of the host sediment is of Riss glacial (Alpine chronostratigraphy) or Vlasian stage (Pindus chronostratigraphy), MIS 10 - MIS 6 respectively. The Novigrad Member, the younger moraine at Novigrad Section, is atributed the same age according to the U-series age of 146,4 ± 4,4 ka BP provided from calcite of an ice-wedge cast infill.

Two U-series ages of 121,6 ± 3,9 ka BP and 110,2 ± 3,4 ka BP, obtained from spary calcite layers in a large cavity, coinside with warm period of MIS 5e following Termination II at 130 ka. The cavity is actually a remnant of a small cave with ca 20 cm thick calcite layers, which gave the age of precipitation during Riss/Würm interglacial (MIS 5e), and not the age of the surrounding sediments.

DAY 1

Location 1 - VELIKA PAKLENICA CANYON (National Park Paklenica)

Topics: GLACIGENIC SEDIMENTS (tillite, glaciofluvial), GLACIOTECTONICS

Figure 1. Velika Paklenica canyon viewed from the sea.

Glacigenic deposits were studied in Velika Paklenica area that comprises the deep valley of Velika Paklenica brook, which extends for ca 3,5 km northwestwards from its spring area at 900 m a.s.l. (Fig. 2), and then turns southwards, the well known Velika Paklenica Canyon, and after ca 8 km ends in alluvial fan in the vicinity of Starigrad-Paklenica town (Fig. 3). Pleistocene sediments are

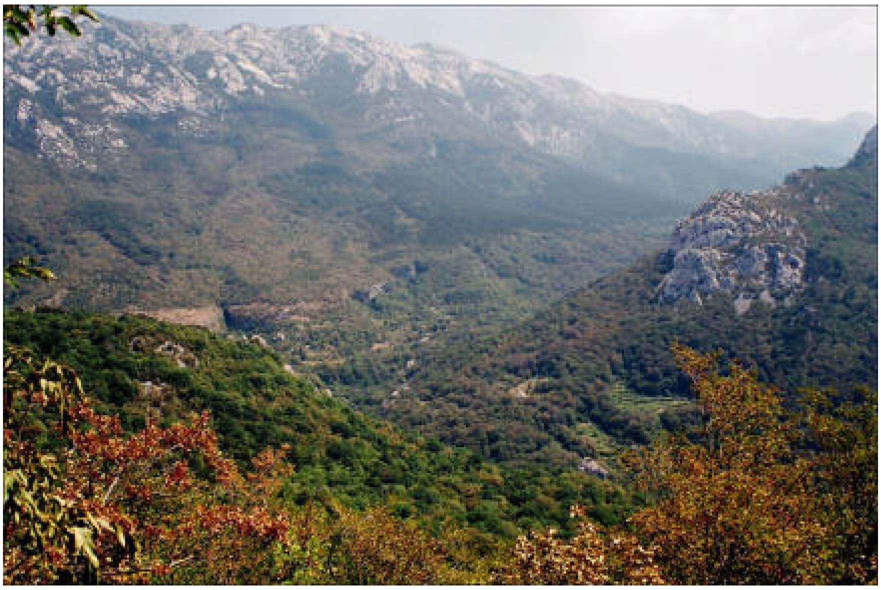


Figure 2. The upper valley of the Velika Paklenica brook extending SE-NW, where glacial and proglacial deposits are found. Photo taken in 2005.

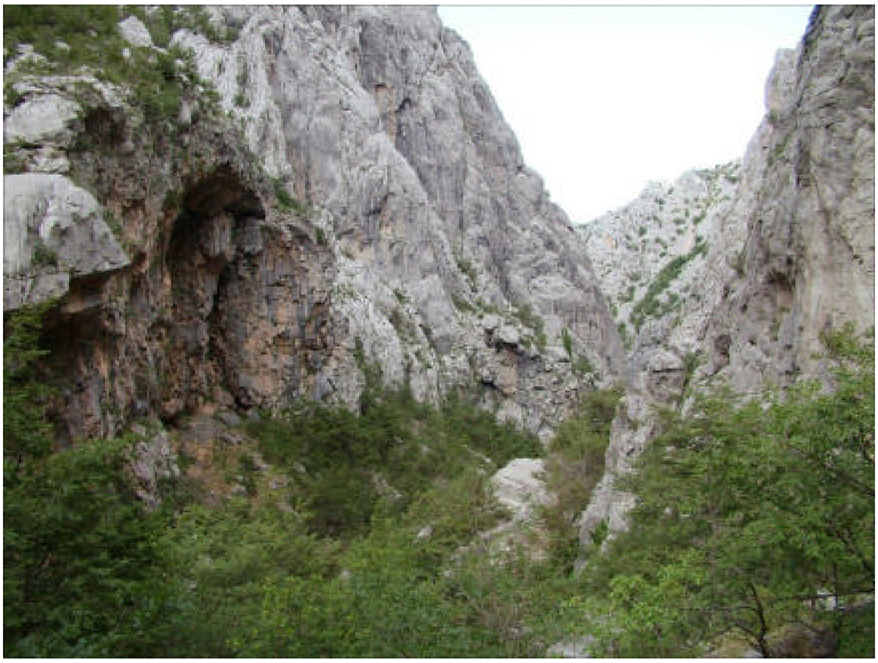


Figure 3. Glacial deposits below Anica Luka in the middle section of the Velika Paklenica canyon.

Photo taken in 2007.

exposed all the way through the upper valley of Velika Paklenica, striking SE-NW, and the lower deep valley of N-S strike.

The generally NE-SW oriented canyon of Velika Paklenica is developed in Jelar-breccia in the lower part and Jurassic limestones and dolomites in the upper part (Majcen et al. 1970). Its NW-SE tributary is developed partly in Jurassic carbonates and partly in Lower Triassic clastics and Middle Triassic carbonates (Šušnjar et al. 1973). Pleistocene sediments are, thus, in contact with various lithostratigraphic units, and are represented by clast-supported to matrix-supported diamicts locally characterized by outsized clasts (megablocks) of various lithologies. These sediments are interpreted as of glacial origin (till and reworked till) and stratified conglomerates of glaciofluvial origin (L. Marjanac 2012). Among other researchers, only Milojevic (1922) also recognized them as of glacial origin.

Figure 4. Proglacial and glacial sediments at in the lower part of the Velika Paklenica canyon. Photo taken in 2005.

Figure 5. Proglacial and glacial sediments at in the lower section of the Velika Paklenica canyon. Photo taken in 2005.

Figure 6. Glaciofluvial and glacial deposits in the lower section of the Velika Paklenica canyon. Photo taken in 2005.

LITHOFACIES

Mega-Diamict, coarsegrained-matrix-supported, massive (MDcmm)

A very specific lithofacies is classified as mega-diamict, a mega-brecca or mega-conglomerate because of common occurence of boulders 1 to 5 m in diameter and mega-boulders or mega-blocks, which are 15 to 25 m across. The rest of the sediment that appears as "matrix" to this outsized debris consits of predominating gravel to boulder (less than 1 m in diameter) debris and very litle matrix composed of silt to granule-size sediment, including subordinate percentage of clay component. Beacause of these specific characteristics, the sediment was named "coarsegrained-matrix supported diamict" instead of clast-supported (Fig. 7).

The debris is in general well packed, but there are also empty interspaces, which document removal of fines by washout processes. These interspaces are locally filled with micritic calcite secondary cement or only drusy or fibrous calcite cement, which was at several locations sampled for U-series dating. The clast roundness varies from subangular to rounded. The percentage of particular type of clasts is variable so mega-diamicts include all transitional types from breccia to conglomerate, which is described relative to a particular location of occurrence. Larger boulders are often faceted with rounded keels/edges. Many clasts are fractured or chrushed. Striations and grooves were found on many of them at various locations. Clast sorting and imbrication is locally present. The characteristics like ice-faceted and polished clasts, ice-shattered clasts, ice-striated clasts and sediment

Figure 7. Megadiamict lithofacies (MDcmm). Anica moraine in Velika Paklenica is the mega-diamict (mega-conglomerate). Boulders are subrounded, polished, faceted and imbricated. The sedimentary texture is masked by supraficial secondary carbonate precipitate. Photo taken in 2009.

texture proves the glacial origin of mega-diamicts. They are interpreted as subglacial, englacial or supraglacial till, which had built morainal bodies, namely lateral or ground moraines.

The mega-diamict (mega-breccia) lithofacies was recognized at many locations along the coast, on Adriatic islands, southern Velebit and North Dalmatia (Fig. 8). It is easily recognizeable lithofacies, and was first studied and described in Velika Paklenica at Anica Luka (Marjanac & Marjanac, 2004; Marjanac & Marjanac, 2011; Marjanac L. 2012). This site was chosen for the type-locality of the mega-diamict lithofacies, defined as the Paklenica Member (Marjanac L., 2012).

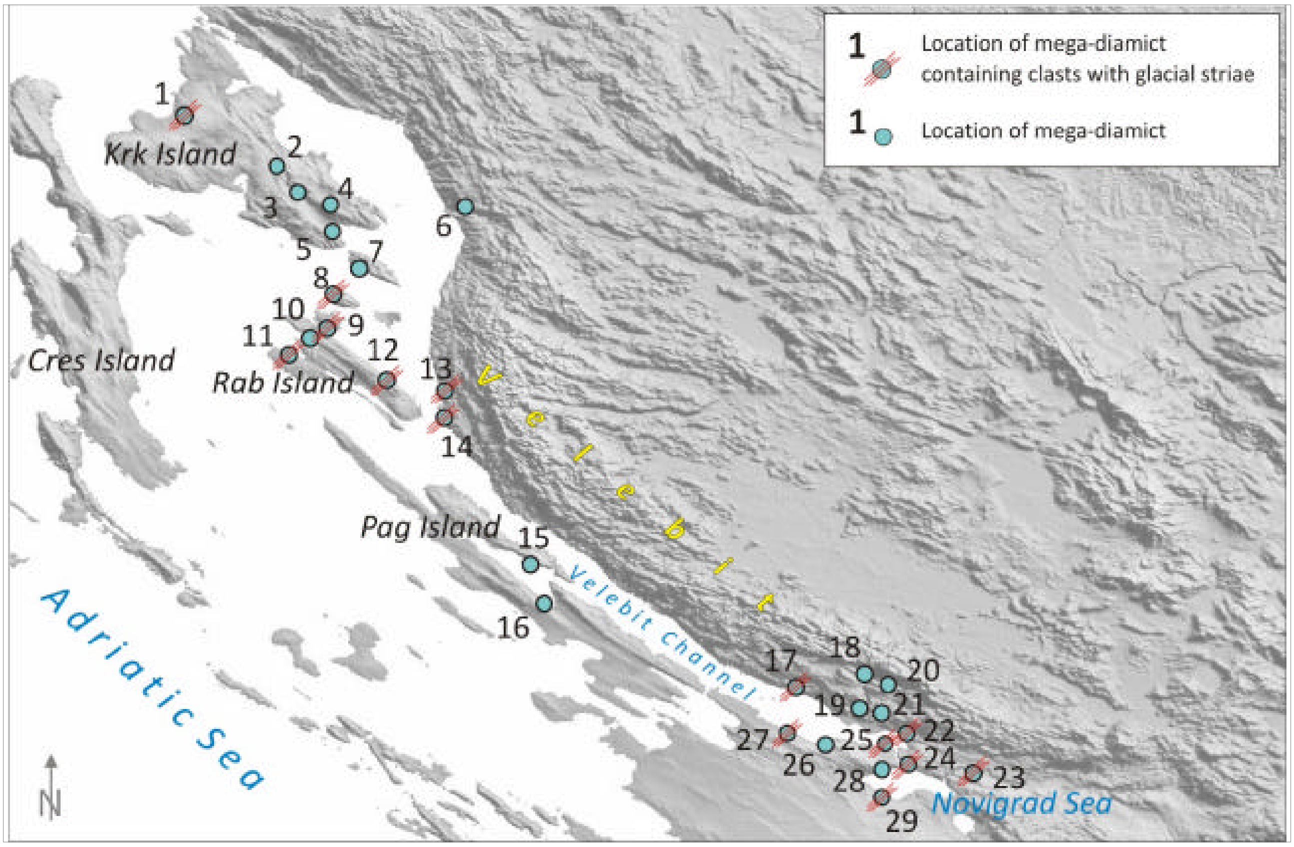


Figure 8. The megadiamict lithofacies was recognized at 29 locations within the study area from the Krk Island to Novigrad Sea. Location list: 1 - Malinska, 2 - Baba, 3 - Suha Ricina, 4 - Jurandvor, 5 - Baška - Gajevi, 6 - Senjska Draga, 7 - Prvic, 8 - Grgur, 9 - Lopar, 10 - Supetarska Draga, 11 - Kalifront, 12 - Krklant, 13 - Jedrelica Draga, 14 - Jablanac - Stinica, 15 - Metajna, 16 - Pag, 17 - Kusaca, 18 - Bezimenjaca, 19 - Velika Paklenica Canyon, 20 - Velika Paklenica valley, 21 - Mala Paklenica Canyon, 22 - Provalija - Modric, 23 - Obrovac, 24 - Maslenica, 25 - Ždrilo, 26 - Ražanac 1, 27 - Ražanac 2, 28 - Posedarje, 29 - Novigrad.

MORAINES

Paklenica moraines are represented by three typical litofacies, matrix-supported diamict (Dmm), clast-supported diamict (Dcm) and mega-diamict (MDcmm), including transitional types. Based on later discussed characteristics, the diamicts are interpreted as glacial tills or tillites composed of subglacial or supraglacial debris. The Paklenica diamicts occur in Veliko and Malo Rujno valleys, Bezimenjaca valley and Velika Paklenica brook valley, both striking NW-SE, in full extent of the Velika Paklenica Canyon striking NE-SW, then in the canyon of Mala Paklenica, and the area of

Starigrad-Paklenica (areas marked yellow in Fig. 9.). The mega-diamicts also occur at coastal locations (marked yellow in Fig. 9.) along the coast of Velebit Channnel and commonly extend bellow the sea level. Moraine thickness varies from few tens of centimeters in Veliko Rujno to more than 100 m at Rujanska Kosa.

Figure 9. Tills/tillites of all lithofacies types are found in the yellow-coloured areas of Veliko and Malo Rujno, Velika and Mala Paklenica, and on many locations along the coast of Velebit Channel.

Paklenica Member

The Paklenica Member is regionaly recognized mega-diamict lithofacies. Its type locality is Velika Paklenica Canyon bellow Anica Luka (Fig. 7, 10).

The sediments consists of very large lithoclasts (mega-blocks) enclosed (”floating”) in a coarsegrained matrix which itself is a clast- or matrix-supported diamict (breccia or conglomerate). Predominating limestone and dolomite debris spans in size from cobbles to mega-boulders. The

Figure 10. Tillite of the Paklenica Member below Anica Kuk is a mega-diamict lithofacies (MDcmm). Characteristic are mega-blocks of 10 m to over 25 m arcross. Blocks are subrounded and commonly have grooved and striated rather flat bottom. Photo taken in 2006.

boulders attain 1 to 10 m in diametre (largest measured is 25 m) (Fig. 10). The cobbles and smaller boulders are subrounded to rounded, commonly sphaerical to oval, most of them ice-fasetted and polished, and some bullet-shaped (Fig. 13). The sediment is extremely unsorted to poorly sorted. Elongated boulders usually lay on their larger surface with longer axis commonly horizontal (Figs. 12). Local imbrication indicates push and transport direction. Elongated large clasts, two to several meters long, are found even in vertical position within the coarsegrained matrix, which was possible only if debris was mixed with ice during accumulation and transport. Glacial striae (Figs. 14) are rarely preserved, or possibly masked by secondary cements, or destroyed by corrosion. Glacially polished surfaces are visible but usually destroyed by corrosion (karstification). Ice-shattered clasts are frequent, best visible in mega-diamict at the Kneževici site. Ice-fracturing commonly broke lithoclast into two or three

Figure 11. A patch of tillite (mega-diamict of Paklenica Member) in sharp contact with bedrock along the slopes of the Velika Paklenica canyon bellow the Anica Kuk. Photo taken in 2006.

Figure 12. An exposure of mega-diamict located near entrance to Velika Paklenica gorge. The characteristic mega-bloks lay among up to metre-sized cobbles, within the coarsegrained matrix. The mega-block on the left is 6 m across, and the one on the right is 10 m across. Their bottom and side surfaces are polished. The one on the right is also fractured. Most of the cobbles are fasetted and rounded. Photo taken in December of 2011.

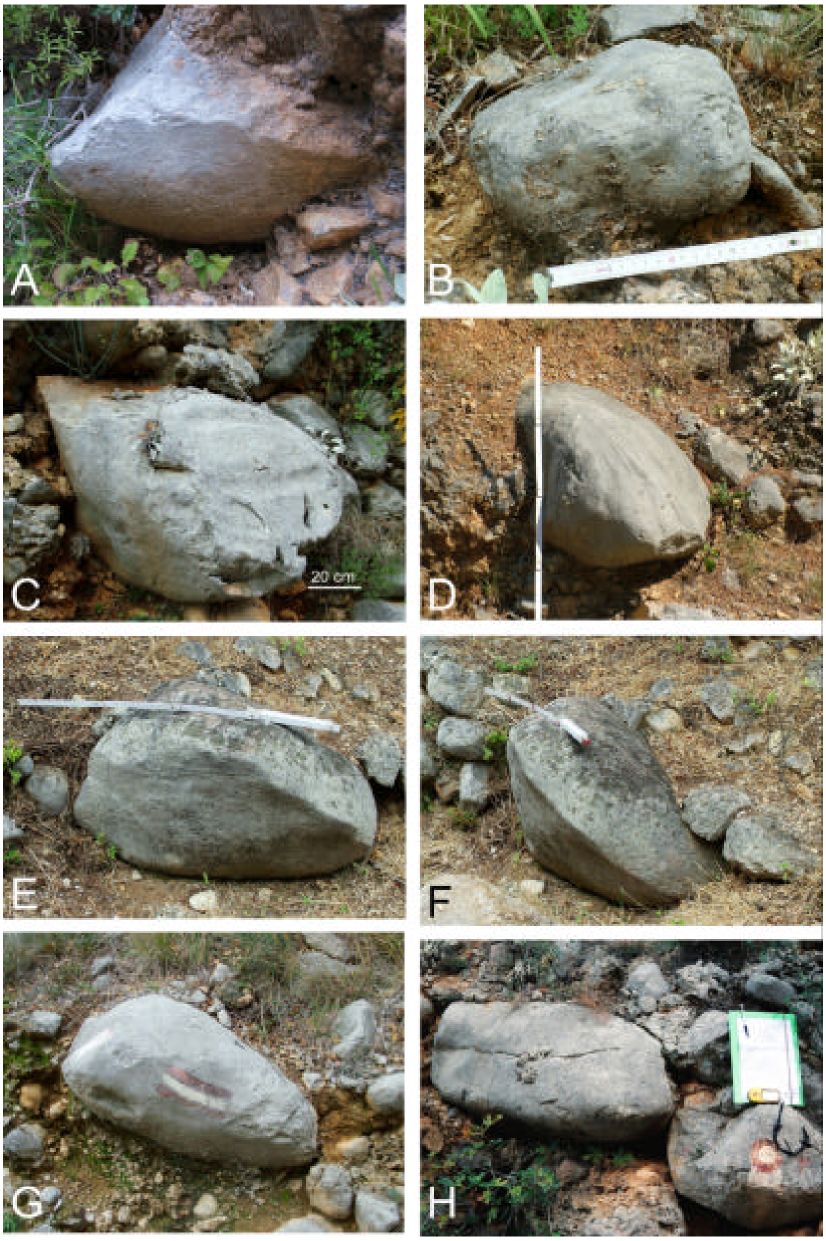


Figure 13. Boulders of various shapes found in the Paklenica till (mega-diamict lithofacies) in the lower section of the Velika Paklenica canyon exposed along the road. A - partially ice-fasetted with well rounded and polished bottom surface; B - rounded and striated; C - fasetted, sharp-pointed at one end and rounded and grooved on other side; D - bullet-shaped side of a polished boulder; E - ice-fasetted and polished; F - polished discoidal boulder with sharp keel; G - rounded and polished; H - ice-fasetted and rounded.

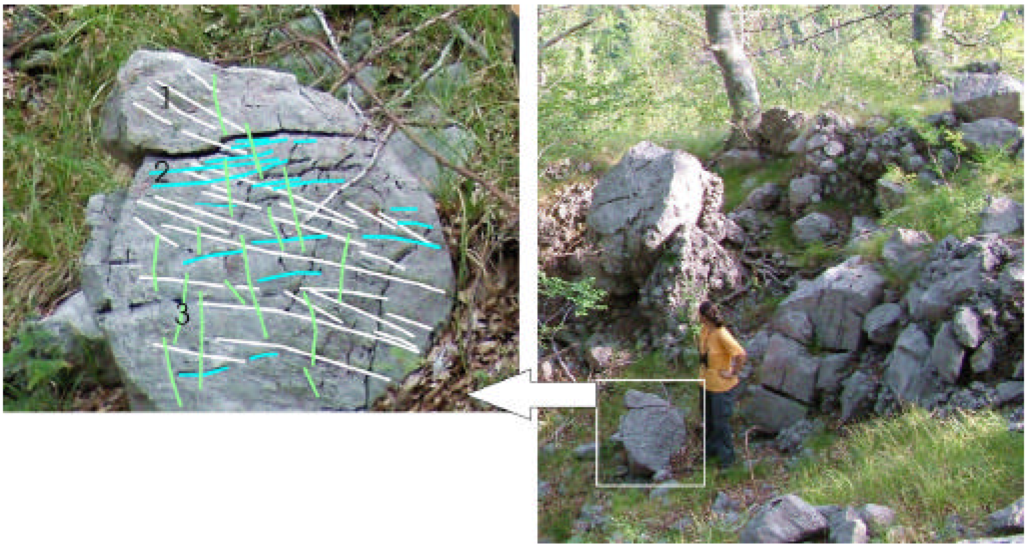


Figure 14. A rounded discoidal limestone boulder of 1 m diameter with three systems of glacial striae was found in the mega-diamict (Mdcmm, Paklenica Member) in the valley of the Velika Paklenica brook. Photo taken in 2004.

pieces, and due to pressure and transport motion those fragments were more-or-less disslocated ffrom each other. There are also boulders with more-or-less eroded and smoothened karren, which provide evidence of preglacial karstification.

The mega-diamict at the Anica Luka was interpreted as rockfall sediment by Perica (1993), and later as terminal moraine of the V. Paklenica by Marjanac & Marjanac (1999).

The Paklenica Member is found from bellow the modern sea level (Ždrilo site) to around 600 m a.s.l. (Velika Paklenica), locally in association with the ovelaying kame terrace deposits (Krk, Pag, Paklenica). The furthest seawards extent is indicated by its remnants on the Krk, Rab and Pag Islands and the SW coasts of the Velebit Channel and Novigrad Sea. The Interpretation as ground moraine is based on many findings of faceted, polished and striated clasts. This moraine documents an extensive ice advance when glaciers have overrided the glacilacustrine deposits exposed at Ždrilo and Kusaca localities, though at Novigrad section the Paklenica Member occurs bellow the glacilacustrine sequence, which indicates different age of glacilacustrine deposits in Velebit Channel and Novigrad Sea.

The mega-diamict is more-or-less cemented with micritic calcite, rarely drusy calcite. The U-series dating of drusy calcite yielded two dates of minimum age of till, one >350 ka in Paklenica and the other 340 ka at Ždrilo site, indicating their Middle Pleistocene age.

In the lower section of the Velika Paklenica canyon, Paklenica Member is more complex and consists of three cycles, each composed of tillite and reworked tillite, which may be considered as subunits marking ice advance-retreat cycles. This is clearly visible at the road-cut section shown in Figure 15. The moraine overlaying a reworked tillite represents the third visible cycle. The contact between the two intervals is irregular, sharp and erosional. The reworked subglacial till is a matrix- to clast-supported conglomerate. It is locally well sorted into gravel ribbons, locally poorly sorted abound in micritic matrix, and locally inversly graded. Sorting and grading occured during higher discharge of subglacial melt-water. The massive parts consist of randomly oriented rounded clasts which is characteristic for subglacial transport with lot of matrix. Traction and shearing due to ice advance produced local imbrication of clasts, and shearing plains are locally visible. There are numerous cavities filled with spary calcite, which was sampled at one location and U-series dating yielded age of 159.8 ka, which contrasts the one of 339.6 ka. This could mean that this sediment is younger, but it is more likely that the calcites were precipitated at very different times.

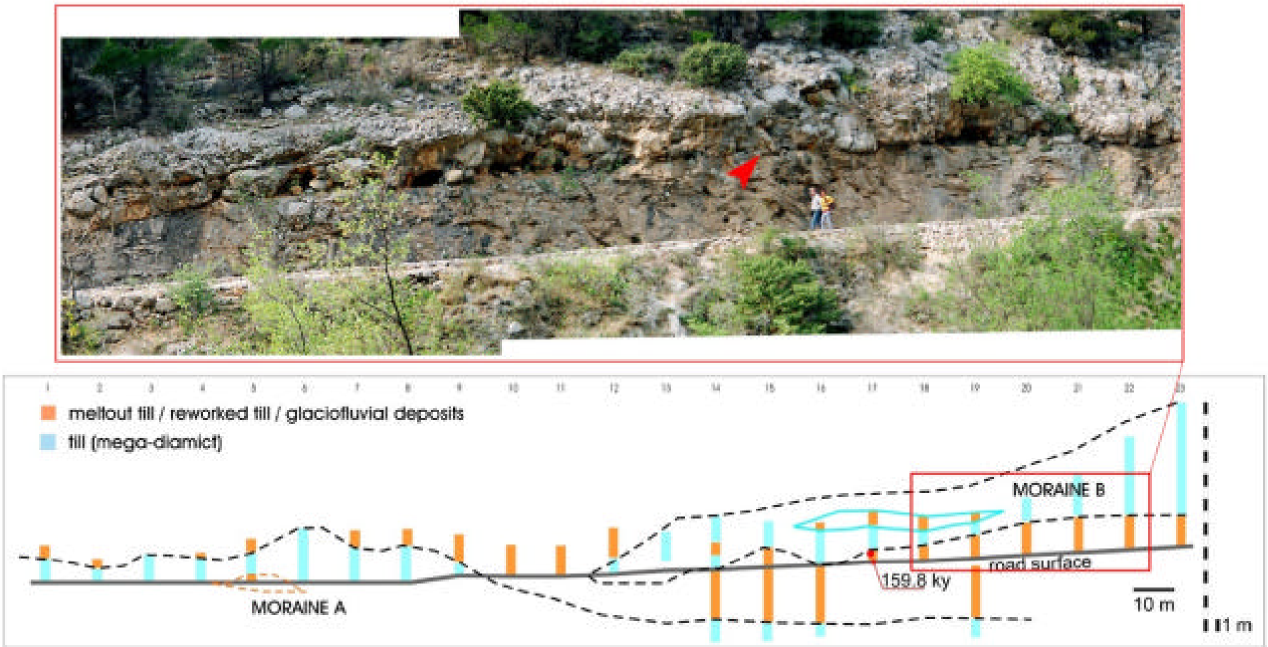


Figure 15. The road-cut exposure in Velika Paklenica shows the third cycle of glacier advance during deposition of the Paklenica Member. Mega-diamict (mega-breccia) with large boulders lays at sharp contact above reworked tillite of the previous cycle. Line-art reconstruction shows two morainal bodies and reworked tillite between. Location of dated calcite sample is marked bellow the contact with younger morainal body.

D A Y - 2 and D A Y - 3

LOCATION: Novigrad Sea coast

TOPICS: GLACIGENIC SEDIMENTS (tills, glaciofluvial, glaciolacustrine, paleosols), SEDIMENT DEFORMATIONS, PROGLACIAL AND PERIGLACIAL LANDFORMS (crioturbation, ice-wedge casts)

The Novigrad Sea southwest coast is characterized by cliffs and otherwise low coast where Pleistocene deposits are exposed in length of 3,5 km. Their thickness varies between 2 and 15 meters. The sediments were logged in detail at seven locations and the complete 3 km long outcrop was mapped based on digital photo mosaic. Successive photographing of the outcrop was done from a boat. Photo-profile was produced by stitching 73 photographs , and then it was used as a background for reconstruction of lateral and vertical facies relation and interpretation with help of field data (Marjanac et al, 2006; Marjanac L., 2012). These deposits lay mainly over Cretaceous limestones, but also over Paleogene clastics on the southeast side of the study zone. The contact with bedrock can be traced all the way, although it is locally covered with soil.

GLACIGENIC DEPOSITS

MORAINES

Novigrad moraines occur in association with different glacial and non-glacial facies. The quality of exposure is very good and different facies could be traced for three kilometres more-or-less continuosly, except for few intervals of coastal cliffs. The lateral facies transition was studied by using a digital photo-mosaic.

Two distinct diamict lithofacies, interpreted as subglacial tills (ground moraines), were recognized at the Novigrad Section:

- an older till, the mega-diamict lithofacies ascribed to the Paklenica Member (Novigrad M-1)

- a younger till, the matrix-supported diamict attributed as the Novigrad Member (Novigrad M-2).

Paklenica Member

The mega-diamict lithofacies at the Novigrad section posesses all charcteristics of the Paklenica Member previously described at its type locality in Paklenica, except its visible thickness is dominantly smaller, up to 5 m above sea level at most. The mega-diamict (allo-unit 1) is discontinuously exposed in length of about 1,5 km, forming a hummocky topography. Otherwise, it extends below the sea level, so its thickness must be greater than exposed. At studied location the Novigrad M-1 till was deposited over the Cretaceous limestone bedrock exposed bellow at sea level and in the hinterland, indicating that inherited relief of deposition was a hilly terrain. Locally, the bedrock limstone appears polished and also karstified, but probably prior to glaciation. The Novigrad M-1 till is overlain either by glaciofluvial or glaciolacustrine deposits. It is common to find transitional facies which are gravel deposits interpreted as meltout till or glaciofluvial outwash deposits.

Figure 1. Older Novigrad moraine (M-1) with a mega-blok. Photo taken in 2003.

The clast sizes span from small to very large boulders or mega-blocks, the largest measured is over 10 m across (Fig.1, 4). The boulders are rounded and more or less sphaerical, some are elongated or platy, and many are ice-fasseted, polished and rarely have pitted corrosion surface (Fig. 2). Boulders are tipically ice-shattered or broken under pressure (Fig. 3). Glacial striae or grooves were frarely found. Blocks and boulders, washed out from the Novigrad M-1 till lay loose in piles along the coast (Fig. 5).

The Novigrad mega-diamict is commonly reworked, fines are washed out and boulders resorted. In depressions of the hummocky moraines there occur inversley graded boulder beds (Fig. 5, 6), indicating wash-out process and reworking of moraine surface. Those boulders are well packed and form a boulder pavement. Large tabular boulders are locally imbricated paralel to bedrock slope, probably a result of push pressure during glacier advance. Boulder-clast lithologies variate predominantly among carbonate rocks, usually limestones (crystaline, micritic, stromatolitic, rudist-rich, foraminiferal). Amongs finer debris, clasts of Paleogene foraminiferal limestone and hybrid arenites are found.

Figure 2. Boulders in older till (M1, Paklenica Member): rounded and ice-polished (A), ice-fasetted, well rounded and polished (B), rounded and ice-plished (C), ice-fasetted and polished (D), angular with pitted corrosion surface (E) and fasetted with pitted corrosion surface (F).

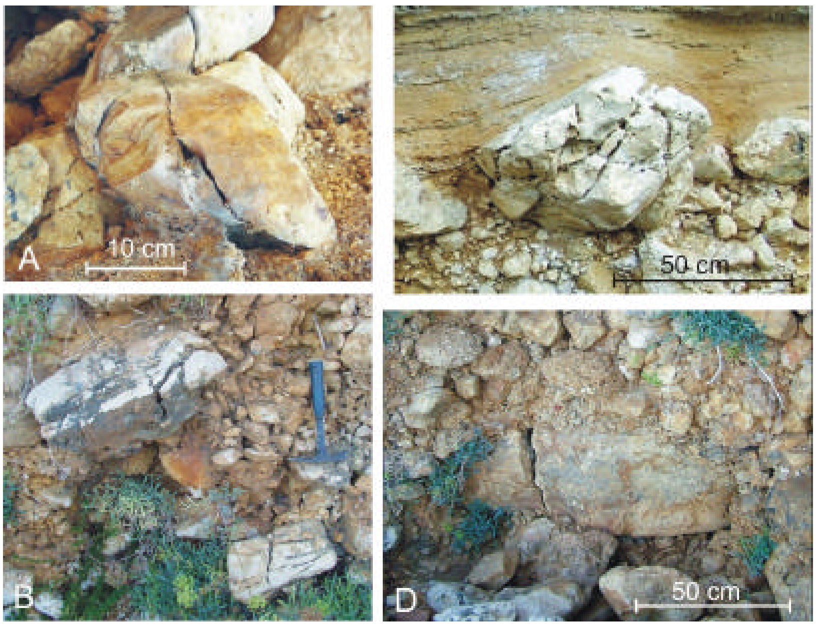


Figure 3. Boulders in Novigrad M-1 till are commonly ice-shattered (A, B, C) and some broken in half due to vertical pressure (D).

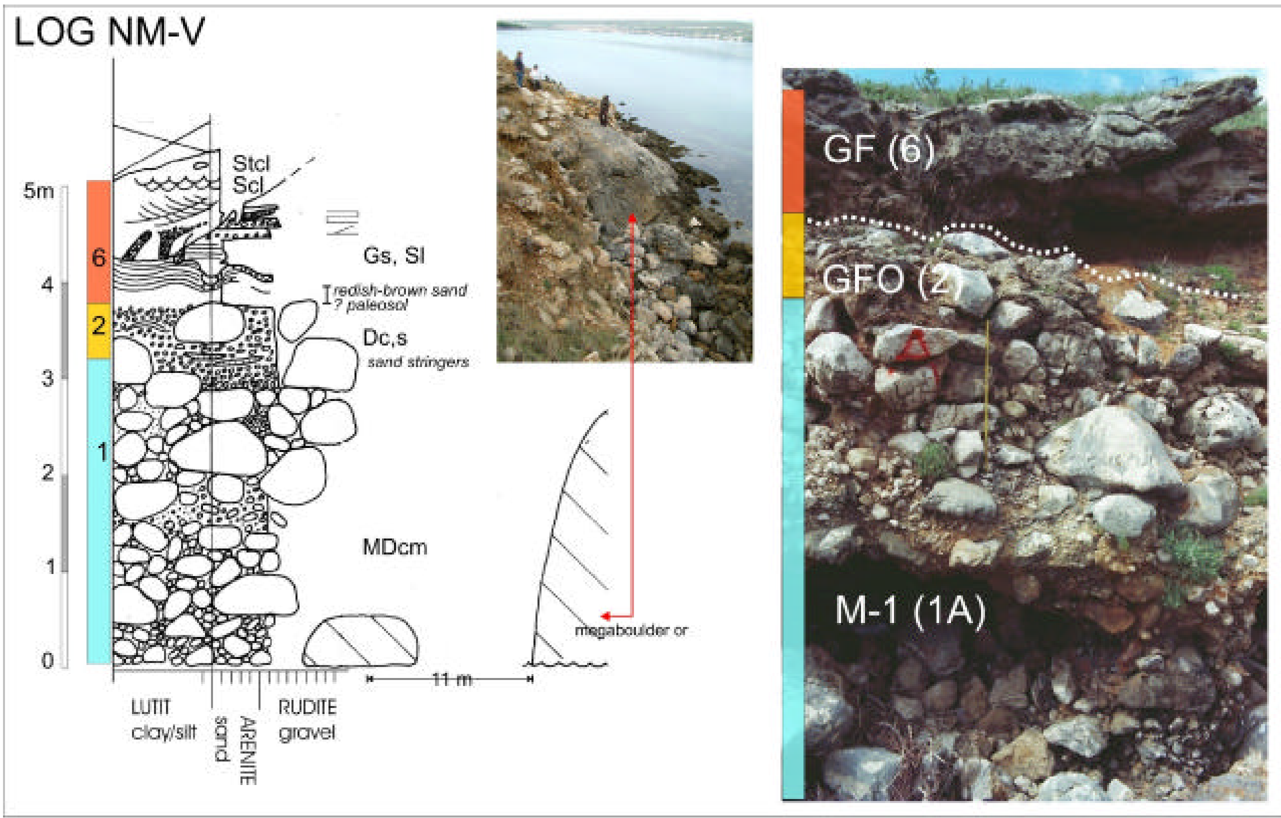


Figure 4. A typical cross-section of the Paklenica Member mega-diamict lithofacies (1) exposed at the Novigrad section. There is a mega-block exposed close to location of presented sediment log (figure bellow and App. x-3). The sediment log shows glacial (1), proglacial (2), and glaciofluvial (6) deposits .

Figure 5. Loose boulders and mega-blocks of the Novigrad M-1 till are locally washed out and remained as piles along the coast of Novigrad section. Boulders are commonly ice-fasetted and polished, but due to weathering polished surfaces are corroded. Photo taken in 2008.

At the Novigrad section, as mentioned before, a typical meltout till was recognized atop of the Novigrad M-1 subglacial till (Fig. 8). The sediment is a clast-supported massive gravel (Gcm) or stratified (Gc,s). It drapes the irregular surface of the subglacial till (MDcmm). As ice melts away, englacial debris settles down, while silt and sand are washed away by meltwaters.

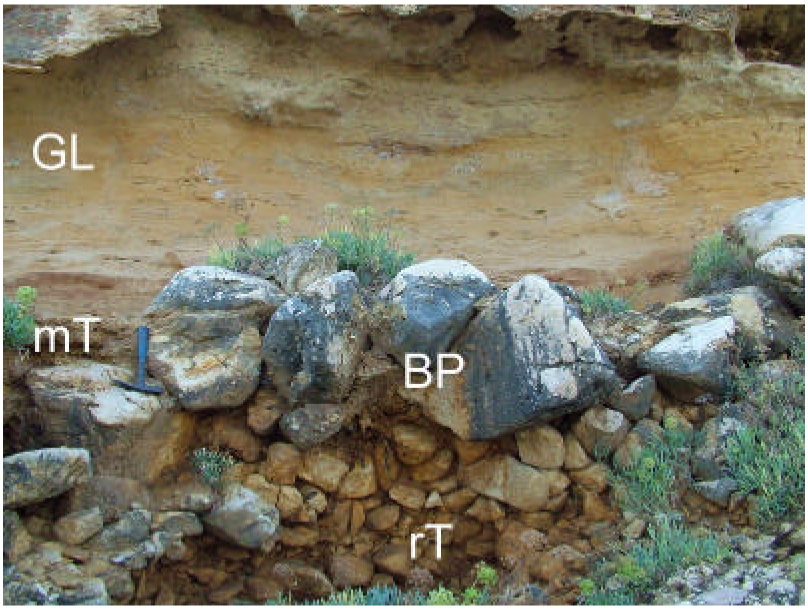


Figure 6. Boulder pavement (BP) overlain by glaciolacustrine sediment (GL). Gravel sediment (glacial outwash or meltout till (mT)) is locally found in gaps between boulders above the reworked till (rT). Photo taken in 2008.

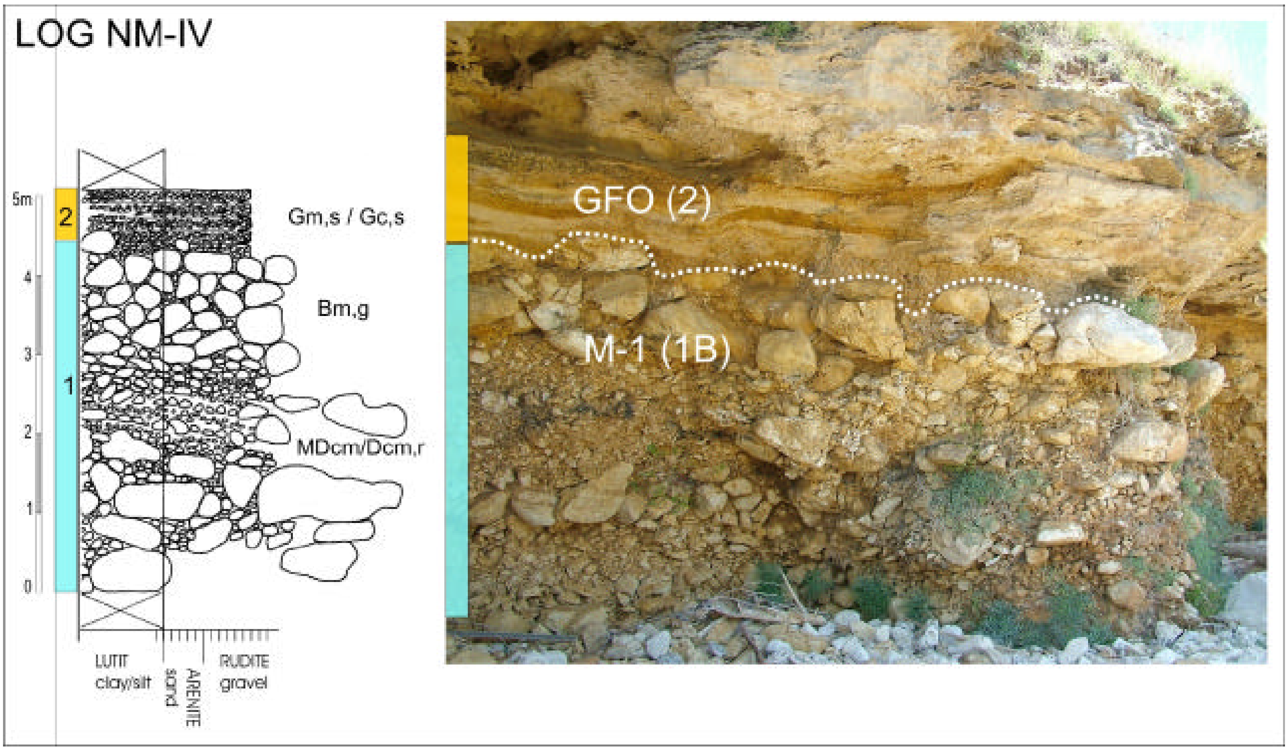


Figure 7. The Paklenica Member mega-diamict shown in sediment log (1) is the older moraine (M-1) exposed at the sea-level at Novigrad section. This till is partly washed out and reworked, thus lacks a finegrained component, which produced openwork texture and clast support. Linear segregation of larger boulders occured and produced a boulder layer visible at the top of the till interval (Bm). Inverse grading is locally visible. On the top of the boulder-layer were deposited glaciofluvial outwash gravels (2) that are stratified.

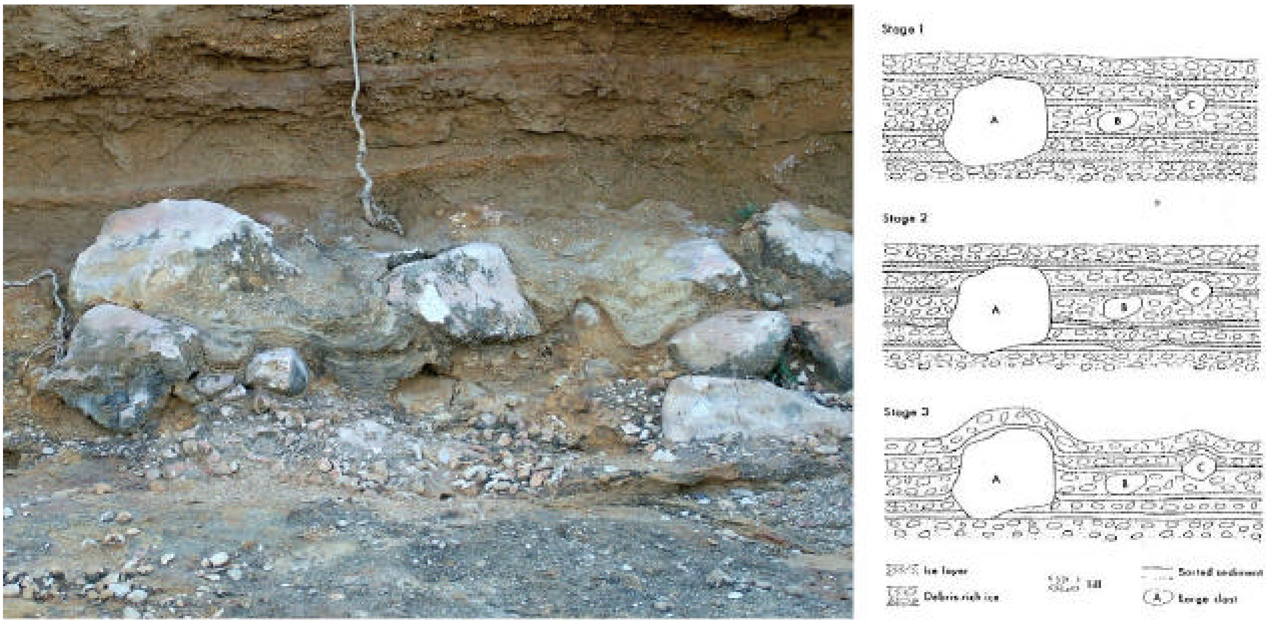


Figure 8. The meltout till atop of Novigrad M-1 subglacial till (MDcmm). The third stage of meltout till development, as sketched by Shaw (1977), is clearly recognized. Photo taken in 2009.

Novigrad Member

The Novigrad section is the type locality for description of the Novigrad Member represented by matrix-supported diamict lithofacies (Dmm). This diamict is interpreted as subglacial till named Novigrad M-2 or younger Novigrad moraine. It is preserved and exposed at the NW side of the Novigrad section, a minor occurrence acording to other facies (allounit 5). This younger till overlays the glaciolacustrine sandy deposits at very sharp and irregular contact (Fig. 9). There are no deformations visible in underlying deposit within span of the exposure. Visible depth of erosion is up to 3 m. There is bauxite sediment in the base of contact which looks like deformed soft-sediment clast, though it is not clear whether deformation is due to former depositional conditions or is related to Novigrad M-2 till deposition. Otherwise, there are a lot of bauxite deposits at K/T boundary exposed in Northern Dalmatia, which were ripped and transported by glaciars.

The Novigrad M-2 till is 2-4 m thick. It is poorly cemented, and composed of debris from gravel to boulder size and finegrained sandy matrix (Fig. 9). There are also meter-sized clasts but are not so common as in the Novigrad M-1 till. The clasts of 50-100 cm large are predominantly ice-fasetted, medium to well rounded and polished. Many are tabular and elongated, fewer are medium sphaerical. Larger clasts (more than 1 m) are rare but of same characteristics. Clasts smaller than 50 cm in diameter are predominantly subangular to medium rounded, commonly platy or splinter shaped, rarely rounded and subspherical. Such differences indicate mixture of longer transporeted and shaped debris and shorter transported debris may be even of local origin. Some large tabular sandstone clasts present in till indicate local origin, because such lithology is found at Novigrad section within older glaciolacustrine interval, which at the same time documents high rate of erosion. Clast lithology varies within different limestone types, and other lithologies are rarely found, like red siltstone with bivalves, red laminated calcarenite, micaceous red sandstone (all Lower Triassic clastics), and laminated brownish-grey sandstone (Eocene clastics). One clast of Triassic gypsum sediment was also found, and togeather with Triassic clastics indicate a very long trasport from area of Knin.

Among the isolated clasts or clustered debris occur lenses of laminated sand and silt sediment, and pockets of masive sand mixed with eroded paleosol which had developed above glaciolacustrine deposits. The sediment was most likely deposited as the subaerial hyperconcentrated debris flow (Nemec, 2009), but due to sand parts it could be subaquatic slightly diluted, though not in contradition with glacigenic interpretation.

The Novigrad M-2 till is overlaped with glaciofluvial sediments.

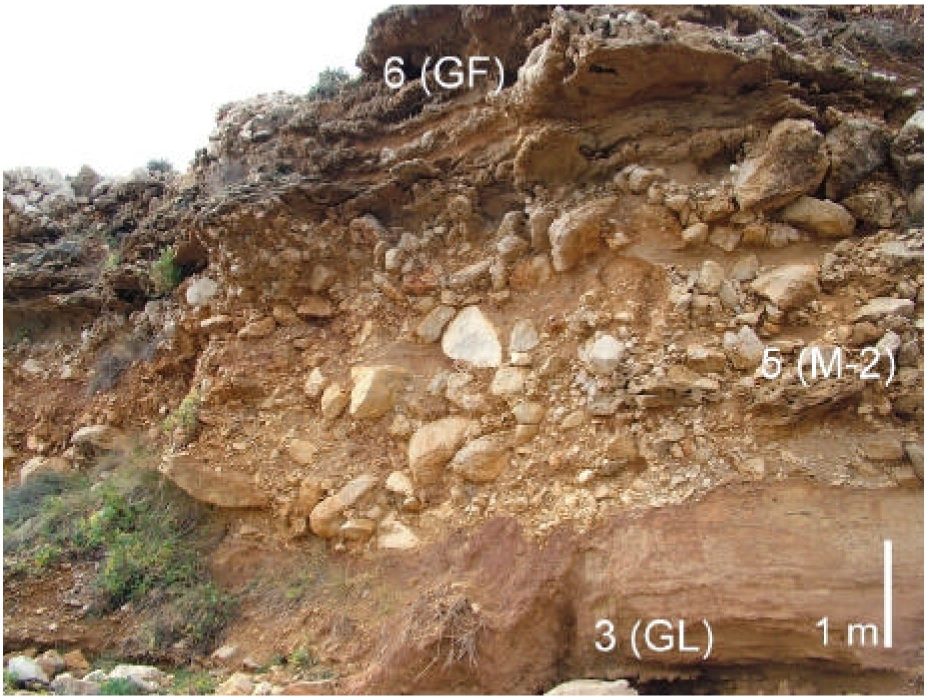


Figure 9. The Novigrad M-2 till (younger Novigrad moraine) overlies the glaciolacustrine (GL) sand deposits at sharp, irregular contact. Glaciofluvial (GF) deposits lay atop of till. Photo taken in 2010.

GLACILACUSTRINE SEDIMENTS

Lithofacies

Clay

Clay sediment occurs within younger glacilacustrine interval composed of cross-laminated and ripple-laminated sands, and it forms massive or faintly laminated layers up to 10 cm thick, or occurs in lenticular bedded sand-silt intervals as shown in the Log N-4b of the Novigrad section. Such redish-brown clay layers, which occur within glacilacustrine sequence of Novigrad section, are commonly eroded by currents produced by subglacial meltwaters flowing into a proglacial lake basin. The clay is locally very bioturbated (Fig. 10), and locally contains irregular lenses of clayey calcisiltites with current ripple lamination (Fig. 12).

Varved-like calcisiltite

Calcisiltite are 40 - 80 % carbonate, appear massive, but a vague horizontal lamination is visible produced by alternation of silt and clayey silt laminae or beds. Weathered surface of the sediment is masking even this vague lamination. There are several horizons with isolated clasts up to 10 cm in diameter (exceptionally 20 cm), which are faceted or rounded, and interpreted as dropstones (Fig. 10). Biota in siltites is poorly diversified and represented by two cold-water ostracod species *Candona neglecta* Sars and *Scottia browniana* Kempf, and characean gyrogonites. Rare bioturbation also occurs.

The massive, faintly laminated calcisiltites were deposited from sususpension in a proglacial lacustrine environment. The dropstones found at several levels within siltite unit were brought and discharged by floating and undermelting ice-blocks. Soft sediment deformation under fallen dropstone is visible locally if the sediment at the lake bottom was well laminated.

At Novigrad section, they occur in association with older glacial deposits (tills) and younger glacifluvial deposits.

Sand / Calcarenite / Hybrid arenite

Sediments composed of arenite-size grains, regardless of mineral composition, are herein called “sands” if unconsolidated. Since most of the sand deposits are predominantly composed of carbonate particles, they are called calcarenites. In sediment successions also occur sand deposits with about half carbonate and half non-carbonate debris (quartz sand), thus named hybrid arenites. Sands or arenites are generally loose to poorly cemented. Cementation is commonly selective, so it is usual to find an exposure completely cemented at the surface. Selective cementation of particular layers (especially fine-grained) is also common, probably due to difference in clay content, meaning that less clay content enables faster cementation. However, the fine-grained sands are well cemented at some levels making odd-shaped concretions generally in horizontal position, which is common at all studied locations.

Sand sediment vary from fine-grained to coarse-grained, and gravelly. The fine-grained sands (calcarenites) occur in large part of Novigrad section representing glacilacustrine and glacifluvial deposits.

Figure 10. Glaciolacustrine sediments with dropstones.

Bedding is very different and includes: cross-bedding (planar or trough-cross), lenticular, wavy and flaser bedding common in fine-grained sands, and horizontal bedding. Sinsedimentary deformations occur locally and are described and discussed in relation to a particular section (Baška, Pag, Novigrad). Common structures of fine-grained sands/calcarenites are normal grading in massive sand-to-silt layers, horizontal or wavy parallel lamination, ripple-lamination (current, climbing, and wave ripples), cross-lamination (planar or trough-cross) and scour-and-fill lamination. These are characteristic for the younger glacilacustrine unit of the Novigrad section (Figs. 13, 14).

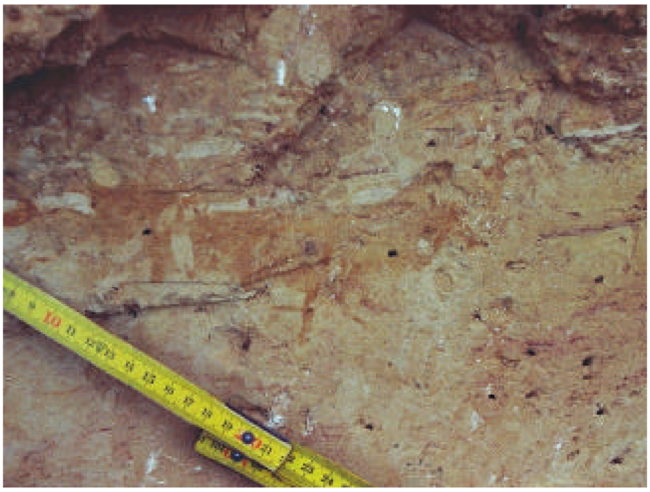


Figure 11. Intensively bioturbated interval. Glacilacustrine sequence of Novigrad section. Photo taken in 2004.

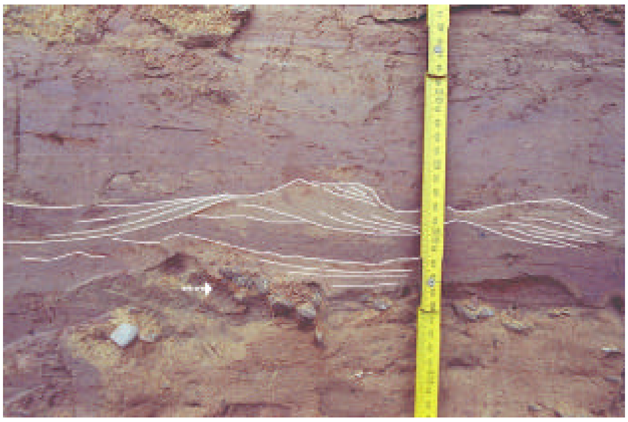


Figure 12. Clay sediment of glacilacustrine sequence at Novigrad section, with isolated clayey silt current ripples. There is a dropstone stringer bellow the clay bed deposited by undermelting of rafting ice-blocks. Photo taken in 2004.

Very fine-grained lenticular bedded calcarenites are interbedded with marls and clay laminae which may be interpreted as “varve-couplets” of proximal lake environment.

The varved-like calcisiltites occur in the **lower (older) part** of the glacilacustrine allo-unit and their visible thickness from sea-level up is three meters at most, since their base is not exposed. Surface weathering and cementation masks the vague lamination resembling varves (Fig. 10). There are several horizons with ice-rafted-debris (IRD). These isolated cobble-size limestone clasts are commonly faceted and rounded, and are classified as dropstones. The dropstone structure, as presented by Benn & Evans (2010) is not recognized in the calcisiltites probably because of their massive texture.

The calcisiltites can be classified as calcareous marls, and were deposited from suspension in a quiet environment. Amount of noncarbonate component spans within 10 to 70 %. The vague horizontal lamination is due to minor variations in clay content, which resembles varves. Alternation of more clayey and less clayey calcisiltites can be interpreted as annual winter-summer cyclicity. Sedimentation occurred in distal proglacial environment, away from dynamic terminoglacial zone. Seasonal summer thawing produced ice blocks with IRD.

The **upper (younger) part** of the glacilacustrine allo-unit is represented with generally rippled calcarenites. Calcarenates vary from those with 90 % carbonate component to hybrid arenites with ca 50 % carbonate. This package consists of lenticular, wavy and flaser-bedded calcarenites.

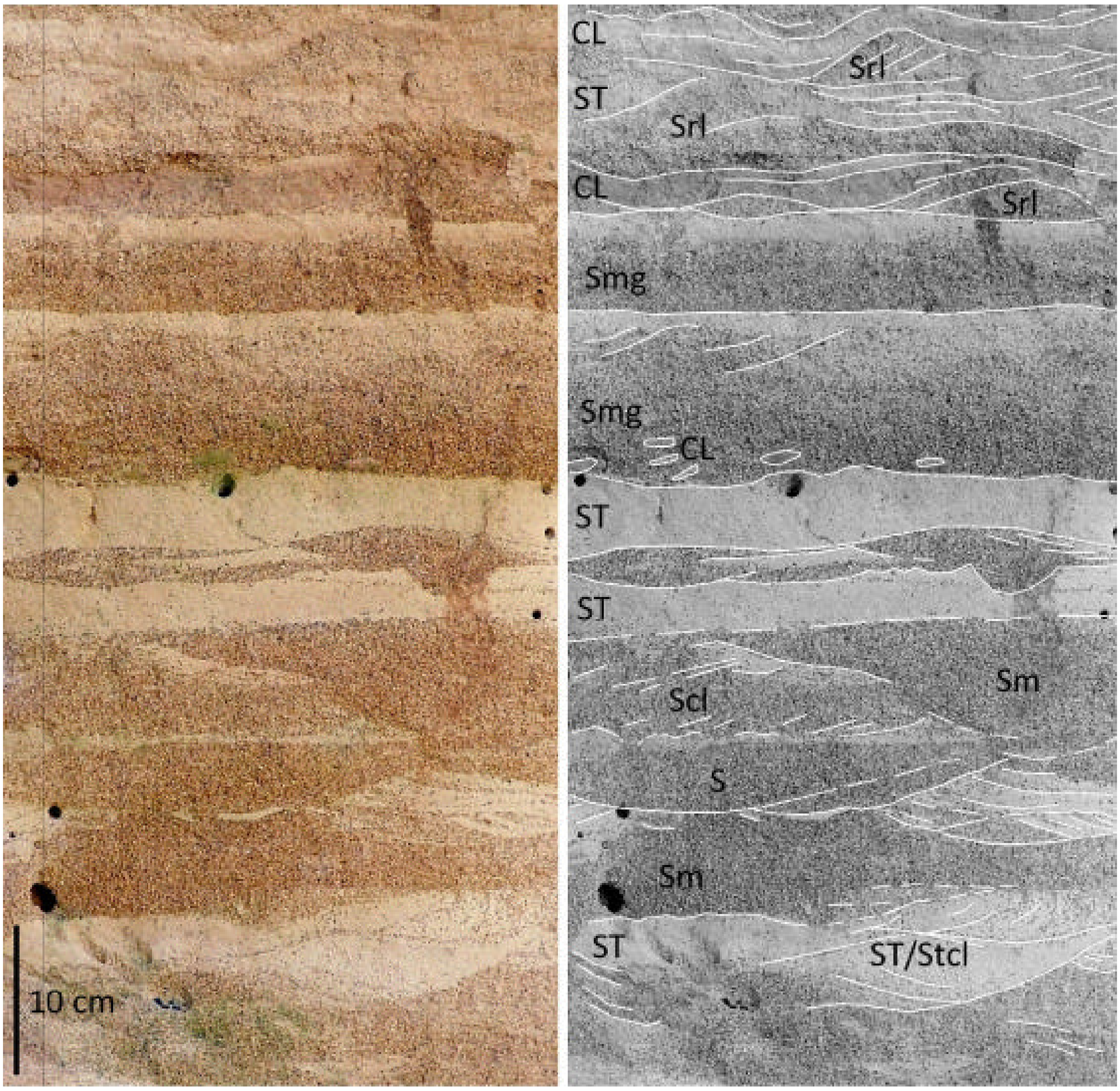


Figure 13. Detail of the younger glacilacustrine unit of Novigrad section, showing ripple and cross laminated calcarenites. Some sand layers are normally graded to silt (Smg). Some are faintly graded or ungraded, rippled, and sometimes representing few centimeters high isolated ripples ("starving ripples" in the middle within silt layer (ST)). Contacts are sharp and erosional. Rare clay laminae (CL) occur atop of ripples. Current ripples indicate transport from left to right, as well as imbricated mud chips in the normally graded sand bed (Smg).

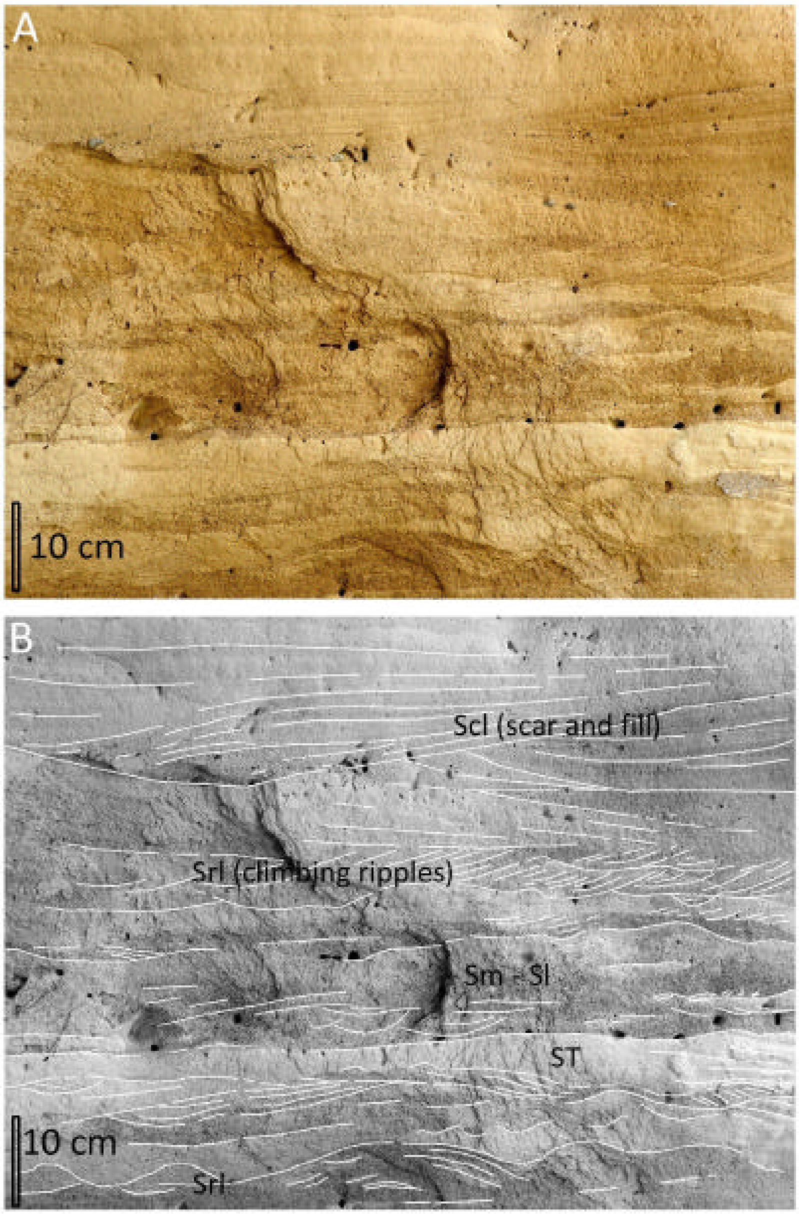


Figure 14. Detail of the section above the one shown in Figure 15. A - field view; B - interpreted image. Three intervals of laminated calcarenites are recognizable: the lower with “starving ripples” and faint cross lamination, the middle one with massive graded sand and climbing sand ripples above, and the upper interval with scour-and-fill sand-silt sediment.

Calcarenites also occur in the whole length of the Novigrad section, and their thickness is 1 - 5 m, although their real thickness is not known due to erosional contact with the overlying sediments.

The variability in development of lenticular (log N-4b in Fig. 14), wavy and flaser-bedding is partially visible in various segments of the Novigrad section, indicating transitions from subtidal to wave dominated environment of deposition (Reineck & Singh, 1973). The wave-rippled calcarenites (N-3 and N-4b in Fig. 15) indicate periods of decresed sediment input and shallowing of the lake, while intervals with domination of current-ripples indicate periods of intensified subglacial melt. Soft sediment deformations occur in lenticular bedded intervals as shown in the log N-4b (Fig. 15), and small-scale ice wedge casts (1-3 cm) were noticed in flaser bedded intervals.

In the upper section of the rippled calcarenites locally occur “linguoid” structures (Fig. 16), usually associated with “kettle-like forms” and sedimentary wedges. They are very similar to accumulation tongues of rill marks (usually better developed in finer sediment), which form in thin water film (2 cm at most) or by sudden expulsion of water from sediment due to compaction, and are considered as a document of intermittent subaerial exposure of the surface (Reineck & Singh, 1973). The water expulsion from the sediment likely to have produced the accumulation tongue forms at the Novigrad section. The water originated from thawing of buried ice ("kettle-forms"), and produced very dense and highly-concentrated flows emerging to the surface. Alternatively, pressure caused by

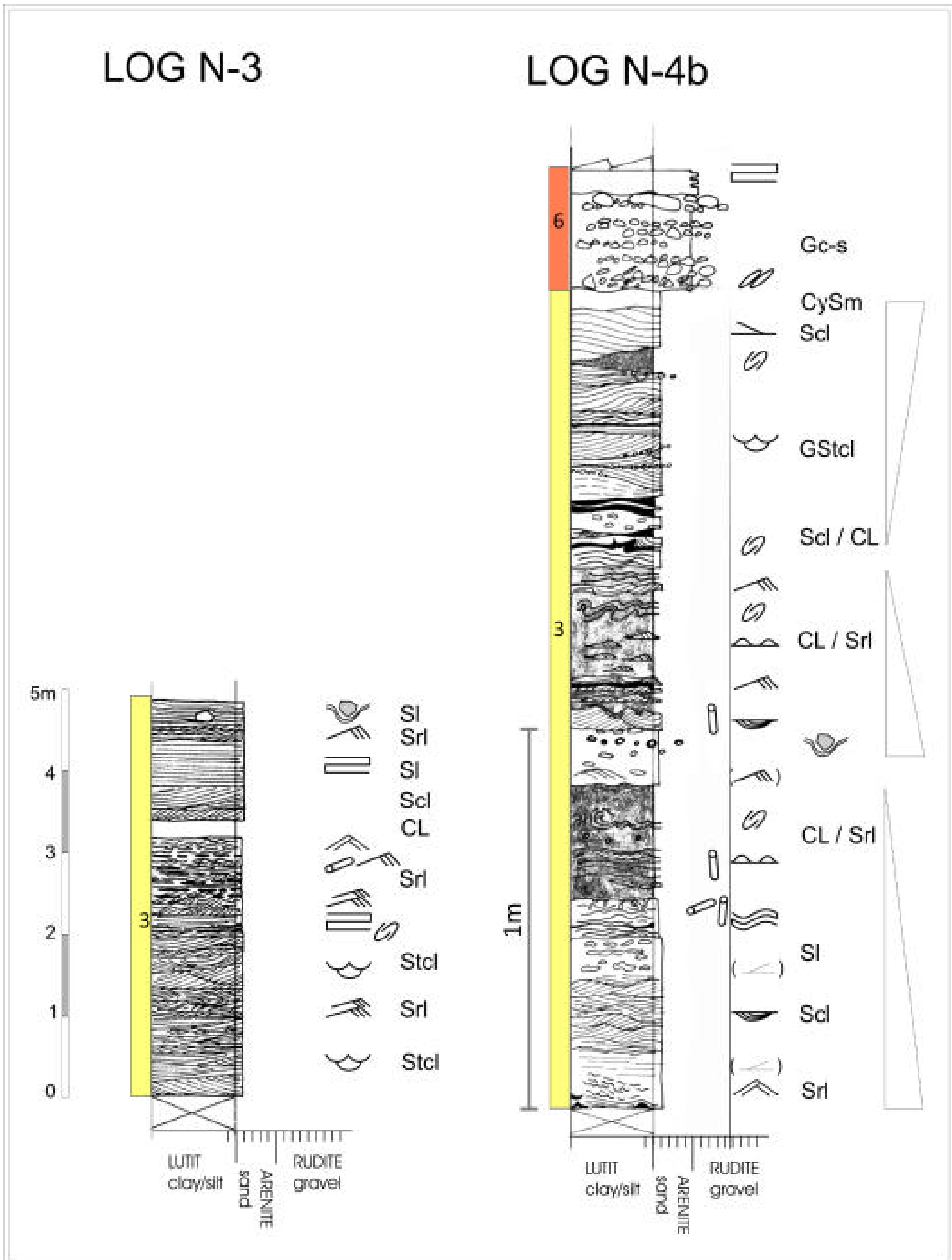


Figure 15. The sediment log N-3 and a detailed log N-4b present the younger part of the glacilacustrine allo-unit 3 represented with rippled calcarenites. Correlation of logs is shown in Appendix 5/1. Two fining upward trends, and one coarsening upward trend are visible in the log N.4b. Dropstones occur before the second fining upward sequence, which indicate glacial retreat and thawing phase when IRD are brought into the lake. Thicker cross- and trough-cross laminated calcarenites mark the coarsening-upward sequence, which ends by erosional contact with overlaying glacifluvial deposits.

Figure 16. Linguoidal sediment forms occurring within younger glacilacustrine calcarenite unit may be rill mark accumulation tongues. Both photographs show unidirectional tongues, and arrows indicate flow direction. The largest tongues (photo bellow) are about 1 m long and 20-30 cm wide. Photos taken in 2010.

Figure 17. Larger dropstones occur in rippled calcarenite interval. When settling on the lake bottom dropstones compressed and slightly deformed the bottom soft sediment, producing typical dropstone structure.

glacial push could have caused water expulsion from the lake sediment, and the highly-concentrated flows suddenly froze as they emeerged to the surface and dried. Thus they could have been preserved by early cementation and later burrial with sediment. According to visible unidirectional or centrifugal distribution of these accumulation tongues, it is possible that all described processes took a role. In the same zone also occur larger dropstones with typical dropstone structure (Benn & Evans, 2010) (Fig. 17). Some are faceted and rounded, and some are of irregular shape, but all span in diameter between 10 - 30 cm.

GLACIFLUVIAL SEDIMENTS

Glacifluvial sediments studied at the Novigrad section are intensivelly eroded, and isolated sections are preserved along the coastal Novigrad section. Though, fluvial channels and large point-bars are distinctive. The cross-sections through fluvial channels vary from perpendicular to tangential. The widest channel is 22 m across (Fig. 18). The orientation of the point-bar bed-sets indicate on low-sinuosity meandering river, which migrated laterally with flow direction along the present day coastline.

Fluvial incision eroded different previously deposited glacigenic sediments of Novigrad, including a pedogenic complex. Thus fluvial sediments are in contact with glacilacustrine sediments, older subglacial tills or glacial outwash sediments. The visible depth of erosion is up to 3 m.

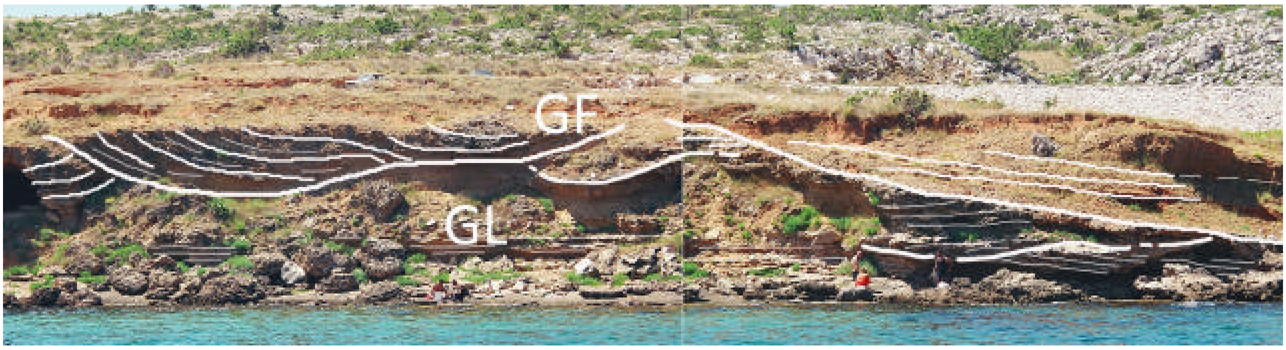


Fig. 18. Glacifluvial sequence (GF) of the Novigrad section. Fluvial channel are incised into glacilacustrine unit visible in the middle. The sediments are trough-cross and planar-cross bedded calcarenites and calcirudites. Superimposed channels are result of lateral migration of the channel. See reconstruction in Fig. 5.169/2, Section Novigrad 6-7. Photo taken in 2003.

The fluvial sequence of the Novigrad section is represented with planar-cross bedded and trough-cross bedded coarse-grained calcarenites and fine-grained calcirudites; the angle of bedding depends on the orientation of the cross-section in relation to the channel strike. Pebble and cobble size gravel occurs locally at the base of a channel fill, composing channel-lag conglomerates. The channel cross-beds, often tangetial and striking parallel to channel flow orintation, are interpreted as point-bars.

The channel fill deposits exposed in a profile cross-cutting the channel (Fig. 19.) give better insight in sediment structures. This cross-section shows 22 m wide assimetrical channel, which was filled by lateral accretion of the point-bar. The upper portion of the channel sediments is eroded, so initially, the channel was much deeper and wider. At bottom of sigmoidal cross-beds occur small sand dunes perpendicular to their strike as shown in line-art in Figure 18. Abundant rhizoconcretions indicate that point-bar was frequently vegetated. At the channel bottom there is a lenticular bed of massive to lminated gray silty clay up to 10 cm thick. It was deposited from suspension in quiet water ponded at the channel bottom after its incision, before the point-bar growth. Clay sediments overlays a

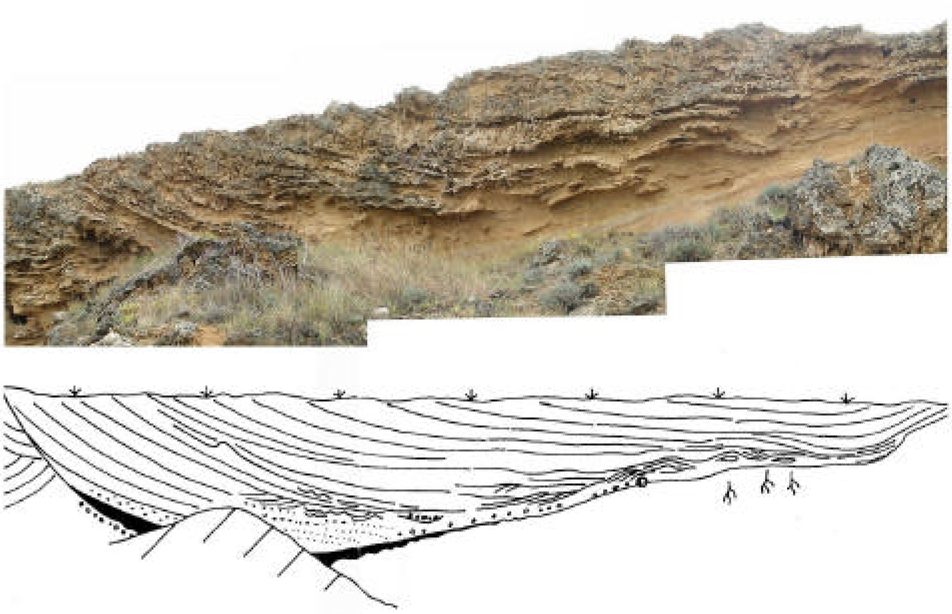


Figure 19. Fluvial channel fill deposits in cross-section nearly perpendicular to the channel strike. Accretion of point-bar cross-beds gradually filled the channel. Selective cementation of coarser-grained layers made good distinction of bedding. Vertical rhizoconcretions are common on nearly each horizon. Detail of the cross-section is shown in Figure 5.164. Photo taken in 2006.

redish paleosol horizon with Fe-Mn nodules 5-10 cm large, which indicate a longer period of stagnant water and low oxigenation, corresponding to sedimentation of grey clay. Rare fossil rhizoids visible in the paleosol indicate paleo-vegetated surface, probably with grass.

At only one location the glacifluvial sediments overlay the younger Novigrad till (Novigrad Member). There it contains a lot of boulder-size debris, which could be indicative of initially a terminoglacial environment.

Figure 20. Glacifluvial outwash deposits (GO) overlaying the older Novigrad moraine (M1) and underlaying the glacilacustrine deposits (GL). There is a cross-bedded gravel bar bellow. Above are horizontal to low-angle planar bedded gravels and sands, the sheet-flood deposits. Photo taken in 2010.

An earlier stage of glacifluvial deposition is represented with planar cross-bedded gravel (calcirudite), low-angle planar cross-bedded sand and gravel (Fig. 20), trough-bedded coarse-grained sands (calcarenites) and trough cross-laminated gravelly calcarenites (Fig. 20). The sediments are well cemented except the trough-bedded calcarenites. The coarser sediments deposited during high yield of debris and high melt-water energy to transport gravel on the outwash plain, forming gravel bars and channel-fills (Fig. 21). Higher discharge and velocity of glacial melt-waters produced planar low-angle gravel flood-sheets topped with thiner sand layers, locally rippled as the flow velocity decreased. Trough-bedded and trough-laminated sands and gravels deposited in shallow channels of braided strams on the outwash plain.

These sediments were deposited above the older Novigrad moraine (Paklenica Member), and as locally visible, underlay glacilacustrine deposits (Fig. 21).

Figure 21. Braided stream deposits, fully cemented. Nice hummocky gravel bars are developed bellow trough-cross laminated gravelly coarse sand (pebbly coarse-grained calcarenite). There is a horizontal cavern bellow of lenticular cross-section. Layers of calcite crystals that grew at the cavern bottom were dated by uranium series and yielded ages 121 ky and 110 ky BP (see Chpt. 8). Photo taken in 2010.

PROGLACIAL AND PERIGLACIAL LANDFORMS

POSSIBLE ICE-BERG SCAR FILL

At several locations at Novigrad Section, within glaciolacustrine sediments, occur sedimentary features resembling an ice-berg scar fill (Fig. 22, 23). The coarse-clastic sediment fills of irregular shape occur in the younger glacilacustrine sandy unit, and consist of gravel to cobble size debris with a lot of bauxite debris. Bauxite occurs at K/T boundary and is exposed at many locations in northern Dalmatia. Bauxite was eroded and drifted by ice, and during ice retreat phase, there must have been ice-bergs grounding on the glacial lake bottom, scaring the bottom and filling with the debris.

Figure 22. Cavity within glaciolacustrine sediments filled with coarser material, probably originated as an iceberg scar fill.

Figure 23. The same feature as in Fig. 22. These are found at several locations within glacilacustrine interval at Novigrad Section.

SEDIMENT WEDGES (ICE-WEDGE CASTS)

The sediment wedges are common feature at the Novigrad section. They are interpreted as ice-wedge casts according to their morphology and structure, and associated facies. The sediment wedges occur at three different horizons, and are probably of different age too. At the first horizon they are in glacilacustrine sediments, in the second horizon they are related to the younger Novigrad moraine M2, and in the third horizon they occur in glacifluvial sediments. Few wedges penetrated very deep, from paleosol to older Novigrad moraine M1 (Fig. 24).

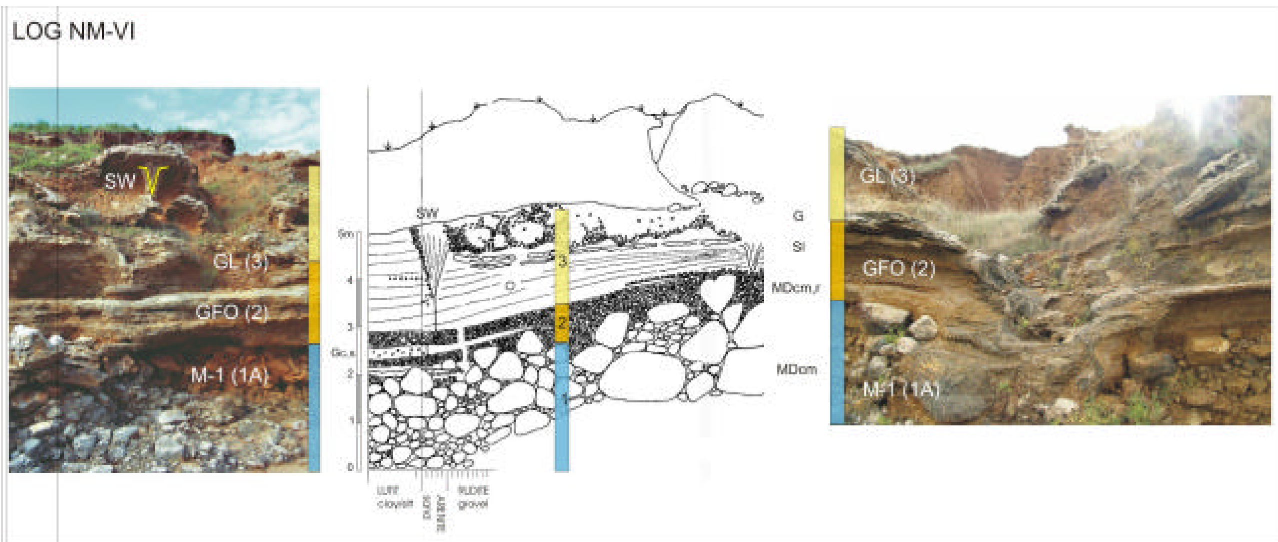


Figure 24. Sediment wedges in glacifluvial and glacilacustrine host-sediments. The one on the left is a smaller cemented wedge cast composed of fine-grained diamict. On the right, there is a very large wedge with unconsolidated infill that was more-or-less eroded. This wedge penetrated down to level of moraine-1.

Figure 25. Sediment wedge in flat-pebble conglomerates of the glaciofluvial unit. The wedge is filled with finegrained cemented calcarenite with dispersed flat pebbles. The walls are cemented and clearly marked by a zone of subvertically oriented flat pebbles. Photo taken in 2007.

Their size, shape and sediment fill is greatly variable. The width as well as the depth of sediment wedges spans from a few tens of centimetres to several meters. They are wide or narrow V-shaped in vertical cross-section, and are elongated or irregular, as well as circular in plan view.

Host-sediment to most wedges are laminated calcarenites of either lacustrine or fluvial origin. Bending of laminae or stratification downwards along the wedge margins is commonly visible, but locally they are cut strait by the wedge. This characteristic is rarely visible in coarse-grained host-sediment as in the case of flat-pebble conglomerate, where flat pebbles are vertically resorted along the wedge walls (Fig. 25). The sediment wedge margins are usually well defined, and the infill is frequently subvertically "striated" (cf. Washburn, 1973) at least near the margins, and sometimes seem massive. The sediment fill is different from one to another wedge, varying from fine-grained calcarenite or pebbly calcarenite to coarse-grained rudite (pebble- to cobble-size gravel, or bouldery diamict), thus they can generally be grouped as fine-grained and coarse-grained wedges. The wedge infill depends on type of sediment that was deposeted above ice-wedges before they melted. So, some large wedges have paleosol inside (Fig. 24 right). A common characteristics of nearly all fine-grained sediment wedges is that sediment fill is well cemented, or just walls of the wedge are cemented and they are found hollow inside. Few wedges do not have any marginal cemented sediment, but are recognized just as cemented clacarenite dike with "fluidal" surface morphology (Fig. 26). The wedges with coarse sediment infill do not have

Figure 26. Fine-grained sediment wedge in Novigrad moraine-1, composed of calcisiltite and shows "fluidal" structure. The age of associated calcite cement is dated by U-series as of 146 ka BP.

Figure 27. Sediment wedge, ca 2 m deep, in glacilacustrine sediments bellow the younger Novigrad moraine-2. The wedge is filled with unconsolidated gravelly calcisiltite. The wedge walls are clearly marked with a cemented zone due to easier water percolation along the wedge walls. The overlying moraine eroded lake sediments and part of the wedge. Photo taken in 2006.

Figure 28. Sediment wedge in glacilacustrine sediments bellow younger Novigrad morane-2. The wedge is filled with coarsegrained matrix-supported diamict, possibly moraine material. There is clear margin between laminated lake sediments and the wedge sediment. Photo taken in 2006.

cemented margins, but they are defined by sharp change in grain size between the host-sediment and infill (Figs. 27, 28). The coarsest infill is a clast-supported diamict composed of small boulders up to 20 cm in diameter, and very little sandy matrix.

The sediment wedges are associated with other types of proglacial deformations like various collapse structures that could not be defined due to degraded outcrops. In the upper horizon of the flat-pebble conglomerates, which is also the top level of the sediment wedge, occur sediment deformations, probably caused by gelifluction during presumably fast thawing of ice-wedges under sediment. Above the older Novigrad moraine-1 and close to the base of the large sediment wedge shown in Figure 24, occur dish-structures that are interpreted as cryoturbation. These characteristics clearly indicate an ancient proglacial to periglacial environment. The large wedges and collapse structures, as well as kettle-forms described later, can possibly resemble a period when occured transition from proglacial to periglacial climate, and after a period of ice-wedge thawing. The chornology is not yet clear, although the sediment wedge in Figure 26 is older than 146 ka BP as indicated by U-series age of the calcite cements associated with the wege.

CRYOTURBATIONS

Dish structures about 30 cm in diametre are visible at a single horizon (Fig. 30) within glaciofluvial outwash gravel deposits above the older Novigrad M-1 moraine, the Paklenica Member . They are interpreted as cryogenic structures, which formed at the beginning of deglaciation when it was still cold enough for water to freez within water-saturated gravel sediment.

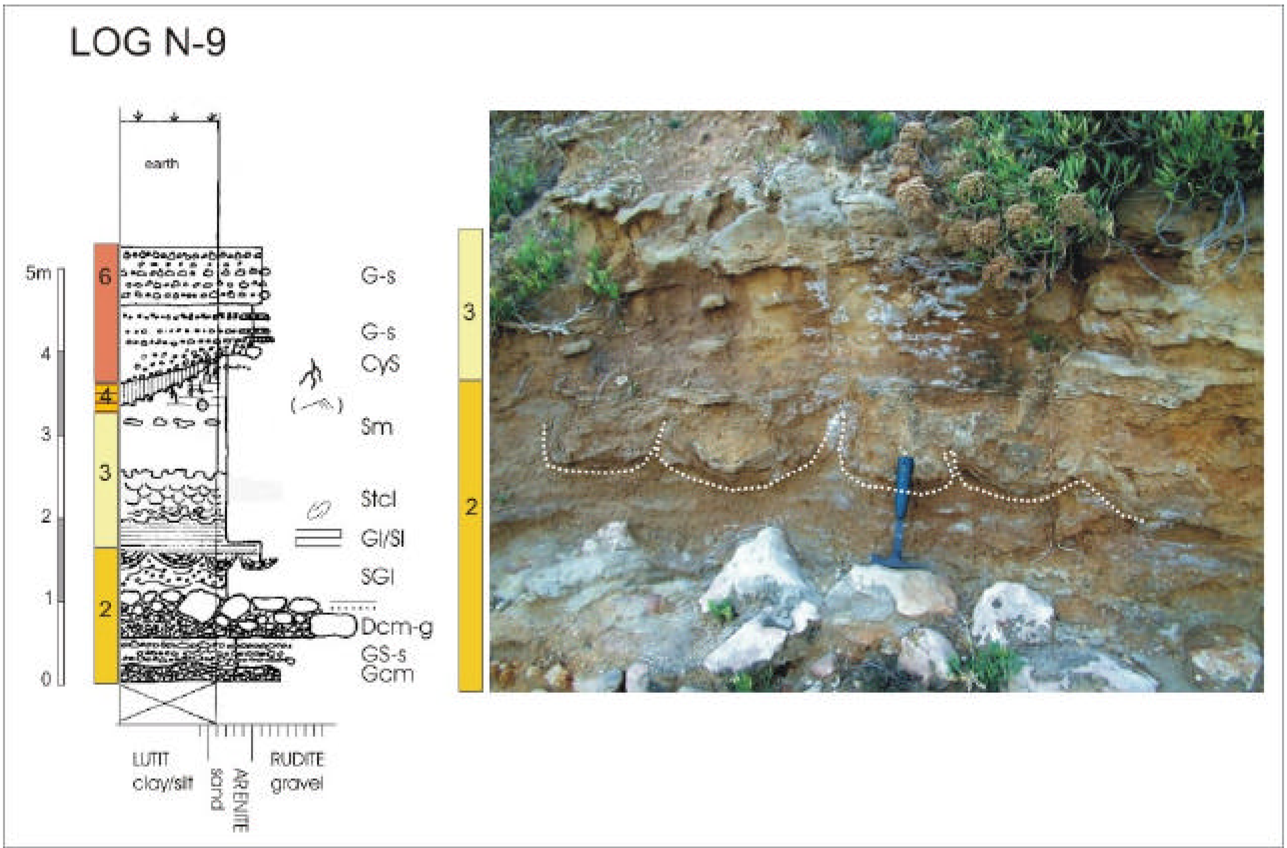


Figure 30. Dish structures in glacifluvial sand-gravel sediments above the older Novigrad moraine M1. The structure is interpreted as cryoturbation, which indicates an interruption in sedimentation. Photo taken in 2006.

Figure 31. Flat pebble conglomerate is exceptional gravel deposit and occurs only at Novigrad section. It represents fluvial beach deposit. There is one of few distinct intervals with steep imbrication to vertical orientation of flat pebbles, probably caused by ice frosting.

Freezing effects are also visible in flat-pebble conglomerates, which are probably represent river beach deposits. There are several horizons with steep to vertical orientation of flat pebbles, which is only caused by freezing of pore water causing reorientation of clasts (Fig. 31). Cryoturbation effects in this conglomerate is probably related to sediment wedges (ice-wedge casts) in glaciofluvial allo-unit of Novigrad Section, both indicatin another cooling phase.

KETTLE-FORMS

Kettles are by definition rounded collapse structures formed by melting of burried ice blocks, and commonly filled with collapsed sediments. The fossil kettle-forms at the Novigrad section were first described by Marjanac et al. (1990). They are very simillar to modern kattles, but not all their characteristics are preserved, they are herein described as "kettles" *sensu lato*. They can be observed at several location in length of about one kilometer along the Novigrad Sea coast.

Kettles are circular dish-like depressions, one to three metres across and 0,5 - 1 m deep (Fig. 29). They are restricted to the upper interval of the ripple-laminated calcarenites in the glaciolacustrine allo-unit3 of the Novigrad section, which is exposed at the SW part of coast.

Kettles occur isolated, but also "grouped" and even stepwise connected. Their walls are subvertical or overhanged, while their bottoms are more-or-less or concave, but also flat (Fig. 29). Kettles are commonly found hollow, sediment-empty, probably due to holocene erosional processes. The walls as well as the bottoms are composed of the well cemented fine-grained calcarenite appearing to be of chaotic massive structure. In the centre of two kettles there is a cemented "heap" of calcarenite (Fig. 29). Only one kettle-form is exposed in vertical cross-section where its concave bowl-shape is clearly visible, and also the cemented chaotic structured clacarenite of the "bowl".

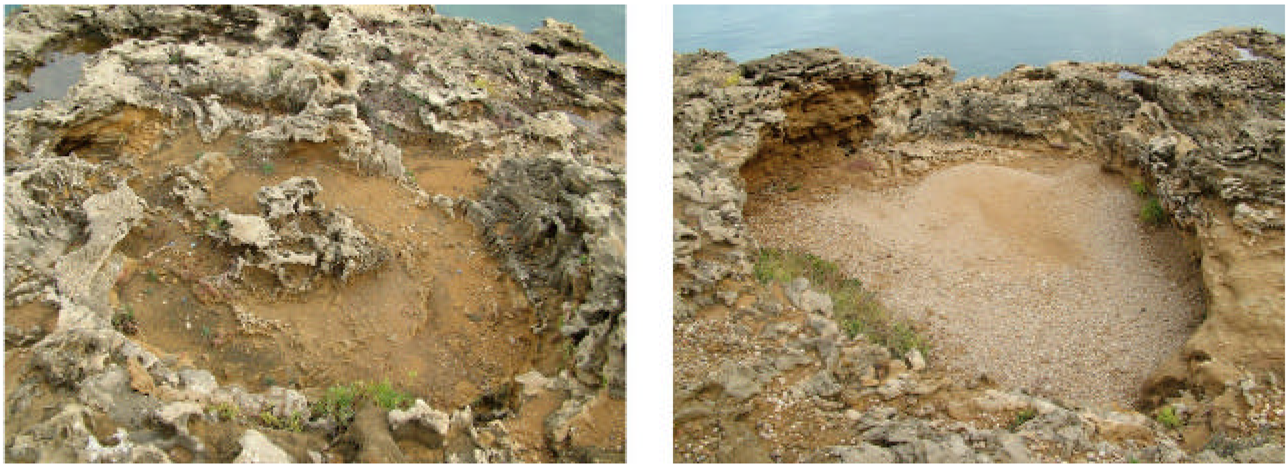


Figure 29. Circular kettles. The flat bottoms are cemented finegrained infills.

Noticeable characteristic of the kettles are linguoid structures radially oriented along the kettle rim, commonly showing centrifugal dispersion of sediment. They are about 10 - 30 cm long. Exceptionally large ones (Figs. 16) are found in form of ca 10 m long sheet of deformed sediment at the sea level bellow the sandy lacustrine interval. Such linguoid structures were evidenced by Bishop & Lindqvist (1987) as sand fingers or ephemeral mass-flow features resulting from rapid dewatering of sand-water suspensions by infiltration into porous substrate. This process could have occured by gelyfluction due to sudden ice-block thawing, which was burried in sandy lacustrine sediments.

The ripple-laminated interval of the glacilacustrine unit is interpreted as of rather shallow proximal proglacial lake, thus many grounded and later buried ice-blocks could have existed in this zone. As the ice receided, lake gradually dried out and a proglacial zone turned into a temporary permafrost area with a lot of buried ice. Such situation corresponds to proglacial subenvironment of continental glaciation as modeled by Brodzikowsky & van Loon (1991) showing a periglacial environment that includes terminoglacial, proglacial and extraglacial subenvironment.

Location 4 - K A R I N

Topics: GLACIGENIC SEDIMENTS (glaciolacustrine, till), SUBGLACIAL DEFORMATIONS, TUFFA DEPOSITS

GLACILACUSTRINE SEDIMENTS

Glacilacustrine sediments exposed near Karin are laminated calcisiltites (marls) to fine-grained calcarenites. Their visible thickness along the coast is only 30 - 60 cm, because the base is not exposed. These marls are light yellowish-grey colored, with fine parallel varved-like lamination , similar to Ždrilo but not so contrasting and distinct. Ostracods are common in marls. The glacilacustrine sediments were eroded and deformed within a shearing zone formed by an advancing glacier (Fig. 3.). Correlation with Novigrad glacilacustrine sequence is not clear, but presumably marls correspond to older unit at Novigrad Section .

Laterally, the glacilacustrine sediment is preserved in greater thickness of ca 3-4 m. It is a younger interval composed of several laminated packages of calcisiltites and calcarenites (Fig. 1). Calcarenite interbeds, which clearly indicate more proximal depositional zone, indicated also by a planar cross bedded package 5 (Fig. 1) that are small Gilbert-type delta forsets. Proximal deposition is also indicated by graded and current-rippled bed (package 2) deposited from a turbidity current, as well as a massive bed with dropstones within package 2. This unit is more likely equivalent to the upper younger interval of the glacilacustrine sequence at the Novigrad section.

After glacial period and postglacial erosion these deposits were overgrown by tuffa that built a large bioherm, of which only a small portion is preserved (Fig. 2). The age of tuffa is not known, but could originate from the last or one of the previous interglacials, Riss/Wurm or Mindel/Riss.

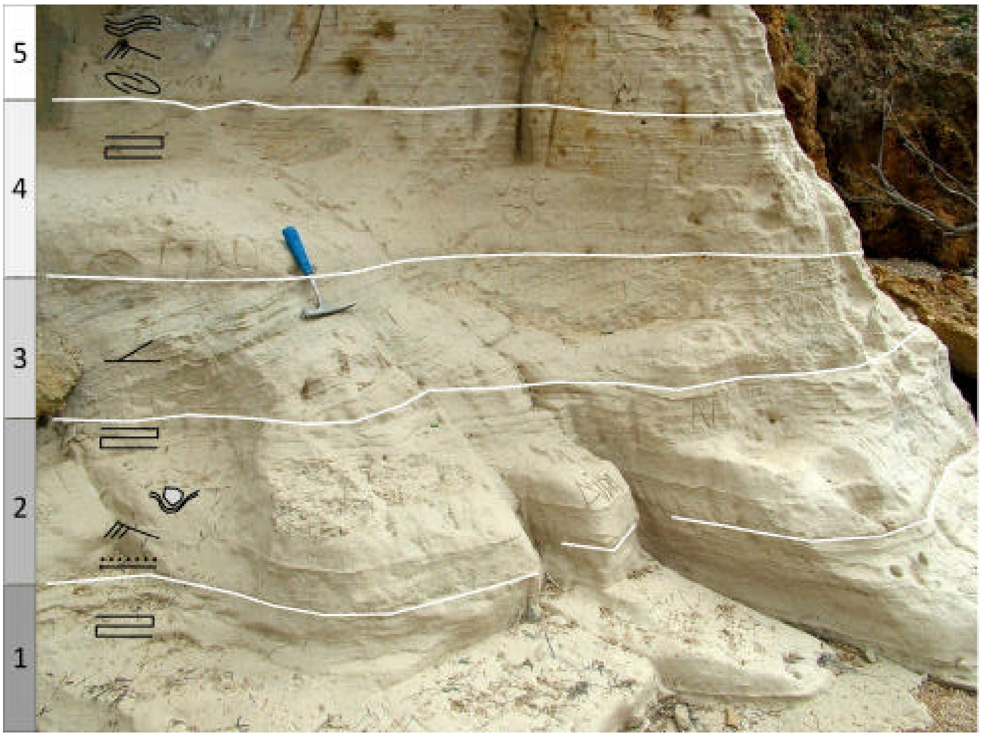


Figure 1. Glacilacustrine sediments at Karin Sea coast, which occur laterally to the other outcrop (Fig. 5.138.). This succession consists of five sediment packages separated by clear boundaries: 1 - horizontally bedded (marls) composed of laminated and massive layers; 2 - a package consisting of graded fine-grained gravel bed with ripples, massive marl layer with dropstones, and parallel laminated siltite; 3 - planar-cross bedded package that consists of alternation of calcisiltite and 1 - 3 cm thick calcarenite beds; 4 - vaguely to clearly horizontally laminated calcisiltite and fine-grained calcarenites; 5 - a composite package with synsedimentary soft-sediment deformations and wave and current ripples in the lower part, and parallel horizontal to wavy laminated siltites and fine arenites. The sedimentary characteristics indicate proximal depositional environment of the paleolake. Photo taken in 2008.

Figure 2. Erosional remnant of a large tuffa bioherm/barrier that grew over erosional surface of the glacilacustrine sediments. Photo taken in 2008.

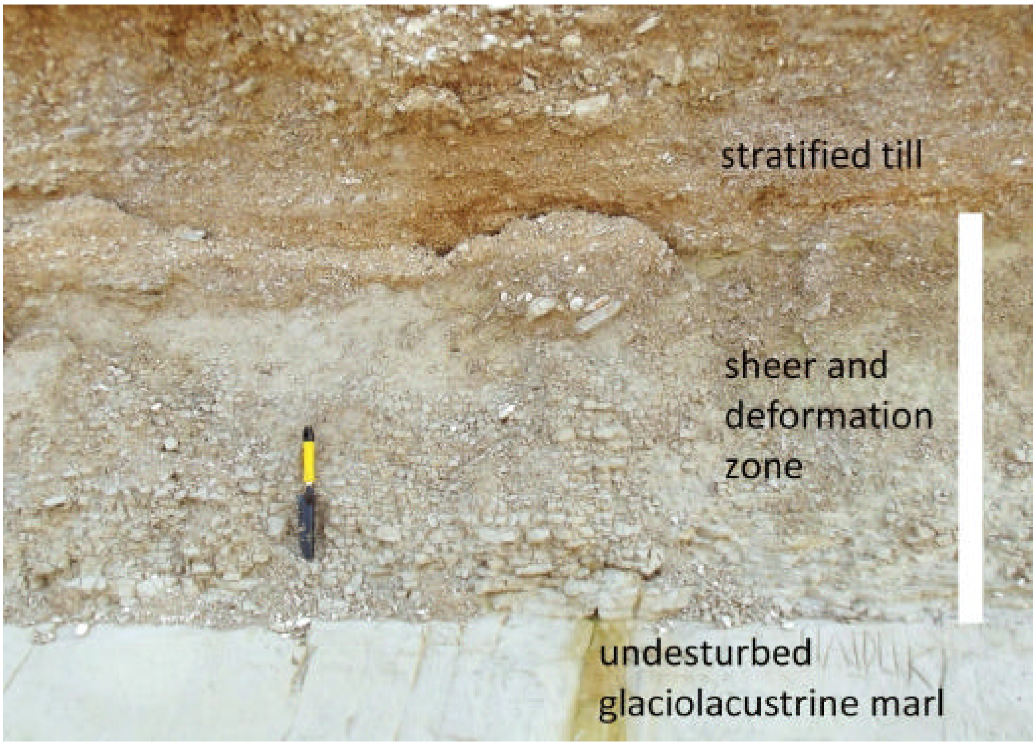


Figure 3. The Karin till is a matrix-supported diamict (Dmm) with more matrix in lower part closer to underlaying glaciolacustrine sediments. Sediment is unorganized and clasts are randomly oriented. There is less matrix in upper part. Photo taken in 2006.

KARIN TILL

Diamict sediment exposed at the Karin section (Fig. 3) is interpreted as subglacial till and based on its characteristics and location it probably belongs to the Novigrad Member. This till is a semi-consolidated matrix-supported diamict lithofacies (Dmm). It lays over glaciolacustrine laminated sediments. There is no sharp contact, but a very distinct transitional mixing zone, where subglacial debris was mixed with the underlying soft glaciolacustrine deposit and oriented flame texture or loading is visible. Therefore, the percentage of matrix decreases upwards, being dominant in lower part of till interval and indistinct in the upper part. Average clast size is 1-30 cm.They are variously shaped, platy, splinter or sphaerical. Bullet shaped (Fig. 4) clasts are rare. The clast orientation is very random, but above the mixing zone appear clusters of imbricated clasts (Fig. 5). Effects of shearing are visible in marl clasts (Fig. 6) due to movement under pressure in subglacial zone. The same is indicated by in one direction oriented flame structures (Fig. 5). Deatailed measurement of clast orientation has not been done yet, so the ice movement direction was tentatively southwestwards. Both till and glacilacustrine sediments were largely eroded in postglacial phase, so the real thicknesses can not be even estimated.

Figure 4. Till loaded into underlaying glaciolacustrine sediment. There is a bullet shaped clast, much larger than other clasts. Photo taken in 2006.

Figure 5. Karin till overlays glaciolacustrine laminated sediment (marl). Mixing zone with oriented flame and load texture is visible. In upper section till is better sorted, poorly stratified, and there are clusters of imbricated platy clasts. Transport and push direction from left to right. Photo taken in 2006.

Figure 6. Glaciolacustrine sediment is at the bottom. Loading and shearing occured in the mixing zone. Sheared clast is on the left. Photo taken in 2006.

Location 5 (optional) - OBROVAC

Topics: Moraine of Paklenica Member

The mega-diamict lithofacies (MDcmm) interpretid as till is recognized as the Paklenica Member based on all typical characteristics. The diamict is a semiconsolidated sediment. It is exposed at the roadcut section near the Obrovac town. It is unsorted to poorly sorted, and consists of large clasts "floating" in poorly cemented coarse-grained (gravel-size) matrix. The clasts are commonly medium- to well-rounded, elongated to subsphaerical, and range in size from gravel of 20 cm to blocks of several meters across, with no particular orientation. Exceptional are mega-blocks measuring 5 m to more than 15 m in longer axis (Fig. 7, 8). Lithologically, the clasts and blocks are derived from Tertiary (Oligocene) carbonate clastics - the Promina-conglomerates. The contact with bed-rock is not visible, and the sediment is additionally tectonized, with several minor subvertical faults visible.

Figure 7. The mega-block, at least 10 m across, is derived from thick-bedded Promina-conglomerates which built large part of Norther Dalmatia. The block's bootom surface is polished and grooved. It lays in coarsegrained matrix abound in rounded and striated boulders. Photo taken in 2008.

All large clasts and blocks have glacial striae on all their surfaces (Fig. 10). The striae are differently oriented, some are long and straight, some are short, curved or straight. They are mm-size shallow grooves, commonly tightly spaced and grouped as sub-parallel striae. Some groups of striae are mutually crossed at sharp angles. The curved striae indicate rotation of the block, whereas the straight ones indicate block sliding over hard substrate. Ice-shatered clasts also occur. Fractures and dislocation along shear planes document transport under pressure.

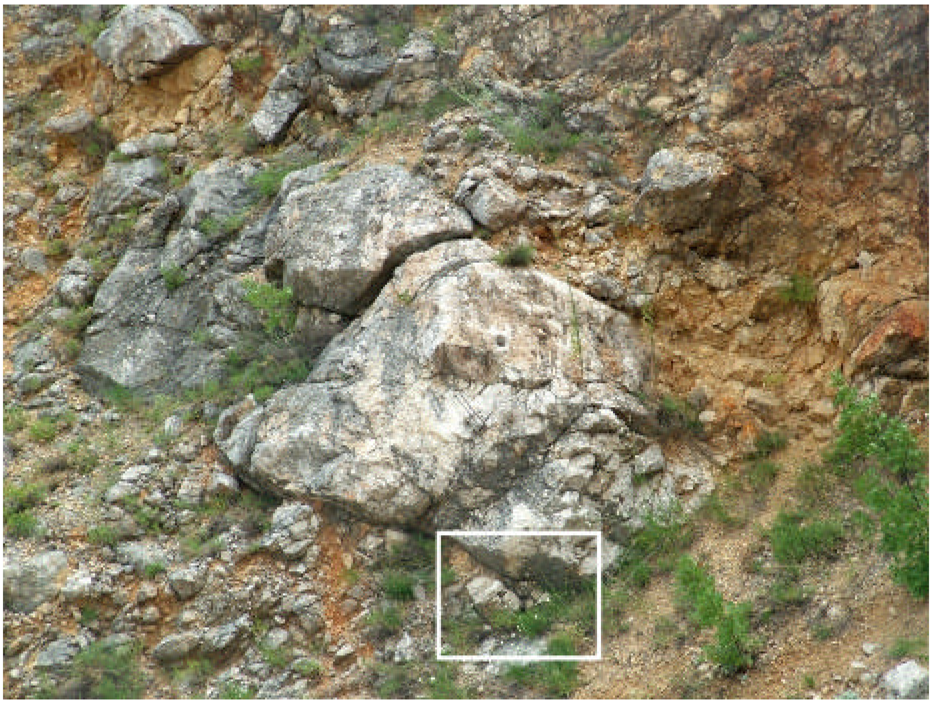


Figure 8. A rounded and fasetted mega-blok (2-3 m x 7 m) with polished bottom surface. It derives from Promina-conglomerates, and its roundness and polished surfaces indicate longer subglacial transport. Diamict arround it appears as coarsgrained matrix. Many boulders are ice-shattered and crushed (Fig. 9). Photo taken in 2008.

Figure 9. Detail framed in Figure 5.106. shows rounded ice-shattered boulder. Coarsegrained matrix inbetween consists of subangular to rounded debris and sandy matrix.

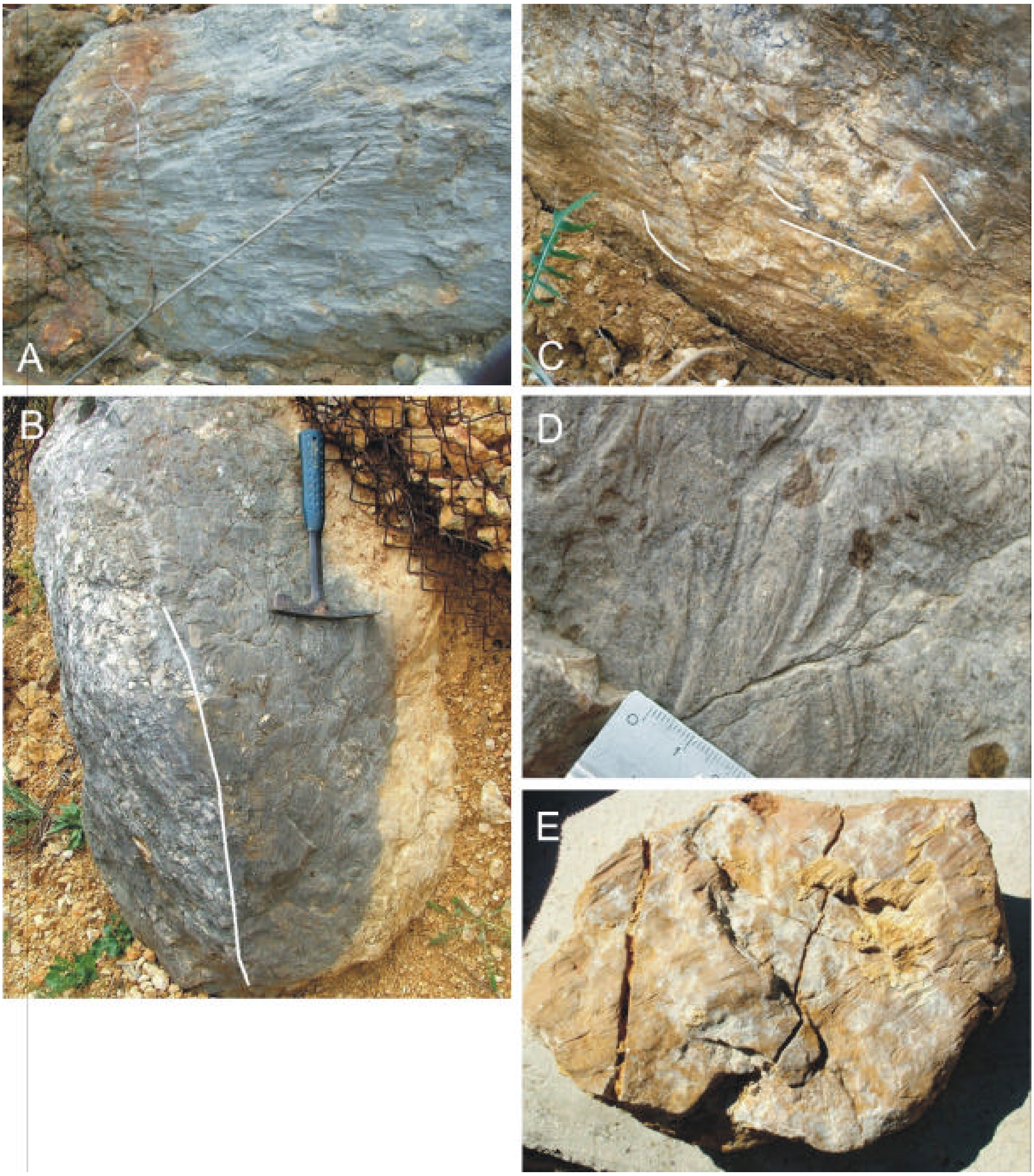


Figure 10. Lithoclasts with glacial striae and grooves found in the Obrovac moraine. All boulders are from the Promina-beds (conglomerates are A, B, C, D; micritic limestone E). A - boulder with straight glacial striae focused to left zone indicating transport from right to left; B - ice-fasetted and polished boulder with three systhems of striae on each side of the keel (white line); C - detail of the left side of B boulder with straight striae and grooves in two different orientations, and arched striae; D - detail of the right side of B boulder with predominant arched striae; E - ice-shattered and striated clast. Photos taken in 2006.

Location 5 - ŽDRILO

Topics: GLACIGENIC SEDIMENTS (glaciolacustrine, till), GLACIOTECTONICS (macro and micro), PALEOSOLS

Ždrilo area is in the Northern Dalmatia, located on the southwest side of the Velebit Channel oposite to Seline and Starigrad-Paklenica. Pleistocene sediments are preserved in small coves north of the Ždrilo village. Only glaciolacustrine sediments are in Poljica cove (Fig. 1), both glaciolacustrine and glacial deposits (moraines) (Fig. 2) are in two coves, one westwards and another eastwards. Milojevic (1933) recognized lacustrine sediments as of Pliocene age. The U-series age 339,6 ka of calcite cement from the overlying moraine tels that these glacilacustrine sediments were deposited during Middle Pleistocene or earlier.

Figure 1. A coastal exposure of Pleistocene glaciolacustrine sediments preserved in a cove near Ždrilo village. . Photo taken in 2009.

The Ždrilo sites with till and glacilacustrine sediments are unique sites and deserves protection as a geoheritage sites, though lacustrine sediments are easily eroded, thus their protection is hard. Abundance of plant macrofossils makes them very valuable. Fossil leafs were found here for the first time and are still studied (Adžic 2012, Adžic et al 2013). Sediments are considered Middle Pleistocene or possibly Early Pleistocene. Their age is assumed acording to 347 ky minimum age of the overlaying moraine.

Figure 2. Paklenica Member at the Ždrilo section. Left from people are visible glacilacustrine sediments, significantly deformed and mixed with morainal debris.. Photo taken in 2010.

GLACIAL SEDIMENTS (Paklenica Member)

Ždrilo is onother significant locality for glacial interpretation of mega-diamicts and definition of the Paklenica Member. The exposure shows glacially deformed glaciolacustrine varved sediments bellow and the mega-diamict with megablocks above (Fig. 2), with very irregular contact. It is actually a mixing zone where mega-blocks occur enclosed in previously deposited glaciolacustrine finegrained sediment and also mega-blocks (ripup clasts, Fig. 3) of semi-consolidated

Figure 3. The Ždrilo site. The overriding glacier eroded glaciolacustrine sediments and produced rip-up clasts visible within mega-diamict deposit (tillite). Visible size of the clast is 3x12x5 meters. Photo taken in 2011.

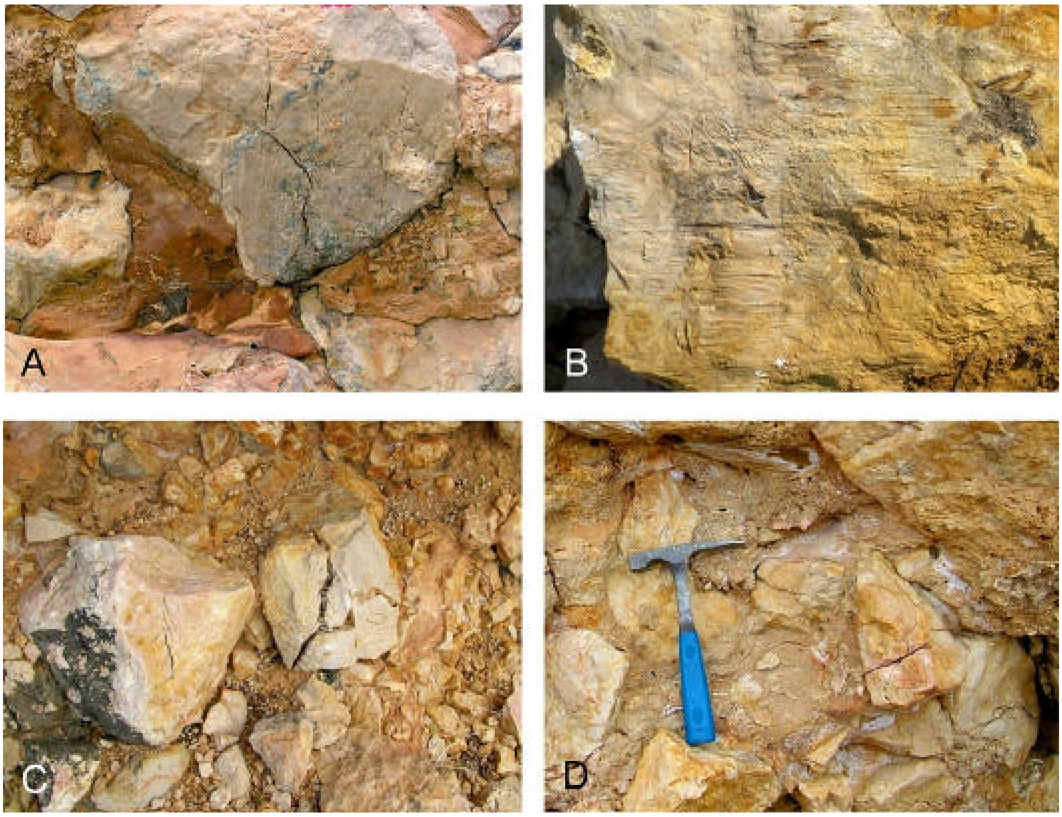


Figure 4. Lithoclasts of the Ždrilo mega-diamict are polished (A), striated (B) and ice-shattered (C, D). Photos taken in 2011.

lacustrine sediment enclosed in mega-diamict. This chaotic sediment is subglacial till accumulated during a phase of glacial advance. Many ice-fasetted, polished, striated and ice-shattered clasts occur in the Ždrilo mega-diamict (Fig. 4) that is rather well cemented with a lot of calcite filled voids. The U-series dating of the calcite yielded minimum age of till at 339.6 ka BP.

GLACILACUSTRINE SEDIMENTS

Glacilacustrine sediments of the Ždrilo section are typical varved sediments (varvite lithofacies, Fig. 7), composed of alternating clay and silt laminae representing annual winter-summer cyclicity. Estimated thickness of sediments is about 20 m. They are steeply inclined (Fig. 5 left) and tectonized due to glacial push, which is also indicated by frequent small scale soft-sediment deformations (Fig. 5 right).

Varve sedimentology was not studied yet in detail, but numerous plant macro fossils were collected and determined by Adžic (2012), who also studied varves in 1 m thick interval.

Adžic (2012) determined the fossil leaves and found prevailance of *Taxodium* sp. (Fig. 6). Leafs of *Quercus* sp. and *Zelkova* sp. were also frequent, and those of *Castanea* sp., *Acer* sp., *Fagus* sp., *Liquidambar* cf. *europea*, *Buxus* sp., *Pterocarya* sp., *Tilia* sp., and fruit of *Ulmus* sp. were rare. Species like *Taxodium*, *Zelkova*, and *Liquidambar* are not found any more in this region.

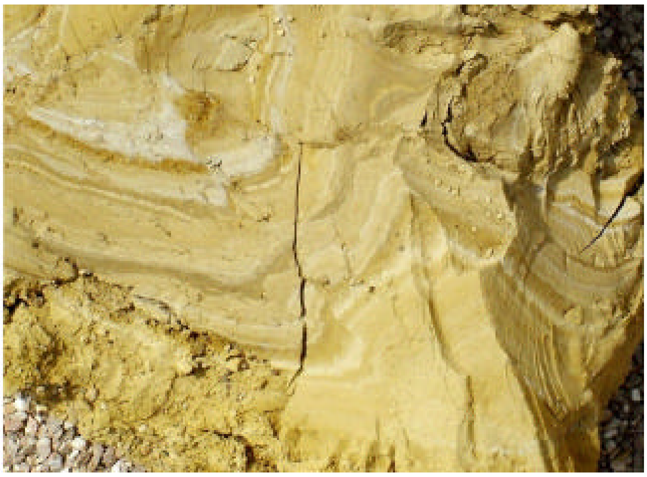


Figure 5. Varvites at Ždrilo section are inclined at 30° - 70° and dip southeastwards, as shown on the left. Frequent small-scale deformations like faults and folds are visible in the sediment (right), produced during glacial advance. Photos taken in 2011.

Figure 6. Fossil leaf of *Taxodium* sp. Scale is 5 cm.

Varves, both dark and light-coloured laminae contain well preserved juvenile and mature ostracods. Hajek-Tadesse (personal communication, 2010) determined the following species: *Scottia pseudobrowniana* Kempf, *Candona neglecta* Sars, *Eucypris* sp. (juvenile form), *Pseudocandona hartwigi* (G.W. Müller) and *Mixtacandona*?, *Paralimnocythere* cf. *psammophila* (Flössner).

Varvite

An alternation of clay and silt to very fine-grained sand laminae are defined as varved clay-silt or varvite. Generally, varves are rhythmic alternation of clay and silt to fine sand laminae. The term "varve" resembles layers in periodical repetition and was first used in 1862 by Gerard de Geer (Zolitschka, 2007), who defined varves as annual cycle composed of coarse-grained light colored summer lamina and a fine-grained dark colored winter lamina.

The varved clay-silt sediments, just preliminary investigated, occur at the Ždrilo section in Poljica cove. Varvite (Fig. 7) is semi-consolidated (hard when dry) deposit and consists of light to dark brown and rusty brown silt laminae in alteration with white to light grey clayey laminae. The boundaries between silt and clay laminae are sharp, sometimes with developed small-scale flame structures, sometimes marked by erosional surfaces and sometimes marked by bioturbations. In the section studied by Adžic (2012) the silt laminae vary from 1 mm to 10 cm in thickness. The clay laminae are considerably thinner, 1 to 30 mm. Traces of bioturbation are visible at the contact of silt and clay laminae. Silt and clay laminae are in most cases further differentiated which might imply the variation of sediment inflow during their deposition. At the boundary between dark and light laminae

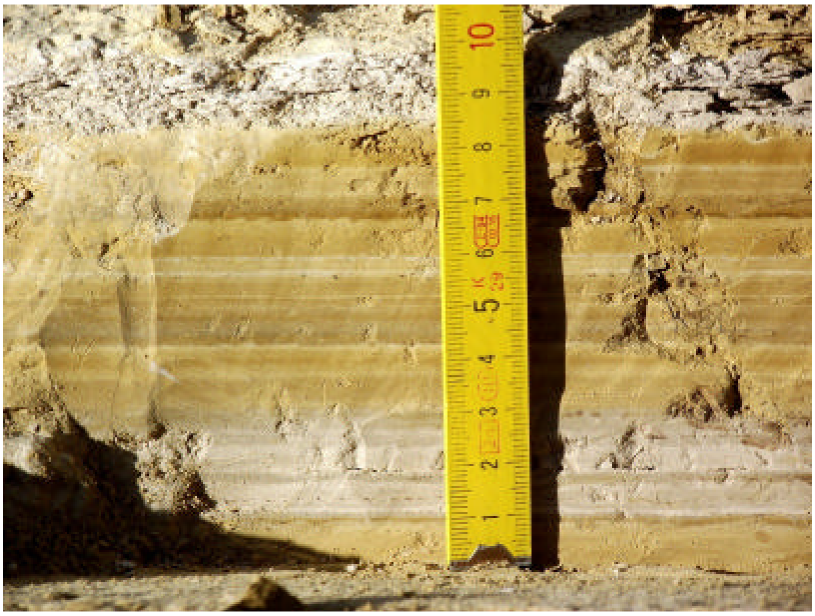


Figure 7. Varvite at Ždrilo section in Poljica cove, which is very finely laminated clay-silt sediment. Thicker light laminae at the bottom may represent longer winters with very short summers, and complex darker varves may reflect longer summers with oscillating weather conditions. Photo taken in 2010.

Figure 8. Glaciotectonically inclined varvite sediments of Ždrilo.

many plant macro fossils are preserved. Adžic (2012) determined more than 70 specimens. In both light grey and brown laminae well preserved ostracods were found and several species determined.

Varvite of the Ždrilo section was deposited in a proglacial lake environment as indicated by dropstones found in varved-like siltites at the Seline section (a proximal part of the paleolake), and overlaying lodgement till (Figs. 2). The light colored laminae represent winter seasons when lake froze and sediment intake was low (only clay), and darker laminae represent summer seasons when sediment (silt and sand) input was much higher due to melt-waters and rain-falls. Thickness variability of both light and darker laminae, and their complexity, may reflect longer or shorter winters, and wetter or dryer summers.

RECONSTRUCTION OF PALEOCLIMATE

The studied succession of glacigenic Pleistocene sediments in Northern Dalmatia allows for reconstruction of palaeoenvironments, sedimentary bodies, and these are utilized for the reconstruction of paleoclimate. The studied sediments are subdivided into several allostratigraphic units (Marjanac Lj., 2012) which reflect depositional pattern as driven by climate changes (Fig. 1). Six informal allo-chrono members are introduced marking either ice-advance or ice-retreat stages.

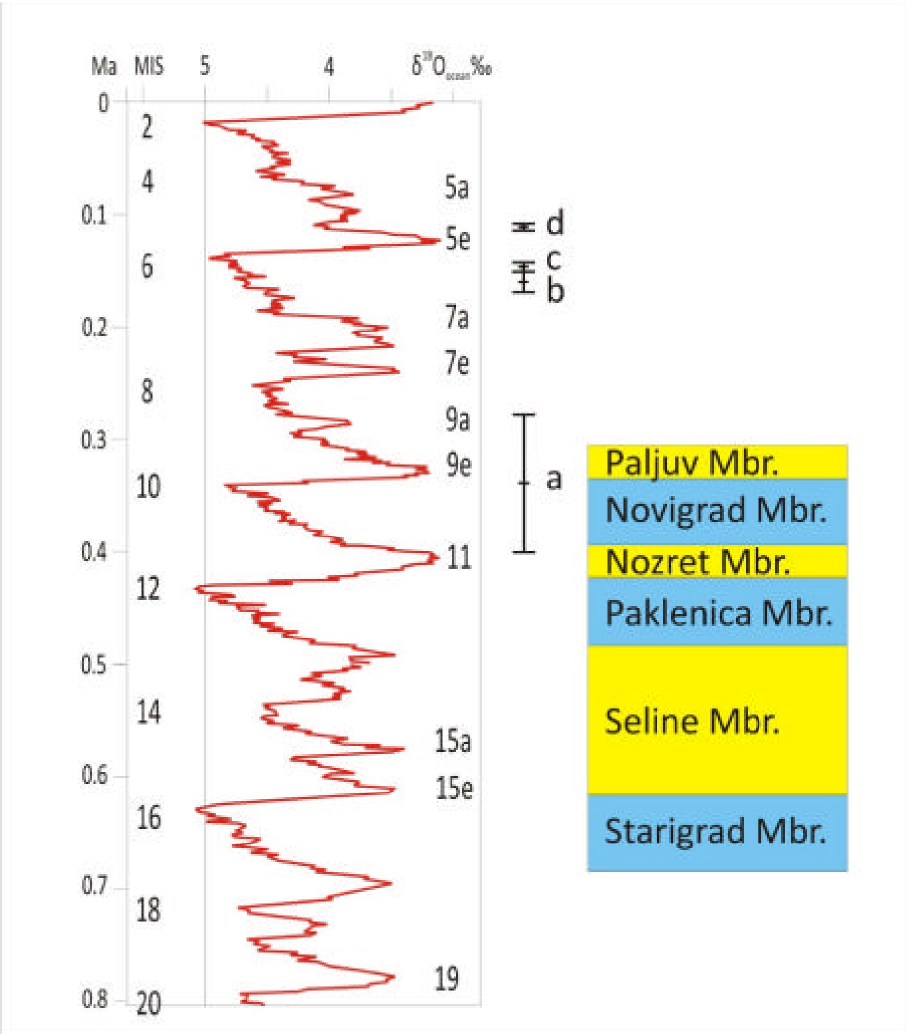


Figure 1. Reconstruction of paleoclimate and allostratigraphic units. Paleotemperature curve and MIS stages are redrawn from Cohen and Gibbard (2011) and Winograd et al. (1992). a) secondary calcite in Ždrilo section moraine dated as 339,7 ± 61,4 ka BP, b) secondary calcite in Paklenica section moraine dated as 159,7 ± 8,2 ka BP, c) cement in an ice wedge fill dated as 146,4 ± 4,4 ka BP, d) cements in the ? paleocavern infill dated as 110,2±3,4 ka BP. Samples **b** and **d** are cements in structures developed in Nozret Mbr. lacustrine silts, thus indicating the age of diagenetic cementation. Numerous ice-wedge infills are found at 3 distinct levels within the Nozret Mbr. indicating tundra-type climate with ? seasonal freezing and thawing of water-rich sediments, possibly permafrost.

First ice-advance stage, Starigrad Member

The earliest ice-advance stage, herein named the Starigrad Member, was the time of major environmental change in the SE Europe. The Adriatic Sea receded for as much as -130 to - 150 m (Van Straaten, 1970; Šegota, 1982) and the newly formed lowlands were filled with fresh-water lakes. The depression of the Adriatic sea-level must have been caused by major expansion of the continental ice (Van Straaten, 1970; Rabineau et al., 2006), which in turn was caused by major change in climate.

The Starigrad Member does not have one type section, but the number of outcrops in environs of Starigrad and Seline settlements provide insight into it's composition. The best outcrops are located along the coastal road in Seline environs, and modern Seline fan delta coastal section (older part of the Seline Section), and isolated outcrops and excavation pits located in Starigrad environs. This informal unit comprises: a) ground moraines (basal tills), b) alluvial fan conglomerates, c) deltaic conglomerates and d) glaciolacustrine silt, which are all exposed along the northern coast of the modern South Velebit Channel and adjacent road-cuts and excavation pits.

The Starigrad Mbr. moraines are exposed in discontinuous exposures along the coastal road-cut between settlements of Seline and Rovanjska, and in excavation at the Starigrad cemetery. Further to the northwest, these moraines are exposed in many road-cuts of the coastal road between Starigrad and Rijeka. Starigrad Mbr. moraines are very coarse-grained diamict with sandy to gravelly matrix, sometimes also openwork with infiltrated terra rossa. The clast size is in range from pebbles to blocks several meters across. Most of coarse-grained clasts are poorly rounded and quite a few bear nice striations on their smooth surfaces. The contact with base-rocks is very sharp. The moraines locally overlie several distinctly different lithologies; micritic limestones of Lower to Upper Cretaceous age, Cenomanian to Turonian limestones, and Paleogene to Neogene Jelar-Breccia (Ivanovic et al., 1973) in the area of southern Velebit Channel between Rovanjska and Starigrad, and Jurassic limestones, Cenomanian to Turonian limestones, and Paleogene to Neogene Jelar-Breccia in the area of central and northern Velebit Channel (Mamužic et al., 1969; Šušnjar et al., 1970).

The contact between bed-rock and basal moraine of the Starigrad Mbr. is an irregular surface with topography of several meters which is leveled by till which infills the available accommodation space. The debris in till lithologically corresponds to the base-rocks, so where Jelar-Breccia occurs in the base, the till comprises predominantly debris of the same lithology, which indicates local source of the coarse debris.

Alluvial conglomerates of the Starigrad Mbr. are exposed in several excavation sites in Starigrad and Seline environs, and in Starigrad and Seline modern fan deltas. These alluvial conglomerates are clast-supported diamicts composed of well-rounded debris in sandy matrix, crudely to well stratified, commonly with partly dissolved clasts. The alluvial debris is compositionally identical in Starigrad and Seline sections, and debris of Permian age indicate transport from distant source in upper part of the Paklenica gorge. Cobbles in the lower part of the unit in the Seline Section are nicely striated which indicates short transport of the debris. The debris of alluvial conglomerates was water-transported from the advancing ice-wedge and deposited in shallow braided fluvial systems on an outwash plain. The outwash plain distally fed an alluvial fan, which was developed at the margin of South Velebit depression during it's filling with water to become a periglacial lake. Thick alluvial unit in lower part of the informal Seline Mbr. represents proximal part of this alluvial fan.

The Starigrad Mbr. sediments are so far undated, but from physical stratigraphic correlation we assume it's age might correspond to MIS 16.

First ice-retreat stage, Seline Member

The first ice-retreat sediments are attributed to informal Seline Mbr. which has type section (Seline Section) at the SE coast of the modern Seline fan delta.

The retreat of glacier ice provided melt water which filled the lake basins. As the lake level rose and standing body of water was established, glacial outwash streams formed succession of Gilbert-type deltas at the lake margin, which are exposed along the central part of the section. The ice retreat was not uniform, but punctuated by several ice-advance pulses, which resulted in the lake-level fall and drainage of delta tops and foresets, some of which developed dessication cracks. The ice-advance pulses pushed terminal moraines close to the lake margin, and slope instabilities at front of the moraine ridge initiated mass flows which deposited matrix-supported gravelly conglomerates atop the deltaic sediments. The renewed ice-retreat provided new melt water which re-filled the lakes and fluvial systems provided debris for construction of new deltas and lacustrine silts which predominate in the South Velebit Lake (Seline and Žegar sections). The deposition during late stage of the South Velebit Lake was strongly influenced by calving of an ice tongue which apparently reached to the lake margin and provided numerous icebergs floating over the lake and releasing dropstones at the Seline section.

The lakes also recorded seasonal changes in temperature and precipitation, particularly in the Ždrilo Section of the South Velebit Lake, which are documented by fossil flora. Fossil leaves in the lacustrine sediments of Ždrilo and Seline sections allowed reconstruction of paleoclimate which preceded the onset of major (second) ice-advance of the Paklenica Mbr. which eventually caused glaciotectonic deformation of the lake margin.

Fossil flora of the Ždrilo Section lacustrine sediments comprises 14 different taxa, but only two have entire margins (Adžic, 2012). The Wolfe's equation yields MAT of the South Velebit Lake hinterland to be 5,51 ± 2,86 EC, whereas Kowalski's equation gives MAT 3,89 ± 2,72 EC. Mean annual precipitation (MAP) was reconstructed after the Rauker-Webb method (Leaf Architecture Working Group, 1999) and the calculated MAP was 679 mm (Adžic, 2012).

Lj. Marjanac (2012) speculated that the Seline glaciodeltaic complex could represent the advance of Elsterian glaciation or even an earlier one.

Second ice-advance stage, > 350 ka BP, Paklenica Member

The informal Paklenica Mbr. is best exposed in it's type section (Paklenica Section) in the Velika Paklenica Canyon.

The Paklenica Mbr. (also referred to as "megadiamict lithofacies", Marjanac Lj., 2012) is characterized by large blocks which commonly attain volume of 500 m^3 or more. The Paklenica Mbr. was originally defined by Lj. Marjanac (2012) who claimed (p. 122) that it "*consists of three cycles, each composed of tillite and reworked tillite, which may be considered as subunits marking ice advance-retreat cycles*". The advancing glaciers eventually spread over the South Velebit Lake and strongly deformed distal lacustrine sediments at the Ždrilo Section. Our preliminary data indicate that the glaciers prograded at least 2 km farther southwestward from the Ždrilo Section.

The minimal age of the Paklenica Mbr. is > 350 ka BP at the Paklenica Section and 339,7 ± 61,4 ka BP at the Ždrilo Section, as revealed by U-series dating of secondary calcite (Marjanac Lj., 2012). Consequently, the deposition of tillites most likely correlates with the MIS 12. The Paklenica Mbr. regionally correlates with the Ninkovici Member in Montenegro which is attributed Skamnelian Stage (also correlated to MIS 12) as defined in Greece (Hughes, 2011).

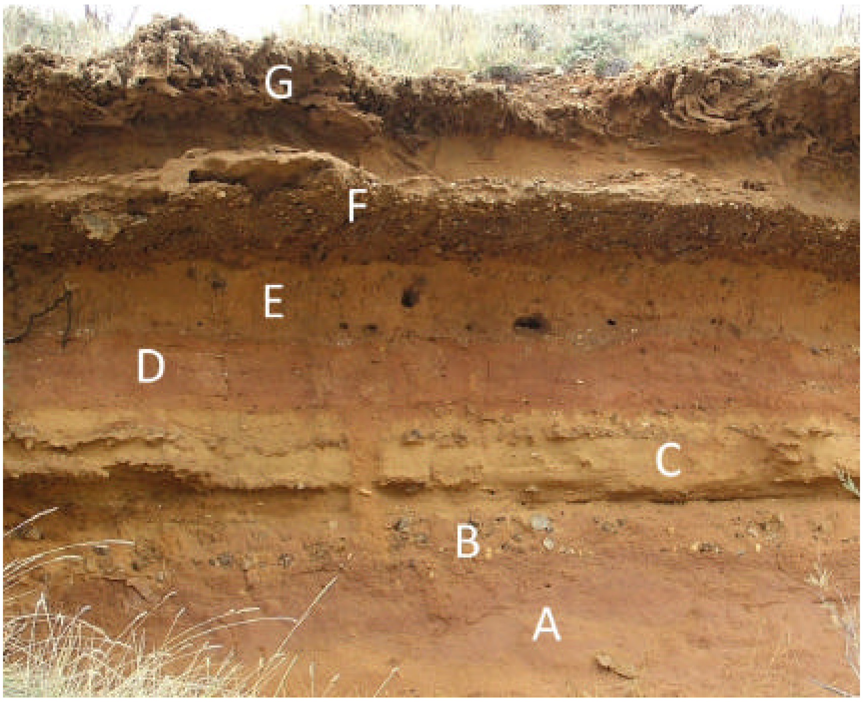
Second Ice-retreat stage, Nozret Member

The Paklenica Mbr. is overlain by ice-retreat glaciofluvial sediments of the informal Nozret Mbr. which is best exposed along the southern coast of the Novigrad Sea, where it was studied in 2,5 km long Novigrad Section, which is the member's type section. The Nozret Mbr. comprises reworked moraines of the Paklenica Mbr., glaciofluvial sediments, glaciolacustrine fine-grained sediments, and paleosols.

The ice-retreat at the Novigrad Section first resulted in reworking of the underlying Paklenica Mbr. moraines by running meltwater which filled the Novigrad Sea Lake basin. The lacustrine sedimentation was dominated by silt and fine sand, which were fed by fluvial input as documented by deposition of hyperpicnal turbidites. In proximal position at the Paklenica Section, this ice-retreat is characterized by deposition of kame-terraces and coarse-grained glaciofluvial outwash sediments, whereas calving of the ice front created icebergs which rafted across the Novigrad Sea Lake and released dropstones.

This ice-retreat stage culminated in lake drying and development of 2 m thick paleosol (Fig. 2). This paleosol horizon consists of reddish-brown soil with Fe-Mn coated pebbles below, ochre-colored and rippled, selectively cemented sand in the middle part, and brown soil with rhizoids above, which document the change in climate from humid to semi-arid, and again to humid and warm above. The upper paleosol was vegetated by plants which grew on fluvial deposits above. The new climate change is indicated by rapid progradation of fluvial systems which deposited gravelly channel fills. This fluvial (probably pluvial climate) period proceeded new cooling of climate which is documented by expansion of the Novigrad Mbr. moraines above.

The age of the Nozret Mbr. is unknown because of the lack of datable material, and is herein provisionally correlated with MIS 11. Secondary cements of a void in lacustrine sediment provided the age of 121,6 ± 3,9 ka BP and 110,2 ± 3,4 ka BP (which correlates with MIS 6 to MIS 5e), whereas the cement of topographically higher ice-wedge provided the age of 146,4 ± 4,4 ka BP.



Paleosol of the Nozret Member at the Novigrad Sea section, Nozret locality. The outcrop is 3 m high. A) reddish-brown paleosol, B) layer of black pebbles, C) rippled ocre finegrained sand, partly cemented, D) brown paleosol with scattered pebbles, E) brown soil with rhyzoids which reach not deeper than the pebble layer in base, F) rippled pebbly sand layer, G) pebbly sand disturbed by cryoturbations and ice wedging. Photograph taken in October 2007.

Third ice-advance stage, Novigrad Member

The Novigrad Mbr. moraines overlie the Nozret Mbr. at the Novigrad Section, but are exposed less extensively than the underlying member. This informal unit comprises basal tills and numerous sediment wedges, which are developed at three horizons and penetrate deep into the underlying Nozret Mbr. sediments.

The sediment wedges are interpreted as infills of Ice-wedges, which indicate tundra-type climate with seasonal (?) freezing and thawing of water-rich sediments, possibly permafrost, during gradual deterioration of climate at the onset of Novigrad Mbr. ice-advance.

The ice-advance is documented by the overlying ground moraines of the Novigrad Mbr. (Marjanac Lj., 2012) at the Novigrad and Karin sections. At the Paklenica Section it was tentatively referred to as “youngest moraine” by Lj. Marjanac (2012), which is corrected herein. During the Novigrad Mbr. ice-advance, glaciers reached the position of previous, Paklenica Mbr. ice-advance, although the maximal extent of the ice is unknown in both cases. The Novigrad Mbr. ice-advance was strongly erosive, and locally removed most of the underlying paleosol and younger part of lacustrine sediments at the Novigrad Section.

Secondary calcite in moraines of the Novigrad Member at the Paklenica Section are dated as 159,7 ± 8,2 ka BP in age, which correlates with cooling at MIS 6, but we prefer to attribute the formation of the Novigrad Member moraines to Riss glacial, MIS 10 respectivly.

Third ice-retreat stage, Paljuv Member

The youngest informal unit, the Paljuv Mbr. is exposed in a small part of the Novigrad Section and in sand-pits in the environs of the Paljuv and Smilcic settlements. This unit comprises fluvial sediments of glacial outwash plain, a sandur.

The Paklenica and Novigrad sections reveal that the moraines of the Novigrad Mbr. are overlain by coarse-grained glaciofluvial deposits of shallow braided streams, attributed to the informal Paljuv Mbr., which document retreat of the ice and formation of extensive glacial outwash plain. The overlying sediments of this unit are not exposed elsewhere, so it is unclear what were the distal equivalent deposits of glaciofluvial gravels.

This sediments of this stage are undated, but probably correlate with MIS 5a.

It is possible that there exists an even younger ice-advance stage at the Paklenica Section, but the difficult lateral correlation of individual sections and outcrops, and lack of dating prevents the attribution of moraines in the upper reach of the Paklenica Canyon to certain part of the stratigraphic succession.

Discussion

All of the evidence presented document extensive glaciation of the Croatian Dinarides., though our focus of interest was the coastal part of the mountain range. The valley glaciers have originated at high parts of the Velebit Mt. in particular, which is pock-marked by countless dolines that even in modern climate act as efficient snow traps. There is also evidence that glaciers extended from central Dinarides towards the modern Novigrad Sea and Velebit channel.

The snow-line for the southern Velebit Mt. was reconstructed at 1.600-1.700 m (Poljak, 1947), 1.217 m (Belij, 1985), and ca. 920 m a.s.l. (Nikler, 1973), but the new data on ice distribution indicate its altitude on southern Velebit Mt. coastal slopes of just 830 m (as a median of the lowest altitude reached by a glacier, - 40 m, and height of the ridge which divided "Adriatic" from "Dinaric" snow accumulation "basins", 1.700 m).

Postglacial isostatic rebound of coastal Dinarides was in the order of magnitude from 8 m to 360 m based on the highest recorded marine Pleistocene sediments (Jurišic-Polšak et al., 1992; Marjanac T. and Marjanac Lj., 2000), and more than 60 m on the island of Krk as indicated by marine sublittoral sediments of the Late Pleistocene age (Marjanac et al., 1992/93), which should also be taken into account in reconstruction of the ice maximal extent and paleo snow-line.

The sea-level fall of Pleistocene Adriatic Sea was a gradual process, in response to continental ice buildup, and it is very likely that the sea-retreat was also oscillatory in time. The early sea-level fall during the deposition of Starigrad Member sediments must have been in the order of -50 m, because lake basins in karst, such as in Northern Dalmatia, would be filled with sea water if the sea-level was not depressed below the level of the basin bottom. The data for sea-level depression on the Adriatic Sea shelf (Van Straaten, 1970; Šegota 1982) were not corrected for subsidence and the observed "terraces" have not been dated, so the direct correlation with the Mediterranean data (Rabineau et al., 2006) is not possible, but still provide general indication of the sea-level fall in the order of -130 to -150 m. The South Velebit Lake was probably dammed at its northwestern end by an ice wall. The three islets (Ražanac Veliki, Ražanac Mali and Donji Školj) on this hypothetical dam host "glacial pavement" and fragments of carbonate clastics (possibly Jelar-Breccia of the Velebit Mt. provenance) and flysch sandstones. This "dam" is elevated in relation to the surrounding bottom for 30-40 m.

The existence of large lakes on karstified bedock which could be efficiently drained down to the regional water table, at that time lowered probably for 100 m or more, needs an explanation. The only way to maintain lakes in the karst setting would be complete flooding of the karst underground, which would be possible a) under very pluvial conditions, b) in case of shallow sea-level depression, lowered just below the lake basin bottom, or c) during glacial climate where at least part of the ground water would be frozen in form of permafrost. Permafrost would be a hydrological barrier, and could provide conditions for the formation of “hanging lakes” (lakes hydrologically detached from the local water table).

The low-lying ground moraines with striated clasts document a conservative extent of the ice progradation in eastern Adriatic coastal area. The volume of ice is currently unknown, but it must have been significant to account for lithosphere depression which is evidenced by documented glacioisostatic rebound (Marjanac T. and Marjanac Lj., 2000). The ice that reached the northern Adriatic islands of Krk and Pag, as well as covered the most of the Bukovica area, suggests abundant snow accumulation and restricted ablation.

Large volume of subglacial water must have disappeared in karstified bedrock, to get resurfaced only in karst springs which occur in large number all along the eastern Adriatic coast. The permeable karst bedrock which build most of the Dinaric Mts. controlled the ice hydrology, what needs to be studied further, but warrant establishment of a new - Dinaric model of glaciation (Marjanac Lj. et al., 2008).

Fossil assemblage and sediments of Pleistocene proglacial lakes have great importance in reconstruction of paleoclimate in Northern Dalmatia, and extent of glaciation in central Europe, particularly since South Europe is known as Pleistocene refugia for most of plant species (Follieri et al., 1986; Magri, 1998; Kuntzman et al., 2009, etc.).

The paleotemperature reconstructed after fossil leaves (3,89 ± 2,72 EC and 5,51 ± 2,86 EC) is higher than the temperature inferred by Bognar et al. (1991) and Perica and Orešic (1999). The reconstructed paleoprecipitation of 679 mm is also lower than previous authors’ (Bognar et al., 1991) estimates. This discrepancy is very likely a consequence of different approaches in paleoclimate study; actualistic extrapolation of climatological data used by Bognar et al. (1991) and Perica and Orešic (1999), and paleobotanical paleoclimate proxy used by Adžic (2012).

The data presented herein show depression of paleotemperature in the order of 10,45 EC in relation to modern average annual temperature for the closest meteorological station Starigrad (16 EC, 1992-2009 series, Krklec, 2012), which is similar to depression of 11,1 EC reported by Hughes et al. (2007) for MIS 12 (Skamnelian Stage) in Greece.

The paleoprecipitation reported herein is 530 mm below the modern value for Starigrad (1.209,5 mm, 1992-2009 series, Krklec, 2012). Modern precipitation on the Velebit Mt. (1.973 mm, 1980-2009 series, Krklec, 2012) is an underestimate, because it refers only to primary precipitates (rain, snow), whereas the contribution of frost, dew and mist accounts for additional 249 % (343 % in December, 171 % in August, 1955-1965 series, Kirigin, 1967), which allows estimate of more realistic precipitation value which would be around 6.886 mm! This means that the precipitation at the Adriatic coast (e.g. Starigrad) is significantly lower than on the Velebit Mt, and the difference is 5.676,5 mm, meaning that the high mountain receives more than five times (569,3 %) the precipitation of the coastal area. Taking into account this difference and extrapolating reconstructed MIS 12 precipitation of 679 mm at the South Velebit Channel to the Velebit Mt., the paleoprecipitation in the high coastal mountains was ca. 3.865,5 mm, which is close to paleoprecipitation of 3.371 ± 200 mm reported by Hughes et al. (2007) for glaciated Pindus Mountains in Greece during the Skamnelian Stage.

The age of secondary calcite cements in moraines certainly post-dated the formation of moraines. The calcium-enriched percolating waters could reach the open spaces in moraines just after sufficient amount of overlying carbonate debris was dissolved by aggressive water in warm climate, probably during an interstadial when biogenic production sufficiently raised the level of atmospheric CO_2, the process which might be also augmented by formation of humic acids in vegetated soil. The secondary calcite was probably crystallized in open intergranular voids tens of thousands of years after the deposition of the host sediment. Since we see that many of the clasts in Seline section conglomerates are leached, it is possible to speculate on much later karstification, or even of several epochs of leaching and cementation in succession.

Abstracts

(Abstracts are sorted alphabetically according to the first author)

Poster

Varved lacustrine sediments in the South Velebit Channel, Croatia

Ivana Adzic, Tihomir Marjanac and Ljerka Marjanac

Introduction

Pleistocene lacustrine sediments were found in the South Velebit Channel on both north and south coasts. These sediments are exposed on the north shore of the Velebit Channel near Seline in a 500 m long and 4-5 m high exposure, and on the opposite side of the channel at the Ždrilo locality in a 150 m long and 10 m high coastal exposure. Scattered outcrops of lacustrine sediments can also be found at the coasts of Novigrad and Karin Inland Seas, near Žegar and Ervenik settlements as well as in several karst poljes in Northern Dalmatia (Fig. 1). Pleistocene lacustrine sediments of the Novigrad and Karin Sea were briefly described by Marjanac et al. (1990) and Marjanac & Marjanac (2004), who interpreted the lake as formed in a proglacial setting due to common dropstones. The lacustrine sediments in Žegar, Ervenik and in Kninsko polje were studied by Malez & Sokač (1969) and Sokač (1975), who described a rich ostracod fauna indicative of cold climate. Glacigenic sediments were extensively studied in the coastal Dinaric Alps area (Marjanac et al. 1990, Marjanac & Marjanac 2004), and dating of secondary calcite from a moraine which overlies these lacustrine sediments yielded the minimal age of >350,000 years BP.

The lacustrine sediments of Seline and Ždrilo sections were studied from 2009-2011, and a well preserved fossil flora and gastropod moulds were collected. The collected flora comprises 10 specimens of fossil leafs at the Seline section, and more than 70 specimens at the Ždrilo section. The studied fossil flora belongs to 15 tree taxa of 9 families. In addition to fossil plants, mollusc moulds of Unionidae and Gastropoda were found at the Seline section, whilst Congeria–like bivalves and ostracods were found in the sediments from the Ždrilo section.

Description of studied sediments

Seline section

The lacustrine sediments of the Seline section are located in front of the Mala and Velika Paklenica Canyons (Fig. 1), where two stratigraphic intervals of lake sediments are divided by a conglomerate layer. Their close position with regard to the glacial valleys of the Paklenica and Velebit mountain range makes this section and the appropriate lake margin a proximal zone under moderate influence of the glacial debris input.

The older sediment package is well stratified, with common dropstones, whereas the younger is massive without evident stratification. The studied sediments in this profile are light brown, ochre to whitish coloured, are made of silt and sand grains, and do not comprise clayey laminae. The fossil plant debris is abundant but fossil leafs are rare. There also occur frequent moulds of fossil gastropods and bivalves, as well as cobble-size dropstones. The dropstones occur both in older and younger packages of lacustrine sediments and document the proglacial character of the lake.

The conglomerate interbed, which divides the two lacustrine intervals, is a distal part of deltaic fan bodies akin to those which underlie the oldest package of lacustrine fine-grained sediments and were interpreted as Gilbert-type deltas.

Ždrilo section

Pleistocene proglacial lake sediments are also exposed on the southeast coast of the Velebit Channel, at the Ždrilo locality. The position of this section on the opposite side of the modern Velebit Channel and consequently on the opposite side of the paleolake, makes it distal in relation to the sediment sources on the Velebit mountain range and the feeding glaciers. The lacustrine sediments are moderately to highly disturbed due to glacial push, and partly submerged under the modern Adriatic Sea, which makes the study of the whole sediment succession difficult. However, the outcrops are good enough for the study of the younger package of lacustrine sediments, which are locally overridden and eroded by thick lodgement till.

The Ždrilo section lacustrine sediments are perfectly laminated, with well defined varves. The sediments comprise light to dark brown and rusty brown siltstone laminae in alteration with white to light grey clayey laminae. The boundaries between silt and clay laminae are sharp, sometimes with developed small-scale flame structures, sometimes marked by erosional surfaces and sometimes marked by bioturbation. The mid-part of the section was studied in detail, and the silt laminae vary from 1 to 111 mm in thickness. The thickest one is massive and undifferentiated. The clay laminae are considerably thinner with thicknesses between 1 and 30 mm. Traces of bioturbation were observed at the contact of silt and clay laminae, with burrows in underlying silt laminae infilled with clay from above. Silt and clay laminae are in most cases further differentiated which might imply the variation of sediment inflow during their deposition. In one part of the laminated lake sediment in Ždrilo, folding and reverse faults can be observed. This unique case of faulting and folding may indicate a synsedimentary deformation.

The moraine sediments were found on a lateral section in a distance of 300 m. Due to the glacier advance, overridden varved sediments were tilted, eroded and deformed, and a 13 m long slab of lacustrine sediment is incorporated into the moraine.

Fossil flora and fauna from proglacial lake sediments

Lacustrine sediments of the Ždrilo section are rich in plant macrofossils. Most abundant are leaves of *Taxodium* sp. More than 30 specimens of *Taxodium* sp. fossil leaves, varying from poorly to excellently preserved were collected and photographed. The *Taxodium* leaves were found on silty laminae and were covered by a thin film of clay, which is common also for all other fossil leafs at the Ždrilo section. They occur throughout the section, and in most cases together with fossil leaves of *Zelkova* sp. and *Quercus* sp.

Aforementioned *Quercus* sp. and *Zelkova* sp. were second best represented by the number of specimens at the Ždrilo section; eight specimens of *Quercus* sp. and five specimens of *Zelkova* sp. were found. Two specimens of *Quercus* sp. were also found in lake sediments at the Seline section. Leaf fossils from Ždrilo are grey and well preserved, whereas those from the Seline section are rusty brown and poorly preserved. The leaf size of *Quercus* sp. varies from 30 to 100 mm. Five specimens of *Zelkova* sp. were found in the Ždrilo section, and one was found in the Seline section. The specimens were well preserved except for the few, with an invisible leaf nervature but the leaf edges were perfectly recognizable. The leaf size varies between 20 and 30 mm.

The plant macrofossils represented by two specimens were *Castanea* sp., *Acer* sp. and *Fagus* sp, found at the Ždrilo section. The leaves of *Fagus* sp. were found in sediment along with the *Zelkova* sp. and numerous *Taxodium* sp. fragments.

Other plant macrofossils found in varved lake sediments at the Ždrilo and Seline sections, are represented by a single specimen; such as *Liquidambar* cf. *europea*, *Buxus* sp., *Pterocarya* sp., *Tilia* sp., and fruit of *Ulmus* sp. One specimen was recognized as a member of Moraceae family. The fossil leaf of *Tilia* sp. was also found in lake sediments of the Seline section.

Few specimens were poorly preserved and were hard to determine because of the lack of important diagnostic features such as leaf nervature, leaf base or leaf apex. Those are arbitrarily assigned to certain taxa: *Zelkova*, *Parrotiopsis*, *Pyrachanta* and *Buxus*-like specimens.

Poorly preserved specimens of fossil fauna were found in lacustrine sediments both in Seline and Ždrilo sections. Since the diagnostic features were missing, the specimens were determined only by their general characteristics. Seven specimens of fossil gastropods and bivalves were collected in lake sediments of the Seline section, whilst a large number of Congeria-like bivalves was found on a bedding plane of the Ždrilo section lacustrine sediment. Ostracods with unornamented shells and of different sizes were found in the Ždrilo section lacustrine sediments.

Short discussion and conclusions

The fossil assemblage and the sediments of Pleistocene proglacial lakes have great importance in reconstruction of the paleoclimate in Northern Dalmatia and of the extent of glaciations in central Europe. In the south of Europe were the refugia for most of the plant species during the Pleistocene (e.g., Follieri et al. 1986, Magri 1998, Kuntzman et al. 2009). Findings from the localities on the eastern Adriatic coast, Ždrilo and Seline, can contribute to a better understanding of the response of plant communities to glaciations and cold climate.

Plant taphocoenoses found in lake sediments in Ždrilo and Seline correspond to mixed temperate forest vegetation, based on *modern* vegetation distribution pattern. It is generally perceived that the genus *Quercus*, *Fagus*, *Ulmus*, *Acer*, *Liquidambar*, *Castanea*, *Tilia* and *Zelkova* represent typical temperate vegetation, whereas the genus *Taxodium* and *Pterocarya* being representatives of humid climate. Our findings are at odds with this model, the fossil leafs were found in sediments of a lake that was in direct contact with active (advancing) glaciers, as indicated by numerous dropstones and overlying ground moraines. Modern distribution patterns of certain taxa are, we believe, a consequence of several abiotic factors, such as the distribution of glacial ice. The modern plant distribution may neither represent their true distribution nor their climatic affinities in geological history.

The results presented in this paper are at the moment preliminary, and further, more detailed research is planned for the near future, in order to get better understanding of Pleistocene vegetation in the Dinaric Alps.

Acknowledgments

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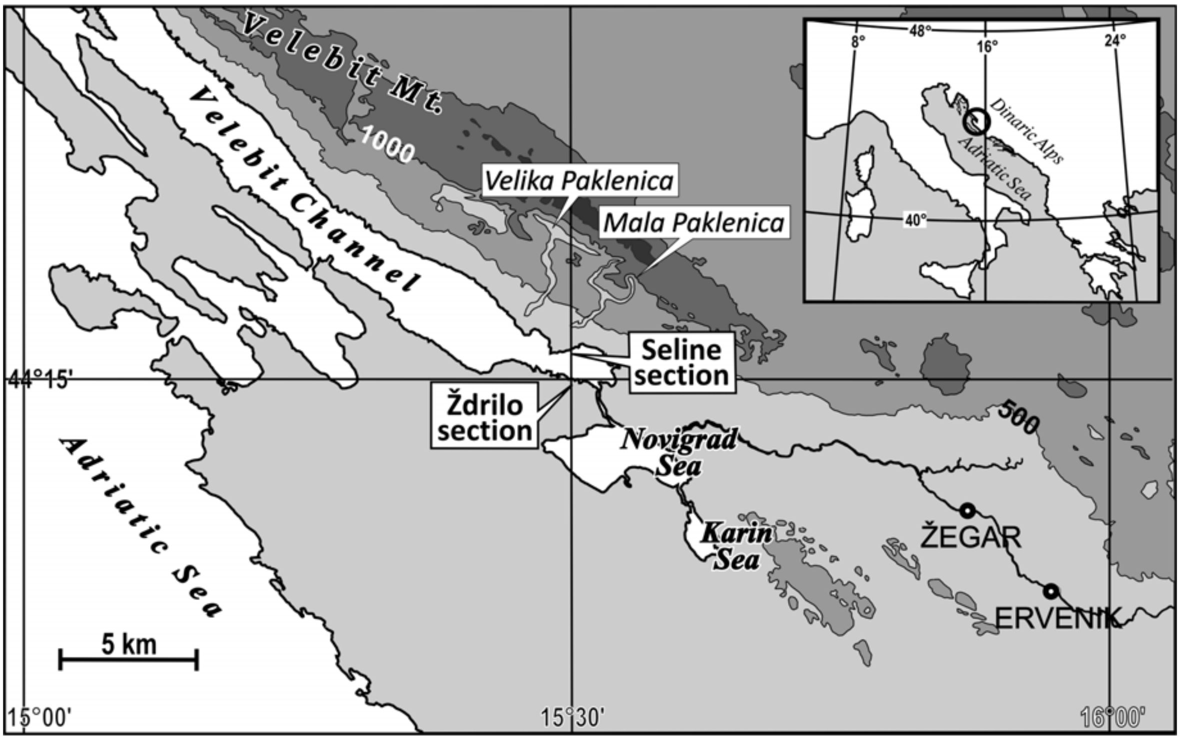

Fig. 1: Location of studied sections on the eastern Adriatic Sea coast.

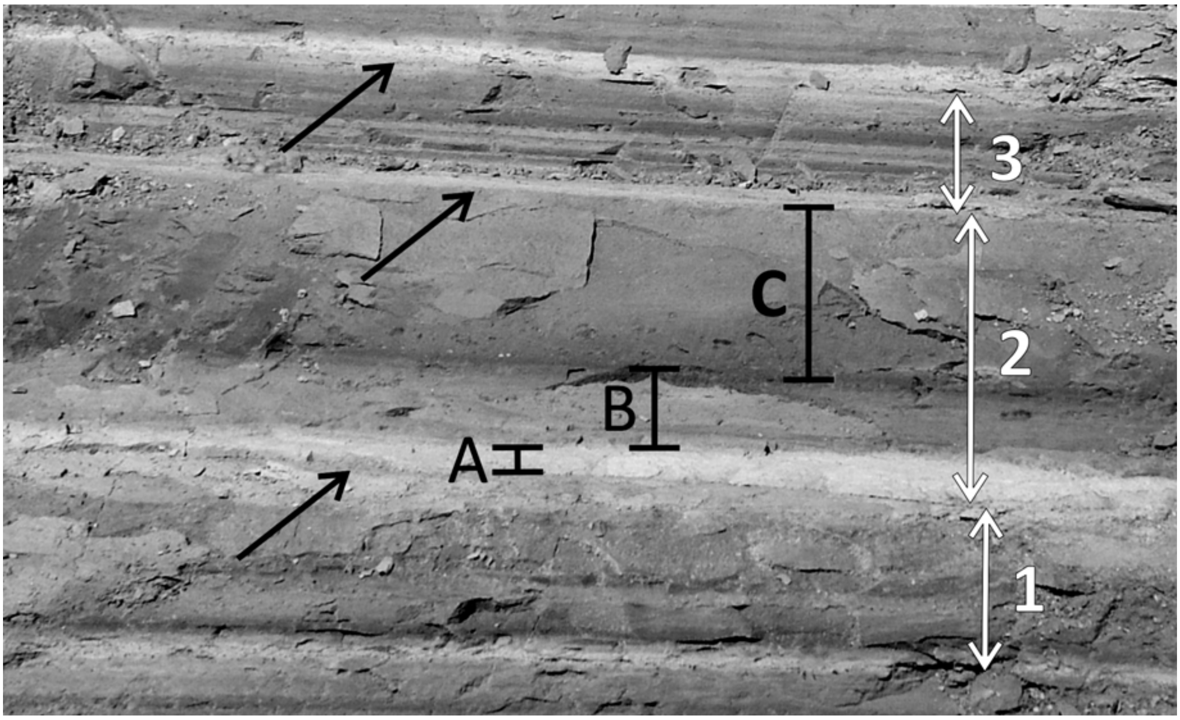

Fig. 2: Varved lacustrine sediment of the Ždrilo section. The section is 15 cm thick. White numbers (1-3) indicate annual layers (varves); a couplet consists of winter layer (white) and spring/summer layer (grey). Packet 3 is a complex varve, probably formed during a year with several freeze and thaw periods. A - winter layer; B - spring layer; C – summer/autumn layer. Arrows point to the autumn/winter boundary comprising fossil leaves.

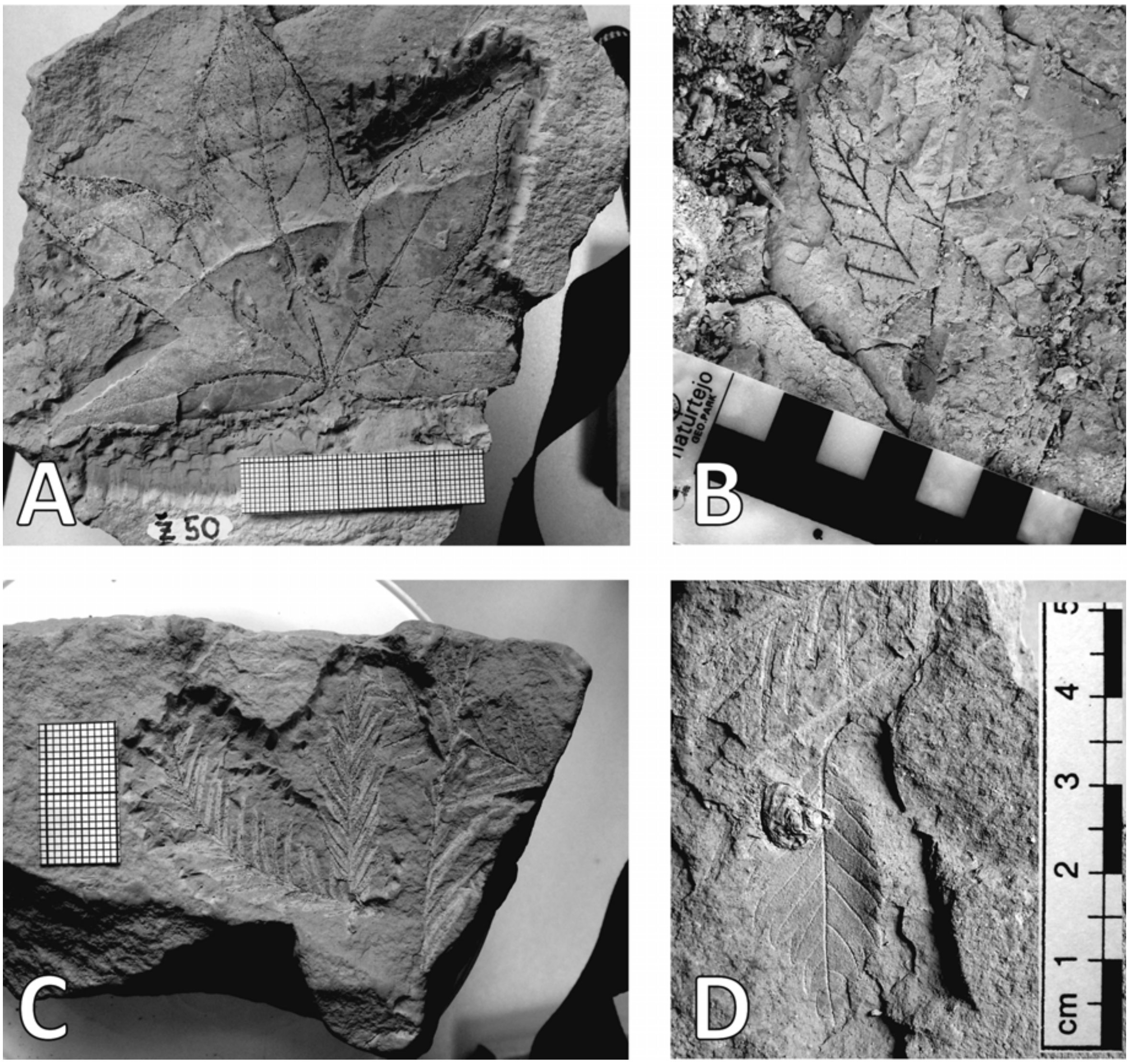

Fig. 3: Fossil flora from Ždrilo section varves. A) *Liquidambar* cf. *europea*, B) *Quercus* cf. *trojana*, C) *Taxodium* sp., D) *Zelkova* sp.

Poster (presented by N. Roberts)

Reconstructing Holocene climate and environmental variability using ITRAX core scanning technology: preliminary results from Nar Crater Lake, Turkey

Samantha Lee Allcock and Neil Roberts

A wide variety of climate information can be extracted from non-biological components of lake sediments. Physical and chemical properties of lake sediments can be related to climate signals either through varve thickness measurements or through geochemical analysis. Traditional methods for extracting these data often rely upon time consuming and destructive techniques. New approaches now utilise ITRAX core scanning to provide rapid high-resolution records. Annually laminated

Fossil flora from the Pleistocene lacustrine sediments at Ždrilo and Seline (Northern Dalmatia, Croatia)

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Plant macrofossils, mostly leaf impressions, were found in the Pleistocene lacustrine sediments at the seashore outcrops of the South Velebit Channel (locations Ždrilo and Seline), and for the first time a total of 79 specimens were collected during 2011-2012 research period (research still in progress) and 13 taxa were determined, belonging to 9 families (Adžić 2012). The plant macrofossils are apparently of Middle Pleistocene age or even older, according to 339.4±61.4 years minimum age of the overlying glacial sediment at Ždrilo location (Marjanac, 2012). The sediments deposited in a proglacial lake, which occupied the southern part of present Velebit Channel, are associated to glaciers of the South Velebit Mt. at the onset of Mindel Glacial (Skamnelian Stage) (Marjanac, 2012).

The Seline lacustrine sediments are varved-like, but consist of predominantly massive silt to clayey-silt beds, otherwise vaguely laminated. Dropstones are common and more frequent than in Ždrilo sediments. Ostracods are found in sediments of both sections, while only at Seline section occur moulds of large gastropods and *Unio*-type mollusks. The sediment succession represents a proximal depositional zone of a proglacial paleo-lake (Adžić, 2012; Marjanac, 2012).

The Ždrilo Lacustrine sediments are typical varved glaciolacustrine sediments consisting of alternation of clay, silt-clay and clayey-silt laminae or thin beds (Adžić et al, 2012; Marjanac, 2012). Besides abundant plant fossils (Fig. 1), there are well preserved ostracod shells and poorly preserved juvenile mollusk shells. These varvites deposited in a more distal zone of a proglacial paleo-lake than Seline sediments. The plant remains predominantly occur as leaf impressions, commonly on bedding plains and locally within a massive clayey-silt beds.

The most abundant fossil plant is *Taxodium* leaf type (absent in the Seline section sediments). Only one fossil fruit was found in the Ždrilo section and it is interpreted as *Ulmus* sp. fruit. All the specimens are relatively small in size, ranging from 10-80 mm, with mean value 30,9 mm. The most common blade class is microphyll (LAWG, 1999). Following by the number of specimens are oak leaves (*Quercus* spp.) and zelkova (*Zelkova* cf. *carpinifolia*), found both at the Ždrilo and Seline sections. Taxodium is typical relict taxa today prevalent on the east coast of the Northern America. Recent areal of the genus *Zelkova* is restricted to Asia, Sicily and Crete (Søndergaard & Egli 2006). Zelkova disappeared gradually on the European continent (Foglieri et al 1986). Two fossil leaf impressions of *Liquidambar* cf. *europea* were found at Ždrilo. Recent distribution of the genus Liquidambar comprises the area of the North America and East Asia (Komarnik, 2004). The *Quercus* spp. leaves were also relatively common in both sections represented by three different types of leaves, one ascribed to the *Quercus* cf. *trojana* leaf type. Other determined taxa are *Alnus* sp., *Pterocarya* sp., *Castanea* sp., *Fagus* sp., *Acer* cf. *rubrum*, *Buxus* sp., *Tilia* sp. The plant taphocoenosis found in lacustrine sediments represents mixed temperate forest vegetation, based on modern vegetation distribution pattern. The mixed temperate forest vegetation belt comprises large area and cannot be associated only with mild temperatures. Most of the determined taxa belong to genera that form different climax phytocoenosis today, which indicates that the vegetation was well developed and zoned.

Very recently, a number of new specimens were collected that will hopefully yield new data for more precise reconstruction of Pleistocene vegetation in this region.

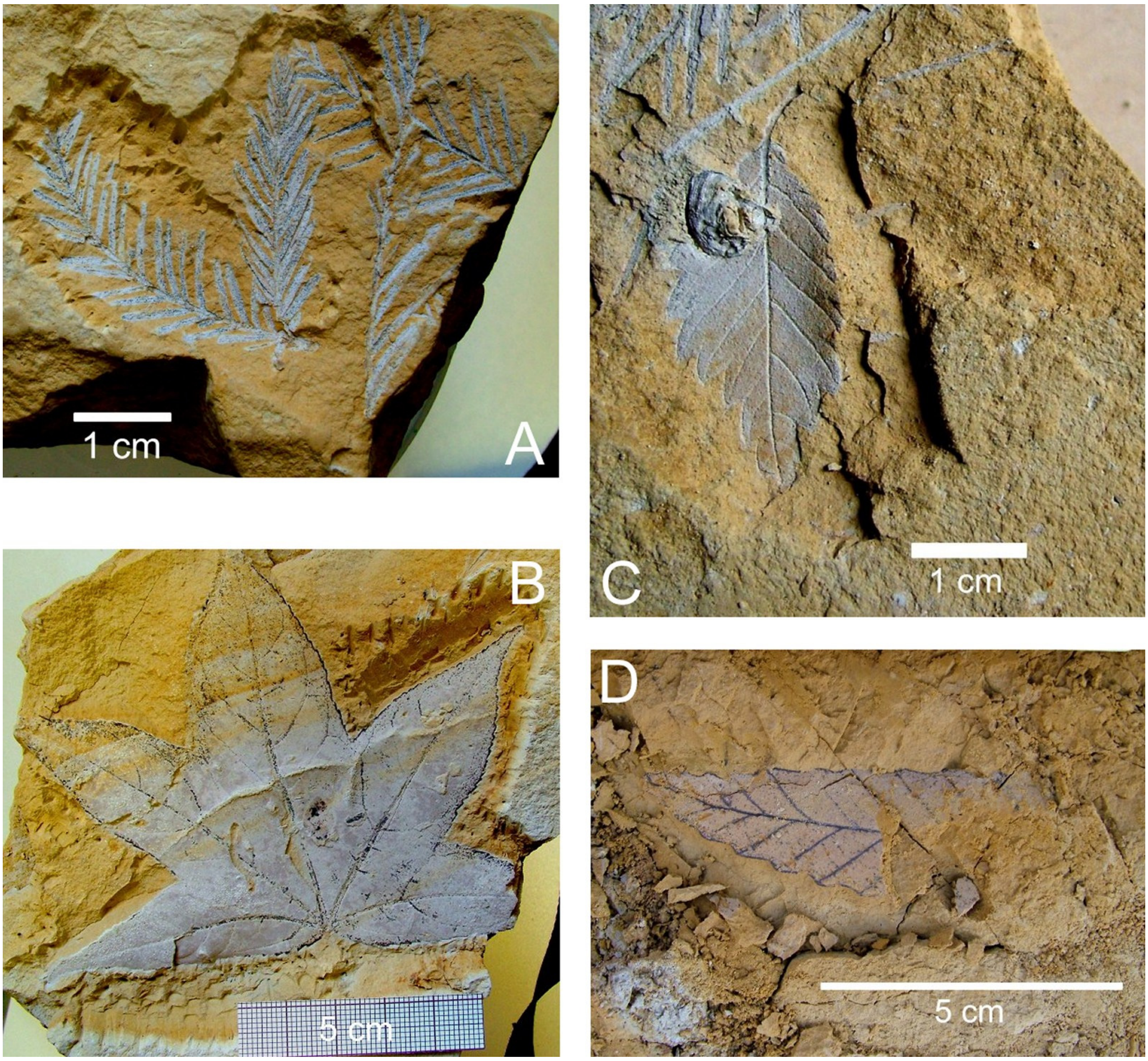

Figure 1. Plant macrofossils from Ždrilo varved sediments. A – *Taxodium* sp., B – *Liquidambar* cf. *europea*, C – *Zelkova* sp., D – *Quercus* cf. *Trojana*.

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Poster

Distribution of Pleistocene glaciolacustrine deposits in southwestern Croatia

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Pleistocene lacustrine fresh-water sediments are found throughout Croatia, although in its northern part they were revealed only by drilling (Šercelj 1969, Sokač 1976, Babić et al. 1978, Sokač et al. 1982). In this short review the emphasis is given to south-western Croatia where many extensive outcrops of typical glaciolacustrine sediments occur (Fig. 1). Recently, studied sites (1 to 6 in Fig. 1) are located along the northeast and southwest coasts of the Velebit Channel and along the southwest coast of the Novigrad Sea and represent remnants of Middle Pleistocene proglacial lacustrine sediments. Other sites (7 to 12 in Fig. 1) are presented upon the data from General Geological Maps of Yugoslavia and respective explanation books (Majcen & Korolija 1973, Ivanović et al. 1976 and 1978, Grimani et al. 1976, Sokač et al. 1976), and upon the data published until the 1990ies. Most of these deposits were recognized as “Neogene Süsswasserbildungen” (Neogene freshwater sediments) and marked on the Austro-Hungarian Geological Maps of Croatia (Schubert 1905, 1907, 1912), and breefly reviewed in Table 1.

Karst poljes Kninsko polje, Mokro polje, Žegarsko polje and Erveničko polje are filled with glaciolacustrine sediments which were successively deposited following the retreat of the Middle Pleistocene glaciers. The age attribution is based on ostracod assemblages studied by Malez & Sokač (1968), Malez et al. (1969) and Sokač (1975), and mammal findings reviewed by Malez (1968). The early Pleistocene (Villafranchian) was also documented in Kninsko polje and Strmica (Fig. 1, localities 11 and 12; Malez et al. 1969, Šimunić 1970). Malez (1968) compared the lacustrine succession of Strmica with the Leffe basin in Italy.

Nevertheless, much greater significance for the reconstruction of Pleistocene environmental and climatic changes as well as for the extent of the Dinaric glaciation (Marjanac et al. 2008), have the glaciolacustrine deposits at Novigrad Sea (Fig. 1, locality 5; Fig. 2C) described by Marjanac et al. (1990) and Marjanac & Marjanac (2004, 2006), varved sediments at Ždrilo (Fig. 1, locality 4; Fig. 2A) that are currently studied (master thesis in preparation by I. Adžić), and glaciolacustrine sediments in alternation with proglacial deltaic conglomerates at Seline (Fig. 1, locality 2; Fig. 2D). Their age is 350 ky at minimum as achieved by Uranium series dating of secondary calcite cement sampled in the overlaying ground moraines at the Ždrilo locality. This leads to the conclusion that the sediments were deposited before or partially during the Mindel/Elster glaciation (MIS 12), which will hopefully be shown by detailed future studies. These glaciolacustrine sediments (Fig. 1, locations 1-6) are found above and below the present sea level (Table 1) and have been greatly destroyed and disturbed by the advancing ice, which is documented by overlaying ground moraines visible at locations Kusača cove, Ždrilo and Novigrad (Fig. 1, locality 1, 4 and 5).

Further detailed studies of varved sediments at Ždrilo and varve-like sediments at Seline and Novigrad will greatly improve our knowledge about glaciations and climate changes in the Mediterranean region. The age of moraines and the assumed age of glaciolacustrine sediments with well preserved fossil leaves of cold climate flora

(Adžić et al., this volume) are new documents of the extensive glaciation of the Dinarides in the Middle Pleistocene, which call for reconsideration of our perception of climatic and paleogeographic conditions in the Mediterranean during the Pleistocene.

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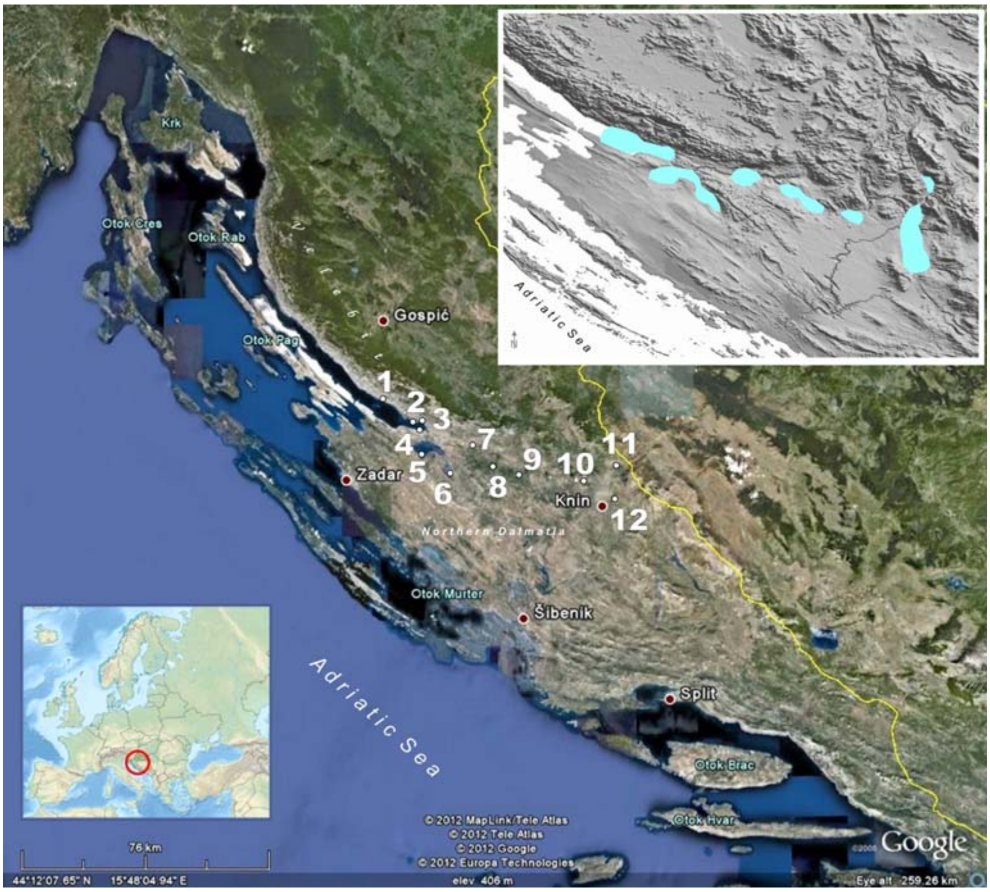

Fig. 1: Location of south-western Croatia where glaciolacustrine sediments are found at 12 locations listed in Table 1. The map at the top right corner shows the possible extent of glacial lakes.

Tab. 1: Review of most important occurrences of Pleistocene lacustrine deposits in south-western Croatia. Most of them were first recognized as Neogene freshwater sediments, and by later studies were interpreted as of Middle Pleistocene age.

	Sediments / paleoenvironment / stratigraphy		
Locations (Fig. 1)	*Registered on Austro-Hungarian geological maps of Croatia in the scale 1:75.000*	*Registered on General geological map of Yugoslavia in scale 1:100.000*	*Recent study, largely unpublished*
1 - Kusaèa Cove 0 - 10 m a.s.l.	Neogene freshwater sediments (Schubert 1907)	not registered	glaciolacustrine sediments, Middle Pleistocene, under study
2 - Seline coastal cliff 0 - 6 m a.s.l.	Neogene freshwater sediments (Schubert 1907)	not registered	proglacial lake sediments (proximal varved-like deposits; proglacial deltaic conglomerates), Middle Pleistocene, under study
3 - Provalija 1 - 2 m a.s.l.	Neogene freshwater sediments (Schubert 1907)	not registered	poorly preserved Seline-type sediments, under study
4 - Ždrilo 0 - 10 m a.s.l.	Neogene freshwater sediments (Schubert 1905)	not registered	varved sediments (clay/silt/sand) of proglacial lake, Middle Pleistocene, under study
5 - Novigrad coastal cliff 0 - 20 m a.s.l.	Old Quaternary sands and marls (Schubert 1905)	not registered	varve-like unit with dropstones (silt and clayey silt) and ripple laminated unit (sands, silt, rarely clay), proglacial lake deposits in association with moraines and glaciofluvial deposits, Middle and Upper Pleistocene; still under study (Marjanac et al. 1990, Marjanac & Marjanac 2004)
6 - Karin 0 - 40 m a.s.l.	not registered	not registered	laminated clayey silt deposits, glacial lake, Middle Pleistocene, under study
7 - Bilišane 20 - 90 m a.s.l.	Neogene freshwater sediments (Schubert 1905)	Middle Pleistocene (Riss glacial) lacustrine marls and clays (Ivanović et al. 1973)	revision in plan
8 - Ervenièko polje	Neogene freshwater sediments (Schubert 1912)	Middle Pleistocene (Riss glacial) lacustrine marls and clays (Ivanović et al. 1973)	revision in plan
9 - Žegarsko polje 50 - 90 m a.s.l.	Neogene freshwater sediments (Schubert 1912)	Middle Pleistocene (Riss glacial) lacustrine marls and clays (Ivanović et al. 1973)	revision in plan
10 - Mokro polje 200 m a.s.l.	Neogene freshwater sediments (Schubert 1912)	Middle Pleistocene (Mindel - Riss) lacustrine marls and clays (Malez & Sokač, 1969)	revision in plan
11 - Strmica	Neogene freshwater sediments (Schubert 1912)	Lacustrine chalk and swamp-lacustrine sediments with mamals and gastro-pods (Villafranchian, Mindel glaciation), clay with gastropods of Mindel-Riss interglacial (Grimani et al. 1972)	revision in plan
12 - Kninsko polje	Neogene freshwater sediments (Schubert 1912)	Lacustrine chalk and swamp, lacustrine sediments with mamals and gastropods (Villafranchian, Mindel glaciation), clay with gastropods of Mindel-Riss interglacial (Grimani et al. 1972)	revision in plan

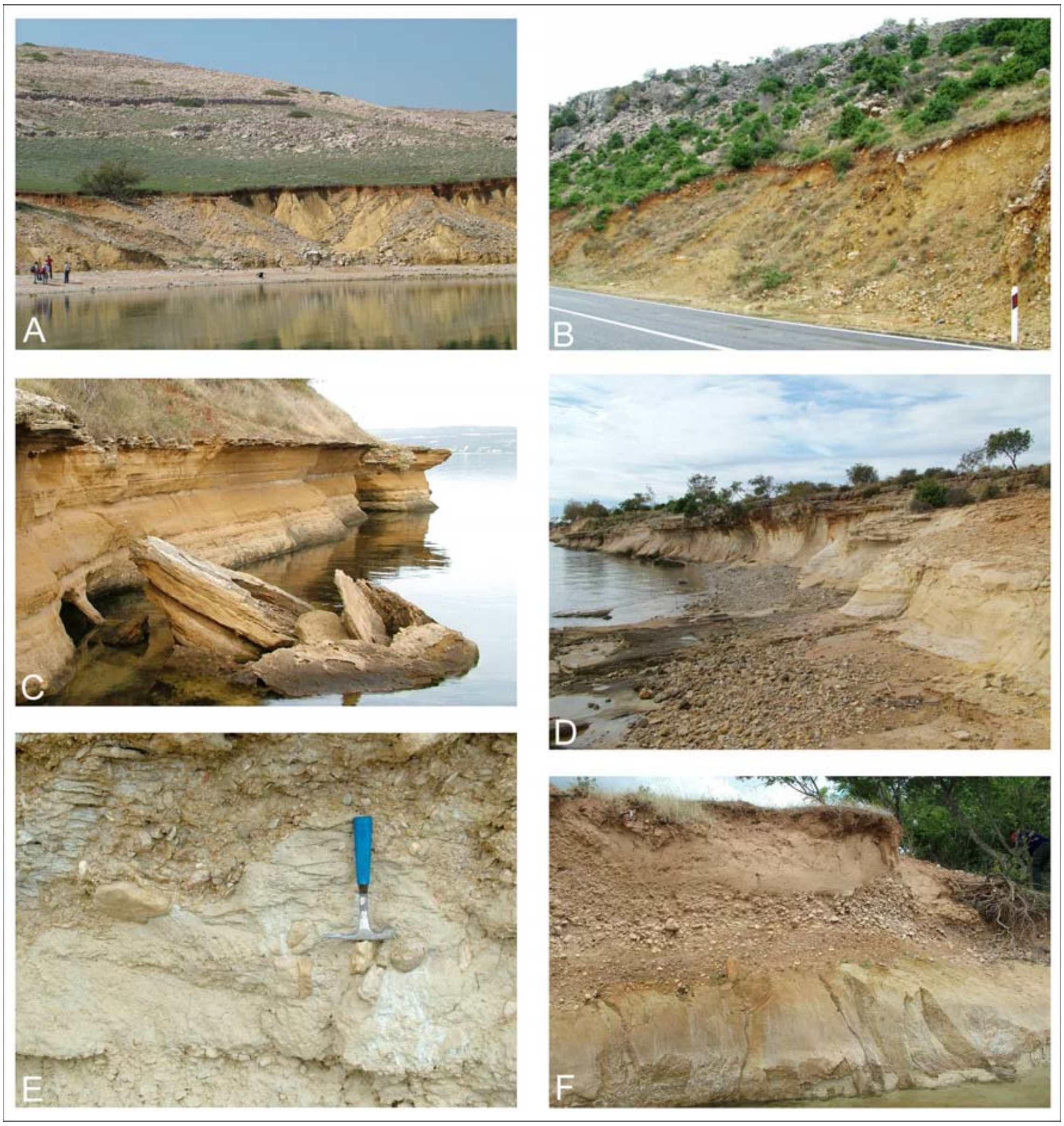

Fig. 2: Outcrops of Middle Pleistocene glaciolacustrine sediments in southwestern Croatia. A) Varved sediments with fossil flora and fauna (distal facies) at location 4 - Ždrilo; B) Laminated silt/clay sediments disturbed by overlaying ground moraine at location 1 - Kusača cove; C) Varve-like sediments with dropstones at the coastal section of location 5 - Novigrad; D) Varve-like sediments with gastropods and bivalve moulds (proximal facies) at the coastal section of location 2 - Seline; E) Laminated clayey silt sediments disturbed by overlaying ground moraine at location 6 - Karin; F) Clayey silt lacustrine sediment covered with paleosol and younger glacigenic deposits, exposed at location 9 - Žegarsko polje.

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