Megabeds in Istrian Flysch as markers of synsedimentary tectonics within the Dinaric foredeep (Croatia)

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Abstract

Istrian Flysch was deposited during the Eocene in the Dinaric foredeep and is composed of hemipelagic marls and various gravity flow deposits. The latter are predominantly 5-40 cm thick turbidites, developed mostly as laminated and cross-rippled sandstone beds (Tb-e, Tc-e and Td-e Bouma sequences). In addition to the turbidites, there are deposits characterized by a significant thickness, occasionally more than 10 m, described as complex (bipartite) megabeds. The megabeds are composed of debrites in the lower part (Division I), and high-density turbidites in the upper part (Division II). The distinct clast composition of each megabed indicates that the lithoclasts were derived from tectonically active slopes and fault scarps along which collapses of the different parts of the Cretaceous to Palaeogene neritic carbonate succession, that underlie the Flysch, occurred. The Division II deposits are well cemented, normally graded calcirudite/calcarenites composed mostly of orthophragminids, nummulitids, and red algae, originating from outer ramp environments. Redeposited marl, observed in the matrix of the debrites and as intraclasts in some megabeds, implies that the collapses along the synsedimentary fault scarps and steep slopes also occurred within the foredeep itself, during the rapid tectono-sedimentary evolution of the Dinaric foreland basin.

1. INTRODUCTION

There is no generally accepted definition of the term 'megabed' (MARJANAC, 1996; FALLGATER et al., 2016) but they usually refer to deposits of exceptionally large-volume sediment gravity flows (megaflows) that are rheologically complex, and that produced much thicker beds than the surrounding succession (FALLGATER et al., 2016). Exceptionally thick beds with a virtually basin wide extent are called "Seismoturbidites" by MUTTI et al. (1984). The term "Megaturbidite" is used by BOUMA (1987) for thick layers (compared to the host rock), that are laterally extensive, different in composition from the host rock, and lack submarine fan geometries even if they cover several depositional processes (LABAUME et al., 1987). The debrite components in beds, labeled as Megaturbidites or Seismoturbidites, are volumetrically much more important than the derivative turbidite component (PAYROS et al., 1999) and therefore, these terms are considered to be inappropriate for these deposits (PAYROS et al., 1999). Some gravity flow deposits with couplets or triplets related to debris flows and turbidity currents are called hybrid event beds (HAUGHTON et al., 2003, 2009; TALLING, 2013). Similar carbonate sediments, composed of breccias, conglomerates, bioclastic arenites, and marls from other regions, especially those from Dinaric foreland basins, are interpreted as megabeds (TUNIS & VENTURINI, 1992; MARJANAC, 1996; GOBO et al., 2021) or mass transport deposits (OGATA et al., 2014, 2019). In the Central Dalmatian basin, a slightly younger southeastern part of the Dinaric foreland basin, MARJANAC (1990, 1991, 1993, 1996) described 4 types of megabeds: 1) megaturbidites, 2) "reflected" turbidites, 3) composite turbidites, and 4) complex, bipartite type beds, composed of debrite and turbidite parts. Bipartite beds described by MARJANAC (1996) are considered equivalent to Olistostromes (ABBATE et al., 1970). The debrite part is composed of a) extra basinal clasts – Foraminiferal limestones, b) rolled and

compressed basinal sediments composed of arenite and marl alternations and c) foraminiferal debris. The turbidite part is normally graded, composed mostly of foraminiferal debris and lacking large lithoclasts (MARJANAC, 1993). In the slightly older counterparts of the Dinaric foreland basin north of Istria, (Friuli and the Julian basin in Italy and Slovenia), the mass transport deposits (MTDs) that are described in 5 subunits (U1-U5) were deposited by different depositional processes. The authors (OGATA et al., 2014) indicate that the processes generating the Friuli and Julian MTDs are composed of a) a debris-blocky flow/avalanche bearing out-sized carbonate and siliciclastic slide blocks (responsible for the deposition of subunits U1 and U2), b) a diluted debris/grain flow (deposition of subunit U3), and c) an upper high- to low-density fully turbulent flow (deposition of subunits U4 and U5). Mass flows can transport and incorporate both intra- and extra-basinal material and their formation commonly implies processes of stratal disruption and lithological mixing and thus forming a characteristic "block-in-matrix" fabric (PINI et al. 2012; OGATA et al., 2020). Thus, the single event beds that display bipartite organization, with each part inferred to reflect a distinct depositional process, are referred also as MTDs. Among other MTDs, bipartite megabeds, composed of debrite and turbidite parts, are also described in the Dinaric wedge-top basin in Northern Dalmatia (GOBO et al., 2021).

In this research, sedimentological and petrographic data about megabeds of the Istrian Flysch is used to shed some light on the environmental conditions, depositional mechanisms, and the origin of the resedimented coarse-grained carbonate material. To determine the variations and provenance of the carbonate material, qualitative and quantitative analyses of carbonate clasts were performed. Furthermore, the analysis of bioclastic grains was carried out to determine the original depositional palaeoenvironments of the redeposited bioclasts. The relatively tectonically

undisturbed Dinaric foreland deposits that were not involved in the External Dinarides fold-and-thrust belt are exclusively exposed in centra Istria since other equivalent parts of the foreland are covered by Neogene deposits and/or by the Adriatic Sea (KORBAR, 2009). Thus, Istria is an excellent location for further studies of the rather complex foreland basin evolution.

There are no deep seismic and exploration wells in Istria needed for relevant basin modeling. However, the presented research resulted from some insight in the formation, composition and spatial distribution of some megabeds. For further correlation of the studied megabeds, more detailed geological mapping and precise biostratigraphic analyses are needed. So far, this research has provided new data about the Istrian megabeds regarding the composition, and provenance of the carbonate material, facies models and triggering mechanisms.

2. GEOLOGICAL SETTING

The Istrian peninsula is located on the northwestern part of the Eastern Adriatic Coast and it predominantly belongs to the Adriatic foreland (Fig 1). The NE mountain belt of the peninsula (Fig. 1) belongs to the fold-and-thrust belt of the External Dinarides, formed during Alpine orogenesis, caused by the collision of the Adriatic microplate (Adria) and the Eurasian plate (SCHMID et al., 2008; KORBAR, 2009; ŠPELIĆ et al., 2021). The oldest rocks on the Istrian peninsula are the Jurassic and Cretaceous limestones that were deposited on the pre-orogenic long-lasting Adriatic carbonate platform (VLAHOVIĆ et al., 2005). A regional

unconformity separates the Jurassic-Cretaceous shallow-marine carbonate succession from the Palaeogene synorogenic carbonates deposited in the distal foreland (OTONIČAR, 2007). This Late Cretaceous and Early Palaeogene unconformity is marked by palaeokarst that occurred during the forebulge uplift and the emersion of the Adriatic Carbonate Platform (OTONIČAR, 2007). Also, a broad Istrian anticline, striking NE-SW, was probably formed during the Late Cretaceous, since the deformed and palaeokarstified Cretaceous carbonates are diachronously overlain by the Palaeogene succession (MATIČEC et al., 1996). The lowermost part of the Palaeogene succession is characterized by localized occurrences of the freshwater or brackish Kozina beds (ŠIKIĆ & POLŠAK, 1973; MARJANAC & ĆOSOVIĆ, 2000; ĆOSOVIĆ et al., 2008). The Kozina beds are overlain by Ypresian to Middle-Late Lutetian Foraminiferal limestones (DROBNE, 1977; MARJANAC & ĆOSOVIĆ, 2000) which were deposited on a fully marine carbonate ramp (ĆOSOVIĆ et al., 2004) developed in the distal part of the Dinaric foreland basin (OTONIČAR, 2007).

The Foraminiferal limestones are often informally subdivided into four separate members: Miliolid-, Alveolinid-, Nummulitid- and Discocyclina limestones (DROBNE 1977; ŠIKIĆ & PLENIČAR, 1975; VELIĆ et al., 2003; VLAHOVIĆ & VELIĆ, 2009). The units are generally in superposition and indicate progressive deepening of the ramp (ĆOSOVIĆ et al., 2004) during the migration of the foreland basin to the SW (OTONIČAR, 2007; KORBAR, 2009). The Foraminiferal limestones are overlain by
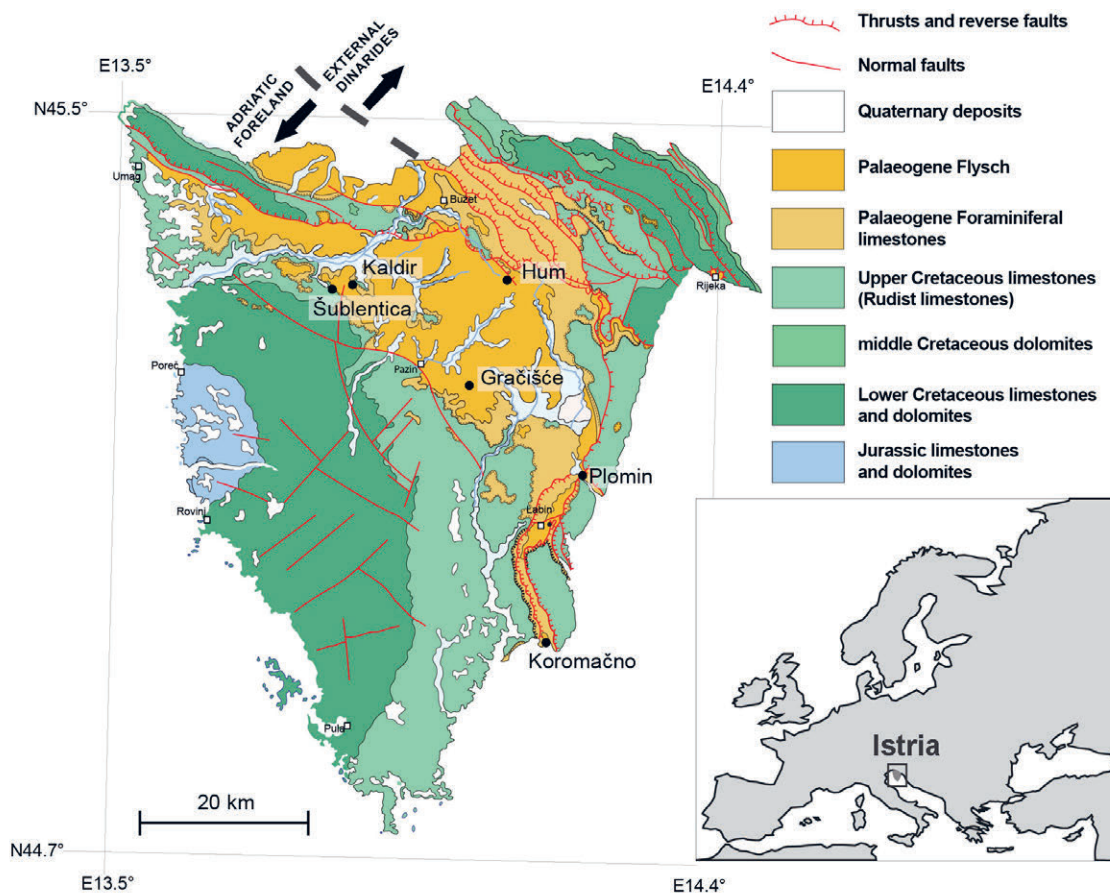
Figure 1. The geological map of the Croatian part of the Istrian peninsula with the studied locations indicated by black circles (CROATIAN GEOLOGICAL SURVEY, 2009). Globigerina marls are not separated as a lithostratigraphic unit but as a member within the Foraminiferal limestones. However, according to new data and more detailed maps, Globigerina marls within the investigated area, are reclassified and published as a member within the Istrian flysch (BERGANT et al., 2020) as presented in Fig. 2.

the so-called Transitional beds composed of "*Marls with crabs*" and "*Globigerina marls*". The "*Marls with crabs*" are clayey fossiliferous wackestones and packstones (ŠIKIĆ & PLENIČAR, 1975; MARJANAC & ĆOSOVIĆ, 2000; TARLAO et al., 2005), deposited during the gradual transition from the neritic carbonate ramp to the deeper-water distal foredeep. Massive "*Globigerina marls*" (or "*Subbotina Marls*") are deposited in deeper environments and are considered to be hemipelagic deposits (JURAČIĆ, 1980). The clastic part of the foreland succession is deposited in the foredeep and is referred to as Flysch (MARINČIĆ, 1981). In the wider eastern Adriatic region Flysch is recognized as a major lithostratigraphic unit, which marks the beginning of the Dinaric orogenic deformations in the area (AUBOUIN et al., 1970; BABIĆ & ZUPANIČ, 1983; KORBAR, 2009). The whole Istrian Palaeogene succession (Figs. 1 and 2) is probably deposited within an underfilled peripheral foreland basin as described by SINCLAIR (1997), with Flysch deposited in the foredeep in front of the once migrating Dinaric wedge (OTONIČAR, 2007; KORBAR, 2009).

Based on the plankton and benthic foraminiferal ratio, ŽIVKOVIĆ & BABIĆ (2003) have estimated the water depth of the foredeep to about 900-1200 m. The Flysch is characterized by the alternation of hemipelagic marls and gravity-flow deposits (predominantly turbidites) composed of a) mixed carbonate-siliciclastic detritus or b) carbonate detritus (MAGDALENIĆ, 1972; MARINČIĆ, 1981; BABIĆ & ZUPANIČ, 1996; MARINČIĆ et al., 1996; BERGANT et al., 2003). Mixed carbonate-siliciclastic turbidites show longitudinal palaeotransport directions toward the ESE which led to the conclusion that the material was supplied from the rising Dinarides and from the Alps (MAGDALENIĆ, 1972; MARINČIĆ et al., 1996; BABIĆ & ZUPANIČ, 1996). These turbidites are regarded as turbidites deposited by low density turbidity currents (MARINČIĆ et al., 1996). Carbonate beds are often thin turbidites but also thick, bipartite beds composed of breccias, conglomerates, bioclastic arenites/siltites, and marls (BABIĆ & ZUPANIĆ, 1996; BERGANT et al., 2003), and show a palaeotransport direction towards the NNE, generally perpendicular to the SE direction of the mixed carbonate-siliciclastic turbidites (BABIĆ & ZUPANIČ, 1996). BABIĆ & ZUPANIČ (1996) conclude that the carbonate detritus was supplied from the foreland uplift (forebulge), situated to the south, characterized by carbonate shoals and subaerial exposure.

The progressive evolution of the Istrian foredeep fill has been documented by MARINČIĆ et al. (1996) and is described as the Istrian Flysch – a succession of clastic rocks characterized by a coarsening upward trend and outlined with zones of "distal" and "proximal" Flysch. According to MARINČIĆ et al. (1996), the total thickness of the Flysch succession is estimated to be around 300-350 m (Fig. 2).

Although some published (MIKES et al., 2008) and unpublished studies argued for a Late Oligocene or even Miocene age of the Istrian and Dalmatian Flysch, the majority of the researchers confirm a Middle Eocene age (AUBOUIN et al., 1970; KRAŠENINNIKOV et al., 1968; PICCOLI & PROTO DECIMA, 1969; MAGAŠ, 1973; POLŠAK & ŠIKIĆ, 1973; ŠIKIĆ & POLŠAK, 1973; ŠIKIĆ & PLENIČAR, 1975; BENIĆ, 1991; ŽIVKOVIĆ & BABIĆ, 2003; BABIĆ et al., 2007; ŽIVKOVIĆ & GLUMAC, 2007). We accepted the Middle Eocene age proposed by BABIĆ et al. (2007) and ĆORIĆ et al. (2008), since their data was obtained from the investigated logged successions and by more than one biostratigraphic method.
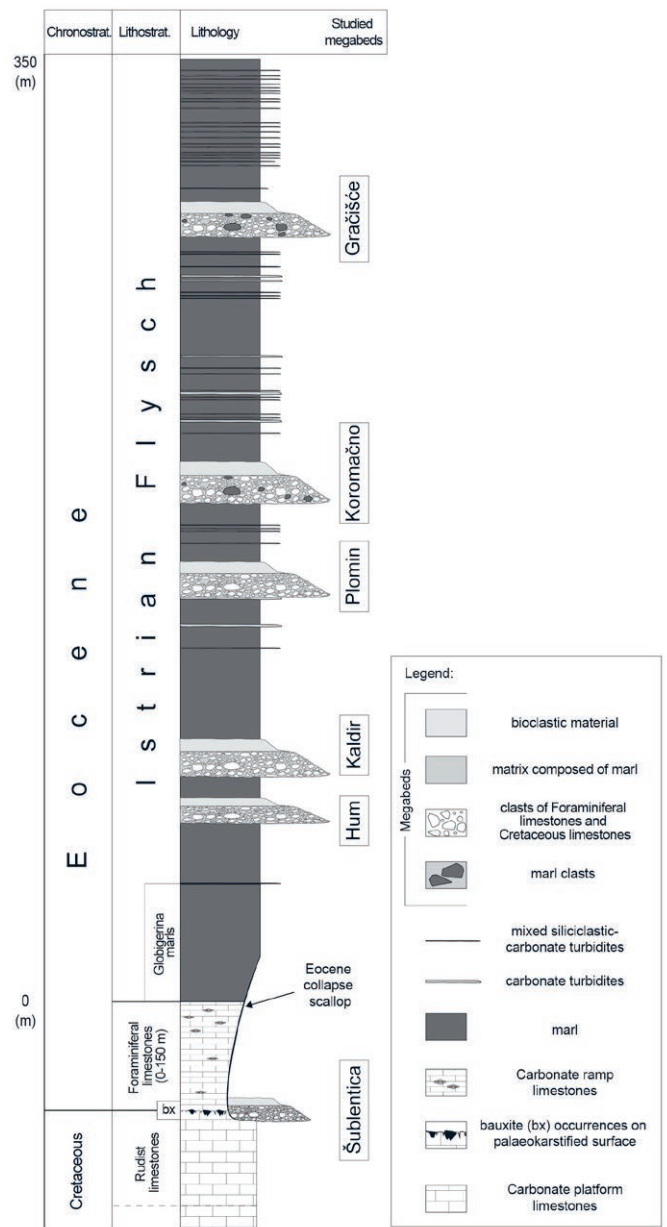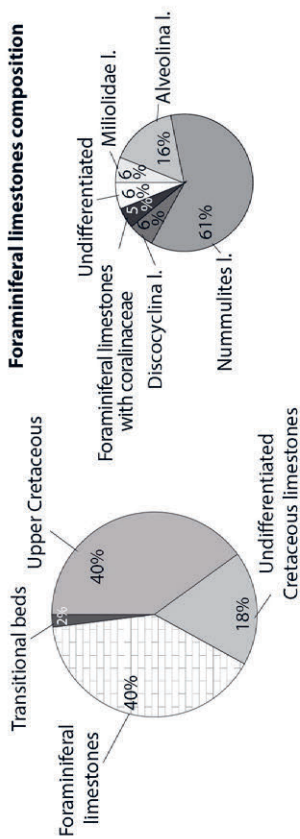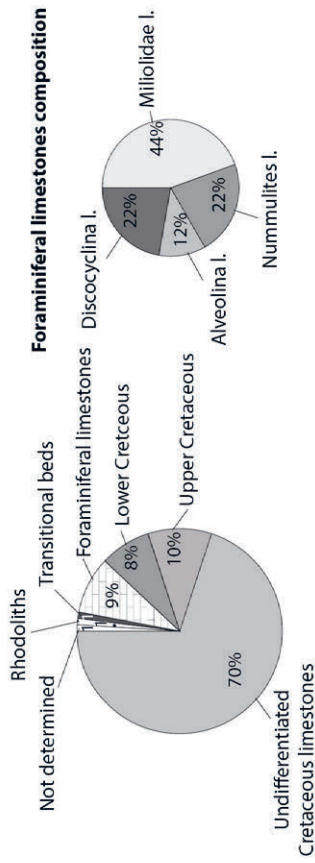

Figure 2. The schematic geological column of the Middle Eocene Istrian Flysch succession and the underlying Cretaceous and Palaeogene neritic carbonates, with the general relative stratigraphic positions of the investigated sections. Intervals of the underlying Cretaceous Rudist limestones and Palaeogene Foraminiferal limestones are not in a general scale given for Flysch.

For this study, six different megabeds were investigated. The locations of the investigated beds are presented in Fig 1. The relative stratigraphic position of each megabed was determined according to the data of direct observation in the field, from the published and unpublished geological maps, and the results of previous biostratigraphic research. We can conclude that the studied megabeds are present in the different stratigraphic positions within the Istrian Flysch succession. The Kaldir, Šublentica, and Hum megabeds are located in the lower part, while the Gračišće, Koromačno, and probably the Plomin megabeds are in the middle part of the Istrian Flysch succession (Fig. 2). According to ŽIVKOVIĆ & BABIĆ (2003) the age of the Gračišće megabed is Bartonian (plankton foraminifera zone P11-P13). The Kaldir megabed is considered to be of a Middle Eocene age based on the vicinity of the investigated sections by ŽIVKOVIĆ & GLUMAC (2007). The ages of other megabeds are based on the data pro-
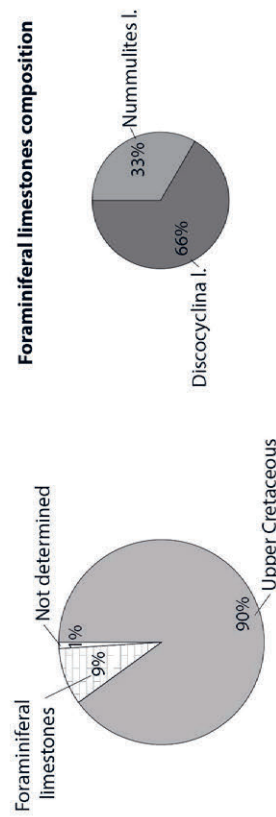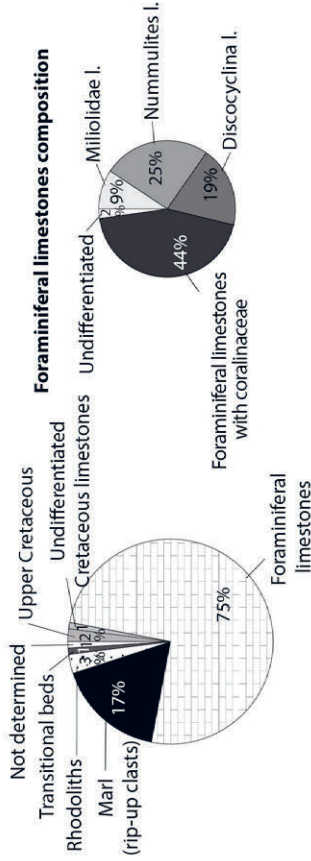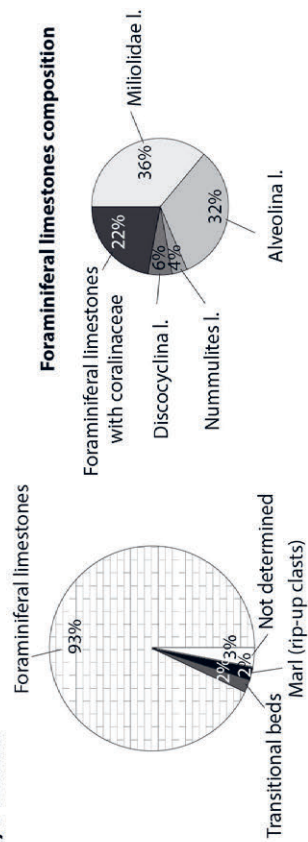
A) Šublentica

Foraminiferal limestones composition

Transitional beds
Upper Cretaceous
40%
2%
40%
Foraminiferal
limestones
18%
Undifferentiated
Cretaceous limestones

Foraminiferal limestones
with coralinaceae
Undifferentiated
Miliolidae l.
6%
5%
6%
Discocyclina l.
6%
16%
Alveolina l.
61%
Nummulites l.

B) Hum

Foraminiferal limestones composition

Discocyclina l.
22%
44% Miliolidae l.
12%
22%
Alveolina l.
Nummulites l.

Rhodoliths
Transitional beds
Foraminiferal limestones
Lower Cretceous
Upper Cretaceous
Not determined
9%
8%
10%
70%
Undifferentiated
Cretaceous limestones

C) Kaldir

Foraminiferal limestones composition

33% Nummulites l.
66%
Discocyclina l.

Foraminiferal
limestones
Not determined
1%
9%
90%
Upper Cretaceous

D) Gračišće

Foraminiferal limestones composition

Miliolidae l.
2% 9%
25% Nummulites l.
19%
Discocyclina l.
Undifferentiated
44%
Foraminiferal limestones
with coralinaceae

Not determined
Transitional beds
Rhodoliths
Marl
(rip-up clasts)
Upper Cretaceous
Undifferentiated
Cretaceous limestones
3%
2%
1%
17%
75%
Foraminiferal
limestones

E) Plomin

Foraminiferal limestones composition

Miliolidae l.
36%
22%
Foraminiferal limestones
with coralinaceae
6%
4%
32%
Discocyclina l.
Nummulites l.
Alveolina l.

Foraminiferal limestones
93%
Transitional beds
Not determined
2% 3%
2%
Marl (rip-up clasts)

F) Koromačno

Foraminiferal limestones composition

Undifferentiated
6%
11%
14%
5%
3%
Foraminiferal limestones
with coralinaceae
Discocyclina l.
Nummulites l.
Miliolidae l.
61%
Alveolina l.

Marl
(rip-up clasts)
16%
3%
Transitional beds
80%
Not determined
Foraminiferal
limestones

Figure 3. Division I clast composition.

Petrinjak et al.: Megabeds in Istrian Flysch as markers of synsedimentary tectonics within the Dinaric foredeep (Croatia) **103**

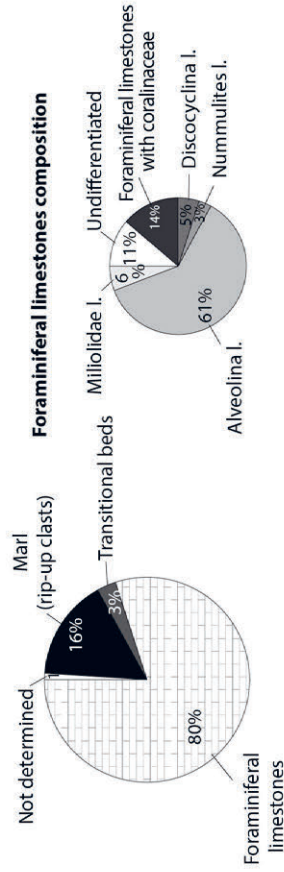Geologia Croatica

vided on basic geological maps: the Plomin megabed – Middle Eocene according to ŠIKIĆ & POLŠAK (1973), the Koromačno megabed – Middle to Upper Eocene according to MAGAŠ (1973), the Šublentica megabed – Middle Eocene according to POLŠAK & ŠIKIĆ (1973), and the Hum megabed – Middle Eocene according to ŠIKIĆ & PLENIČAR (1975). Since the information on the megabeds age is somewhat scarce, their precise correlation is not yet possible. For a better understanding of the stratigraphic relationships between the megabeds more precise dating is needed.

3. METHODS

During the field investigation, information on boundary types, sediment composition, layer thickness, grain size, fossil content, and internal structures was collected and presented on graphic logs. Because of the recognized general compositional variation within all the studied megabeds, two different methodologies were used:

1) Analysis of coarse-clast composition of breccia, referred to as Division I;

2) Analysis of the composition of calcirudites and calcarenites, referred to as Division II.

1) To determine the clast compositions representative for Division I of each megabed, the most exposed parts of the outcrops were selected. Between 200 and 300 clasts within the selected areas were classified and counted. The clasts were categorized based on their fossil content and lithological characteristics. The

fossil content was determined by hand lens examination in-situ where possible. In addition, some samples were analyzed microscopically. The categories are based on the lithostratigraphic units presented on the Geological map (Fig. 1). The categories are: Lower-, Upper-, or undifferentiated Cretaceous limestones, Foraminiferal limestones, Flysch (Marls), rhodoliths, and undetermined clasts. The large rhodoliths (>5 cm in diameter), observed in two megabeds are added to separate categories although they are not attributed to any lithostratigraphic unit presented in Fig 1. The Cretaceous clasts were classified on the basis of their foraminiferal content according to VELIĆ (2007). Foraminiferal limestones were additionally separated according to their predominant large benthic foraminifera content of the Miliolid-, Alveolinid-, Nummulitid- or Discocyclina limestones as described by POLŠAK & ŠIKIĆ, (1973); ŠIKIĆ & POLŠAK, (1973); ŠIKIĆ & PLENIČAR, (1975); VLAHOVIĆ & VELIĆ, (2009), and an additional Algal foraminiferal limestones category. Clasts of Foraminiferal limestones abundant in red algae (rhodoliths and coralline debris) were separated out as Algal foraminiferal limestones. The Foraminiferal limestones with abundant glauconite grains were categorized as Transitional beds. Clasts that had no distinguishable features were labeled as "not determined". Photomicrographs of the most characteristic clasts for each bed are presented as a supplement (Plates 1, 2, and 3). Limestone clasts were distinguished according to DUNHAM's (1962) classification modified by EMBRY & KLOVAN (1971).

Table 1. Results of Division II bioclastic material analysis.

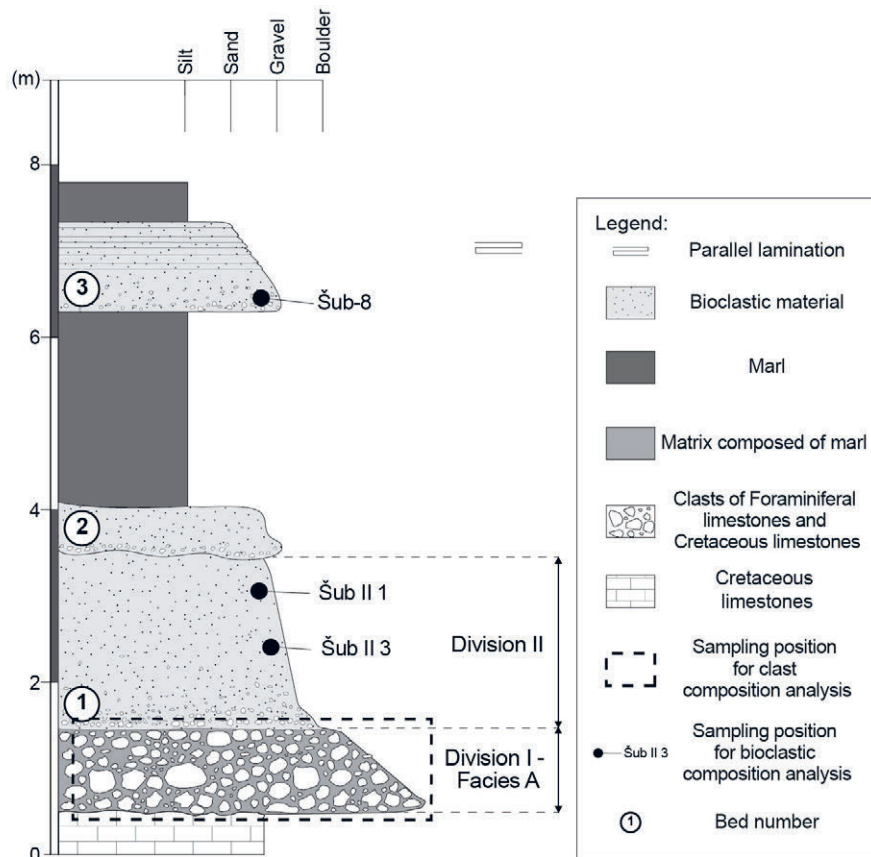| Log	Group/ Sample	1 Lithoclasts (%)	2 Matrix (%)	3 Cement (%)	4 Ortophragminids (%)	5 Nummulitids (%)	6 Encrusting foraminifera (%)	7 Red algae (%)	8 Bryozoans (%)	9 Encinoderms (%)	10 Mollusks (%)	11 Rotallid foraminifera and hyaline fragments (%)	12 Not determined (%)
Hum	Hum 2	13	0	0	54	9	0	9	0	2	0	11	1
	Hum 3A 1	17	0	0	32	26	0	12	2	5	0	4	1
	Hum 3A 2	21	0	0	36	15	2	9	1	2	3	8	3
	Hum 3B	10	2	0	54	6	0	13	2	2	0	10	2
	Hum 5a	6	5	1	52	14	0	7	0	1	0	8	6
	Hum 5b	3	4	1	37	3	0	18	4	2	0	19	9
Plomin	PL-4	12	4	0	35	33	1	9	1	2	0	3	2
	PL-3	11	8	0	35	27	2	9	1	4	0	2	3
Kaldir	Kaldir 1a	1	5	0	41	5	0	23	3	0	0	14	7
	Kaldir 1b	5	6	1	35	7	0	24	1	2	0	14	4
Šublentica	Šub-II 1	6	9	0	29	11	0	24	0	5	2	10	4
	Šub-II 3	13	11	0	27	18	0	11	1	3	3	10	1
	Šub-8	16	4	0	26	28	0	17	0	2	0	5	1
Gračišće	Gračišće 1	8	7	0	33	11	0	20	6	4	0	9	2
	Gračišće 2	16	6	0	31	25	0	17	1	1	0	4	0
Koromačno	KOR-II I	27	5	0	16	13	0	28	0	3	0	5	3
	KOR-II 2	22	4	0	21	13	0	31	1	1	0	4	3

Figure 4. The Šublentica column shows an unconformable (erosional) contact of the Cretaceous limestones and the overlying Šublentica megabed (Istrian Flysch).

2) To determine the composition of calcirudites and calcarenites, thin sections of 17 selected samples were prepared and analyzed by standard petrological microscope. The sampling locations are marked on each log. The Division II samples were determined as bioclastic calcarenites to calcirudites composed predominantly of skeletal debris. The modal distribution of the components in thin section was estimated using a point-counting method described in FLÜGEL (2004). During point-counting, the constituents were classified into 12 groups: 1) lithoclasts, 2) matrix – micrite, 3) cement – sparite, 4) orthophragminid, 5) nummulitid, 6) encrusting foraminifera, 7) red algae, 8) bryozoans, 9) echinoderms, 10) molluscs, 11) hyaline fragments and 12) non-determinable grains. The modal distribution of the main constituents was estimated by point-counting 200-300 grains.

Due to sparse directional structures in the Istrian megabeds, the palaeotransport directions have been measured only in one location (Hum). The structures used to measure palaeotransport directions are ripple marks and a flute cast.

4. RESULTS

All the six studied megabeds are distinguished from other gravity flow deposits of Flysch succession by their thickness, composition, and internal bipartite structure. Clast composition for all Division I breccia is given in Fig 3., while the composition of the analyzed Division 2 calcirudite and calcarenite is given for each studied megabed in Table 1.

Within Division 1, two facies types are distinguished, as Facies A and Facies B. Facies A is a clast supported breccia with sparse marl matrix. Facies B is a chaotic, marl dominated, matrix-rich breccia with rip-up clasts, and a greater total thickness than Facies A.

4.1. The Šublentica Section

The unconformable contact of the Istrian Flysch and the Cretaceous limestones is described at the Šublentica section (WGS84 coordinates: lat 45° 19' 2.3808", long 13° 48' 29.8404"). A hiatus was recognized in this section and the megabed directly overlies the Upper Cretaceous Rudist limestones (Fig. 4). The boundary is discordant and erosional (Fig. 5) suggesting tectonic tilting and the partial collapse of the underlying neritic carbonates prior to or synchronously with the deposition of the megabed. The Division I breccia interval is 1.5 m thick, poorly sorted and clast supported. Carbonate clasts are from 0.1 to 1 m in size. Upper Cretaceous limestones (40%) and Foraminiferal limestones clasts (40%) predominate, while undifferentiated Cretaceous limestone clasts (18%) and Transitional beds (limestones with glauconite; 2%) are less abundant. The matrix is composed of marl and large benthic foraminifera (nummulites and orthophragminids). Fig. 3a shows the composition of the Division I breccia, with selected clast microfacies photomicrographs of Foraminiferal and Cretaceous limestones presented in Plate 1 A, B, and C. The breccia gradually transitions to the Division II interval which consists of normally graded calcirudite and up-section to normally graded calcarenites. The most common constituents of Division II material are orthophragminids (26-29%), nummulitids (11-28%), red algae (11-24%), and lithoclasts (6-16%). The proportions of all constituents in the investigated samples are shown in Table 1 and illustrated in Plate 1D. The section ends with the alternation of marl and amalgamated normally graded calcirudite beds (Fig. 4).

4.2. The Hum Section

A 40 m thick interval of the Palaeogene foredeep basin fill was logged near the town of Hum (WGS84 coordinates: lat 45° 21'

Petrinjak et al.: Megabeds in Istrian Flysch as markers of synsedimentary tectonics within the Dinaric foredeep (Croatia)   105

Geologia Croatica

Figure 5. Photograph of the Šublentica outcrop showing a discordant and erosional boundary between the Cretaceous limestones and overlaying megabed.

3.5706", long 14° 2' 42.5466", Fig. 6). The interval is composed of an alternation of marl and five carbonate beds. The most prominent bed is the 9 m thick megabed Hum 3 (Fig. 7A) which shows the characteristic bipartite structure with visible Division I and Division II components. The other carbonate turbidite beds (labeled Hum 1, 2, 4, 5 on Fig.6) are composed of normally graded bioclastic calcirudite/calcarenite of various thicknesses (0.6 – 3 m). The lower bedding surface of each bed is sharp and erosional, implying that the gravity flow eroded previously deposited basinal sediments. The Hum 3 megabed is composed of Division I breccia/conglomerate in the lower/bottom part, and the Division II – normally graded calcirudite/calcarenite in the upper part. The maximum thickness of the laterally thinning breccia/conglomerate interval is 5 m, and the lower bedding surface is erosional. The majority of visible clasts vary in size from a few cm to 0.75 m in

diameter. Boulders/clasts are mostly (sub)rounded although rarely some angular clasts occur. The Division I conglomerate/breccia is clast supported with a sparse matrix (referred to as Facies A, Fig 7A). Matrix is composed of marl, small lithoclast fragments and foraminiferal debris (nummulitid and orthophragminid tests). The major lithological components are Cretaceous limestones (88%) while Foraminiferal limestones (9%) and other constituents (3%) are less abundant. Interestingly, the Lower Cretaceous limestone clasts were only observed in this megabed. The clast composition is presented in Fig. 3B and selected photomicrographs of Lower-, Upper Cretaceous and Foraminiferal limestone clast microfacies are presented in Plate 1E, F, and G.

Division II is composed of normally graded calcirudite and calcarenite with the following composition: orthophragminids (32-54%), nummulitids (6-26%), and red algae (9-13%), as pre-
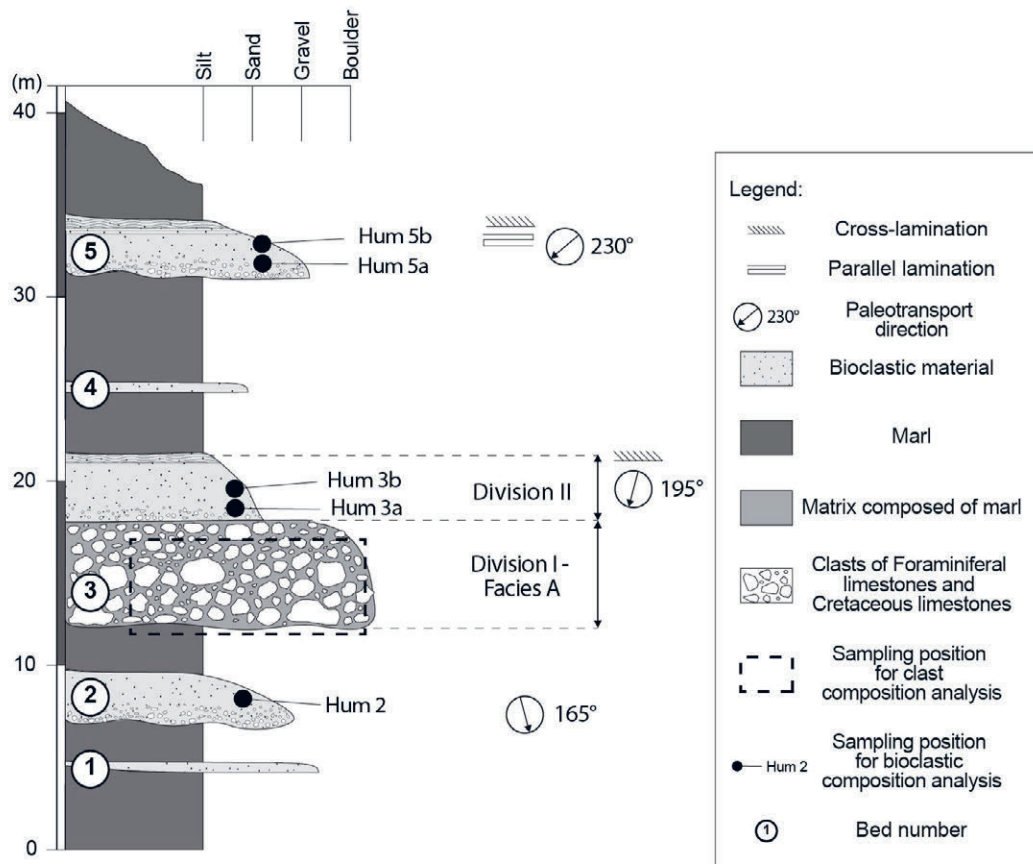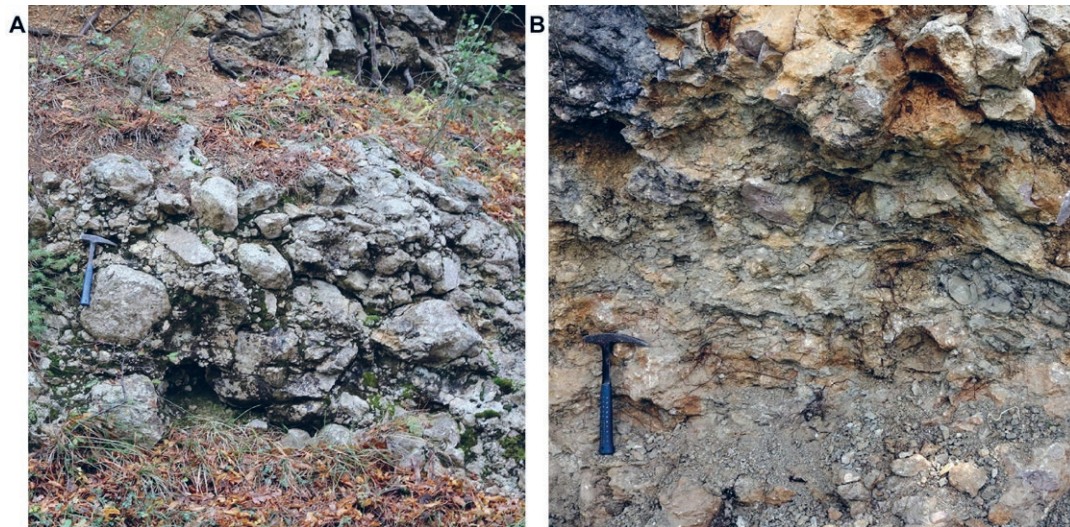

Figure 6. Geological column showing the 10 m thick Hum megabed (3) and carbonate turbidites (1, 2, 4 & 5).

Figure 7. The outcrop photographs of the Division I deposits, showing clast supported breccia with sparse marl matrix (Facies A). **(A)** Hum megabed Division I - clast supported breccia/conglomerate with sparse matrix; **(B)** Plomin megabed Division I - clast supported breccia with sparse marl matrix. The geological hammer is 32 cm long.
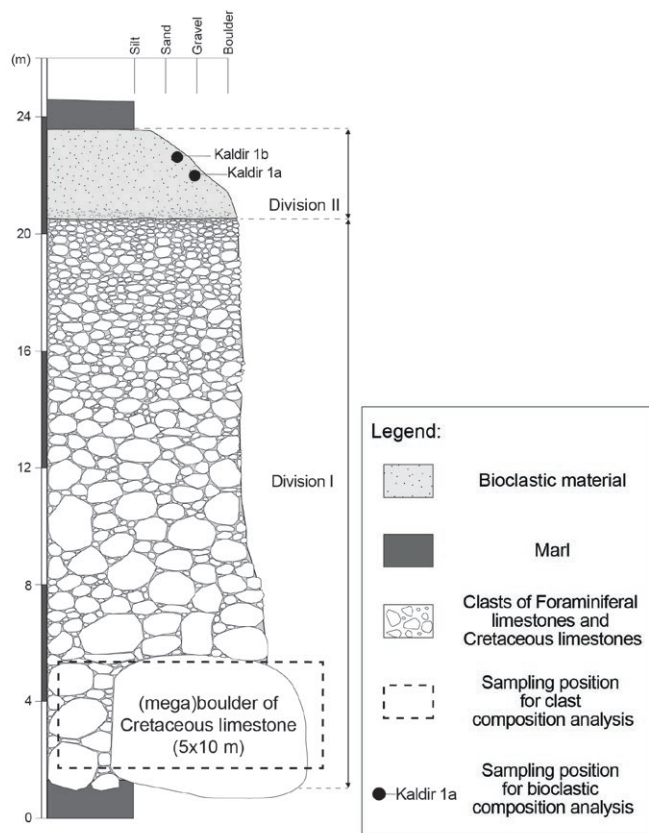
sented in Table 1. The Hum 2 and 5 beds are also composed of normally graded calcirudite and calcarenite with the same main constituents, but in different proportions (Table 1).

Based on the uniform composition, it is assumed that the carbonate detritus source for the turbidites (Hum 2 and 5), and megabed (Hum 3) was the same. A palaeotransport direction of 165° was measured from flute casts observed on the lower bedding plane of the Hum 2 turbidite (Fig. 6), and 195° on ripple marks observed on the upper bedding plane on the Hum 3 mega-

bed, and 230° on turbidite Hum 5 (Fig. 6). These data, though insufficient for statistical assessment, indicate that palaeotransport of the more proximal megabeds was locally generally towards the S, as measured in the Hum Section (Fig. 6).

4.3. The Kaldir Section

The studied outcrop of the Kaldir megabed is located near Kaldir village (Fig. 1, WGS84 coordinates: lat 45° 18' 43.1598", long 13° 51' 16.9056"). This megabed (Fig. 8) is approximately 25 m thick, composed of limestone breccia (Divison I) in the lower part and the normally graded calcirudite/calcarenite in the upper part (Division II). The geographic distribution of the Kaldir megabed is shown on Fig. 9. When compared to the other megabeds, the Kaldir Division I displays a significant difference in clast size and shape and very low marl content. The contact between the Kaldir megabed and the underlying marl is sharp and erosional. The largest clast lies directly on the underlying marl at the bottom of the sequence and has a visible dimension of 5 x 10 m (Fig. 10A). The breccia is clast supported, unsorted with a sparse matrix composed of fine-grained rock debris. Clasts are angular, indicating short transport distances. A normal gradation is visible towards the upper part of Division I. The clast composition is as follows: Upper Cretaceous limestones 90%, Foraminiferal limestones 9%, and undetermined clasts 1%. Also, a bauxite clast was observed. The composition is presented in Fig. 3C, while clast microfacies of Upper Cretaceous and Foraminiferal limestones are presented in Plate 2 A, B, C. The majority of the Foraminiferal limestone clasts are classified as Discocyclina limestones. Some of the Discocyclina limestone intraclasts (plasticlasts) are plastically deformed between the larger Cretaceous boulders and are tightly packed (Fig. 10B). This phenomenon indicates that some of the Discocyclina limestones were not fully consolidated during their resedimentation and deposition in the breccia. The transition to a normally graded 3 m thick calcirudite/calcarenite (Division II) unit is gradual. The most common constituents of bioclastic material are: orthophragminids (35–41%), red algae (23–24%), and rotaliid foraminifera including hyaline fragments (14%). The proportions of all constituents in the investigated samples are shown in Table 1 and illustrated in Plate 2D.
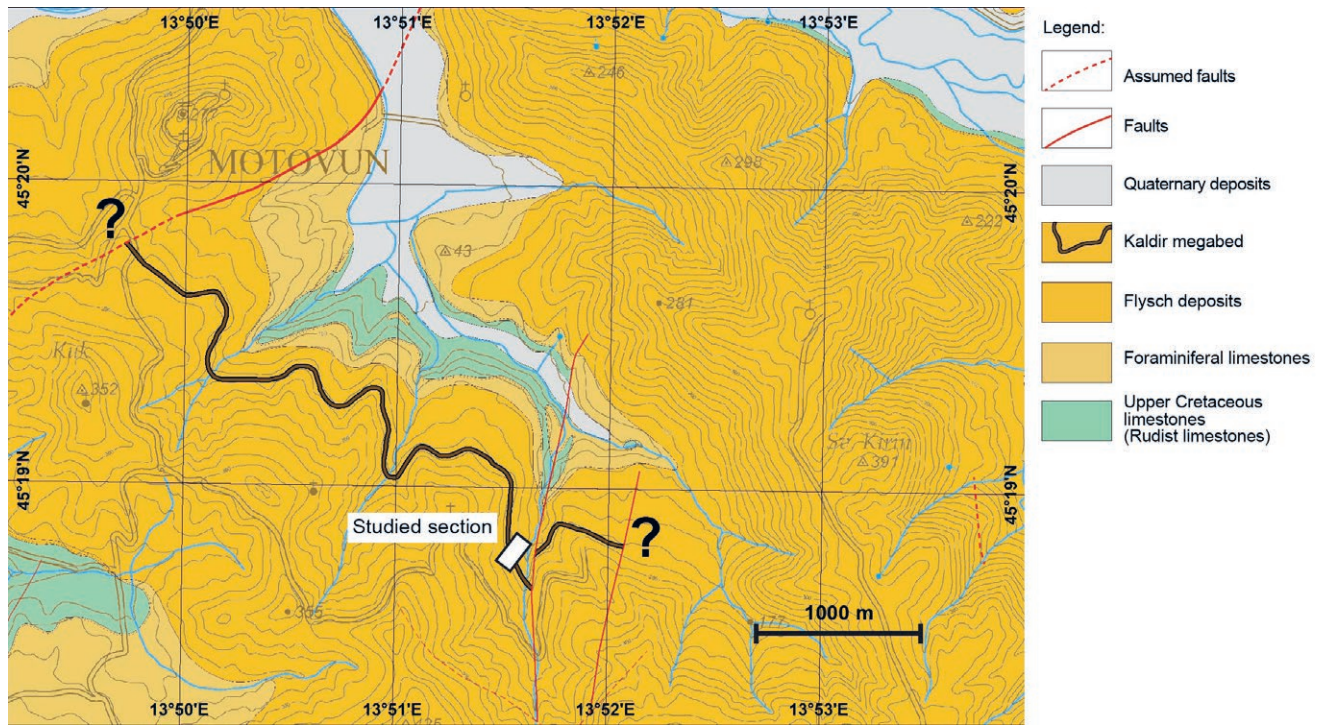

Figure 8. The Kaldir megabed column.

Petrinjak et al.: Megabeds in Istrian Flysch as markers of synsedimentary tectonics within the Dinaric foredeep (Croatia)   **107**

Geologia Croatica

Figure 9. Geological map showing the Kaldir megabed spatial distribution, modified after BERGANT et al. (2020).

4.4. The Gračišće Section

The Gračišće megabed is located south-east of the town of Gračišće (WGS84 coordinates: lat 45° 12' 59.6844", long 14° 0' 29.7", Fig. 1). The contact with the underlying marls is covered by vegetation and the lower bedding surface of the Gračišće megbed is therefore not visible. The megabed is a bipartite bed with chaotic breccia (Division I) that is matrix supported (referred to as Facies B) in the lower part and a well cemented, normally graded calcirudite/cal-carenite in the upper part, with a total thickness of 40 m (Fig. 11). The lower breccia interval is 25 m thick, lenticular in shape, and pinches out laterally. This breccia is matrix supported with pre-dominantly sub-angular clasts (Fig. 12A). The most abundant clasts are Foraminiferal limestones (75%) and marl clasts (17%), while rhodolith fragments (3%), Upper Cretaceous limestones (2%), un-differentiated Cretaceous limestones (1%), Transitional beds (1%) and undifferentiated clasts (1%) are less represented. The compo-sition is presented in Fig. 3D and the selected Algal foraminiferal limestone clast microfacies photomicrograph is presented in Plate 2E. The matrix is a mix of marl, fragmented bioclasts and smaller lithoclasts. Bioclasts are mostly foraminiferal debris (nummulitids and orthophragminids) and rhodoliths. Most clasts are < 10 cm di-ameter, while marl clasts are significantly larger and can be up to 50 cm across (Fig. 12B). The Division I breccia gradually transi-tions into a well cemented, normally graded calcirudite/calcarenite in the upper part of the section. The most common constituents of Division II material are: orthophragminids (31-35%), nummulitids (11-25%), red algae (17-20%), and lithoclasts (8-16%). The ratios of all constituents in the investigated samples are shown in Table 1 and illustrated in Plate 2F.
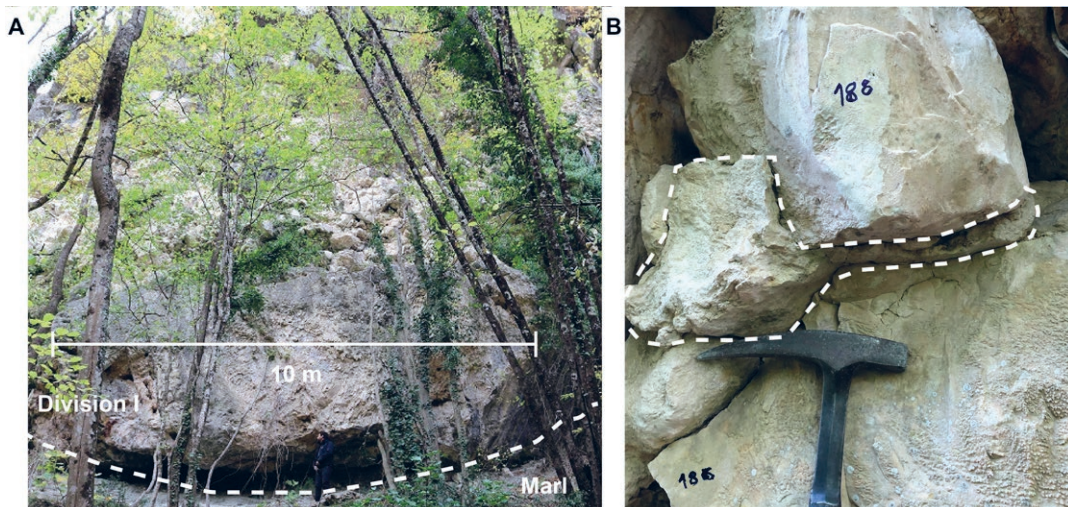

Figure 10. The Kaldir Division I breccia. **(A)** The 10x5 m boulder of the Upper Cretaceous limestone in the base of the Kaldir megabed. The contact between the Kaldir megabed and the underlying marls is sharp and erosional. **(B)** The Discocyclina limestones occur as plastically deformed clasts compressed between the larger Cretaceous clasts. The geological hammer head is 19 cm long.
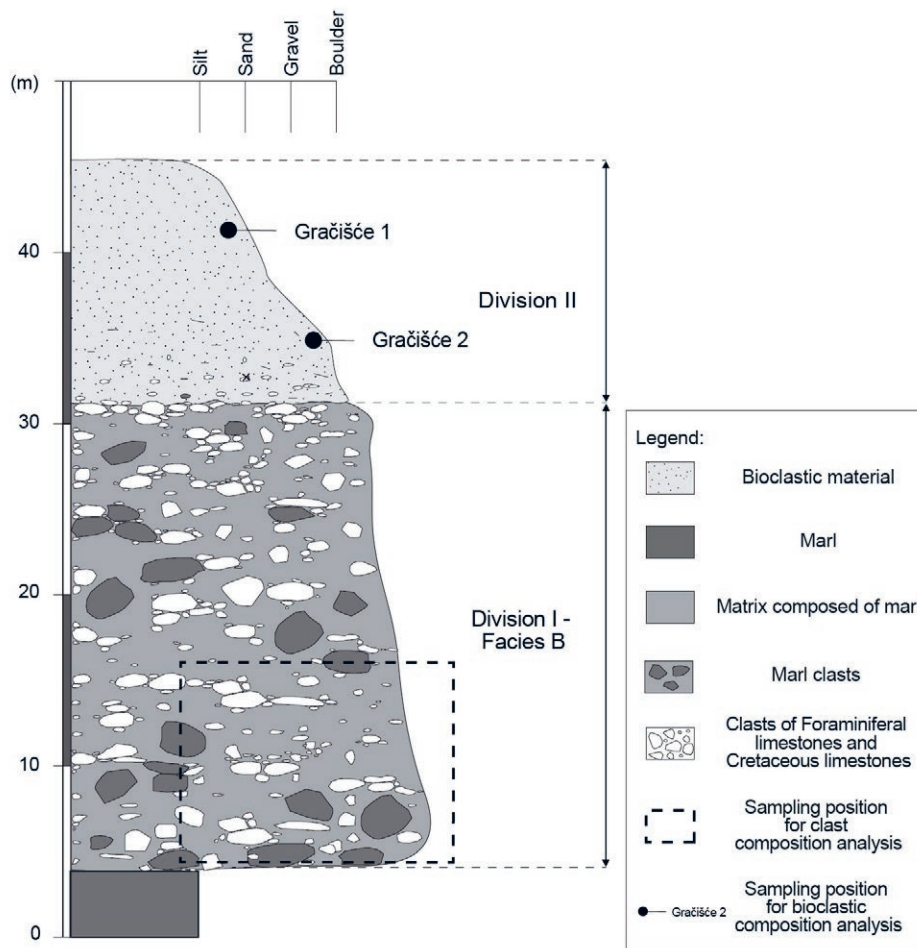
Figure 11. The Gračišće megabed column.

4.5. The Plomin Section

The Plomin megabed crops out on the road cut NW of Plomin village (WGS84 coordinates: lat 45° 8' 45.6612", long 14° 10' 19.5198"). As a consequence of tectonic deformation along the nearby N-S striking fault (Fig. 1) the beds are relatively inclined with average bed dip azimuth and dip angle of 150/40. The lower part of the Plomin megabed and the contact with the underlying marls is covered by vegetation and colluvium. The studied bed is composed of a 3 m thick Division I breccia in the lower part (Fig. 7B) and 17 m of normally graded bioclastic calcirudite/calcarenite in the upper Division II (Fig. 13). The breccia is composed of boulder-sized clasts with an average longer axis of 20–30 cm. The largest measured clast is 50 cm in diameter. The lithological composition of the breccia is Foraminiferal limestones 93%, Transitional beds 2%, marl 2%, and undetermined clasts 3%. The
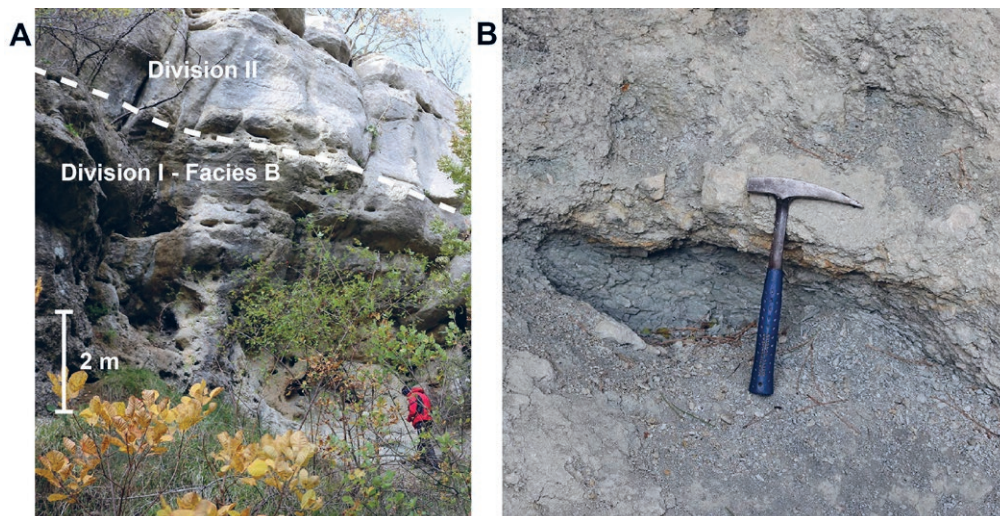

Figure 12. Photographs of the Gračišće megabed **(A)** The outcrop of the Gračišće megabed with marked divisions. The holes (casts) within Division I are formed because of the selective erosion of marl clasts. **(B)** Photographs of marl clasts within Division I, Facies B of the Gračišće megabeds. The marl clasts are significantly larger than the limestone clasts. The geological hammer is 32 cm long.

clast composition is presented in Fig. 3E and selected photomicrographs of Foraminiferal limestone clast microfacies are presented in Plate 3A, B, and C. The breccia is mostly clast supported, with a sparse matrix. The matrix is a mix of marl, fragmented bioclasts and smaller lithoclasts. Bioclasts are mostly foraminiferal debris (nummulitids and orthophragminids) and rhodoliths. The carbonate breccia (Division I, Facies A) gradually transitions to a 17 m thick normally graded calcirudite/calcarenite (Divison II) and the matrix content decreases. Calcirudite is a well cemented, normally graded bed without a marl matrix, with a maximum clast size of 10 cm in diameter. The most common constituents of bioclastic material are ortophragminids (35%), nummulitids (27–33%), lithoclasts (11–12%), and red algae (7–18%). The proportions of all constituents in the investigated samples are shown in Table 1 and illustrated in Plate 3D. Marl clasts occur in the middle part of the calcirudite zone, have an elongated shape, parallel orientation, and are 30-40 cm long and up to 6 – 10 cm thick. The size of the marl clasts gradually decreases towards the upper part of the calcirudite zone. Calcirudite gradually transitions to calcarenite (normal gradation) with visible parallel lamination and indistinct cross lamination unsuitable for palaeotransport measurements. The upper part of this megabed ends with a massive marl interval. The Plomin megabed is overlain by an interval of about 20 m of continuous Flysch, composed of marl and thin carbonate and mixed carbonate and siliciclastic turbidites.

4.6. The Koromačno Section

The Koromačno section of the Istrian Flysch is located in Koromačno quarry (WGS84 coordinates: lat 44° 58' 10.8366", long 14° 7' 53.94"). Besides Division I and Division II, a Transitional zone is outlined in the Koromačno megabed (Figs. 14 and 15A). The Transitional zone has characteristics of both the lower Division I and upper Division II. The characteristics of Division I are large marl clasts (largest measured clast with long axis of 1 metre). The similarity with the upper Division II is the composition of a distinctly graded calcirudite fabric. The lower bedding surface of the Koromačno megabed is not exposed at this location, but underlying calcarenite and marl beds are recognized in the vicinity.

The lower Division I (Facies B, Fig 15B) interval is composed of a matrix supported breccia with large clasts of marl and limestone lithoclasts. The clast composition is: Foraminiferal limestones 80%, Transitional beds 3%, marl clasts 16%, and undetermined clasts 1%. The clast composition is presented in Fig. 3F and selected Foraminiferal limestone clasts microfacies photomicrographs are presented in Plate 3 E, F, and G. As in the Gračišće megabed, the matrix is a mix of marl and fragmented bioclasts (nummulitids and orthophragminids and rhodoliths).

In the middle part, labeled as the Transitional zone, the content of the marl matrix rapidly decreases and well cemented cal-
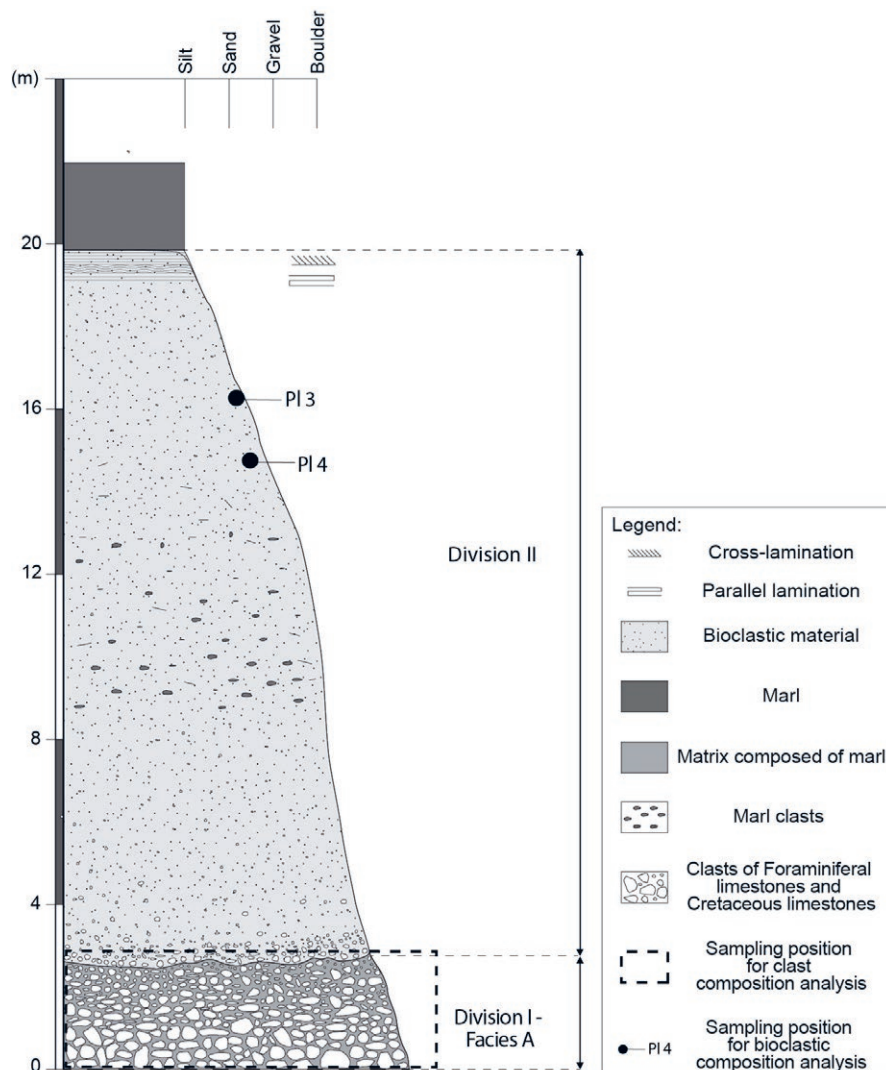

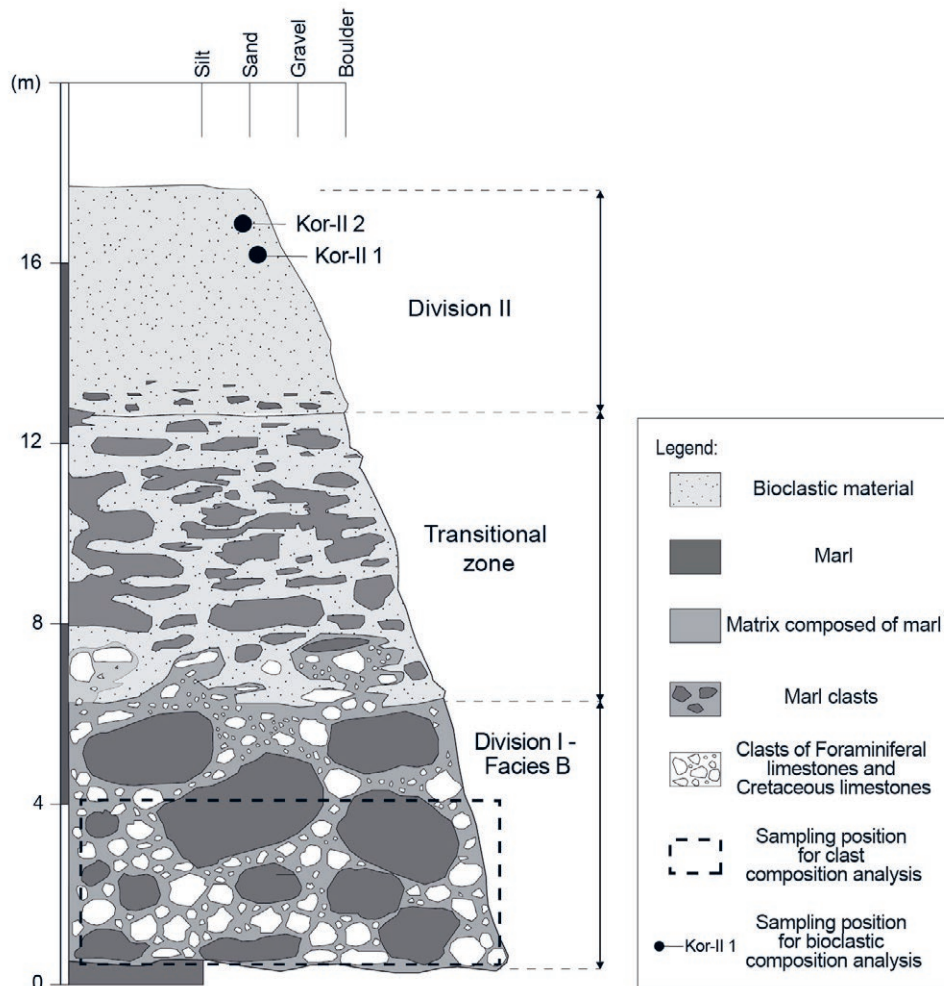**Figure 13.** The Plomin megabed column.

Geologia Croatica

Figure 14. The Koromačno megabed column.

cirudite becomes dominant. The largest clasts are outsize marl clasts with long axis dimensions of 1 cm to 1 m. Marl clast size decreases up-section. Transitions between these parts are gradual. The Division II interval follows the Transitional zone and is marked by the absence of marl clasts. It is composed of normally graded calcirudite and calcarenite. The most common constituents of Division II material are: red algae (28-31%), lithoclasts (22-27%), orthophragminids (16-21%), and nummulitids (13%). The ratios of all the constituents in the investigated samples are shown in Table 1 and illustrated in Plate 3H.

5. INTERPRETATIONS

The studied beds are bipartite, composed of debris flow deposits in the lower part (Division I) with a gradual transition to a high-density turbidity current deposit in the upper part (Division II).

5.1. Division I

Within Division I two facies types are recognized and both are interpreted as debris-flow deposits that suggest "*en masse*" deposition after cohesive freezing.
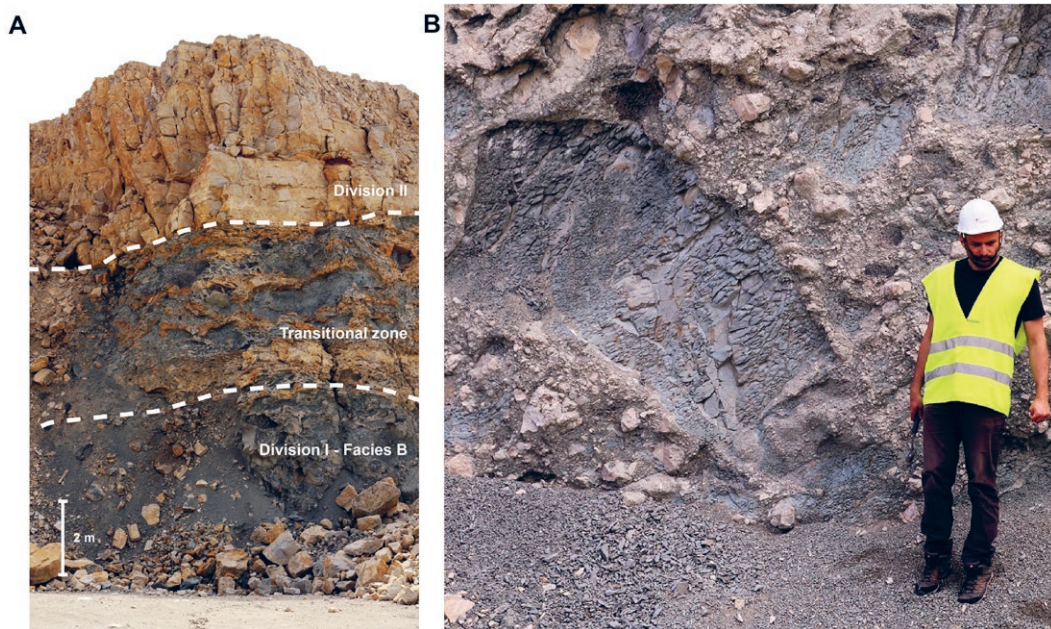
Facies A is a clast supported conglomerate/breccia, normally graded, with sparse matrix. This facies is observed at the Hum, Plomin, and Šublentica sections. The lithological composition of the clasts is different in each of the investigated beds (Fig. 3). The marl (rip-up) clasts in Facies A are found only in the Plomin section. Weak normal grading is recognized in the upper part of the division at the Hum and Šublentica sections. The matrix is composed of marl and bioclasts, mostly nummulitids and orthophragminids.

Facies B of Division I is a chaotic, matrix-supported breccia with outsized rip-up clasts, and a greater total thickness than Facies A. The characteristic by which the described facies are distinguished is the amount of matrix and the marl content. Facies B is observed at Koromačno and Gračišće. The matrix is a mix of marl, fragmented bioclasts and smaller lithoclasts. Bioclasts are mostly foraminiferal debris (nummulitids and orthophragminids) and rhodoliths.

The bipartite organization is a consequence of the transformations from debrite flow to turbidity current, as the debris flows are considered to be one of the mechanisms for generating turbidity currents (HAMPTON, 1972; LOWE, 1982; MULDER & ALEXANDER, 2001; SHANMUGAM, 2006; FELIX et al., 2009). Facies A deposits are related to clast-dominating debris flows, while Facies B deposits are related to more marl (mud) rich debris flows. Observed differences in the matrix and the marl content might be related to differences in the initial composition of the mass flow and the evolution of the flow.

The Division I at Kaldir megabed is singled out for its unique properties: total thickness, clast size and angular shape, and total lack of matrix. The clast size (largest measured clast is 5x10 m) and angular clast shapes suggest a very short transport distance. The lack of matrix indicates a transport mechanism different to a cohesive debris flow, probably a large-scale submarine rock-avalanche.

Petrinjak et al.: Megabeds in Istrian Flysch as markers of synsedimentary tectonics within the Dinaric foredeep (Croatia)　　　　111

Geologia Croatica

Figure 15. (A) Outcrop of the Koromačno megabed showing two divisions and a transitional zone in the middle. The chaotic, matrix supported breccia in the lower part (Division I) gradually transitions into the transitional zone, composed of cemented calcirudite breccia with large marl clasts (Transitional zone). The normally graded calcirudite lacking outsized marl clasts is located at the top (Division II). **(B)** Marl clast within Division I breccia, Facies B part of Koromačno megabed. The clast dimension is 2 x 1 m at outcrop.

5.1.1. The composition of Division I clasts

The studied clast composition indicates that Division I material (clasts) was derived from different parts of the Cretaceous to Palaeogene neritic carbonate succession that underlies the Eocene Flysch. The most common clasts determined in each megabed, categorized according to the previously defined major lithostratigraphic units, are Foraminiferal limestones and Upper Cretaceous Rudist limestones, as shown in Fig. 1. The Lower Cretaceous clasts are only observed in the Hum megabed. Rare bauxite and karstified Cretaceous limestone clasts were only recognised in the Kaldir megabed. The karstified Upper Cretaceous limestone boulder with bauxite karst infills has been described by TARLAO et al., (1995) in a debrite within the Istrian Flysch southwest of Pazin (Fig. 1). The palaeo-karstified Cretaceous limestones and bauxite clasts are related to the regional unconformity within the Adriatic Carbonate platform succession that was formed during the Late Cretaceous and Early Palaeogene emersion of the forebulge (OTONIČAR, 2007).

5.2. Division II

Division II intervals are up to 10 m thick, clast supported, and normally graded, calcirudite/calcarenites and are seen in all the studied megabeds. Towards the top of the interval there is a gradual transition, first from calcirudite to calcarenite, and eventually to calcisiltite grain size. In the uppermost part of Division II, horizontal and cross lamination are observed in calcarenites or calcisiltites in the Hum and Plomin megabeds. Division II is overlain by a massive marl deposited from the turbidity current tail. Division 2 of the megabeds is interpreted as a co-genetic turbidite deposited by a high- to low-density current (LOWE, 1982).

5.2.1. The composition of Division II

As result of point-counting calcirudite/calcarenite samples of the Division II interval, 12 different constituents are distinguished and grouped. The results of Division II composition analysis (Table 1) shows that the most abundant grains in Division II are or-

thophragminids, nummulitids, red algae, and lithoclasts. This specific composition shows a clear predominance of bioclastic material derived from the outer carbonate ramp environments as described in Eocene carbonate ramp models in HALLOCK & GLENN (1986), ĆOSOVIĆ et al. (2004), and BASSI (2005). The coralline rhodolites were probably formed along intrabasinal, isolated banks, characterized by strong water currents and reduced sediment input (RASSER & PILLER, 2004; BARATTOLO et al., 2007). The lithoclasts observed are grains of older limestone rocks from the Cretaceous-Palaeogene limestone succession (extraclasts). The most abundant extraclasts are mudstones or wackestones containing sparse unidentifiable bioclasts. The matrix is micrite (Group 2), while sparite cement is scarce (Group 3). The Large benthic foramniferal taxa are assigned to groups 4, 5 and 11. The other skeletal grains are grouped according to their taxa. The calcirudite and calcarenite microfacies of Division II with some of the most abundant constituents is presented in Plate I D, H, Plate II D, F and Plate III D, H.

6. DISCUSSION

6.1. Palaeotransport directions

In the palaeotransport model for the Pazin (Istrian) Basin provided by BABIĆ & ZUPANIČ (1996), the palaeotransport direction of carbonate beds composed of debrite and turbidite unit is towards the NNE. Also, BABIĆ & ZUPANIČ (1996) suggest the existence of land and shelf environments to the SSW of the former Pazin Basin from where the carbonate material was derived. Since the data about the palaeotransport directions found in the studied megabeds is scarce, we can assume that the major source of carbonate material were fault dissected or a locally over steepened distal foredeep slopes (cf. SINCLAIR, 1997; BARNOLAS & TEIXELL, 1994), that were located along the southern margin of the Istrian Flysch basin, as proposed by BABIĆ & ZUPANIČ (1996). According to that model, all the studied megebeds were deposited by gravitational flows on the distal slopes of the foredeep, along the

transitional zone between the basin and the distal carbonate ramps to the S, indicating the transport was towards the N.

However, palaeotransport measurements within this study were derived from only one megabed on the Hum section and two from the thick carbonate turbidites in the succession (Fig. 6). According to this data the paleaotransport of more proximal megabeds was locally towards the S.

Combining the observed data within this study (palaeotransport direction on Hum section) and older research (BABIĆ & ZUPANIČ, 1996), we can assume that the carbonate detritus had multiple sources and transport directions, with the major transport direction towards the N and minor transport towards the S (Figs 16 and 17).

6.2. The source of shallow-water bioclastic detritus

Shallow-water bioclastic detritus is a constituent of the studied megabeds and is observed in Division I mixed with marl in the matrix, and as grains of bioclastic calcirudite/calcarenites of Division II. The source area of the bioclastic detritus was a synchro-

nous shallow water carbonate ramp attached to Flysch basin from the south (Fig. 16).

Carbonate ramps in a foreland basin setting could be formed on an underfilled foreland basin margin (SINCLAIR, 1997; BOSENCE 2005) or developed on overthrusts and thrust folds, as described in Northern Dalmatia (ĆOSOVIĆ et al., 2018). Since thrusts and thrust-top deposits are not recognized in the northern part of the Istrian Flysch basin, a more probable location for the ramp is in the South, as a distal, marginal (forebulge) part of the Dinaric foreland basin (OTONIČAR, 2007). The distal margin of low-latitude, underfilled foreland basins is a favoured site for the accumulation of large carbonate platforms and ramps (SINCLAIR, 1997; BOSENCE 2005). Alternatively, it can be argued that the bioclastic detritus originated from stratigraphically older, weathered Foraminiferal limestones. If that were the case, its composition would include fossils from other Foraminiferal limestone strata, e.g. alveolinid or miliolid tests, but no such grains were recognized in this study. The absence of these characteristic foraminifera lead to the conclusion that the bioclastic detritus came from synchronous outer-ramp environments that were attached to the Istrian Flysch basin from the South. However, there is also the
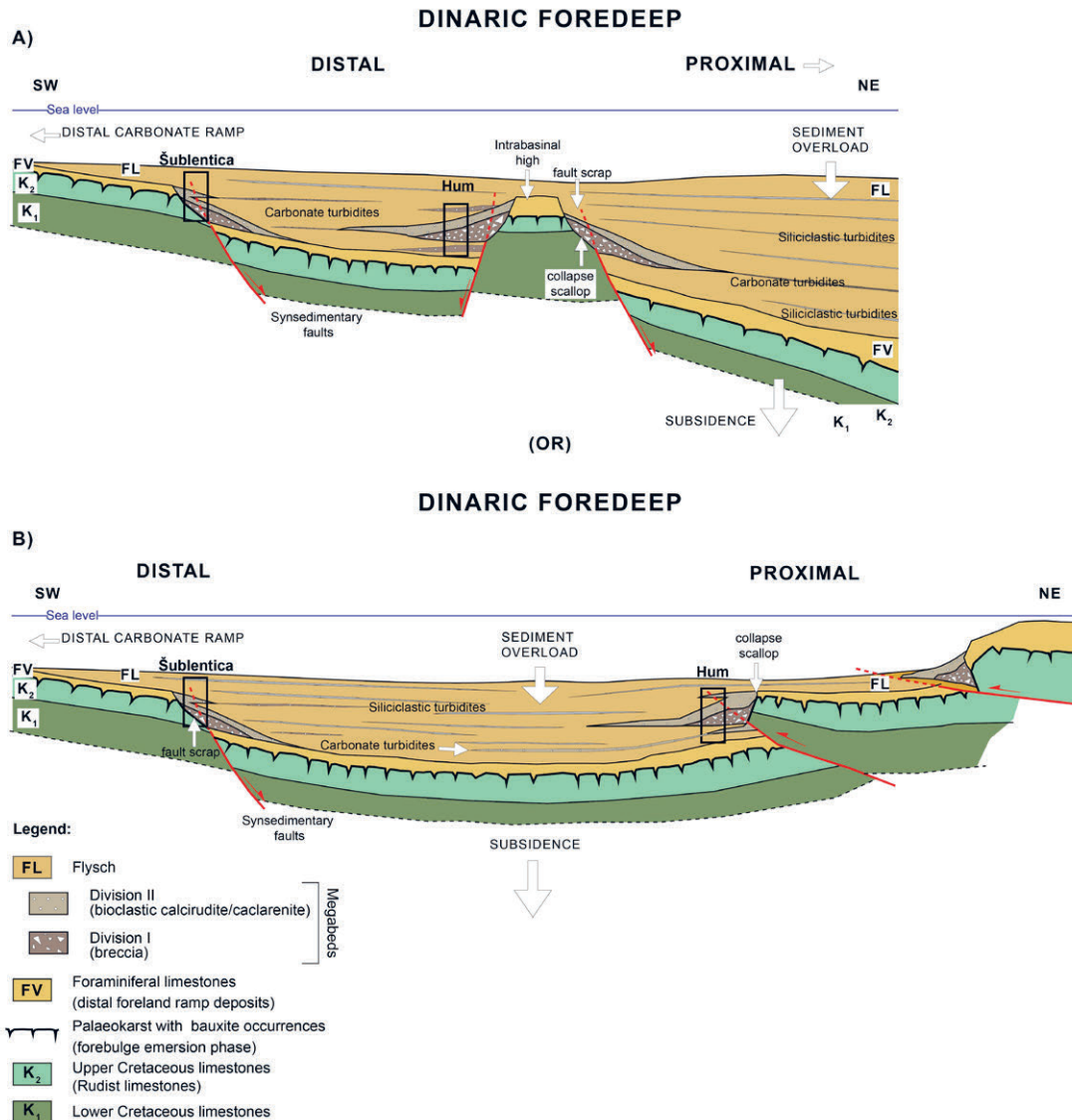

Figure 16. Two possible options of schematic reconstructions of the Istrian foredeep basin after megabed deposition. **(A)** All megabeds are related to extensional tectonics and normal faulting in the distal foredeep. **(B)** Proximal megabeds are related to compressional tectonics and reverse faulting in front of the Dinaric orogenic wedge. Not to scale. See discussion in the text.

Petrinjak et al.: Megabeds in Istrian Flysch as markers of synsedimentary tectonics within the Dinaric foredeep (Croatia)   113

Geologia Croatica

possibility that some bioclasts originally originated from the outer ramps are derived from semi-consolidated (uncemented) clayey limestones from the collapsed succession along the foredeep slope.

6.3. Interpretation of the internal divisions and comparison with previous works

As far as sedimentary processes are concerned, the megabeds may be considered as complex beds which were deposited by a range of sedimentary processes e.g., submarine rock avalanche, debris flow, and high-density turbidity currents. As mentioned earlier, the distinct bipartite organization is a consequence of the flow transformations from debrite flow to turbidity current (HAMPTON, 1972; LOWE, 1982; MULDER & ALEXANDER, 2001; SHANMUGAM, 2006). This distinct architecture can be related to beds with similar internal organization. Comparison with hybrid event beds (HAUGHTON et al. 2003, 2009; TALLING, 2013) indicates that the bipartite megabeds described in this study are lacking the basal layer that is present in tripartite hybrid beds, and are much thicker than the described hybrid event beds in papers by HAUGHTON et al., (2003, 2009) and TALLING (2013). The Division I facies types described here bear comparison with the divisions of megabeds from the published literature. The megabeds described in AMY et al. (2007) from the Pïera Cava basin (SE FRANCE) are very similar to the Istrian megabeds described in this research and the authors differentiate two facies types within coarse-grained beds - facies F1: cohesive debris-flow deposit comprised of poorly sorted, metre-long clasts

and a significant proportion of muddy matrix; and facies F2: clast-rich debris-flow deposits with a minor proportion of cohesive matrix. The carbonate megaturbidites described by LABAUME et al. (1987) from the Eocene Hecho Group (SW-Pyrenean Foreland Basin, Spain) are up to 200 m thick and composed of a megabreccia unit in the lower part and the turbidite in the upper part. The megabreccia unit is subdivided into separate divisions: a largely clast supported and poorly organized breccia (Division I) and carbonate breccia which contains an abundance of rip-up clasts of slope marlstone and basin plain turbidites (Division II). TUNIS & VENTURINI (1992) describe megabeds in the Julian basin as couplets of megabreccia in the lower part and a graded calcarenite and marl in the upper part. The described vertical sections of megabeds is further subdivided into two megabreccia units and three turbidite units. Unit l is a megabreccia which mainly consists of big blocks of shallow water limestone olistoliths. Unit 2 is also carbonate megabreccia, but can be recognized by the lack of large limestone olistoliths, for the numerous disc-shaped clasts of calcareous mudstone and for the rip-up siliciclastic turbidites with some interbedded calciturbidites. PAYROS et al. (1999) recognized a downcurrent change in megabed composition from immature, homogeneous debrite in the proximal part, a differentiated, two-storey bipartite debrite and a turbidite in the middle part, and a base-missing debrite overlain by turbidite, or even a turbidite alone, in the distal part. The megabeds containing bipartite breccia outcrops show that each unit consists of a
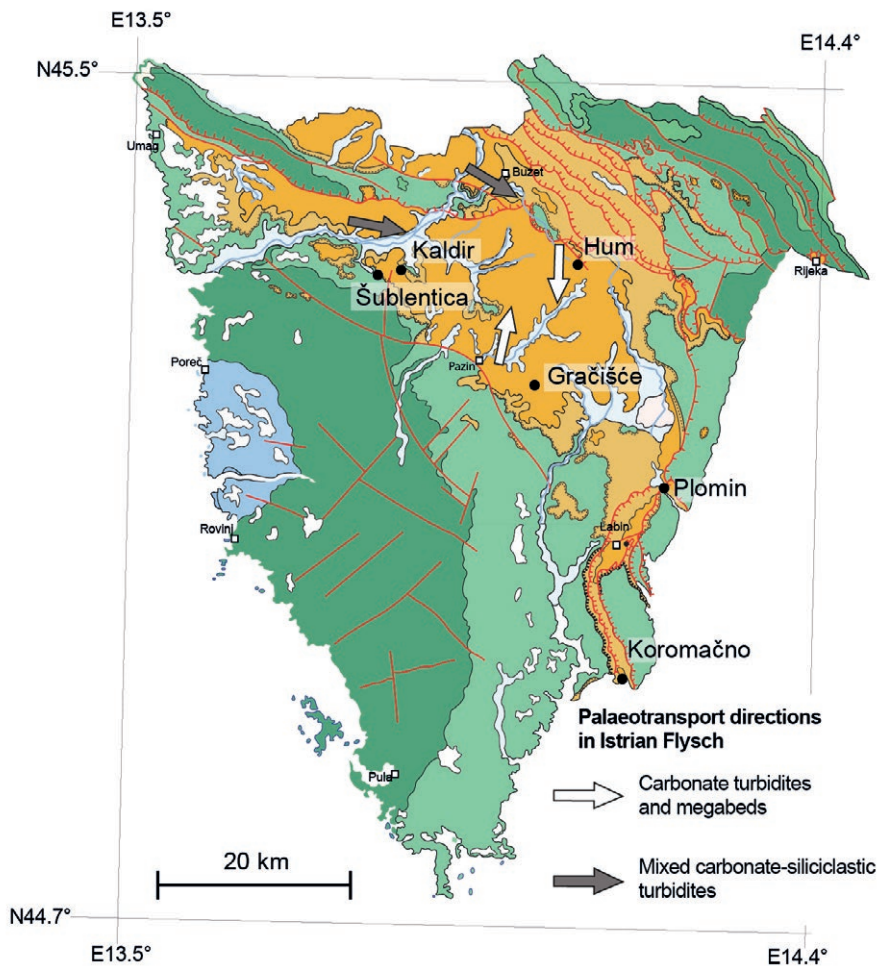
Figure 17. Geological map showing palaeotransport directions in the Eocene Istrian Flysch. The palaeotransport direction data are taken from MAGDALENIĆ (1972), MARINČIĆ et al. (1996) and BABIĆ & ZUPANIČ (1996).

clast-supported breccia overlain by a mud-supported breccia and then capped with a graded calcarenite.

To recapitulate, the authors LABAUME et al. (1987); TUNIS &VENTURINI (1992); PAYROS et al. (1999) describe two subdivisions within a lower, debrite unit: clast supported breccia with olistoliths in the lower part and mud supported breccia containing mudstone rip-up clasts in the upper part. These subdivisions are roughly similar to the Facies A and Facies B described here within Division I. However, within the studied megabeds of the Istrian Flysch, vertical differentiation of facies within Division I itself is not recognized.

The Division I breccia at Kaldir was probably deposited in the early stage of a mass transport event, probably a submarine rock avalanche or some other large-scale grain flow. The dynamic classification of mass transport deposits and evolutionary relationships among the processes responsible for sub-unit formation, from slide/slump and turbidity currents as end-members of such a broad spectrum are described by SHANMUGAM (2006), FESTA et al. (2019) and OGATA et al. (2020). However, the submarine rock avalanche deposits are rarely mentioned in the sediment mass transport spectrum so the exact mechanism of the Kaldir megabed deposition is not yet clear.

HAGN et al. (1979) described the Gračišće olistostrome as containing up to 1 cubic metre sized Cretaceous and Palaeogene boulders, smaller fragments of grey shale and a very rich fossil fauna that lived in the environment of the carbonate shelf. The authors (HAGN et al., 1979) assumed that the fauna and olistoliths originated from different sides of the basin, and that they were resedimented by separate mechanisms and mixed only in-situ, during the final sedimentation. This assumption cannot be maintained because all the biogenic detritus is evenly distributed in the debrite part, as a subordinate constituent of the marly matrix, mixed with larger limestone and marl clasts. Also, the bioclastic detritus is the main constituent in the upper turbidite part (Division II).

6.4. Triggering mechanisms and depositional models

The clast composition indicates that the detritus of each megabed was derived from a different part of the Cretaceous to Palaeogene neritic carbonate succession, as well as from the Flysch itself, as marl clasts are observed in some megabeds. It can be assumed
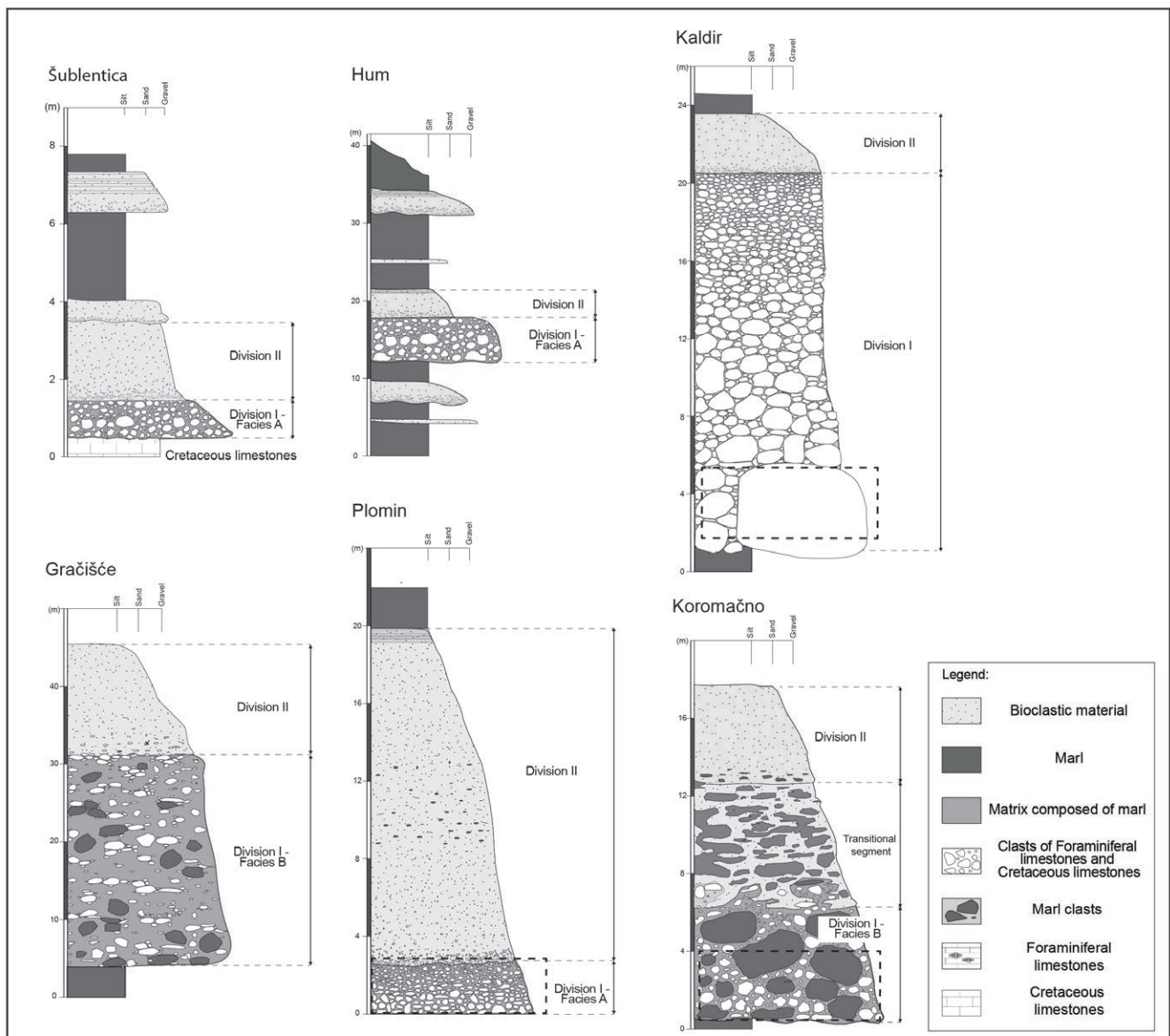
Figure 18. A comparative figure showing simplified logs of all the megabeds. The major differences are in the structure of the Division I breccia – deposited by either a mud- or clast- dominated debris flow, or a submarine avalanche. Also, note that each Division I breccia is characterized by a specific composition (Fig. 3).

Petrinjak et al.: Megabeds in Istrian Flysch as markers of synsedimentary tectonics within the Dinaric foredeep (Croatia) **115**

Geologia Croatica

that the synsedimentary faults that generated submarine failures formed along the carbonate ramps within the fast evolving distal foredeep (cf. SINCLAIR, 1997; BARNOLAS & TEIXELL, 1994, Fig. 16). The faulting also led to the exposure of the older carbonates along the fault scarps thus exposing them to erosion along the steep slopes. The slope collapses, eventually occurring along the fault scarps, generated the mass flows which transported the large quantities of carbonate material (both bioclastic detritus from synchronous carbonate ramps and clasts from older neritic limestones) from the scalloped scarps (Figs. 2 and 16), and also reworked the autochthonous basinal marls. The earthquakes related to the tectonic evolution of the approaching Dinaric orogen could have been the main triggering mechanism for the submarine collapses. The tectonic triggering mechanisms related to deposition of the megabeds in the perialpine foreland basins have already been documented and described (MUTTI et al., 1984; KLEVERLAAN, 1987; PINI et al 2012; OGATA et al., 2020).

TARLAO et al. (1995) supposed that the ongoing orogenic deformation led to subaerial exposure of the basement carbonate succession. In this way the carbonate margins could have been weakened by subaerial processes and thus have been more prone to slope failures. If that was the case, the whole carbonate succession would have been karstified, both Cretaceous and Foraminiferal limestones. However, no karstified Foraminiferal limestones were seen within the megabed clasts. This brings us to the conclusion that the only period of emergence and subaerial exposure was prior to deposition of the Foraminiferal limestones, the Upper Cretaceous to Palaeogene forebulge stage as described by OTONIČAR (2007) and KORBAR (2009).

Furthermore, the studied megabeds are located randomly in the stratigraphy, without any precursive or successive facies associations, suggesting a seismically triggered slope collapse. In other cases, they would occur within major changes in sedimentation patterns, such as at the base of a coarse-grained fan as in the Middle Dalmatian basin, where deposition of the megabeds is attributed to periods of accelerated sea-level rise (MARJANAC, 1996). In the Middle Dalmatian Basin, megabeds have been related to accelerated sea-level rise sometime after a lowstand, since they are interbedded with fan deltas (MARJANAC, 1996) which is not the case with the Istrian megabeds. Although the connection between global sea level change and deposition of the Istrian megabeds is not yet established, a possible sea level drop during the Middle Eocene could have had an impact on resedimented carbonates in Istria.

Time correlation between the Istrian megabeds and global sea level data (e.g. HAQ et al., 1987) is not yet possible, since the available data about the megabeds age is too imprecise. Moreover, the megabeds are present in various stratigraphic parts of the Istrian Flysch. The Kaldir, Šublentica, and Hum occurrences (Fig. 2) are positioned in the lower part of the Istrian Flysch succession while those at Gračišće, Plomin, and Koromačno (Fig. 2) are in the middle, and thus were probably deposited during various sea level stands. Thus, the collapse events are more probably related to tectonic activity than to a specific sea level stand (Fig. 16). The diverse influence of tectonics on the sediment deposition in foreland basins has been documented at various locations in the literature (KLEVERLAAN, 1987; BARNOLAS & TEIXELL, 1994; PAYROSE et al., 1999; TOMASSO & SINCLAIR, 2014; GOBO et al., 2021).

Although we concluded that depositions of the megabeds are mainly induced by tectonics, it is not yet clear if collapses that generated mass flows are rather related to normal faulting within the distal part of the foredeep basin (Fig. 16A) or also to thrust faulting in the proximal part, i.e., in front of the orogenic wedge (Fig. 16B). During the evolution of the Istrian foreland basin the normal faults could have dissected the distal foredeep and even generated intrabasinal topographic highs (horsts) and in that way exposed the older rocks along the fault scarps (Fig. 16A). Also, the backstepping and retreat of the carbonate platforms, located in the distal parts of the foreland basin, could induce the collapse of platform margins as described in the Jaca basin, and Pyrennian foreland (BARNOLAS & TEIXELL, 1994). The alternative option is that some megabeds, at least the most proximal location of Hum, are related to aborted thrust faults in front of the orogenic wedge (Fig. 16B).

7. CONCLUSIONS

Based on the data presented here, several concluding remarks can be made about the Istrian megabeds.

Megabeds in the Middle Eocene Istrian Flysch are considered to represent single event bipartite mass transport deposits with a complex structure that implies a complex flow mechanism and flow transformations. The lower parts of the megabed (Division I) are composed of debris flow deposits or even rock avalanche deposits (Kaldir). The upper part (Division II) is composed of turbidity current deposits.

The megabeds are composed of: a) lithoclasts derived from older neritic limestones underlying the Flysch; b) bioclastic sediments derived from synchronous carbonate ramps, and c) reworked basinal sediments (predominantly hemipelagic marls).

In addition to different structural features, each megabed has a distinct clast composition (Lower and Upper Cretaceous limestones as well as the Eocene Foraminiferal limestones) indicating that each bed is a sedimentary record of a specific local slope failure that scalloped a different part of the Cretaceous to Palaeogene carbonate succession underlying the Flysch. Thus, each described megabed probably represents a separate local collapse within the Dinaric foredeep.

The synsedimentary faults dissected the floor of the evolving distal Dinaric foredeep and exposed the basement rocks along the submarine fault scarps. Seismic shocks related to the approaching orogen are proposed as the main triggering mechanism for the collapses along the fault scarps and/or oversteepened slopes.

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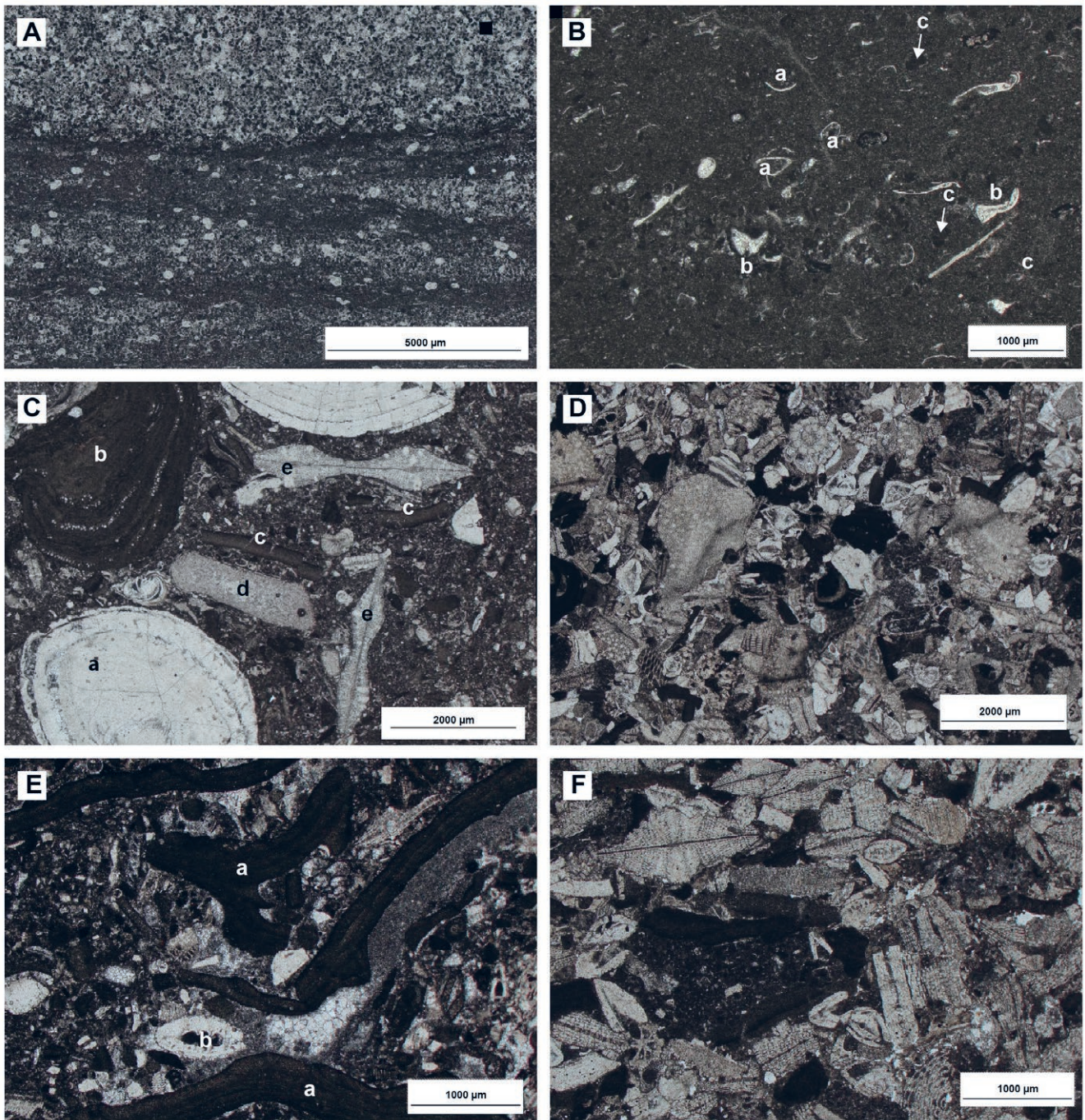
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Petrinjak et al.: Megabeds in Istrian Flysch as markers of synsedimentary tectonics within the Dinaric foredeep (Croatia)   117

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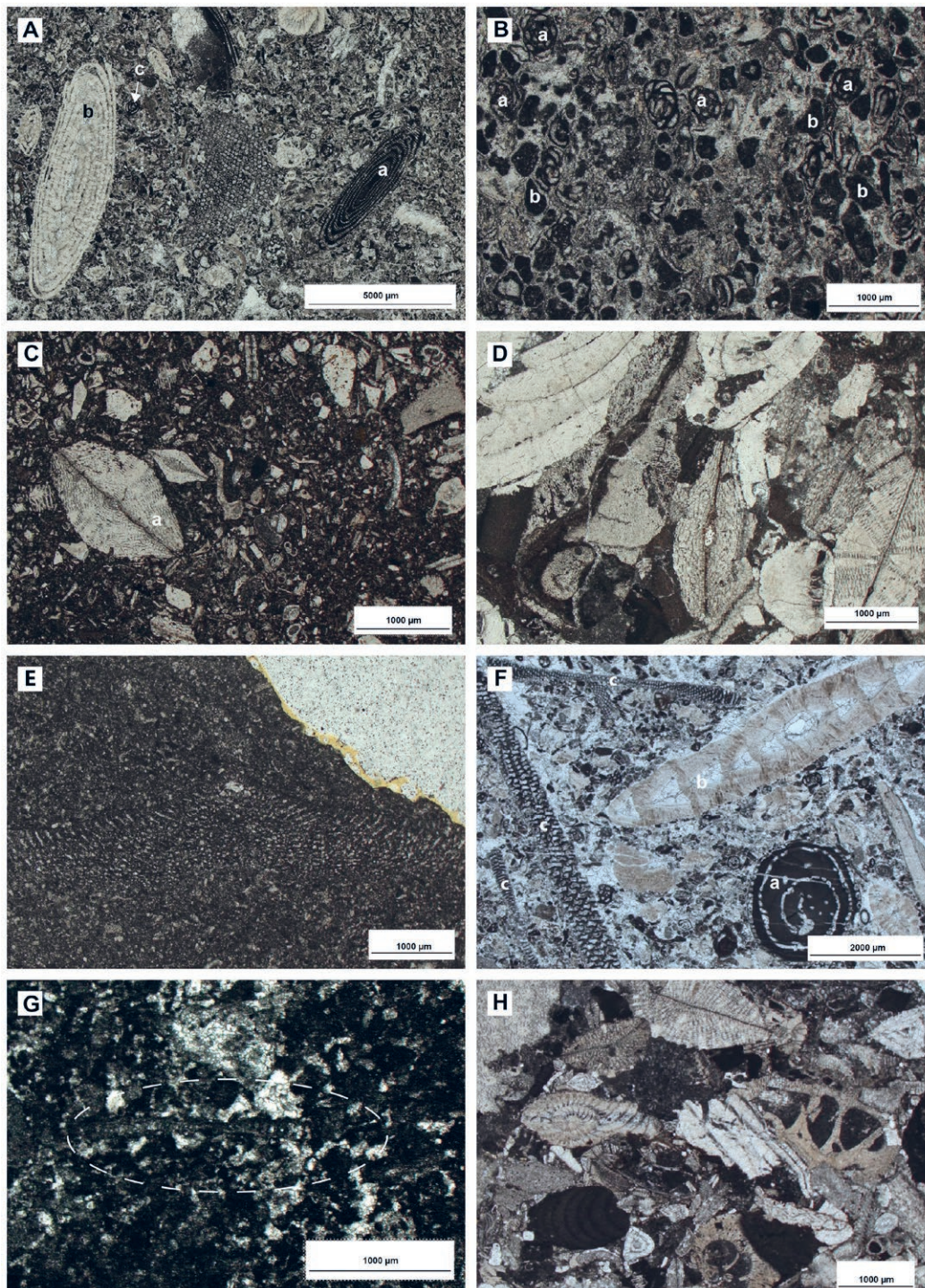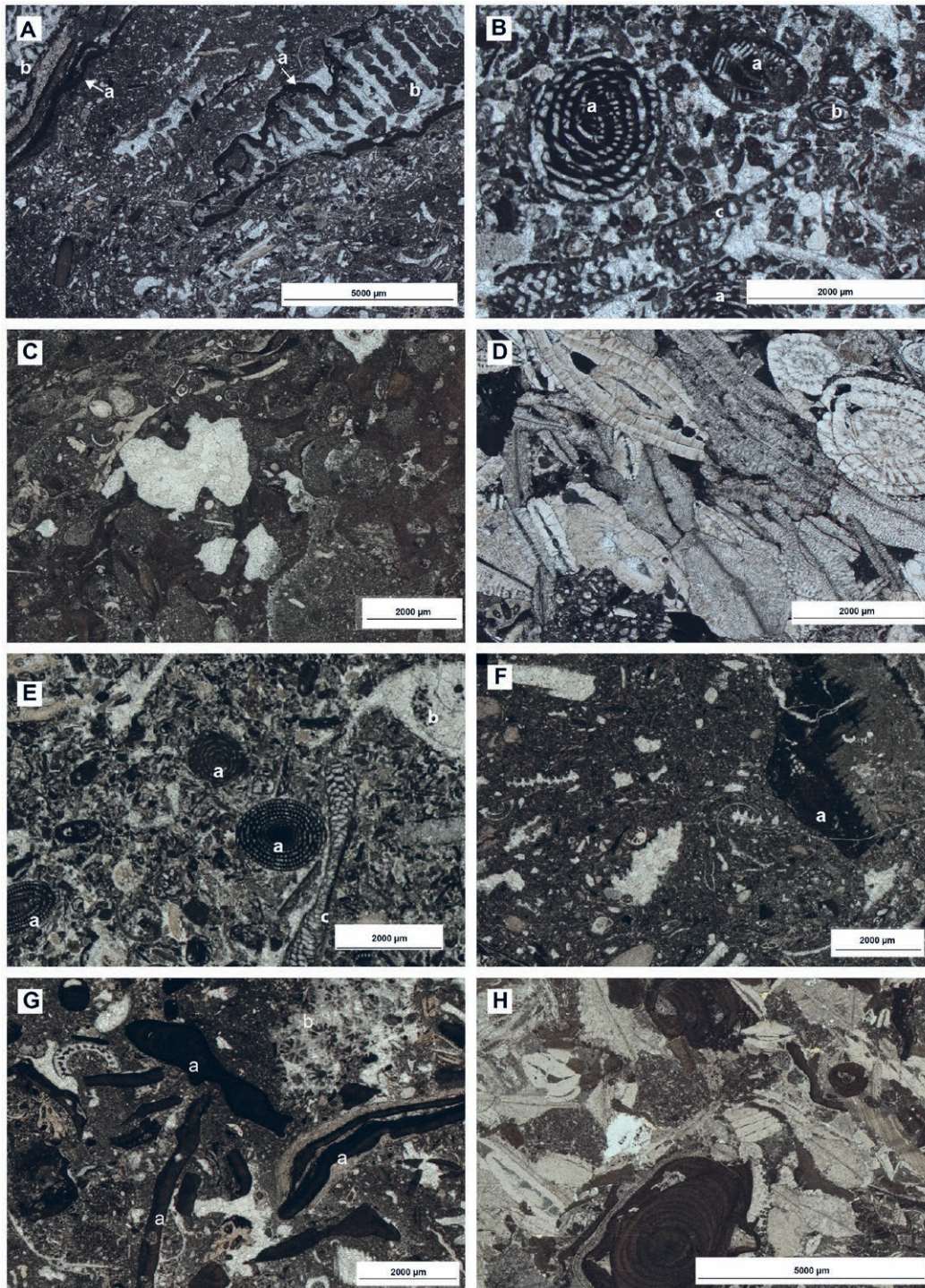
Plate 1. Photomicrographs of the microfacies of the most common clasts from Division I breccia (A, B, C, E, F, and G) and microfacies of bioclastic material form Division II (D and H) of the Šublentica and Hum sections.

A – Nummulitid-alveolinid packstone-grainstone showing the association of alveolinids (a), nummulitids (b) and miliolid (c). Sample Šub-7. Middle Eocene. Šublentica section;

B – Peloid-miliolid packstone-grainstone showing miliolids (a) and peloids (b). Sample Šub-43, middle Cretaceous (Albian-Cenomanian). Šublentica section;

C – Orthophragminid wackestone showing ortophragminid test (a) with other bioclastic detritus. Sample Šub-43. Middle Eocene. Šublentica section;

D – Densely packed, well-sorted foraminiferal calcirudite showing large benthic foraminifera tests (mostly orthophragminids and nummulites), red algae (rodoliths), mudstone lithoclasts, and biodetritus (fragments of large benthic foraminifera, encrusting foraminifera, and echinoderms). Sample Šub-II 3. Middle Eocene. Šublentica section;

E – Foraminiferal wackestone showing *Palorbitolina lenticularis* (BLUMENBACH, 1805). Sample Hum–123. Lower Cretaceous (lower Aptian). Hum section;

F – Nummulitid-alveolinid grainstone showing an association of alveolinids (a), nummulitids, (b), *Asillina* sp., and *Orbitolites* sp. (c). Sample Hum 85. Middle Eocene. Hum section;

G – Foraminiferal wackestone showing the recrystallized transversal section of Cenomanian foraminifera *Broeckina (Pastrikella) balcanica* (CHERCHI, RADOIČIĆ & SCHROEDER, 1976). Sample Hum–286. Upper Cretaceous. Hum section;

H – Densely packed, well-sorted foraminiferal calcirudite showing fragmented large benthic foraminifera tests (mostly discocyclines/orthophragminids, nummulites, and unidentified rotaliid foraminifera), red algae, and biodetritus. Sample Hum 3b. Middle Eocene Hum section.

Petrinjak et al.: Megabeds in Istrian Flysch as markers of synsedimentary tectonics within the Dinaric foredeep (Croatia) **119**

Geologia Croatica

Plate 2. Photomicrographs of the microfacies of the most common clasts from Division I breccia (A, B, C, E, F, and G) and the microfacies of bioclastic material form Division II (D and H) of Kaldir and Gračišće sections.

A – Laminated peloidal wackestone-packstone with rare ostracods. Sample K-132. Upper Cretaceous (Cenomanian). Kaldir section;

B – Ostracodal mudstone-wackstone, showing ostracods (a), recrystallized *Thaumatoporella* sp. (b) and *Aeolisacus* sp. (c). Sample K-152. Upper Cretaceous. Kaldir section;

C – Foraminiferal wackestone-floatstone showing nummulitids (a), red algae – rodoliths (b), red algal crusts (c), echinoderm fragment (d) and orthophragminides (e). Sample K-num. Middle Eocene. Kaldir section;

D – Densely packed, well-sorted foraminiferal calcarenite showing large benthic foraminifera tests (mostly orthophragminids and nummulites), red algae (corallinacea) and biodetritus - fragments of foraminifera, echinoderms, bryozoans and bivalves. Sample Kaldir 1A. Middle Eocene. Kaldir section;

E – Algal wackestone showing red algae framework (a), nummulitids (b), and unidentified bioclastic detritus. Sample Gr-199. Middle Eocene. Gračišće section;

F – Densely packed, well-sorted foraminiferal calcarenite showing large benthic foraminifera tests (mostly orthophragminids and nummulites), red algae crusts, and other biolastic detritus (fragments of large benthic foraminifera, encrusting foraminifera and echinoderms) and mudstone-wackeston lithoclasts. Sample Gračišće-1. Middle Eocene. Gračišće section.

Plate 3. Photomicrographs of the microfacies of the most common clasts from Division I breccia (A, C, D, and E) and microfacies of bioclastic material form Division II (B and F) of Plomin and Koromačno sections.

A – Algal wackestone showing red algae (a) encrusting coral fragments (b) and other unidentified bioclasts. Sample Pl-II 123. Middle Eocene. Plomin section;

B – Alveolinid packstone-grainstone showing association of alveolinids (a), miliolids (b), and *Orbitolites* sp. fragment (c). Sample Pl II-124. Middle Eocene. Plomin section;

C – Foraminiferal-algal bindstone showing red algae encrusting mudstone lithoclasts and unidentified bioclast. Sample Pl-II 87. Middle Eocene. Plomin section;

D – Densely packed, well-sorted foraminiferal calcirudite showing large benthic foraminifera test (mostly orthophragminids and nummulites), biodetritus of red algae, and a skeletal wackestone lithoclast. Sample Pl-3. Middle Eocene. Plomin section;

E – Alveolinid grainstone showing association of alveolinids (a), nummulitids (*Asillina* sp.), b) and *Orbitolites* sp (c). Sample KOR II 112. Middle Eocene. Koromačno section;

F – Bioclastic-Algal wackestone with red algae framework (a) and bioclastic detritus. Sample KOR II 162. Middle Eocene. Koromačno section;

G – Algal wackestone showing red algae framework (a), corals (b), and bioclastic detritus. Sample KOR II 179. Middle Eocene. Koromačno section;

H – Densely packed, well sorted foraminiferal calcirudite showing large benthic foraminifera tests (mostly discocyclines/orthophragminids and nummulites), red algae (corallinacea), and biodetritus (fragments of large benthic foraminifera, encrusting foraminifera, and echinoderms). Sample Kor II KA1. Middle Eocene. Koromačno section.