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Article

A stratigraphic gap within the Toarcian to Tithonian succession of the Slovenian Basin in the Kneža Valley (Julian Alps, NW Slovenia)

Stratigrafska vrzel v toarcijskem do tithonijskem zaporedju Slovenskega bazena v dolini Kneže (Julijske Alpe, SZ Slovenija)

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Ključne besede: Slovenski bazen, srednje do zgornje jurska stratigrafska vrzel, Južne Alpe, Perblanska formacija, Tolminska Formacija, dolina Kneže

Abstract

The Slovenian Basin was the largest Mesozoic inter-platform deeper-marine palaeogeographic unit of the transitional zone between the present-day Southern Alps and the Dinarides. In this study, we present the sedimentology and biostratigraphy of the Toarcian to Tithonian succession of the last unstudied large outcrop belt of the Slovenian Basin Jurassic rocks, which occurs in the Kneža Valley in the foothills of the Julian Alps in NW Slovenia. The studied succession is typical of the southern part of the Slovenian Basin preserved in the Podmelec Nappe, the lowest thrust unit of the eastern segment of the Southern Alps. In two detailed sections, we logged the hemipelagic limestones of the uppermost Krikov Formation, the clay-rich Toarcian Perbla Formation, siliceous pelagites, and resedimented limestones of the Aalenian to Lower Tithonian Tolmin Formation, and calpionellid-bearing Upper Tithonian to Lower Berriasian Biancone Limestone Formation. The thickness of the Perbla Formation follows the eastward thickening trend typical of the successions along the southern part of the basin. The Tolmin Formation shows a high abundance of resedimented limestones, which is also in accordance with the previously established northward waning of resediments within the entire basin. A distinctive feature of the Kneža Valley succession is the unusually small thickness of the radiolarian cherts of the Tolmin Formation (its Upper Member). This indicates a stratigraphic gap, which is related to the Bajocian-Bathonian collapses of the basin's southern slopes and the margin of the Adriatic Carbonate Platform.

Izvleček

Slovenski bazen predstavlja največjo mezozojsko interplatformno globljemorsko paleogeografsko enoto, katera danes izdanja v Južnih Alpah na meji z Dinaridi. V tem prispevku predstavljamo sedimentološko in biostratigrafsko raziskavo toarcijskega do tithonijskega zaporedja poslednjega še neraziskanega večjega pasu izdankov jurskih kamnin Slovenskega bazena, ki se nahaja v dolini Kneže ob vznožju Julijskih Alp v severozahodni Sloveniji. Preučevano zaporedje je značilno za južni del Slovenskega bazena, ki ga danes najdemo v Podmelškem pokrovu, najnižji narivni enoti vzhodnega segmenta Južnih Alp. V dveh detajlnih profilih smo zajeli hemipelagične apnence vrhnjega dela Krikovske formacije, z glinami bogato toarcijsko Perblansko formacijo, kremenične pelagite in presedimentirane apnence aalenijske do spodnje tithonijske Tolminske formacije ter kalpionelidne apnence zgornje tithonijske do spodnje berriasijske formacije Biancone apnenca. Debelina Perblanske formacije se ujema s predhodno ugotovljenim trendom večanja debeline te formacije v zaporedjih južnega dela bazena proti vzhodu. Tolminska formacija vsebuje veliko presedimentiranih apnencev, kar ustreza predhodno ugotovljenemu postopnemu izklinjanju resedimentov znotraj celotnega bazena v smeri severa. Posebnost zaporedja v dolini Kneže je nenavadno majhna debelina radiolarijskih rožencev zgornjega člena Tolminske formacije. To kaže na stratigrafsko vrzel, katero povezujemo z bajocijsko-bathonijskimi rušitvam južnih pobočij bazena in roba Jadranske karbonatne platforme.

Introduction

The Slovenian Basin (SB) is a large-scale inter-platform deeper-marine palaeogeographic unit that originated in the Middle Triassic due to prominent regional extension related to the westward propagation of the Neotethys Ocean. It remained at basinal depths until the end of the Cretaceous, when it turned into a south-propagating flysch basin (Buser, 1996; Vrabec et al., 2009; Rožič, 2016). To the north, it was bordered by the Julian Carbonate Platform, which drowned at the end of the Early Jurassic and subsequently became a pelagic plateau known as the Julian High (Šmuc, 2005). To the south, it passed into the large-scale Adriatic (also known as Dinaric or Friuli) Carbonate Platform, which persisted until the end of the Cretaceous, with sporadic occurrences of shallow-water carbonates up until the Eocene (Buser, 1996; Vlahović et al., 2005; Jurkovšek et al., 2013). To the west, the SB pinched out (Rožič et al., 2024), while to the east it probably opened up towards the Neotethys Ocean (e.g. Goričan et al., 2018). Today, the SB successions form the lowermost nappes of the eastern Southern Alps (Buser, 1987; Placer, 2008), but are also found within the "transitional zone" between the External and Internal Dinarides in

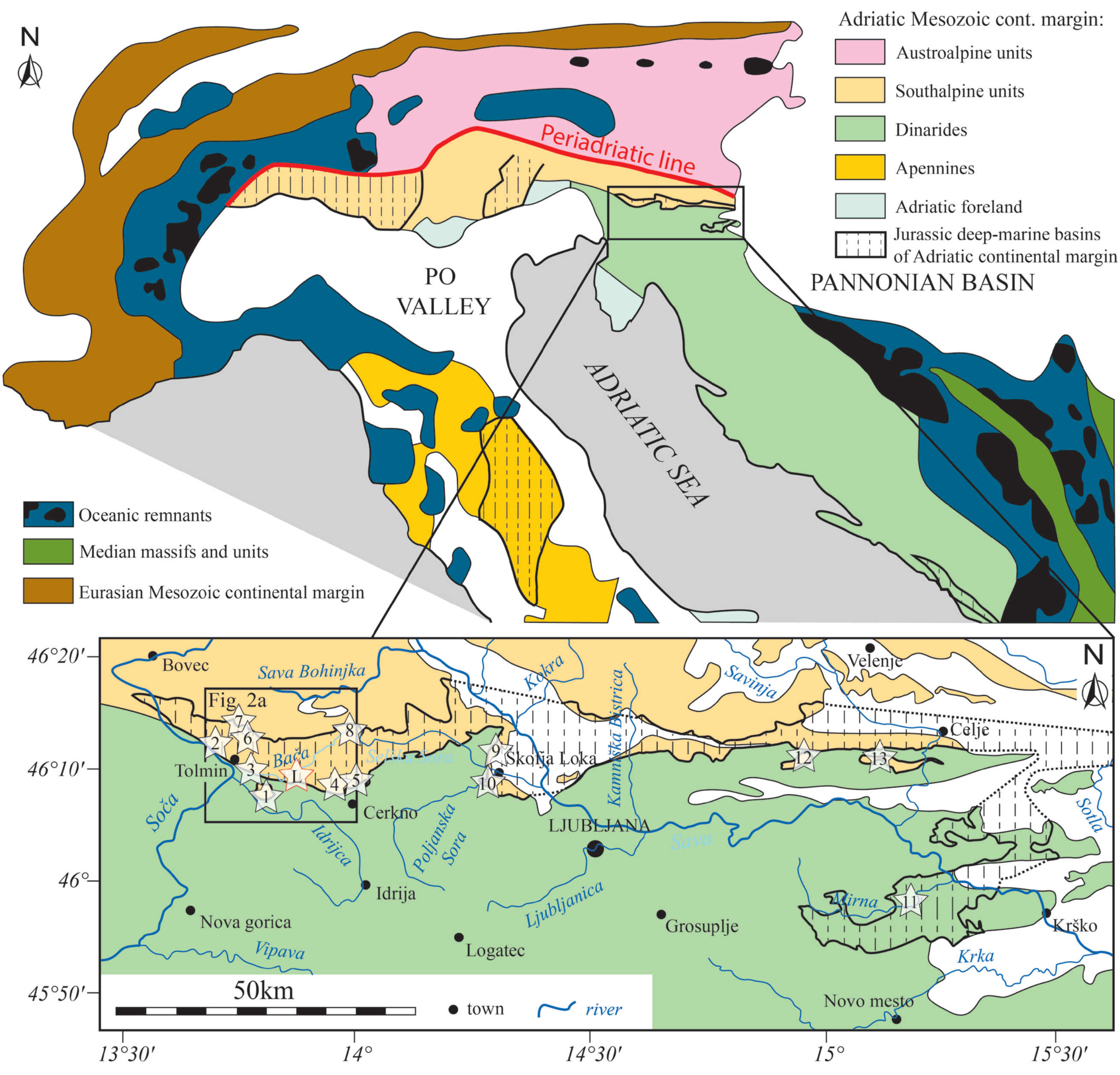

Fig. 1. Major geotectonic units of the Mediterranean-Alpine region (simplified after Channell & Kozur, 1997), showing the present-day position of the main Jurassic basins of the Adriatic continental margin (Rožič, 2009) (above), and an enlarged segment of the eastern Southern Alps and the northern Dinarides (below), where the Tolmin Basin represents the western segment of the Slovenian Basin (boxed area enlarged in Fig. 2a). The map is compiled according to Placer (1999), Buser (2010), and Rožič (2016), and shows the locations of the sections presented herein (L – Liščak) and previously studied sections (1 – Lovriš (Ponikve Klippe), 2 – Mrzli vrh, 3 – Poljubinj, 4 – Zakojška grapa, 5 – Zapoškar, 6 – Perbla, 7 – Javor, 8 – Kobla, 9 – Škofja Loka-Trnje, 10 – Škofja Loka-Podpurflca, 11 – Mirna, 12 – Čemšeniška Planina, 13 – Mrzlica).

eastern Slovenia (Ogorelec & Dozet, 1997; Placer, 2008; Rožič et al., 2022; Scherman et al., 2023), where they presumably form discontinuous remnants of a large-scale Dinaridic nappe (e.g. Rožič, 2016) (Fig. 1).

The most extensively studied interval of the SB successions is the upper Lower Jurassic to lowermost Cretaceous part, including the Perbla, Tolmin, and Biancone Limestone formations. Studies are particularly concentrated in the western part of the SB, between the towns of Cerkno and Tolmin (Cousin, 1973, 1981; Rožič, 2009; Rožič et al., 2019, 2022; Rožič & Reháková, 2024). This SB segment is also known as the Tolmin Basin (for details see Rožič, 2009). In this area, the SB succession is preserved in three nappes: the upper Kobla Nappe, the middle Rut Nappe, and the lower Podmelec Nappe. These nappes are composed solely of Ladinian-Maastrichtian deep-marine deposits, and within such setting Jurassic strata form discontinuous outcrop belts (Buser, 1987) (Fig. 2a). Successions from almost all of these outcrop belts have already been studied in detail (Rožič, 2009; Rožič et al., 2018, 2022), including the Ponikve Klippe, which lies south of the Southalpine thrust border (Rožič et al., 2014, 2022). These studies enabled precise palaeogeographic reconstruction and highlighted SB evolutionary phases within the investigated time interval. Practically the only large outcrop belt that remained unstudied is located in the central part of the Podmelec Nappe, in the area of the Kneža Valley. In this paper, we complement previous studies and present detailed sedimentological logs, microfacies, and biostratigraphy of two laterally positioned sections within the Liščak gorge (a tributary of the Kneža River).

Geological setting

The studied succession is located in the deeply incised Kneža Valley in the southern foothills of the Julian Alps in northwestern Slovenia. Structurally, the area belongs to the eastern segment of the Southern Alps, specifically to the Tolmin Nappe (sensu Placer, 1999, 2008), which is a composite thrust unit composed of several smaller nappes and thrust sheets (Buser, 1987): the lower Podmelec Nappe, the middle Rut Nappe, and the upper Kobla Nappe. According to existing regional maps (Buser, 1987, 2010), the Jurassic succession in this part of the Kneža Valley is separated

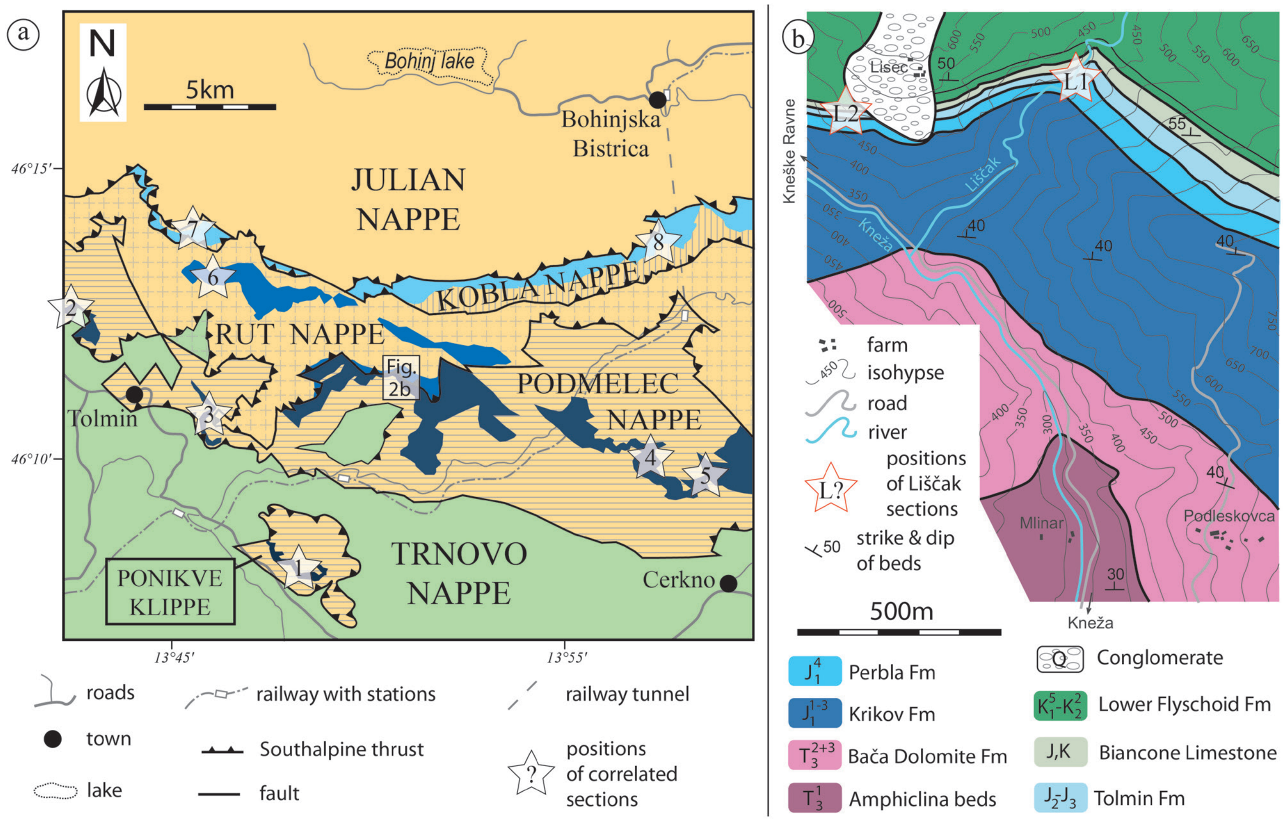

Fig. 2. Structure of NW Slovenia with outcrop belts of the Jurassic Slovenian Basin successions (light blue – within Kobla Nappe, medium blue – within Rut Nappe, dark blue – within Podmelec Nappe and Ponikve Klippe) (simplified from Buser, 1987), showing locations of previously studied sections (for names, see captions of Fig. 1) and the boxed area representing b) the detailed geological map of the Liščak area with locations of the Liščak sections (L1 – Liščak 1, L2 – Liščak 2). Please note that on the regional map (Fig. 2a) a thrust fault is drawn within the Jurassic outcrop belt of the Kneža Valley, which was not detected during our detailed geological mapping (Fig. 2b) and the Jurassic succession is continuous.

by an internal thrust fault and therefore belongs to two different nappes, i.e. the Podmelec and the Rut nappes (Fig. 2a) (the succession studied herein would belong largely to the latter). However, our detailed geological map of the studied area does not support this interpretation and instead indicates a continuous Jurassic succession, at least in the central part of the Kneža Valley, which belongs entirely to the Podmelec Nappe (Fig. 2b).

The SB succession in the Kneža Valley begins with the Carnian Amphiclina beds characterised by alternating clastic and carbonate (hemi)pelagic and gravity-flow deposits (Skaberne et al., 2024). This passes into the Norian–Rhaetian Bača Dolomite Formation, composed of bedded dolomite with chert nodules and subordinate dolomite breccias (Gale, 2010, 2012). Above, a thin basal limestone breccia bed marks the boundary with the Hettangian–Pliensbachian Krikov Formation, otherwise dominated by hemipelagic and subordinate resedimented limestones (Rožič et al., 2017; Novak Zakeršnik, 2024). The Perbla and Tolmin formations studied here follow. The first is Toarcian in age and composed almost entirely of marls with subordinate shales, while the second is Aalenian–early Tithonian and consists of siliceous pelagites and resedimented limestones. The upper Tithonian to Berriasian Biancone Limestone Formation is deposited continuously on the Tolmin Formation rocks and composed of pelagic limestone with rare chert nodules and a single calciturbidite bed (Rožič and Reháková, 2024). With a prominent stratigraphic gap, the Aptian–lower Cenomanian Lower Flyschoid Formation follows, consisting of alternating shales/marls and resedimented limestones. Further up, the upper Cenomanian–Turonian "Globotruncana limestone" succeeds, marked by alternating varicoloured clayey limestone (pelagites) and resedimented limestones. We note that Buser (1986, 1987) mapped this succession as a separate stratigraphic unit, whereas Cousin (1973, 1981) included it with the Lower Flyschoid Formation. Upwards, it passes into the Coniacian–Campanian Volče Limestone, which is generally similar in composition, except that clay content is largely absent and the pelagic limestone is grey. The entire Cretaceous succession contains chert nodules and lenses (Buser, 1986).

Methods

For the central Kneža Valley, including most of the Liščak gorge, a detailed geological map was elaborated (Fig. 2b) using the all-outcrops method combined with the geological boundary tracing method. Two sedimentological sections were logged at a scale of 1:100. The main section (Liščak 1) is located within the Liščak gorge (N 46°11'39", E 13°50'37"). This section is difficult to access, and climbing experience and equipment are almost essential. The supplementary section (Liščak 2) is located in a small gorge near the path leading from the Kneža Valley to the abandoned Lisec farm (N 46°11'33", E 13°50'10"). Microfacies analysis and foraminiferal biostratigraphy were carried out on 43 thin sections prepared from limestone beds. Seven chert samples were treated with hydrofluoric acid and the residues were examined for radiolarians, but due to poor preservation of skeletons they did not yield identifiable specimens.

Description of sections

In the main section (Liščak 1), the uppermost part of the Krikov Formation, Perbla, Tolmin, and Biancone Limestone formations, and the basal breccia of the Lower Flyschoid Formation were logged over a thickness of 100 m (Fig. 3). The section begins with the uppermost 6 m of the Krikov Formation, composed entirely of grey, thin-bedded micritic to slightly clayey limestone with occasional chert nodules. The contact with the overlying strata is sharp. The subsequent Perbla Formation is 51 m thick and consists almost entirely of marls/shales, which are typically dark-coloured (often black) and laminated (Fig. 4a). Laminations are bedding-parallel, but some slumping-related inclination and gentle folding were observed (Fig. 4b). Intercalations (beds and lenses) of clayey and micritic limestone are present, which are very rare in the lower part and become progressively more abundant in the upper part of the formation. The upper boundary is transitional and was placed at the point where carbonate beds begin to predominate.

The Tolmin Formation is 31 m thick. Based on the composition of background sediments, the formation is divided into two members (e.g. Rožič, 2009). The Lower Member is 22.5 m thick and dominated by grey to dark grey, thin-bedded (up to 10 cm, exceptionally 35 cm) siliceous limestones, which often contain nodules and lenses of black chert. Some beds are entirely silicified. Marl/shale interlayers still occur in some intervals (Fig. 4c), mostly as thin laminae and films on bedding planes. From the 18th to 20th meter of the member, beds become reddish in colour (Fig. 4d), whereas the uppermost 2 m are characterised by medium-bedded, light grey, normally graded calcarenites. This interval also contains rather thick (up to 20 cm) black chert beds. The

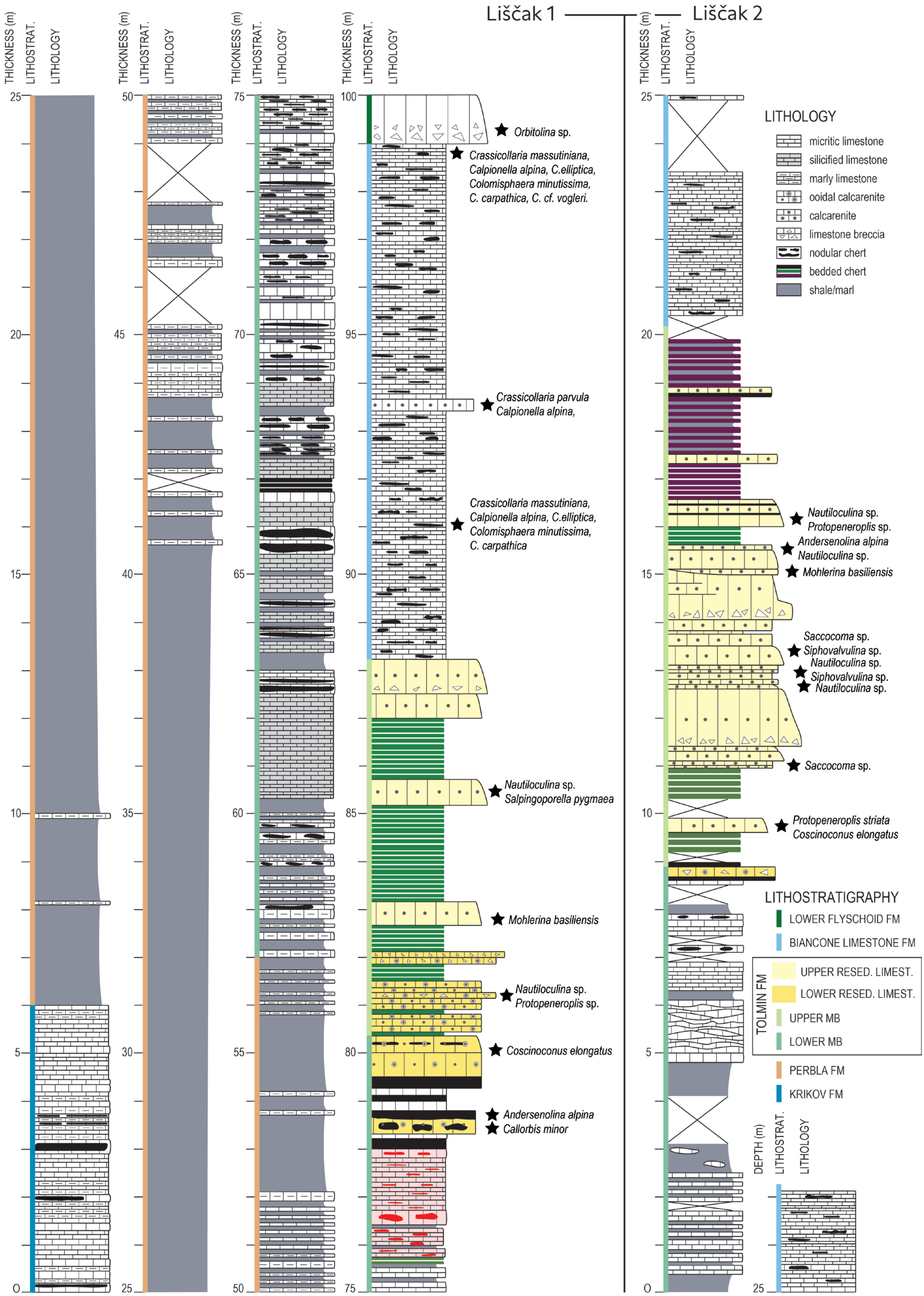

Fig. 3. Logged sections of the Kneža Valley with the positions of the main biostratigraphic markers.

Upper Member is 8.5 m thick. The transition is marked by thin-bedded calcarenites and subordinate limestone breccias. Upwards, it passes into a succession dominated by green, thin-bedded (up to 10 cm) radiolarian cherts (Fig. 4e) with two thin, amalgamated limestone breccia beds and medium-bedded, normally graded calcarenites (Fig. 4f), the latter defining also the top of the Tolmin Formation.

The Biancone Limestone Formation is 11 m thick and composed of light grey to almost white, thin-bedded micritic limestone with sporadic chert nodules and a single calcarenite bed. The section ends with a limestone breccia bed one meter thick, which marks the beginning of the Lower Flyschoid Formation.

The supplementary section (Liščak 2) is 27 m thick (Fig. 3). It begins with the uppermost 9 m of the Lower Member of the Tolmin Formation, which is generally very similar to those of the Liščak 1 section, but contains more marl interlayers, less chert, and practically no calcarenites. The Upper Member of the Tolmin Formation is 11.5 m thick and shows prominent differences compared to the Liščak 1 section. In the basal 2 m, it begins with limestone microbreccia and normally graded calca-

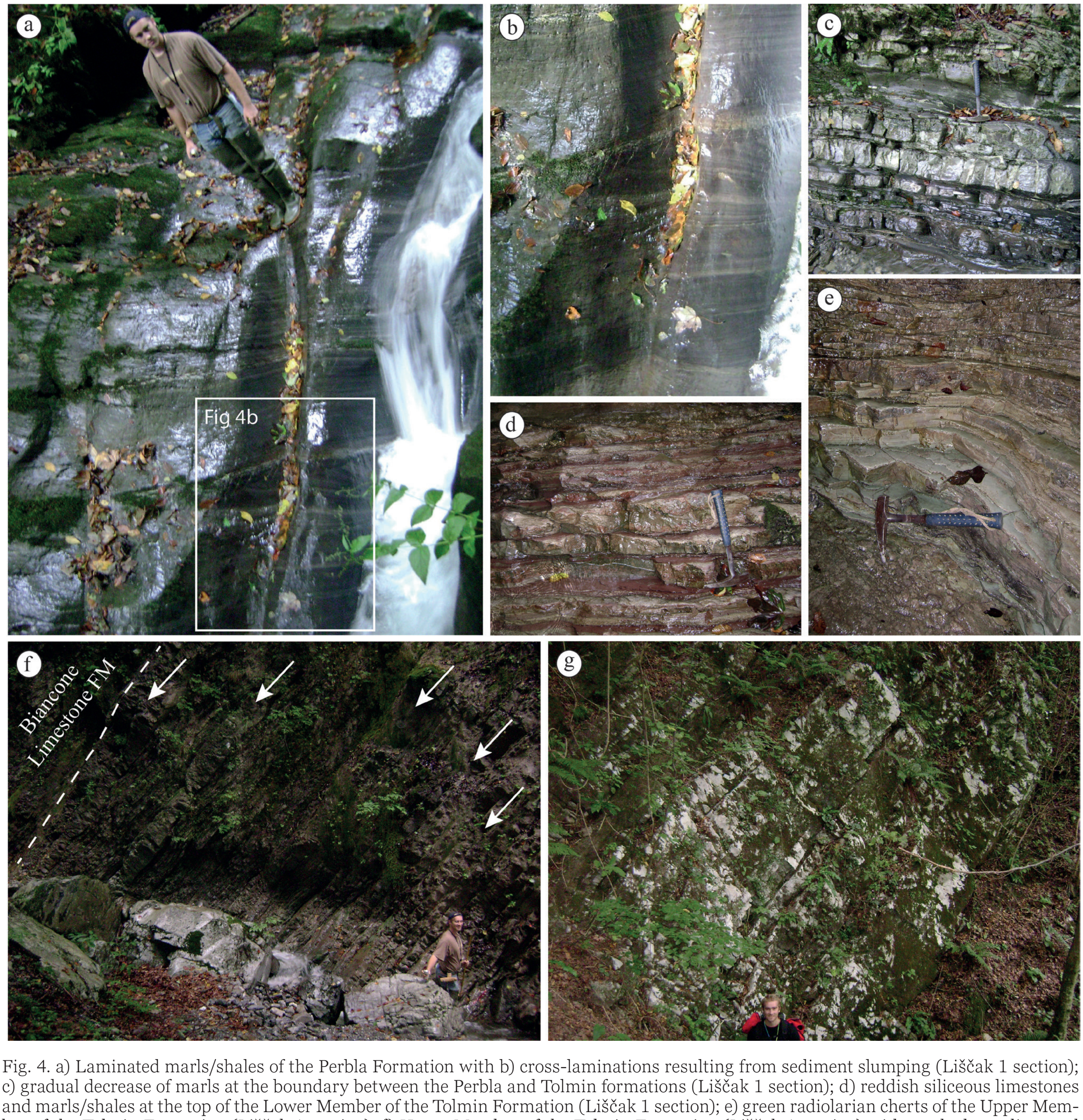

Fig. 4. a) Laminated marls/shales of the Perbla Formation with b) cross-laminations resulting from sediment slumping (Liščak 1 section); c) gradual decrease of marls at the boundary between the Perbla and Tolmin formations (Liščak 1 section); d) reddish siliceous limestones and marls/shales at the top of the Lower Member of the Tolmin Formation (Liščak 1 section); e) green radiolarian cherts of the Upper Member of the Tolmin Formation (Liščak 1 section); f) Upper Member of the Tolmin Formation (Liščak 1 section) with marked resedimented limestones (arrows) and boundary with the Biancone Limestone Formation (dashed line); g) thick interval of Upper resedimented limestones (Liščak 2 section).

renite beds (30 cm thick) intercalated within green, thin-bedded radiolarian chert. This is followed by a 4.5 m thick interval of grey, often normally graded calcarenite. Limestone microbreccia occurs at the bases of the two thickest beds (Fig. 4g). The rest of the member is again characterised by an alternation of normally graded calcarenites and thin-bedded radiolarian chert. The latter is green in the lowermost part of this interval, and violet higher up the interval. In the topmost 2.5 m, marl/shale interlayers (thin laminae) occur between chert beds. The section ends with the 7 m-thick Biancone Limestone Formation, composed solely of micritic limestone. The calcarenite bed recorded within the Biancone Limestone Formation in the Liščak 1 section is missing or not exposed.

Already here we note that the studied sections are dominated by (hemi)pelagic sediments, which indicated a basin-plain sedimentary environment. Normally graded calcarenites and limestone breccias, which characterize the Tolmin Formation, are resedimented limestones and originated from the high-density turbidity currents. Thin-bedded, non-graded limestone breccias from the Liščak 1 section could also be calcidebrites. Rapid deposition of resedimented limestones enabled sedimentation of carbonate material below the CCD (for further discussion and correlation see below).

Microfacies Analysis

Microfacies analysis focused on resedimented limestones (calcarenites and limestone breccias) of the Tolmin Formation, which, in accordance with previous studies (Rožič & Popit, 2006; Rožič, 2009; Rožič et al., 2014, 2019, 2022), are divided into two levels: Lower and Upper resedimented limestones (sensu Rožič, 2009). The subdivision is based on their occurrence within the succession and their composition.

Lower resedimented limestones

In the Liščak 1 section, the Lower resedimented limestones occur in an interval almost 4 m thick (from 78.3 to 82.1 m) at the transition between the two members of the Tolmin Formation (Fig. 3). They are mostly coarse- to medium-grained grainstones, with normal grading visible in some beds. The predominant grains are intraclasts (rarely with recognisable internal composition of pelletal and fine-ooidal packstone), peloids, and predominantly tangential, highly micritised ooids (Fig. 5a). Some peloids are large and oval, most probably originating from completely micritised ooids. Rare aggregate grains also occur. Bioclasts are predominantly echinoderm fragments (crinoid plates as well as echinoid spines). Twinning lamellae inside them as well as surrounding syntaxial cements can be bent. Other fossils include foraminifera (*Textularia*, *Lenticulina*, rare Trocholinidae, *Callorbis, Nautiloculina* and *Protopeneroplis*; for details see below) and fragmented bivalves. Sparitic fields/grains some mm in size occur in this microfacies, which probably originate from recrystallisation-prone bioclasts. With fining, ooids, large oval peloids, and intraclasts become subordinate, and small peloids (pellets) and intraclasts start to predominate (Fig. 5b). Cements are drusy-mosaic and syntaxial around echinoderms. Silicification is present, macroscopically visible as chert nodules, while in thin sections (made from limestones), selective silicification of micritic grains, some biogenic grains, and lithoclasts was observed.

Within the Lower resedimented limestone, we also include limestone breccia beds that occur at 81.2 and 82.0 metres in the Liščak 1 section. Although no diagnostic fossils were found at this level, we place them here due to the composition of the ooid-rich matrix between clasts, which is very similar to the underlying beds. The lowest coarse-grained bed of the Liščak 2 section (at 8.8 m) is limestone breccia with highly silicified matrix, which obliterates its primary composition. However, the shapes of the primary grains are still visible and are often circular. Therefore, we also consider this bed as a part of the Lower resedimented limestones.

Clasts in the limestone breccia are diverse and correlate with previously distinguished clast-types of the Lower resedimented limestones and their lateral and more proximal development of the Ponikve Breccia Member of the Tolmin Formation (Rožič et al., 2019, 2022). Because the age and sedimentary environments of clasts were previously described and discussed, herein we simply provide a correlation with previously determined clast-types. We note that clasts were divided into four principal groups according to their age: T1-6 – Upper Triassic, LJ1-4 – Lower Jurassic, MJ1-4 – Middle Jurassic, and UD1-11 – undetermined (for further details on clast composition and sedimentary environments see Rožič et al., 2022).

Common shallow-water clasts include (A) poorly sorted intra/bioclastic pelletal packstone (T2 in Rožič et al., 2022) (Fig. 5c). In one such clast, a transition to calcimicrobic laminae is visible; another contains aggregate grains and oncoids with intraclastic or bioclastic cores (LJ1 in Rožič et al., 2022). Similar in composition is (B) generally coarser grainstone, in which cortoids are also common (Fig. 5d) (T3 in Rožič et al., 2022). One

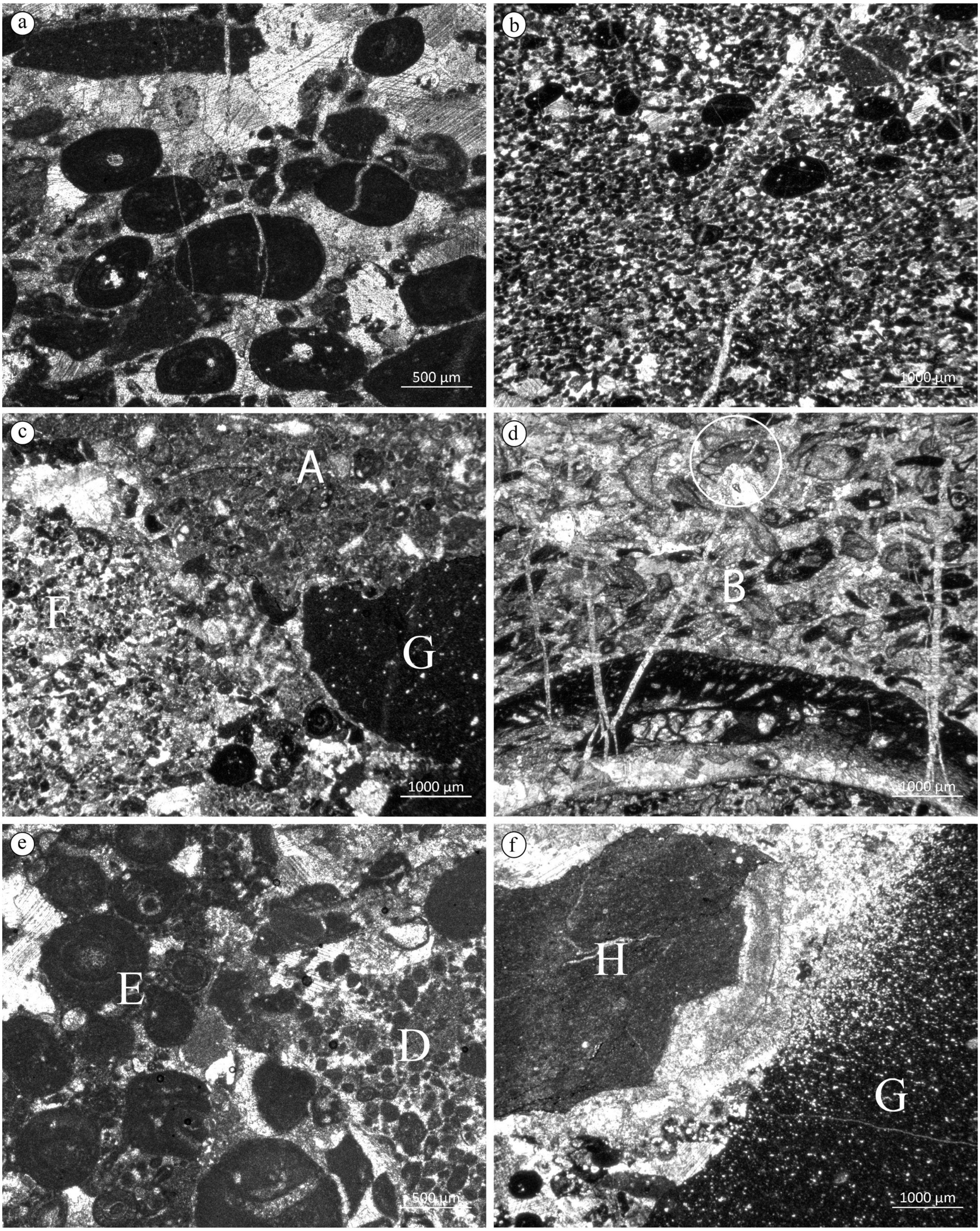

Fig. 5. Micrographs of the Lower resedimented limestones (L1 – Liščak 1, L2 – Liščak 2): a) grainstone composed of ooids, peloids (micritised ooids and pellets), intraclasts and crinoids (L1 – 78.8 m); b) alternation of laminae of fine-grained pelletal/bioclastic, partly washed packstone (below) and poorly sorted grainstone of similar composition with micritised ooids as an addition (above) (L1 – 78.8 m); c) lithoclasts of intra/bioclastic packstone (A-type), fine-grained pelletal bioclastic packstone (F-type) and pelagic wackestone (G-type) (L1 – 82.0 m); d) cortoidal, intra/bioclastic grainstone (B-type) with a large bivalve shell encrusted by microproblematica and ?*Duostomina turboidea* Kristan-Tollmann (encircled) (L2 – 8.8 m); e) partly cemented ooidal lithoclast (E-type) and ooidal, pelletal, intraclastic, partly washed packstone (D-type) (L1 – 82.0 m); f) chert clast (H-type) serving as a core for laterally vanishing silicification in the surrounding matrix and pelagic wackestone lithoclast (G-type) (L1 – 81.25 m). Silicification in all micrographs appears as transparent, shiny fields and grains.

shallow-water clast (C) also contains a large, highly recrystallised solitary coral (T5 in Rožič et al., 2022). Less common are (D) grainstones (rarely partly washed packstones) containing mainly pellets, intraclasts, and ooids (Fig. 5e) (LJ1 in Rožič et al., 2022). In one case (E), a clast composed of ooids and rare intraclasts and bioclasts (LJ2 in Rožič et al., 2022) shows only minor cementation with rim and meniscus cements, while the internal parts of the pores are filled with microsparite similar to that of the surrounding matrix (Fig. 5e). This indicates a penecontemporaneous origin for this clast. It is similar to aggregate grains and some intraclasts with visible internal composition found in the calcarenites (described in the previous paragraph) as well as in the matrix of the breccia. Fine-grained pelletal/bioclastic pack/grainstones (F) (Fig. 5c) of unclear origin are rare (UD1 in Rožič et al., 2022).

Deep-marine lithoclasts include (G) wackestones and more rarely mudstones or packstones, composed of radiolarians and thin-shelled bivalves (Figs. 5c, f). In some of these clasts, small ooids and planktonic foraminifera are present (MJ4 in Rožič et al., 2022), indicating these clasts are penecontemporaneous to the sedimentation of the breccia beds. Similarly, we find a single radiolarian chert clast (H) (UD11 in Rožič et al., 2022), which served as a core for the further silicification of the surrounding sediment (Fig. 5f).

Upper resedimented limestones

The Upper resedimented limestones occur within the Upper Member of the Tolmin Formation in the Liščak 1 and Liščak 2 sections (Fig. 3). The predominant microfacies is coarse- to medium-grained, usually graded grainstone, and rarely packstone. In contrast to the Lower resedimented limestones, bioclasts dominate these beds and are also more diverse. The most frequent bioclasts are echinoderm fragments (crinoids and echinoids), but *Crescentiella morronensis* (Crescenti) (*Tubiphytes*-type microproblematica) grains are also abundant (Fig. 6a). The latter often occur in oval form with a single circular chamber in the central part of the grain, but irregular, multi-chamber grains also occur. Rarer bioclasts are foraminifera (*Lenticulina*, *Mohlerina,* Trocholinidae, *Nautiloculina* and *Protopeneroplis*; for details see below), calcisponge fragments, calcimicrobial grains (*Cayeuxia* was identified), dasycladalean algae, bivalves, brachiopods, ostracods, and bryozoans. Like the Lower resedimented limestones, completely recrystallised biogenic grains are present. In some of these grains, a possible bryozoan structure may be recognised. In two thin sections (e.g. at the 11th and 13.4th meter of the Liščak 2 section), echinoderm fragments dominate, among which *Saccocoma* sp. fragments were identified. Non-skeletal grains are intraclasts (which can be microsparitic) and pellets. Rare large peloids and ooids are present. With fining, non-skeletal grains become more abundant (Fig. 6b). Some thin sections at the top of the Tolmin Formation (e.g. at 15.6 meter of the Liščak 2 section) have more abundant intraclasts and pellets associated with textulariid foraminifera. The cement is drusy-mosaic and syntaxial around the echinoderms, while silicification is selective and observed in micritic and some biogenic grains.

At the base of the thick, coarse-grained graded calcarenite beds (mainly in the Liščak 2 section), limestone microbreccia with a rudstone texture occurs. These large grains consist largely of lithoclasts, among which several types are present. Lithoclasts of shallow-water origin are very similar to those described above (labelled A–E) (Fig. 6c). In addition, highly recrystallised lithoclasts with partially visible microbial laminar growth were identified. Fine-grained pelletal/bioclastic packstone lithoclasts (labelled F above) are more common. In contrast, deep-marine lithoclasts (labelled G above) are very rare (Fig. 6d), while chert lithoclasts (labelled H above) were not detected. At this level, the breccias also contain large biogenic grains, mostly fragments of bryozoans (Fig. 6e), calcisponges, and, more rarely, bivalves. Some of these grains have encrusting foraminifera overgrowths (Fig. 6f). The completely recrystallised grains described above can also be large (up to several mm). Breccias of this level grade into the grainstones described above. In general, the matrix between large grains corresponds to the surrounding calcarenites, but in some beds, completely well-rounded, large peloids occur. Occasionally, these grains show indistinct concentric laminae and/or a sparitic core with a gradual transition to micrite. These grains could be micritised ooids or unusually well-rounded *Tubiphytes*-type grains. The latter is more certain for grains with sparitic cores. Such grains are most common in the uppermost bed of the Liščak 1 section (87.7 m) but were documented also in the thickest bed of the Liščak 2 section (11.5 m).

Background sediments

The background sediments of the studied sections were not studied in detail. However, a few thin sections made from micritic limestones of the Krikov Formation, the Perbla Formation, and

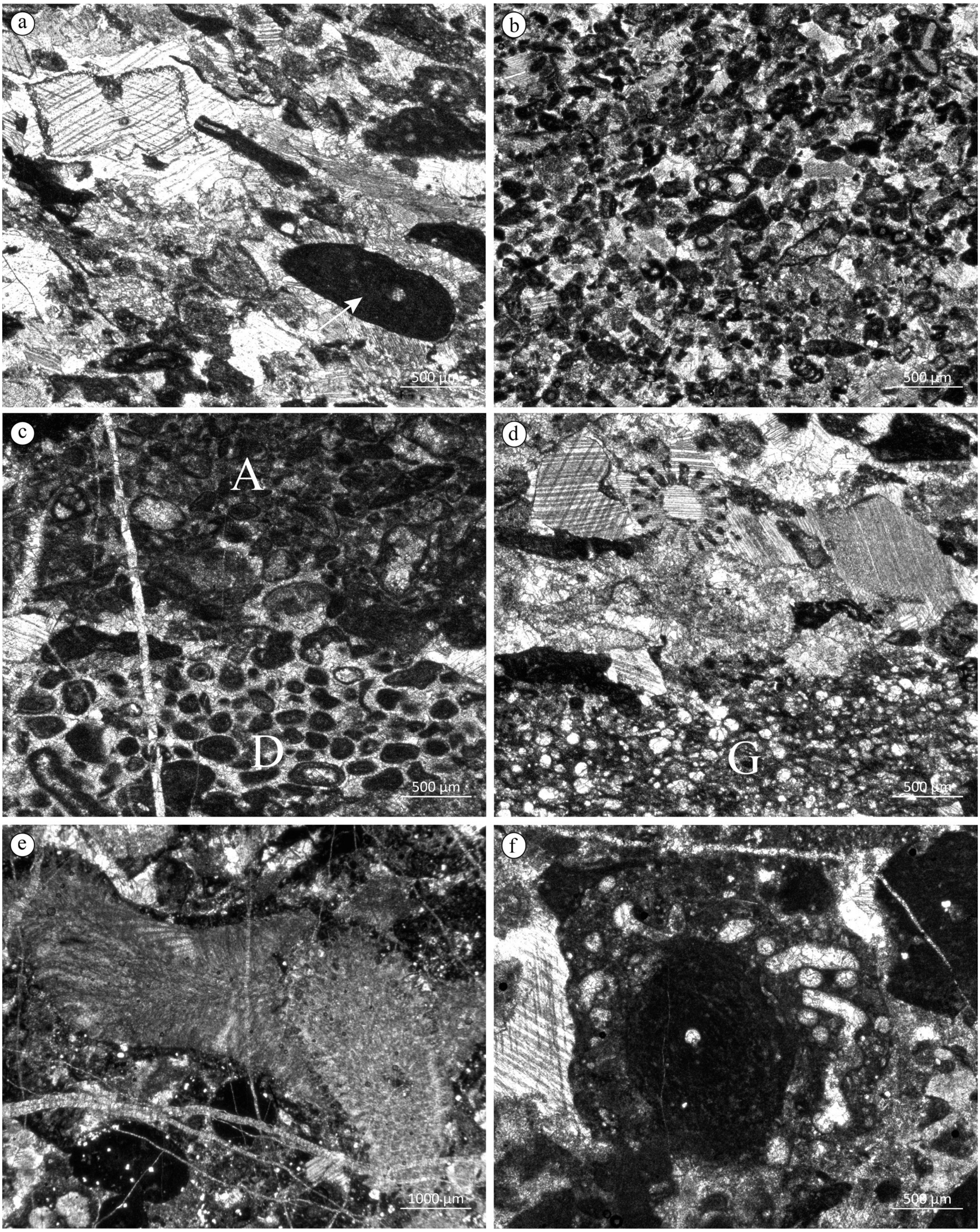

Fig. 6. Micrographs of the Upper resedimented limestones (L1 – Liščak 1, L2 – Liščak 2): a) coarse-grained grainstone composed of *Tubiphytes*-type microproblematica (arrow), intraclasts (microsparitic and micritic), pellets, and bioclasts – note the curved twinning lamellae in the echinoderm fragment and the surrounding syntaxial cement (L2 – 12.8 m); b) fine-grained, partly washed packstone composed of pellets (including fine intraclasts) and bioclasts (crinoids/echinoderms, foraminifera, small *Tubiphytes*-type grains) (L2 – 18.9 m); c) lithoclasts of pelletal, intra/bioclastic packstone (A-type) and ooidal, peloidal, intraclastic grainstone (D-type) (L2 – 11.5 m); d) lithoclast of pelagic packstone composed of partly calcified radiolarians (G-type) in a matrix dominated by echinoderms (L2 – 11.5 m); e) large bryozoan grain (L1 – 87.7 m); f) complex biogenic grain with a core of *Tubiphytes*-type microproblematica encrusted by foraminifera (and final patches of microbial mud) (L1 – 82.7 m).

the Lower Member of the Tolmin Formation indicate monotonous composition of a mudstone/wackestone structure with pelagic fossils such as (mostly calcified) radiolarians, thin-shelled bivalves, sponge spicules, rare echinoderm fragments, and ostracods. Apart from calcified radiolarians, calpionellids also occur in the Biancone Limestone (for details on this formation, see Rožič and Reháková, 2024).

Biostratigraphy

We present here biostratigraphic data from resedimented limestones, from which several age-diagnostic foraminifera and dasycladacean algae were identified (see Fig. 3 for their occurrence in the sections). Although these specimens derive from resediments, they occur as isolated individuals, show no prominent diagenetic alteration, and are considered penecontemporaneous with the resedimentation.

In the Lower resedimented limestones, the foraminifer *Callorbis minor* Wernli & Metzger (Fig. 7a) was identified. This species is currently known from the Bajocian (Wernli & Metzger, 1990), and its presence is consistent with the previously determined Middle Jurassic (Bajocian–Bathonian, ?Callovian) age of these beds (Rožič, 2009; Goričan et al., 2012; Rožič et al., 2022).

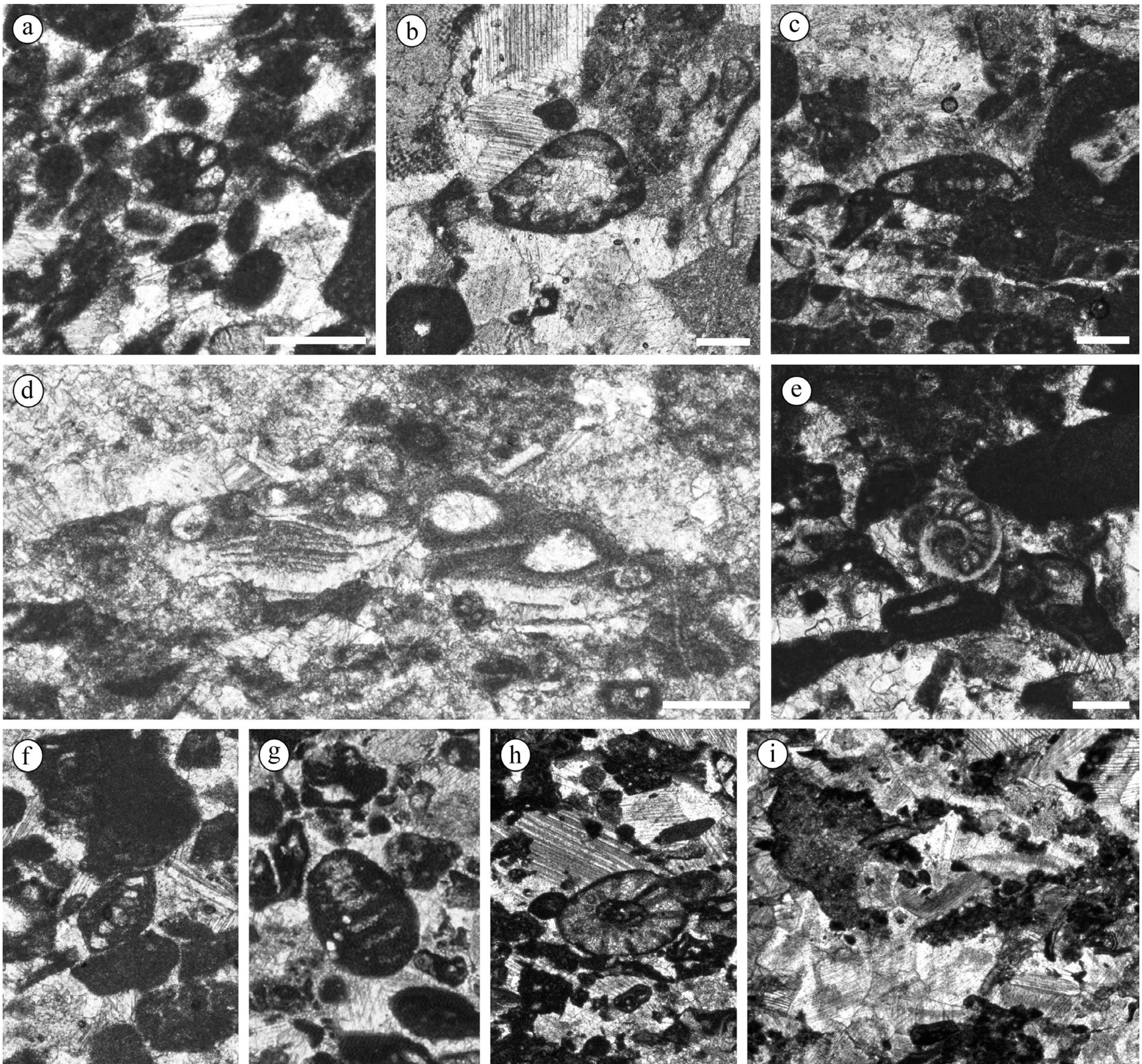

Fig. 7. Biostratigraphy of the Kneža Valley sections (L1 – Liščak 1, L2 – Liščak 2) (in all micrographs the scale-bar is 200 μm long): a) *Callorbis minor* Wernli & Metzger (L1 – 78,6 m), b) *Andersenolina alpina* (Leupold) (L1 – 78,7 m), c) *Nautiloculina* sp. in Lower resedimented limestones (L1 – 81,25 m), d) *Mohlerina basiliensis* (Mohler) (L2 – 15.0 m), e) *Protopeneroplis striata* Weynschenk (L2 – 9.7 m), f) *Nautiloculina* sp. in Upper resedimented limestones (L1 – 85,7 m), g) *Coscinoconus elongatus* Leupold (L2 – 9.7 m), h) *Salpingoporella pygmaea* Gümbel (L1 – 85.4 m), i) *Saccocoma* sp. fragments (L2 – 13.4 m).

In addition, foraminifera from the Trocholinidae family (*Andersenolina alpina* (Leupold) (Fig. 7b), *Coscinoconus elongatus* Leupold), *Nautiloculina* sp. (Fig. 7c) and *Protopeneroplis* sp. were found in these beds.

In the Upper resedimented limestones, the foraminifera *Mohlerina basiliensis* Mohler (Fig. 7d), *Protopeneroplis striata* Weynschenk (Fig. 7e), *Nautiloculina* sp. (Fig. 7f), *Andersenolina alpina* (Leupold), *Coscinoconus elongatus* Leupold (Fig. 7g), *Siphovalvulina* sp., and the dasycladacean alga *Salpingoporella pygmaea* Gümbel (Fig. 7h) were determined. *Mohlerina basiliensis* ranges from the Bathonian to Valanginian (Schlagintweit, 2012), confirming the previously established Late Jurassic (Kimmeridgian, Early Tithonian) age of these beds (Rožič, 2009; Goričan et al., 2012). We note that in the second lowest calciturbiditic bed of the Liščak 2 section (9.7 m), *P. striata* and *C. elongatus* were identified. Although these foraminifera are common in the Lower resedimented limestone (e.g. Rožič, 2009), the composition of this bed (dominated by various bioclasts) indicates that it belongs to the Upper resedimented limestones. The stratigraphic range of these foraminifera allows for such an occurrence, as they are also common in Upper Jurassic platform margin carbonates (Velić, 2007; Atasoy et al., 2018). Further-

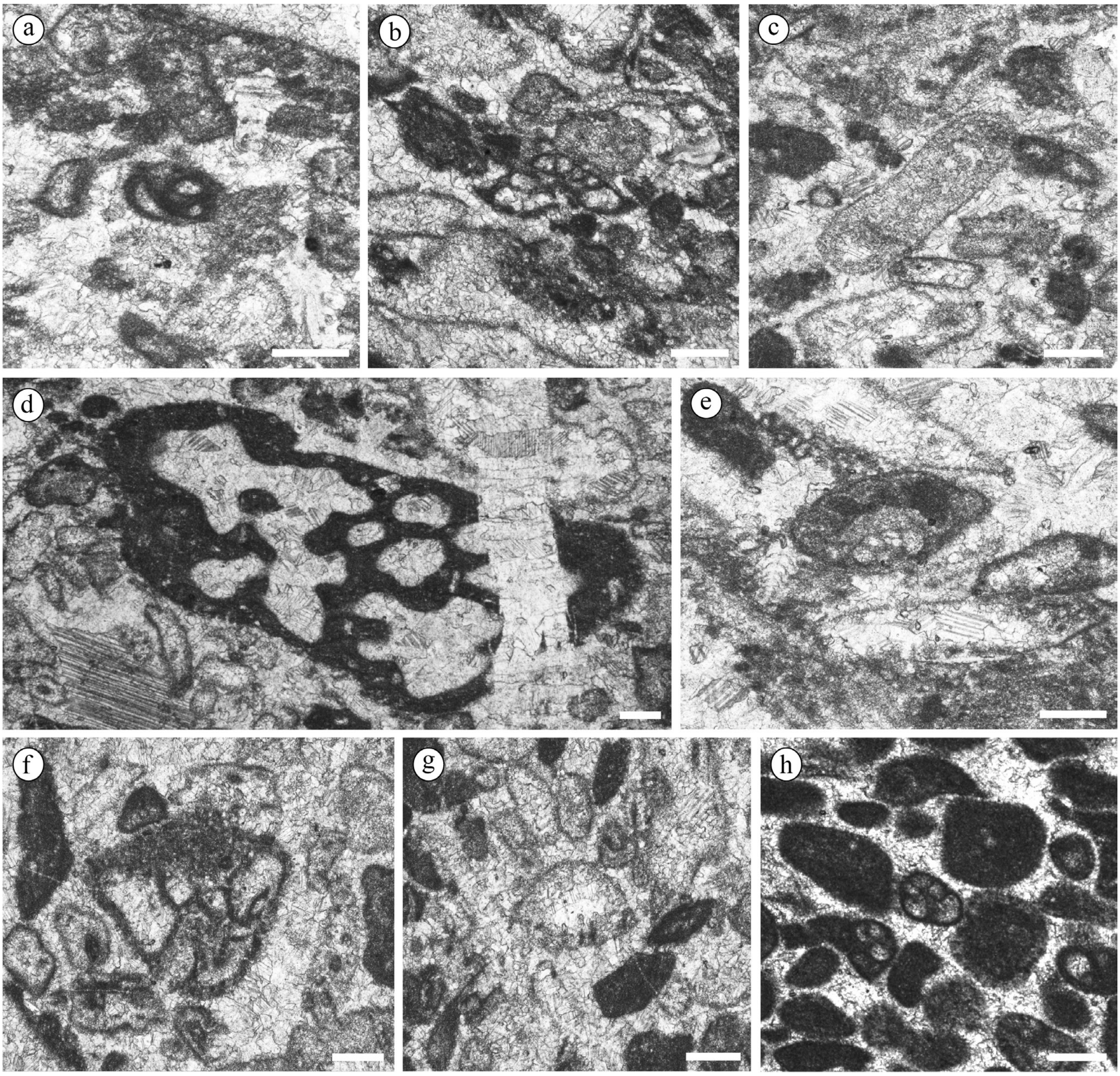

Fig. 8. Foraminiferal biostratigraphy of lithoclasts in the Kneža Valley sections (in all micrographs the scale-bar is 200 μm long, a–h are B-type lithoclasts found at 8.8 m of Liščak 2 section, g is D-type lithoclast found at 14.2 m of Liščak 2 section): a) *Galeanella tollmanni* (Kristan), b) *Kristanita humilis* (Kristan), c) ?*Aulotortus sinuosus* Weynschenk, d) *Alpinophragmium perforatum* Flügel, e) ?*Duostomina placklesiana* Kristan-Tollmann, f) *Variostoma coniforme* Kristan-Tollmann, g) *Trocholina* ex gr. *intermedia* Frentzen (incl. *Trocholina umbo* Frentzen), h) *Siphovalvulina gibraltarensis* BouDagher-Fadel et al.

more, in the next bed, fragments of *Saccocoma* sp. (Fig. 7i) were recognised, indicating an Upper Jurassic age for this bed. In the Biancone Limestone Formation, the Middle Berriasian *Calpionella* Zone, *Elliptica* Subzone was determined in the middle part of the formation (Fig. 3; for details see Rožič & Reháková, 2024).

Among lithoclasts, the richest fauna was determined in coarse cortoid grainstone lithoclasts (labelled B above) indicating Norian-Rhaetian age (see Gale et al., 2012): *Galeanella tollmanni* (Kristan) (Fig. 8a), *Kristanita humilis* (Kristan) (Fig. 8b), ?*Aulotortus sinuosus* Weynschenk (Fig. 8c), *Alpinophragmium perforatum* Flügel (Fig. 8d), Duostominidae (?*Duostomina placklesiana* Kristan-Tollmann (Fig. 8e), ?*Duostomina turboidea* Kristan-Tollmann (Fig. 5d), *Variostoma coniforme* Kristan-Tollmann (Fig. 8f)), and *Trocholina* ex gr. *intermedia* Frentzen (incl. *Trocholina umbo* Frentzen) (Fig. 8g). In grainstone lithoclasts with pellets, intraclasts, and ooids (labelled D above), *Siphovalvulina gibraltarensis* BouDagher-Fadel et al. indicates Lower Jurassic age of this lithoclast (Fig. 8h).

Correlation with other Jurassic sections of the Slovenian Basin and discussion

Four changes in pelagic sedimentation were recorded in studied sections: A) rapid change from (hemi)pelagic carbonate to clay-rich sedimentation assigned to the Pliensbachian–Toarcian boundary; B) recovery of carbonate sedimentation towards the Middle Jurassic; C) Bajocian shift to pure siliceous pelagites; and D) abrupt mid-Tithonian overturn to calcareous pelagic sedimentation. These changes correspond to those documented earlier within the SB and other basins of the western Tethys (Šmuc, 2005; Rožič, 2009; Goričan et al., 2012, 2018, 2022; Picotti & Cobianchi, 2017; Masetti et al., 2012; Lodowski et al., 2024; Rožič & Reháková, 2024). In the SB, these changes also define the boundaries between the Krikov, Perbla, Tolmin, and Biancone Limestone formations, as well as between the two members of the Tolmin Formation (Rožič, 2009).

More detailed correlation of Kneža Valley successions with other successions of the SB is also consistent with pre-existing data. For example, the uppermost part of the Krikov Formation, which was logged for this study, is composed solely of (hemi)pelagic limestones (Fig. 3). The rest of the Krikov Formation in the Kneža Valley is also dominated by background sediments, whereas resedimented limestones occur only sporadically (Cousin, 1973, 1981; Rožič et al., 2017; Novak Zakeršnik, 2024). The composition of the Krikov Formation in the Kneža Valley described herein further proves that during the time of its deposition (Hettangian–Pliensbachian), the north-lying Julian Carbonate Platform was the main source area for resediments (Rožič, 2009). Namely, the resediments within the Krikov Formation which dominate the northern SB sections become less frequent in the central part and are very distal and rare within the sections from the southern SB margin, including the Liščak sections (Fig. 9).

The Toarcian Perbla Formation reveals pelagic, clay-rich sedimentation in an oxygen-depleted, deeper-marine environment, where laminations are well preserved (Fig. 4a). However, this period is marked by a significant regional extensional event related to the second rifting phase of the Alpine Tethys (Berra et al., 2009), which in the wider study area led to the disintegration and subsequent drowning of the Julian Carbonate Platform (Šmuc, 2005; Šmuc & Goričan, 2005). The same extension is documented in the internal segmentation of the SB, recognisable by the prominent changes in the lateral thickness of the Perbla Formation and the internal gravity-driven redeposition of the pelagic sediment (Rožič, 2009; Rožič & Šmuc, 2011). In the Kneža Valley area, this extension-driven faulting led to tilting of the local sea floor, as evidenced by the minor sliding and slumping of the laminated marls/shales in the lower part of the Perbla Formation (Fig. 4b). The transition to the highly siliceous calcareous pelagic sediments of the overlying Tolmin Formation at the beginning of the Middle Jurassic is gradual, as also recorded in the other sections of the SB deposits (Rožič, 2009).

In the Kneža Valley succession, Lower resedimented limestones (in the form of calciturbidites and subordinate calcidebrites) begin to occur towards the top of the Lower Member of the Tolmin Formation. This is consistent with other successions of the SB, where they also appear around the mid-Bajocian boundary with overlaying radiolarian cherts of the Upper Member of the Tolmin Formation (Goričan et al., 2012). In contrast to the resediments of the Krikov Formation, the Lower resedimented limestones are particularly present in the southern part of the SB (Poljubinj, Zapoškar sections), become rarer and thinner in the central part (Perbla section), and absent in the northern part of the SB (Javor, Kobla sections) (Fig. 9; Cousin, 1973; 1981; Rožič & Popit, 2006; Rožič, 2009). Such distribution indicates that the source area of these resediments were the marginal ooidal shoals of the south-lying Adriatic Carbonate Platform.

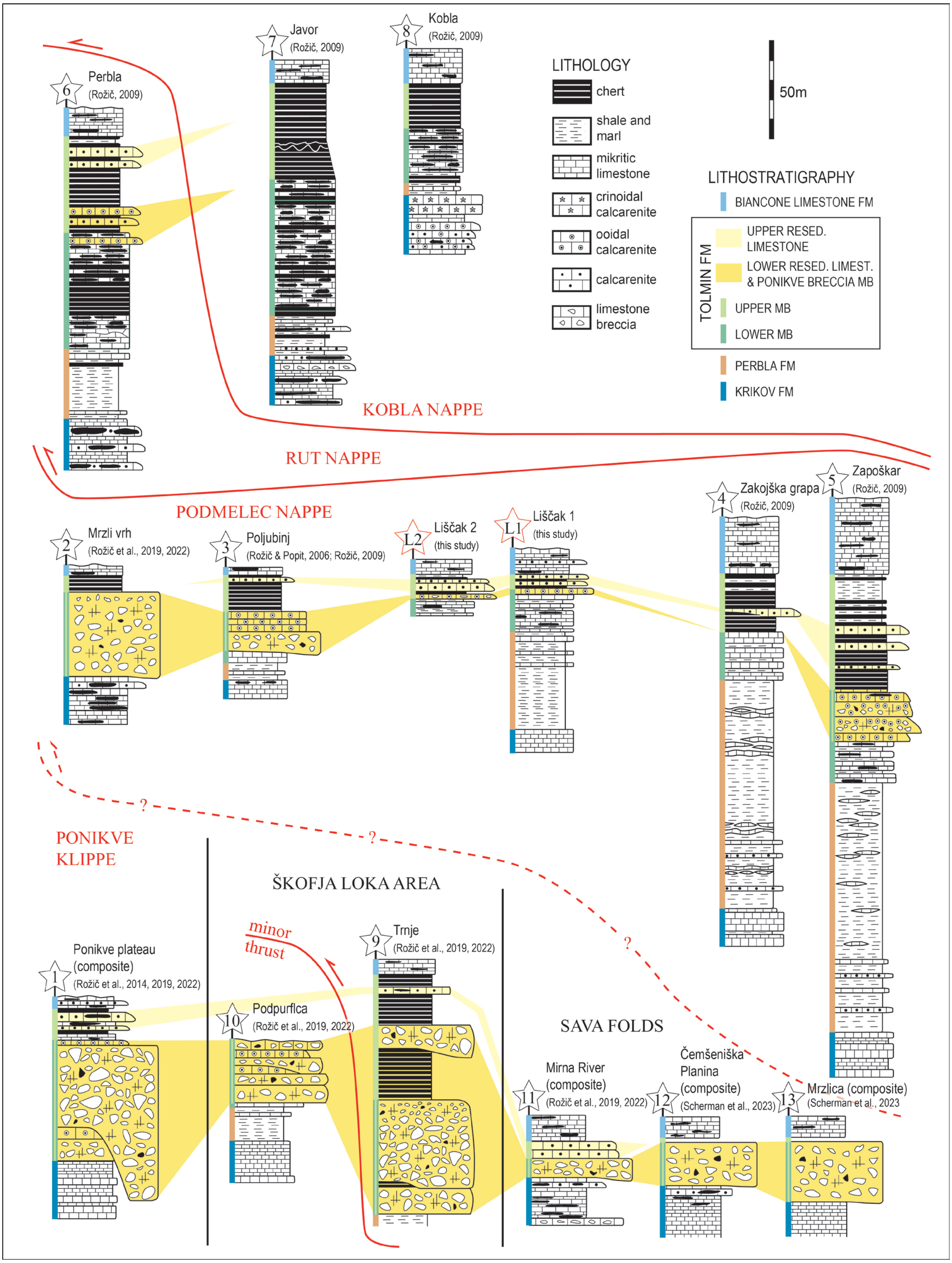

Fig. 9. Correlation of the Kneža Valley (Liščak) sections with previously studied sections of the Slovenian Basin shows that the Kneža Valley, which is relatively abundant in resedimented limestones, fits well with the general distribution scheme. These limestones are dominant in the southernmost margins of the basin (Ponikve Plateau, Škofja Loka area, and Sava Folds, including the westernmost Mrzli vrh; in our opinion these sections, with the exception of Mrzli vrh, could belong to the separate nappe), are abundant in the southern part (Poljubinj, Liščak, Zapoškar sections – Podmelec Nappe), become diluted in the central part (Perbla section – Rut Nappe), and disappear towards the north (Javor and Kobla sections – Kobla Nappe). Within the Podmelec Nappe, we observe a general thickening of the Perbla Formation towards the east (due to differential subsidence), whereas within the Tolmin Formation we document lateral changes in the presence and thickness of (Lower) resedimented limestones.

The Upper resedimented limestones are present in both sections, and their occurrence correlates well both stratigraphically and palaeogeographically with other SB sections, where Upper resedimented limestones are found in the upper part of the Tolmin Formation. The spatial distribution is the same as it is for the Lower resedimented limestones, which points to the Adriatic Carbonate Platform as a source area. However, the shift from ooid-rich (Lower resedimented limestones) to bioclast-dominated (Upper resedimented limestones) calcarenites indicate prominent changes in the source area. Their recurrence in the Late Jurassic (?Kimmeridgian) is attributed to the demise of coral-stromatoporoid reefs (resedimentation was strongly inhibited during reef-growth) and subsequent change to the sedimentation of bedded *"Clypeina"* limestone on the Adriatic Carbonate Platform (Turnšek, 1997; Buser & Dozet, 2009).

Short-distance lateral changes in the thickness of the Upper resedimented limestones between the Liščak 1 and Liščak 2 sections indicate an eastward shift of the depocentre within this stratigraphic interval. In the west (Liščak 2 section), the resediments are thicker and even amalgamated in the lower part, while further up the section they occur rarely. In addition, more clay-rich, reddish background sediments characterise the top of the Tolmin Formation. In the east (Liščak 1 section), the Upper resedimented limestones are rare in the lower part of the Upper Member but dominate the top of the Tolmin Formation. In contrast to Liščak 2 section, reddish background sediments are also absent. Because the top of the Tolmin Formation in Liščak 1 section is marked by two rather thick calciturbiditic beds an erosion within the channel is proposed to explain their absence in this section. The transition to Biancone Limestone in both sections is sharp, as in other recorded SB sections (Rožič & Reháková, 2024).

In Slovenia, deformed calcite twinning lamellae have to date only been reported from the marbles of the Pohorje area (Vrabec et al., 2004). However, we have detected them in resediments from the Kneža Valley sections, specifically in echinoderm fragments and associated syntaxial cements (Fig. 6a). These correspond to Type III, which indicates the heating of SB successions of the Podmelec Nappe prior to exhumation to temperatures above 200°C (Ferrill, 1991; Burkhard, 1993; Ferrill et al., 2004). This is consistent with previous observations of vitrinite reflectance combined with apatite fission track analysis, which determined temperatures exceeding 290 °C in SB successions (Rainer et al., 2016). It also explains the demagnetisation of SB successions detected in the Biancone Limestone Formation within the same structural unit (Lodowski et al., 2024). Tectonic loading is most likely the reason for the heating of these sediments, as the Podmelec Nappe is the lowest of all Southalpine nappes in the area (Placer, 2008; Goričan et al., 2018).

As described thus far, the Kneža Valley succession correlates well with the development characteristic for the southern parts of the SB, which occasionally received some resedimented, coarse calcareous material from the south-lying Adriatic Carbonate Platform. The quantity of resedimented material varies laterally along the southern margin (within the Podmelec Nappe successions). The thickness of the Lower resedimented limestones on Mt. Porezen (east of the Kneža Valley) ranges from 25 m of amalgamated, resedimented limestones in the Zapoškar section to virtually zero in the nearby Zakojška grapa section. To the west of the Kneža Valley, these beds again reach thicknesses of 20 m in the Poljubinj section near the town of Tolmin (Rožič & Popit, 2006; Rožič, 2009). Thus, lateral changes between the Liščak 1 and Liščak 2 sections correspond to the described lateral alternations. Additionally, in all other SB sections, a rather thick succession (usually several tens of meters) of pure radiolarian cherts is interstratified between the Lower and Upper resedimented limestones, documenting a prominent period of quiet background sedimentation without the influx of resedimented material. In contrast, the Upper resedimented limestones in the Kneža Valley almost directly overlie the Lower resedimented limestones while resediments-free radiolarian cherts are missing. This, together with the unusually low thickness of the Upper Member of the Tolmin Formation (approximately 10 m in the Kneža Valley compared to 20 m to 60 m in other sections), suggests a prominent gap in this part of the succession. The exact duration of the gap cannot be determined, but given the described facts and previous dating (interval of resediment-free radiolarites is ?Callovian to lower Kimmeridgian), we can estimate a maximum gap extending from the Late Bajocian to the Kimmeridgian, but the gap is likely narrower. The origin of this gap is debatable: in recent years, it has been shown that in the southernmost parts of the SB, the Lower resedimented limestone passes into the Ponikve Breccia Member of the Tolmin Formation, which is in most places a succession ten to almost one hundred metres thick dominated by thick and coarse-grained (often blocky) limestone breccia beds. A similar succession is also observed towards the east, in the Škofja Loka area and in the "transitional zone between the External and Internal Dinarides" (Rožič et al., 2019; 2022; Scherman et al., 2023). Below the Ponikve Breccia is a prominent gap, and these beds often lie directly above the Krikov Formation. A stratigraphic gap is usually present above as well, as the Ponikve Breccia is overlain either by very thin radiolarian cherts (Mrzli vrh section in Rožič et al., 2019, 2022), Upper resedimented limestones (Mirna section in Rožič et al., 2019, 2022) or directly by the Biancone Limestone (Čemšeniška Planina section in Scherman et al., 2023). The Ponikve Breccia, as well as the Lower resedimented limestones representing its basinal equivalent, were formed during major collapses and the subsequent retreat of the Adriatic Carbonate Platform margin (Rožič et al., 2019, 2022). This prominent sedimentary event was related to major tectonic perturbations in the region, which was situated between the opening of the Alpine Tethys to the north and west (Bill et al., 2001; Manatschal & Müntener, 2009; de Graciansky et al., 2011; Masini et al., 2013; Handy et al., 2015; Ribes et al., 2019; Le Breton et al., 2021) and the initiation of subduction within the Neotethys to the east (Borojević Šoštarić et al., 2014; Gawlick et al., 2017; Gawlick & Missoni, 2019; Bragin & Djerić, 2020; Schmid et al., 2020; van Hinselberg et al., 2020). On the local side, these events led to the formation of the rugged sea-floor relief in the southern part of the SB (e.g. the Kneža Valley and Zakojška grapa areas). Locally elevated areas (including the Kneža Valley area) acted as by-pass zones during major resedimentation events in the Middle Jurassic times. From that time on, the Kneža Valley area was starved of sediments up until the Kimmeridgian, when it became unified once again with the rest of the SB and radiolarites and Upper resedimented limestones started to deposit. However, other processes such as the removal of sediment by erosion (e.g. slumping) prior to deposition of the interval with the Upper resedimented limestones cannot be excluded in the formation of the described stratigraphic gap.

Conclusions

The Kneža Valley succession represents the last unstudied large outcrop belt of Jurassic rocks within the western part of the Slovenian Basin. The results presented here therefore complement existing knowledge of the detailed sedimentary evolution of this large-scale interplatform deeper-marine palaeogeographic unit. The studied interval encompasses the uppermost Krikov Formation (Pliensbachian), dominated by hemipelagic limestone; the clay-rich Perbla Formation (Toarcian); the Tolmin Formation, characterised by highly siliceous pelagites and resedimented limestones (Aalenian–Lower Tithonian); the Biancone Limestone Formation, composed of pelagic, calpionellid-bearing limestone (Upper Tithonian–Berriasian); and extends up to the basal breccia bed of the Lower Flyschoid Formation (Aptian). The studied succession correlates well with the other successions typical for the southern part of the Slovenian Basin. All vertical changes in pelagic sedimentation correspond to those previously described, and the presence of resedimented limestones with lateral variations in thickness is also typical for the southern part of the SB. The major peculiarity of the Kneža Valley succession is a stratigraphic gap that occurs in the middle part of the Tolmin Formation. The gap is inferred from the unusually thin radiolarian cherts (Upper Member) of the Tolmin Formation and the fact that the Upper resedimented limestones (dominated by echinoderms, *Tubiphytes*-type microproblematica, and intraclasts) lie directly above the Lower resedimented limestones (characterised by peloids and ooids). This contrasts sharply with the other sections within the Slovenian Basin, where the Upper Member of the Tolmin Formation reaches several tens of meters and the two levels of resedimented limestones are separated by an interval some tens of meters thick composed entirely of radiolarian chert. The maximum duration of this gap is estimated to extend from the Late Bajocian to the Late Kimmeridgian, but is probably narrower. Its origin is related to the large-scale collapses and retreat of the south-lying Adriatic Carbonate Platform initiated by the Bajocian regional tectonic perturbation.

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