CROATIAN ACADEMY OF SCIENCES AND ARTS
Department of Natural Sciences
Institute of Quaternary paleontology and geology
Croatian National INQUA Committee

D I G

4th International field workshop on DInaric Glaciation

Early/Middle Pleistocene glaciations of NE Mediterranean - filling the gaps in reconstructing its geological history and climate change;

Focus on glaciogenic sedimentary palaeoenvironments of Krk Island

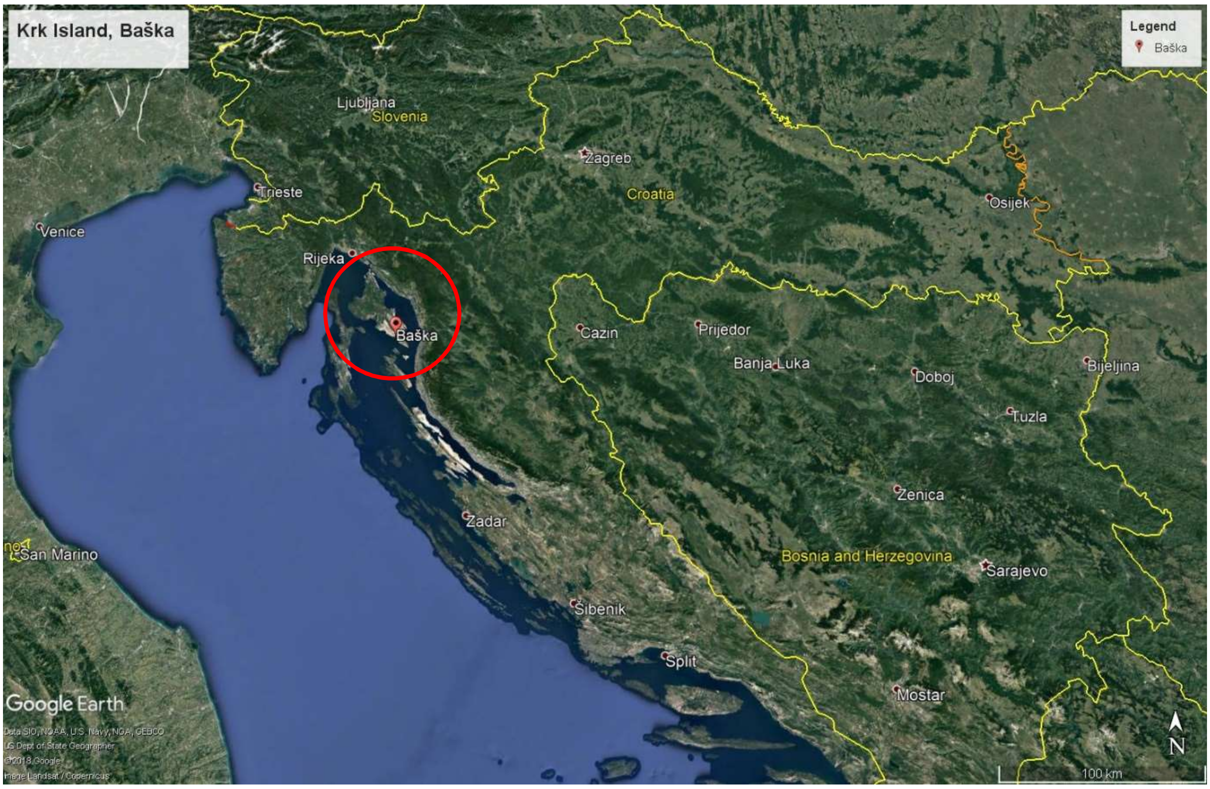
FIELD GUIDEBOOK

Ljerka MARJANAC, Tihomir MARJANAC & Marina ČALOGOVIĆ

Baška on Krk Island, Croatia, May 2018

D I G
– 4th Workshop on Dinaric Glaciation:
Early/Middle Pleistocene glaciations of NE Mediterranean – filling the gaps in reconstructing its geological history and climate change
Focus on glaciogenic sedimentary palaeoenvironments of Krk Island

21st – 26th May 2018
Baška on Krk Island, Croatia



KRK ISLAND is the largest Adriatic island with an area of 410 km^2 located in Kvarner bay together with islands of Cres, Pag, Rab and Lošinj. Its largest part is built of carbonate rocks: Cretaceous limestones and dolomites, Eocene Foraminiferal limestones, Eocene Flysch (siliciclastic sediments), Eocene-Oligocene carbonate coarse-clastic breccia, and Quaternary breccias and sands and gravels (Šušnjar et al., 1963; Mamužić et al., 1969). Newer explorations revealed an asteroid-impact origin of the Post-Eocene coarse-clastic breccia (Marjanac et al, 2002, 2003, 2006). Sedimentary research of Pleistocene deposits reviled their glacigenic origin (Marjanac & Marjanac 2004, Marjanac 2012, Marjanac & Marjanac 2017).

Position of the observation sites:

1 – ČRNAC, 2 - BABA , 3 – GAJEVI, 4 - JURANDVOR 1, 5 - JURANDVOR 2, 6 - ZAROK

Program

ARRIVAL DAY - MONDAY 21/05/2018

10.00 - 18.00	Individual arrival, registration, accommodation in Baška
18.00 – 19:30	Dinnner
19.30 - 22.00	Introductory lectures: Geology of Krk Island, T. Marjanac Review of Quaternary deposits of Krk Island, Lj. Marjanac Impact structure of Krk Island, T. Marjanac

FIELD DAY 1 - TUESDAY 22/05/2018

Pleistocene impact structure and associated sediments + Baba tillite (T. Marjanac, M. Čalogović, Lj. Marjanac)

09.0 – 16.30	Fieldwork: location 1 – ČRNAC (impact associated sediments); location 2 – BABA (glacial deposits, recognizing differences between glaciogenic and impact breccias)
16.30 – 18.00	Free time
18.00 – 19.30	Dinner
19.30 – 22.00	Discussion and summary of the Field day 1. Introduction to field day 2.

FIELD DAY 2 - WEDNESDAY 23/05/2018

Sedimentology of kame-terraces in Baščanska draga valley (Lj. Marjanac & T. Marjanac)

09.00 - 16.00	Fieldwork: location 3 – GAJEVI (glacial deposits of different phases of ice extent in Baščanska draga valley)
16.00 - 18.00	Free time
18.00 - 19.30	Dinner
19.30 - 22.00	Discussion and summary of the Field day 2. Introduction to field day 3.

FIELD DAY 3 - THURSDAY 24/05/2018

Sedimentology of kame-terraces in Baščanska draga valley (Lj. Marjanac & T. Marjanac)

09.00 - 14.00	Fieldwork: location 4 – JURANDVOR 1 (kame-terrace deposits and its structure); location 5 – JURANDVOR 2 (associated erratic blocks).
14.00 – 15:30	Free time
15.30 - 18.30	Guest lectures and discussion: S. Furlani, G. Monegato
18.30 – 20.00	Dinner
20.00 - 22.00	Guest lecture and discussion: P.D. Hughes. Introduction to field day 4.

FIELD DAY 4 - FRIDAY 25/05/2018

Glaciogenic complex Zarok (Lj. Marjanac & T. Marjanac)

09.00 - 16.30	Fieldwork: location 6 – ZAROK (Pleistocene sediments complex, from marine to glaciofluvial, composed of 14 allostratigraphic units. Field practice in outcrop mapping and sediment logging.
16.30 – 18.00	Free time
18.00 – 19.30	Dinner
20.00 – 22.00	Discussion and summary of the Field day

FIELD DAY 5 - SATURDAY 26/05/2018

Presentation and discussion day

10.00 - 13.00	Students' presentations on their own research/thesis + discussion
13.00 – 14.00	Lunch
14.00 – 16.00	Summary of the Workshop
16.00 – 17.00	Free time
17.00 – 22.00	Visit to Vrbnik (dinner included)

Sedimentary evidence of Pleistocene asteroid impact event on Krk Island

Tihomir Marjanac & Marina Čalogović

Asteroid and comet impacts are important catastrophic events in the Earth history, and their recognition and timing allow us to document the rate of cosmic catastrophes and resultant environmental stress. Some of these events left their mark in geological record as the cause of very rapid (almost instantaneous) climate changes, biotic stresses, and extinctions. Geologically young impact events left their mark in topography as impact craters (astroblemes), whereas older events are preserved as impact structures without visible crater, but display impact-generated facies such as breccia lense and impact melt-rocks as erosional remnants. Most old impact structures are deeply eroded (e.g. Rochechouart in France, Bischoff & Oskierski 1987), but some are buried by younger sediments and unexposed (e.g. Chixculub offshore Yucatan, Hildebrand et al. 1991).

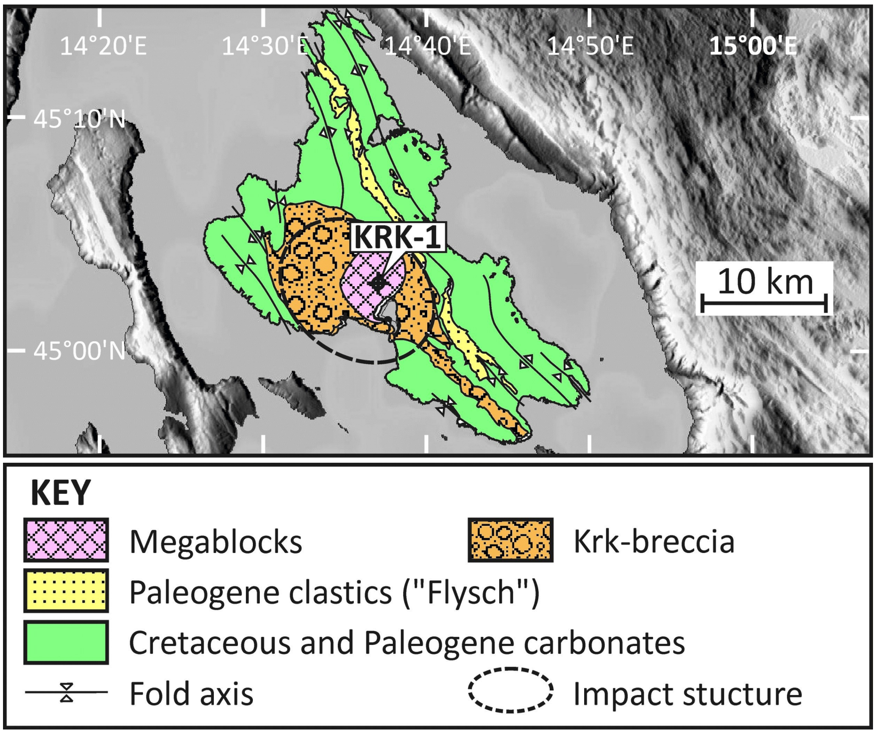


Fig. 1: Geological map of Krk Island, simplified after Mamužić et al. (1969), Šušnjar et al. (1970) and Marjanac et al. (2003).

The island of Krk is site of proposed impact structure (Marjanac et al. 2001, 2003) which is located in central part of the island (Fig. 1) and has reconstructed size of 11 x 14 km. The structure was drilled by Krk-1 exploration well in 1967, and recognized as a breccia lense by Đurasek et al. (1981) (Fig. 2). The well was drilled through breccia for 1500 m, and revealed significant stratigraphic incompleteness (Fig. 3).

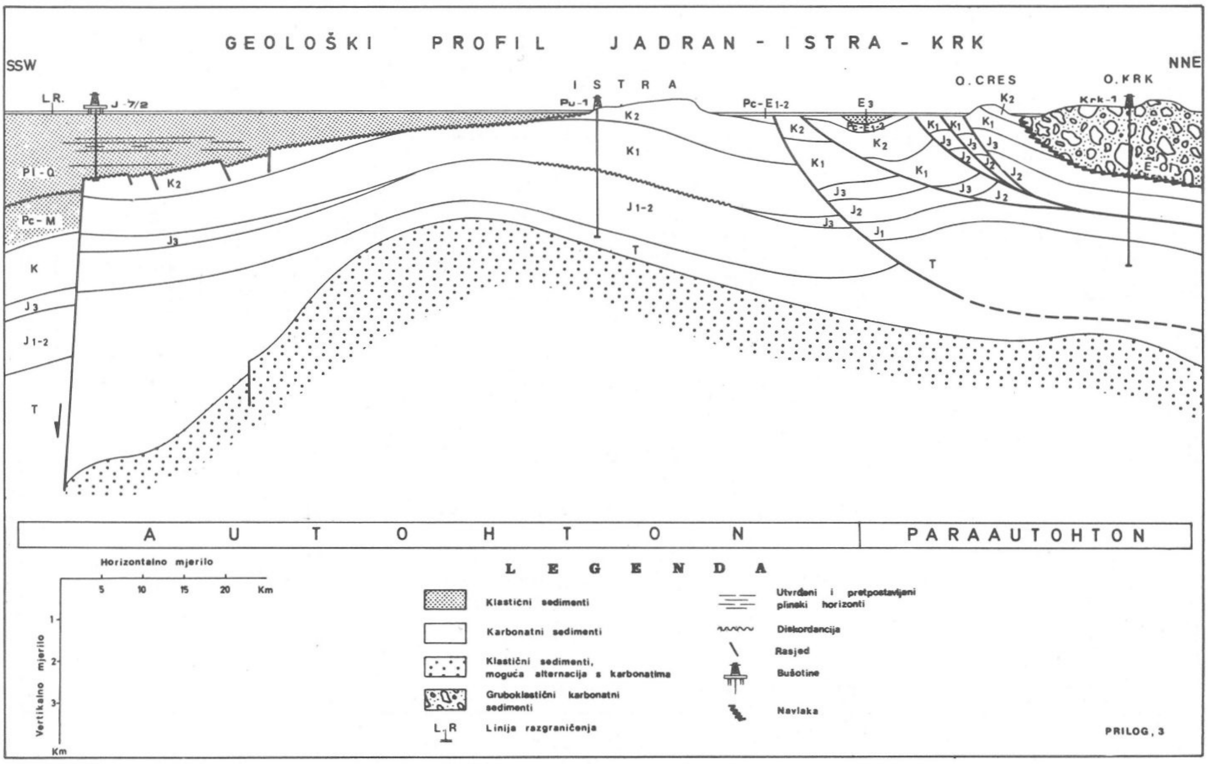


Fig. 2: Section from Đurasek et al. (1981) reveals Krk-breccia as a lensoid body, with significant hiatus in its base.

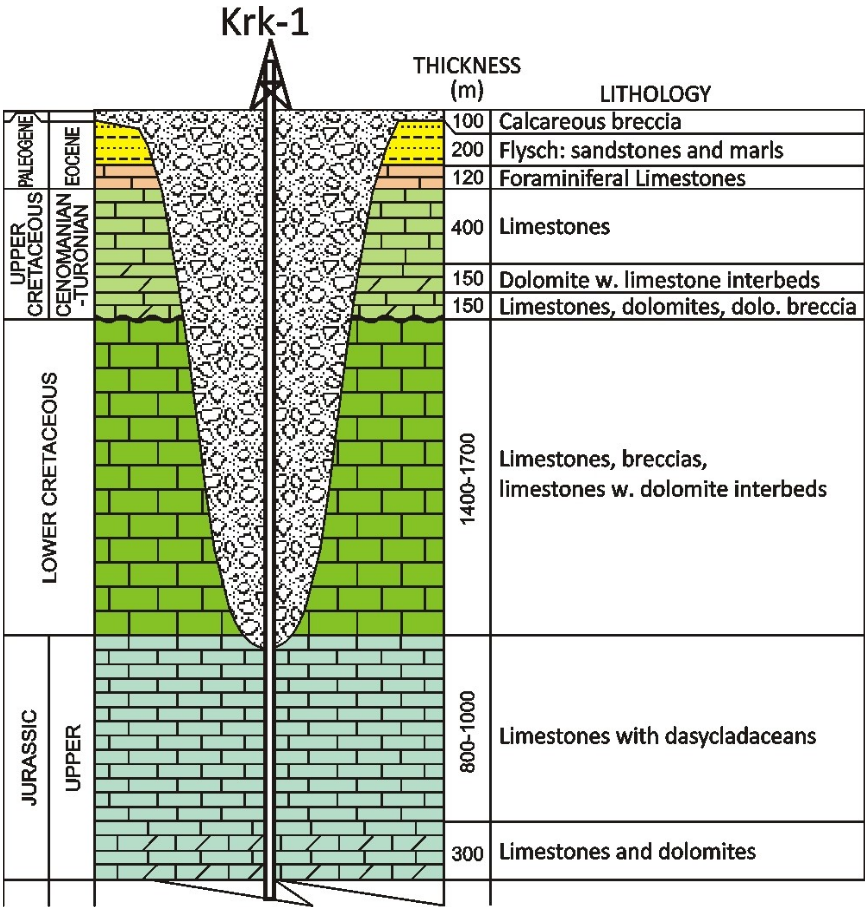


Fig. 3: Stratigraphic column of the Krk-1 well.

The drilled breccia was reinterpreted by Marjanac et al. (2001, 2003) as central-peak impact structure with the depth of 1500 m, completely filled with fall-back and flow-back breccia, largely uneroded (Fig. 4). The centre of the structure was recognized as St. Mihovil's hill which is built of scattered megablocks in random orientations. The crater-fill breccia is recognized as informal lithostratigraphic unit of the Krk-breccia, which covers the area of 150 km^2 of Krk Island, but occurs as erosional remnants also on Rab Island (Figs. 1 and 5).

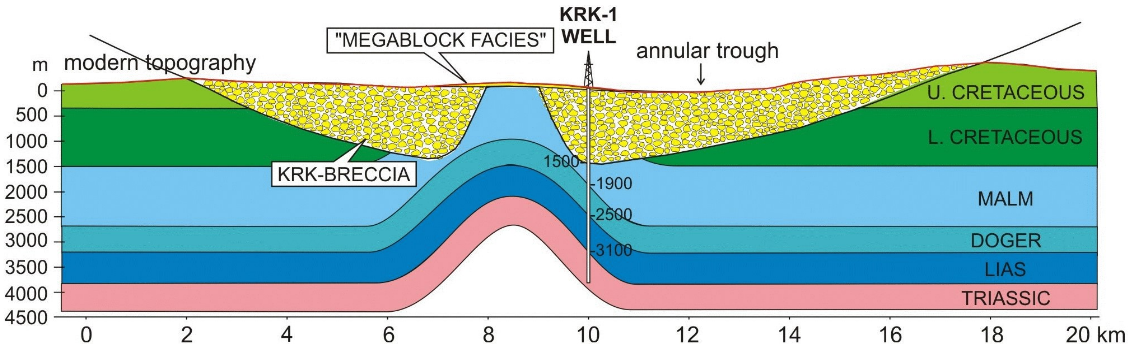


Fig. 4: Section through Krk impact structure (from Marjanac et al. 2003).

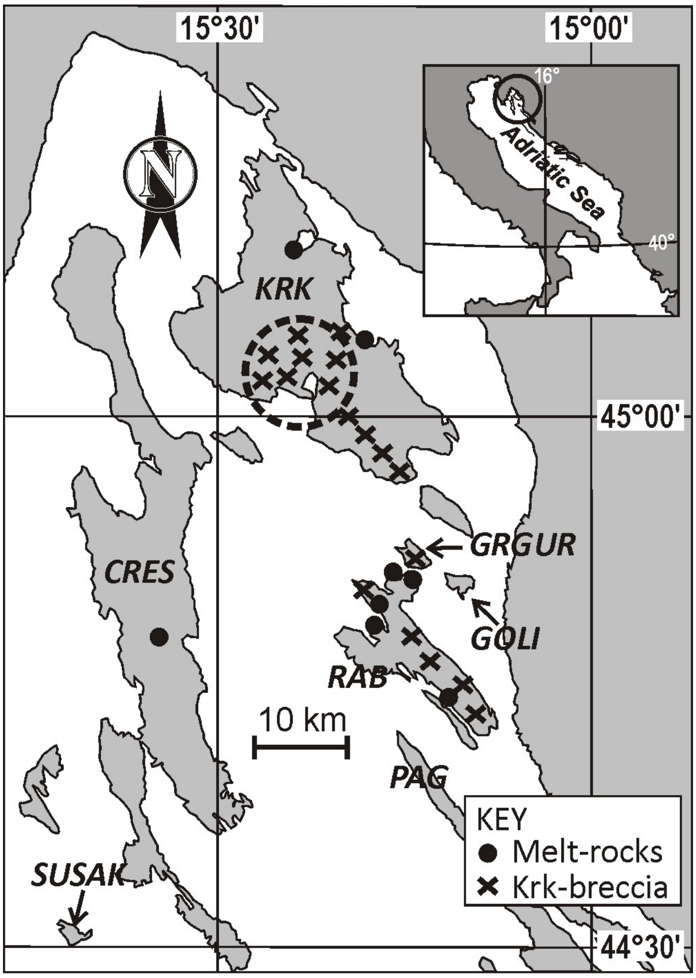


Fig. 5: Distribution of Krk-breccia and melt-rocks, and Krk impact structure (dashed circle).

Krk-breccia

The Krk-breccia is generally chaotic grain-supported polymict breccia with variable amount of reddish carbonate matrix which locally gives the breccia appearance of matrix-supported sediment. The breccia is locally stratified and crudely bedded, built of coarse angular debris which ranges from millimetre to over 10 metres across, surrounded by micritic carbonate matrix (Fig. 6). The outcrops on western slope of Veli Vrh, NE from the Punat Bay reveal the base of Krk-breccia which is made of strongly tectonized (fractured) Late Cenomanian-Turonian limestones which are directly overlain by thin inversely-graded finer-grained clast-supported breccia (Fig. 7).

Fig. 6: Krk-breccia, matrix-rich variety locally called “mandolato”.

Fig. 7: Normal contact of Krk-breccia with Cretaceous limestones.

The Krk-breccia compositionally and structurally differs from other types of breccias which occur in wider area. Other important breccias in the wider area are A) Cenomanian clast-supported monomict breccia on Cres Island (Magaš 1968) which is composed exclusively of dolomite debris, and B) clast-supported, unbedded, chaotic polymict Jelar-breccia (originally Jelar-beds, Bahun 1974) (Velebit-breccia *sensu* Vlahović et al. 2012) which occurs along Velebit Mt. coastal slopes and comprises granule- to cobble-size (locally boulder-size) debris in stratigraphic range from Early Cretaceous to Early Eocene and attains thickness of over 400 m (Vlahovic et al. 2012).

Fig. 8: Krk-breccia. Clasts of Nummulitic limestone, above and next to hammer.

The Krk-breccia comprises clasts of Early Cretaceous micritic limestones, Late Cretaceous limestones, K/T boundary bauxite clasts, clasts of Early-Middle Eocene Alveolina limestones and Nummulite limestones (Fig. 8), clasts of Middle-Late Eocene “flysch” sandstones (Fig. 9) and clasts of “flysch” marls (Marjanac et al. 2003).

The largest are clasts of Alveolina limestones, over 10 m in diameter (actually 12 x 8 x 5 m), which occur in the lower section of the breccia. The debris is locally imbricated (Fig. 10) showing NE (upslope!) directed transport in thickness of ca. 1 m. Some clasts are *in-situ* shattered with matrix filling the gap (Fig. 11). The breccia is locally crudely stratified (Fig. 12), sometimes with loading (? water-escape) structures between individual beds (Fig. 13).

The Krk-breccia in central part of the island, in the proposed impact structure covers large area and attains thickness of at least 1500 m, but elsewhere it occurs in scattered outcrops (Fig. 5) on top or modern topography. The breccia thickness there is small, sometimes just a few metres, but still displays its lithological and stratigraphical complexity. Patches of Krk-breccia coincide with water ponds on Krk and Rab islands which are formed on “flysch” marls or heterolithics, that seem to represent clasts in breccia. However, only smaller marl clasts are recognized *in situ* on Rab Island.

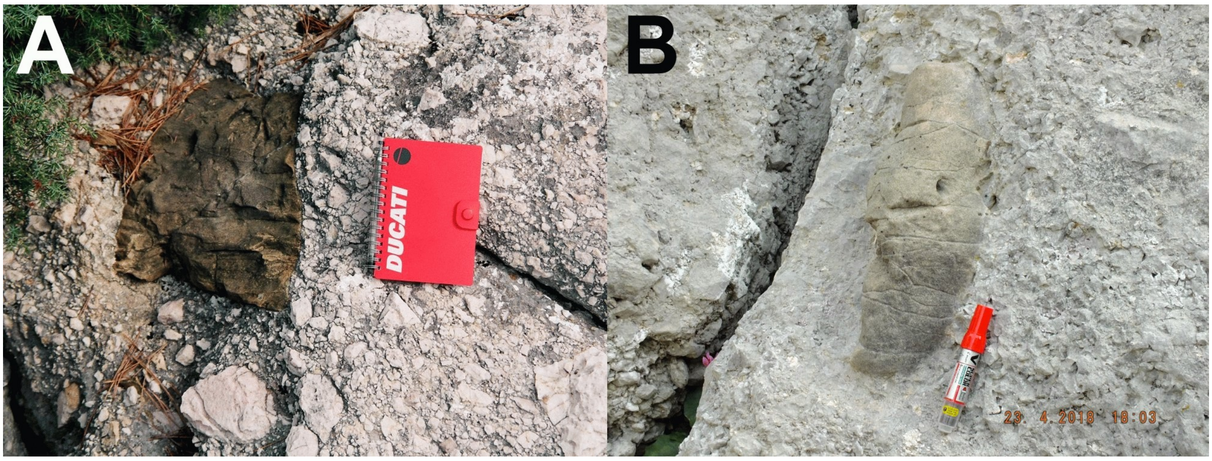


Fig. 9: Krk-breccia. A) Eocene sandstone clast on Krk Island, B) sandstone clast on Rab Island.

Fig. 10: Imbricated debris in lower part of Krk-breccia. Impact structure centre is to the left, margin to the right. Imbrication documents outflow of the debris.

Since the Krk-1 well was drilled, and extraordinary thickness of breccia became known, there were only a few unpublished attempts to interpret its origin. The contemporaneous hypotheses were that the breccia represents infill of a karst-fissure which was drilled by accident or that it is a tectonical breccia. The karst-fissure infill interpretation is recently revived by Vlahovic et al. (2012) who did not differentiate Krk-breccia from his Velebit-breccia. However, Marjanac et al. (2001, 2003) interpreted the breccia as an asteroid impact crater infill, based on its distribution which was mapped in 2000-2003, study of well log, and the study of its composition and structure. The impact site location has also prominent paleo-geomagnetic signature recognized in data from Márton et al. (1990) by Marjanac et al. (2003).

Fig. 11: Krk-breccia. Shattered limestone clast with matrix in gap. Document of rapid deposition and *in-situ* fracturation.

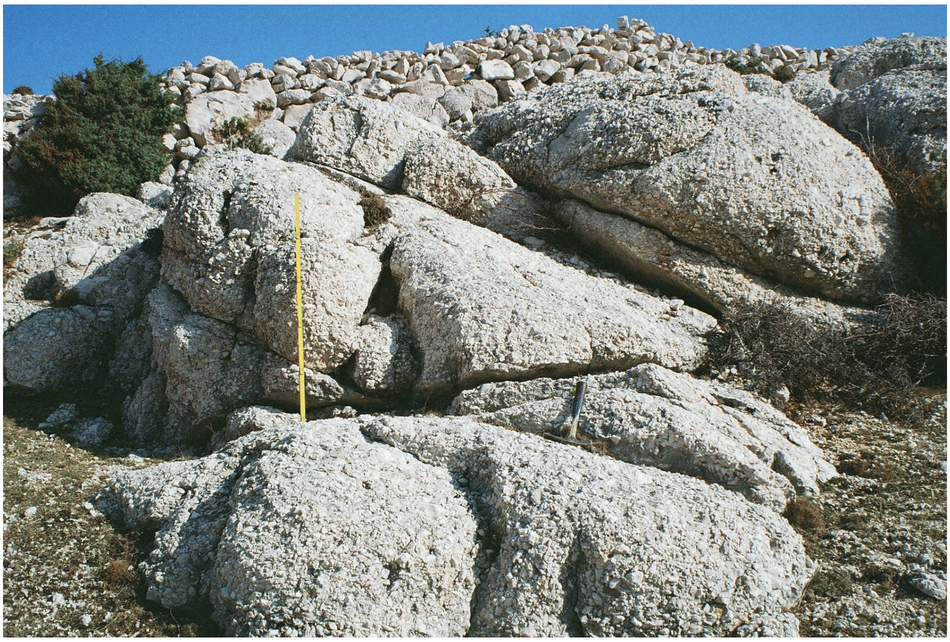


Fig. 12: Stratified Krk-breccia. Bedding documents outward-directed transport from the impact structure (from the left).

Fig. 13: Krk-breccia. Loading at the contact of two breccia beds, possible water escaping structure

The Punat-Veli Vrh section reveals the breccia structure which shows upslope (!) imbrication of debris (Fig. 10) that was caused by outward-directed flow of debris in the early stage of crater development, which is rapidly reversed as the debris started to flow back into the expanding crater during its modification stage. Towards the crater centre the backward-directed flow was separated from the initial crater-fill breccia, causing crude bedding (Figs. 12 and 13) followed by water-expulsion in form of loading structure (Fig. 13).

The process of crater formation, modification and final infill was very quick, lasted few minutes to few tens of minutes (Melosh 1989). The steep crater rim topography was modified by back-flow of debris and later erosion.

The Krk and Rab Islands were glaciated in Middle Pleistocene (Marjanac 2012, Marjanac & Marjanac 2016) and large parts of the Krk-breccia were eroded, so only patches were left on Rab Island.

Melt rocks

Large impacts have sufficient energy to evaporate and melt the target rocks at the impact structure (crater) centre. A part of this melt may remain in the crater as a melt pool, but a part may be jettisoned out of the forming crater and sprayed over the surroundings, forming melt-rocks by cooling and incorporating unmelted xenoliths (Fig. 14). Xenoliths may be only surficially melted, "toasted" with thermally-altered reaction rim. Melt-rocks are macroscopically glassy with gas vesicles, but microscopically may display quench texture.

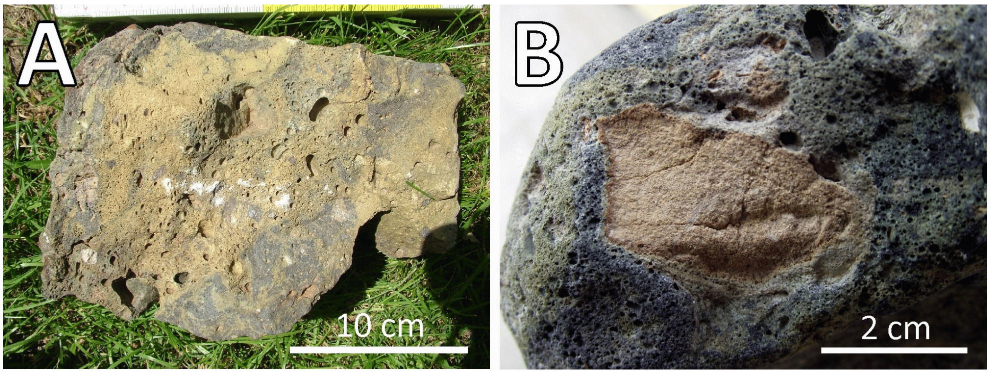


Fig. 14: Melt-rocks from Rab Island (A, B), with large xenoliths of Eocene "flysch" sandstones (B) with reaction rim.

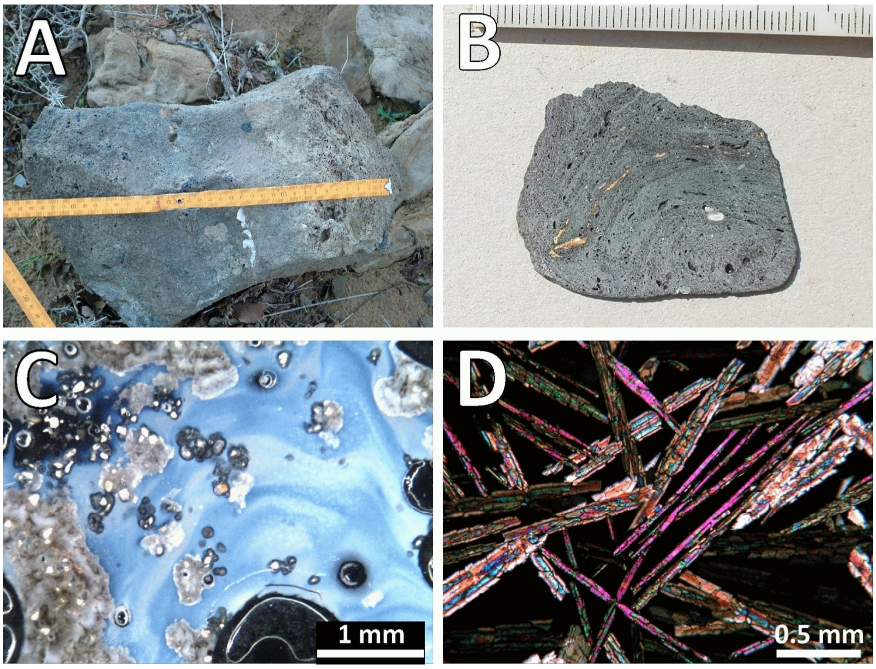


Fig. 15: Melt-rocks. A) Dark blue block in the field, Rab Island. B) Cut cobble from Krk Island, note flow-banding and chert xenoliths. C) Microphotograph of vesicular Rab glass with schlieren and dispersed Quartz, Cristobalite, and Tridymite crystals and small Clinoenstatite laths. The glass is turquoise blue in reflected light, orange-brown in transmitted polarized light with crossed polars. Polarized light and crossed polars. D) Microphotograph with crossed polars of Rab melt-rock, note quench texture of intergrown Wollastonite.

The melt-rocks are found as fragments of variable sizes, ranging from pebble to small blocks which lay scattered on modern beaches (Fig. 5) on Krk, Cres and Rab Islands. The largest melt-rock blocks are found on Rab Island and have mass over 30 kg, variable number of vesicles, and characteristic blue colour in reflected light (Fig. 15). Xenoliths in melt-rocks are pebble-size cherts and cobble-size Middle-Late Eocene sandstone fragments, commonly with reaction rim caused by thermal alteration of quartz sand (Fig. 14B).

The study of melt-rocks from this area is still in progress (Čalogović et al. 2015) and preliminary data on their composition are provided in Table 1, against the data on chemical composition of Krk flysch (after De Min et al. 2014) and Susak loess (after Mikulčić Pavlaković 2006). The chemical composition of melt-rock amorphous ("glassy") phase shows predominance of SiO_2 (Table 1) and relatively low CaO content, which differs from composition of Krk "flysch" (De Min et al. 2014) and is closer to the composition of Susak Island loess (Mikulčić Pavlaković 2006).

Table 1: Chemical composition of melt-rocks from Krk and Rab Islands

	Rab (GR 2, 2/2; 365/5)	**Krk VR-6**	**Krk (KC-3; 4)**	**Krk flysch[1]**	**Susak loess[2]**
SiO_2	64.03-67.82	70,81	65.74-68.67	38,06	47.72-62.25
Al_2O_3	7.82-8.86	15,8	16.23-17.80	4,25	9.65-12.07
K_2O	1.41-1.64	3,7	1.67- 1.92	0,8	1.53-2.20
CaO	15.85-20.90	0,9	0.86- 5.89	28,76	7.35-11.77
TiO_2	0.60-0.68	0,77	0,95	0,39	0.54-0.77
MnO	0.09-0.10	0,06	0.04-0.07	0,1	0.07-0.09
*FeO	1.60-3.49	4,7	5.31-7.24	1,94	
*Fe_2O_3	1.84-3.87	5,22	6.57-8.08		3.19-4.44
Na_2O	0.99-1.23	1,82	0.65- 1.01	0,87	1.64-2.86
MgO	1.36- 1.52	1,46	1.62-1.71	1,53	3.49-5.94
Cr_2O_3	0.04-0.05	0,08	0.03-0.04		0.01-0.02
SrO	0.03- 0.05	na	na-0.01		
ZrO_2	na-0.04	0,03	0.02-0.03		
NiO	0,01	0,005	0.02- 0.03		
CuO	na	0,004	0,01		
ZnO	na-0.01	0,02	0.01-0.02		
P_2O_5					0.14-0.22
Cl	0.04-0.07	0,04	0.06-0.21		

The age of the impact event

Post-Eocene age of the Krk impact event was attributed by Marjanac et al. (2003) after the stratigraphic composition of the youngest debris in the Krk-breccia, but the direct evidence of age is missing, so far. The stratigraphic contact on Rab Island (Fig. 16) reveals that the Krk-breccia underlies Middle Pleistocene till, but that also does not provide precise age evidence. However, compositional affinity of melt-rocks with Adriatic Pleistocene loess opens a possibility to date the impact event as pre-Middle Pleistocene.

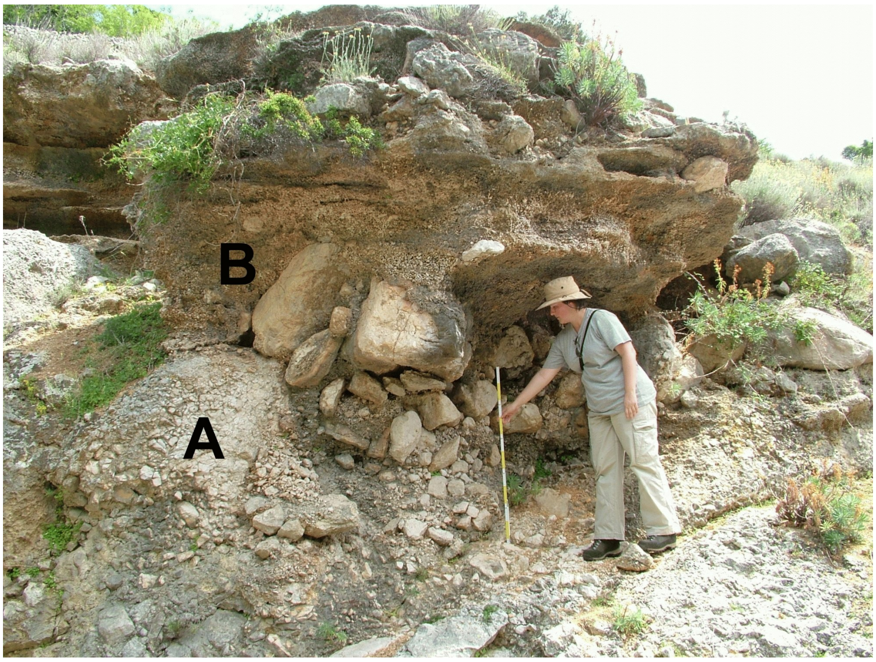


Fig. 16: The contact of Krk-breccia (A) with Pleistocene glaciogenic sediments (B) on Rab Island.

Discussion

The relationship of the Krk impact with glaciation of the Krk island is unclear. The Krk-breccia is overlain with glaciogenic sediments (Fig. 16), so it seems that the Krk impact pre-dated maximal expansion of the middle Pleistocene Dinaric ice-cap, but post-dated deposition of even older loess. However, loess on Susak Island is dated as of Late Pleistocene age (Mikulčič Pavlaković 2006). This controversy suggests that the age of loess on Krk Island must have been older than on Susak. Durn (2003) recognized pre-Late Pleistocene loess and Eocene flysch as a source lithologies of terra rossa soil in Istria. Terra rossa also underlies loess on Susak Island, and must have been much older, but nevertheless younger than Late Eocene “flysch” clastics.

Conclusion

Krk-breccia on Krk and Rab Islands represents important clue on recent geological hazard event which impacted the world climate sometime in Early Pleistocene, and represents a sedimentary body composed of debris of very wide stratigraphic span. Its origin is a matter of controversy, and for that reason it deserves detailed study and recognition as a formal lithostratigraphic unit.

Topics for discussion in field

1) Krk-breccia composition and structure
2) Debris transport mechanisms
3) Possible environmental consequences of large asteroid impacts
4) Marine, terrestrial or ice impact?

References

Bahun S. (1974): Tektogeneza Velebita i postanak Jelar-naslaga. Geol. vjesnik 27, 35-51.

Bischoff L. & Oskierski W. (1987): Fractures, Pseudotachylite Veins and Breccia Dikes in the Crater Floor of the Rochechouart Impact Structure, SW-France, as Indicators of Crater Forming Processes. In: Research in Terrestrial Impact Structures (ed. Jean Pohl), Friedr. Vieweg & Sohn, Braunschweig, 5-29.

Čalogović M., Marjanac T., Fazinić S., Strmić Palinkaš S., Tomša A. M. & Marjanac L. (2015): Chemical composition of impact glass and suevite-type partial melts of the Rab Island and their relation with the proposed Krk impact structure in Northern Adriatic, Croatia. Bridging The Gap III: Impact cratering in nature, experiment and modelling. Freiburg 21.-26.9.2015. 1088.pdf.

De Min A., Princivalle F. & Lenaz D. (2014): Geochemistry of Late Mesozoic - Early Cenozoic turbidites from the NE part of the Adria microplate. Periodico di Mineralogia 83/2, 141-158.

Durn G. (2003): Terra Rossa in the Mediterranean Region: Parent Materials, Composition and Origin. Geologia Croatica 56/1, 83-100.

Đurasek N., Frank G., Jenko K., Kužina A. & Tončić-Gregl R. (1981): Prilog poznavanju naftno-geoloških odnosa u sjeverozapadnom dijelu jadranskog primorja. Complex Oil-geological Aspects for Offshore and Coastal Adriatic Areas Symposium, Split 1981, Proceedings, 1, 201-213.

Hildebrand A.R., Penfield G.T., Kring D.A., Pilkington M., Camargo A.Z., Jacobsen S.B. & Boynton W.V. (1991): Chixculub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico. Geology 19, 867-871.

Magaš N. (1968): Osnovna geološka karta SFRJ 1:100000. List Cres, L 33-113. Inst. Geol. Istraž. Zagreb, Savezni geol. zavod, Beograd.

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

Marjanac, Lj. (2012): Glacial and periglacial sediments of Kvarner, Northern Dalmatia and Southern Velebit Mt. – Evidence of Dinaric glaciation. Ph.D. thesis, University of Zagreb, 278 p.

Marjanac T. & Marjanac Lj. (2016): The extent of middle Pleistocene ice cap in the coastal Dinaric Mountains of Croatia. Quaternary Research 85/3, 445-455.

Marjanac T., Tomša A.M. & Marjanac Lj. (2001): Preliminary evidence of impact origin of the Krk-breccia, Island of Krk, eastern Adriatic. 7th Workshop of the IMPACT Programme: Submarine craters and ejecta-crater correlation. Svalbard 2001, Abstracts and Proceedings of NGU 1, 59-61.

Marjanac T., Tomša A.M. & Marjanac Lj. (2003): Krk-breccia, Possible Impact-Crater Fill, Island of Krk in Eastern Adriatic Sea (Croatia). Cratering in Marine Environments and on ice (eds. H. Dypvik, M. Burchell, P. Claeys), Impact Studies, 115-134, Springer, Berlin.

Márton E., Milicevic V. & Veljovic D. (1990): Paleomagnetism of the Kvarner islands, Yugoslavia. Physics of the Earth and Planetary Interiors 62, 70-81.

Melosh H. J. (1989): Impact Cratering: A Geologic Process. Oxford Univ., New York. 245 pp

Mikulčić Pavlaković S. (2006): Mineraloške karakteristike pijesaka i piroklastita otoka Suska. MSc. Thesis, University of Zagreb.

Šušnjar M., Bukovac J., Nikler L., Crnolatac I., Milan A., Šikić D., Grimani I., Vulić Ž. & Blašković I. (1970): Osnovna geološka karta SFRJ 1:100000, List Crikvenica, L 33-102, Institut za geološka istraživanja Zagreb, Savezni geološki zavod Beograd.

Vlahovic I., Mandic O., Mrinjek E., Bergant S., Cosovic V., De Leeuw A., Enos P., Hrvatovic H., Maticec D., Miksa G., Nemec W., Pavelic D., Pencinger V., Velic I. & Vranjkovic A. (2012): Marine to continental depsoitional systems of Outer Dinarides foreland and intra-montane basins (Eocene.Miocene, Croatia and Bosnia and Herzegovina). 29th IAS Meeting of Sedimentology, Schladming, Field Trip Guide, Journal of Alpine Geology 54, 405-470.

DINARIC GLACIATION – A SHORT STORY

Ljerka Marjanac & Tihomir Marjanac

Sedimentary research carried on since 1988 yielded abundant new evidence of glaciation of the Croatian Dinarides (Dinaric Alps) (Marjanac et al., 1990; Marjanac and Marjanac, 2004; Marjanac, 2012; Marjanac and Marjanac, 2016). Pleistocene deposits were studied at key-sites on eastern Adriatic islands and coastal Dinarides. The studied coarse-grained sediments were for the first time interpreted as of glaciogenic origin (glacial, glaciofluvial, glaciolacustrine and glaciodeltaic). Glacial sediments, tills and tillites, occur in association with other glaciogenic deposits. Radiometric analyses of these extensive glaciogenic deposits enabled identification of six allo-litho-chronostratigraphic members: Starigrad, Paklenica and Novigrad Members representing glacial periods, and Seline, Nozret and Paljuv Members probably representing Middle Pleistocene interglacial periods. On the basis of identified stratigraphical Members and distribution of glacigenic deposits and depositional paleoenvironment sequences, four glacial stages Starigradian, Paklenican, Novigradian and Dinarian are proposed as the first regional chronostratigraphic framework of the Dinaric Glaciation.

Extensive new research in the future is essential to develop and test the proposed regional chronostratigraphy in Croatia and correlations with other Mediterranean regions. Further research is needed in order to understand the extent of the ice over the wider Dinaric Alps during different cold stages. The relationships between glacial sequences in Croatia and Montenegro as well as neighbouring areas such as in Bosnia and Herzegovina and Albania all require more research. Further study of the fossil assemblage of the lacustrine sediments (such as at Ždrilo, Seline, Novigrad, Karin) should also provide valuable data on paleovegetation, paleoclimate and geochronology.

Geochronology

Glacigenic sediments of the eastern Adriatic and coastal Dinarides of Croatia were studied in detail (Marjanac and Marjanac, 1999; Marjanac and Marjanac, 2004; Marjanac et al., 2012; Marjanac, 2012; Marjanac and Marjanac, 2016) but due to lack of fossil material geochronology of the sedimentary units is based on allo-, litho- and morpho-stratigraphy *sensu* Hughes (2010) and Hughes et al. (2010, 2011). Early radiocarbon dating and later U-series dating (Table 3) contributed to chronostratigraphic interpretation of Pleistocene glacial sediments and proposal of the chronostratigraphic framework of the Dinaric glaciation (Marjanac and Marjanac 2015) as presented herein

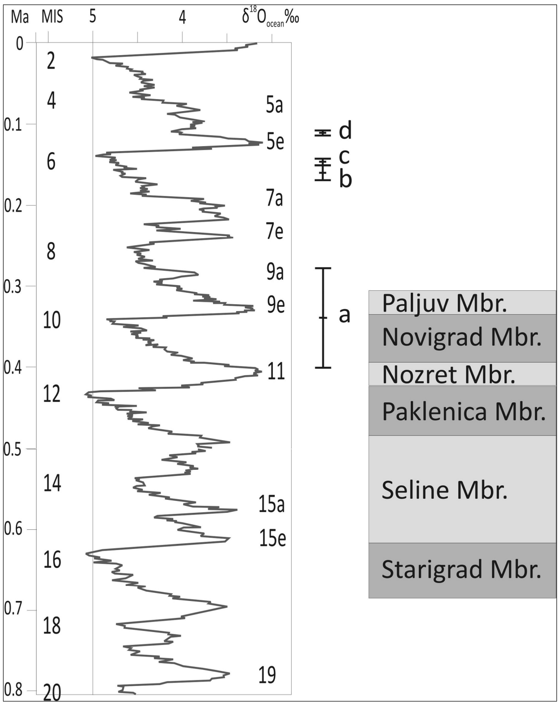
Allo-morpho-lithostratigraphy

Tills and tillites built various sedimentary bodies – different types of moraines of which only erosional remnants can be found in the Croatian Dinarides. These are subglacial, englacial and supraglacial tills/tillites forming ground moraines, terminal or lateral moraines that belong either to Starigrad, Rujno, Paklenica or Novigrad Member as evidence of glacial phases.

Defined Seline, Nozret and Karin Members represented with glaciolacustrine sedimentary units as evidence of beginnings or endings of glacial phases.

Paleoclimatic conditions and glaciation pattern

Glacigenic sediments of the Croatian Dinarides provided evidence of palaeoclimatic conditions and glaciation pattern different than previously known. Identification of allo-morpho-lithostratigraphic members and chronostratigraphic interpretation enabled recognition of three cycles of ice-advance and ice-retreat stages.



a) First ice-advance stage, Starigrad Member

The earliest ice-advance stage marked by 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 a major change in climate. The Starigrad Member sediments indicate ice-contact environments spanning from proglacial outwash plane, subglacial deltaic to proglacial lacustrine. Clast lithologies indicate transport from distant sources of the Velika and Mala Paklenica canyons. The Starigrad Member sediments are so far undated, but from physical stratigraphic correlation, we assume its age might correspond to MIS 16.

b) First ice-retreat stage, Seline Member

The first ice-retreat is evidenced by glaciolacustrine sediments of the informal Seline Member. Type localities are the Seline coast section (proximal facies) and the Ždrilo section (distal facies) on the opposite side of the Velebit Channel (Marjanac, 2012). The ice retreat produced excessive melt waters that formed a proglacial lake. As the lake level rose and a standing body of water was established, glacial outwash streams formed a succession of Gilbert-type deltas at the lake margin, which is 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 desiccation 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 gravely conglomerates atop of deltaic sediments. The renewed ice-retreat provided new meltwater which re-filled the lake and fluvial systems provided debris for construction of new deltas and lacustrine silts which predominate in the reconstructed glacial paleolake Velebit (Seline and Ždrilo sections). The deposition during the late stage of the paleolake Velebit was strongly influenced by calving of the ice tongue, which apparently reached to the lake margin and provided numerous floating icebergs that provided abundant dropstones found in sediments of the Seline section. The lakes also recorded seasonal changes in temperature and precipitation, particularly in the Ždrilo Section of the paleolake Velebit, which are documented by fossil flora. Fossil leaves in the lacustrine sediments of the Ždrilo and Seline sections allowed reconstruction of paleoclimate which preceded the onset of second (major) ice-advance of the Paklenica Member which eventually caused glaciotectonic deformation of the lake margin. Adžić (2012) determined 14 different taxa of fossil flora from the Ždrilo section and gave the first estimation of paleotemperatures in the hinterland of the Velebit paleolake based on the Wolfe's equation that yielded MAT 5.51 ± 2.86 °C and Kowalski's (2002) equation that yielded MAT 3.89 ± 2.72 °C. Estimation of mean annual precipitation (MAP) using the Rauker-Webb method (Leaf Architecture Working Group, 1999) and the calculated MAP was 679 mm (Adžić, 2012). Marjanac (2012) speculated that the Seline glaciodeltaic complex could represent the advance of Elsterian glaciation or even an earlier one, herein proposed as Starigradian glacial stage.

c) Second ice-advance stage, Paklenica Member

The Paklenica Member includes all moraines built of till/tillite described as mega-diamicts, the most prominent glacial lithofacies in the coastal Dinarides and east Adriatic islands. These tills are predominantly ground moraines, but appear also as lateral or push moraines. The size span of rounded, polished and striated boulders and blocks (up to 30 m in diameter) indicates massive expansion of an ice cap that might have covered the whole of Dinarides during the glacial maximum herein proposed as the Paklenican Stage. Glaciers descending from this ice cap eventually spread over the Velebit paleolake and strongly deformed distal lacustrine sediments at the Ždrilo section. Advancing ice eroded a large part of the Starigrad and Seline Members in the area of the South Velebit Channel. Our preliminary data indicate that the glaciers prograded at least 2 km farther south-westward from Ždrilo, so their length from the Paklenica canyon head was ca. 13 km. The distribution of moraines attributed to the Paklenica Member indicates that simultaneous ice advance occurred from different directions; from the areas of the Velebit Mt. and from the areas east of Novigrad Sea and Karin Sea, possibly even from the central Dinarides in Bosnia and Herzegovina (Fig. 16). Tills located in the vicinity of Rijeka and its hinterlands (research in progress) may be time equivalent, indicating ice maximum expansion in Gorski Kotar region, possibly from Slovenia.

d) Second Ice-retreat stage, Nozret Member

The Nozret Member comprises glacial outwash gravels that locally drape older moraine of the Paklenica Member, glaciofluvial and glaciolacustrine sediments overlaying the Novigrad moraine M-1. The ice-retreat manifested first in subglacial reworking of the older moraine of the Paklenica Member by melt-waters which gradually filled the Novigrad glacial paleolake, which was at some time interval a part of the Velebit paleolake, otherwise is one in a row of ancient glacial lakes (Marjanac et al., 2012) that mark an ice route from the Knin area and even farther distance. The lacustrine sedimentation is characterized by deposition of hyperpicnal turbidites and clastic varves. The Novigrad paleolake was an ice-contact lake that included subglacial depositional processes in the lake basin bordered by paleo-topography, and calving of the ice front created icebergs that released dropstones, which are common at three visible horizons.

This ice-retreat stage is marked by deposition of kame-terraces on the Krk, Rab and Pag islands and in the upper section of the Velika Paklenica canyon (Marjanac, 2012).

At the Novigrad section, ice-retreat stage culminated in lake drying and development of a thick paleosol complex. This paleosol horizon consists of reddish-brown soil with Fe-Mn coated pebbles below, ochre-coloured and rippled, selectively cemented aeolian sand in the middle part, and brown soil with rhizoids above, which document warmer period with humid/arid oscillations of climate. Another more humid period allowed incision of a meandering river along the ice-margin with flat-pebble beaches that were subjected to cryogenic processes characteristic of periglacial environments (Marjanac, 2012), indicating the onset of a cooling period towards another ice-advance stage marked by the Novigrad Member.

e) Third ice-advance stage, Novigrad Member

The Novigrad Member moraines are exposed less extensively at the Novigrad Sea and Karin Sea sections. At present state of research, it is not known whether any moraine of Gorski Kotar or other areas belongs to the Novigrad Member. Subglacial processes of advancing ice are best documented at the Karin section, and characteristic features indicate paleotransport from the east. Tills of the Novigrad Member likely have wider distribution eastwards and north-eastwards of Karin Sea. Moraines in the Knin area possibly belong both to the Paklenica and Novigrad Members, or even to the Starigrad Member, but this assumption needs to be verified by future datings.

The thickness of the Novigrad Member ground moraines is 5 m at least, though this interval is not complete due to the postglacial erosion as apparent at the Novigrad Sea section. The ending of this stage resulted in the establishment of periglacial conditions and environments with numerous ice-wedge casts, the sediment wedges (Marjanac, 2012). The farthest extent of this glacial stage proposed herein as Novigradian is not known yet.

f) Third ice-retreat stage, Paljuv Member

The youngest informal unit, the Paljuv Member comprises fluvial sediments of glacial outwash plain, a sandur, and is exposed in a small part of the Novigrad section and in sand-pits in the environs of the Paljuv and Smilčić settlements. The Novigrad section reveals that the moraine of the Novigrad Member is overlain by coarse-grained glaciofluvial deposits of shallow braided streams, attributed to the informal Paljuv Member, documenting ice retreat and formation of extensive glacial outwash plain.

Outwash plains must have existed also in other areas, but alluvial sediments cannot yet be correlated or attributed to either of ice-retreat stages without geochronological data.

The late- and post-Pleistocene inundation of Adriatic Sea probably covered a large part of glacial outwash deposits.

Location map showing the distribution of Starigrad, Paklenica, Novigrad and Rujno Members and reconstructed ice margin during glacial maximum documented by Paklenica Member. Arrows show directions of ice expansion during informal Paklenican Stage.

Acknowledgements

The initial research was a part of INA-Naftaplin project in 1988, which was in 1991 aborted by the war. The study has continued by grants from the Croatian Ministry of Science, Education and Sports: 119303, 0119401 and 119-000000-1164 awarded to TM.

Radiocarbon dating, which included sample preparation and isotope measurements, was undertaken in the Laboratory for Low Radioactivity at the Institute "Ruđer Bošković" in Zagreb, in the period 1989 - 1990, financed by the INA-Naftaplin research project. The Uranium-series dating was 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 Philip Hughes (University of Manchester) and financially supported by the UK Natural Environment Research Council (NERC Award IP-1109-0509). We would like to thank Peter van Calsteren and Louise Thomas at the Open University for their help in U-series dating.

We also thank our former students Ana Marija Tomša, Ivana Adžić, Luka Blažić, Dragana Šolaja and Dražen Perica for their selfless support during many field campaigns. We are grateful for fruitful discussions in the field with Wojtek Nemec, Stanislav Leszczyński, Christoph Meyr, Bernd Zolitscka, Jurij Kunaver and Julien Moreau. We thank the local families Adžić, Jović and Marasović for their logistical support and the Management of the National Park Paklenica who kindly allowed research in the protected area of the Park.

References

Adžić, I., 2012. Fosilna flora pleistocenskog proglacijalnog jezera u južnom Velebitskom kanalu i interpretacija paleoklimatskih prilika u sjevernoj Dalmaciji. M.Sc. Thesis, Faculty of Science, University of Zagreb, Croatia.

Hughes, P.D., 2010. The role of geomorphology in Quaternary stratigraphy: morphostratigraphy, lithostratigraphy and allostratigraphy. Geomorphology 123, 189-199.

Hughes, P.D., Woodward, J.C., 2016. Quaternary Glaciation in the Mediterranean Mountains: A New Synthesis. In: Hughes, P.D., Woodward, J.C. (Eds.), Quaternary glaciation in the Mediterranean Mountains. Geological Society of London Special Publications 433, pp. 1-23.

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

Hughes, P.D., Woodward, J.C., van Calsteren, P.C., Thomas, L.E., 2011. The Glacial History of The Dinaric Alps, Montenegro. Quaternary Science Reviews 30, 3393-3412.

Marjanac, L., 2012. Glacial and periglacial sediments of Kvarner, Northern Dalmatia and Southern Velebit Mt. – Evidence of Dinaric glaciation. PhD Thesis, Faculty of Science, University of Zagreb, Croatia.

Marjanac, L., Marjanac, T., 1999. Polyphase kame terraces on the Island of Pag (Eastern Adriatic, Croatia). In: Kirsimä, K., Ainsaar, L. (Eds.), Field Symposium on Pleistocene Stratigraphy and Glacial Chronology - Southern Estonia 1999: May 18-23, 1999 Estonia: Abstract Volume. The University of Tartu, pp. 34-35.

Marjanac, L., Marjanac, T., 2004. Glacial history of Croatian Adriatic and Coastal Dinarides. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations - Extent and Chronology. Developments in Quaternary Science, vol. 2a, Elsevier, Amsterdam. pp. 19-26.

Marjanac, Lj., Marjanac, T., 2012. Distribution of Pleistocene glaciolacustrine deposits in southwestern Croatia. TERRA NOSTRA – Schriften der GeoUnion Alfred-Wegener-Stiftung, Vol. 2012/1, 3rd PAGES Varves Working Group Workshop, Manderscheid, March 20-24/ 2012, Program and Abstracts, pp. 59-63.

Marjanac, T., Marjanac, L., 2016. The extent of Middle Pleistocene ice cap in coastal Dinaric Mts. of Croatia. Quaternary Research 85 (3), 445-455.

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

Rabineau, M., Berné, S., Olivet, J-L., Aslanian, D., Guillocheau, F., Joseph, Ph., 2006. Paleo sea level reconsidered from direct observation of paleoshoreline position during Glacial Maxima (for the last 500,000 yr). Earth and Planetary Science Letters 252, 119-137.

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

Van Straaten, L.M.J.U., 1970. Holocene and Late - Pleistocene sedimentation in the Adriatic Sea. Geologische Rundschau 60 (1), 106-131, Stuttgart.

Glacigenic sediments of Krk Island

Ljerka Marjanac & Tihomir Marjanac

Glacigenic deposits encompass all types of sediments deposited in direct contact with ice (glacial) or by ice influence (glacifluvial, glacilacustrine, glacimarine). Glacial deposits are by definition sediments carried by active or stagnant ice and accumulated in ice-contact zones, namely subglacial, inglacial and supraglacial. Their detailed distinction and subdivision of sedimentary environments, facies and facies association were adopted as the framework for the studied Pleistocene glacigenic deposits. This framework was simplified and modified according to specific conditions of studying ancient glacial environments, which predominantly refer to the degree of preservation of sedimentary bodies and landforms.

Glacial sediments – tills and tillites

The ancient glacial environment is traditionally recognized by finding tills or tillites and glacial landforms. Till or tillite (lithified) is a diamict, an unorganized sediment, unsorted, with large variety of clast sizes usually floating in fine-grained matrix (commonly clay or silty/sandy clay), and composing sediment bodies called moraines, which in modern environments are specific geomorphologic forms depending on their position in relation to active or stagnant ice (medial, lateral, basal and terminal).

When studying ancient glacial environments, it is commonly very hard to recognize morainal bodies due to a variable degree of preservation. They are usually degraded by erosion or destructed by a younger glacial advance, or even completely destroyed. Therefore, the conclusion on the origin is based on detailed study and analyses of sediment remains and their structural and textural characteristics. Recognition of till or tillite can also be a problem if various field criteria are not met, which also include some regional criteria like glacial landforms and erosional features.

The advantage of the presented study area is that each Pleistocene glaciation was weaker than the previous one, so the sediments attributed to the Middle Pleistocene have not been destroyed by the Late Pleistocene glaciation - the Last Glacial Maximum (LGM). Nevertheless, erosional processes active during interglacial/interstadial times and Holocene were significant and most of those sediments were reworked or destroyed and redeposited in the Adriatic basin. Thus, today we can find only erosional remnants of the Pleistocene sediments in restricted exposures, but fortunately at many locations within the study area.

The study of Pleistocene sediments led to the recognition of glacially derived deposits - tills (unconsolidated) and tillites (consolidated). Tills/tillites are considered as primary sediment type of glacigenic origin. They strictly accumulate in direct contact with ice in form of subglacial, inglacial or supraglacial till.

Tills and tillites are represented by different types of diamict lithofacies: matrix-supported breccia or conglomerate, clast-supported breccia, and the most prominent type – the mega-breccia. The type-locality of the mega-breccia lithofacies is in Velika Paklenica, but it occurs on Krk Island at locations Baba and Gajevi.

BABA tillite (location 2)

Baba is an erosional remnant of a massive morainal sedimentary body that is a 24 m high tooth-like rock in the middle of the valley. It is a coarse-grained-matrix-supported breccia, the mega-diamict lithofacies, composed of a densely packed sand- to boulder-size debris with very little clay matrix. Secondary carbonate cement or drusy calcite cement occurs locally. Boulder clasts 1-2 m in diameter are common and float in the coarse-grained matrix. Some of them are ice-faceted with rounded keels/edges. Clasts are predominantly subrounded, although debris of pebble size is angular to subangular. Limestone clasts predominate here. Many clasts are fractured or crushed with a clear dislocation along fractures (ice-shattered clasts).

The tillite was deposited over Eocene "flysch" clastics. Sedimentary characteristics and its position indicate that accumulated in the terminoglacial zone where mixing of subglacial, intraglacial and supraglacial debris is possible, as documented by the presence of both angular and rounded debris.

Baba tillite (mega-diamict lithofacies)

Kame-terraces of Baščanska draga valley

The kame-terraces form in ice-contact zone and are commonly extensive sedimentary bodies developed by sediment accumulation in the zone between a valley glacier ice-margin and a valley slope. They are characterised by glacifluvial deposition during the ice stagnation or recession. The accommodation space grows as ice melts, and first deposit lateral dump moraines, which form a substrate for glacifluvial accommodation. Rather complex sedimentary bodies can form as a reflection of ice-volume fluctuation. It is common that accumulation space of the kame terrace is destabilized by the ice recession, and disintegration of those sediments can occur, which decreases their preservation potential. Thus they are rarely described from ancient glacial environments. Various phases of its degradation and aggradation can be recognized in modern glacial environments.

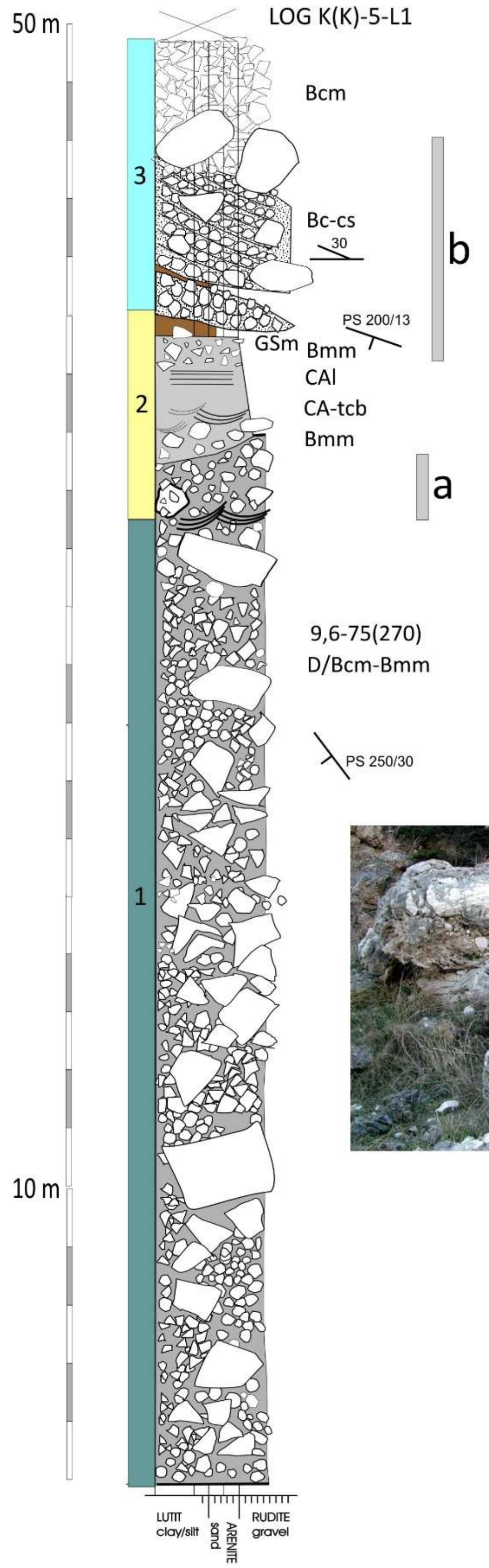
Different processes of accumulation are included in kame-terrace formation. Firstly, a glacier must carry abundant supraglacial debris, and even inglacial debris in ice-marginal cracks and a lot of cryoclastic slope material is commonly accounted for. When ice tongue melts, supraglacial marginal debris is dumped along valley slopes and stratified away from the ice margin. The slopeward dip of the stratified moraine is the main characteristic of these lateral ice-contact sedimentary bodies, which, if preserved, can form expressed terraces in the relief of a glaciated valley. These characteristics are visible at locations Gajevi and Jurandvor. Supraglacial debris can mix with cryoclastic debris avalanching from valley slopes. The advancing ice melt enlarges the accumulation zone, and more meltwaters enter the area, so glacilacustrine, glacifluvial and alluvial deposition can take place. Sediment accumulation fills up the space between ice and the valley slope forming a kame terrace.

In Baščanska Draga valley they represent erosional remnants of larger sedimentary bodies which extended along both valley slopes. They are partly preserved on the southwest and northeast slopes of the valley and are best exposed at Gajevi and Jurandvor. They occur between the modern sea level and 200 m a.s.l. Their estimated (preserved) maximum hight is about 200 m, and estimated lateral extent is more than 1 km.

Gajevi kame-terrace (location 3)

The Gajevi kame-terrace has vertical extention between 50 m and about 200 m a.s.l. It consists of four allostratigraphic units: unit 1 is composed of the mega-breccia, unit 2 is the galcifluvial trough cross-bedded calcirudite with large boulders inclosed by periodical avalanching of the supraglacial marginal moraine, unit 3 are cross-bedded massive breccias dipping slopewards at around 30°, and unit 4 is younger tillite. The oldest associated sediment is the matrix-supported breccia attached to the vertical section of the valley slope and represents the lateral moraine at maximum extent of the valley glacier.

GAJEVI LOWER KAME TERRACE



b

Cross bedded clast-supported breccia (diamict) of the unit 3, down-lapping on unconsolidated gravelly calcarenite of the glacifluvial unit 2. Clinoform bed is visible at the bottom of unit 3.

Koso uslojena breča sa zrnskom potporom (diamikt) jedinice 3, koja naliježe na nekonsolidirani šljunkoviti kalkarenit glacifluvijalne jedinice 2. Klinoformni sloj breče vidi se u baznom dijelu jedinice 3.

a

Lower section of the glacifluvial unit 2, with trough-cross bedded calcirudites. Large boulders are supraglacial moraine avallanched from ice margin.

Donji dio glacifluvijalne jedinice 2, s koritasto-koso uslojenim kalkruditima. Veliki klasti predstavljaju supraglacijalnu morenu koja se obrušavala s rubova ledenjaka.

ALLOSTRATIGRAPHIC UNITS

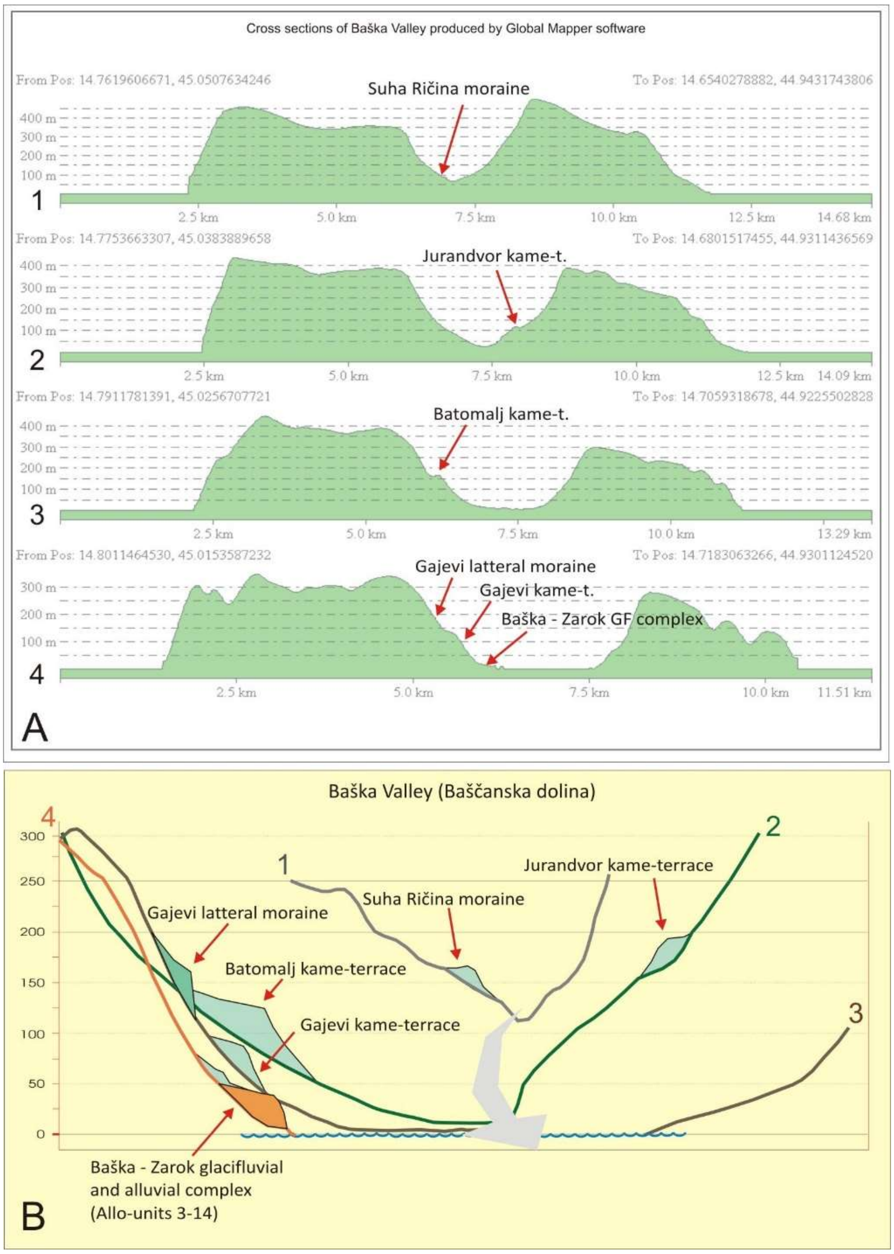
4	Younger tillit / *Mlađi tilit*
3	Lateral dump moraine / *Bočna stratificirana morena*
2	Glacifluvial deposits / *Glacifluvijalni sedimenti*
1	Paklenica Member tillite / *tilit Paklenica člana*

Sediment log and interpretation of the Gajevi kame-terrace.

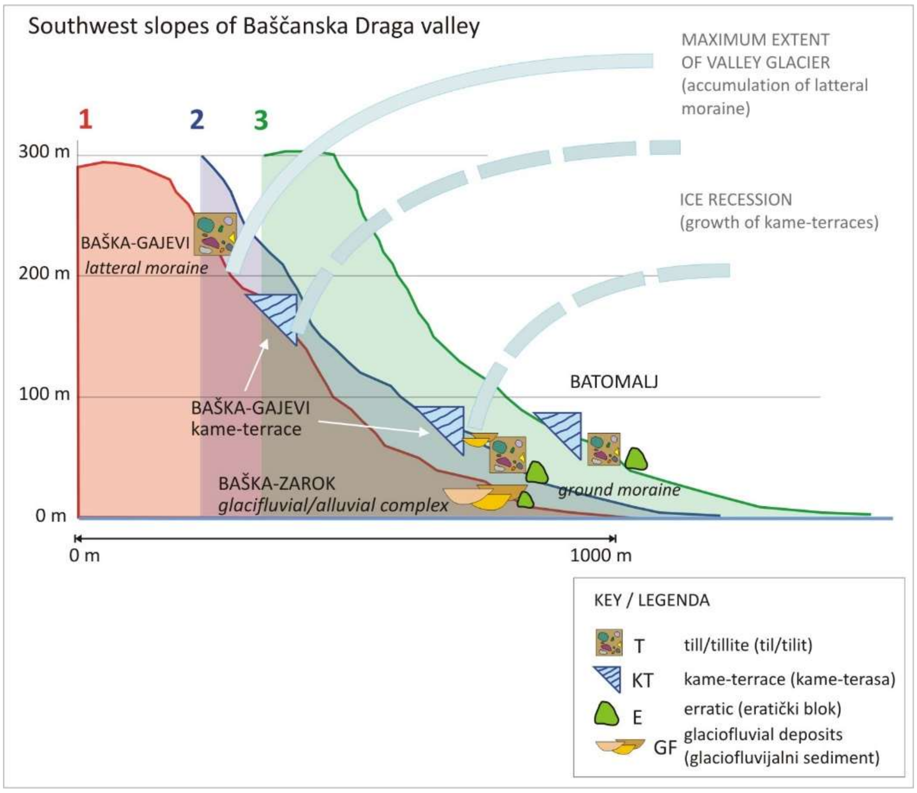
Jurandvor kame-terrace (locations 4 and 5)

The Jurandvor kame-terrace is located between 150 and 190 m a.s.l. It is morphologically prominent terrace, about 250 m long and about 200 m wide. It is traceable further along the valley slope towards Baška for about 1 km, but with interruptions.

The terrace is built of coarse-grained poorly-sorted carbonate breccia, locally interbedded with cross-bedded coarse-grained calcarenites. The sediments dip slopeward at an angle of 30-40°, and their visible thickness is about 45 m. There are abundant cobles and metre-sized blocks.



The four cross sections of Baščanska Draga valley (A) with position of the kame-terraces.



Three phases of the Baška valley glacier reconstructed from the kame-terrace deposits.

Proglacial and periglacial sediments

A vastness in front of a glacial terminus, considered as periglacial area, differs in terms of a terrestrial terminus or if ice cap or glacier ends in a marine or lake basin. Generally accepted definition of the term “periglacial” is that the periglacial area covers a continental area with permafrost and cryogenic processes, while the term “proglacial” referrs to the depositional environment in front of an ice cap or a glacier, directly influenced by meltwaters and thawing and freezing processes.

Herein, both terms are used in the sense that proglacial (ice-proximal) sediments are those deposited in the ice front area and periglacial (ice-distal) are those deposited away from direct influence of the ice, but still affected by cryogenic processes and waters from distant ice.

ZAROK glacifluvial complex (location 6)

Detailed sediment logging and outcrop mapping enabled differentiation of 14 allostratigraphic units (see Appendix).

Allostratigraphic units 1 and 2 mark marine transgression and compose a transgressive fining-upward sedimentary sequence ranging from shoreline to shallow shelf deposits. Unit 1 lays at pronounced angular unconformity above the tectonically steepened Eocene clastics (Paleogene ”flysch”). It consists of the matrix- to clast-supported conglomerate and breccia occurring along the transgressive contact. Unit 2 consists of shallow marine cross-bedded and rippled calcarenites with Pleistocene benthic foraminifers Astrononion stelligerum, Bulimina fusiformis, Bucella frigida, Elphidium Crispum, and Ammonia beccarii. These two units

Allostratigraphic units 3 to 14 are terrestrial depositional units predominantly composed of sands and gravels deposited in fluvial environments, but also matrix-supported breccias occur. Their boundaries are erosional and commonly associated with paleosoils.

Interpretation of the allo-units

Presented allostratigraphic units and their arrangement indicate a complex depositional history, with different intensity of erosional periods or events manifested in deep erosional incisions into paleorelief. The erosional events of lower intensity formed shallow and medium-size channels, which laterally migrated and were conduits for subaerial debris flows that filled the channels. It is clearly visible that all allostratigraphic units are bounded by more-or-less pronounced erosional surfaces marking either onset of outwash and flooding, fluvial incision and deposition, or non-depositional period and soil formation like 5A, 10A, 12A and 14A.

The erosional boundary of the allo-unit 3 marks the onset of the first glacifluvial depositional cycle represented by the allo-units 3 and 4. After Early Pleistocene marine transgression (allo-units 1 and 2) of unknown duration, deposited terrestrial clastics of the allo-unit 3. Because of still insufficient data and lacking age of the allo-unit 3, it is just assumed that a stratigraphic gap between the units 2 and 3 represents the Early/Middle Pleistocene boundary. The sediment characteristics of the allo-unit 3 show that there must have existed an exuberant source of debris and high energy subaerial environment for transport and deposition. The paleotransport directions, channel orientation and low gradient, and deep erosion of the chute channel deposits indicate that the source could not have been in nearby slopes seen today, but only in a proglacial zone of a temperate glacier. This is also indicated by the characteristics of the following younger allo-unit 4 that consists of braided stream sediments, which are commonly deposited in proglacial outwash plains. The erosional character of this unit is not distinct, meaning that ice was receding slowly and meltwaters had lower energy, thus formed braided water flows and deposited finer debris - sands and fine gravels. Thereafter, it is possible that the units 3 and 4 represent one of the glacial periods within "Cromerian complex" recognized in NW Europe.

The pronounced erosional boundary of the allo-unit 5 is marked by the paleosol 5A, the radish-brown clay probably accumulated in freshwater ponds formed on paleorelief before deposition of unit 5 characterized by fluvial deposition.

The allo-units 6, 7, 8 and 9 are recognized as two glacial outwash cycles consisting of chute channel phase and flood plane/basin phase. The allo-unit 6 is dominated by chute channel sediments incised in older allo-units 2 and 5, thus characterized by a pronounced erosional boundary. Not so erosive and extensively preserved allo-unit 7, dominated by sheet-flood deposits (alternation of gravel, sand and clay) may indicate seasonal flooding by thawing glacier, which can be compared to varve sedimentation. Its connection with the glacial environment is indicated by buried erratic boulder found in this unit. These sediments also contain frequent granules of andesite that are considered exotic clasts, because their only source is in the upper part of the Senjska Draga on the Velebit Mt. Another phase of intensive erosion via chute channels is marked by allo-unit 8, which is minor in preserved volume compared to other units. A large faceted and polished boulder found in allo-unit 8 indicates the proximity of a glacier. The overlaying sediments of allo-unit 9 represent another outwash phase with sheet-flood sediments. The sediment complex is attributed to rather extensive Mindel (Elsterian) glaciation period interpreted on the basis of Ždrilo and Paklenica moraines that were dated to a minimum age of 350 ka BP and attributed to the Elsterian glaciation (MIS 12).

The well developed and burnt paleosol 10A is tentatively attributed to the Middle Pleistocene warm period MIS-11 or MIS-9e, but likely represents Riss-Mindel interglacial, the Holsteinian when wildfires could have occurred.

The allo-units 10 and 11 represent a phase of deposition from flood basin to the fluvial channel. Thick point-bar and channel fill sediments indicate the existence of a large meandering river with the wide and deep channel. Paleotransports show nearly N-S orientation of the preserved section of one meander. This cycle assumingly represents a deglaciation phase and the last Middle Pleistocene glacial and postglacial period.

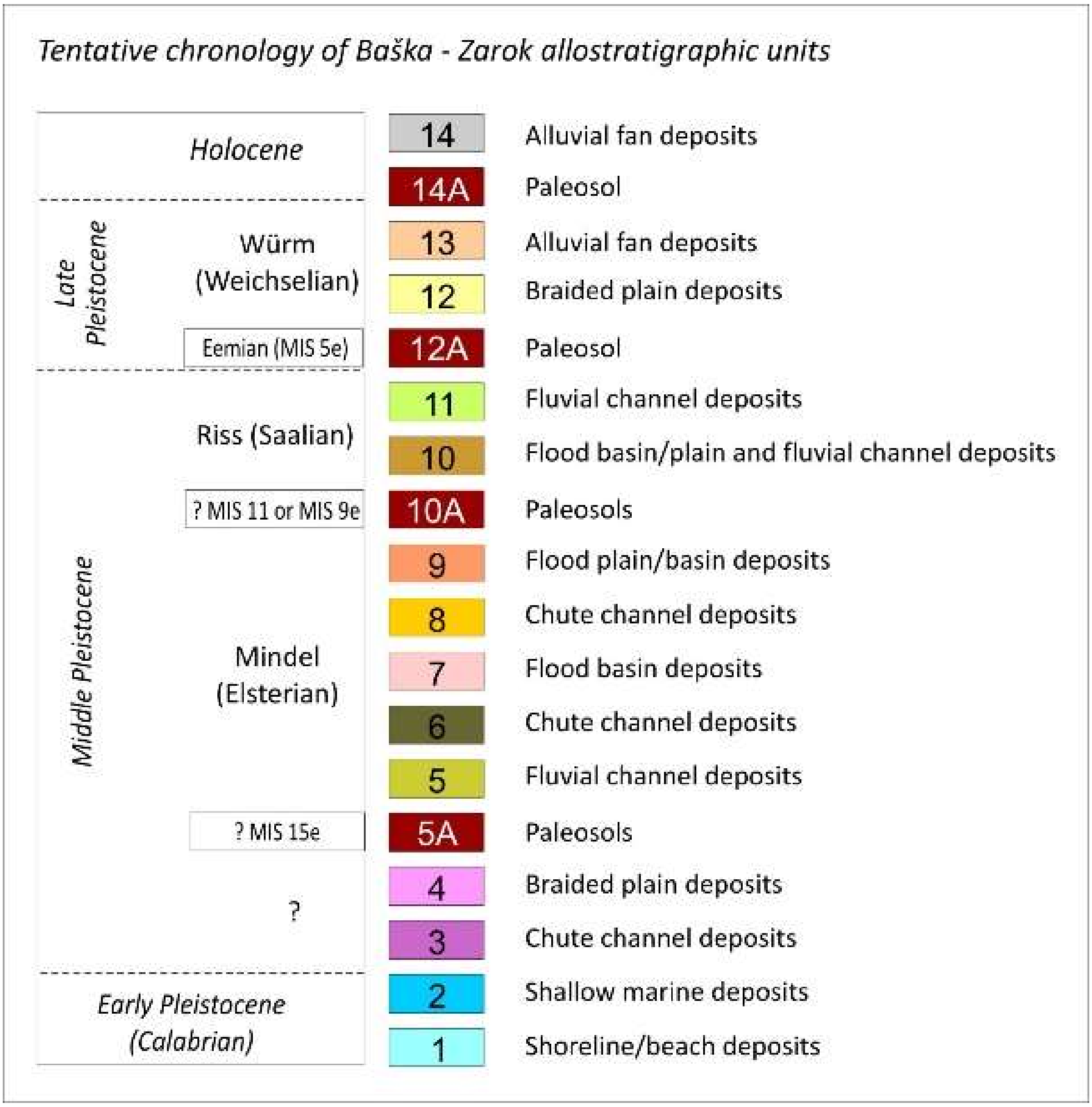
The depositional cycle represented by allo-units 12 and 13 is attributed to the Late Pleistocene documented by the 14C age of the paleosol 12A (dated to 28 ka BP) that corresponds to LGM. That means that a wildfire occurred at that time, but the soil developed earlier, presumably during the Eemian interglacial and was eroded by deposition of unit 12.

The allo-unit 12 represents a periglacial outwash plain and deposition in the braided river which restrained with the end of the last glacial. The allo-unit 13 documents another phase of erosion and resedimentation of older clastics in an alluvial fan. The youngest paleosol 14A presumably marks the Pleistocene - Holocene boundary.

Glacifluvial sediments of Zarok section (units 3 to 9)

Glacifluvial sediments of Zarok (units 9 to 14)

Eratic boulder within unit 7 of Zarok complex.


Tentative chronology of Baška - Zarok allostratigraphic units
Holocene
Late Pleistocene
Würm (Weichselian)
Eemian (MIS 5e)
Middle Pleistocene
Riss (Saalian)
? MIS 11 or MIS 9e
Mindel (Elsterian)
? MIS 15e
?
Early Pleistocene (Calabrian)
14 Alluvial fan deposits
14A Paleosol
13 Alluvial fan deposits
12 Braided plain deposits
12A Paleosol
11 Fluvial channel deposits
10 Flood basin/plain and fluvial channel deposits
10A Paleosols
9 Flood plain/basin deposits
8 Chute channel deposits
7 Flood basin deposits
6 Chute channel deposits
5 Fluvial channel deposits
5A Paleosols
4 Braided plain deposits
3 Chute channel deposits
2 Shallow marine deposits
1 Shoreline/beach deposits