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Middle Jurassic limestone megabreccia from the southern margin of the Slovenian Basin

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Abstract

The Slovenian Basin is a Mesozoic deep-water paleogeographic unit, located along the border between the eastern Southern Alps and the Dinarides, that records geodynamic signals from the opening of both the Piedmont-Liguria and the Neotethys oceanic domains. In the Middle Jurassic, it was bordered by the Dinaric (Adriatic) Carbonate Platform to the south and the Julian High submarine plateau to the north. The southern margin of the basin is characterized by a several tens of meters thick sedimentary sequence of Bajocian-Bathonian (Callovian?) age that is dominated by limestone megabreccia shed from the Dinaric Carbonate Platform, sedimented by debris-flows in a toe-of-slope sedimentary environment. It is accompanied by rud/grain/packstone beds sedimented via (high-density) turbidity-flows. This megabreccia unit represents the proximal equivalent of the lower resedimented limestones of the Tolmin Formation. The matrix within lithoclasts indicates resedimentation from ooidal shoals and the erosion of basinal and slope sediments. Lithoclasts are of Norian to Lower Jurassic age, and originated from (A) platform margin carbonates, i.e. Triassic marginal reef and Lower Jurassic sand-shoal limestones, (B) deep open-shelf or slope coarse bioclastic limestones, and (C) older basinal rocks. The lithoclast analysis enables the reconstruction of the platform-basin transitional zone that is not preserved (exposed) due to overthrusting. The limestone megabreccia indicates enhanced tectonic activity causing repeated collapse of the platform margin, probably connected to the initiation of intraoceanic subduction within Neotethys followed by ophiolite obduction onto the eastern distal margin of the Adria.

Keywords Limestone megabreccia · Resedimented limestone · Middle Jurassic · Slovenian Basin · Southern Alps · Dinarides

1 Introduction

The Slovenian Basin (SB) represents a Mesozoic deep-water paleogeographic domain characterized by a continuous succession of deeper marine sediments, largely, but not exclusively, preserved within the Tolmin Nappe of the eastern Southern Alps (western Slovenia) and its lateral continuation to the east (Fig. 1a–c). Sedimentation in the SB initiated in the Ladinian, coeval with the opening of the eastward adjacent Neotethys Ocean and lasted until the end of the Mesozoic. The SB was bordered by the Dinaric (Adriatic, Friuli) Carbonate Platform (DCP) to the south

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and by the Julian Carbonate Platform (JCP) to the north (Buser 1989, 1996; Vrabec et al. 2009; Rožič 2016). Later, the development of this part of the passive margin of Neotethys was also affected by the opening of an additional ocean, namely the Piemont-Ligurian (Alpine Tethys) Ocean located to the northwest (e.g. Schmid et al. 2008). The influence of the opening of the latter is evident through four pulses of intense synsedimentary tectonic activity recorded within the Norian to Middle Jurassic succession of the SB (Fig. 1d).

A first pulse of middle Norian age is documented by dolomite-chert breccia megabeds within the Bača Dolomite formation (Gale 2010) and the formation of synsedimentary normal faults (Oprčkal et al. 2012). This tectonic pulse probably coincides with the formation of small-scale basins within the Dolomia Principale (Hauptdolomit) platform (Jadoul et al. 1992; Bertotti et al. 1993; Cozzi 2002; Haas 2002).

The second pulse occurs at the Triassic-Jurassic boundary or slightly postdates it. It is indicated by limestone breccia megabeds, synsedimentary slumps and block tilting that mark the base of the Hettangian-Pliensbachian Krikov Formation (Rožič et al. 2017). This pulse correlates with the disintegration and partial drowning of the Hauptdolomit/Dachstein Limestone platform of the Adria northern margin (Mandl 2000; Berra et al. 2009; Haas et al. 2014).

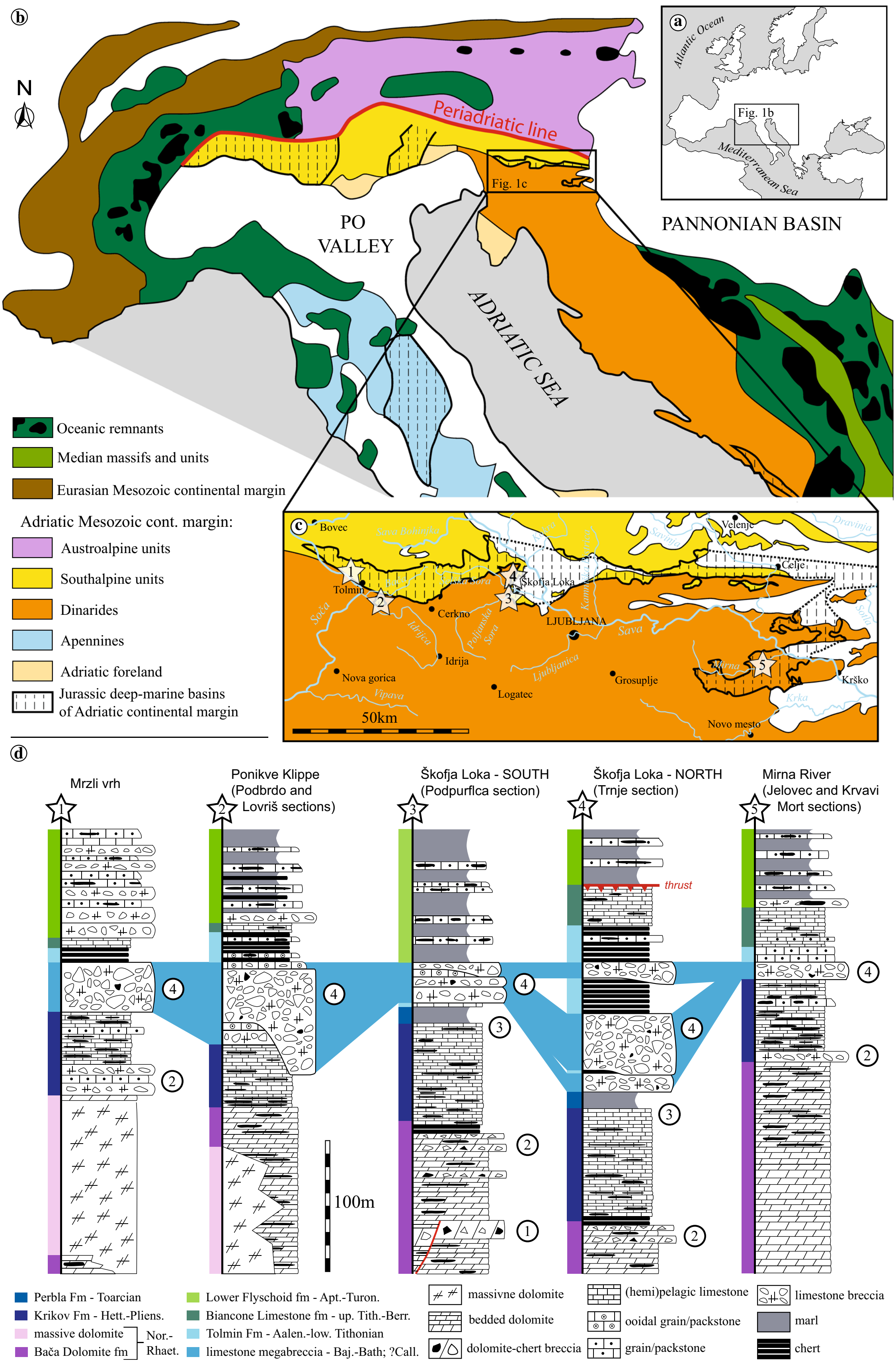
The third pulse is late Pliensbachian-Toarcian in age and leads to a dramatic disintegration, neptunian dyke formation and subsequent drowning of the adjacent Julian Carbonate Platform in the north (Šmuc 2005; Šmuc and Goričan 2005; Črne et al. 2007; Šmuc and Rožič 2010; Rožič et al. 2014a). This tectonic pulse is less evident in the Slovenian Basin, but it might be indicated by the change in composition of calciturbidites at the top of the Krikov Formation (from ooidal/peloidal to crinoidal/lithoclastic) and by the highly variable thickness of the overlying Toarcian marl-dominated Perbla Formation (Rožič 2009; Rožič and Šmuc 2011). This event coincided with the second rifting pulse recorded at the western margin of the Adria in the present-day Southern Alps (Berra et al. 2009).

In this paper, we provide evidence of a fourth tectonic event characterized by the deposition of massive blocky limestone breccias (referred to below as a limestone megabreccia unit, as they are often accompanied by subordinate calciturbidites), largely preserved between the Krikov (Hettangian to Pliensbachian) or Perbla (Toarcian) Formation and the upper member of the Middle Jurassic Tolmin Formation. Previously, these breccias were either completely overlooked or not recognized as megabreccias, because they contain a small amount of matrix between boulder-size lithoclasts (Rožič et al. 2013a). In the present paper we provide a detailed description of the sedimentary features and lithoclastic composition for the first time. We also provide (at least crude) evidence for a Bajocian-Bathonian age of this major platform-margin collapse, which is consistent with the Middle Jurassic geodynamic frame of the Alpine-Dinaridic domain.

Fig. 1 **a** Position within Europe (boxed area marks part presented in Fig. 1b); **b** Major geotectonic units of the Mediterranean-Alpine region with present-day position of Jurassic basins (compiled after Bosellini et al. 1981; Goričan 1994, Chanell and Kozur 1997; Bartolini et al. 1999; Placer 2008; Rožič 2016) (boxed area is enlarged in Fig. 1c); **c** border area between Alps and Dinarides with major geographic markers (towns, rivers), distribution of Slovenian Basin outcrops, and locations of the studied sections (marked by numbered stars used in Fig. 1d); **d** Schematic Norian to Turonian Slovenian Basin successions that include the sections presented herein (limestone megabreccia intervals of the Ponikve Klippe and the Mirna River successions represent combinations of more sections). Numbered circles point to tectonic pulses that occurred in (1) the middle Norian (Gale 2010; Oprčkal et al. 2012), (2) the latest Rhaetian to earliest Jurassic (Rožič et al. 2017), (3) the late Pliensbachian to early Toarcian (Rožič 2009; Rožič and Šmuc 2011), and (4) the Bajocian-lower Bathonian, ?Callovian (presented herein) ▶

2 Geological setting

In the late Anisian and Ladinian the western shelf of the Neotethys Ocean was subjected to tectonic segmentation, accelerated subsidence and magmatic activity, which was related to the westward propagation of this ocean (Meliata-Maliac-Vardar; Schmid et al. 2008 and references therein). The horst-and-graben structure was partly obscured by prograding carbonate platforms and was finally levelled over the course of the increased terrestrial input in the Carnian (Brusca et al. 1982; Breda et al. 2009; Caggiati et al. 2012). After the late Carnian, vast carbonate platforms (i.e., Dolomia Principale/Hauptdolomit, Dachstein Limestone) were installed on the entire Adria rifted margin (Mandl 2000; Haas 2002; Vlahović et al. 2005; Gale et al. 2015; Caggiati et al. 2017). In areas close to Neotethys, however, deep-water conditions prevailed in several basins during the Late Triassic and later (Buser 1989; Goričan 1994; Haas 2002; Črne et al. 2011). The SB is one such long-lived basin, maintaining its deeper-marine character from the Ladinian to the Maastrichtian. In present-day coordinates the SB is oriented approximately W–E. During the late Triassic, it was bordered to the south by the shallow Dinaric Carbonate Platform (DCP) producing carbonate up until the early Cenozoic (Buser 1989; Vlahović et al. 2005; Drobne et al. 2009), and by the Julian Carbonate Platform (JCP) to the north. The latter disintegrated and subsided at the end of the Lower Jurassic and became a


b
N
Periadriatic line
Fig. 1c
PO VALLEY
ADRIATIC SEA
PANNONIAN BASIN
a
Atlantic Ocean
Fig. 1b
Mediterranean Sea
Oceanic remnants
Median massifs and units
Eurasian Mesozoic continental margin
Adriatic Mesozoic cont. margin:
Austroalpine units
Southalpine units
Dinarides
Apennines
Adriatic foreland
Jurassic deep-marine basins of Adriatic continental margin
c
Bovec
Velenje
Tolmin
Celje
Škofja Loka
Cerkno
LJUBLJANA
Sava
Idrija
Nova gorica
Logatec
Grosuplje
Krško
Novo mesto
Vipava
Soča
Idrijca
Ljubljanica
Krka
50km
d
Mrzli vrh
Ponikve Klippe (Podbrdo and Lovriš sections)
Škofja Loka - SOUTH (Podpurflca section)
Škofja Loka - NORTH (Trnje section)
Mirna River (Jelovec and Krvavi Mort sections)
thrust
100m
Perbla Fm - Toarcian
Krikov Fm - Hett.-Pliens.
massive dolomite
Bača Dolomite fm
Nor.-Rhaet.
Lower Flyschoid fm - Apt.-Turon.
Biancone Limestone fm - up. Tith.-Berr.
Tolmin Fm - Aalen.-low. Tithonian
limestone megabreccia - Baj.-Bath; ?Call.
massivne dolomite
bedded dolomite
dolomite-chert breccia
(hemi)pelagic limestone
ooidal grain/packstone
grain/packstone
limestone breccia
marl
chert

pelagic plateau in the Bajocian, known as the Julian High (Buser 1989; Šmuc 2005; Šmuc and Rožič 2010; Rožič et al. 2014a).

The Jurassic of the SB begins with the Hettangian to Pliensbachian Krikov Formation (Fig. 1d) composed of calciturbidites and hemipelagic limestone (Cousin 1981; Buser 1986). Calciturbidites dominate in the northern part of the SB and become reduced (diluted) towards the south. Consequently, in the south (including the areas described herein) the same formation is composed almost exclusively of micritic, i.e. hemipelagic and diluted-calciturbiditic limestone. This distribution indicates that the source area of resedimentation was the JCP in the north (Rožič 2009). After the disintegration of the JCP, pelagic sediments dominated in the SB until the end of the Jurassic. During the Toarcian, the marl/shale-rich Perbla Formation was deposited (Rožič 2009). The subsequent Middle and Upper Jurassic Tolmin Formation is composed of siliceous limestone (lower member of Aalenian to middle Bajocian age), which is succeeded by radiolarian cherts (upper member of late Bajocian to lower Tithonian age) (Rožič 2009; Goričan et al. 2012a, b). In the southern part of the SB, two levels of carbonate resediments occur. The lower level of resedimented limestones appears close to the boundary between the two members of the Tolmin Formation and represents the distal continuation of limestone megabreccia unit described in this paper. The upper level of resedimented limestones is located in the uppermost part of the Tolmin Formation (Rožič and Popit 2006; Rožič 2009). The Jurassic-Cretaceous transition is marked by a quick shift to carbonate pelagites of the Biancone Limestone (Buser 1989).

Today, the successions of the SB in western Slovenia are exposed in the Tolmin Nappe located along the southern boundary of the eastern Southern Alps, thrusted onto the pre-existing nappes of the External Dinarides towards the south during the Miocene (Fig. 1c). The Ponikve Klippe (area 2 in Fig. 1), which contains key sites related to the studied limestone megabreccia unit, represents a small erosional remnant of the Tolmin Nappe. The sequences of the SB wedge out west of the town of Tolmin (Buser 1986; Placer 1999, 2008). Towards the east, the SB successions follow the Southalpine Thrust Front that generally runs in a W-E direction from Tolmin in the west to Celje in the east (Placer 2008). This general strike is only interrupted in central Slovenia, in the area of Škofja Loka (Fig. 1c), where it deviates abruptly to the south for approximately 15 km (Placer 2008; Demšar 2016). This change in orientation may have been caused by a transtensional fault wedge post-dating thrusting (Rožič et al. 2015). In the east and southeast (near area 5 of Fig. 1c), the SB succession also occurs within the Dinarides (Buser 1989; Rožič 2016). East of the area of Fig. 1c, the SB succession is covered by late Paleogene and Neogene sediments of the Paratethys, with the eastern prolongation of the SB as yet unproven.

3 Methods

Detailed geological mapping was performed in all of the selected areas. Sedimentological sections were logged at the 1:100 or 1:50 scale and sampled in dense intervals. Microfacies and foraminiferal biostratigraphy of nearly 300 thin-sections were analysed. Lithoclasts were grouped according to their supposed sedimentary environment (facies zones) and compared with Standard Microfacies Types (after Wilson 1975; revised in Flügel 2004). Classification of carbonates follows Dunham (1962), with modifications by Embry and Klovan (1972). In the Ponikve Klippe sections, 22 samples were collected for conodont studies. Samples that weighed an average of 2 kg were treated in acetic acid, followed by heavy liquid separation. Only one lithoclast (from the topmost part of the Lovriš section) yielded age-diagnostic conodonts, and the recovered microfossil material is housed at the Geological Survey of Slovenia. In most sections cherts above, within and below the limestone megabreccia unit were sampled for radiolarians (treated with diluted 9% hydrofluoric acid), but yielded no results.

4 Description of sections

The Mrzli vrh section (N46°12′43″, E13°41′49″) was logged in one of the westernmost outcrops of the SB on Mt. Mrzli vrh, north of the town of Tolmin (area 1 in Fig. 1c). In the Ponikve Klippe (area 2 of Fig. 1c), we investigated the Podbrdo (N46°08′06″, E13°47′50″) and Lovriš (N46°07′55″, E13°48′14″) sections located on the slope between the Šentvid Plateau and the Idrijca Valley. The limestone megabreccia unit was additionally sampled close to the bottom of the valley, near the village of Idrija pri Bači (N46°08′26″, E13°47′07″). These three sections are distributed along a laterally continuous occurrence of the limestone megabreccia unit. Near the town of Škofja Loka, SB successions were studied at two locations. South of the town (area 3 in Fig. 1c) the Podpulfrca section (N46°09′31″, E14°17′24″) was logged, additional sampling was done along the main road at N46°09′12″, E14°17′25″). North of the town (area 4 in Fig. 1c) we logged the Trnje section (N46°10′57″, E14°17′03″). These two sections are separated by a thrust-fault. All of the listed sections so far structurally belong to the Southern Alps (Placer 2008). Among the southeastern SB successions that structurally belong to the Dinarides (Fig. 1c) two closely located sections were logged in the valley of the Mirna River (area 5 in Fig. 1c), the Jelovec section (N45°59′23″, E15°13′43″) and the Krvavi Mort section (N45°59′19″, E15°14′07″).

In most sections the limestone megabreccia unit lies, with erosional contact, directly on the Hettangian-Pliensbachian Krikov Formation (Fig. 1d). The latter consists almost exclusively of micritic limestone, except in the Mrzli vrh and Mirna River areas, where sporadic calciturbidites are present. In the Škofja Loka sections, the erosional gap is less pronounced and the limestone megabreccia unit overlies Toarcian marl in the Trnje section (Perbla Formation), and Aalenian siliceous limestone in the Podpurflca section (lower member of the Tolmin Formation).

At Mrzli vrh the limestone megabreccia unit is represented by a single 44 m thick bed. Lithoclasts are boulder-sized at the base of the bed and grade to cm-size at the top. With sharp contact the limestone megabreccia is overlain by a several meters thick succession of radiolarian cherts of the Tolmin Formation, which is followed by Biancone Limestone. Laterally, all of the described successions are eroded, and basal resedimented limestones of the overlying mid-Cretaceous Lower Flyschoid formation are in direct contact with the Krikov Formation (Rožič 2005).

The Podbrdo section is the best-exposed section within the Ponikve Klippe. The limestone megabreccia unit is 57.5 m thick, composed of amalgamated beds, and divided into four subunits. The lowest subunit consists of three beds of limestone breccia (0.6, 2.3 and 8.4 m thick) that contain cm-sized lithoclasts (maximum 20 cm large). The middle bed shows grading in the uppermost 30 cm. The second subunit is almost 5 m thick and dominated by ooidal pebbly packstone and fine-grained limestone breccia. Beds at the base of the second unit are several tens of centimetres thick, and become less expressed upwards. This subunit gradually passes into a third subunit, which is composed of a limestone megabreccia 37 m thick with some lithoclasts reaching up to 10 m in size. The fourth subunit is 4.2 m thick and composed of two graded fine-grained limestone breccia beds (1.3 m and 2.5 m thick, respectively) followed by three thin packstone beds.

The Lovriš section was logged 630 m southeast of the Podbrdo section. It is almost completely composed of limestone megabreccia that was logged for 75 m, though the breccia unit may be even thicker. Upwards, this unit ends with two thin (15 cm and 10 cm) packstone beds. A similar succession dominated by very thick limestone megabreccia was observed in another sampling locality 1130 m northwest of the Podbrdo section. This indicates that the limestone megabreccia unit of the Ponikve Klippe is marked by very thick blocky limestone breccia bodies with erosive contacts. The limestone megabreccia unit is overlain by a succession 18 meters thick composed of thin-bedded chert, siliceous hemipelagic limestone and sporadic calciturbidites of the Tolmin Formation, and further upwards by Biancone Limestone (Rožič et al. 2014b).

In the Škofja Loka area, the limestone megabreccia unit in the Podpurflca section is approximately 50 m thick and composed of several amalgamated beds. It was deposited in a minor channel that cuts less than 2 meters into the underlying strata and is composed of alternating limestone (mega)breccia and subordinate pack/grainstone beds. The bedding planes are generally indistinct (amalgamated), and beds are defined only by abrupt changes in clast/grain size. Bed thickness varies from several tens-of-centimetres to almost 10 m. In the Podpulfrca section to the south, the limestone megabreccia unit is overlain, after a prominent stratigraphic gap, by the mid-Cretaceous Lower Flyschoid formation. In the Trnje section to the north the limestone megabreccia unit is 58 m thick. Here we notice that its occurrence is localized between two closely located vertical faults, and the rocks are tectonically highly disturbed. This makes logging and also microfacies analysis of the limestone megabreccia unit less reliable in this section. The limestone megabreccia unit is probably made up of two graded beds (20 m and 38 m), each beginning with boulder-sized lithoclasts at the bases and cm-sized lithoclasts at tops of both beds. At the base of the upper bed, a 1.5-m-thick laterally out-pinching bedded chert body occurs. From the outcrop it was not possible to determine whether it constitutes erosional remains below a channelized upper bed, or alternatively, a large chert lithoclast that occurs in the basal part of the upper bed. Here the limestone megabreccia unit is overlain by a 70-m-thick upper member of the Tolmin Formation that is dominated by radiolarian chert. In the middle part of this interval, another limestone breccia up to 20 m thick is deposited in an erosional channel. This breccia corresponds to the limestone megabreccia of the main (58 m thick) interval in terms of structure, facies and composition.

In the Mirna River Valley area the limestone megabreccia unit is fully exposed in the Jelovec section and represented by a single 10 m thick graded bed. This bed contains metre-sized blocks at the base, whereas cm-sized lithoclasts are dominant in the uppermost part of the bed. In the supplementary Krvavi Mort section, where the structure is well visible in the riverbed, it becomes evident that boulder-sized lithoclasts may occur also in the upper part of the bed. Here the limestone megabreccia unit is overlain by medium-bedded grain/packstone with a combined thickness of 8 m. These beds differ in composition from comparable beds of the limestone megabreccia unit, and have not yielded age-diagnostic fossils. They are probably younger and correspond (in composition) to the upper resedimented limestones of the Tolmin Formation. They are directly overlain by the Biancone Limestone. The absence of radiolarian cherts between the limestone megabreccia unit and the Biancone limestone indicates a prominent stratigraphic gap within the Middle and Upper Jurassic parts of the succession.

5 Composition of the limestone megabreccia unit

The studied limestone megabreccia unit is dominated by breccias containing diverse assemblies of lithoclasts, which differ in age and facies, and record erosion along resedimentation paths of individual beds that were shed by diverse gravitational currents. The intergranular space among large lithoclasts is filled with packstone composed of grains that are likely to be penecontemporaneous with resedimentation and that reveal the sedimentary conditions in the source areas.

5.1 Composition of sand-sized matrix and associated calcarenite beds

The composition of the sand-sized matrix found among large lithoclasts is the same as that of the associated calcarenite beds. It varies between sections or even among individual beds of the same section, but is always characterized by the presence, and often predominance, of ooids. The texture of the matrix is typically packstone, but in some calcarenite beds a grainstone texture was also observed.

Two types of ooids occur in the matrix: small- to medium-sized radial and/or coarse micritized ooids. When they occur together this results in a bi-modal size distribution of matrix-grains (Fig. 2a, b). The cores of ooids are peloids and bioclasts (foraminifera, gastropods, crinoids, ostracods, bivalves, etc.). Besides ooids, other grains such as intraclasts, peloids (pellets), aggregate grains (lumps) and bioclasts appear in the matrix. Among the bioclasts, echinoderm fragments are common. Foraminifera are predominantly trocholinas, textularids, and lagenids. Trocholinas in particular tend to dominate the assemblage. Fragmented thin-shelled bivalves occur occasionally. Other bioclasts (bivalves, brachiopods, gastropods, etc.) are very rare. Oncoids some millimetres in size can appear in abundance in the second and fourth units within the Podbrdo section (Fig. 2a). They are spheroidal and consist of alternating spongiostromate/porostromate layers. Oncoids were documented also in the Mirna Valley area (Krvavi Mort section) and in the Škofja Loka area (Podpulfrca section). Their cores are micritic or may contain bioclasts (gastropods, bivalves, fragments of encrusting foraminifera or calcimicrobes). Fragments some millimetres in size of echinoderms, bivalves, corals, grains composed of calcimicrobes, bryozoans, and microbially encrusted, completely recrystallized clasts (presumably recrystallization-prone bioclasts, such as chaetetids) were also observed.

The matrix in the Mrzli vrh section differs from that of the other sections. It is made up of a fine-grained packstone composed predominantly of fragmented thin-shelled bivalves and other bioclasts (echinoderms, sponge spicules). Pellets, as well as phosphate and sporadic glauconite grains also occur. Micritized ooids are present, but very rare (Fig. 2c).

The matrix of the limestone megabreccia in the Ponikve Klippe and Mrzli vrh sections is mostly dolomitized. In the first, it is best preserved in the pebbly calcarenites of the lower part of the Podbrdo section (from the 15th to 20th metre-mark), whereas in the latter the primary composition is recognizable only in the uppermost part of the limestone megabreccia bed. The micritic lithoclasts were also locally affected by dolomitization.

In all sections small (sand-sized) lithoclasts also occur within the matrix. Where calcarenite interfingers with the breccia, the composition of these lithoclasts generally corresponds to the composition of lithoclasts within the breccia. In calcarenites that overlie the limestone megabreccias in the Podbrdo and Jelovec sections, an upward increase of crinoids is evident. This is particularly well expressed in the Jelovec section, in which overlying beds could already be Upper Jurassic in age.

The matrix of the limestone megabreccias and the accompanying grain/packstone beds contain isolated, age-diagnostic foraminifera that indicate the Middle Jurassic age of this interval. In almost all sections *Protopeneropsis striata* Weynschenk was found. Other age-diagnostic foraminifera are *Andersenolina palastiniensis* Henson and *Mesoendothyra croatica* Gušić. In the Ponikve Klippe, the latter was found also inside the calciturbidite that appears less than 1 m above the limestone megabreccia unit, i.e. in the lowermost Tolmin Formation. This narrows the age-range of the investigated limestone megabreccia unit (at least at this locality) between the Bajocian and the lower Bathonian (cf. Velić 2007). Further upwards, already in the upper part of the Tolmin Formation, the radiolarian sample indicated middle to late Oxfordian to early Kimmeridgian age (for details see Rožič et al. 2014b).

5.2 Composition of lithoclasts

We classed the lithoclasts of the limestone megabreccia unit into five groups according to their supposed original position on the platform-to-basin transect. The age of the lithoclast groups was also determined when possible.

A first group of lithoclasts is present in all sections and resulted from the erosion of pelagic carbonates (Fig. 3a, b).

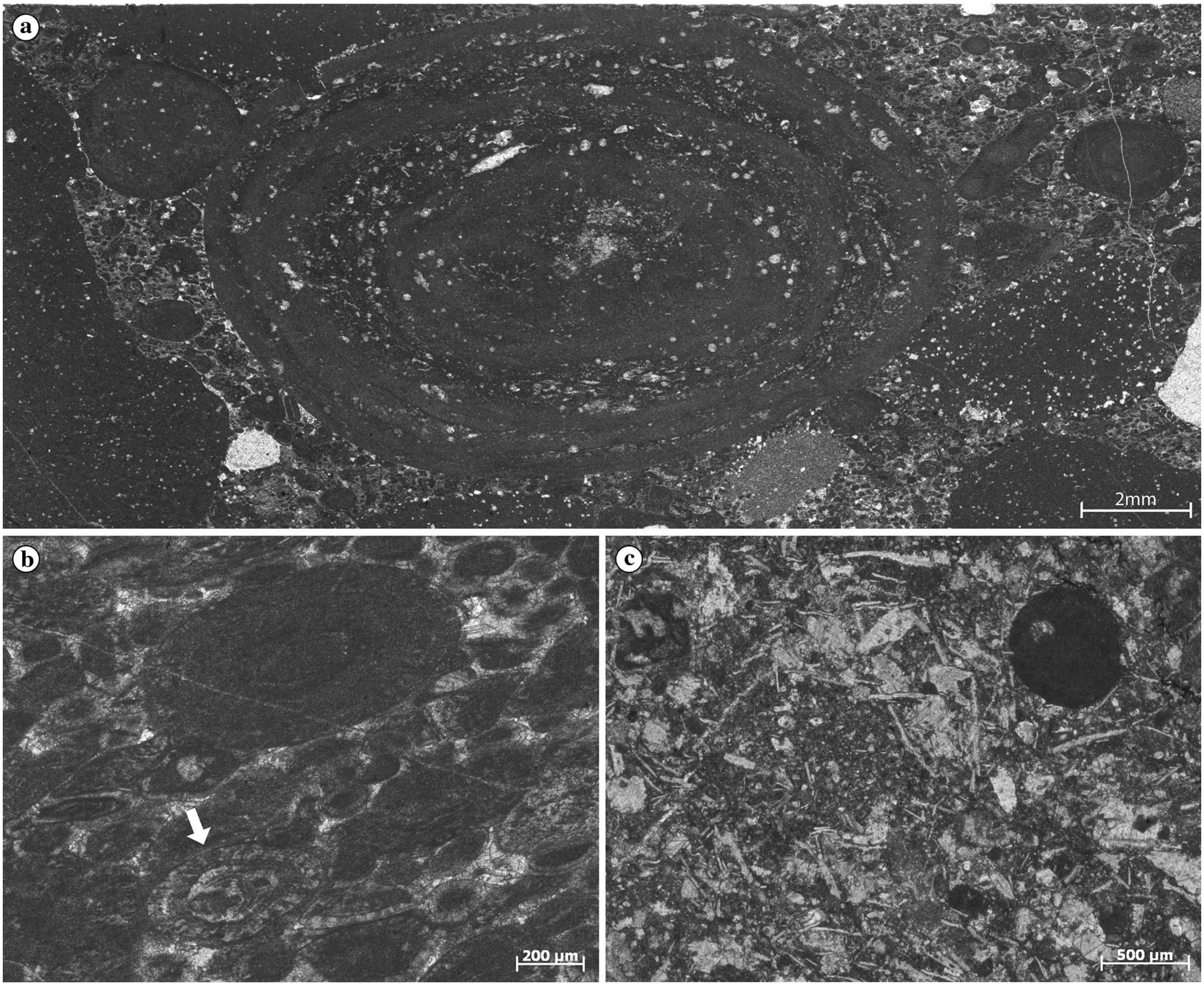


Fig. 2 Composition of pack/wackestone matrix between lithoclasts: **a** characteristic resedimented Middle Jurassic shallow-water grains are ooids that dominate in sand-sized matrix and cm-sized oncoids; **b** resedimented ooids from the matrix often show bi-modal size distribution (arrow points to foraminifer *Protopeneroplis striata* Weynschenk inside ooid core), **c** matrix from Mrzli vrh section consists of fragmented thin-shelled bivalves and other bioclasts, and very rare micritized ooids

These are mainly wackestone with various pelagic fossils, such as radiolarians, calcispheres, and thin-shelled bivalves. Other grains are ostracods, sponge spicules, echinoderm fragments, and rarely lithoclasts, as well as juvenile ammonites and *Protoglobuligerina* sp. planktonic foraminifera. The latter indicate that at least parts of these lithoclasts are Middle Jurassic in age (cf. Caron and Homewood 1983; Tappan and Loeblich 1988; Darling et al. 1997) and can generally be considered as penecontemporaneous with the sedimentation of the limestone megabreccia. The presence and abundance of particular grains varies within lithoclasts, and they range in texture from almost grain-less mudstone to packstone. The latter is dominated by thin-shelled bivalves and ammonites (these lithoclasts are common in Mirna River sections) (Fig. 3c). In the Ponikve Klippe, such packstones are densely packed; i.e. thin-shelled bivalves are wrapped around subordinate oval grains, such as intraclasts, rare echinoderms and Triassic Duostominidae foraminifera. Presumably, these lithoclasts derive from the erosion of a Triassic fine-grained calciturbidite succession. Another type of eroded resediments is well-sorted packstone composed of intraclasts and bioclasts (mostly echinoderms and subordinate foraminifera) (Fig. 3a).

A second group of lithoclasts is represented by eroded slope and outer-shelf limestones. Most typical is the medium- to coarse-grained bioclastic wackestone (Fig. 3d), locally packstone. Predominant grains are echinoderms (crinoids as well as urchin spines), ostracods, juvenile ammonites, foraminifera (miliolids, textularians, lagenids,

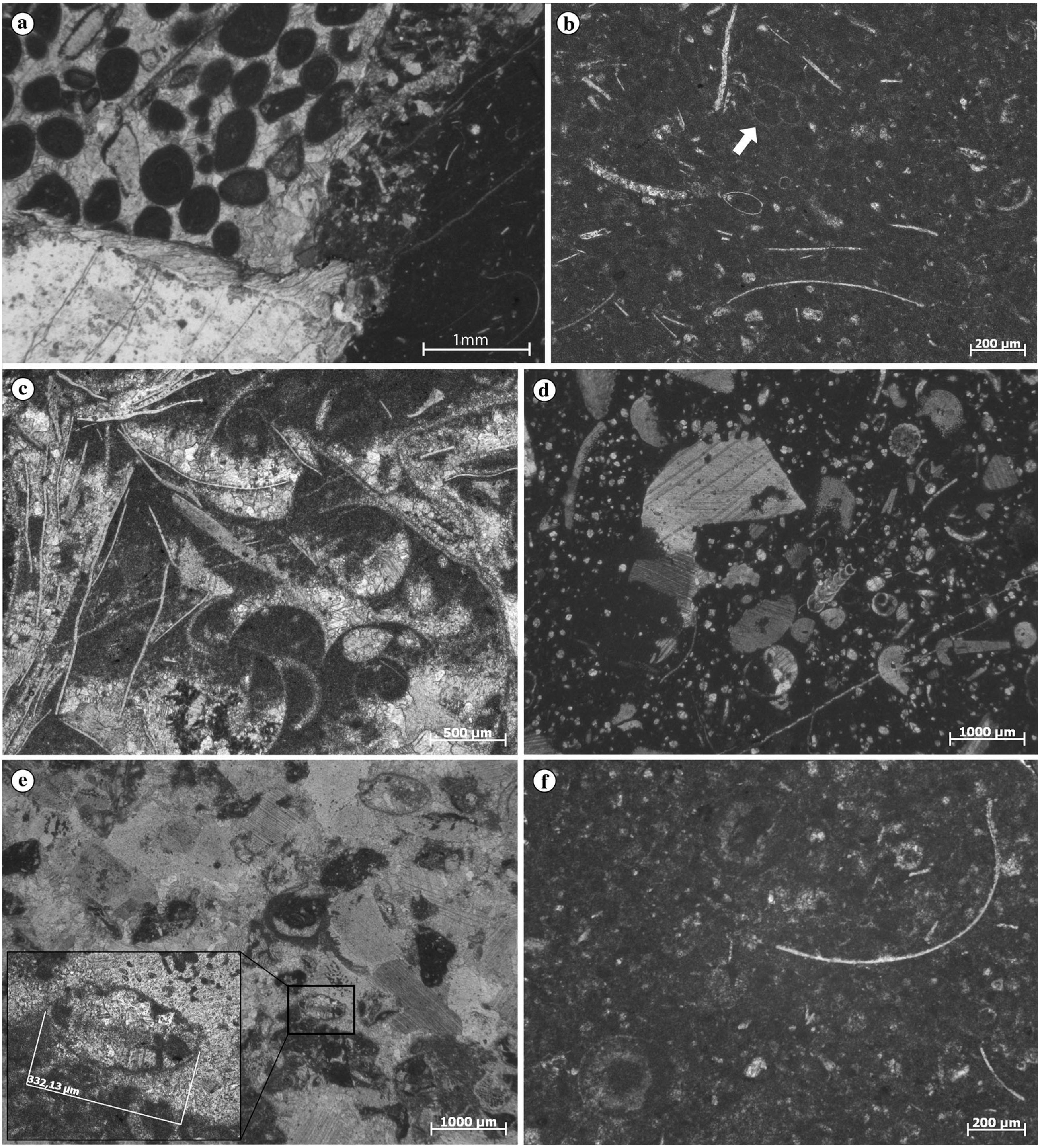


Fig. 3 Composition of limestone breccia lithoclasts: **a** lithoclasts derive from diverse sedimentary environments and are predominantly limestones (upper left—ooidal grainstone, upper middle right—"resedimented packstone", right—pelagic wackestone, lower left—chert); **b** early Middle Jurassic pelagic wackestone litho/intraclast (arrow points to planktonic foraminifer *Protoglobuligerina* sp.); **c** pelagic packstone lithoclast composed of thin-shelled bivalves and ammonites; **d** coarse bioclastic wackestone lithoclast with echinoderms, foraminifera, sponge spicules, and mollusks; **e** bioclastic grainstone lithoclast composed of echinoderms and rare intraclasts (in boxed area foraminifer *Involutina liassica* Jones is enlarged); **f** ooidal wackestone lithoclast with thin-shelled bivalves

ophthalmidiids), sponge spicules and thin-shelled bivalves. Peloids, bryozoans, large bivalve and/or brachiopod shells are rare. Stromatactis-like cavities and bioturbations were observed. Based on microfossils such lithoclasts were classified into three age groups. Crinoid-dominated lithoclasts contain foraminifera *Lencticulina* sp., *Decapoalina* sp. and *Miliolipora cuvillieri* Brönnimann & Zaninetti and are of upper Carnian to Rhaetian age. A second age group contains abundant sponge spicules, locally also crinoids, small miliolid and ophthalmidiid foraminifera. Their Early Jurassic age was evidenced by foraminifera *Involutina farinacciae* Brönnimann & Koehn-Zaninetti and *Involutina liassica* Jones. The first two age groups were recognized in every locality, with the exception of the Mrzli vrh section. A third age group was determined only in the Mirna Valley sections. These lithoclasts additionally contain ooids and small lithoclasts (pelletal ooidal grain/packstone, wackestone with thin-shelled bivalves and radiolarians, and mudstone with fenestral pores). The Middle Jurassic age of these lithoclasts is indicated by *Protopeneroplis striata* Weynschenk.

A transition of coarse bioclastic wackestone to grainstone was observed in some lithoclasts. Compared to wackestone, grainstone contains more common echinoderms, intra/lithoclasts, and large shells. Such grainstone occurs also as isolated lithoclasts; for these an Early Jurassic age was determined with *Involutina liassica* Jones (Fig. 3e) and a Middle Jurassic age with *Protopeneroplis striata* Weynschenk.

Another type of lithoclasts presumably originates from rocks of a deep open-shelf facies: pack/wackestone, usually with fine- to medium-grained ooids and other grains, such as pellets, intraclasts and bioclasts (echinoderms, foraminifera, ostracods, thin-shelled bivalves, calcispheres, radiolarians and sponge spicules) (Fig. 3f). In a few lithoclasts, *Protoglobuligerina* sp. planktonic foraminifera are present, indicating a Middle Jurassic age of these lithoclasts.

The third group of lithoclasts contains eroded-reef and fore-reef limestones (Fig. 4a–c). Very typical are boundstone lithoclasts in which dominant frame-builders are corals and calcisponges (stromatoporoids, inozoan sponges and chaetetids), whereas encrusting organisms are calcimicrobes, foraminifera, and occasionally *Thaumatoporella* sp. and *Bacinella irregularis* Radoičić. Intergranular spaces and cavities are filled with cement or sediment (described within the next group). Similar in composition is bioclastic rudstone, which is composed of large, fragmented reef-builders, intraclasts and smaller bioclasts. Lithoclasts of reefal limestone can be also present among coarse grains. Rarely, a floatstone texture is also present. The age of this group of lithoclasts is Norian to Rhaetian, as indicated by corals ?*Astraeomorpha pratzi* Volz, *Retiophyllia paraclathrata* Roniewicz, *Retiophyllia fenestrata* Reuss, *Tropidendron mlinaricensis* Turnšek, sponges *Atrochaetetes cycliformis* Bojko, ?*Battaglia minor* Senowbari-Daryan & Shaefer, *Cryptocoelia* sp., and foraminifera *Galeanella tollmanni* (Kristan), *Decapoalina schaeferae* Zaninetti, Altiner, Dager & Ducret, *Alpinophragmium perforatum* Flügel and others.

The fourth group appears in all sections and is believed to originate from sand shoals facies, but could as well be partly lagoonal or derived from within the reef area. It is divided into two Norian-Rhaetian sub-types and one Lower Jurassic sub-type. The first of the Triassic sub-types is grainstone, locally partly winnowed packstone, composed of intraclasts, pellets and diverse bioclasts (Fig. 4d): fragmented bivalves (often in the form of cortoids), foraminifera, echinoderms; rare are gastropods, brachiopods, calcimicrobes (can form cores of large intraclasts a few mm in size), and oncoids. Micritic grains tend to be recrystallized to microsparite. The Norian-Rhaetian age of these lithoclasts was proven by the presence of foraminifera *Galeanella tollmanni* Kristan, *Auloconus permodiscoides* Oberhauser, *Triasina hantkeni* Majzon and others. A second Triassic sub-type is similar in composition to the previous one (transition between both was observed within the same lithoclast). It is packstone, locally wackestone with abundant pellets (in few lithoclasts, decapod pellets were recognised), whereas foraminifera predominate among the bioclasts. Additionally, ostracods, dasycladalean algae, *?Thaumatoporella* sp., and rare isolated corals appear. This facies may show bioturbation and can contain fenestrae and large, cement-filled dissolution voids. The foraminiferal assemblage in these lithoclasts is similar to the first sub-type, with some additional species, among which *Decapoalina schaeferae* Zaninetti is stratigraphically important. Both Norian-Rhaetian sub-types formed in a back-reef area, on sandy shoals and probably also in the transition to the lagoon. However, we emphasise that these two facies are found also as sediment among reef-building organisms in the boundstone lithoclasts.

In structure and composition the third sub-type is similar to the first, but the grains are less recrystallized, and generally it contains fewer fossils and cortoids, while aggregate grains and ooids are additionally present (Fig. 4e). Foraminifera are mostly textulariids. In rare cases large bioclasts are present (bivalves, brachiopods, dasycladalean algae and solitary corals). Some lithoclasts contain laminae of oncoid and/or gastropod rudstone or ooidal grainstone. The latter can also be present as an individual lithoclast type (Fig. 3a). The Lower Jurassic age of these clasts is evidenced by corals *Phacelophyllia termieri* Beauvais, *Rhabdophyllia phaceloida* Beauvais, *Thecactinastraea krimensis* Turnšek, *Funginella domeriensis* Beauvais, and foraminifera ?*Lituosepta recoarensis* Cati, *Siphovalvulina* sp., *Orbitopsella* sp., and *Involutina liassica* Jones. Some lithoclasts of this sub-type might be assigned to the Middle Jurassic, as they contain foraminifer *Nautiloculina*

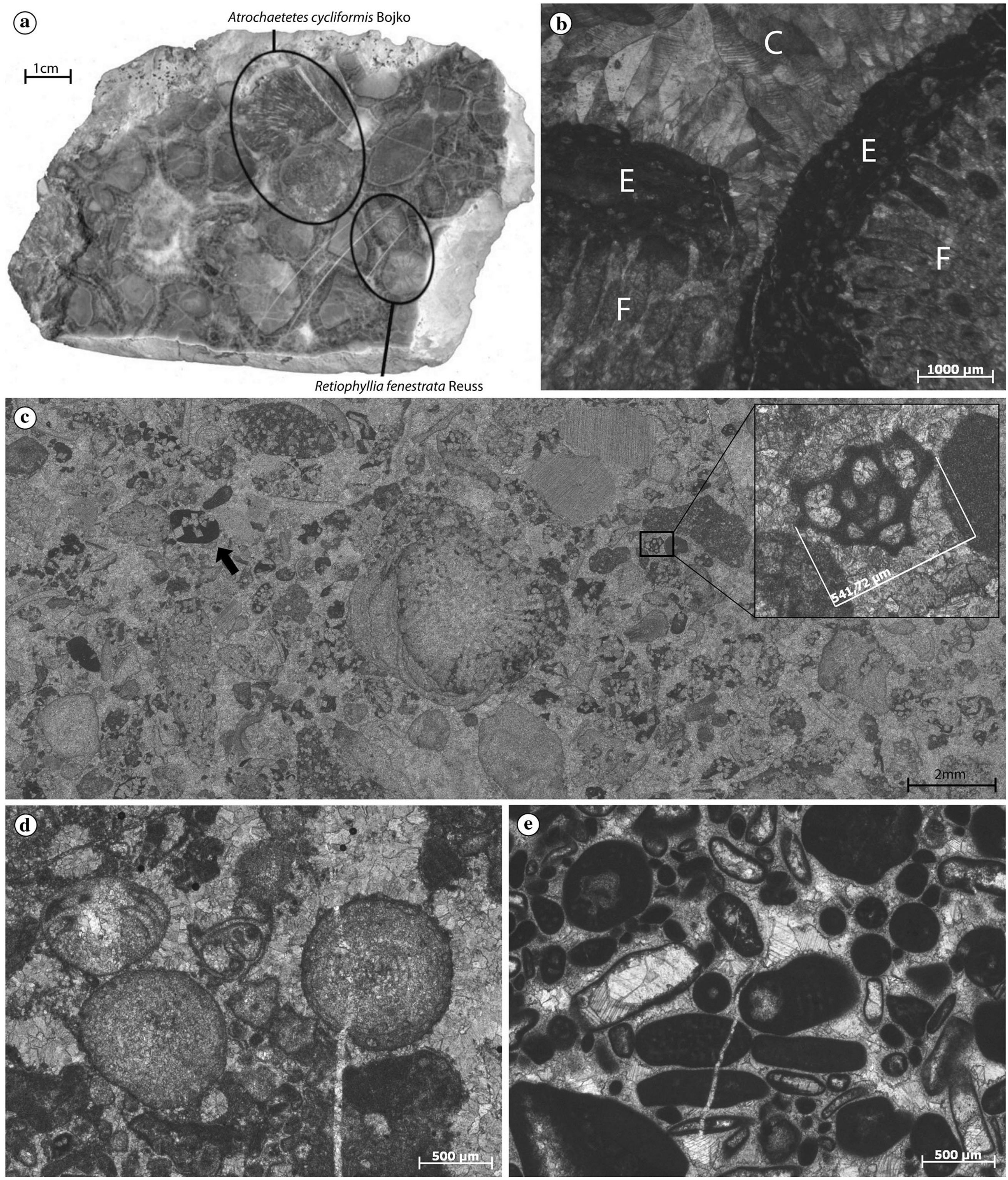


Fig. 4 Composition of limestone breccia lithoclasts that derive from platform margin limestones: **a** polished surface of boundstone sample with Norian-Rhaetian coral *Retiophyllia fenestrata* Reuss and chaetetid *Atrochaetetes cycliformis* Bojko; **b** Norian-Rhaetian reef limestone lithoclast composed of chaetetid frame-builders (F), calcimicrobic encrusters (E), and cement (C) (thin-section was made from the sample in Fig. 4a); **c** Norian-Rhaetian bioclastic rudstone lithoclasts with large fragmented frame-builders and other bioclasts (in boxed area foraminifer *Miliolipora tamarae* Gale, Rettori & Martini is enlarged) and partly dolomitized intraclasts (indicated by arrow); **d** Rhaetian partly-washed pelletal bioclastic packstone lithoclast with foraminifer *Triasina hantkeni* Majzon; **e** Lower Jurassic pelletal bio/intraclastic grainstone lithoclast with foraminifer ?*Lituosepta recoarensis* Cati and micritized ooids (peloids)

oolithica Mahler, but exact determination of this species is problematic due to its poor state of preservation.

The fifth and last group of lithoclasts includes lithoclasts of indeterminate age and/or sedimentary environment. Fine-grained packstone is common in all sections. They may have a partly winnowed fabric, are bioturbated, may contain small fenestrae, and are composed almost exclusively of pellets. Other grains are rare bioclasts, such as small foraminifera, calcispheres?, and ostracods. Some lithoclasts also contain sponge spicules and other thin-shelled bivalves. The matrix is mostly microsparite. Such lithoclasts could derive from the erosion of reefal, deeper basin or lagoonal formations. In the Lovriš section a clast of this type yielded Sevatian to lower Rhaetian conodonts *Norigondolella steinbergensis* and *Zieglerioconus rhaeticus*. The other three lithoclast types of unknown affinity show strong diagenetic alterations. The first are strongly recrystallized lithoclasts that appear in the Škofja Loka and Ponikve Klippe sections. They have a partly recognisable primarily float/rudstone structure with large fossils (bivalves, gastropods, ammonites and brachiopods). The second are dolomitic lithoclasts from the Mrzli vrh and the Ponikve Klippe sections that may have been formed via complete dolomitisation of micritic lithoclasts. The third are chert lithoclasts (Fig. 3a), which are present in all sections. As a rule, they are composed of microcrystalline quartz, subordinately chalcedony, and some contain carbonate crystals. Their sedimentary fabric (grain/packstone, boundstone) is locally recognizable. Some of these lithoclasts are reworked older cherts, while others are diagenetically silicified carbonate clasts. Selective silicification of some large bioclasts (within matrix) and boundstone lithoclasts was observed.

6 Sedimentary analysis and regional emplacement

6.1 Sedimentary processes and environment

The limestone megabreccia unit lies above older strata with an erosional contact. A prominent stratigraphic gap (usually at least the Toarcian and Aalenian are missing) is pointed out at the contact (Fig. 1d). Thick and coarse-grained beds are products of mass movements. As indicated by their massive structure, inverse and/or normal grading, and the presence of micrite-rich matrix, they originated from debris flows. The size of the lithoclasts (often 10 m in diameter) indicates that these beds originate from large-scale collapse of the northern margin and slope of the DCP. Thinner and generally finer, normally graded beds (microbreccia, grain/packstone), which occur within or often above the thick megabreccia beds, were deposited as turbidites, often as a high-density turbidites (cf. Lowe 1982) or hyper-concentrated density flows (cf. Mulder and Alexander 2001). Some grainstone beds lack textures typical for turbidites, but this can be explained through sorting of the material in the source area characterized by ooidal shoals.

The facies association points to the deposition on the lower slope or toe-of-slope (Fig. 5). This depositional environment stands in contrast to that of the under- and overlying strata characteristic for a basin-plain environment (Mullins and Cook 1986). The underlying Krikov formation is dominated by hemipelagic limestone, and the overlying upper member of the Tolmin Formation is composed of radiolarian chert and, in the case of the Ponikve Klippe, of siliceous limestone and chert (proximal equivalent of radiolarian chert). In the under- and overlying successions, resedimented limestones occur only sporadically or are absent. These differences in the depositional conditions indicate that the investigated limestone megabreccia unit formed under extraordinary conditions, which led to large-scale collapses along the northern margin of the DCP. Although potentially several processes may trigger the formation of megabreccias (e.g. Spence and Tucker 1997), we attribute the origin of the limestone megabreccias presented here to increased tectonic activity based on the following arguments: (1) their contrast to the surrounding pelagites described above, (2) the large extent and lateral continuity of the limestone megabreccia unit, and (3) the deeply incising erosion that led to lithoclasts characterised by a wide range of sizes, ages and environments. As deduced from the foraminiferal datations of the Ponikve Klippe sections, major resedimentation events occurred during a relatively short time, namely between the (upper?) Bajocian and the lower Bathonian. As evidenced by another thick limestone megabreccia bed that is interstratified between radiolarian cherts of the Škofja Loka northern (Trnje) section, large-scale resedimentation events also occurred some time after the main collapse.

6.2 Correlation with the inner Slovenian Basin

If we correlate the presented sections with sections previously studied from the inner part of the SB, the limestone megabreccia unit represents the proximal equivalent of the lower resedimented limestones of the Tolmin Formation (Rožič 2009) (Fig. 5). In previously studied sections, a limestone breccia still appears in the southern parts of the SB, but it is generally finer and laterally discontinuous. It forms bed-sets of resedimented limestones up to 25 metres thick that are otherwise dominated by calciturbidites. Further towards the central part of the basin, these beds progress into isolated calciturbidites interstratified between

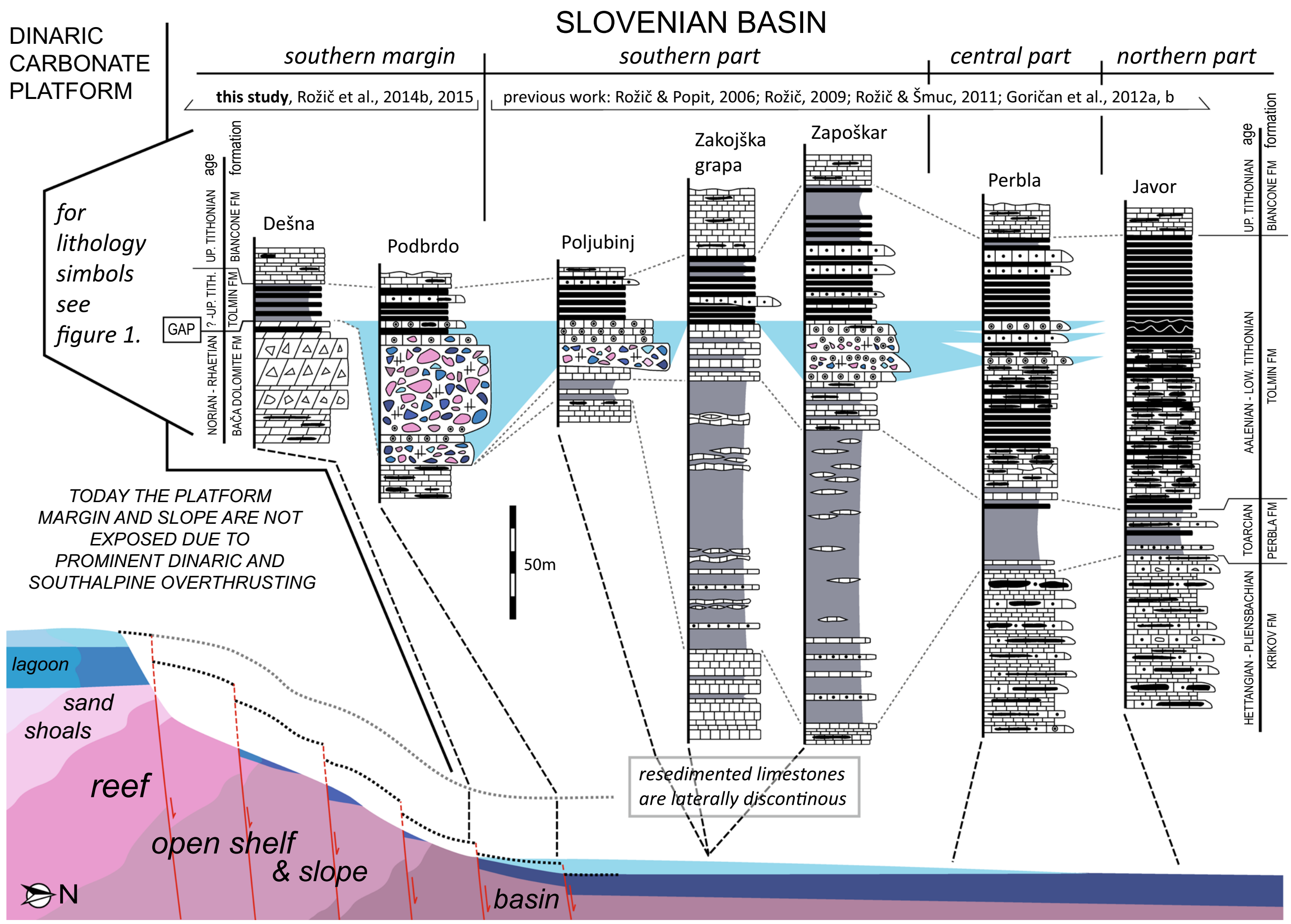


Fig. 5 Correlation of Middle Jurassic (Bajocian-Lower Bathonian, ?Callovian) limestone megabreccia unit presented herein, with previously studied Slovenian Basin sections: Dešna section of the Škofja Loka area (described in Rožič et al. 2015) sedimented in marginal part of the Slovenian Basin marked by erosion and sediment by-pass, Podbrdo section (selected as most representative for limestone megabreccia and combined with data from Rožič et al. 2014b) is characterized by thickest and coarsest limestone megabreccia that sedimented at toe-of-slope environment and originated from collapses of the fault-dissected platform margin and slope areas. Towards the inner parts of the Slovenian Basin resedimented limestones become laterally discontinuous, decrease in thickness and coarseness, and calcidebrites are replaced by calciturbidites (Poljubinj, Zakojška grapa and Zapoškar sections). In the central part of the Slovenian Basin, they become sporadic (Perbla section) and completely disappear in the northern part (Javor section), where resedimentation events are presumably connected with synsedimentary slumps within radiolarian cherts

pelagic sediments. Calciturbidites start occurring at the boundary between the lower and the upper member of the Tolmin Formation. Resediments are dated to the middle Bajocian and occur at least until the lower Callovian, and possibly even in the lower Oxfordian (Rožič 2009; Goričan et al. 2012b). This is in accordance with the above-described succession of the Trnje section. In the northern part of the basin, resediments are no longer present, but close to the boundary of the members synsedimentary slumps do occur (Rožič 2009). These could be related to the same process that triggered the pronounced resedimentation in the southernmost SB margin.

6.3 Source area and reconstruction of early Middle Jurassic platform-basin transitional zone

The composition of the limestone megabreccia provides a basis for inferring the conditions in the source area and evaluating the degree of erosion of older strata. This is particularly important, because today the transitional zone (including platform external margin, outer shelf/slope, and most proximal basinal environments) between the DCP and the SB is missing due to thrusting of the basinal over platform successions. The early Middle Jurassic platform-basin architecture is revealed in the matrix and penecontemporaneous litho/intraclasts. The matrix within the limestone megabreccia, which is very similar to the composition of accompanying calciturbidites, is dominated by ooids, which suggests that resedimentation events originated at the northern margin of the DCP, which was characterized by ooidal shoals in the Middle Jurassic (Bosellini et al. 1981; Buser 1989; Miler and Pavšič 2008; Buser and Dozet 2009; Ogorelec 2011; Dozet and Ogorelec 2012; Masetti et al. 2012). Oncoids also occur in limestone megabreccia matrix and often show a layered spongiostromatic/porostromate composition. Comparable oncoids are reported from the Middle (also the early Upper) Jurassic ooidal limestones in the area west of Ljubljana (Flügel 2004, p 129; Dozet and Buser 2009), which paleogeographically belong to the northern margin of the DCP, which is characterized by extensive sand shoals (Buser 1989).

The matrix within the limestone megabreccia contains, apart from sand-sized grains, also micrite with pelagic fossils, mostly in the form of fragmented thin-shelled bivalves. This indicates the erosion and incorporation of unconsolidated basinal sediments into the debris flows. The erosion of semi-consolidated, coeval basinal sediments is indicated also by the presence of basinal litho/intraclasts that contain planktonic foraminifera. The composition of the matrix from the Mrzli vrh section is different, as it lacks abundant ooids and oncoids, implying that this event was probably triggered from the distal deep slope area, which is devoid of resedimented shallow-water grains.

We consider lithoclasts of coarse bio/lithoclastic wackestone (occasionally pack/grainstone) and ooidal pack/wackestone to be derived from eroded early Middle Jurassic partly consolidated shelf and/or slope sediments. Lithoclasts that occur in bio/lithoclastic limestone clasts indicate that on the DCP-SB transitional zone older, well-lithified strata were exposed and eroded. We suggest that the slope was segmented (?fault-dissected), which enhanced the erosion. Corresponding, generally coeval limestones are reported from (A) Toarcian–early Bajocian crinoidal-ooidal limestone successions that record the post-transgression reestablishment of shallow-water sedimentation on the DCP northern margin (Miler and Pavšič 2008; Črne and Goričan 2008) and (B) Bathonian to early Kimmeridgian successions of the submarine plateau adjacent to the DCP that was studied on the Mt. Kobariški Stol in NW Slovenia (Šmuc 2012). Coarse bioclastic limestone from the Mt. Kobariški Stol succession lacks lithoclasts.

6.4 Reconstruction of pre-Middle Jurassic platform margin and slope from lithoclasts

Pre-Middle Jurassic lithoclasts can reach the size of boulders and originated from the disintegration of a Norian-Lower Jurassic platform margin, open shelf, slope and basin limestones. Norian-Rhaetian lithoclasts are dominated by limestones that originated on marginal reef and adjacent sedimentary environments. Boundstone lithoclasts correspond to the Late Triassic reefs that were dominated by coral-stromatoporoid frame-builders (Flügel 1981, 2002; Turnšek 1997). Fore-reef breccia is probably also present in the form of litho/bioclastic float/rudstone, but these facies could at least partly originate within the reef area. Norian-Rhaetian grain/packstone lithoclasts correspond to a facies that is common to back-reef areas (Gale et al. 2013), but also come from the reef itself. The latter is directly evidenced inside some large reef lithoclasts, where these facies fill the space between the frames of the main reef. Simultaneously, in the deep open shelf coarse bioclastic (crinoid, bivalves, foraminifera, etc.) limestones were formed. Marginal coral-stromatoporoid reefs are typical for platform margins during this time along the entire Neotethys western passive margin (Mandl 2000; Krystyn et al. 2009; Haas et al. 2014; Caggiati et al. 2017; Gawlick et al. 2017c). On the platforms that surrounded the SB, the Norian-Rhaetian reefs are common throughout the JCP located to the north (Buser et al. 1982; Turnšek and Ramovš 1987; Turnšek and Buser 1991; Turnšek 1997; Ogorelec 2011). In contrast, they are not known from the margin of the DCP located to the south (Ogorelec and Rothe 1993; Buser and Dozet 2009). The lack of reefs on the DCP may be attributed to the thrust structure, which buried the platform margin below the thrust sheet composed of SB strata. But we propose that their absence could (at least locally) be connected to their destruction and resedimentation during the Middle Jurassic collapse events described here. Similar, but more extensive events were recently reconstructed from the Sirogojno Melange of the Inner Dinarides of SW Serbia (Gawlick et al. 2017c).

Lower Jurassic lithoclasts indicate that after the end-Triassic mass-extinction of reef organisms (Flügel 2002; Kiessling et al. 2007), the DCP margin became dominated by carbonate sand shoals (Buser 1989). Marginal facies are represented by ooidal grainstone, but close to lagoon peletal/intraclastic grainstones are common (Črne and Goričan 2008; Dozet and Buser 2009; Ogorelec 2011; Gale 2015; Gale and Kelemen 2017). Reef build-ups are sporadic within Lower Jurassic deposits and corals occur in the form of small patch-reefs (Turnšek and Košir 2000; Turnšek et al. 2003). Representatives of frame-builders are the same as those determined in some Lower Jurassic grainstone lithoclasts. Another group of Lower Jurassic lithoclasts consists of coarse bioclastic wacke/grainstone lithoclasts. Corresponding Pliensbachian limestones are reported from the deepened JCP margin (Šmuc and Goričan 2005; Šmuc and Rožič 2010; Goričan et al. 2012a; Rožič et al. 2014b), and are also reported from other deepened platforms of the western Tethys (Böhm et al. 1999; Gawlick et al. 2009, Haas et al. 2014). Although such facies are not known from the northern DCP, the presence of these lithoclasts also proves similar sedimentary conditions on the deep open shelf and the slope between the DCP and SB.

Based on the following arguments an erosion of pre-Middle Jurassic basinal strata is evident, although it has not been proven by fossils: (1) the limestone megabreccia unit lies with a prominent time gap over older strata and (2) corresponding microfacies types are frequent in the Late Triassic and the Lower Jurassic SB succession (Cousin 1981; Rožič 2009; Rožič et al. 2009, 2013b; Gale et al. 2012, 2014). We note that in the Škofja Loka area another basinal succession is observed on the Dešna Hill (located 1 km SE of the Podpurflca section), where radiolarian cherts of the Tolmin Formation directly overlie the Bača Dolomite (Rožič et al. 2015). In this succession, the stratigraphic gap encompasses a range that covers at least the Lower Jurassic and a part of the Middle Jurassic (Fig. 5). We explain this with the paleogeographic position on the southernmost margin of the SB, which experienced prominent erosion and sediment by-pass.

6.5 Emplacement of the limestone megabreccia within the geotectonic frame of the Alpine-Dinaridic domain

The paleogeographic location of the SB between the Piemont-Ligurian and Neotethys oceans is indicated by the influence of geodynamic events taking place in and near both oceanic domains, which experienced major perturbations in Bajocian-Bathonian times (Schmid et al. 2008; de Graciansky et al. 2011; Masini et al. 2013). To the west, the earliest ophiolites of the Piemont-Ligurian Ocean, which provide evidence of the opening of the Piemonte-Liguria Ocean, are dated to the Bajocian; however, most dating yielded Bathonian and Callovian ages (Chiari et al. 2000; Bill et al. 2001; Manatschal and Müntener 2009; de Graciansky et al. 2011). Consequently, the entire western rifted margin of Adria experienced accelerated subsidence, documented by the re-establishment of sedimentation on submarine plateaus (Bertotti et al. 1993; Šmuc 2005; Martire 1996; Martire et al. 2006; Šmuc and Rožič 2010) and a progressive shift to more siliceous sedimentation inside the basins—although the latter could at least partly be also attributed to the enhanced productivity in surface-waters (Bertotti et al. 1993; Chiari et al. 2007; Rožič 2009; Goričan et al. 2012b). At the same time, the DCP margin turned into a highly productive ooidal factory, and adjacent basins, especially those located to the west, received large amounts of resedimented ooids (Bosellini et al. 1981; Goričan 1994; Šmuc and Goričan 2005, Masetti et al. 2012, Picotti and Cobianchi 2017).

Both coinciding sedimentary events (the shift to siliceous pelagites and the increased resedimentation of ooids) are recorded in the previously studied, more central successions of the SB (Rožič 2009). However, the large-scale collapse of the northern margin of the DCP, documented by the present study of the limestone megabreccia unit, are hard to explain only with the initiation of the drifting phase in a piece of Adria that is far from the ocean-continent transition to the Piemont-Liguria Ocean.

The main geodynamic context leading to the deposition of the limestone megabreccia is rather related to events taking place in the Neotetyhs domain. During this time this domain experienced the initiation of intraoceanic subduction dated as Aalenian to Oxfordian in age based on the dating the formation of metamorphic soles (Schmid et al. 2008 and references therein; Borojević Šoštarić et al. 2014). Convergence finally led to the obduction of ophiolites during the latest Middle Jurassic according to Bortolotti et al. (2013), but most probably not before latest Jurassic to Berriasian times according to others (Mikes et al. 2008; Schmid et al. 2008; Gallhofer et al. 2017). Recent studies of sedimentary (carbonate-clastic radiolaritic) mélanges in the Inner Dinarides, however, suggest that the onset of ophiolite obduction began as early as the Middle Jurassic (Gawlick et al. 2016, 2017a, b, c, 2018). These authors propose that shortly after the onset of obduction the most distal parts of the Adria passive margin (Hallstatt Zone) became involved in the developing nappe stack. Rocks of a distal margin were subsequently exhumed and resedimented to deep-water radiolaritic basins that formed anew in front of the propagating thrust belt (Gawlick et al. 2017a, c). The oldest polymict mass-flow deposits (composed of Late Triassic Hallstatt Limestone) within such basins were dated to Late Bathonian/Callovian (Gawlick et al. 2018). A similar geodynamic evolution was previously reconstructed also for the Austroalpine part of the Adria eastern shelf (Gawlick et al. 2009, 2012).

We propose that deformation related to plate convergence in the Neotethys domain (subjected to intraoceanic subduction or maybe even to earliest obduction) could have been transferred to the inner margin of the Adria adjacent to the Neotethys, especially in areas that experienced older major extensional dislocations during the Middle Triassic rifting events. The SB-DCP transitional zone represents just such an area, but the exact nature of deformation is hard to determine because the entire zone is today covered by basinal thrust-sheets. A possible tectonic scenario sees the forming of a forebulge centred along the outermost margin of the DCP, which is characterized by the Middle Jurassic emersion surface (Tišljar et al. 2002; Vlahović et al. 2005; Otoničar 2015; Picotti and Cobianchi 2017). If we take into consideration the classical active margin models (e.g. Bradley and Kidd 1991), at the transition zone towards the propagating thrust belt a normal faulting is expected. This may have affected the SB-DCP transition zone, which caused the (re)activation of normal faults along the SB margin (as presented in Fig. 5). This then resulted in increasing relief differences, i.e. slope segmentation and basin deepening. Consequently, collapses of the DCP northern margin occurred that led to the formation of the limestone megabreccia beds.

7 Conclusions

A Middle Jurassic, limestone megabreccia unit several tens of meters thick occurs along the southern margin of the Slovenian Basin. This unit is made up of coarse debris flow deposits, locally alternating with rud/grain/packstone calciturbidites. These rocks were formed along the toe of carbonate platform foreslopes and correspond to the previously described lower resedimented limestones of the Tolmin Formation from the inner parts of the Slovenian Basin.

The limestone megabreccia unit formed as a result of repeated collapse of the northern margin of the Dinaric Carbonate Platform during the Bajocian to Bathonian interval, but may also have continued later (Callovian?). Its origin is likely related to tectonic activity at the eastern margin of the Adria adjacent to the Neotethys that was subjected to compression after assuming a lower plate position during intraoceanic subduction in Mid-Jurassic times, subsequently leading to ophiolite obduction.

The composition of the limestone megabreccia enables a reconstruction of the Norian to early Middle Jurassic platform-basin transitional zone that is today not preserved (exposed) due to Late Alpine overthrusting. The pack/wackestone matrix within the lithoclasts reveals that gravity-flows originated from ooidal shoals, which in the Middle Jurassic fringed the Dinaric Carbonate Platform. Apart from ooids and oncoids, the matrix is composed of (admixed) micrite and fragmented thin-shelled bivalves, which indicates the erosion of penecontemporaneous slope and basinal sediments. Some basinal litho/intraclasts with planktonic foraminifera are also presumed to be of early Middle Jurassic age, whereas penecontemporaneous outer shelf/slope lithoclasts indicate that these facies zones were dominated by bioclastic (crinoidal, thin-shelled bivalve, foraminiferal) limestone that often contained resedimented ooids.

Pre-Middle Jurassic platform margin lithoclasts are often of metre size and represent the eroded Norian-Rhaetian limestones of the reef and associated environment, and the Lower Jurassic grainstone characteristic of sandy shoals. Outer-shelf/slope sedimentary environments are represented by lithoclasts of (Late Triassic as well as Lower Jurassic) coarse bioclastic wackestone (subordinate grainstone) with abundant echinoderms (crinoids), thin-shelled bivalves, sponge spicules, foraminifera, and occasionally ammonites. Part of the basinal litho/intraclasts is believed to have resulted from the erosion of pre-Middle Jurassic basinal rocks.

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