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A glimpse of the lost Upper Triassic to Middle Jurassic architecture of the Dinaric Carbonate Platform margin and slope

Pogled v izgubljeno zgornjetriasno in spodnjejursko arhitekturo pobočja in roba Dinarske karbonatne platforme

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Ključne besede: Slovenski bazen, Dinarska karbonatna platforma, srednja jura, apnenčaste breče, drobirski tok, stratigrafija, Ponikvanska breča

Abstract

In the southernmost outcrops of the Slovenian Basin the Middle Jurassic coarse-grained limestone breccia (mega)beds are interstratified within a succession that is otherwise dominated by hemipelagites and distal turbidites. In this paper, these beds are described as the Ponikve Breccia Member of the Tolmin Formation. We provide descriptions of the studied sections with detailed geological maps and analysis of the breccia lithoclasts. From the latter, a non-outcropping margin of the Dinaric Carbonate Platform is reconstructed. In the Late Triassic the platform margin was characterized by a Dachstein-type marginal reef. After the end-Triassic extinction event, the platform architecture remained, but the reefs were replaced by sand shoals characterized by ooids. In the late Early Jurassic and/or early Middle Jurassic a slope area might have been dissected by normal faults and a step-like paleotopography was formed. In the Bajocian, during a period of major regional geodynamic perturbations, extensional or transtensional tectonic activity intensified and triggered the large-scale collapses of the Dinaric Carbonate Platform margin producing the limestone breccias described herein. This may in turn have caused a backstepping of the platform margin, as is evident from the occurrence of Late Jurassic marginal reefs that are installed directly above the Upper Triassic and Lower Jurassic inner platform successions.

Izvleček

V najjužnejših izdankih Slovenskega bazena se znotraj zaporedja, v katerem sicer prevladujejo hemipelagične kamnine in distalni turbiditi, pojavljajo (vele)plasti srednjejurske debelozrnate apnenčeve breče. V prispevku so te plasti opisane kot Ponikvanska breča in sicer kot člen Tolminske formacije. V opisu podajamo podroben opis proučenih profilov, vključujoč detajlne geološke karte in analizo litoklastov v breči. Iz slednjega je bilo možno rekonstruirati danes nerazgaljeni rob Dinarske karbonatne platforme. V poznem triasu je bil zanj značilen dachsteinski tip obrobnega grebena. Po triasno-jurskem izumrtju je arhitektura platforme sicer ostala enaka, vendar so grebene nadomestile peščene plitvine, za katere so značilni ooidi. V pozni spodnji juri in/ali zgodnji srednji juri je bilo območje pobočja razčlenjeno najverjetneje z normalnimi prelomi in nastala je stopničasta paleotopografija. V bajociju se je v času velikih regionalnih geodinamskih sprememb okrepila ekstenzijska ali transtenzijska tektonska aktivnost, ki je sprožila obsežne porušitve robnega dela Dinarske karbonatne platforme in nastale so tukaj opisane apnenčaste breče. To bi lahko povzročilo umik roba platforme, kar je razvidno iz pozicije zgornjejurskih obrobnih grebenov, ki se pojavljajo neposredno nad zgornjetriasnim in spodnjejurskim zaporedjem notranjega dela platforme.

Introduction

The present-day geological structure of the territory of Slovenia is largely the result of the Late Cretaceous and post-Cretaceous tectonic shortening of the continental crust stemming from the Alpine orogenesis (Placer, 1999; Vrabec & Fodor, 2006). The nappe structure is especially evident in western Slovenia, where successions of three large Mesozoic paleogeographic units meet at the thrust faults (Fig. 1). Successions of the Triassic–Early Jurassic Julian Carbonate Platform (JCP hereinafter) and of the Early Jurassic–Late Cretaceous Julian High are preserved in the Krn Nappe, which forms most of the Julian Alps and the Kamnik-Savinja Alps (Placer, 1999). The Krn Nappe is in thrust-tectonic contact with the Tolmin Nappe to the south. The latter is characterised by deeper-marine successions deposited in the Slovenian Basin (SB hereinafter). Further south, the Tolmin Nappe is in turn thrusted over the Trnovo and Hrušica Nappes of the External Dinarides, consisting largely of shallow-marine carbonates of the Dinaric Carbonate Platform (DCP hereinafter) (Placer, 1999). According to Vlahović et al. (2005), the latter is a local synonym for the northern sector of the Southern Tethyan Megaplatform (Middle Triassic–Toarcian), and of the Adriatic Carbonate Platform (Toarcian–end of Cretaceous).

The central unit of the Mesozoic topography is the SB, which lies between the Julian and Dinaric Carbonate platforms, which separates them but also provides a common sedimentary basin, acting as a sink for carbonate resediments shed from either of them. From the Early Jurassic to the beginning of Toarcian, the main source of carbonate shed into the SB was the JCP (Rožič, 2006, 2009). However, a dramatic decline in the proportion of resedimented limestone was recorded during and after the Pliensbachian, when the JCP tectonically disintegrated and carbonate production ceased (Šmuc, 2005; Šmuc & Goričan, 2005; Rožič et al., 2014a).

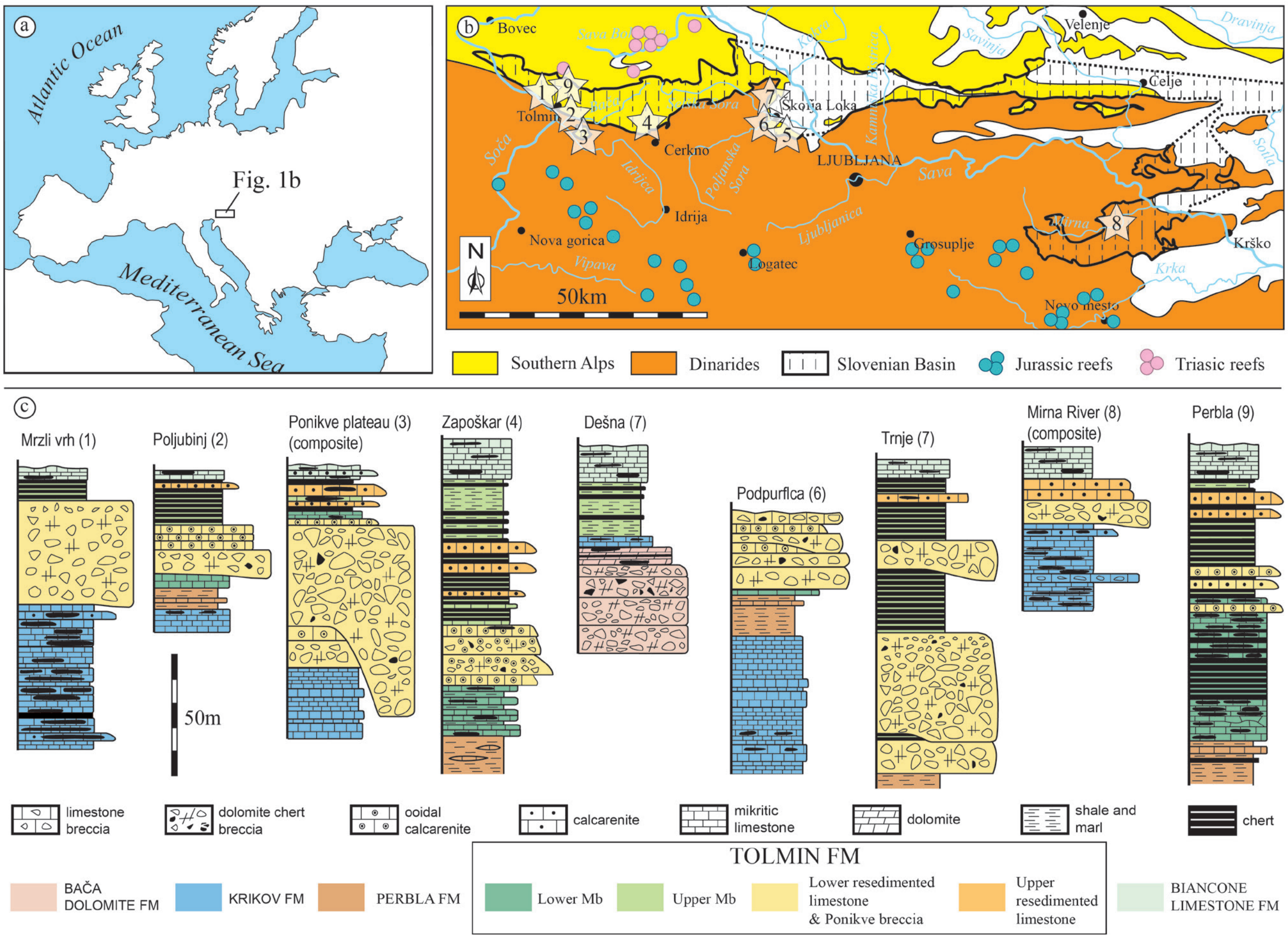

Fig. 1. a) Position of the studied area within the Europe; b) Present day distribution of three major Mesozoic paleogeographic units of the Southalpine-Dinaric transition: Julian Carbonate Platform (yellow without stripes), Dinaric Carbonate Platform (orange without stripes) and Slovenian Basin (areas with stripes). Upper Triassic (pink circles) and Upper Jurassic (blue circles) locations of marginal reefs are marked (compiled from Turnšek, 1997, Placer, 1999 and Rožič, 2016); c) Schematic sections of the Ponikve Breccia Member and Perbla section as a type locality of the Tolmin Formation (section localities are marked on Fig. 1b).

Younger, Toarcian to end-Jurassic deposits from the SB are instead dominated by hemipelagic sediments (Rožič, 2009). In the southern parts of the SB, however, sporadic resedimented limestones occur also in the Middle and Upper Jurassic, mainly in the form of calciturbidites less than a meter thick interbedded within radiolarite. They are interstratified in two distinct levels dated to Bajocian–Callovian and Kimmeridgian–lower Tithonian, respectively (Rožič & Popit, 2006; Rožič, 2009; Goričan et al., 2012). Instead of being derived from the "north", these carbonate resediments originated in the "southerly" lying DCP. The extensive research of the southernmost outcrops of the SB showed that the lower (Bajocian–Callovian) resedimented limestones laterally pass into successions of limestone megabreccias and subordinate calciturbidites up to 80 m thick (Fig. 1c). These resediments likely record the collapse of the DCP margin (Rožič et al., 2019).

The composition of the resediments and their regional significance were recently presented by Rožič et al. (2019), but a more detailed analysis of the "lost" margin of the DCP was not included in such. The aims of this paper are thus: 1) to formalize breccia megabeds as a member of the Tolmin Formation and to describe its lateral occurrences by contributing supplementary data on the local geological settings of the studied section, 2) to present a detailed clast analysis (microfacies, biostratigraphy, paleoenvironment) of the recently studied sections (Rožič et al., 2019) and the Poljubinj and Zapoškar sections from older studies (Rožič, 2009), and 3) to reconstruct the Norian–Rhaetian, Lower Jurassic, and early Middle Jurassic margin stratigraphy of the DCP on the basis of clasts from megabreccias.

Clast analysis also aims to answer two prominent regional questions. The first is the question of the structure and composition of the non-preserved Norian–Rhaetian marginal reefs on the south-lying DCP. To the contrary, however, the Upper Jurassic marginal reefs of the DCP are well documented, but they are positioned far towards the inner parts of the platform. Our study at least partially answers the second question; namely, it elucidates the causes for the back-steeping of the DCP margin.

Geological setting

The SB is a large-scale (at least several tens of kilometres wide and extending W-E across the entire territory of present-day Slovenia) intraplatform basin that shows continuous Ladinian to Maastrichtian deeper-marine sedimentation that was bordered by the DCP to the "south" and the JCP to the "north" (present-day directions). The latter disintegrated in the Pliensbachian and by the Bajocian turned into the submarine plateau called the Julian High (Buser, 1996; Šmuc, 2005; Šmuc & Rožič, 2010). The most continuous succession of the SB is preserved in the Tolmin Nappe, which is the lowermost nappe of the eastern Southern Alps (Placer, 1999, 2008). In the eastern part of Slovenia, the equivalent deeper-marine successions are also found within the so-called Transition Zone between the Internal and the External Dinarides, where they form nappes covering the shallow-marine successions of the DCP (Buser, 1996, 2010; Rožič, 2016). All of the studied sections represent the southernmost outcrops of the SB, distributed from the town of Tolmin in the west to the Mirna River Valley near the town of Sevnica in the east. Further to the east, the Mesozoic rocks are covered by the Neogene sediments of the Central Paratethys (Buser, 2010).

The Ladinian succession of the SB is dominated by Pseudozilian beds, by volcanoclastic, clastic, and less frequently carbonate sediments. A similar succession is observed also in the Carnian Amficlina beds, but with fewer volcanoclastics (Buser, 1989, 1996). In the southern part of the SB a large-scale platform collapse was documented within the Carnian strata (Gale et al., 2016). After the reestablishment of continuous carbonate production on the DCP in the Norian, the SB became dominated by carbonates, mostly by Norian–Rhaetian Bača Dolomite (Buser, 1996), and locally limestones of the Slatnik Formation (Rožič et al., 2009; Gale et al, 2012).

The Jurassic succession of the SB begins with the Hettangian–Pliensbachian Krikov Formation, which is characterized by alternating hemipelagic and resedimented limestones. The latter dominate in the northern part of the SB, suggesting that the JCP was the main source of the resediments (Rožič, 2006, 2009). After the disintegration of the JCP, the SB became starved of (resedimented) carbonate, resulting in the deposition of the Toarcian marlstone-dominated Perbla Formation and Aalenian–lower Tithonian chert-dominated Tolmin Formation (Rožič, 2009; Goričan et al., 2012). Two levels of resediments occur within the Tolmin Formation in the southern and central parts of the SB, both shed from the DCP (Rožič & Popit, 2006; Rožič, 2009). The lower level, Bajocian–Bathonian (?Callovian) in age, is a distal equivalent of the limestone megabreccias analysed herein (Rožič et al., 2019).

The Jurassic–Cretaceous transition is marked by a sharp turn to the calcareous hemipelagic sedimentation, and Upper Tithonian–Berriassian Biancone-type limestone was deposited. Above, a poorly understood Valanginian–Barremian stratigraphic gap is present (Buser, 1996; Rožič et al., 2014a). Until the end of the Cretaceous the SB continuously received resedimented limestones from the DCP, but the nature of the hemipelagic sedimentation was changing. During the Aptian–Lower Cenomanian it was marl dominated (Lower Flyschoid formation). The Upper Cenomanian–Turonian succession was characterized by globotruncana-rich marly, varicoloured limestone (included in Lower Flyshoid formation by Cousin, 1981; also in our maps). Coniacian to Campanian is represented by Scaglia-type Volče Limestone, composed of gray hemipelagic limestones with cherts. The Maastrichtian Upper Flyschoid formation is again marlstone dominated. It records a gradual transition to syn-orogen flysch sedimentation (Cousin, 1981; Buser, 1989, 1996).

Methods

A detailed geological mapping (scale 1: 5000) was performed in all investigated areas. Sedimentological sections were logged at 1: 100 or 1: 50 scales. Sections were sampled in dense intervals. Microfacies, corals, and foraminifera from the matrix and clasts of breccias were determined for more than 300 thin sections using an optical polarizing microscope. Approximately 1500 clasts were analysed and divided into 25 groups according to their age and microfacies characteristics. Each group was compared with the Standard Microfacies Types (after Wilson; 1975; revised in Flügel; 2004). Classification of carbonates follows Dunham (1962), with modifications by Embry and Klovan (1971). In the Lovriš section, several samples of conodonts were taken from bigger clasts. A standard technique to recover conodonts was applied using diluted acetic acid followed by heavy liquid separation. One sample was positive. In the Mrzli vrh, Lovriš, and Trnje sections cherts above, within, and below the limestone megabreccia unit were treated (with diluted 9 % hydrofluoric acid) for radiolarians but yielded no results.

Formalization of the Ponikve Breccia Member of the Tolmin Formation

Short description of the Tolmin Formation: The Tolmin Formation was defined by Rožič (2009) as an Aalenian–lower Tithonian unit composed of siliceous hemipelagites (for Perbla type section see Fig. 1c). It was divided into two members. The lower member, Aalenian–middle Bajocian in age, is composed of dark siliceous limestone and chert. The upper member (middle Bajocian–lower Tithonian) comprises varicoloured radiolarite. Calciturbidites are interstratified within the pelagites in the southern and central parts of the SB in two levels. The lower level lies at the boundary between the lower and the upper member of the formation. These calciturbidites were approximately dated to the Bajocian–Bathonian (?Callovian) and named Lower resedimented limestones. The upper level occurs in the uppermost part of the formation. It was dated to the upper Kimmeridgian–lower Tithonian and named the Upper resedimented limestones. Herein, we formalize the limestone breccia megabeds as a new member of the Tolmin Formation, and represents the lateral, proximal variability of the Lower resedimented limestones.

Name: Ponikve Breccia Member – It is thickest and best studied near the Ponikve Village on the Šentviška planota plateau. A similar term is also used for the Ponikve Klippe (that geologically comprises the Šentviška planota plateau), which is considered to represent the southernmost outcrops of the SB in western Slovenia.

Previous work: The Ponikve Breccia Member is characteristic for the southernmost sections of the SB succession. Breccias belonging to this member were previously mentioned by Cousin (1981) from localities near Tolmin, and by Ogorelec and Dozet (1997) from the vicinity of the town of Boštanj near the valley of the Mirna River. Breccias from the Poljubinj and Zapoškar sections were previously described in Rožič and Popit (2006), and Rožič (2009). Middle Jurassic Limestone breccia beds are reported from the Železniki area by Demšar (2016). A first detailed description of the unit was given by Rožič et al. (2019).

Short definition: The Ponikve Breccia Member is usually several tens of meters thick. It can consist of a single or multiple, often amalgamated breccia beds. The member lies with a sharp erosional contact on older basinal formations, most often on the Hettangian–Pliensbachian Krikov Formation dominated by hemipelagic limestone with chert. At the top, the Ponikve Breccia member is conformably overlain by radiolarite or hemipelagic limestone with chert of the Tolmin Formation (Rožič., 2009; Rožič et al., 2014a). In some locations, the upper boundary is marked by a disconformity and younger formations (e.g. Lower Flyschoid formation) are overlain.

The thickness of the limestone breccia beds varies from meter-scale up to almost 80 m. Breccia is coarse grained and often contains meter-sized boulders. It consists of the Upper Triassic to Middle Jurassic basin, slope, and platform margin carbonate lithoclasts. Clasts are embedded in a micrite matrix with ooids and bioclasts (thin-shelled bivalves, crinoids). Breccia beds can be associated with calciturbidites, namely graded microbreccia and calcarenite. Exceptionally, hemipelagic sediments can be interstratified between thick breccia beds. Towards the central part of the basin this member laterally passes into the Lower resedimented limestones of the Tolmin Formation.

Description of the type locality: The type locality of the Ponikve Breccia Member is the Podbrdo section (Fig. 2), located on the SW slopes of the Šentviška planota plateau (N46°08'06'', E13°47'50''), near the village of Ponikve. The section is named after the local name for a gorge and is not to be mistaken for the town of Podbrdo that lies in the Bača Valley.

In this section, the Ponikve Breccia Member lies unconformably on the Krikov Formation dominated by hemipelagic limestone. It is 57.5 m thick and composed of amalgamated limestone breccia and subordinate calcarenitic beds. It begins with three limestone breccia beds (0.6, 2.3 and 8.4 m thick) that contain cm-sized lithoclasts. The succession continues with an interval almost 5 m thick dominated by fine-grained limestone breccia, often matrix supported (pebbly calcarenite). Beds at the base of this interval are several tens of centimetres thick and become less expressed upwards. The thickest and coarsest bed follows, which reaches 37 meters and contains lithoclasts up to 10 m in size. The Ponikve Breccia Member ends with two graded fine-grained limestone breccia beds (1.3 m and 2.5 m thick, respectively) followed by three thin packstone beds.

The Ponikve Breccia Member is overlain by siliceous limestones and cherts of the Tolmin Formation (for details see Rožič et al., 2014a). Two supplementary sections were logged in the vicinity of the type section (see below).

Lateral variability: geological maps of the studied areas and description of the studied sections

The Ponikve Breccia Mb is characteristic for the SB's southernmost (most marginal) sections. So far, it is documented in areas of the sections presented herein. Additionally, Middle Jurassic breccia beds are mapped in the SB outcrops near the town of Železniki (Demšar, 2016) which is located between the Zapoškar and Škofja Loka sections, and near the town of Boštanj (Ogorelec & Dozet, 1997), close to the Mirna sections and the town of Celje (Sherman et al., 2022). The areas of the studied sections are described in a west-to-east direction.

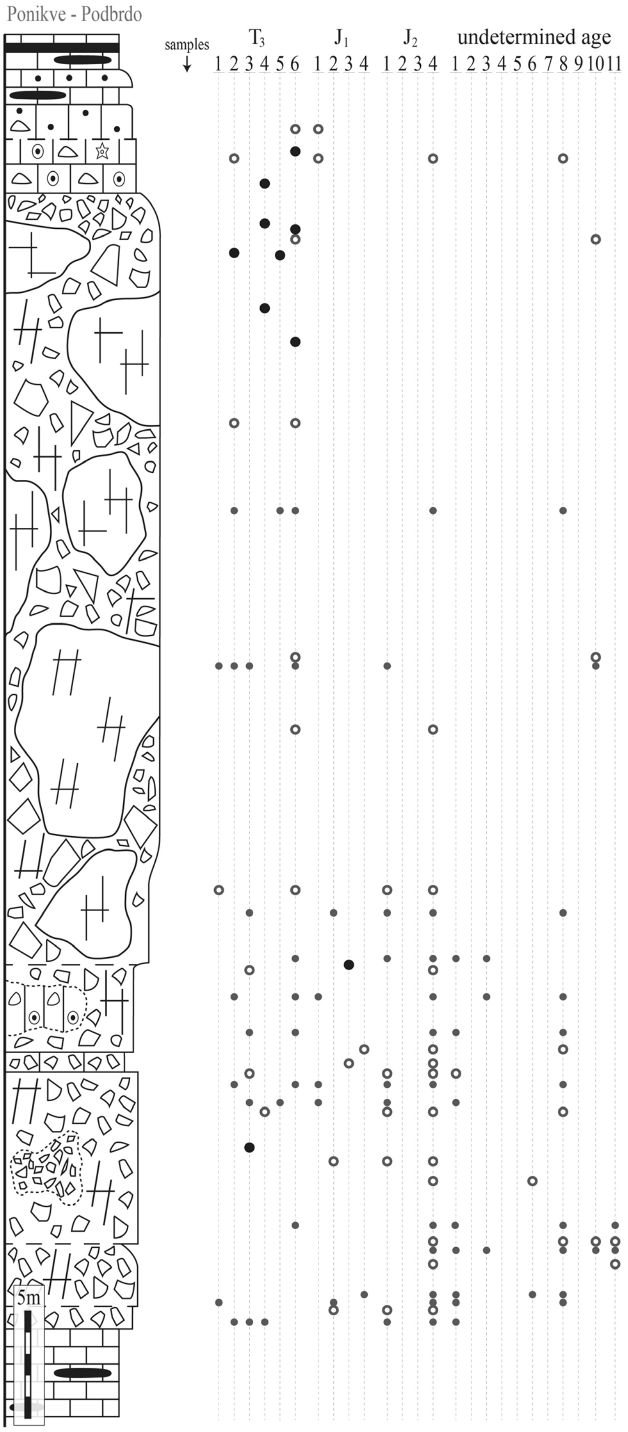

Fig. 2. Detailed stratigraphic log of the Podbrdo section (type locality of the Ponikve Breccia Member) with positions of specific lithoclast types (for legend see Fig. 7).

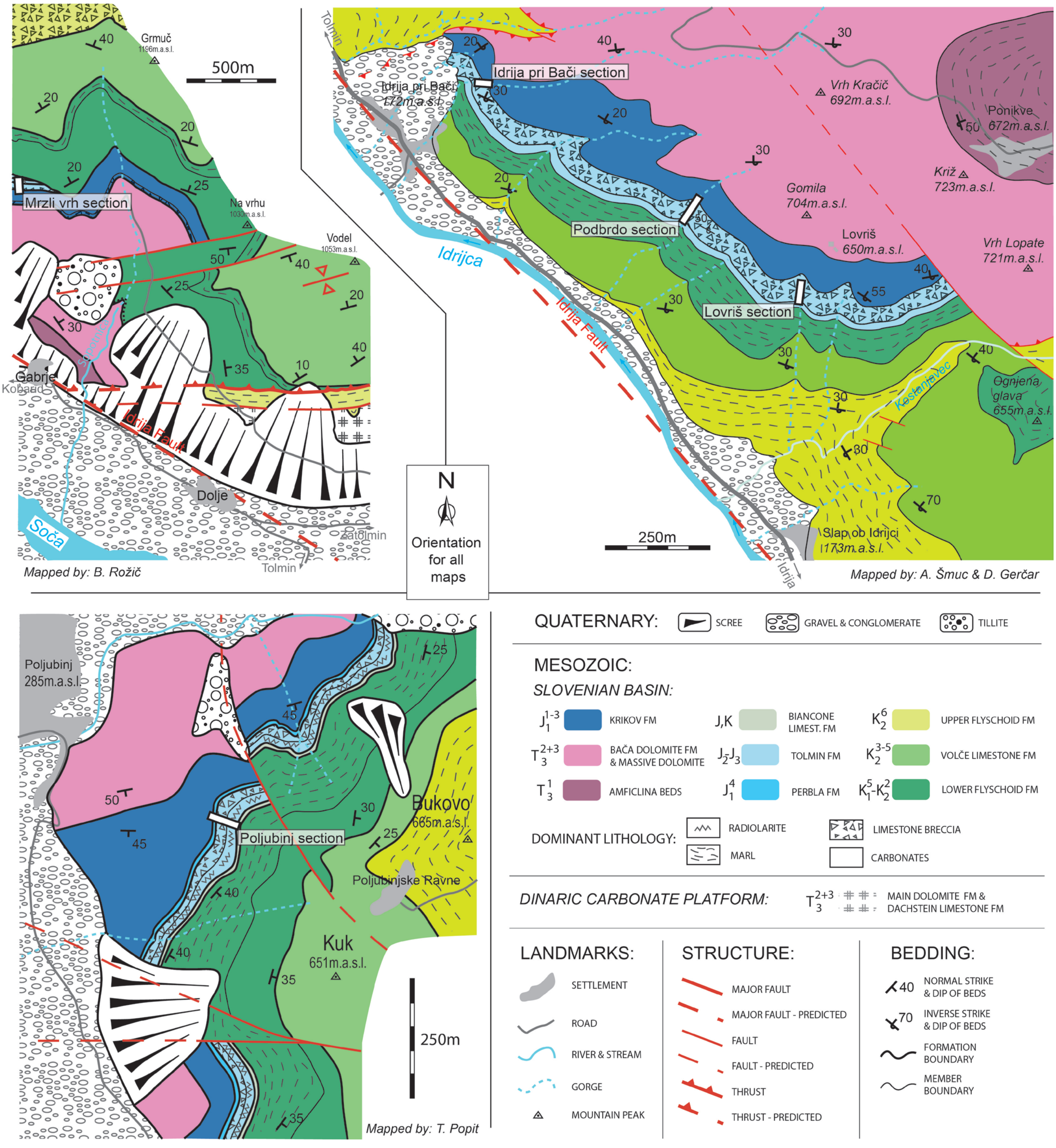

Fig. 3. Geological maps of the Mrzli vrh, Poljubinj and Ponikve Plateau areas with locations of the studied sections.

Mt. Mrzli vrh section

The Mt. Mrzli vrh section was logged 3.5 km NW of the town of Tolmin where the westernmost outcrops of the SB are preserved (Fig. 3). The succession is generally equal to the one described above in the Geological Setting chapter, but the Norian–Rhaetian is dominated by massive dolomite overlain by basal limestone breccia of the Krikov Formation (for details see Rožič, et al., 2017). Some coarser grained calciturbidites (limestone microbreccia) occur within the Krikov Formation.

The studied Middle Jurassic limestone megabreccia occurs solely on the westernmost cliffs of the Mt Mrzli vrh where the section was logged (N46°12’43’’, E13°41’49’’). The contact with the underlying Krikov Formation is erosional. The Ponikve Breccia Member is 44 m thick and composed of a single graded bed with m-sized boulders, with cm-sized clasts at the topmost part of the bed (Fig. 4).

It is overlain by approximately 15 m thick radiolarite of the Tolmin Formation and 4 m of the Biancone-type limestone. The overlying Lower

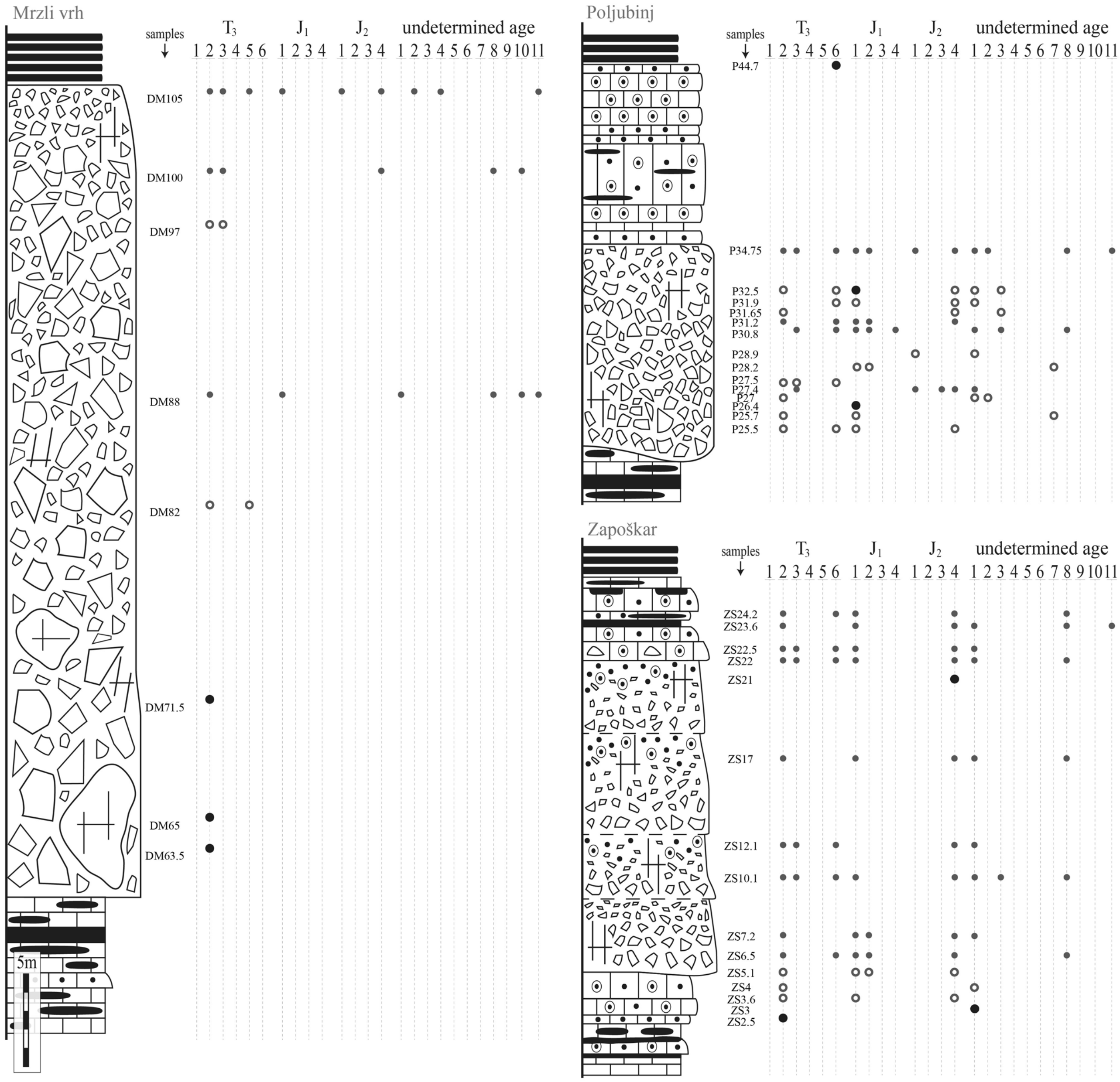

Fig. 4. Detailed stratigraphic logs of the Mrzli Vrh, Poljubinj, and Zapoškar sections with positions of specific lithoclast types (for legend see Fig. 7).

Flyschoid formation is dominated by coarse grained resedimented limestones and forms an angular unconformity with underlying sedimentary rocks. Consequently, all Middle and Upper Jurassic beds are laterally eroded (towards east) and basal limestone breccias of the Lower Flyschoid formation directly overlie the Krikov Formation. In the mapped area, south of two prominent E–W trending faults, the Lower Flyschoid formation lies directly on the massive dolomite, and these faults are proposed to be reactivated paleofaults (for details see Rožič, 2005).

Poljubinj section

The Poljubinj section is located 1.5 km SE of the town of Tolmin, near the Poljubinj Village on the NW slopes of Mt. Kuk (N46°10’43’’, E13°45’28’’). Here, the overall succession shows more continuous and “classical” basinal succession, which is displaced along several NW-SE and W-E oriented faults (Fig. 3).

The Ponikve Breccia Member lies on top of the Perbla Formation (maybe even above a few basal beds of the Tolmin Formation). It is 11 m thick and contains dm-sized clasts (Fig. 4). It is followed by 9 m of thin- to medium-bedded ooidal calcarenites (calciturbidites) and further up by radiolarite of the Tolmin Formation (Rožič & Popit, 2006). The base of the latter was dated with radiolarians to the UAZ8 (middle Callovian to lower Oxfordian) (Goričan et al., 2012).

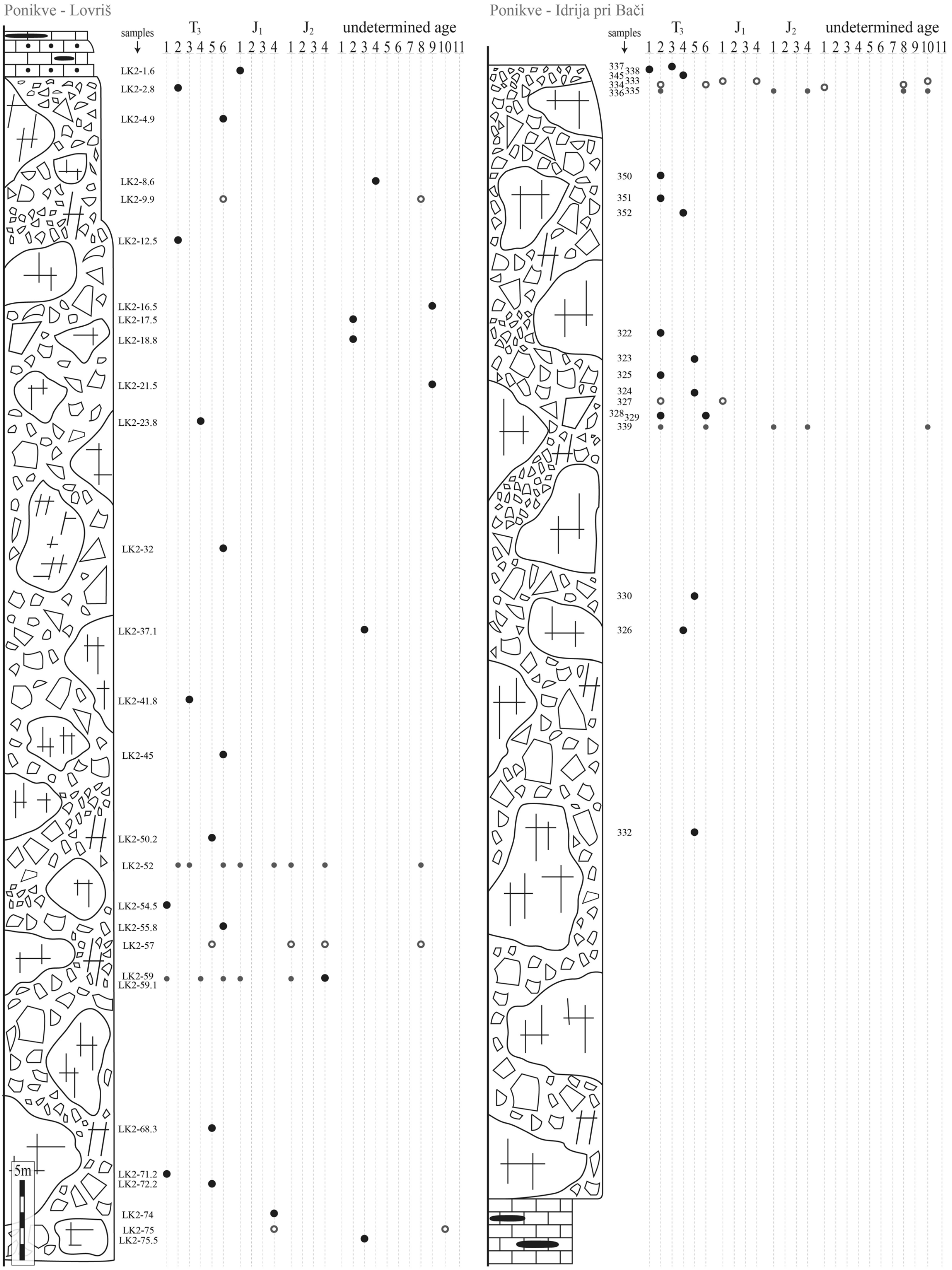

Fig. 5. Detailed stratigraphic logs of the Lovriš and Idrija pri Bači sections with positions of specific lithoclast types (for legend see Fig. 7).

Ponikve Klippe: Idrija pri Bači, Podbrdo, and Lovriš sections

This area is located further to the SE (6 km from the town of Tolmin) on the NE slopes of the Šenviška planota plateau (Fig. 3). The area structurally belongs to the Ponikve Klippe, the only SB succession preserved south of the South-Alpine thrust-front in all of western Slovenia (Buser, 1986; Placer, 1999). The contact with the underlying Trnovo Nappe of the External Dinarides is a thrust that is displaced by NW-SE strike-slip faults.

The SB succession in the Ponikve Klippe is in an overturned position and shows quite typical SB development. The Ponikve Breccia Member forms a continuous belt along the southern slopes of the Šentviška planota plateau facing the Idrijca River Valley. Three sections were logged within this belt. In the Idrija pri Bači section (N46°08'26'', E13°47'07'') on the NW end of the belt, the Ponikve Breccia Member is 80 m thick and seemingly composed of a single breccia bed composed of m-sized boulders (Fig. 5). Towards the SE lies the Podbrdo section, described as the type-section above. The Lovriš section was logged on the SE end of the facies belt (N46°07'55'', E13°48'14''). The single limestone megabreccia bed was logged for 75 m, though the breccia unit may be even thicker, because the lower boundary is covered. This bed contains large limestone boulders that often exceed 10 m in diameter (Fig. 5).

The described lateral changes in thickness and grain size of the member indicate that the topmost (thickest and coarsest) megabreccia bed is channelized into the underlying strata, often completely eroding preceding limestone breccia beds, which are preserved only in the Podbrdo section. The upper and lower boundaries of the Ponikve breccia are the same as in the type-locality section.

Zapoškar section

The Zapoškar section is located 3.5 km north of town of Cerkno in the Zapoška grapa gorge that cuts the southern slopes of Mt. Porezen (N46°09'47'', E13°58'27''). The facies belt is continuous and displaced solely by a minor NW–SE trending fault (Fig. 6). In the Zapoškar section, the succession of the Lower resedimented limestones of the Tolmin Formation is 25 m thick and composed of calcarenites and limestone breccia beds (Fig. 4). The latter are up to several meters thick and positioned in the central part of this succession and can be assigned also as the Ponikve Breccia Member. It lies on the siliceous limestone of the Lower Member of the Tolmin Formation and is overlain by radiolarite of the Upper Member of the Tolmin Formation. Laterally, the Ponikve Breccia Member pinches out completely, and the two hemipelagic members of the Tolmin Formation are in direct contact.

Škofja Loka: Podpurflca and Trnje sections

The investigated area is constrained to a narrow N–S extending belt of the SB outcrops, which starts approximately 1.5 km west of Škofja Loka's old town and extends for several km towards the north. The area is characterized by a rather complicated tectonic structure (Fig. 6). In a relatively small area three nappes (thrust sheets) are recognized. The lowermost is the Trnovo Nappe composed of the DCP succession ranging from Upper Triassic Dachstein Limestone down to the Palaeozoic basement rocks, whereas the upper two consist of the SB successions.

In the middle thrust-sheet, the Carnian to mid-Cretaceous SB successions are found. It is composed of two distinctly diverse successions that exhibit major differences in the Jurassic part of the succession. The thrust sheet starts with shale/marlstone-dominated Amficlina beds which in the uppermost part contain an interval of thin-bedded micritic limestone several tens of meters thick, which is known in older literature as Škofja Loka limestone (Ramovš, 1994). Upwards, it is followed by Norian–Rhaetian Bača Dolomite dominated by bedded dolomite with chert nodules, but in the Norian part thick dolomite-chert breccia beds are present and accompanied by synsedimentary faults (Oprčkal et al., 2012). Upwards, through the cherty interval it passes into the Krikov Formation (named Vancovec limestone in Demšar, 2016) and the thin (10 m) Perbla Formation (here we notice that in the field it is often impossible to distinguish between the micritic limestones of the Krikov Formation and those from Amficlina beds).

The Ponikve Breccia Member is slightly channelized and reaches approximately 50 m in thickness (Fig. 7). It was logged in a Podpulfrca section along the road between the villages of Podpurflca and Gabrovo (N46°09'31'', E14°17'24''). It is composed (often indistinctly) of amalgamated beds of limestone (mega)breccia and subordinate calcarenite beds. Bed thicknesses vary from tens-of-centimetres to almost 10 m. The upper part of the member was additionally logged in a supplementary section located along the main road between Škofja Loka and Cerkno (N46°09'12'', E14°17'25''). The Ponikve Breccia

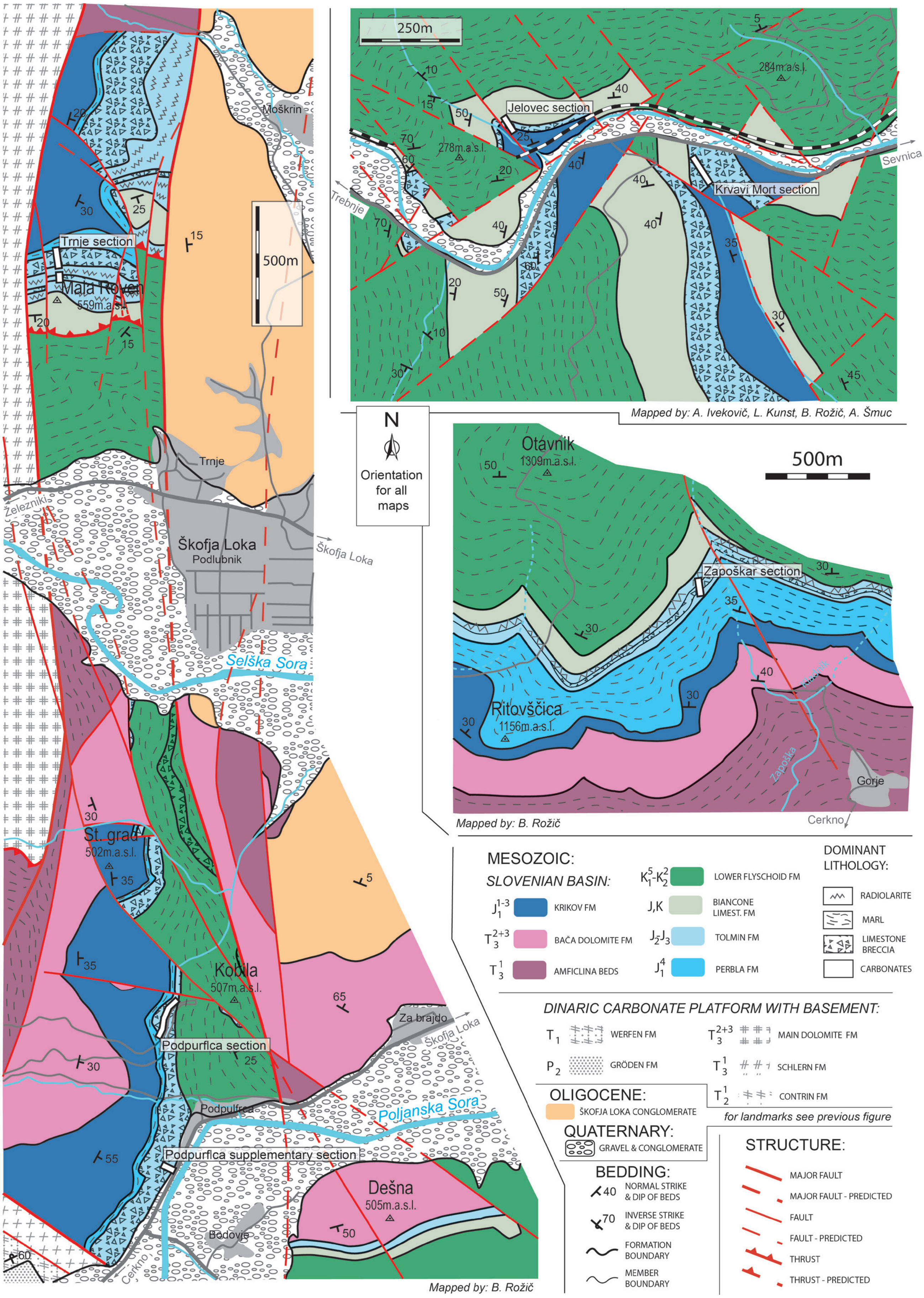

Fig. 6. Geological maps of the Škofja Loka, Zapoškar and Mirna River areas with locations of the studied sections.

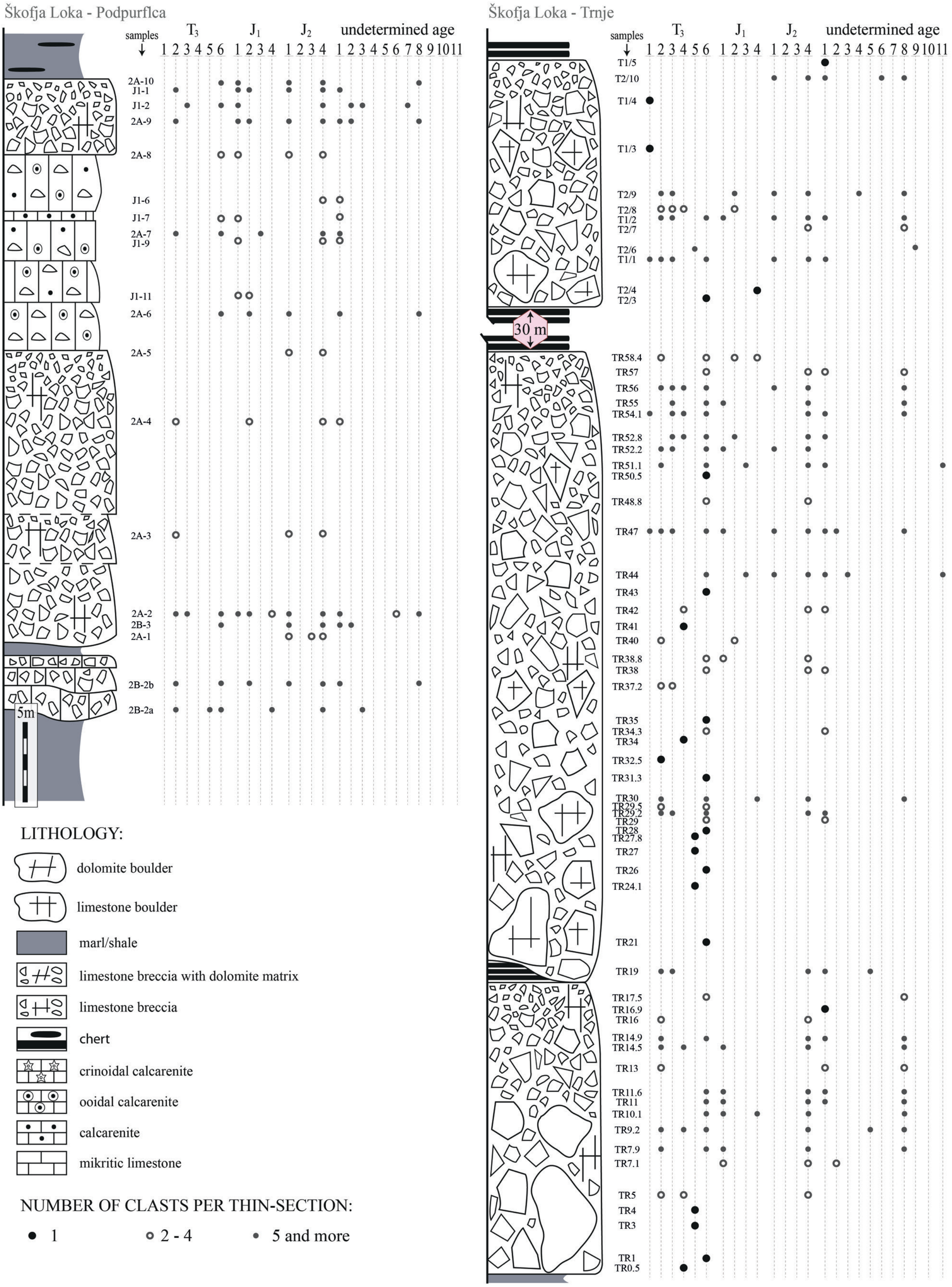

Fig. 7. Detailed stratigraphic logs of the Škofja Loka area: Podpurflca and Trnje sections with positions of specific lithoclast types.

Member is unconformably overlain by the mid-Cretaceous Lower Flyschoid formation. The upper member of the Tolmin Formation, as well as the Biancone-type limestone, were eroded in this area.

In the same thrust-sheet a specific, fault-isolated succession is found on the Dešna hill in the southern part of the mapped area (Figs. 1 and 6). The major part of the hill is composed of Bača Dolomite rich in dolomite breccia. It is overlain, after a long stratigraphic gap, by a thin interval of alternating radiolarite and marlstones (Upper member of the Tolmin Formation). These are overlain by Biancone-type limestone followed by the Lower Flyschoid formation.

In the structurally highest thrust sheet, located north of the Selška Sora River and Trnje Village, the succession is more continuous. Here the Ponikve Breccia Member overlies the Perbla Formation and reaches almost 60 m in thickness (Fig. 7). It is composed of two thick beds (20 and 38 m), separated by a laterally discontinuous interval of reddish radiolarite (alternatively it could be a large chert lithoclast) up to 2 m thick. Both breccia beds show normal grading in the uppermost parts. The Ponikve Breccia Member is followed by a succession of red and green radiolarite some 30 m thick. Upwards, however, another 20 m- thick graded limestone megabreccia bed occurs, whose composition resembles the main interval. Both limestone megabreccia intervals were logged in the Trnje section on the northern slopes of the Mala Roven hill (N46°10’57”, E14°17’03”). Upsection, another 20 m of red-violet radiolarite is found, which is followed by 40 m of the Biancone-type limestone. The contact between the Biancone Limestone and the south-lying Lower Flyschoid formation is a north-dipping thrust fault.

Thrust structures are further dissected by a dense network of generally N–S striking normal faults that occasionally redirect towards a NW–SE strike. In this setting, the eastern blocks (closer to the Ljubljana Field) were downthrown. The structure may have originated in the transtensional wedge between two regional NW–SE oriented faults (Rožič et al., 2015). In the mapped area the greatest downward movements were along the contact with the southwestern fault (seen in SW edge of mapped area in Fig. 6), which caused a further tilting of tectonic blocks (including beds as well as thrust planes). The described southward tilting is responsible also for the atypical, slightly south-dipping thrust plane between the Trnovo Nappe (DCP succession) and the middle thrust-sheet (SB succession with Podpulfrca section).

Mirna River Valley: Jelovec and Krvavi mort sections

The studied area is situated in the Mirna River Valley, between the small villages of Gabrje and Jelovec, approximately 6 km SW of the town of Sevnica (Fig. 6). The area is dominated by a Lower Flyschoid formation. This shale-rich formation was previously mapped as Ladinian beds, but during mapping nanoplankton as well as foraminifers (in calciturbidites) were found and determined the mid-Cretaceous age of this formation (Ivekovič, 2008). Jurassic beds outcrop in the central part of the valley in tectonic blocks separated by SWW–NEE and NW–SE striking faults. The Jurassic succession begins with the Krikov Formation, which is dominated by micritic limestones but contains few calciturbidite (graded calcarenite) beds. It is unconformably overlain by a Ponikve Breccia Member

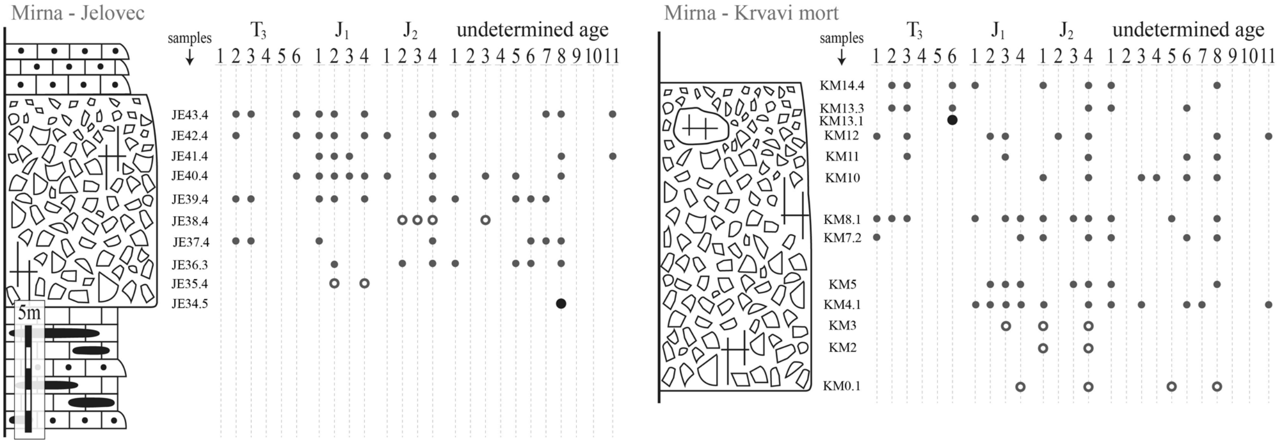

Fig. 8. Detailed stratigraphic logs of the Mirna River area: Jelovec and Krvavi Mort sections with positions of specific lithoclast types (for legend see Fig. 7).

that is composed of a single limestone megabreccia bed. In the Jelovec section, logged in a gorge near the eastern entrance of the Lepi Dob railway tunnel, north of the Trebnje–Sevnica regional road (N45°59’23’’, E15°13’43’’), the breccia bed is 10 m thick and graded (Fig. 8). The supplementary Krvavi Mort section was logged in the Krvavi Mort gorge south of the Trebnje–Sevnica regional road (N45°59’19’’, E15°14’07’’). In this section, the breccia bed is thicker (at least 14 m) with large clasts occurring also in the upper part of the bed. Upsection, the breccia is overlain with sharp contact (logged in the Jelovec section) by an interval of medium-bedded, graded calcarenites (calciturbidites) 8 m thick, which have not yielded age-diagnostic fossils. According to the composition, which is the same as the Upper resedimented limestones of the Tolmin Formation, these calcarenites could already be Late Jurassic in age. Above, the 35 m thick Biancone-type limestone outcrops. In the area studied herein, the interval between the Krikov Formation and the Biancone limestone therefore lacks the hemipelagic sediments of the Perbla and Tolmin formations, which are usually present in other sections. However, radiolarite was reported a few kilometres east by Ogorelec and Dozet (1997).

Microfacies of the Ponikve Breccia Member

The dominant lithology in the Ponikve breccia member is a limestone breccia, whereas in some sections calcarenites also occur. In this paper we focus on the clast- and matrix-analysis of the breccia beds (see below). Calcarenites are often graded grainstone/packstone composed of ooids, peloids, intraclasts, basinal clasts (mud-chips) and bioclasts, i.e. predominantly echinoderms. Other fossils are benthic foraminifers, bivalve, brachiopod and ostracod shells, gastropods, and bryozoans. With fining composition changes into packstone composed of pellets to peloids and bioclasts, predominantly echinoderms, calcified radiolarians, and rare benthic foraminifers (for details see Rožič & Popit, 2006; Rožič, 2009; Rožič et al., 2018).

Composition of the limestone breccia matrix

Apart from the Mt. Mrzli Vrh section, the composition of the breccia matrix is generally uniform in all studied sections. It is mostly packstone, locally grainstone, composed of grains that are believed to be generally contemporaneous with sedimentation. The matrix is locally dolomitized.

The grain composition is variable within and between different sections. However, except for the Mt. Mrzli vrh section, coarse micritized ooids and small- to medium-sized radial ooids with peloids and bioclasts in their cores (foraminifers, gastropods, crinoids, ostracods, bivalves, etc.) are always present and often dominant. The packstone/grainstone exhibit bimodal distribution in the size of the grains (Fig. 9a). Other grains, such as intraclasts, peloids (pellets), aggregate grains (lumps) and diverse bioclasts are also present (Fig. 9b). The most common bioclasts are echinoderm fragments and foraminifers, among which the trocholinids dominate over textularids and lagenids. Fragments of thin-shelled bivalves are locally present. Other molluscs (bivalves, gastropods, and brachiopods) are very rare. Other rare bioclasts are corals, calcimicrobes, bryozoans, and microbially encrusted, completely recrystallized clasts (presumably recrystallization-prone bioclasts, such as chaetetids).

Alongside the aforementioned grain types, oncoids were also observed. They are abundant in the lower part of the Podbrdo section and were documented in the Mirna Valley area (Krvavi Mort section), as well as in the Škofja Loka area (Podpulfrca section). The cores of the oncoids are either micritic or contain bioclasts, such as gastropods, bivalves, fragments of encrusting foraminifers, or calcimicrobes.

In contrast to breccias in other sections, the matrix of breccias in the Mt. Mrzli vrh section is a fine-grained packstone with fragmented thin-shelled bivalves and other bioclasts, among which echinoderms and sponge spicules prevail. Pellets, phosphate, and glauconite grains occur sporadically, whereas micritized ooids are present, but very rare.

Both at the Ponikve Klippe and at Mrzli vrh the matrix of the limestone megabreccia is mostly dolomitized. Locally the dolomitization affects the micritic lithoclasts as well. The primary texture and composition of the matrix are preserved only in the pebbly calcarenites of the lower part (from the 15th to the 20th metre-mark) of the Podrbdo section (Ponikve Klippe) and partially in the uppermost part of the limestone megabreccia bed in the Mrzli vrh section.

In addition to the above-mentioned allochems, the breccia matrix and calcarenites in all sections also contain sand-sized lithoclasts. Their composition is identical to the composition of the larger clasts described in Table 1. Calcarenites overlying the limestone megabreccia in the Pobrdbo and Jelovec sections show a distinct increase in

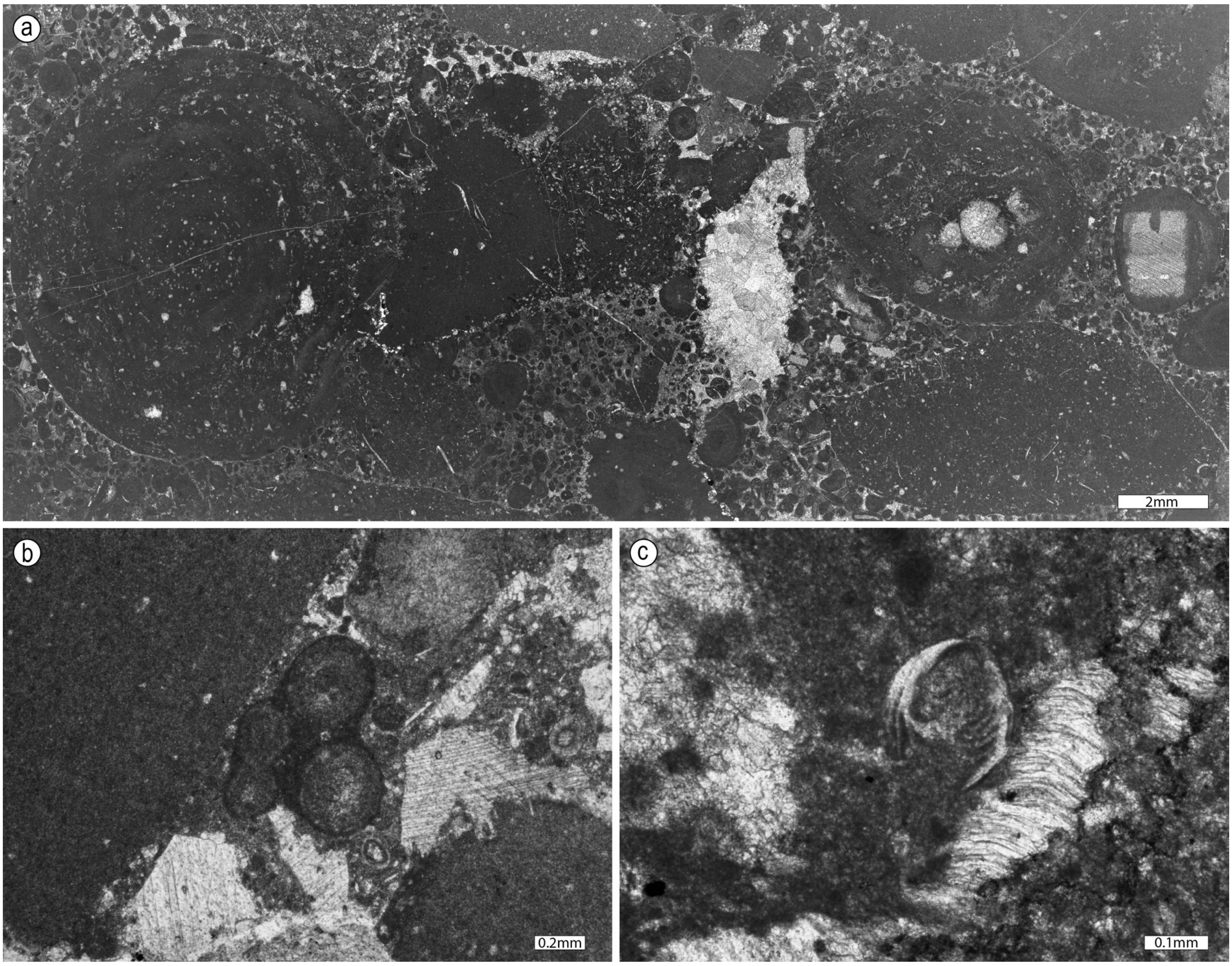

Fig. 9. Matrix of the Ponikve breccia: a) predominant grains are ooids, in some beds large oncoids occur (sample pp21.5), b) other matrix grains are pellets, aggregate grains, and bioclasts such as echinoderms, filaments, etc (sample KM4.1), c) age diagnostic *Protopeneroplis striata* Weynschenk occurs as isolated grain within the matrix (sample KM8.1).

crinoid abundance. This turnover in composition is most apparent in the Jelovec section, in which the overlying beds could already be of Late Jurassic age.

Age of the Ponikve Breccia Member

Some age-diagnostic foraminifers are present in both the matrix of limestone megabreccia and in the calcarenites (packstone/grainstone). They are well preserved, predominantly isolated, or rarely occurring in the cores of radial ooids. *Protopeneroplis striata* Weynschenk (Fig. 9c) is the most omnipresent, with *Andersenolina palastiniensis* Henson and *Mesoendothyra croatica* Gušić also important for biostratigraphy. In the Podbrdo section, *Mesoendothyra croatica* Gušić was found less than a metre above the limestone megabreccia unit in calciturbidite interstratified in the overlying hemipelagites of the Tolmin Formation. The age-range of the limestone megabreccia studied is thus Bajocian–lower Bathonian (cf. Velić, 2007).

In previous studies, a sample of radiolarite which was taken 2.4 m above the Lower resedimented limestones of the Poljubinj section yielded age diagnostic radiolarian assemblages characteristic for a UAZ 8 (middle Callovian-early Oxfordian) (Goričan et al., 2012). In the Lovriš section a sample of radiolarite was taken 13 m above the limestone megabreccia unit and yield-

Fig. 10. T1 (a-c), T2 (d,e), and T3 (f, g) type lithoclasts: a) bioclastic wacke/packstone with echinoderms, foraminifera, filaments and unrecognisable bioclastic debris (sample LK2-54.5), b) slightly dolomitized bioclastic wackestone with echinoderms, filaments, ammonites and unrecognisable fossil debris (could belong to LJ4 clast type) (sample 338), c) Stromataxis structure within bioclastic wackestone (sample LK2-71.7), d) pelletal bioclastic packstone with Duostominidae formaninifera (sample 325), e) partly washed (corroded) matrix of the packstone with pellets, intraclasts, bivalve shell and foraminifera (*Triasina hantkeni*, *Aulotortus* sp.) (sample M65), f) pelletal intra/bioclastic grainstone with Duostominidae formaninifera (sample 337), g) intra/bioclastic grainstone with *Galeanella tollmanni* foraminifera and rare ooids.

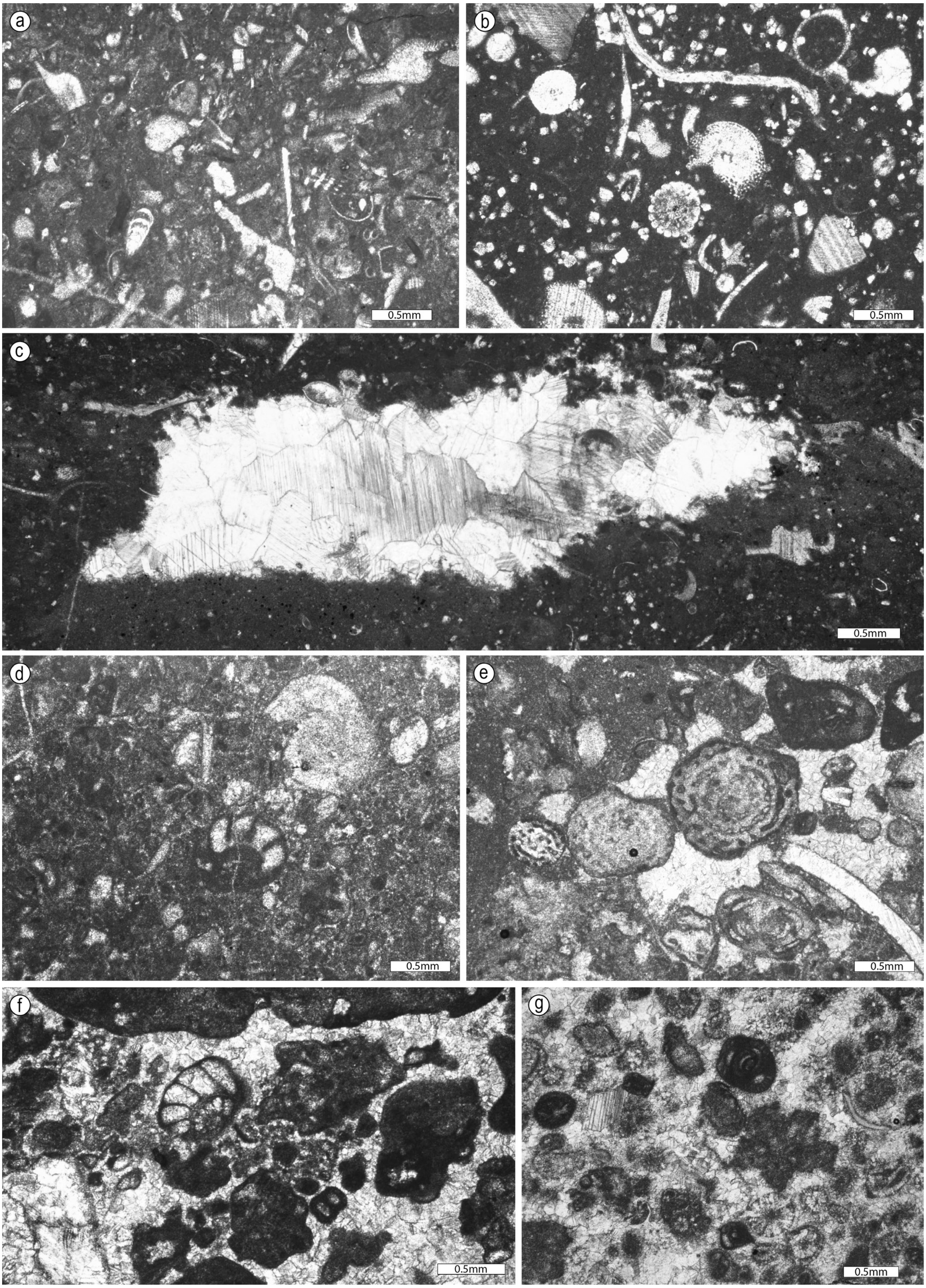

Fig. 10

ed UAZ 9-10 (middle to late Oxfordian to early Kimmeridgian) assemblage (Rožič et al., 2014a). Further basin-ward, the Lower resedimented limestone of the Tolmin Formation (which represents a distal equivalent of the limestone megabreccias presented herein) occur as calciturbiditic beds between radiolarite. Cherts just above the two lowermost calciturbiditic beds were dated to UAZ 4 (upper Bajocian). Cherts close to the uppermost beds were dated to the UAZ 8-10 (middle Callovian–early Kimmeridgian) (Goričan et al., 2012).

Compiling the available data, we conclude that major resedimentation events occurred within a relatively short interval between the Bajocian and early Bathonian. However, it is possible that some large-scale collapses occurred also later during the Middle Jurassic. This is evident particularly in the Trnje section, in which a thick radiolarite interval is interstratified between two limestone breccia megabeds.

Clast analysis

Clasts from breccias of the Ponikve Breccia Member are divided into 25 microfacies types (Table 1). As mentioned above, the composition of clasts in calcarenites corresponds to the clasts in breccias. The age of 14 microfacies types was determined. Six microfacies types are Late Triassic in age, and for most, we could narrow the age to the Norian–Rhaetian. Four microfacies types were assigned to the Early Jurassic, and four to the Middle Jurassic. The exact age for clasts belonging to the remaining 11 microfacies types could not be determined. Below we provide some basic descriptions; for further details see Table 1.

The first microfacies type (T1) from the Upper Triassic clasts is a bioclastic wackestone, which also contains deep-water fauna (Figs. 10a-c). The second microfacies type (T2) is a pelletal bioclastic packstone (often partly washed) with abundant foraminifers (Figs. 10d, e). The third microfacies type (T3) is a grainstone similar in composition to the previous microfacies type, but contains large amount of intraclasts, and in some clasts also cortoids (Figs. 10f, g). Microfacies types T2 and T3 are believed to originate in sand shoals and in transition to the lagoon, but they may also come from the reef area (they are often observed as sediment fills between reef frames of boundstone clasts). The fourth microfacies type (T4) is a bioclastic rudstone with bioclasts made of reef-building organisms (Figs. 11a-c), and a similar fifth microfacies (T5) also contains reef lithoclasts (Figs. 11d-f). These two microfacies types could represent forereef sediments, or an inter-reef breccia. The last Triassic microfacies type (T6) is a typical reef boundstone with corals and calcisponges (stromatoporoids) as the main framebuilders (Fig. 12).

The first Lower Jurassic microfacies type (LJ1) is a grainstone similar to the third Triassic microfacies type (T3) but contains less bioclasts and additional ooids and aggregate grains. Grains of this microfacies type generally show less recrystallization (Figs. 13a-d). The second microfacies type (LJ2) is an ooidal grainstone, which in some clasts passes into a microfaceis of the previous group (Figs. 13d-f). Both microfacies types (LJ1 and LJ2) are believed to originate from sand shoals, the first one closer to the transition with the lagoon. The third microfacies type (LJ3) is a crinoid-dominated grainstone (Figs. 14a, b), which in some clasts passes into a bioclastic wackestone (microfacies type LJ4) composed of diverse bioclasts revealing open-marine conditions (Figs. 14c-f). This clast microfacies type is similar in composition to Triassic bioclastic limestone (T1) but generally contains more sponge spicules.

Middle Jurassic clasts are divided into 4 microfacies types. First is an ooidal packstone/wackestone (MJ1) with a variable amount of ooids (Figs. 15a, b). Namely, in some packstone clasts ooids are dominant, while in others only sporadic ooids are found in a wackestone composed of pelagic fossils. Lithoclasts showing a transition from both end-members are present. The next two microfacies types are found only in the Mirna sections. The first of these two (MJ2) is a crinoidal limestone rich in lithoclasts (otherwise similar to LJ3) (Fig. 15c). The same is characteristic for the next microfacies type (MJ3), which in composition closely resembles older bioclastic limestones (T1 and LJ4 microfacies types) but also contains quite an abundance of lithoclasts (Figs. 15d, e). The last Middle Jurassic clast microfacies type (MJ4) is a mudstone/wackestone

Fig. 11. T4 (a-c), T5 (d-f) type lithoclasts: a) rudstone composed of diverse bioclasts (often encrusted by microbial laminae) deriving from the reef area (sample pp50.2), b) Calcisponge (left) and a microbial grain (right) as large grains of the bioclastic rudstone (sample pp50.2), c) foraminifera (Duostominidae and *Galeanella tollmanni*) and other reef debris as smaller grains of the bioclastic rudstone (sample pp52.0), d) reefal litho/bioclastic rudstone additionally contain lithoclasts (sample LK2 72.2), e) peloidal packstone lithoclasts with *Galeanella tollmanni* and bivalve fragments (sample LK2 57.2), f) a coral fragment (sample pp 57.6).

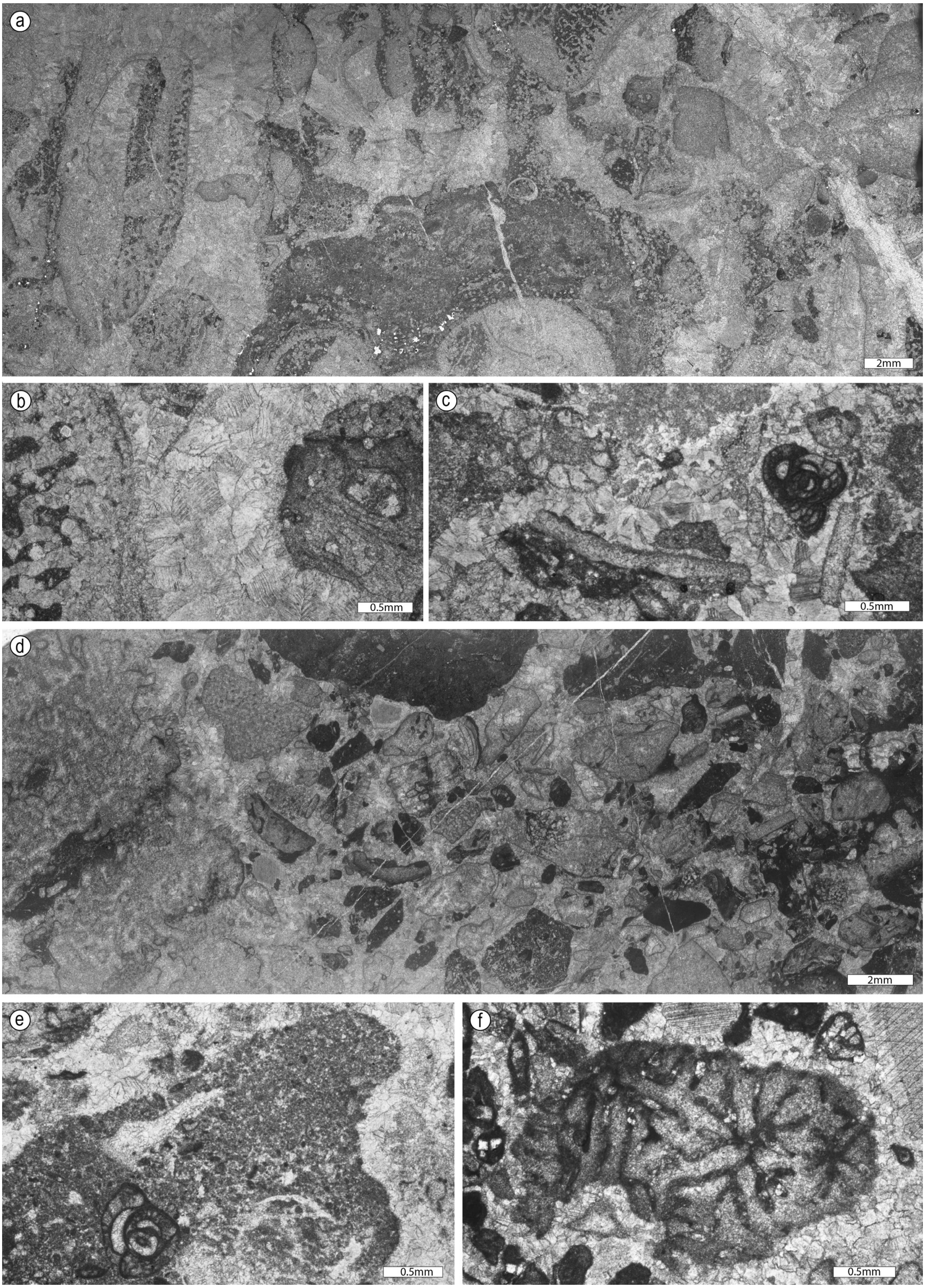

Fig. 11

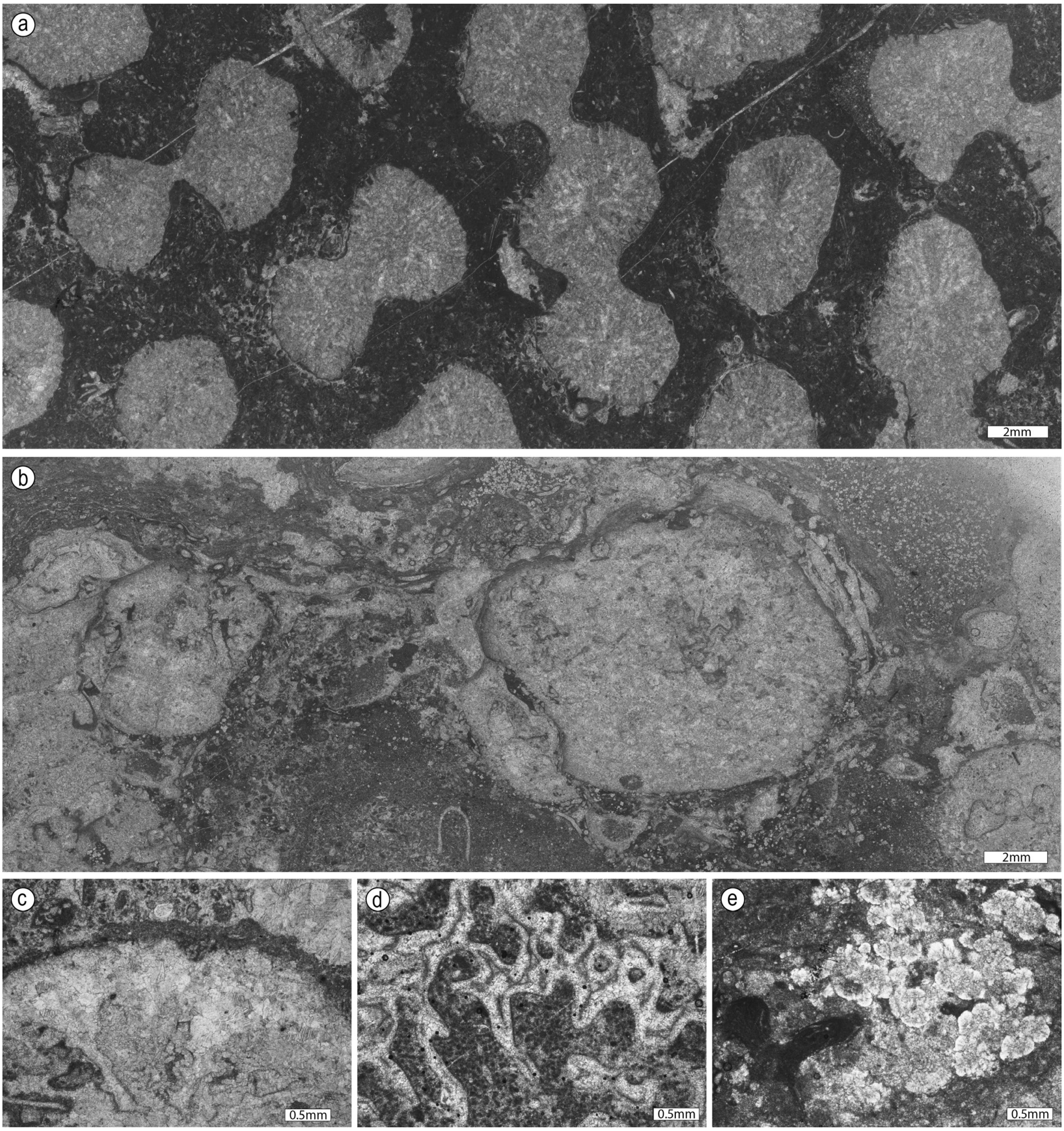

Fig. 12. T6 type lithoclasts: a) coral boundstone with pelletal packstone with corrosive voids infilling a space between corallites (sample 315D), b) Recrystallized frame building calcisponges with encrustations of microbialites, foraminifera and serpulids (sample pp37), c) coral with microbial crust and peletal/bioclastic grainstone matrix between corallites (sample pp57.3), d) calcisponge with voids filled with peletal packstone (sample JE42.2), e) *Baccanella* sp sp and microbial mound (sample LK2 4.8).

with pelagic fossils (Fig. 15f). Herein we note that age of this clast group was assigned due to the presence of planktonic foraminifers (cf. Caron & Homewood 1983; Tappan & Loeblich 1988; Darling et al. 1997). These foraminifers, however, do not occur in all clasts and large amount of these clasts could also be older.

The age of 11 microfacies types could not be univocally determined. The first such microfacies type (UD1) is common in almost all sections. It is a pelletal packstone that probably originated from a great variety of environments (Fig. 16a). Namely, in some clasts fenestrae were observed, while in others we noticed sponge spicules and thin-shelled bivalves (filaments) indicating open marine conditions. These clasts are likely of variable age. Similar microfacies was observed within the reef-frame of the boundstone clasts (T6) and furthermore, from one such clast we retrieved upper Norian (Sevatian) to lower Rhaetian

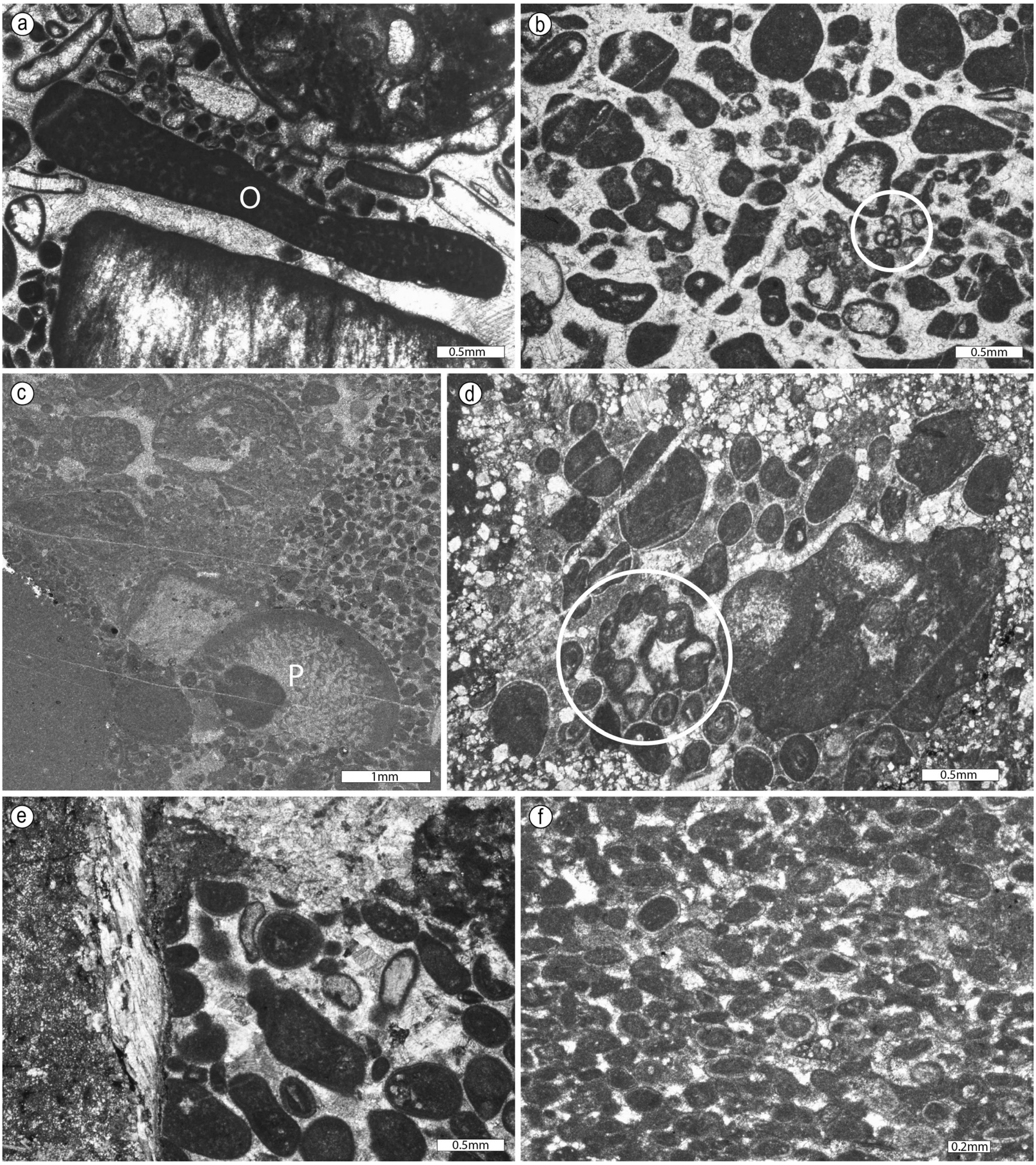

Fig. 13. LJ1 (a-d), and LJ2 (d-f) type lithoclasts: a) grainstone with pellets, intraclasts, micrite rimmed bioclasts (cortoids) and foraminifer *Orbitopsella* sp. (O) (sample 327), b) grainstone with intraclasts, peloids, aggregate grains (lumps), and *Siphovalvolina* sp. (encircled) (sample JE34.4), c) partly washed packstone lithoclasts with intraclasts, pellets, and fragments of calcareous algae and coral *Phacelophyllia termieri* (P); mudstone clast (lower left) and ooidal matrix (sample pp19.6), d) transitional LJ1-LJ2 lithoclast in dolomitized matrix with intraclasts, ooid-dominated and foraminifera *Reophax* sp. foraminifera, which agglutinated ooids (encircled) (sample pp5.2), e) grainstone with ooids, peloids, intraclasts and bioclasts, and chert clast (UD11) to the left (crossed polars) (sample KM12), f) partly washed packstone with ooids and pellets as dominant grains (sample pp5.2).

conodonts. On the other hand, they can contain coarse laminas rich in ooids and intraclasts that are typical for first two Lower Jurassic microfacies types (LJ1, and LJ2). The next microfacies type (UD2) is a wackestone with coarse intraclasts (also some ooids and pellets), which originated in a quiet environment probably adjacent to the high-energy conditions (Fig. 16b). The third microfacies type (UD3) is a fine-grained and well-sorted packstone with pellets and bioclasts (Fig. 16c). It probably represents clasts of eroded calciturbidites. The next three microfacies

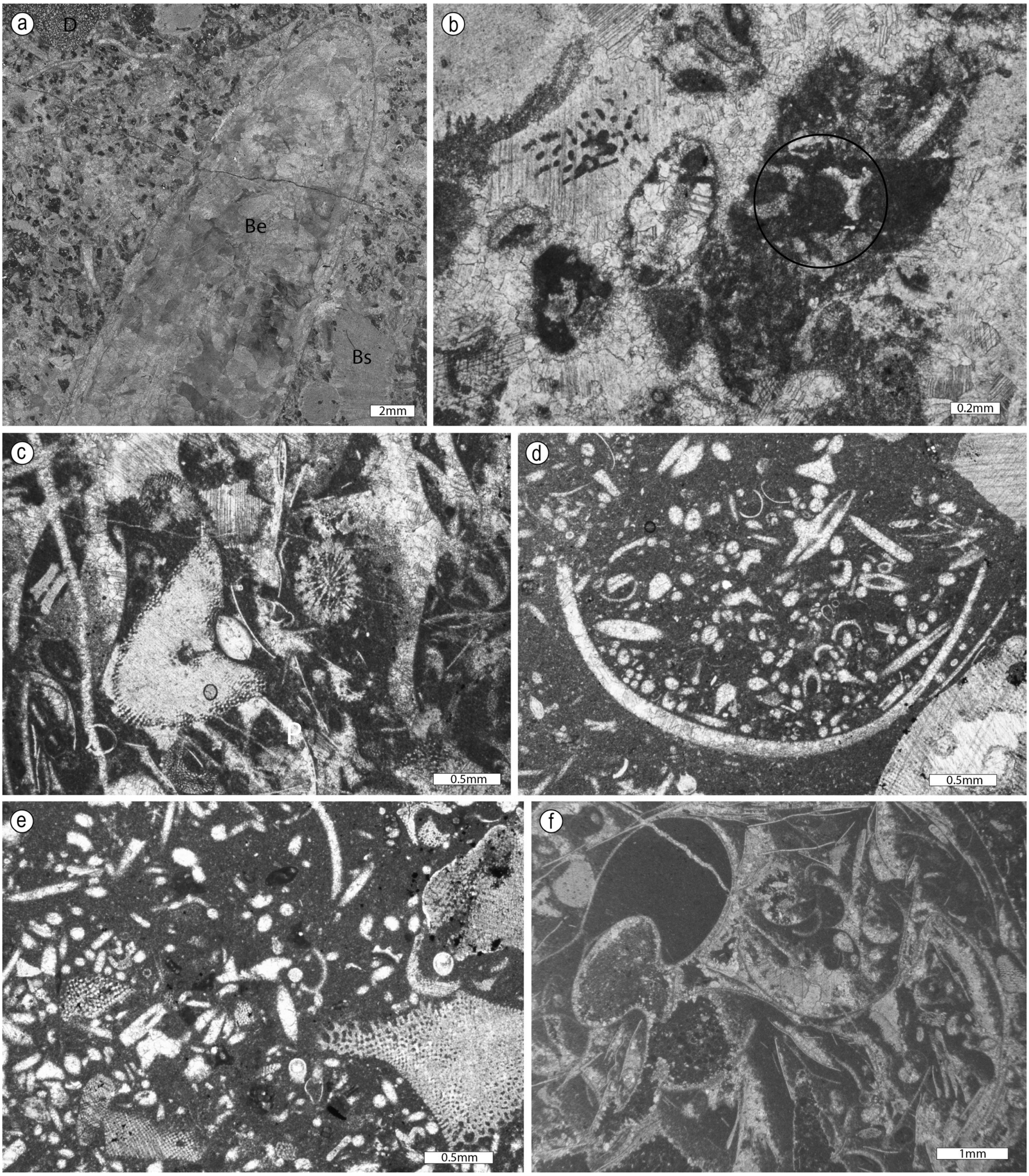

Fig. 14. LJ3 (a, b), and LJ4 (c-f) type lithoclasts: a) crinoidal grainstone with intraclasts, a dolomitized lithoclast (D), belemnite (Be) and bivalve shell (Bs) (sample pp21.05), b) crinoidal grainstone with wackestone litho/intraclasts, and foraminifer *Involutina liassica* (encirceled) (sample KM4.1), c) packstone with echinoderms (crinoids), filaments and ostracods (sample JE37.4), d) wackestone with bivalve shell, sponge spicules, echinoderms and ostracods (sample LK2-74.2), e) wackestone with echinoderms, sponge spicules and foraminifera (sample LK2-74.2), f) floatstone with ammonites, filaments and crinoids (sample KM10).

types represent sediments from an open-shelf or slope environment. The first of these (UD4) is a wackestone composed of crinoids and ophthalmidiid foraminifers and small pellets (Fig. 16d). Next is a spiculite crinoidal packstone (UD5) (Fig. 16e), and last is a filament packstone/grainstone (UD6) (Fig. 16f). The next microfacies type (UD7) is a packstone with coarse grained pellets that presumably originated from a lagoon (Fig. 16g). The Last four microfacies types do not bear certain information on sedimentary environments and age. First of these (UD8) is an almost

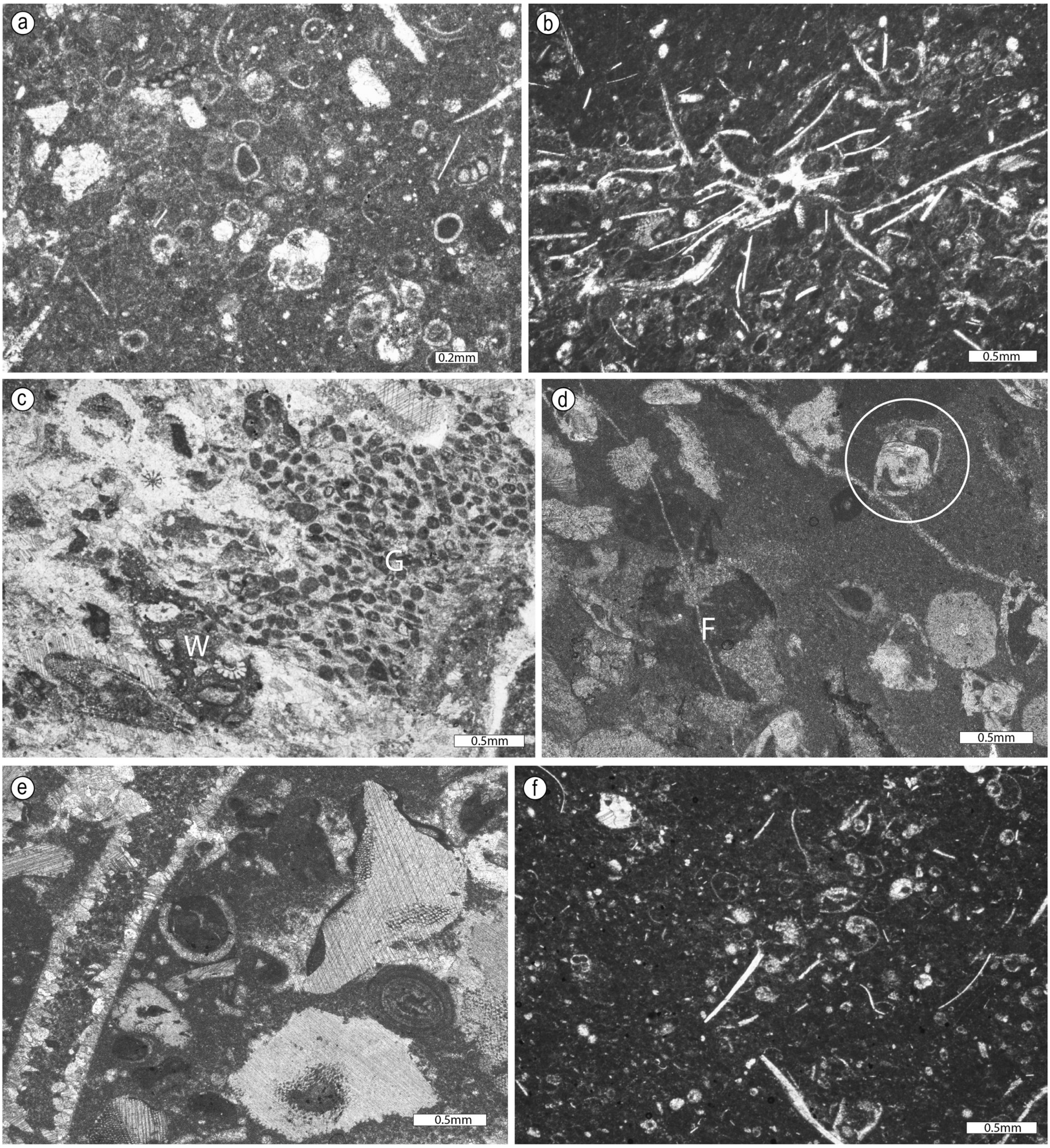

Fig. 15. MJ1 (a, b), MJ2 (c), MJ3 (d, e) and MJ4 (f) type lithoclasts: a) wackestone with superficial ooids, benthic and plankton foraminifer, filaments and unrecognisable bioclasts (sample pp5.3), b) lamina with abundant filaments and peloids (sample KM3), c) grainstone composed of echinoderms (crinoids) and pelletal/ooidal grainstone (G) and bio/intraclastic wackestone (W) lithoclasts (sample KM5), d) wackestone with crinoids, fenestral mudstone (F) lithoclast, unrecognisable bioslasts and benthic foraminifera with determined *Protopenerolis striata* (sample KM8), e) wackestone dominated by crinoids and ooids with fracture filled with dog-tooth rim cement and matrix of the breccia (sample KM5), f) hemipelagic wackestone with calcified radiolarian, filaments, plankton foraminifer and other bioclasts (sample KM0.1).

pure mudstone. In some clasts, pelagic fossils indicate open-marine conditions. Next is a recrystallized limestone (UD9), which sporadically shows ghosts of large fossils such as bivalves and ammonites (Fig. 16h). In the Ponikve Klippe and Mrzli vrh sections dolomitization is present and some clasts are completely replaced by dolomite (UD10). Last microfacies type (UD11) are chert clasts. In some cases, they most certainly represent replacement cherts, as they show relicts of the primary packstone, grainstone, and boundstone texture.

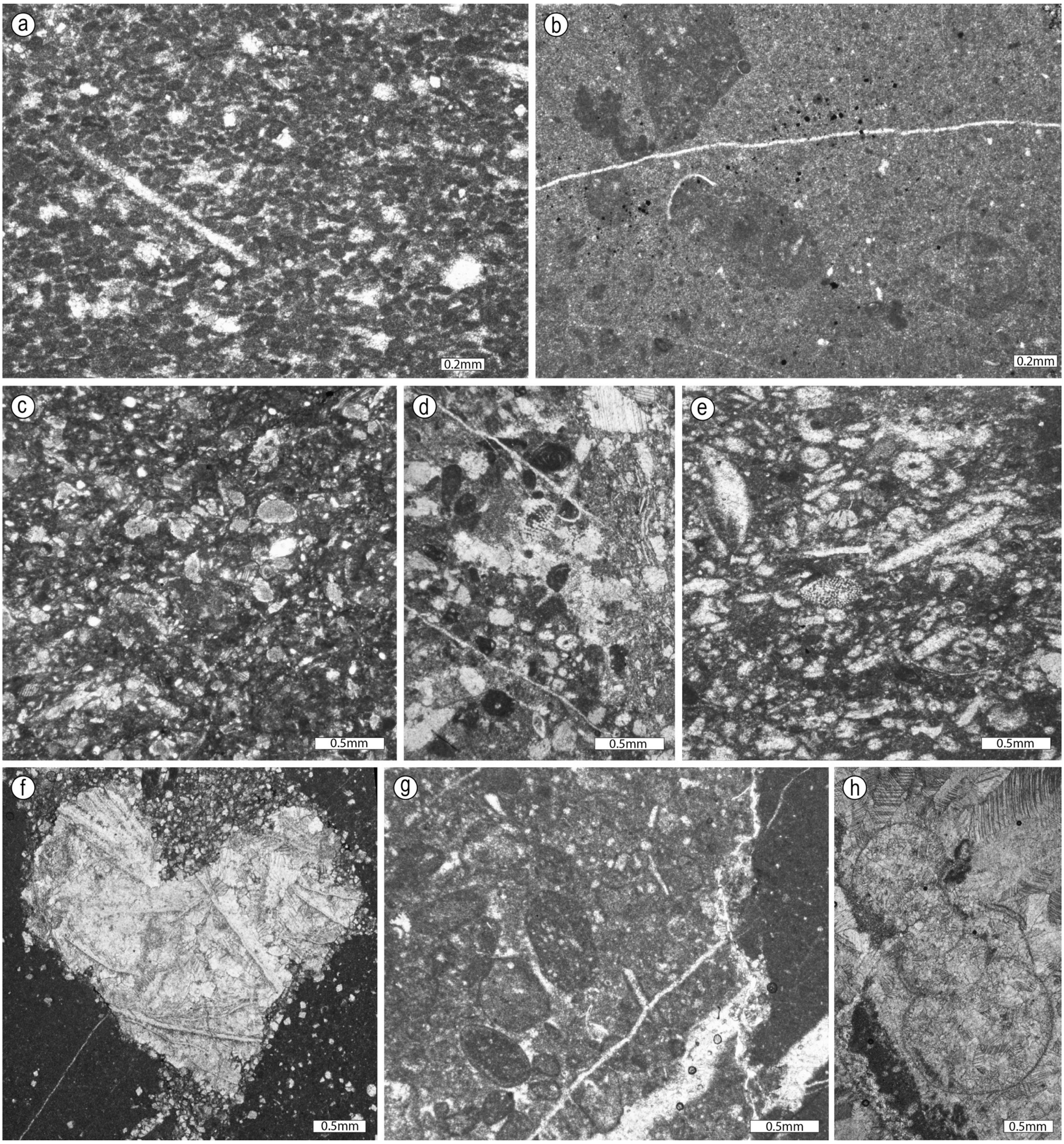

Fig. 16. age-undetermined (UD) lithoclasts: a) pelletal packstone with subordinate bioclasts (UD1) (sample pp18.0), b) intraclastic wackestone with ostracodes (UD2) (sample JE40.4), c) well sorted bioclastic/pelletal packstone (UD3) (sample KM0.1), d) wackestone composed predominantly of echinoderms (crinoids) and ophthalmidiid foraminifera (UD4) (sample M105), e) packstone dominated with sponge spicules, and subordinate crinoids, other unrecognisable bioclasts and peloids (UD 5) (sample KM8.1), f) heart-shaped lithoclasts of the filament grainstone (UD6) (sample pp5.5), g) packstone with anemuran pellets, intraclasts, pellets and micritized ooids and bioclasts (UD7) and mudstone (UD8) lithoclasts to the right (sample JE43.4), h) recrystallized floatstone (UD9) with ammonite (sample T2/5).

Table 1. Detailed description of composition, biostratigraphy, and sedimentary environment of microfacies types (abbreviations: M – mudstone, W – wackestone, P – packstone, G – grainstone, R – rudstone, F – floatstone, B – boundstone, D – dolostone, SMF – standard microfacies).

AGE	*CLAST TYPE*	*DESCRIPTION*
Upper Triassic	T1 Bioclastic W	*Composition:* medium-grained grains prevail; ehinoderms (crinoid osscicles, echinoid spines), fragmented large bivalves (exeptionally even cm-sized), thin-shelled bivalves, foraminifers (miliolids, lagenids, and nodosarids), ostracods, amonites, rare bryozoans and peloids. Large intra/bioclasts can have crusts made from calcimicrobes and foraminifers). It can contain laminae of crinoidal G (wash-out sediment; T1/4) and stromatactis (LK2-71.7). *Age:* upper Carnian – Rhaetian (**PODBRDO:** foraminifers *Lencticulina* sp., *Decapoalina* sp., *Miliolipora cuvillieri* Brönnimann & Zaninetti, **LOVRIŠ:** foraminifers *Parvalamella friedli* (Kristan-Tollmann), *Aulotortus sinuosus* Weynschenk, *Aulotortus tumidus* (Kristan-Tollmann)). *SMF and environment*: SMF 8 – open shelf.
	T2 Pelletal bioclastic P	*Composition:* structure is fine-grained P that can be party washed. Some laminae are G or W containing the same type of grains: pellets (peloids) and bioclasts, predominantly diverse foraminifers. Other grains are intraclasts, echinoderms, ostracods (can be abundant is some clasts – pp4.6), bivalves, gastropods; dasycladacean algae, *?Thaumatoporella*. Transition to G (type T3) was observed within the same clast (JE39.4, DM97, TR37.2). This facies is locally bioturbated and contains large scale disolution voids filled with crusts of bladed cements (DM63.5, DM71.5), geopetally filled stromatactis (325), rare oncoids (DM97) and isolated corals (TR32.5). *Age:* Norian-Rhaetian (**PODBRDO:** foraminifers *Galeanella tollmanni* (Kristan), *Miliolipora cuvillieri* Brönnimann & Zaninetti, Duostominidae, **LOVRIŠ:** foraminifers *Galeanella tollmanni* (Kristan), *Decapoalina schaeferae* (Zaninetti et al.), *Alpinophragmium perforatum* Flügel, **MRZLI VRH:** foraminifers, *Auloconus permodiscoides* (Oberhauser), *Parvalamella friedli* (Kristan–Tollman), *Aulotortus sinuosus* Weynschenk, *Aulotortus tumidus* (Kristan-Tollman), *Galeanella tollmanni* (Kristan), Duostominidae, *Duotaxis birmanica* Bronnimann, Whittaker & Zaninetti, *Triasina hantkeni* Majzon, *Agathammina austroalpina* Kristan & Tollmann, Duostominidae *Duotaxis* sp., *Ophthalamidium* sp. and *Variostoma helicta* (Tappan), and microproblematica *Thaumatoporella pavovesiculifera* Raineri). Clasts containing *Triasina hantkeni* Majzon reveal Rhaetian age. ŠKOFJA LOKA-PODPURFLCA: Duostominidae., ŠKOFJA LOKA-TRNJE**:** *Duotaxis* sp., **MIRNA:** foraminifers *Aulotortus* sp. and *Trochammina almtalensis* Koehn-Zaninetti). *SMF and environment*: between SMF18-for and SMF 16; lagoon or sheltered areas within the reef.
	T3 Intra/ bioclastic pelletal G	*Composition:* medium- to coarse-grained G, locally partly washed P; predominant grains are intraclasts, pellets and diverse bioclasts: fragmented bivalves (often in form of cortoids), foraminifers (miliolids, textularids, ...), echinoderms, rare gastropods, brachiopods, and grains composed of calcimicrobes (can form cores of few-mm large intraclasts), oncoids was also detected (337). One clast consists of pellets, abundant foraminifers (predominantly *Galeanella* sp.), frequent small radial ooids, and an oncoid (LK2-41.8). *Age:* Middle to Upper Triassic, predominantly Norian-Rhaetian (**PODBRDO:** foraminifers: ?Duostominidae, *Trochammina alpina* Kristan–Tollmann, *Trochammina jaunensis* Brönnimann & Page, *Aulotortus sinuosus* Weynschenk; **LOVRIŠ:** foraminifer *Galeanella tollmanni* (Kristan), **MRZLI VRH:** foraminifers *Auloconus permodiscoides* (Oberhauser), *Parvalamella friedli* (Kristan–Tollman), *Triasina hantkeni* Majzon). Clasts containing *Triasina hantkeni* reveal Rhaetian age. ŠKOFJA LOKA-TRNJE: foraminifers *Galeanella tollmanni* (Kristan), *Alpinophragmium perforatum* Flügel, Duostominidae ŠKOFJA **LOKA-PODPURFLCA:** foraminifer *Endoteba* ex gr. *controversa* Vachard & Razgallah, **MIRNA:** foraminifer *Galeanella tollmanni* (Kristan). *SMF and environment*: SMF 11, sand shoals at the platfrom margin.
	T4 Bioclastic R	*Composition:* structure passes from R to locally coarse-grained G: predominant grains are bioclasts: large grains are fragments of frame-builders: calcisponges, corals and calcimicrobes; other smaller bioclasts are echinoderms, foraminifers, fragmented bivalve shells, *Tubiphytes*, rare gastropods and dasycladacean algae. Other grains are intraclasts and pellets. Large grains can have microbial encrustations. Bioclasts in some clasts can be altered to cortoids. *Age:* Norian-Rhaetian (**PODBRDO**: foraminifers: *Galeanella tollmanni* (Kristan), Duostominidae, *Reophax* sp., *Aulotortus sinuosus* Weynchenk and *Decapoalina schaeferae* (Zaninetti, Altiner, Dager & Ducret); sponge: *?Cryptocoelia* sp.; coral: *Astraeomorpha pratzi* Volz; **MIRNA:** foraminifers *Galeanella tollmanni* (Kristan), Duostominidae). *SMF and environment*: SMF11, SMF5 reworked reefal material within or on either side of the reef.
	T5 reefal litho/ bioclastic F/R	*Composition:* There are two main constituents. The first are bioclasts of frame-building organisms up to a few mm in size, such as corals and calcisponges. Subordinate encrusters are calcimicrobes and foraminifers. The second main constituent are lithoclasts of A) reefal limestones, including sponge/coral B with the interstices filled with intra/bioclastic pelletal P/G or with sparite; these clasts resamble microfacies T6, B) pelletal intra/bioclastic P/G (resembling clasts of microfacies types T2 and/or T3), C) pelletal P (resembling clasts of microfacies type UD1), and less frequent D) coarse bioclastic limestone with fragmented bioclasts and intraclasts with echinoderms (resembling clasts of microfacies type T1). The space between large clasts is filled by coarse-crystaline cements (fibrous and dog-tooth rim cements, and drusy mosaic cements), less frequently by micrite. In the area of Škofja Loka (Trnje section) matrix contains echinoderms and sponge spicules. *Age:* Norian-Rhaetian (**PODBRDO**: foraminifers: *Galeanella tollmanni* (Kristan), *Reophax rudis* (Brady); Duostominidae; sponge *?Battaglia minor* Senowbari-Daryan & Shaefer, **MRZLI VRH:** foraminifer *Decapoalina schaeferae* (Zaninetti, Altiner, Dager & Ducret); ŠKOFJA LOKA-TRNJE: foraminifers *Decapoalina schaeferae* (Zaninetti, Altiner, Dager & Ducret), *Miliolipora cuvillieri* Brönnimann & Zaninetti, *Galeanella* sp., *Endotriada* sp.). *SMF and environment*: SMF 6 fore- or intra-reef breccias.
	T6 B	*Composition:* The frame is built by corals (mostly faceolid) and sponges (stromatoporoids, inozoan, subordinate chaetetid calcisponges), often encrusted by calcimicrobes and foraminifers, serpulids, in some clasts also by *Thaumatoporella* sp. Baccanella sp. was spotted. Frame-builders tend to be strongly recrystalized. Intergranular space is filled with coarse-crystaline cements (mostly fibrous rim and drusy mosaic or bladed cements), or intra/bioclastic pelletal P/G (closely resembling microfacies types T2 and T3, described above). Sediment can contain birds-eye fenestrae. Some clasts are strongly dolomitized, and some also silicified (TR44). *Age:* Norian-Rhaetian (**PODBRDO:** foraminifers: *Galeanella tollmanni* (Kristan), Duostominidae; *Decapoalina schaeferae* (Zaninetti, Altiner, Dager & Ducret), *Miliolipora cuvillieri* Brönnimann & Zaninetti; **LOVRIŠ:** foraminifers *Endotriada tyrrhenica* Vachard, Martini, Rettori & Zaninetti, *Endotriada* sp., *Miliolipora* sp., **ŠKOFJA LOKA-TRNJE:** *Galeanella* sp., **MIRNA:** foraminifer *Alpinophragmium perforatum* Flügel, and microproblematica *Bacinella irregularis* Radojčić). *SMF and environment*: SMF7; marginal reefs.

AGE	*CLAST TYPE*	*DESCRIPTION*
Lower Jurassic	LJ1 Intra/bioclastic pelletal G with aggregate grains and ooids	*Composition:* medium to coarse-grained G, subordinate partly washed P; in composition similar to microfacies type T3, but contains less fossils with the addition of aggregate grains (lumps) and ooids, whereas intaclasts tend to be irregularly shaped; some grains have micritic margins or encrustations. Oncoids were also detected. In one clast they form laminae of oncoidal R that separate microfacies LJ1 from ooidal G (LJ2). Oncoidal cores are formed of *?Thaumatoporella* and calcimicrobes (JE41.4). Foraminifers are mostly textulariids. Some clasts contain laminae with large gastropods. In clasts with abundant aggregate grains, bivalves, crinoids, calcimicrobic grains, *?Thaumatoporella*, and cortoids were spotted (JE43.4). A clast containing a dasycladacean fragment was also documented, (pp19,7) and another with abundant cortoids and large bioclasts: bivalves, brachiopods, gastropods, dasycladacean algae, ?ammonite, and a foraminifer *Orbitopsella* sp. (327). *Age:* Lower Jurassic (**PODBRDO**: coral *Phacelophyllia termieri* Beauvais; **IDRIJA PRI BAČI:** foraminifers *?Lituosepta recoarensis* Cati, *Orbitopsella* sp., **MRZLI VRH:** foraminifer *?Siphovalvolina* sp., **ZAPOŠKAR:** *Duotaxis metula* Kristan, ŠKOFJA LOKA-PODPURFLCA: *?Siphovalvolina* sp., **MIRNA:** corals *Rhabdophyllia phaceloida* Beauvais, *Thecactinastraea krimensis* Turnšek, *Funginella domeriensis* Beauvais, foraminifers *Involutina liassica* Jones, *?Siphovalvulina* sp.). In one clast in Podpurfica section, a Middle Jurassic foraminifer *Nautiloculina* was determined. *SMF and environment*: SMF 15 to SMF 17; platform margin sand shoals.
	LJ2 Ooidal G	*Composition:* predominant grains are medium-sized, radial ooids, mostly with micritic cores, very subordinate bioclasts. Other grains are intraclasts, peloids, and bioclasts: echinoderms, fragmented mollusks and foraminifers (ophthalmidiid foraminifers, and *Reophax* sp.). In one clast a chaetetid grain was noted (2A-6). Some clasts are partly washed P and have bimodal grain-size distribution with large ooids and bioclasts (mostly crinoids) and small peloids (pellets). Some clasts are composed of fine-grained radial ooids and peloids/pellets (KM5). In one clast this facies passes into oncoidal R (JE41.4) that contains foraminifer *Siphovalvulina* sp. In one clast this facies passes to bioclastic limestone (J2). *Age:* Lower Jurassic (**MIRNA:** *Involutina liassica* Jones, *Siphovalvulina* sp.). *SMF and environment*: SMF 15; platform margin sand shoals.
	LJ3 Crinoidal G	*Composition:* G, also subordinate P that can contain lithoclasts and fossils some mm in size. Predominant grains are crinoids (echinoderms), angular intraclasts, and sometimes pellets. Crinoids can contain micritic encrustations. Other grains are foraminifers (textulariids, lagenids, ophthalmidiid), bivalves (often fragmented), gastropods, ostracods. Grains some few mm in size are lithoclasts of bioclastic W (in facies similar to clast-type T1 and LJ4) and belemnites. In some clasts crinoids strongly predominate or even represent all the grains. These clasts can be often partly silicified. *Age:* Lower Jurassic (**MIRNA:** *Involutina liassica* Jones). *SMF and environment*: SMF 12-CRIN; open shelf/platform slope accumulation of crinoidal debris.
	LJ4 Bioclastic W	*Composition:* grains are mainly medium-sized. Predominant grains are sponge spicules, echinoderms and ostracods. Other bioclasts are amonites, filaments, foraminifers (ophthalmidiids, lagenids, nodosarids, textularids). P and F textures also occurs. These clasts closely resemble type T1 and MJ3, but generally contain more sponge spicules. Without diagnostic fossils it is usually impossible to distinguish the three types. In clasts where it passes to ooidal G (JE35.4) it also contains medium-sized ooids with radial inner and tangential outer cortex (equal to those of ooidal G). Ooids were observed also in one sample (KM5) from the Mirna Valley. This microfacies can also pass to crinoidal G (T2/4). *Age:* Lower Jurassic (ŠKOFJA LOKA-**PODPURFLCA:** *Involutina farinacciae* Brönnimann & Koehn-Zaninetti, **MIRNA:** *Involutina liassica* Jones). *SMF and environment*: SMF 8 – open shelf.
Middle Jurassic	MJ1 Ooidal P/W	*Composition:* fine- to medium-sized tangential and/or radial ooids, peloids (pellets), intraclasts and echinoderms. Other bioclasts are bivalve fragments, foraminifers (lagenids, textularids), ostracods. Some clasts contain quite abundand thin-shelled bivalves (filaments), sponge spicules, calcispheres and/or radiolarians. Ammonites were detected. In the Mirna section, filament-rich clasts also contain planktic foraminifera (KM3.0) and clasts dominant by pellets and subordinate ooids (KM7.2). This microfacies locally passes into bioclastic M/W (microfacies UD5) within the same clast. Specific sub-type of this clasts group (pp14) is composed of alternating laminae of M and P/W with coarse-grained micritized ooids and subordinate intraclasts and echinoderms. Ooid cores are micritic or bioclastic (gastropds, ostracods). Oncoids also appear. *Age:* ?Middle Jurassic (ŠKOFJA LOKA-**PODPURFLCA:** planktic foraminifers). *SMF and environment*: ?SMF15; structural inversion where grains typical of high-energy conditions are resedimented to low-energy, probably deeper water environment.
	MJ2 Lithoclastic crinoidal G	*Composition:* coarse-grained G composed of echinoderms (mostly crinoids), micritic (intra)clasts, fragmented brachiopods and bivalves, and foraminifers (ophthalmidiid foraminifers, lagenids, nodosarids, fragments of sessile foramininifers). Common are also lithoclasts: A) pelletal/intraclastic/ooidal G and P, B) W with radiolarians and filaments, C) fenestral M, D) spiculitic W, and E) bio/intraclastic W. *Age:* Middle Jurassic (**MIRNA:** *Protopeneroplis* sp.). *SMF and environment*: SMF 8 – open shelf, but close to source of lithoclasts.
	MJ3 Litho/bioclastic W	*Composition:* grains are medium- to coarse-grained W with microsparite matrix. Predominant grains are echinoderms (crinoids as well as orchin spines) and foraminifers (ophthalmidiid foraminifers, lagenids, nodosarids). Other grains are micritic (intra)clasts, fragmented bivalves and brachiopod, ooids and ammonites also occur. These clasts closely resemble microfacies types T1 and J2 but contain more lagenid foraminifers and lithoclasts: A) pelletal ooidal G and P, B) W with radiolarians and filaments, and C) fenestral M. Matrix is microsparite. Without diagnostic fossils it is usually impossible to distinguish the three types. *Age:* Middle Jurassic (**MIRNA:** *Protopeneroplis striata* Weynschenck). *SMF and environment*: SMF 8 – open shelf.
	MJ4 Bioclastic (hemipelagic) M/W	*Composition:* predominanly fine-grained W, sometimes with very rare grains (M). Grains are bioclasts, mostly thin-shelled bivalves, ostracods, and calcispheres and/or calcified radiolarians. Rare are lagenid foraminifers, small echinoderms, sponge spicules and other (unrecognisable) small debris. Amonites and gastropods were detected within such clast in the Mirna section (KM0.1, KM4.1), and planktic foraminifers (KM3.0). Tiny pellets are locally visible within matrix. Bioturbation and in one clast (LK2-57) also stromatactis were noticed. These clasts tend to be dolomitized. *Age:* ?; at least part of clasts are Middle Jurassic (**MIRNA:** *Protoglobigerina* sp.). *SMF and environment*: SMF3 pelagic limestone of the deep-water sedimentary environment (?mud-chips).

AGE	*CLAST TYPE*	*DESCRIPTION*
Undetermined	UD1 Pelletal P	*Composition:* fine-grained P that can be partly washed and bioturbated. Predominant grains are pellets. Other are bioclasts, such as small foraminifera, ?calcispheres, and ostracods. Matrix is mostly microsparite. Some clasts contain sponge spicules and other filaments (KM13,4; KM14.4), the latter representing transitional facies to filament P/G (microfacies UD6). Rare clasts of this group can contain small fenestrae (pp18, KM8.1, JE39.4). When laminated, some coarses laminae contain intraclasts and ooids and probably represent transitional facies to ooidal G (JE43.4). *Age:* Large clast from the top of the Lovriš section yielded late Norian to early Rhaetian conodonts *Norigondolella steinbergensis* (Mosher) and *Zieglerioconus rhaeticus* Kozur and Mock, but this clast group is almost certainly also of Jurassic age, as in some clasts it contains laminae of ooidal limestone (for this reason we keep it among undetermined clasts). *SMF and environment*: SMF16 (21) or SMF2; low-energy environment, either restricted lagoon (with subaerial exposure) or open shelf.
	UD2 Intraclastic W	*Composition:* W with medium-sized intraclasts and pellets, micritized ooids were also detected. Some clasts contain ostracods, unrecognisable bioclastic debris, fenestrae, and large dissolution voids filled by blocky calcite (LK2-17.5; LK2-18.8). *Age:* ? *SMF and environment*: ?SMF; stuctural inversion, where grains typical for high-energy conditions are resedimented to a low-energy environment (either lagoon or deeper water).
	UD3 Bioclastic pelletal P	*Composition:* fine-grained P, composed of bioclasts, such as echinoderms, fragmented bivalves (including filaments), ostracods, calcispheres, foraminifers. Half the grains are pellets. Elongated grains are parallel-oriented. *Age:* ? *SMF and environment*: ?SMF4, presumably resedimented limestone (calciturbidite).
	UD4 Crinoidal foraminiferal W	*Composition:* W that laterally pass to partly washed P. It is dominated by echinoderms, ophthalmidiid foraminifers (textularids and lagenids also occur) and small pellets. Rare grains are fragmented bivalves, brachiopods, ostracods and ooids. A subtype of this microfacies occurring in the Lovriš section is P, dominated by echinoderms and pellets. This subtype also contains rare foraminifers. (LK2-8.6, LK 2.8 and LK 12.5) *Age:* ? *SMF and environment*: SMF 12-CRIN; open shelf/platform slope accumulation of crinoidal debris.
	UD5 Spiculite crinoidal P	*Composition:* fine-grained, bioturbated P, composed of sponge spicules and echinodermes. Other grains are foraminifers, ostracods, ?radiolarians, and pellets. Matrix can be recrystalized to microsparite. Some spicules are calcedonic. *Age:* ? *SMF and environment*: SMF 12-CRIN and SMF 2 open shelf/platform slope/basin floor.
	UD6 Filament P/G	*Composition:* The first subtype is G, composed of accumulated filaments (thin-shelled bivalves) and very rare echinoderm fragments. Cement is drusy-mosaic cement (pp; 5.5; pp11.4). The second subtype is P, which is dominated by filaments, but can also contain echinoderms, peloids, foraminifers, and ammonites. Filaments can have thick rims of fibrous cements, mostly concentrated at one side of the shells (in clast within KM7.2 sample infiltration matrix postdates the cementation). One clast is densely packed P, where predominant filaments wrap around intraclasts, rare echinoderms and foraminifers (occurs in the Idrija pri Bači section in samples 354A; 354B). *Age:* ?Jurassic. *SMF and environment*: SMF 12-S open shelf/platform slope/basin floor accumulation of filaments.
	UD7 Coarse peloidal P	*Composition:* coarse-grained P, composed of peloids and rare micritized oval bioclasts (presumambly dasycladacean algae), and intraclasts. Ostracods and small foraminifers were spotted. A sub-type was spotted (JE43.4): W/P with anemuran pellets, other grains are similar, but bivalve fragments, calcispheres and lagenid foraminifers additionally appear. *Age:* ? *SMF and environment*: SMF 16 restricted lagoon.
	UD8 M	*Composition:* mostly pure M. It locally contains ostracods, foraminifers, or pelagic bioclasts (filaments, radiolarians). The matrix is dense micrite, locally microsparite. Rare fenestrae (geopethally filled cavities) occur in few clasts. Some contain numerous fenestrae (T2/10). *Age:* ? *SMF and environment*: SMF23 and 21 or SMF3; restricted low-energy environment (restricted lagoon or anoxic basin).
	UD9 Recrystalized F	*Composition:* strongly recrystalized F (or pure R) with still recognized large fossils, such as ammonites and bivalves (T2/6). Brachiopods and gastropods also occur in other clasts (LK2-16.5). Cements are dog-teeth rim cements, followed by coarsely crystalline bladed cements, and calcisiltite (crystal silt). A little amount of matrix clings to the fossil shells. It is P, composed of tiny pellets and rare ostracods. *Age:* ? *SMF and environment*: ? SMF 8 deep-water environment.
	UD10 D	*Composition:* coarsely crystalline D. The primary texture is locally partly preserved. It is bioclastic M/W (microfacies type UD5), or B (microfacies type T5). *Age:* ?, some are probably dolomitized clasts of Norian-Rhaetian B. *SMF and environment*: ? dolomitization obscured information. Some were presumably reefal, others hemipelagic limestone.
	UD11 chert	*Composition:* microcrystalline chert, locally with concentrated carbonate crystals (in laminae or in patches). One clast laterally passes into B (microfacies T6), a different one into intra/bioclastic pelletal G (microfacies T3). The primary composition of medium-grained P/G is locally recognizable. Silicification can be strong in B clasts (microfacies T6). *Age:* ? *SMF and environment*: mostly replacement chert (contains carbonate and passes into limestone).

Discussion

Facies distribution of the Ponikve Breccia Member and corresponding Lower resedimented limestones of the SB indicates that the southern-lying DCP was a source area of the Middle Jurassic resedimented material. Namely, coarse and thick limestone breccia beds occur solely in the southernmost SB outcrops (structurally lowest nappe), become finer and thinner (in the form of calciturbiditic calcarenites) in the central part of the basin (central nappe), and are completely absent in the northern part of the SB (structurally highest nappe) (Figs. 17 and 18). Additional proof pointing to the source area is provided by the abundance of ooids within the breccia matrix and inside calciturbidites. As the DCP is the only known post-Aalenian active platform in this part of the Adria microplate (review in Vlahović et al., 2005), the DCP is considered the only possible source of these resediments.

The clast- and matrix-analysis of the Limestone Breccia member therefore enables the reconstruction of the non-outcropping DCP margin from three distinct time periods. The Upper Triassic (Norian–Rhaetian) and Lower Jurassic reconstructions are based solely on the records retrieved from the clast analysis. For the Middle Jurassic reconstruction, the data from matrix- and clast analysis was combined, which considered the age of the matrix to be contemporaneous with the sedimentation event of the breccia beds.

The Upper Triassic: a reef-rimmed epeiric platform

Epeiric platforms covering the tropical margins of the Neotethys Ocean generally consisted of a wide tidal flat, a shallow lagoon, and a platform margin rimmed by reefs (Mandl, 2000; Bernecker, 2005). The tidal flat is stratigraphically represented by the Hauptdolomit (Glavni dolomit/Dolomia Principale/"Main Dolomite"), gradually passing into the bedded Dachstein limestone (Mandl, 2000; Bernecker, 2005; Kovács et al., 2011). Characteristic for these beds is the so-called Lofer cycle, comprising a thin breccia member, a laminated mudstone (intertidal stromatolite), and a biogenic wackestone and/or floatstone with large megalodontid bivalves, gastropods, and locally corals (Fisher, 1964; Ogorelec & Rothe, 1993; Satterley, 1996; Ogorelec & Buser, 1996; Haas, 2004; Samankassou & Enos, 2019). The marginal peri-reef belt has been recorded by Piller (1981), Wurm (1982), Haas et al. (2010), Gale et al. (2012), and Martindale et al. (2013), among others. The massive reef limestone is composed of interreef breccias and small patches of coral-sponge-solenoporacean algae reefs. Molluscs, benthic foraminifers, and dasycladacean algae are among the diverse bioclasts within sand-grained detritus (Wurm, 1982; Gale et al., 2013). The slope is characterised by calciturbidites composed of grains derived from the top of the platform and its margin (Rožič et al., 2009; Gale, 2010; Gale et al., 2014). In the interior of the platform small basins of the Kössen type, characterised by depositions of marlstone and limestone and a diminished diversity of benthic fauna came into existence during the Rhaetian. Patch reefs developed at the rims or within these basins. Their composition is comparable to the composition of the marginal Dachstein-type reefs (Schäfer & Senowbari-Daryan, 1981; Kuss, 1983; Bernecker, 2005). In the inner parts of the platform, significantly more restricted basins already formed in the Norian. These basins are characterised by reduced oxygen levels, abnormal salinities and/or eutrophic conditions. Along their margins, small bioherms composed of terebellid worms encrusted in microbiallite were present. (Cirilli et al., 1999; Iannace & Zamparelli, 2002).

Norian–Rhaetian Hauptdolomit and Dachstein limestone of the northern External Dinarides have been most intensively studied by Ogorelec and Rothe (1993). Both formations show characteristics of the internal part of the platform, with well-developed Lofer cycles. In the northern External Dinarides, the Dachstein-type reefs are not preserved (Buser et al., 1982; Turnšek, 1997).

Six microfacies types from clasts (T1–T6) were attributed to the Late Triassic DCP. These clasts can reach the size of boulders. Boundstone with typical Norian–Rhaetian reef-dwelling foraminifers *Galeanella*, *Decapoalina*, *Miliolipora* and *Alpinophragmium* (see Gale, 2012) strongly suggest that the original margin of the DCP was rimmed by Dachstein-type reefs, which later collapsed into the SB together with Lower and Middle Jurassic deposits (Fig. 17). Bioclastic rudstone (T4) and litho/bioclastic floatstone/rudstone are interpreted as reef breccia akin to lithoclastic rudstone Gale et al. (2013). The close affinity with the reef zone is supported by the abundance of framebuilders and reef-dwelling microbiota (e.g. *Decapoalina*, *Miliolipora*, *Galeanella*). Bioclastic wackestone (T1), pelletal bioclastic packstone (T2), intra/bioclastic pelletal grainstone, and possibly also part of pelletal packstone (UD1) were also found in clasts within the litho/bioclastic floatstone/rudstone (T5), some also in boundstone (T6), and thus also likely deposited close to the margin of the platform. This is again supported by the presence of some microfossils. Bioclastic wackestone (T1) might originate in the open-shelf/slope area.

The Lower Jurassic: a lagoon, rimmed by sand shoals

Like the Upper Triassic, the outcropping Lower Jurassic successions from the northern External Dinarides show facies associations characteristic for the inner platform developments. General Lower Jurassic successions from the northern Dinarides were described by Dozet and Strohmenger (2000), Črne and Goričan (2008), Miler and Pavšič (2008), Dozet (2009), Ogorelec (2011), and Gale and Kelemen (2017), among others. An unpublished thesis of Buser (1965) also provides a regional overview of Jurassic successions from southern Slovenia. Lower Jurassic successions from other parts of the Dinarides were (among others) described by Dragičević and Velić (2002), Tišljar et al. (2002), Bucković (2006), Črne and Goričan (2008), Čadjenović et al. (2008), and Martinuš et al. (2012).

Despite the biocalcification crisis at the Triassic/Jurassic boundary (e.g. Kiessling et al. 2007), a carbonate platform continued to exist (Fig. 17). During the Hettangian, carbonate deposition continued under peritidal conditions. Characteristically, laminae are not wrinkled, but planar and smooth. During the Sinemurian and Pliensbachian, the topography of the platform gradually evolved from the epeiric, flat-topped platform into a platform, internally differentiated into lagoon, marginal shoals, and ephemeral emergent areas (Buser & Debeljak, 1996; Gale and Kelemen, 2017). This, together with the recovery and evolution of biota after the Triassic/Jurassic boundary extinction, results in distinct differences in microfacies. A transgressive trend towards more subtidal conditions was noted in central Slovenia, where most of the Sinemurian part of the succession is represented by mudstone and wackestone, subordinately peloidal and ooidal limestone. Oolithic and bioclastic-oolithic grainstone become predominant by the upper Sinemurian, and the facies association also includes mudstone, peloid wackestone, bivalve floatstone and rudstone, and peloid grainstone. In the Pliensbachian, these facies are joined by common oncoid and bioclast floatstone and rudstone, and lithiotid floatstone and rudstone (Gale and Kelemen, 2017). Buser and Debeljak (1996) envisioned the platform margin as dominated by ooidal and crinoidal shoals, and slope covered by breccias.

The Ponikve Breccia Member contains an abundance of clasts that have been attributed to the Lower Jurassic, either based on foraminifers or their microfacies. The clast microfacies types LJ2 (ooidal grainstone) and LJ1 (intra/bioclastic pelletal grainstone) probably originate from the ooidal shoals and a more agitated part of the internal lagoon, respectively.

In contrast, the crinoidal grainstone (LJ3) and the bioclastic wackestone (LJ4) clasts derive from a deeper water sedimentary environment. Lower Jurassic crinoid/sponge spicule rich limestones are characteristic for diverse environments, such as the drowned platforms of the Eastern Alps and the Trandanubian Range (Böhm et al. 1999; Gawlick et al. 2009; Haas et al. 2014), but they also occur in slope settings (Scheibner and Reijmer, 1999; Blomeier and Reijmer, 2002; Merino-Tomé et al., 2012; Della Porta et al., 2014). Here we emphasise that such facies are also typical for the Sedlo Formation, which originated on the JCP margin that experienced tectonic differentiation and accelerated subsidence already in the Pliensbachian (Šmuc, 2005; Šmuc and Goričan, 2005; Praprotnik Kastelic et al., 2013; Rožič et al, 2014b; Valand et al., 2019). This subsidence of the JCP margin correlates to the initiation of a second rifting phase of the Alpine Tethys that is well recognized also in the rest of the Southern Alps (Berra et al., 2009; Masini et al., 2013) and led to the creation of a North Adriatic Basin located west of the DCP (Masetti et al., 2012). This extension must have influenced the northern DCP margin and potentially led to the partial reorganization of the DCP architecture. Namely, it could have created a fault dissected, step-like margin and slope, which would be reflected in a shift from the carbonate platform to the carbonate ramp architecture of the northernmost part of the DCP. Such depositional setting provided open marine conditions favourable for the creation of the described facies-types. Alternatively, the crinoidal limestone could also represent Toarcian facies originating from the drowned platform margin. During this stage, the succession of the DCP is characterised by thin-bedded micritic limestone and crinoidal-ooidal limestone, recording transgression which roughly coincides with the OAE (Vlahović et al., 2005; Črne and Goričan, 2008; Dozet, 2009; Sabatino et al, 2013).

We note that coeval with Lithiotid evolution the re-establishment of marginal reefs is locally documented for the late Lower Jurassic (Leinfelder

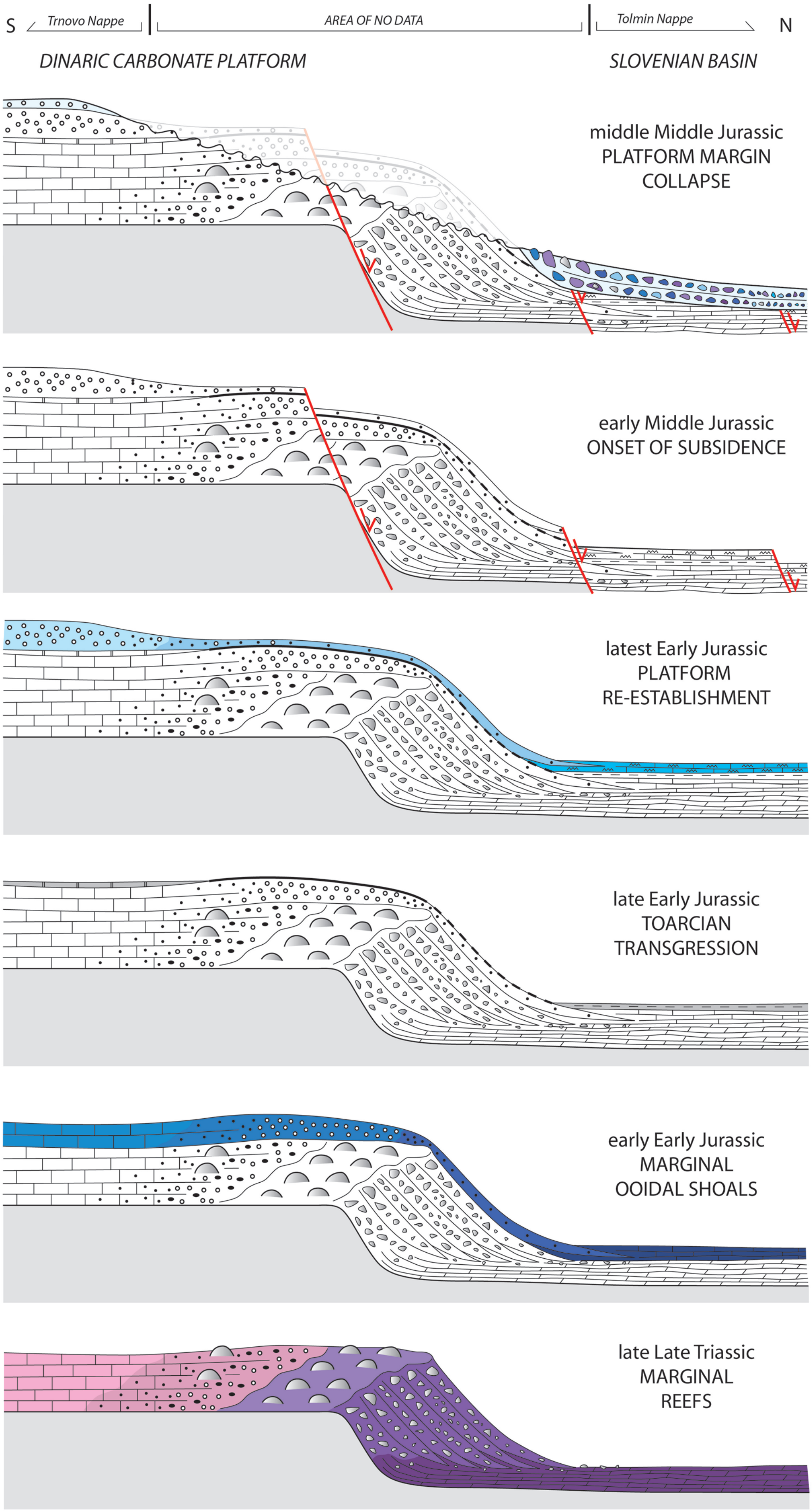

Fig. 17. Reconstrution of the Dinaric Carbonate Platform's northern margin from late Late Triassic (Norian–Rhaetian) reefs, through early Early Jurassic ooidal sand shoals, Toarcian transgression and re-establishment of the carbonate production up to the early- and mid-Middle Jurassic onset of extensional/transtensional tectonics, which led to the collapse of the platform margin and deposition of the Ponikve breccia Member of the Tolmin Formation in the Slovenian basin.

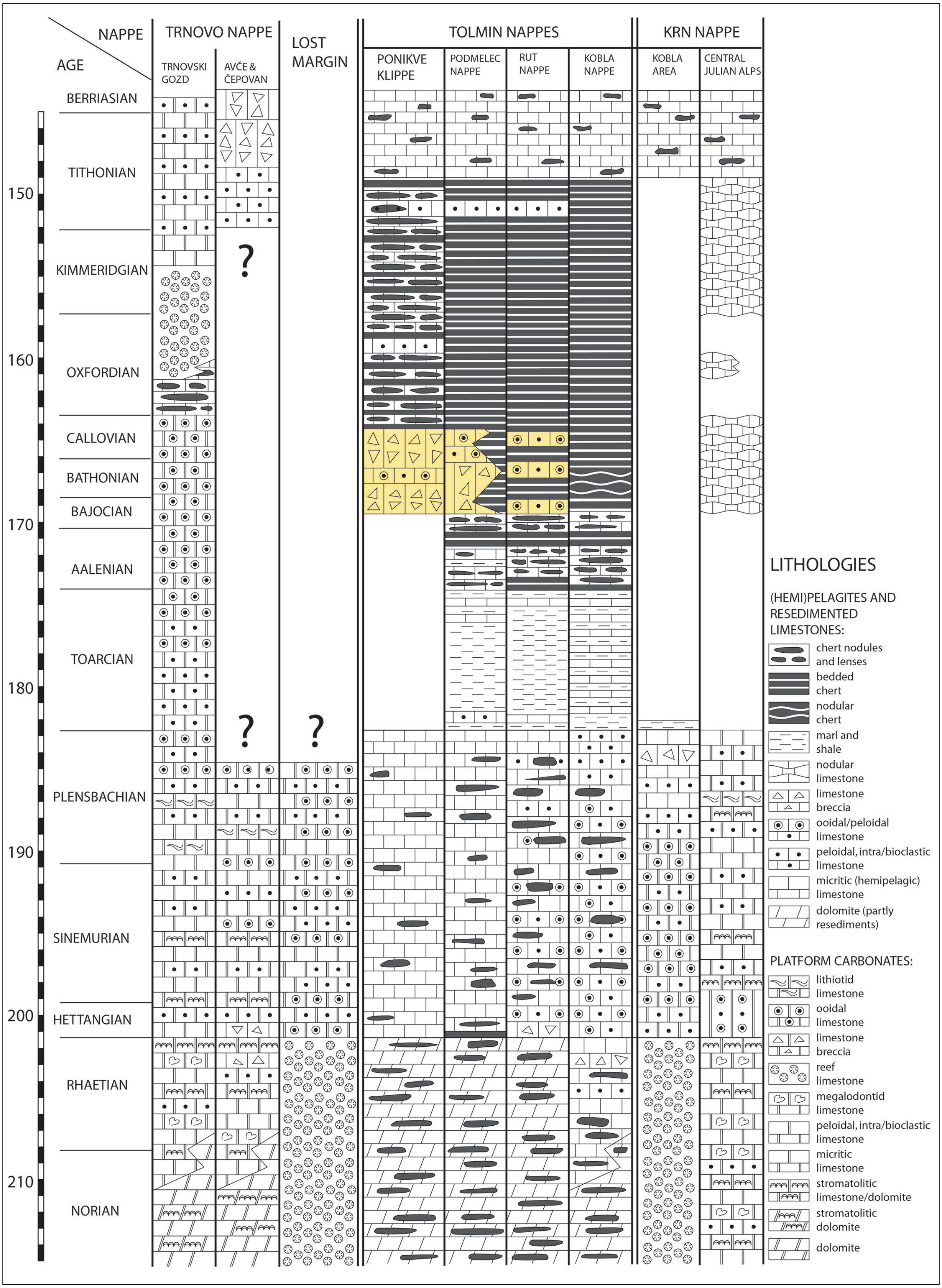

Fig. 18. Stratigraphic columns of the Dinaric Carbonate Platform, Slovenian Basin, and Julian Carbonate Platform with reconstructed (lost) margin of the Dinaric Carbonate Platform. Facies distribution of the Middle Jurassic resedimented limestones (including the Ponikve Breccia) indicate that the south-lying Dinaric Carbonate Platform was a carbonate material source area (compiled from Buser, 1986, 1996, Turnšek, 2007; Šmuc, 2005, Rožič, 2006, 2009; Rožič et al., 2014b; Kovač, 2016; time scale after Cohen et al., 2013; updated).

et al., 2002; Scheibner & Reijmer, 1999; Merino –Tomé et al., 2012; Della Porta et al., 2014). Local occurrence of coral patch reefs is known also from the Pliensbachian of the northern DCP (Turnšek & Košir 2000; Turnšek et al. 2003) with coral species corresponding to those determined in some Lower Jurassic grainstone lithoclasts (type LJ1; Podpurflca and Mirna sections). However, we do not support the existence of barrier reefs on the DCP because: A) Lower Jurassic age was not determined for the boundstone (or related) clasts and B) all other (better preserved) platform margins from the Southern Alps (Clari and Masetti, 2002; Masetti et al, 2012; Francheschi et al., 2013) as well as the DCP are dominated by ooidal sand shoals (Tišljar et al, 2002; Črne & Goričan, 2008; Čadjenović et al., 2008).

Platform-basin transition zone prior to Middle Jurassic collapses

Breccia beds originated in the toe-of-slope and proximal basin plain environments. They sedimented as the result of debris flows and were a product of large-scale collapses of the DCP margin (for details see Rožič et al., 2019). Already within some sections presented herein, breccia beds are associated with turbidites, and towards the inner parts of the SB they pass completely into calcturbiditic layers (named Lower resedimented limestones) which occur within siliceous pelagites of the Tolmin Formation (Rožič, 2009, Goričan et al., 2012; Rožič et al., 2019).

The abundance of ooids and associated shallow-water grains (peloids, intraclasts, aggregate grains, oncoids and some bioclasts) in the matrix of the breccia and associated calciturbidites indicates that the gravity flows began at the DCP margin. Following the Toarcian deepening, the shallow water sedimentation gradually re-established on the margin and crinoid-rich ooidal limestones that pass upwards into pure ooidal limestone were deposited (Fig. 17) (Buser, 1996; Črne & Goričan, 2008; Miler & Pavšič 2008; Buser & Dozet 2009; Ogorelec 2011; Dozet & Ogorelec 2012).

In addition, the breccia matrix contains deeper-water bioclasts, most typically thin-shelled bivalves, whereas crinoids are also considered as predominantly deeper-water grains (see also below the discussion on Middle Jurassic lithoclasts). This indicates the incorporation of deeper-water (outer shelf/slope and basin) sediments into the debris-flows. In the Mrzli vrh section, ooids and associated shallow-water grains are almost entirely absent, while other grains (thin-shelled bivalves, crinoids, sponge spicules, phosphate, and glauconite) point to initiation of this debris flow from the distal deep slope/open shelf area.

Important information on the architecture of the platform-basin transitional area comes from lithoclasts that we have determined to be Middle Jurassic, and therefore contemporaneous with the sedimentation event. Ooidal packstone/wackestone clasts (MJ1) originate from the outer shelf close to the sand shoals. This is indicated by the co-occurrence of ooids and pelagic deeper-marine fauna. Such deposits are known from the Middle Jurassic successions on Mt. Matajur and Mt. Kobariški stol (Šmuc, 2012; Udovč, 2019; Rožič et al., 2022).

Bio/lithoclastic limestones of the MJ2 and MJ3 lithoclasts were proposed to have deposited basin-wards on a step-like slope (Fig. 17). Such paleotopography must have been produced by active faulting, as indicated by the abundance and diversity of lithoclasts, which occur inside these microfacies types (MJ2 and MJ3 lithoclasts types). These “lithoclasts inside lithoclasts” are of shallow-, as well as of deeper-water origin and could be pre-Middle Jurassic or generally contemporaneous with sedimentation of MJ2 and MJ3 lithoclasts types. It seems that their erosion may have been enhanced by the formation of escarpments.

The last type of Middle Jurassic lithoclasts is a hemipelagic limestone (MJ4). These lithoclasts originated with the debris-flow erosion of the contemporaneous, semi consolidated, hemipelagic (lower slope/basin) sediments and are therefore interpreted as “mud-chips”.

Information from lithoclasts of undetermined age

The majority of the lithoclasts of undetermined age was sedimented in deeper-marine environments. Pelletal packstone (UD1) and intraclastic wackestone (UD2) most probably deposited on the outer shelf. At least some of the UD1 clasts are Late Triassic in age, while some could be Jurassic. They were probably located between the typical marginal facies and slope environments similar to ooidal packstone/wackestone (MJ1). Crinoidal foraminiferal wackestone (UD4) and spiculite crinoidal packstone (UD5) correspond to similar crinoid rich clasts, which are typical for the outer shelf/slope environments in different time slices (T1, LJ3, LJ4, MJ2, MJ3).

Filament packstone/grainstone (UD6), mudstone (UD8), and bioclastic pelletal packstone (UD3) mostly originate from the erosion of slope and basin sediments, the first two being hemipelagic, and the last resedimented limestones. Due to the absence of plankton foraminifers, they are considered Aalenian in age or older. Such facies are common in Lower Jurassic and Upper Triassic pelagites (Cousin 1981; Rožič 2009; Rožič et al. 2009, 2013; Gale et al., 2012, 2014). Therefore, debris flows of the Ponikve Breccia did not solely erode the contemporaneous basinal sediments (MJ4), but also older hemipelagic strata. This is also evident from the stratigraphic position of the breccia megabeds that overlie the older basinal successions with a stratigraphic gap (mostly overlying the Hettangian–Pliensbachian Krikov Formation). We already mentioned the basinal succession of the Dešna Hill in the Škofja Loka area, where (Bajocian or younger) radiolarite of the Tolmin Formation directly overlie the Norian-Rhaetian Bača Dolomite (Fig. 5 in Rožič et al., 2019). During the sedimentation of the Ponikve Breccia megabeds this area was bypassed and was very likely deeply eroded by debris flows.

Although shallow-water clasts predominantly originate from the margins of the DCP, some clasts indicate at least minor erosion of the platform interior. Such are coarse peloidal packstones (UD7), pelletal bioclastic packstones (T2), and partially also pelletal packstones (UD1). Due to diagenetic changes, such as recrystallization (UD9), dolomitization (UD10), and silicification (UD11), the origin of the last three lithoclast types is difficult to determine.

The Middle Jurassic collapse of the Dinaric Carbonate Platform margin

The Ponikve breccia originated with major collapses of the entire northern margin of the DCP (Fig. 17). This is evident from: A) breccia megabeds occur in an almost continuous belt from the westernmost outcrops of the SB near Tolmin, through the Škofja Loka area in central Slovenia, to the easternmost occurrences in the Mirna Valley, B) the extraordinary nature of the resedimentation events, with the large-scale debris-flow deposits representing a great contrast to the underlying and overlying successions characterized by basin-plain (hemi)pelagites, and C) clasts indicate deep erosion of the carbonate platform margin cutting down to the Upper Triassic reef limestone. The compilation of available biostratigraphic data indicates that a major part of these events happened in a relatively short time interval in the Bajocian and early Bathonian. Some large-scale resedimentation events post-dated the main collapse events also later (in the late Middle Jurassic). This is evident from the Trnje section in which a rather thick radiolarite succession is interstratified between breccia megabeds.

We associate the formation of the breccia megabeds with the regional tectonic activity (Rožič et al., 2019). The initiation of these events coincides with the major mid-Middle Jurassic reorganisation of oceanic domains surrounding the Adria microplate (de Graciansky et al. 2011; Masini et al. 2013; Schmid et al. 2020). Alpine Tethys (Piemont-Ligurian ocean) that was positioned to the west/northwest, moved from the syn-rift to the post-rift phase (oceanisation) during the Middle Jurassic (Chiari et al. 2000; Bill et al. 2001; Manatschal & Müntener 2009; de Graciansky et al. 2011; Ribes et al., 2019, 2020; Le Breton et al., 2021). Towards the east, the Neotethys domain experienced the initiation of the intraoceanic subduction dated as Aalenian to Oxfordian (Borojević Šoštarić et al. 2014; Schmid et al. 2020 and references therein). This was followed by the obduction of ophiolites onto the Adria margin, but the exact timing of the start of the obduction is still debated and varies from mid-Middle Jurassic (Gawlick et al. 2016; 2017a,b,c; 2018; Gawlick and Missoni, 2019, Bragin & Djerić, 2020), the latest Middle Jurassic (Bortolotti et al., 2013) to the Late Jurassic (Mikes et al. 2008; Schmid et al. 2008, 2020; Gallhofer et al. 2017).

Paleogeographically, the transitional zone between the DCP and the SB was located between the Piemont-Ligurian and the Neotethys oceans. For this reason, it must have been highly influenced by the described tectonic perturbations. The exact nature of the tectonic deformations at the transition zone is obscured by the Cenozoic South-Alpine tectonic overprint. However, an accelerated subsidence is documented in the deep-marine successions across the Southern Alps, including the SB (Bertotti et al. 1993; Martire 1996; Martire et al. 2006; Šmuc 2005; Chiari et al. 2007; Rožič 2009; Šmuc & Rožič 2010; Goričan et al. 2012). Subsidence north of the DCP must have (re)activated normal faults along its northern margin, thus increasing the depth of the SB, enhancing the relief, and consequently produced collapses of the platform northern margin.

Comparison of the lithoclast distribution between sections yields no significant variability. This indicates a rather uniform lateral erosion along the DCP– SB transition zone. The same is also valid for the vertical distribution of lithoclasts in most of the sections. This is expected because most of the logged successions probably belong to the same, single breccia megabed. In the Ponikva-Podbrdo section, which consists of several amalgamated beds, a vertical decrease in Jurassic lithoclasts is visible. This may indicate the progressive downcutting erosion of the gravity-flow events, but it could also be attributed to the size of lithoclasts. We noticed that boulder-sized lithoclasts, which characterize the thickest bed of the Podbrdo section (and also other Ponikve Klippe sections) are predominantly Upper Triassic. This could result in the described distribution. Note that in the upper parts of the Podbrdo and Idrija pri Bači sections, which lack the bolder-sized clasts, Jurassic lithoclasts reappear in greater number.

Backstepping of the Dinaric Carbonate Platform margin

The tectonic subsidence (either forced by extension, transtension, or flexural bending) was not limited solely to the slope between the DCP and the SB, but also influenced the wider transition zone. As discussed in the previous chapter, Middle Jurassic lithoclasts from the breccia point to segmentation of the slope/platform margin and the establishment of a step-like paleotopography. Furthermore, the subsidence of the DCP margin is directly evident from its northern-most outcrops. In western Slovenia, these outcrops are characterized by Upper Triassic and Lower Jurassic (pre-Toarcian) inner platform (lagoon/intertidal) carbonates. In the Idrijca Valley, Upper Cretaceous deep-marine (allodapic) limestones of the Volče Limestone Formation directly overlie them (Buser, 1986). This leaves the time of the subsidence wide open. Similar conditions are known from the Soča Valley (Ogorelec et al., 1976; Buser, 1986), but the most recent geological study of the Dobler Hydropower area showed that the Lower Jurassic platform limestones are directly overlain by uppermost Jurassic or lowermost Cretaceous deeper marine sediments, i.e. limestone breccia with a calpionellid-rich micritic matrix (Kovač, 2016). This narrows the drowning of this area to the Middle to Late Jurassic period. Similar conditions are described from eastern Slovenia, where Upper Triassic and often Lower Jurassic inner platform carbonates are overlain by latest Jurassic–Berriasian Biancone-type limestone (Babić 1973, 1979; Aničić & Dozet, 2000; Aničićć et al, 2004; Buser, 2010; Poljak, 2017; Rehakova & Rožič, 2019). At Mt. Gorjanci the Lower Jurassic, so-called Krka Limestone is overlain by the siliceous pelagites that are dated to Bajocian–Tithonian (Rižnar, 2006; Skobe et al., 2013; Poljak, 2017). This data from eastern Slovenia indicates that the first prominent subsidence of the DCP margin occurred between the late Early Jurassic and the latest Late Jurassic. Considering the succession of Mt. Gorjanci, we can narrow this interval to the late Early Jurassic–middle Middle Jurassic. A connection to the DCP margin collapse discussed herein appears highly probable.

Indications of the (Middle) Jurassic platform margin retreat also appear in the form of the changed position of the Upper Triassic and Upper Jurassic marginal reefs. In this paper (and Rožič et al., 2019), we present evidence for the existence of Upper Triassic reefs on the DCP margin that were located north of the existing platform outcrops. Today, they are covered by South-Alpine nappes (SB successions), or alternatively, could have been largely destroyed by redepositional events described herein. In contrast, Upper Jurassic reefs are well known and were paleontologically studied in detail (Turnšek, 1997). They are generally located south and southwest of the successions described in the previous paragraph (Fig. 1). These reefal limestones are traced from the Trnovski gozd area, through central Slovenia to Bela Krajina and further SE throughout the External Dinarides (Turnšek et al., 1981; Buser, 1978; 1996; Turnšek, 1997; Vlahović et al., 2005).

In western Slovenia, Upper Jurassic reefs are underlain firstly by Middle Jurassic thin-bedded limestone with cherts, followed by Middle Jurassic ooidal limestones which gradually pass into thin layers of Toarcian crinoidal limestone. These formations are characteristic of the DCP margin or open shelf. Downwards, these lithostratigraphic units pass into the abovementioned pre-Toarcian carbonates of the inner platform (lagoon/intertidal environments). From the described succession, we cannot precisely determine the time of the backstepping, but it must have occurred after the Pliensbachian. While the Toarcian deepening can still be attributed to the major eustatic sea-level rise, the following successions clearly indicate a general shift from inner platform to long-lasting open-marine environments.

In eastern Slovenia (Trebnje area), the Late Jurassic reefs and (fore-reef) breccia overlie the deep-marine hemipelagic and resedimented limestones with cherts, which are probably also Late Jurassic in age. Further downward, beneath a prominent stratigraphic gap, Lower Jurassic limestones equivalent to those from Western Slovenia, i.e. Toarcian crinoidal/ooidal limestones and pre-Toarcian lagoon/intertidal limestones are found (Otoničar, 2015). Also from this succession, an approximately Middle Jurassic platform retreat seems entirely plausible.

Taking into consideration all of the data presented herein, we propose that the collapse of the platform margin and formation of the Ponikve breccia Member is not the main factor behind the backstepping of the DCP margin. More likely, it represents an extraordinary and extensive sedimentary response to the tectonic processes that caused a significant topographic reorganization of the platform-margin–slope–basin transition.

Conclusions

Hemipelagic sediments and subordinate calciturbidites characterize the Jurassic successions of the Slovenian Basin's southern margin. The main and most striking exception are thick limestone breccia beds, which form successions up to 80 meters thick originating from large-scale debris-flows. These are largely dated to the Bajocian and early Bathonian, but some also occurred later in the Middle Jurassic. We define this limestone breccia as a Ponikve Breccia Member of the Tolmin Formation.

Detailed analyses of lithoclasts allowed for a reconstruction of the Dinaric Carbonate Platform's northern margin, which is no longer preserved nor exposed on the surface due to overthrusting. In the Upper Triassic, a reef complex typical of other Dachstein-type platforms characterized the Dinaric Carbonate Platform margin. In the Lower Jurassic, following the Triassic/Jurassic Boundary calcification crisis, the Dinaric Carbonate Platform margin was dominated by ooidal sand shoals. The Dinaric Carbonate Platform inherited a flat-topped architecture in the early Lower Jurassic and possibly longer. Towards the end of the Lower Jurassic the platform margin may have partially subsided.

Following the Toarcian deepening, shallow-marine conditions on the Dinaric Carbonate Platform margin were re-established with ooidal shoals. Towards the basin, a slope dissected by fault-escarpments likely existed.

In the Bajocian, regional tectonic perturbations started to trigger major collapses of the Dinaric Carbonate Platform margin, in turn giving rise to the formation of the Ponikve Breccia. These collapse events changed the architecture of the platform margin and may have brought about the retreat of the Dinaric Carbonate Platform margin. These tectonic- and sedimentary-events may also have been at least partially responsible for the present-day non-existing surface exposure of the Dinaric Carbonate Platform margin carbonates of the Late Triassic and the Early Jurassic age.

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