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GEOME 2
Manuscript received: November 11, 2021
Accepted: Aapril 4, 2022

Geologica Macedonica, Vol. **36**, No. 1, pp. 5–18 (2022)
On print ISSN 0352 – 1206
On line ISSN 1857 – 8586
UDC: 553.548.06(497.11)
https://doi.org/10.46763/GEOL22361005k

Original scientific paper

CONTRIBUTION TO GEOLOGY AND GENETIC PATHWAY OF THE ROPOČEVO BRECCIA – AN "ORPHAN" OLISTOLITHIC BODY WITHIN THE UPPER CRETACEOUS FLYSCH NEAR SOPOT (CENTRAL SERBIA)

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A b s t r a c t: The Ropočevo breccia, a dimension stone highly prized in 20[th] century, has been examined by numerous prominent geologists of the time. It is revisited by researchers still intrigued by its perplexing provenance. Its position as a rigid exotic block of hard and completely metamorphosed carbonate breccia within the moderately lithified Upper Cretaceous flysch sequence remains unsolved due to absence of its source. Large bodies of a monomictic breccia suggest a relatively monotonous protolith carbonate sequence of significant thickness, such as those being formed in a calm marine environment with gradually sinking bottom due to epeirogenic movements. Varicoloured laminations indicate slight variations in the feeding material due to the epeirogenic oscillation of the basin bottom level. There is no regularity in clast distribution regarding size, colour or roundedness degree. This, paired with the occurrence of the "in-place brecciation" suggests a sudden fall of brecciated material due to a "catastrophic" event, such as earthquake, collapse brecciation due to karst dissolution and a large sinkhole formation, or a graben/trench formation as in onset of the extensional processes.

Key words: marble breccia; olistolith; Upper Cretaceous flysch

INTRODUCTION

In Ropočevo village, 30 km SSE from Belgrade (Figure 1), there is a relatively small marble breccia body found as an olistolith within the Upper Cretaceous (Coniacian to Maastrichtian) flysch deposits (Pavlović, 1980) formed within the closing Neotethyan oceanic domain – the Vardar ocean. It is considered to be discovered by J. Žujović in 1893 (Janković, 1971). Anđelković (1953) found another similar olistolithic block of breccia; however, it is nowadays inaccessible for examination underneath the Sopot city. The properties of the rigid marble breccia body and the surrounding flysch sequence make it clear that they have had quite dissimilar temperature histories.

The breccia deposit has been mined since circa 1929 to 1970 for dimension stone used for interior and exterior cladding and paving in many important public edifices and private villas in former Yugoslavia (northern Balkan Peninsula), one of them being the National Museum in Belgrade. The varicoloured appearance of the breccia has made it one of the country's most picturesque and popular dimension stones during that time period (Đorđević et al., 1991). This in turn made the mining and processing financially feasible, regardless of the small size of the breccia body and presence of joints (Delić-Nikolić et al., 2018).

Fig. 1. Geographic position of Ropočevo (source: Google maps).

The drilling explorative works performed after the WW2 have shown that breccia body has an approximately lenticular shape with the length of circa 100 m, maximum thickness of 30 m and sharp boundaries toward the surrounding flysch deposited as regular layers around breccia body (Figure 2). The longer axis of the breccia body trends along NW-SE direction (Janković, 1971).

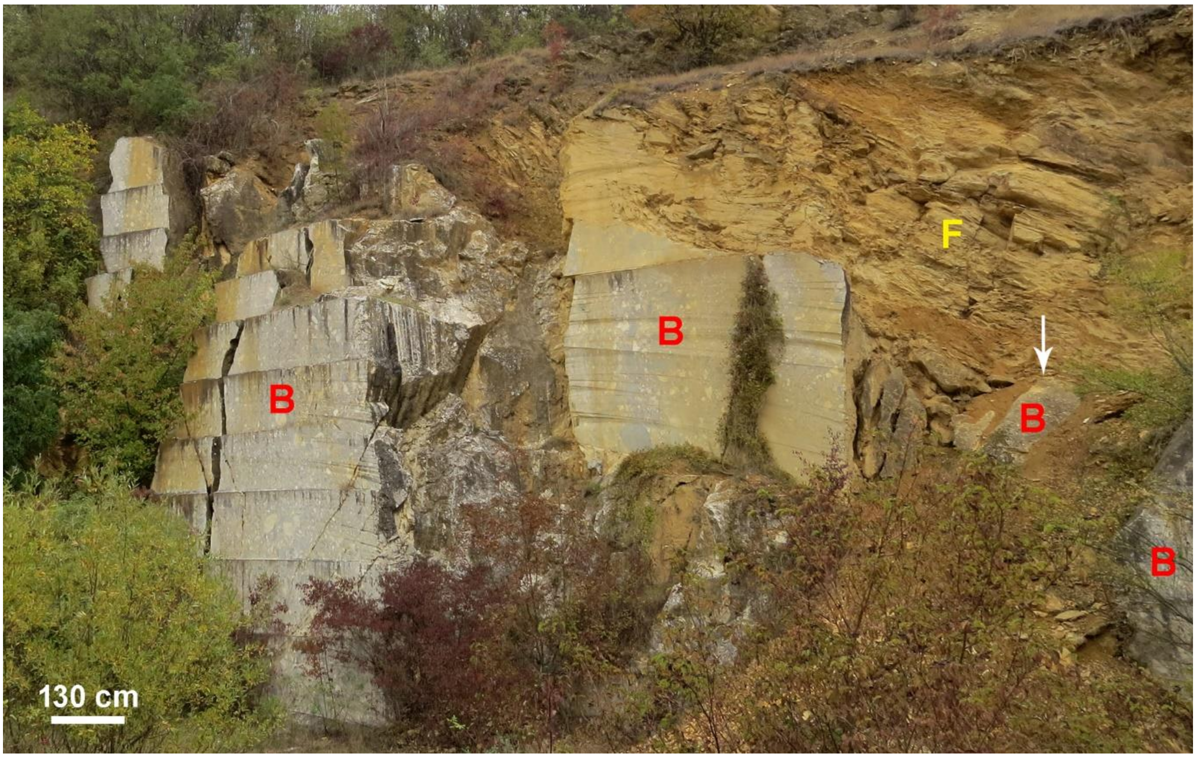

Fig. 2. The appearance of breccia open pit mine in village of Ropočevo today.
Key: B – breccia bodies; F – layers of Upper Cretaceous flysch deposited over and around breccia bodies; white arrow points to smaller blocks of marble breccia emerging from the surrounding flysch due to erosion.

A geologic peculiarity of the Ropočevo breccia deposit is that it comprises an "orphan" exotic megaclast-olistoliths whose source has not been determined despite the several decades of the explorative effort of the Serbian prominent geologists. Some authors still consider that the determination of its provenance would solve some important questions on tectonic evolution of the Sava-Vardar zone (Spahić et al., 2022). Due to the absence of fossil records, its age and provenance are still unknown and the absence of the source rocks is a major impediment to working out its origin and genetic model. It has been hypothesized by Luković (1958, from Janković, 1971) that it might originate from layered marble deposits in Venčac near Aranđelovac, situated 30 km to the south. Venčac marble sequence indeed contains white and light grey horizons with weathered yellowish parts. However, the Turonian-Maastrichtian limestone layers have been metamorphosed into marble locally at Venčac Mt. by Bukulja pluton only in Neogene (Brković et al., 1980), while there is solid evidence (presented in Janković, 1971 and references therein) that the consolidated marble breccia lens slid into the Upper Cretaceous flysch sequence contemporaneously with its deposition. The more recent examinations (Trivić et al., 2010) have shown the Venčac marble sequence as a part of the Birač formation of Carboniferous age, but agree on its metamorphism in Neogene. More differences are found by petrographic analyses (unpublished data of IMS Institute Stone and aggregate laboratory archives): Venčac marbles often include macroscopic calcite-limonite veins and microscopic quartz and muscovite grains, none of which have been found in marble clasts of the Ropočevo breccia.

This work aims in presenting the newly found data on Ropočevo marble breccia as a pathway to future provenance studies, and its hypothesized genetic pathway based on complete data set – both former and new.

GEOLOGIC SETTING

The geology of the area has been shown in great detail in Anđelković (1953), Janković (1971), Brković et al. (1980), Radulović (1987), Sajić (1987), Zrnić et al. (1998).

Two of thus far discovered exotic breccia bodies (Anđelković, 1953) as megaclasts of the unknown provenance and age have fallen or glided into the Upper Cretaceous (Coniacian to Maastrichtian) flysch during its ongoing deposition. The flysch formed within the regional environment of the closing Neotethyan oceanic basin, within the convergent margins setting, before the collision and complete closure that happened in Maastrichtian (Toljić et al., 2019). These syn-contractional turbidites comprise gray sandstone, sandy marlstone, limy marlstone and limestone with pelagic microfauna and rare tiny benthic foraminifers (Toljić et al., 2018). In the Ropočevo deposit, the flysch members underlying breccia body are represented by dark grey marly limestone, marlstone or marly sandstone. The overlying flysch sequence is made up of marlstone, sandstone, limestone or marly sandstone (data from Janković, 1971 and references therein, from the time period when the hanging wall existed – before the largest part of the largest breccia body has been mined out). The contact between the breccia body and surrounding flysch layers is very sharp and clear.

The Maastrichtian collision and subsequent extension in Neogene have created a complicated tectonic picture of the area – folding, faulting, thrusting, differential movement of tectonic blocks and magmatic activity. The ophiolitic melange of Middle to Late Jurassic age has been obducted over younger formations (cropping out further north at Trešnja). Neogene extension resulting in terrain subsidence also caused the formation of large lacustrine areas that have existed during Miocene (Brković et al., 1980; Figure 3). Neogene magmatic activity created the ring volcano-tectonic structures and hydrothermal alterations as evidence of subvolcanic intrusions 5 km to the west of Ropočevo at Stenička Bara–Babe village area, quartzlatite pyroclastics, rhyolite dikes and the extensive Pb-Zn-Cu-Ag hydrothermal veins accompanied by silification in the Babe village (Radulović, 1987).

Marly sediments predominate within the Upper Cretaceous flysch formation east of Babe, while the sandy sediments predominate west of Babe village, marking the transition from the deeper marine environment into the sublittoral environment westward (Anđelković, 1953). Parts of Upper Cretaceous flysch are enclosed and metamorphosed by Neogene magmatic bodies. However, the flysch sediments surrounding the Ropočevo breccia bodies show no evidence of such thermal influence.

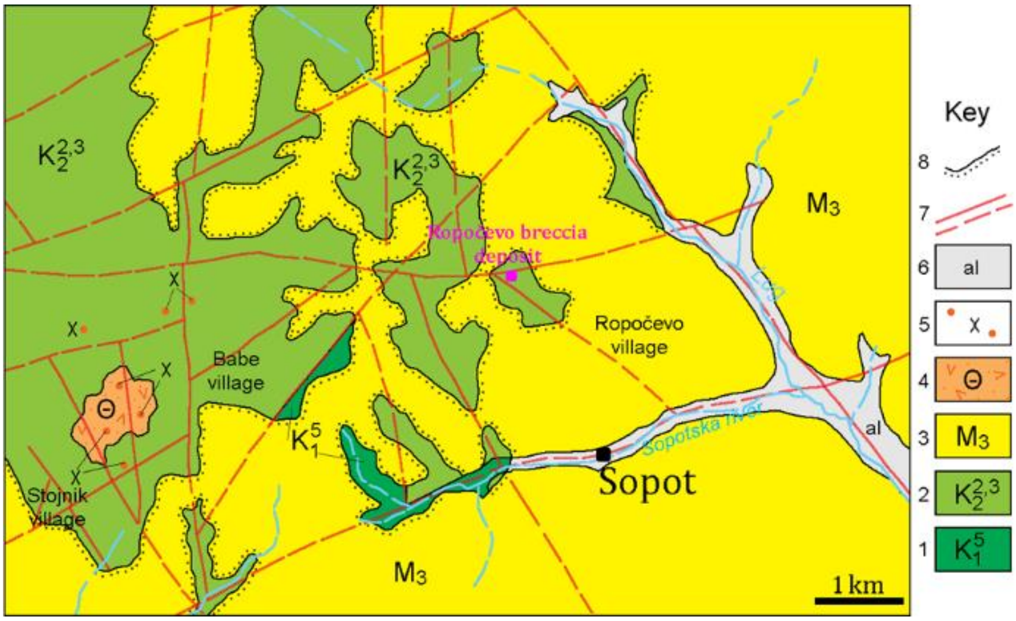

Fig. 3. Simplified geologic map of the Babe–Ropočevo area (modified from Brković et al., 1980).
Key: 1) Lower Cretaceous sediments: Albian sandy marlstone, marly limestone, ferruginous sandstone;
2) Upper Cretaceous flysch: marlstone, sandstone, sandy marlstone, sandy limestone, marly claystone and reef limestone;
3) Upper Miocene* (Sarmatian oolithic and sandy limestone and Pannonian sand, sandy clay, sandstone); 4. quartzlatite pyroclastics;
5) rhyolite dikes; 6. alluvium; 7) faults, observed and assumed; 8) transgressive stratigraphic boundary.
*Division of Miocene for Paratethys domain (e.g. Rundić, 2006)

EXPERIMENTAL SECTION

The examinations of marble breccia have been performed both on historical pavings in several available locations in Belgrade (Military air force command building in Zemun, monastery of Archangels Gabriel and Michael in Zemun, shopping centre by Marko Orešković monument in Novi Beograd) and in the Ropočevo deposit.

Examinations in the Ropočevo deposit

The soundness and durability of the marble breccia have enabled the stone surfaces obtained by sawing performed in the 1970ies to remain stable to this day (Figure 2), while the surrounding flysch sediments are subject to notable erosion. These surfaces enable the observation of clasts, fabric, porosity, karstification and fracturing. The noted conditions include the following:

The rock has a coarse detrital clastic (psephitic) texture and homogeneous structure. It is made up of varicoloured marble clasts and a cementing matrix that is also showing some variations in colour. No clasts of other rock types have been found within the breccia, including flysch, suggesting that it has been formed neither within it, nor contemporaneously with it, despite former hypotheses (Janković, 1971).

Predominant clast colours are white and grey. Less often, yellowish and dark grey clasts are present (Figure 4). Small, black marble clasts are very rare. Many clasts show laminated structure reflected through the changes in colour, reminiscent of carbonate sequences formed within the mud-mounds (Gilli, 1992).

The size of clasts varies greatly – from barely visible to several tens of centimetres in diameter (Figure 4). The largest dimension of the largest clast visible in the deposit is 136 cm (Figure 5). The largest clasts are always the grey ones.

Fig. 4. Appearance of clasts on an open surface in the Ropočevo deposit (hammer height = 33 cm). Left side: red arrows pointing to in-place brecciation

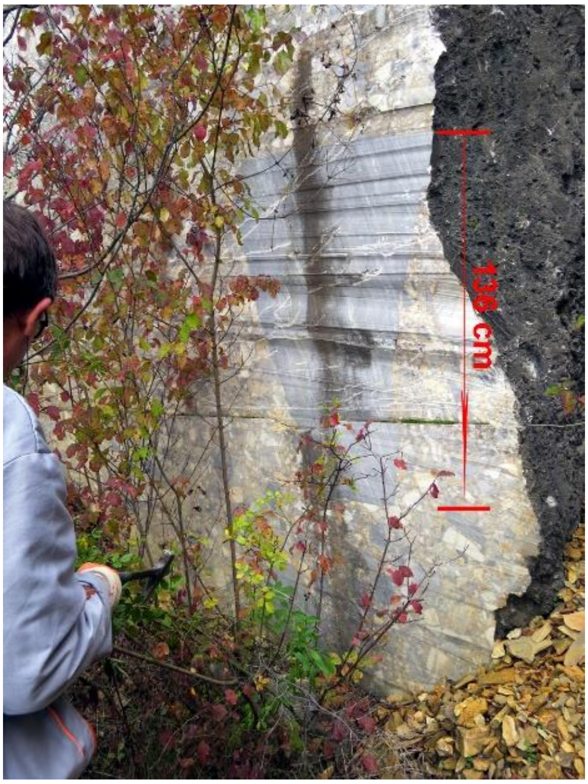

Fig. 5. The largest clast observed in the Ropočevo deposit.

The matrix composition is clayey-marly with iron-bearing minerals as colouring (Janković, 1971). It is cementing the clasts into a rock so hard it is almost impossible to break off a piece. As no signs of silification have been established, the breccia is most probably somewhat metamorphosed (metabreccia). Matrix colour within the deposit today is yellowish-grey. Although not present today in the deposit, the breccia body used to comprise also the parts with ochre and purple matrix colour. The slabs cut out of these parts can be observed in various edifices today, where they were used for paving.

Drilling explorations performed during the 20th century (Janković, 1971) resulted in the ore body model of one large, compact body. However, based on the new data, it appears that the deposit actually consists of a number of smaller breccia bodies instead of a single lens-shaped block. The drilling is probably done through the central part of the deposit, while presently remaining parts are representing its peripheral area. Due to rebalancing of these larger, competent bodies and erosional removal of the surrounding flysch sediments, more of the smaller breccia bodies are emerging behind the larger ones (Figure 2, white arrow). These smaller bodies generally measure up to 1 m in height and up to 50 cm in thickness.

Also, as the larger breccia bodies are gravitationally rebalancing due to erosional release, it is uncovered that the flysch layers have deposited between them, with a steeper dip than the surrounding flysch layers (Figure 6), proving that there was not only one breccia body that slid into the flysch basin. This also proves that breccia was not concordantly deposited within the flysch, as was thought by earlier authors.

Fig. 6. Steeply dipping flysch sediments (A) deposited between the two breccia bodies, showing the gradual transition into the roof flysch sediments with a smaller dip angle (B). Rigid brec-cia bodies showing relaxation-extensional fracturing (C)

Gravitational rebalancing of the rigid marble breccia bodies within the softer flysch sequence being eroded away had caused the formation of the unloading relaxational (extensional) fractures in breccia bodies (Figures 2 and 6, markings "C", Figure 7).

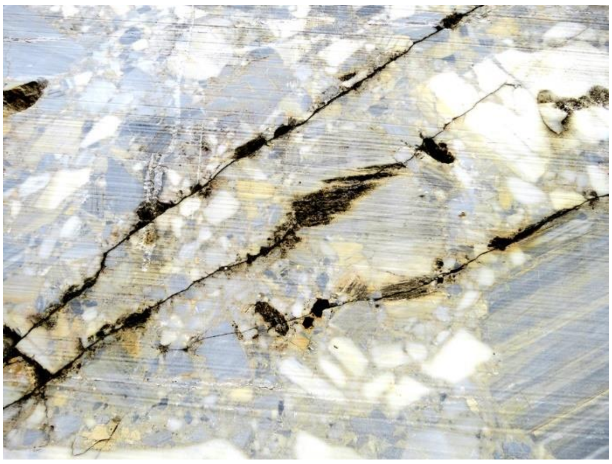

Fig. 7. Selective meteoric flushing of the marble clasts along fractures

Along these extensional-relaxation fractures, the seepage of meteoric water has caused a selective wash-out of certain breccia clasts. It can be observed that the clasts of homogeneous white and grey marble had remained intact through the meteoric flushing, while the laminated ones have been leached and had become extremely porous or are washed out completely (Figure 7). It is probably what Janković (1971) considered a karstification process, since no other prominent vestiges of karstification have been found within the deposit. Rare and faintly expressed rosy-coloured cracks found in some clasts might be the evidence of the incipient karstic processes to which the original calcareous sequence might have been subjected for a relatively short time period before the catastrophic event that had (created and) redeposited the clasts.

There are also the zones of increased porosity along some irregular directions visible in the unmined breccia bodies, not visibly connected to either faults or joints. Here the pores actually are small vugs up to 1 cm in diameter. The subsequent postedpositional circulation (seepage) of meteoric waters with Fe-hydroxide along these pores has caused the cement to locally become yellowish.

Smaller pieces fallen loose off the larger breccia bodies have accumulated within the marly and sandy layers of the flysch sequence, forming a concordant intercalation. This intercalation can involve some larger pieces (Figure 8). The flysch blocks containing the marble clasts intercalation have been found dislocated due to erosion and gravity influence and have not been found in situ.

Fig. 8. A concordant marble clasts intercalation within a marly layer of flysch

Beside the subtle differences in the composition of calcareous laminae due to the presence of impurities, reflected through the changes in colour (white-light grey-dark grey-yellowish) there are also some rare intercalations within the calcareous sequences of the clasts which are notably different in composition. There are two observed intercalations (laminae) types with different mineral composition compared to the purer Ca-carbonate: ferruginous-clayey type and (presumably) microbial mat type.

The ferruginous-clayey type is susceptible to accelerated (in geological sense) meteoric flushing, leaving behind the elongated, irregularly shaped open spaces surrounded by rust-coloured less soluble zones within the marble clast (Figure 9a). The earlier authors suggested that these represent the less metamorphosed limestones (Janković, 1971). However, as they are alternating with fully metamorphosed marble, their metamorphism degree must be equal.

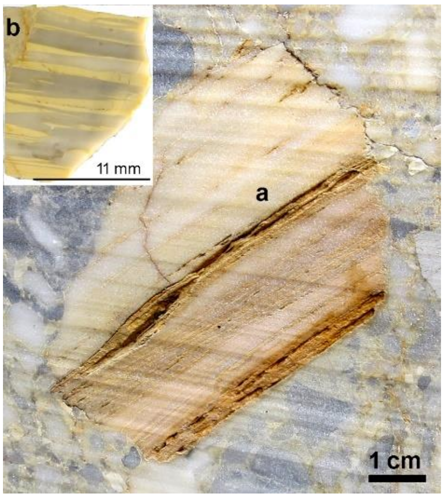

Fig. 9. a) Meteorically flushed ferruginous-clayey intercalation within the marble clast, **b)** Marble clast with microbial mat laminae

The second type of laminae (Figure 9b) are conspicuously more opaque than the surrounding marble laminae, yellowish and macroscopically appear to be from 0.1 to 2 mm thick. These tend to be significantly less susceptible to weathering than the first type and they strongly resemble the mineralised and metamorphozed microbial mat laminations. Lighter laminae (yellowish in our case) are represented by dispersed micritic allochem ("micropeloid") and the darker ones are denser micrite. Micropeloid is considered to be of bacterial origin, or more generally – microbial (Gilli, 1992). In the primary limestone, they most probably appeared as those shown in Figure 5b of Schefer et al. (2010), belonging to Steinalm formation of Anisian age, situated in Studenica quarry.

Some larger clasts (of any colour) are broken apart in the place of accumulation ("in-place brecciation" – Mussman and Read, 1986). These secondary clasts remain unseparated or slightly separated in place of deposition (red arrows in Figure 4; paired arrows pointing toward each other show the direction that would bring the separated clast pieces back together). This occurrence in typical for tectonic breccias and not for sedimentary breccias (Gilli, 1992).

Examination of the historical pavings

The paving slabs have kept their shape and colours, both in interior and exterior. The slab faces subjected to wearing by pedestrian traffic are scratched and worn; however, this is visible only when the observer is at least at 50 cm from the observed surface. Where slabs containing yellowish marble clasts are subjected to the influence of rain, freeze-thaw seasonal action and are near the iron decorative pieces such as a mat holder, the rust from the iron penetrates the body of the slab causing the conspicuous colouration.

Most often, the marble clasts that can be observed in pavings are between 1 cm and 7 cm in diameter. Those observable in the deposit today are somewhat larger (Figure 4). The roundedness degree is also variable. Some clasts are as sharp as if the transport has been completely absent, while the others show a variable degree of rounding (Figure 10).

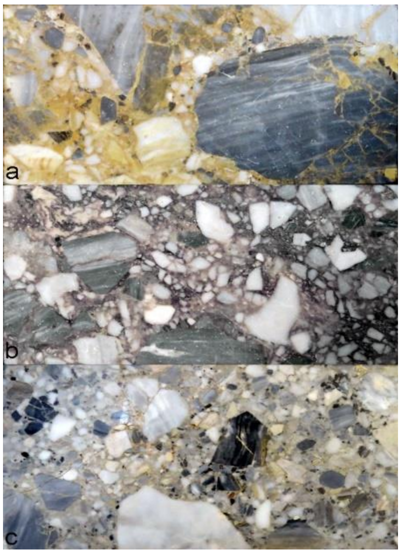

Fig. 10. The three colour varieties depending on the matrix colour: **a)** ochre, **b)** purple, **c)** grey (a,b – paving slabs in the Archangels Gabriel and Michael Monastery in Zemun; c – exhibition of the decorative stone of Yugoslavia in IMS Institute in Belgrade)

The clasts are irregularly distributed within the matrix – the large clasts, the small ones and the medium large ones, angular, subangular and rarely rounded ones, with no visible rule of distribution or preferential directions. Gradation is completely absent. The clasts can be so densely packed up to the point that there is very little matrix between them, but they are mostly matrix-supported.

Wavy, irregular boundary between the purple and ochre zone can be observed in Figure 11. The incidence of clasts of certain colour and degree of roundedness in purple-coloured and ochre-coloured matrix zones is shown in Table 1.

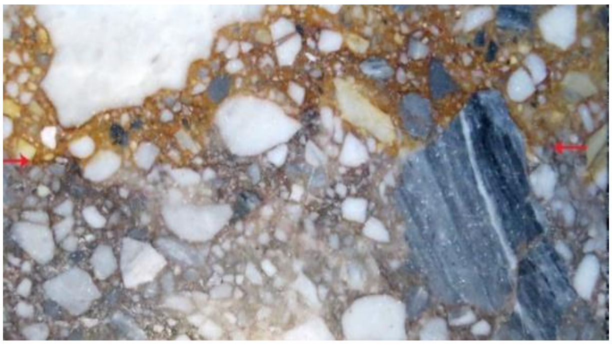

Fig. 11. Wavy boundary between ochre- and purple-coloured matrix zones marked with red arrows (floor of Archangels Gabriel and Michael Monastery in Zemun)

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The incidence of clasts of specific colours and roundedness degrees observed in slabs in historical pavings.

Cement colour		White marble			Homogenous and banded light grey marble			Dark grey, banded marble			Black marble			Yellowish marble		
		Small	Moderate	Large	Small	Moderate	Large	Small	Moderate	Large	Small	Moderate	Large	Small	Moderate	Large
Purple (hematite-colouring)	NR	X	X	<	<	X		<	<<		<<					
	PR		<	<		X	X		<	<		<<				
	R								X							
	Notes				Large PR are BIS by the boundary with ochre-coloured cement zone			Dark grey clasts are more rounded than other clasts as if they were transported somewhat longer distance or were softer								
Ochre (limonite-colouring)	NR	X	X				<<	<<	<<		<			X		
	PR	X	X	X		<<	<<			<				X	<	
	R														<	
	Notes	Large PR are BIS when they contain light grey and yellowish bands			Large PR are rarely ever BIS			Large NR and moderately large NR are BIS, probably softer due to larger content of organic matter or clay						Many yellowish clasts are BIS, probably due to softness (limestone-marble?)		

Key: NR – angular (non-rounded); PR – partly rounded (subangular), having both non-rounded and rounded parts; R – rounded clasts;
X – abundant and predominating; < – more rare; << – very rare; BIS – broken in the place of clast deposition ("in-place brecciation").
Clasts' diameter size: small – under 2 cm; moderate (moderately large) – from 3 cm to 7 cm; large – over 7 cm

In breccia zones with purple matrix, white clasts predominate – small, moderately large, more rarely large, non-rounded and partly rounded (Figure 10b). In descending order of incidence, the light gray clasts follow, which are medium to large, non-rounded, or more rarely partly rounded. Dark grey clasts are rarer, moderately large to large, partly rounded, more rarely angular. The rarest clast colour is black. The black marble (limestone) had probably existed only as small portions – thin horizons within the grey parts of the primary carbonate sequence.

In breccia zones with ochre-coloured matrix, white clasts also predominate, partly rounded, more rarely angular, small to large (Figure 10a). The next clast colour in the descending order of incidence is yellowish, most often small, angular to partly rounded, more rarely moderately large, partly rounded to rounded. The clasts with alternations of grey and yellowish stripes, yellowish and white, and yellowish, grey and white combinations are present. Both purely white and yellowish clasts can be present independently next to each other and both colours can be present in one clast as alternating stripes.

At the boundary between the zones of purple and ochre-coloured matrix, the only apparent change is the oxidation level of the iron impurities within it (hematite-limonite), while the clast colour incidence significantly changes only for the yellowish ones. They are present only within the ochre-coloured zone, or within the purple zone near its boundary with the ochre-coloured zone. This might suggest that yellow tinge in the white marble is not primary, but a consequence of its top layers' exposure to weathering. In modern position of the breccia body, the yellowish and white clasts are present in irregular dispositions along the entire open section, suggesting that the presence of the yellowish clasts is not a consequence of Fe-hydroxide seepage in situ, at least not entirely.

Microscopic examination

Microscopic examination under polarizing light focused specifically on smaller-sized clasts breccia parts in order to examine the matrix, and the clasts containing yellowish opaque laminae (the second type described above). Petrographic examinations are performed in the Stone and aggregate laboratory of the IMS Institute. Microscopic analysis is performed on thin sections with polarizing microscope Ernst Leitz RP 48. Field of view for all microphotographs is (1.55 × 0.88) mm.

Microscopic analysis has shown that the breccia is made up of the clasts and matrix. Clasts are unrounded. The white clasts are made up of former limestone, probably grainstone, completely metamorphosed into marble. The grey and yellowish clasts are made up of laminated, finely crystalline former limestone metamorphosed into marble to a somewhat lower degree. The clasts are monomineral, with no grains other than calcite. The marble itself, within the clasts, has a granoblastic texture and homogeneous structure.

Based on the size of calcite grains, the clasts can be divided into two types: finer- and coarser-grained. Finer-grained type marble is made up of isometric calcite grains of minimal size (0.1×0.1) mm with straight boundary shapes. This type contains parallel laminae of varying thickness (from below 0.1 mm to ~0.75 mm), probably of carbonate-clayey composition (Figure 12a,b; for macro-image see Figure 9b). Coarser-grained marble clasts are made up of calcite crystals of size up to approx.-imately (0.3×0.2) mm, also with straight boundary shapes (Figure 12c-h).

The matrix is limonitic-clayey with calcite grains 0.05–0.15 mm in diameter, uniformly distributed throughout the matrix. The distances between the clasts are most often between 0.2 and 1.5 mm. Since the matrix contains tiny calcite crystals, it probably originated from dissolution of the parental carbonate rock itself.

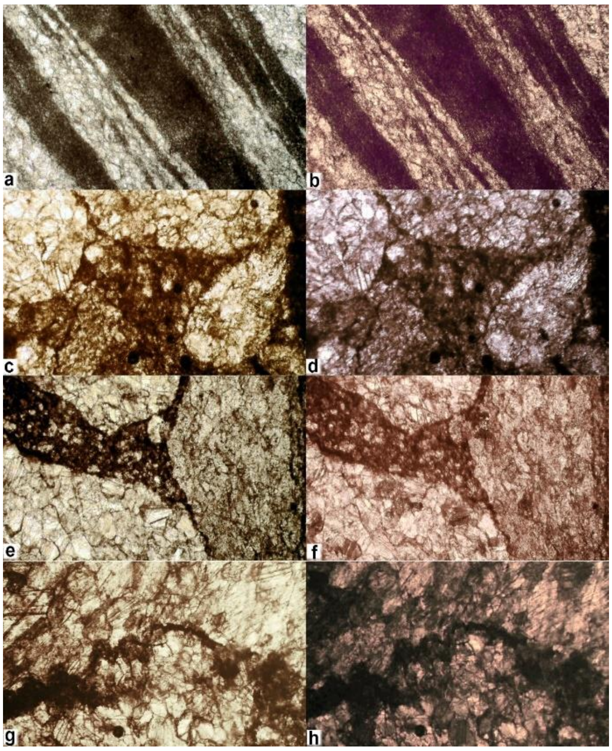

Fig. 12. Microphotographs of marble breccia: **a.** Lamination inside a light grey marble clast, PPL; **b.** Ibid., XPL (macro shown in Fig. 9b); **c-f.** appearance of marble clasts within a matrix (c,e – PPL; d,f – XPL); **g.** calcite grains of a marble clast with a veinlet of impurities, PPL; **h.** Ibid., XPL

Technical properties testing

Testing of the technical (physico-mechanical) properties is performed in Stone and aggregate laboratory of the IMS Institute in Belgrade and the results are shown in Table 2. The testing is performed according to the appropriate Serbian standards which are compatible with the cited European norms. The testing results of Venčac marble samples are given in parentheses for comparison.

Table 2

Technical properties of the Ropočevo breccia

Tested property	Testing method	Units	Testing results	
			Value range	Average value
Water absorption	SRPS B.B8.010 /EN 13755	%	0.10–0.26 (0.11–0.39)	0.14 (0.20)
Uniaxial compressive strength: – dry	SRPS B.B8.012 /EN 1926	MPa	119–199 (91–158)	163 (121)
– water–saturated			162–180 (58–153)	170 (97)
– after 25 freeze–thaw cycles			140–164 (62–135)	157 (97)
Resistivity to abrasion	SRPS B.B8.015 /EN 14157	cm^3/50 cm^2	23.49–24.87 (29.55–30.21)	24.29 (29.84)
Flexural strength	SRPS B.B8.017 /EN 12372	MPa	12.17–15.68 (–)	13.96 (–)
Apparent density	SRPS B.B8.032 /EN 1936	g/cm^3	2.680–2.730	2.700 (2.674)
Particle density		g/cm^3	–	2.750 (2.713)
Porosity		%	–	0.018 (1.7)

The stone is stable and resistant to frost action through freeze-thaw cycles and salt crystallization

DISCUSSION AND CONCLUSION

The absence of a parental rock formation has deprived the geologists of a large amount of information on the origin of the Ropočevo marble breccia. Yet, the intrigue by its geological position within the anachronous sedimentary flysch formation does not recede. The precise age of marble hasn't been determined either, due to the absence of the fossil remains in it. As no fossil remains or the parental rock source are available, we can hypothesize on its genetic pathway based on the available data:

Old hypotheses on genetics

Without the mentioned data, the apparent concordant position of the breccia body within the flysch sequence of Upper Cretaceous age has given birth to many hypotheses on how a relatively small breccia body might have formed during the closure of the Neotethyan ocean (we presume that the previous authors interpreted the smallest grains deposited concordantly within the marly flysch layer as the entire marble breccia is a concordant body).

Many senior geologists, partaking in examination of this enigmatic deposit, have been considering its possible genetic scenarios, most of which considered the breccia to have been formed concordantly and coevally, where it is today, trying to locate the original source of the clasts. Such viewpoints are long time abandoned and even Janković (1971) had noticed an absolute absence of flysch clasts within the marble breccia as a proof that it is in fact an exotic block – an olistolith.

Obradović (1967, from Janković, 1971) was the first to recognize this breccia body as an exotic block that slid into the flysch basin from elsewhere. Janković (1971) went on to conclude on its origin as an olistolith. He explained that the eastern margin of the flysch basin (East Vardar zone) was made up of Palaeozoic schist with marble portions that were eroded, reworked and redeposited within the littoral-sublittoral environment, while at the same time suggesting that the primary breccia formed within the calm environment. Further on, he hypothesized that Senonian (Coniacian to Maastrichtian) earthquakes caused parts of semilithified breccia to break off and slide into the deeper parts of the basin. On the other hand, Luković (1958, from Janković, 1971) believed that the breccia body originated from the "Palaeozoic belt that existed along the eastern flanks of the flysch basin from Belgrade towards the south, up until the Neogene". This Palaeozoic belt would have been made up of micaschist, phyllite and slate with marble lenses, identical to geology of Venčac Mt. This view might partly be true; however, the "Palaeozoic belt" might have been the eastern flanks of Jadar block terrane and placed west of the flysch basin. Such sequences indeed exist today as a part of the nappe-stacked Adria margin, formed in a vast and stable carbonate platform, outcropping over 60 km to the west (Filipović et al., 1973). Thick, predominantly Ca-carbonate sequence begins with Upper Permian and continues until Middle Triassic, having total thickness of 420 m. The Lower Triassic limestone lacks fossil remains, since it has been formed after end-Permian extinction (Pomar, 2020).

Venčac marble sequence on the other hand is ~ 40 km to the south, Cretaceous (or Carboniferous – Trivić et al., 2010) in age and metamorphosed by Bukulja intrusion in Neogene (Brković et al., 1980), while the Ropočevo breccia body has already glided into the flysch sequence during Upper Cretaceous.

Breccia metamorphosis level

Flysch sedimentary units surrounding breccia bodies are not metamorphosed, suggesting that the two formations had different thermal histories and that metamorphic degree of the marble in breccia has been accomplished elsewhere. There is no evidence of the soft sediment deformation during compaction, so the carbonate formation has already been lithified/metamorphosed into marble before the erosion and clast formation.

The macroscopic appearance of the breccia gives an impression that all the present clasts are marble, however, the microscopic analysis has shown that some clasts are actually an incompletely metamorphosed limestone, possibly from the younger parts of the carbonate formation. Nevertheless, no other rock composition had been noted within breccia, thus permitting it to be classified as monomictic.

Matrix matter origin

Since breccia is monomictic, the material that formed the primary clayey-ferruginous matrix probably originates from the same parental Ca-carbonate sequence. The microscopic analysis has shown that the matrix contains tiny calcite crystals, confirming its origin from dissolution of the parental carbonate rock. Clay as a common constituent of Ca-carbonate rocks remains chemically inert during the weathering process. Iron, another common constituent of calcareous rocks, changes oxidative state depending on the environmental conditions. Both constituents can be eroded and redeposited along with carbonate clasts in hypsometrically lower areas favourable for accumulation. The colour zonation of the matrix would then point to a local water table position in the accumulation locus where the breccia formed.

Clast roundedness

The clast roundedness degree is also variable. Some clasts are as sharp as if the transport had been completely absent; while the others show a certain degree of rounding, pointing to either at least a short transport of the clasts, a different degree of diagenesis/metamorphism within the primary carbonate sequence creating differences in softness degree, or both. This suggests a significant thickness, compositional homogeneity and open surface area of the parental carbonate sequence.

Clast distribution

As is typical for tectonic breccias, the clasts are irregularly distributed within the matrix – regarding size, roundedness degree and colour, with no visible rule of distribution or preferential directions. Gradation is completely absent, suggesting an abrupt movement and redeposition of clasts in a subaerial environment.

Redox boundary (water-table level) influence on matrix colour

The transitions from the zone of purple-coloured matrix into ochre- and grey-coloured matrix can be found, however, the transition from the grey-coloured matrix into ochre-coloured zone matrix has not been observed. As the zoning in the matrix colouring does not correspond to the contemporary position of breccia lens (in the sense of water-table, i.e. redox boundary position), it can be inferred that it formed at the place of the clast accumulation and primary breccia formation, reflecting the position of ground water level existent in that former environment.

In-place brecciation

In-place brecciation of some larger clasts (of any colour) suggests a sudden fall of eluvial-colluvial material from a significant height, such as in "catastrophic" event, rather than the gradual gravitational creeping along the slope. The event might be an earthquake, collapse brecciation due to karst dissolution and a large sinkhole formation (although no significant karstification vestiges can be observed on the marble clasts) or a graben/trench/ escarpment formation as in onset of the extensional processes and major margin collapses.

Yellowish and dark grey clasts are more often broken apart than others, probably due to increased softness at the time, coinciding with the increased contents of impurities (e.g. limonite and clay). Microscopic analysis has proved that indeed grey and yellowish clasts are metamorphosed to a lower degree, originating from younger levels of the primary carbonate sequence.

These secondary clasts remain spatially closely linked in place of deposition, suggesting that there has been no transport after the accumulation of clasts and that cementation happened at that same place, within a relatively calm environment, probably a stagnant on-land water body of seasonally oscillating depth (hence, the oxidative-reductive boundary causing differences in matrix colour).

Preservation of lamination

Lamination and banding of the primary calcareous sequence, reflected through different marble colours, testify of the seasonal changes in the relations between authigenic calcareous sedimentation and terrigenous input of argillaceous matter. Lamination can be easily destroyed by bioturbation and other disruptive processes shortly after deposition. Preservation of primary laminae flatness in the Ropočevo deposit is clear and complete. Preserved lamination testifies of a) absent bioturbation and a calm formation environment of the primary limestone (solely epeirogenic movements) such as a carbonate platform produced by the mud-mound factory (Gilli, 1992; Schlager, 2005), anoxic genetic conditions or a high sedimentation rate yielding burial before the disruption could occur, and b) metamorphism into marble due to subsidence and burial (geothermal influence), in the absence of dynamic-orogenic tectonic movements. Thermal recrystallization lasted for a certain time period until the change in the epeirogenic movement direction had caused the re-emergence of the carbonate sequence to the surface, where the erosion could take place.

Presence of these pattern elements may help in correlation with potential parental rock sequence if it exists today or a genetically related one (e.g. in Drina-Ivanjica or other terranes), if such sequence is found in the future, serving as markers to be paired with other correlation methods.

Fossils

The absence of visible fossil remains – unless exclusively due to metamorphism – points to a schizohaline environment (Jadoul et al., 1992) or the environment otherwise disadvantageous for living organisms known to leave fossil record (disphotic to aphotic, hypoxic to anoxic) or formation in the time period following the mass extinction event (Pomar, 2020).

Similarity with Venčac marble and adjacent calcareous sediments

No plausible parental calcareous sequences matching the observed properties of the Ropočevo breccia are present in the surrounding formations. The oldest rocks present in the area near the Ropočevo village belong to the Upper Jurassic ophiolitic melange, where sandy fossiliferous limestones occur as mylonitised olistolithic blocks and clasts along with abundant chert. Lower Cretaceous limestones are sandy, marly, or ferruginous, occurring as small intercalations or local calcarenitic facies.

Based on microscopic and technical properties, no significant similarities between the Ropočevo marble breccia and Venčac marble as a potential parental rock sequence have been established so far. The higher values of technical properties (such as e.g. compressive strength) of the Ropočevo breccia – a sedimentary rock – compared to the Venčac marble itself, represent an interesting occurrence. For this reasson it is presumed that the breccia has gone through a certain degree of metamorphism along its genetic pathway.

Possible genetic scenarios

Large bodies of monomictic breccia give an impression of a vast, thick, relatively homogeneous parental carbonate sequence, such as those forming in a calm, benthic marine environment, on a continuously subsiding carbonate platform on a distal continental slope along a passive margin. Varying colour laminations testify of a certain input of a fine terrigenous component, probably of seasonal rhythmic character or those typical of carbonate sequences formed in deep shelf mud-mounds (Gilli, 1992; James, 1997; Adams and Kenter, 2013).

The chaotic clast distribution within the marble breccia, the presence of in-place brecciation, the absence of any other rock types among clasts, the negligible degree of clasts' roundedness and other sedimentary structures and evident traits of the

Ropočevo breccia are indicative of clasts' short-distance and abrupt transport from subaerially exposed areas into a local morphologic low as an accumulative landscape structure, and of the inferred significant thickness and a relative compositional homogeneity of the primary sequence. The lack of bedding, grading, sorting, lamination and fossils, the matrix colour zoning partly in earthy tones, the monomictic nature of breccia and presence of in-place brecciation are typical for subaerial depositional environments, such as karst sinkhole fills (Mussman and Read, 1986), formed after subaerial exposure of Ca-carbonate rocks and karstic dissolution period, resulting in collapse paleokarst breccias developed in a vadose to phreatic levels of an on-land aquatic environment. So, the first plausible genetic scenario might be the accumulation in karst-dissolution and collapse sinkholes. However, this scenario might be problematic because there is no evidence of intense karstification such as dissolution visible on the clasts or traces of terra rossa. Karst-related collapse breccias are associated with vadose calcite cements, internal sediments and marked dissolution structures; their deposits show limited areal extension, extreme thickness variability and lack of lateral continuity (Jadoul et al., 1992), and no evidence of these traits can be observed on the Ropočevo breccia except rare, faint rosy-coloured cracks present in some white clasts.

The other genetic scenario might be the abrupt redeposition of eluvium downslope into a local low, forming a scree slope toe deposit. Based on the size of this olistolithic breccia body, the primary breccia body is presumably much larger than a sinkhole fill, but is more comparable in size to scree deposits. However, slope toe deposit scenario might be problematic since the screen has a generally good sorting of clasts by size, i.e. grading, and no such evidence is observed in the Ropočevo deposit. Therefore, slope toe as a primary breccia body formational environment might be excluded since there is no evident sorting and the matrix Fe-colouring zoning reveals the involvement of meteoric diagenetic environment – clast accumulation and lithification within the seasonally changing standing land water body. This environment encompassed a vadose (oxidative) meteoric diagenetic environment, a phreatic (reductive) zone and a capillary fringe transitional zone, depending on the position of the water table level. The oxidative levels gave limonite-coloured matrix zones formed within the vadose meteoric zone; the reductive ones gave grey-coloured matrix zones formed within the phreatic zone; and a transitional zone gave hematite-coloured matrix zone formed within the level of the capillary fringe.

Some sort of a hybrid of the two proposed scenarios might have happened due to the active tectonics, e.g. an abrupt opening of a steep-sided local basin such as graben within the carbonate formation, causing the sudden eluvium rock-fall from a significant height that would cause the in-place brecciation.

As for the primary carbonate sequence formation, the properties of mud-mounds are in accordance with some of the inferred characteristics of the Ropočevo marble breccia protolith: abiotic precipitation without the production of skeletal association and/or environment low in oxygen; intermediate water depths; fine-grained carbonate precipitated in situ with microbe participation resulting in laminated microbialites having microscopically visible peloidal fabric (Schlager, 2005). The original depositional environment of both laminated clasts and grainstone is a possible open marine (subtidal) environment, a deeper water shelf, probably a (Triassic?) microbial mud-mound similar to the one described in the middle Jurassic of the Prealps (Septfontaine, 1983; Gilli, 1992). The absence of coarse-grained allochems, horizontal sedimentary displacements due to tides and storms and sedimentary structures typical of shallow sedimentary environments and presence of rare, small vertical displacements due to synsedimentary movements during the mechanical early diagenesis, typical of deeper water sedimentary environments speak in favour of basinal, open marine origin such as mud-mound instead of littoral/neritic shallow one.

Tentative genetic model

The tentative model of geologic history of the Ropočevo breccia emplacement can be divided into two main phases:

1. The formation of the primary breccia, through sub-phases:

a. formation of the protolith limestone sequence, probably on a slowly sinking deeper shelf, with irregular alternations of monotonous, purely authigenic calcareous precipitation (grainstones associated to a hypothetical mudmound-like structure, found today as monochrome white clasts) with periods of seasonal changes in contents of clay impurities, resulting in interlayering of white and grey laminae and bands, and also with yellowish laminae probably of bacterial origin (deep stromatolites) formed in an open marine platform or basin;

b. its metamorphism into marble, due to sinking of the shelf and deep burial, where both lithification and metamorphism can take place (sinking and burial have been actuated in such manner that laminae have remained perfectly straight, with zero folding),

c. upliftment, exhumation and exposition of the marble sequence,

d. erosion of the marble sequence due to weathering (±karstification), formation of eluvium and colluvium,

e. redeposition and accumulation at a slope toe, escarpment root, in a local subaerial basin, graben, trench or a local sink-hole formed due to karstification and cavern roof collapse, and

f. lithification of this accumulation into a breccia.

2. Chunks and larger blocks breaking-off of the breccia and their emplacement as olistoliths in a flysch basin during the ongoing sedimentation.

Between the phases 1 and 2, there have also been unknown geologic processes at play, including perhaps a transgression, deep and long-time burial and later exhumation prior to or penecontemporaneous with (Neotethyan?) oceanic domain closure, a certain tectonic relocation and another exposure to erosion, this time at the flanks of an active flysch basin. Intense tectonic movements cause the parts of the breccia to break off and gravitationally slide as olistolithic megaclasts into the basin.

Acknowledgements: The authors wish to thank the honoured colleagues for providing their papers (references) and PhD Darko Spahić for useful comments on the manuscript.

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Р е з и м е

ПРИДОНЕС КОН ГЕОЛОГИЈАТА И ГЕНЕТСКИОТ ПАТ НА РОПОЧЕВСКАТА БРЕЧА – „ОСАМЕНО“ ОЛИСТОЛИТСКО ТЕЛО ВО ГОРНИОТ КРЕДЕН ФЛИШ ВО БЛИЗИНА НА СОПОТ (ЦЕНТРАЛНА СРБИЈА)

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Клучни зборови: мермерна breча; олистолит; горнокреден флиш

Ропочевската бреча, градежен камен високо ценет во XX век, е испитувана од бројни истакнати геолози од тоа време. Повторно се разгледува од истражувачи кои сè уште се заинтригирани од нејзиното збунувачко потекло. Нејзината позиција како ригиден егзотичен блок од тврда и целосно метаморфозирана карбонатна бреча во умерено литифицираната флишна низа од горна креда останува нерешена поради отсуството на нејзиниот извор. Големите тела на мономиктична бреча сугерираат релативно монотона протолитска карбонатна секвенција со значителна моќност, како што се оние што се формираат во мирна морска средина со постепено тонење на дното поради епирогените движења. Разнобојните наслојувања укажуваат на мали варијации во принесениот материјал поради епирогената осцилација на дното на басенотот. Не постои законемерност во распределбата на фракциите во однос на големината, бојата или степенот на заобленост. Ова, поврзано со појавата на „локално бречирање“, сугерира ненадеен пад на бречираниот материјал поради „катастрофален“ настан, како што е земјотрес, колапсно бречирање поради карсно растворање и формирање голема празнина во земјата или формирање на грабен/ров, формирање како во почетокот на екстензивните процеси.