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Signs of crustal extension in Lower Jurassic carbonates from central Slovenia

Znaki ekstenzije skorje v spodnjejurskih karbonatih osrednje Slovenije

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Abstract

The Lower Jurassic Podbukovje Formation represents a succession of shallow marine carbonate rocks deposited on the former Southern Tethyan Megaplatform and one of its successors, the Adriatic Carbonate Platform. Several outcrops of the Podbukovje Formation from central Slovenia (southern margin of the Ljubljana Moor) are presented, bearing possible evidence of Early Jurassic extensional tectonics. Peritidal facies of the lowermost, Hettangian – Sinemurian, part of the Podbukovje Formation locally interfingers with bodies of matrix supported pervasively dolomitized polymictic breccia, several metres to tens of metres thick and is locally cut by neptunian dykes some few decimetres to metres wide. The same or slightly younger part of the formation locally contains grabens/half-grabens metres to tens of metres deep and filled with poorly sorted pervasively dolomitized matrix supported polymictic breccia. Small miliolid foraminifera are present within the clasts and in the matrix. Finally, partly dolomitized blocky breccia tens of metres thick locally overlies the Pliensbachian – lowermost Toarcian limestone with lithiotid bivalves. Besides completely and partly dolomitized clasts, the breccia contains a variety of limestone clasts and preserves common radial ooids and some bioclasts within the partially dolomitized matrix.

The Hettangian-Sinemurian breccias and dykes are presumably related to the early, diffused rifting stage of the Penninic (Alpine Tethys) Ocean, whereas Toarcian breccias relate to the main, focused rifting stage. Together with evolving biota and changing paleo-oceanographic conditions, the extensional tectonics may have been an important factor behind the facies changes observed within the Podbukovje Formation.

Izvleček

Spodnjejurska Podbukovška formacija predstavlja zaporedje plitvomorskih karbonatnih kamnin, odloženih na nekdanji Južnotetidini karbonatni megaplatformi in Jadranski karbonatni platformi. V članku predstavljamo nekaj izdankov Podbukovške formacije iz osrednje Slovenije (južni rob Ljubljanskega barja), v katerih so vidni možni dokazi za zgodnjejursko ekstenzijsko tektoniko. Periplimski facies najnižjega, hettangijsko-sinemurijskega dela Podbukovške formacije se lokalno prepleta z nekaj metri do nekaj deset metri debelimi plastmi muljasto podprte povsem dolomitizirane polimiktne breče. Drugod plasti periplimskih karbonatov sekajo neptunski dajki, ki so široki do nekaj metrov in zapolnjeni z dolomikritom. Isti ali nekoliko višji deli formacije ponekod vsebujejo tektonske grabne/polgrabne, zapolnjene z nekaj metri ali desetinami metrov povsem dolomitizirane slabo sortirane, muljasto podprte polimiktne breče. V klastih in vezivu so prisotne drobne miliolidne foraminifere. Delno dolomitizirana blokovna breča je prisotna tudi v zgornjih delih Podbukovške formacije nad pliensbachijsko – spodnjetoarcijskim litiotidnim apnencem. Poleg povsem in delno dolomitiziranih klastov breča vsebuje tudi raznolike klaste apnenca. V vezivu so prisotni radialno žarkoviti ooidi in nekaj bioklastov.

Hettangijsko–sinemurijske breče in dajke povezujemo z zgodnjo, razpršeno fazo razpiranja Peninskega oceana (Alpske Tetide), toarcijske breče pa z glavno, fokusirano fazo razpiranja. Ekstenzijska tektonika je skupaj z razvojem biote in spremembami v paleo-oceanografskih razmerah pomembno vplivala na faciesne spremembe med nižjimi in višjimi deli Podbukovške formacije.

Introduction

The Late Triassic to Early Jurassic paleogeography of central Pangea and the western Tethys Ocean was greatly affected by the opening of the Central Atlantic and related systems of basins belonging to the Penninic Ocean (Ratschbacher et al., 2004; Meschede & Warr, 2019). The main rifting phase started during or at the end of the Pliensbachian and into the Toarcian, and is reflected in the Southern Alps in the subsidence and eventual drowning of smaller platform areas, together with the establishment of marine plateaus (Buser, 1989; Bosellini, 2004; Šmuc, 2005; Berra et al., 2009; Rožič & Šmuc, 2009; Šmuc, 2010; Rožič et al., 2014). The main rifting event was preceded by a phase of diffuse early rifting, which occurred from the late Hettangian to the Sinemurian. In the western and central Southern Alps, this phase is manifested through the subsidence of the Lombardian and Belluno basins (Winterer & Bosellini, 1981; Bertotti et al., 1993; Sarti et al., 1993; Clari & Masetti, 2002; Berra et al., 2009), whereas accelerated subsidence, increase in slope inclination, segmentation, and block tilting have been documented in the basin areas in the eastern Southern Alps (Rožič et al., 2017).

In the External Dinarides, major shifts in carbonate platform facies were described from the uppermost Pliensbachian – Toarcian successions (Dragičević & Velić, 2002; Črne & Goričan, 2008; Sabatino et al., 2013; Martinuš & Bucković, 2015; Ettinger et al., 2021), but the earlier tectonic events are not as well documented and their influence on the evolution of the platform has not yet been fully evaluated (Dozet & Strohmenger, 1996; Knez et al., 2003).

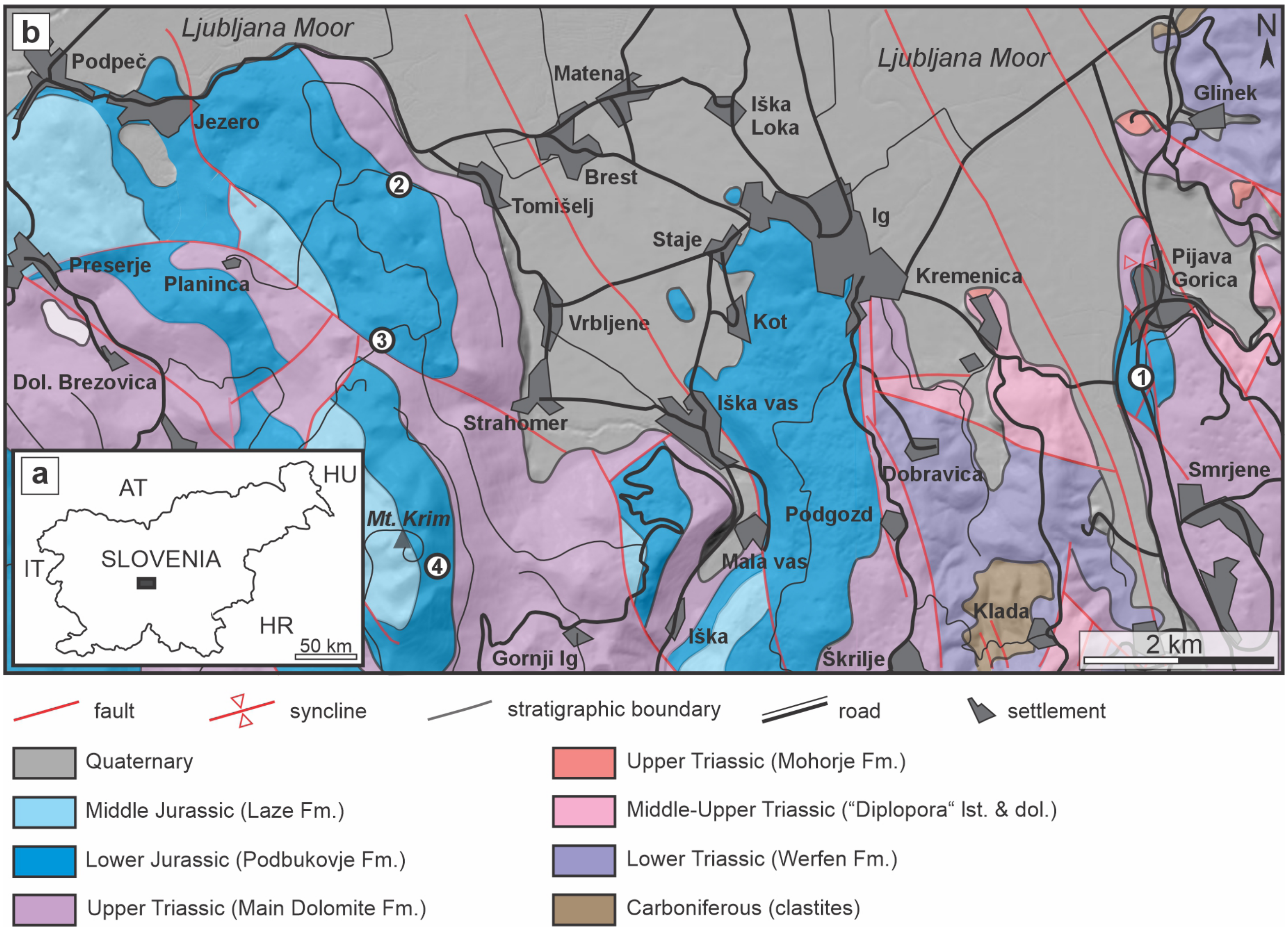

Fig. 1. Location and geological map of the study area. **a:** Outline of Slovenia. Position of the area, shown in Fig. 1b is indicated by a black rectangle. **b:** Detailed map and geological map of the studied area. Position of the described outcrops 1–4 (see text and Table 1) is indicated by the circled numbers 1–4. Geological map (Buser et al., 1967; Buser, 1968) is drawn over the LIDAR digital model of the relief, 2015. Data source: Slovenian Environment Agency. Accessed via portal Geopedia (Sinergise d.o.o.) in May 2023.

The aim of this paper is to present possible evidence for the Early Jurassic extensional tectonics in the area of the present-day External Dinarides (central Slovenia) related to both tectonic phases mentioned above. We suggest that Early Jurassic extensional tectonics was an important force behind the transition from the Hettangian facies association of intertidal flats to the Sinemurian and Pliensbachian shallow lagoon and shoal facies.

Geological Setting

The presented successions of Lower Jurassic rocks deposited in the shallow marine environments of the Southern Tethyan Megaplatform (sensu Vlahović et al., 2005). During the late Early Jurassic, this large entity broke up into several smaller (but still relatively large) carbonate platforms, one of which was the Adriatic Carbonate Platform, which extended from present-day NE Italy to Montenegro and Albania (Dragičević & Velić, 2002; Vlahović et al., 2002, 2005). To the north (present orientation), the platform faced the Slovenian Basin (Buser, 1989, 1996). The Adriatic Carbonate Platform was separated from other platform areas to the west through the formation of the Adriatic Basin that connected the Belluno and the Ionian Basins (Vlahović et al., 2005). The presented outcrops are located in central Slovenia, on the southern rim of the Ljubljana Moor Basin (Fig. 1). Structurally, the area belongs to the Hrušica Nappe of the External Dinarides (Placer, 1999), and is dissected by major SSE-NNW directed dextral strike-slip and associated faults (Buser et al., 1967; Pleničar, 1970; Buser, 1968, 1974).

The Lower Jurassic succession has been assigned to the Podbukovje Formation and subdivided into four to five members (Fig. 2) (Dozet & Strohmenger, 2000; Dozet, 2009; Brajkovič et al., 2022). The lowermost Krka Limestone Member represents bedded intertidal limestone and dolostone (Dozet, 1993). According to Gale (2015), and Gale and Kelemen (2017), Lofer-type cycles of the Hettangian part of this member upwards pass into predominantly subtidal micritic and oolitic limestone. The following Orbitopsella Limestone Member is dominated by thick-bedded limestone in which foraminifera Orbitopsella first occurs. Breccia, oncoid, gastropod, and megalodontid limestone beds are sporadically present (Dozet, 2009). The following Lithiotis Limestone Member contains variety of facies types, deposited under restricted subtidal and intertidal conditions. Lithiotid bivalves occur at several levels and are a distinctive feature of this member (Dozet, 2009). The next, Oolitic Limestone

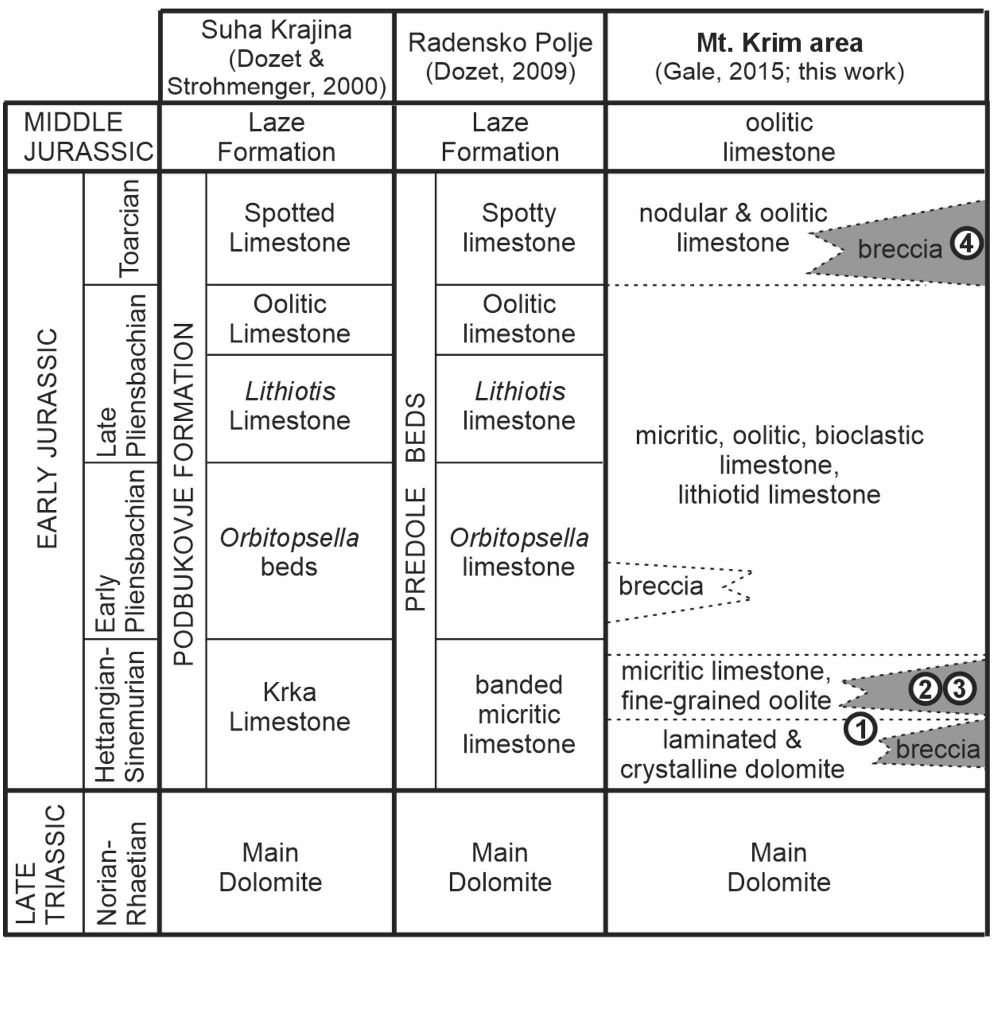

Fig. 2. Lithostratigraphic units of the Lower Jurassic carbonates of central Slovenia and approximate stratigraphic position of the presented outcrops. Schemes for Suha Krajina and for Radensko Polje are drawn after Dozet and Strohmenger (2000) and Dozet (2009), respectively. The lithological units from the Mt. Krim area are modified after Gale (2015).

Member is characterised by oolitic limestone facies (Dozet & Strohmenger, 2000; Dozet, 2009). The Podbukovje Formation ends with the Spotted (or Spotty) Limestone Member, representing succession of thin to medium thick beds of dark grey limestone of nodular-like appearance. Limestone is mostly micritic (Dozet, 2009).

Previous records of Lower Jurassic breccias in southern Slovenia

Although it remains valid to this day that the Lower Jurassic platform carbonates of the southern Slovenia show little or no evidence of Early Jurassic extension, there are a few mentions of breccias that could be related to palaeotectonics. Breccias positioned atop the Upper Triassic Main Dolomite Formation were mentioned from the vicinity of Logatec (Buser, 1965). Ogorelec and Rothe (1993) described breccias at the boundary between the Upper Triassic platform carbonates and Jurassic deposits in the Čepovan-Lokovec section. Blocky breccias exceed 10 m or 20 m in thickness and laterally pinch-out. Fragments of corals within the breccia indicate earliest Jurassic age. Knez et al. (2003) described poorly sorted (clasts ranging in size from very fine pebble to boulder), chaotic, matrix- and clast-supported dolomitic breccia discordantly lying on peritidal carbonates. No fossils were found, but based on the superposition the breccia was formed close to the Triassic-Jurassic boundary. Authors interpreted breccia as "synsedimentary, fault, fissure, or small graben-related, tectonically influenced phenomenon" (Knez et al., 2003, p. 34–35). From younger beds, Buser (1965, 1974) mentioned limestone breccia beds alternating with light grey lower and middle Lower Jurassic limestone in the area between Ivančna Gorica and Trebnje. Lithiotid bivalves have been found in some of the limestone beds, indicating that the sedimentation of breccias lasted up to the Pliensbachian (Buser, 1974). Upper Lower Jurassic to Middle Jurassic dolomitic breccias were also documented between Velika Gora and Loški Potok (Buser, 1965). Breccias were also illustrated in a schematic column of middle Lower Jurassic (?) beds at Korinj, but not explained in detail (Strohmenger & Dozet, 1991). Finally, from the area of Mt. Krim studied herein, Miler and Pavšič (2008) described breccias within the Hettangian and Sinemurian, as well as the Pliensbachian and the Toarcian parts of the succession. The thickness of the breccia beds is not indicated, but the authors mention up to 15 cm large clasts in Toarcian breccias, which have wackestone matrix containing ooids and bioclasts, including miliolid foraminifera.

Methods and materials

The sections of Lower Jurassic shallow marine carbonates presented herein were investigated between the years 2014 and 2022. The sections are situated along roads or hiking trails. The stratigraphic thickness of the studied successions varies from a few metres to several tens of metres and is indicated in the Results sections. For the purpose of petrographic description, 63 samples of rock were cut for thin sections of 28 × 47 mm in size. Thin sections were investigated with a polarizing microscope. Carbonates were classified according to Dunham (1962), and Embry and Klovan (1971). In forming the textural name, we follow recommendations by Wright (1992) putting the predominant component first. Fifteen thin sections of breccias and the surrounding rock were stained with Alizarin Red S dye in order to determine the presence of dolomite. The texture of the dolomite was described in accordance with Sibley and Gregg (1987). Although the term "dolostone" has not gained wide usage among sedimentary petrologists, we use this term here to distinguish dolomitic rock from the mineral dolomite (see also Warren, 2000, p. 7).

Results

The examined outcrops are presented according to superposition. The coordinates of the sections are given in Table 1. Due to the presence of stromatolites, herein presented outcrops 1–3 and the lower part of the section 4 lithostratigraphically belong to the lowermost, Krka Member. Breccias overlying the Lithiotid Limestone Member in the upper part of the section 4 are likely positioned lateral to the lower part of the Spotted/Spotty Member sensu Dozet and Strohmenger (2000) and Dozet (2009).

Table 1. "Coordinates of the presented outcrops and sections."

Locality	Stratigraphic position	Latitude	Longitude
Pijava Gorica (Outcrop 1)	Krka Limestone Member (Hettangian)	45°56'40.29'' N	14°34'17.68'' E
Tomišelj (Outcrop 2)	Krka Limestone Member (Sinemurian)	45°57'46.69'' N	14°28'19.15'' E
Strahomer (Outcrop 3)	Krka Limestone Member (Sinemurian)	45°56'57.24'' N	14°28'0.86'' E
Mt. Krim (Outcrop 4, lower)	Krka Limestone Member (Hettangian)	45°55'16.31'' N	14°28'38.02'' E
Mt. Krim (Outcrop 4, upper)	Unnamed member (Toarcian)	45°55'38.72'' N	14°28'28.90'' E

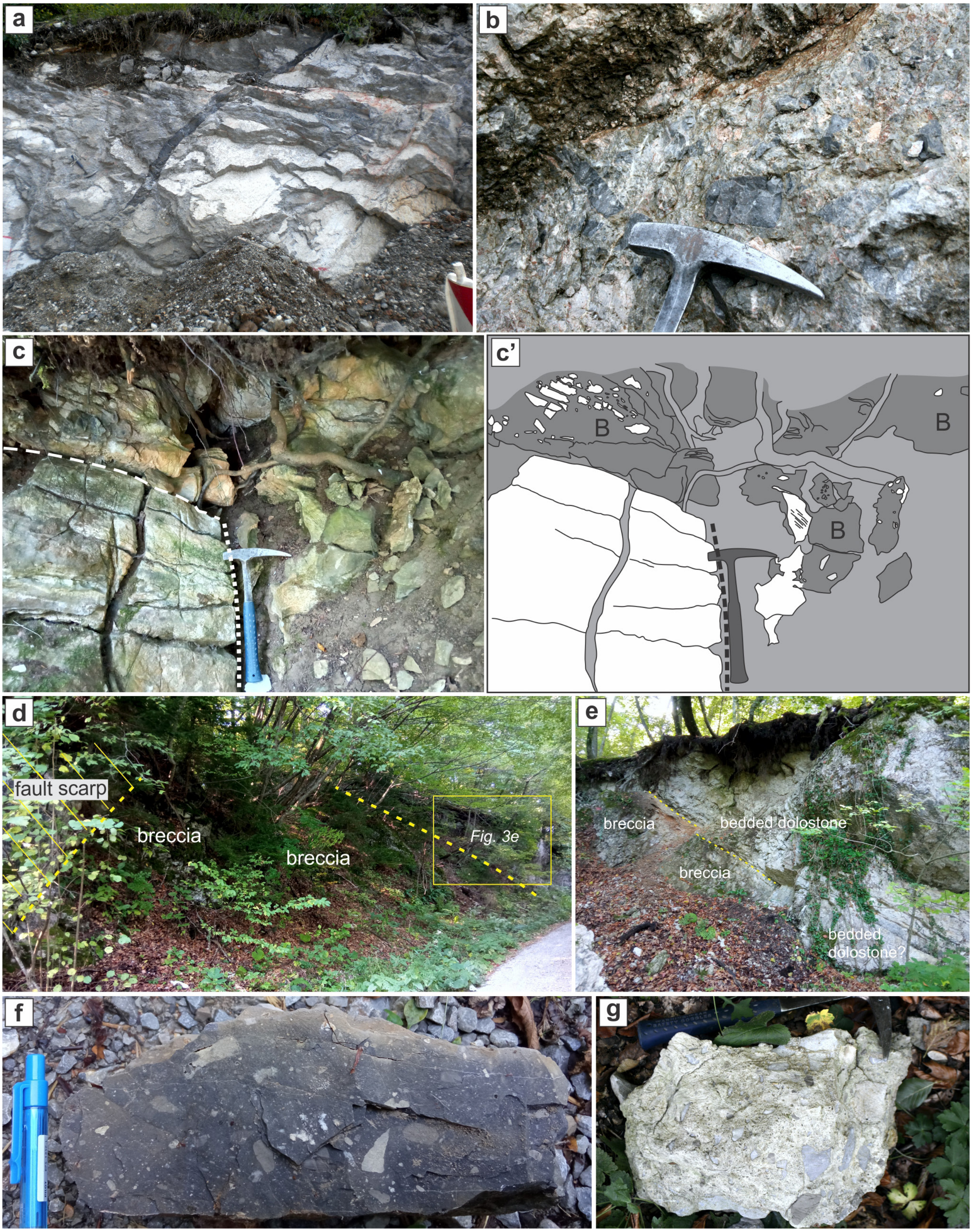

Fig. 3. Field view of the outcrops 1–3. **a:** Neptunian dykes cutting through Lower Jurassic dolostone at Pijava Gorica (outcrop 1). **b:** Clasts of dolostone floating in dolomicrite filling the Neptunian dykes at Pijava Gorica (outcrop 1). **c–c':** Base of the matrix-supported dolomitic breccia in outcrop 2 above Tomišelj (lower 4 m of sedimentary log in Fig. 4). **d:** Eastern side of the outcrop of dolomitic breccia at the roadcut between the Sleme, Strmec, and Trešenk summits west of Strahomer (outcrop 3). Yellow lines indicate the position of a paleo-fault plane (left side) and the bedding plane separating the breccia from the overlying stromatolitic dolomite. **e:** Western side of the outcrop depicted in Figure 3d. Yellow line indicates the position of the upper bedding plane of breccia. **f:** Hand sample of matrix-supported dolomitic breccia from outcrop 2. Note the different colours of clasts and that some clasts (left side of the sample) themselves are matrix-supported breccia. **g:** Hand sample of Toarcian breccia, outcrop 4 (upper).

Outcrop 1: Neptunian dykes within the Krka Limestone Member at Pijava Gorica (Hettangian – ?Sinemurian)

The roadcut between Pijava Gorica and Smrjene exposes medium thick-bedded dark grey dolostone (dolomicrite). The section is crossed by numerous smaller faults, and the bedding orientation changes, so the actual thickness of the succession cannot be determined. Planar laminations (stromatolites) are locally visible. The dolostone is crosscut by dykes filled with darker dolostone (dolomicrite), which locally contains angular clasts of dolostone lithologically identical to the surrounding rock (Fig. 3a–b). The size of clasts ranges from 5 mm to 50 cm. Some of the clasts closely fit together, indicating very short transport, while others float within the matrix.

Outcrop 2: Syndepositional breccia within the Krka Limestone Member above Tomišelj (Hettangian – Sinemurian)

Dolomitized matrix-supported carbonate conglomeratic breccia with characteristic brownish-grey matrix is found at several localities around Mt. Krim. However, due to the intense weathering of the dolostone and the dense vegetation, outcrops with visible relationships with the surrounding lithologies are difficult to find. Dolomitic breccia a few metres thick was discovered roughly west of Tomišelj along a forest road running along the eastern slopes of the small summits Gadna (elevation 521 m) and Srobotnik (elevation 603 m) (Fig. 1).

The described section is approximately 10 m thick (Fig. 4). It starts with thin to thick beds of light grey dolostone (dolosparite and dolomicrite). Stromatolites and desiccation cracks are present in dolomicrite. Upwards (immediately below the breccia level) lies a bed of light grey dolostone 140 cm thick with stromatolite intraclasts in its lower part. The described beds dip at 240/55 and laterally end at a steep scarp, interpreted as a normal paleofault (Fig. 3c). The succession continues with pervasively dolomitized conglomeratic breccia, which covers the paleofault and fills the graben. The breccia is matrix-supported and at least 4.5 m thick within the graben. The clasts vary in colour and are angular to subrounded. Some are shattered into mosaic-like configurations. Clast dimensions decrease upwards: close to the paleofault they measure up to 15 cm, while they are up to 2 cm large near the top of the breccia. In the graben-filling succession (basinward sensu Matenco & Haq, 2020), the breccia is followed by several thinner and possibly internally layered beds of pervasively dolomitized fine-grained polymict breccia. The clasts in this fine-grained breccia consist of crystalline dolostone, as well as completely dolomitised calcimudstone, peloidal-bioclastic packstone, and bioclastic packstone, transitioning to calcimudstone. Dolomitized bioclastic packstone is relatively abundant in miliolid foraminifera (Fig. 5a–b, e). The same foraminifera can also be found within the finely crystalline dolomitized breccia matrix, indicating the same/similar age of the matrix and (at least part of) the clasts. Sinemurian foraminifera were determined from beds lying approximately 60 stratigraphic metres higher in the succession (section "Tomišelj 1" in Gale & Kelemen, 2017).

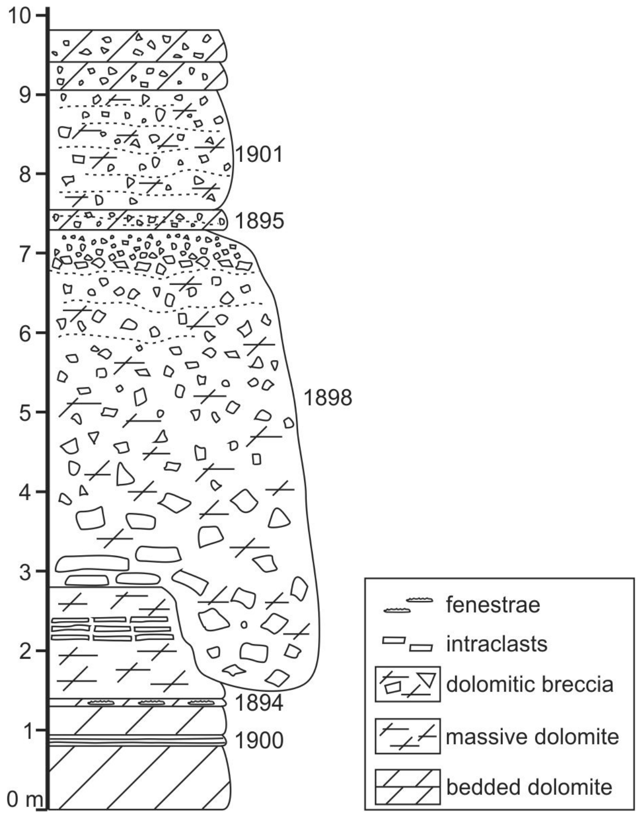

Fig. 4. Sedimentary log of the breccia body within the Lower Jurassic (Hettangian?) Krka Limestone Member above Tomišelj (outcrop 2). Numbers to the right indicate thin section numbers.

Outcrop 3: Matrix-supported dolomitic breccia within the Krka Limestone Member west of Strahomer (Hettangian – Sinemurian)

Roadcuts between the Sleme, Strmec, and Trešenk summits west of Strahomer feature long exposures of pervasively dolomitized matrix-supported breccia, macroscopically identical to the breccia in outcrop 2, described above. At the eastern (lowermost) side of the outcrop bedded light grey dolostone (dolosparite and dolomicrite with rare fenestrae) is exposed (Fig. 3d). The bedded

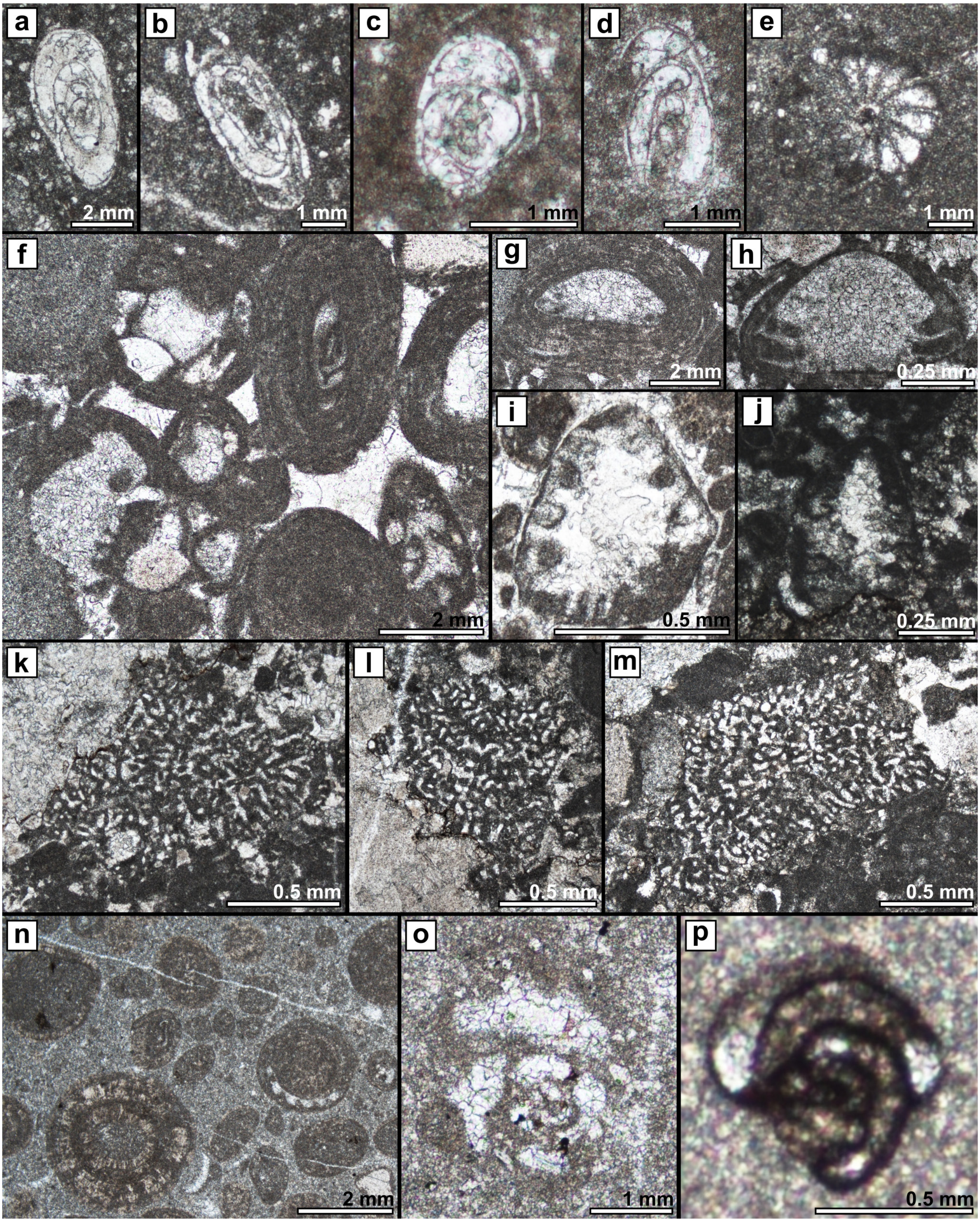

Fig. 5. Selected foraminifera from the described outcrops. **a–b:** Miliolid foraminifera (?*Istriloculina* sp.). Outcrop 2. Thin section 1895. **c–d:** Miliolid foraminifera (?*Istriloculina* sp.). Outcrop 3. Thin section 1903. **e:** Undetermined foraminifera. Outcrop 2. Thin section 1895. **f:** Various foraminifera in ooids (Trocholinidae and Miliolida) and as free particles (?*Ammobaculites* or ?*Everticyclammina* sp.). Outcrop 4 (upper). Thin section 1927. **g:** Trocholinidae (cf. *Trocholina conica* (Schlumberger).). Outcrop 4 (upper). Thin section 1927. **h:** Trocholinidae (cf. *Trocholina conica* (Schlumberger).). Outcrop 4 (upper). Thin section 1920. **i:** Trocholinidae (cf. *Coscinoconus alpinus* Leupold in Leupold and Bigler). Outcrop 4 (upper). Thin section 1933. **j:** *Coscinoconus* sp. Outcrop 4 (upper). Thin section 1916. **k–m:** *Socotraina serpentina* Banner, Whittaker, BouDagher-Fadel and Samuel. Outcrop 4 (upper). Thin section 1930. **n:** Sessile foraminifera on radial ooids. Outcrop 4 (upper). Thin section 1932. **o:** ?*Ammobaculites* sp. Outcrop 4 (upper). Thin section 1914. **p:** *Meandrovoluta asiagoensis* Fugagnoli and Rettori. Outcrop 4 (upper). Thin section 1911.

dolostone dips at 300/25. The beds are truncated along a subvertical (120/80) plane, a possible palaeofault that separates the bedded dolostone from the breccia. The matrix-supported to locally clast-supported breccia is poorly exposed and attains a thickness of at least 25–30 m. Clasts within the breccia are very poorly sorted (Fig. 3f–g). On average, they form approximately 20 % of the rock, but are more abundant near the mentioned paleofault. The clasts are generally a centimetre in size, but the size of the clasts varies considerably between the samples. The largest recorded clasts measure approximately 15 cm, while the smallest are less than 0.2 mm in size. Macroscopically, they are white, greyish-brown, and brown laminated dolomicrite. At the microscopic level, the following lithoclasts can be distinguished: dolomitic tectonic breccia, crystalline dolostone, pervasively dolomitized lithoclasts with recognisable primary composition of mudstone, fenestral mudstone, laminated mudstone (stromatolite), peloidal wackestone, bioclastic-peloidal wackestone and packstone, and intraclastic grainstone. Clasts are angular to subrounded, and highly variable in shape. No connection between lithological composition and roundness was noted. The matrix is brownish dolomicrite. Small benthic foraminifera are rare, both within the clasts and in the matrix (Fig. 5c–d). The breccia is crosscut by younger veins, up to 2 cm thick and filled with dolomitic cement.

At the opposite, western side of the roadcut the breccia at the top laterally and vertically passes into bedded light grey dolostone (dolosparite) and laminated dolostone (dolomicrite) (Fig. 3e). Small-scale cracks, filled with black dolomicrite (seemingly identical to the neptunian dykes in outcrop 1), are present within beds of light grey dolosparite overlying the breccia.

Outcrop 4 (lower part): Dolomitic breccia within the Krka Limestone Member on the NE slope of Mt. Krim (Hettangian-Sinemurian)

A thick succession of pervasively dolomitized breccia is exposed within a 280 m long succession underlying Sinemurian and Pliensbachian limestone on the hiking path from Gornji Ig to Mt. Krim. The area was covered also by a detailed geological map of Miler and Pavšič (2008), where the same breccias are briefly described. The succession was logged schematically because of the poor visibility of bed boundaries (Fig. 6). The lower 100 m of the succession is represented by bedded dolostone, in which stromatolites, birdseyes fenestrae, stromatolitic intraclasts, and black pebbles

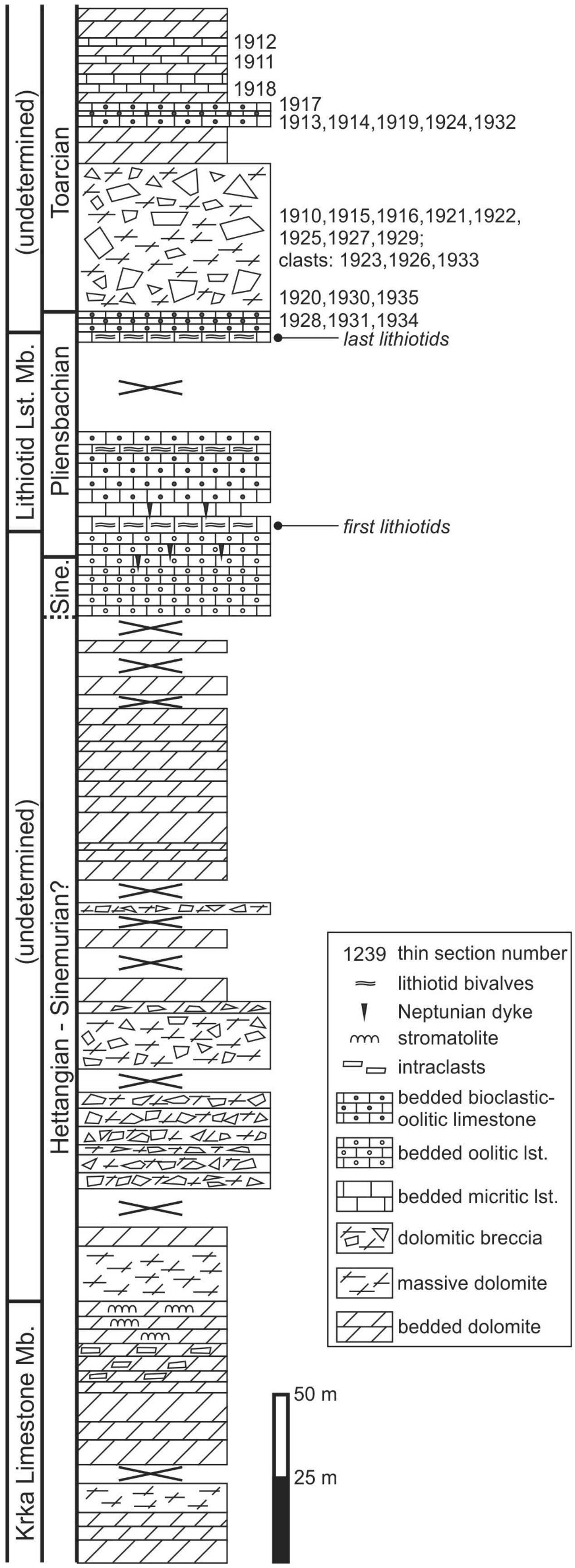

Fig. 6. Stratigraphic succession of Lower Jurassic (Hettangian – Toarcian) beds on the NE slope of Mt. Krim (all of outcrop 4). Numbers to the right indicate thin section numbers.

are locally present. Fractures filled with dark dolostone (dolomicrite) resembling neptunian dykes from outcrop 1, were noticed in the upper part of this interval. The next 50 m of the succession is dominated by chaotic and poorly sorted dolomitic breccias, deposited in beds 3–17 m thick. Breccia is clast or matrix-supported, with clasts ranging from 1 mm to at least 30 cm in size. The average clast size is approximately 5 cm. Clasts are angular to rounded, dolomicritic or dolosparitic, and of different colours. The section continues upwards with thick to massive beds of dolostone, with a single bed of dolomitic breccia at 190 m of the succession. At approximately 290 m of the succession, the dolostone is succeeded by bedded limestone. The lower part of the limestone succession roughly corresponds to the Orbitopsella Limestone Member (although *Orbitopsella* first occurs approximately 30 m above the first limestone bed). The lowest occurrence of the lithiotid bivalves, 41 m above the base of the limestone part of the section, defines the base of the approximately 85-m-thick Lithiotid Limestone Member (Fig. 6). Within the limestone interval, oolitic and bioclastic limestones predominate, with bioclasts becoming more common in the Lithiotid Limestone Member. Micritic limestone is subordinate. Beds are between 5 cm and 160 cm thick. Small-scale neptunian dykes are locally present within this member.

Outcrop 4 (upper part): Dolomitized blocky breccia overlying the Lithiotid Limestone Member on the NE slope of Mt. Krim (Toarcian)

After the highest occurrence of the lithiotid bivalves, a few beds of nearly black limestone (intraclastic-bioclastic grainstone with oncoids) follow. Foraminifera *Haurania deserta* Henson is numerous in some beds, while ?*Bosniella oenensis* Gušić and *Involutina liassica* (Jones) are less common. According to Velić (2007), the stratigraphic range of *H. deserta* is from the late Sinemurian to the end of the Pliensbachian, and *B. oenensis* is limited to the Pliensbachian. Other bioclasts are fragments of bivalve shells, gastropods, calcimicrobes, microproblematica *Thaumatoporella*, echinoderms, and dasycladacean algae.

Limestone is followed by poorly exposed dolostone (dolosparite) with small lithoclasts overlain by one or several beds (this part of the section is mostly covered) of very poorly sorted, coarse-grained partly dolomitized polymictic breccia (Figs. 3g, 6). Clasts are rounded to angular, and on average 3–5 cm large. The largest clasts are up to 30 cm in size. Some clasts completely escaped dolomitization or are only partially dolomitized (mudstone, bioclastic wackestone, oolitic grainstone, pelletal grainstone, bioclastic-intraclastic-oolitic grainstone, peloidal-oolitic-crinoidal grainstone, peloidal-bioclastic grainstone, peloidal grainstone, and lithoclastic-bioclastic rudstone), while the others are completely replaced by dolomite and rarely show their original texture and composition (one exception being oolitic grainstone, mimetically replaced by coarse, planar-s dolomite). The lithoclastic-bioclastic rudstone clasts contain *Socotraina serpentina* Banner, Whittaker, BouDagher-Fadel, and Samuel (Fig. 5k–m), *Siphovalvulina* sp., *Meandrovoluta asiagoensis* Fugagnoli & Rettori, and *Haurania deserta* Henson. Trocholinidae (Fig. 5f–j), Miliolida, and *Pseudopfenderina* were determined from other clasts. Besides the lithoclasts, non-dolomitized radial ooids, fragments of corals, sponges, gastropods, and echinoderms are present in the dolomitized matrix of the breccia. Some ooids formed around tests of foraminifera Miliolida and ?*Siphovalvulina*.

Poorly sorted breccias are followed by poorly exposed dolostone (dolosparite), followed by thin- to medium thick-bedded, almost black limestone (oolitic wackestone, packstone and grainstone, mudstone, rare spiculitic packstone, and bioclastic-pelletal packstone). Ooids are of the radial type. Skeletal material is relatively rare: echinoderms, gastropods, bivalves, ostracods, pelagic crinoids, foraminifera, sponge spicules, and calcareous spheres (radiolarians?) are present. Foraminiferal assemblage comprises common agglutinated sessile forms (Fig. 5n), ?*Ammobaculites* sp. (Fig. 5o), *Meandrovoluta asiagoensis* Fugagnoli & Rettori (Fig. 5p), *Ophthalmidium* sp., *Lenticulina* sp., nodosariids, Textulariida, and Epistominidae. The section ends with bedded dolostone.

For the breccia described above, Toarcian age is assumed. This is supported by the findings of *S. serpentina*, which was described from the upper Lower Jurassic (Toarcian) beds (Banner et al., 1997; Martinuš & Bucković, 2015; BouDagher-Fadel, 2018). Based on the presence of *M. asiagoensis* with the stratigraphic range from Sinemurian to Toarcian (Velić, 2007), Toarcian age is also presumed for the oolites overlying the breccia.

Dolomitization

Although all of the breccias described above show some degree of dolomitization, there are some notable differences between the Hettangian-Sinemurian and the Toarcian breccias. The Hettangian-Sinemurian breccias from outcrops 2, 3, and 4 (lower part) are completely (pervasively) dolomitized (Fig. 7a–b). Non-mimical dolomitization of the clasts includes the growth and replacement of original textures by medium (0.025 mm) to coarse (0.330 mm) subhedral dolomite crystals of equal or different sizes (unimodal or polymodal). Other clasts show mimical replacement by very small subhedral dolomite. Staining with Alizarin Red S revealed that micritic clasts are also composed of dolomite, which is thus very finely crystalline and mimically replaces fine-grained calcimudstone. Pervasive mimical dolomitization by very small crystals of dolomite was also recognized in peloidal grainstone and laminated (stromatolitic) dolomicrite. The matrix of the Hettangian-Sinemurian breccias is non-mimically replaced by equigranular, rarely polymodal, anhedral (?) to subhedral dolomite.

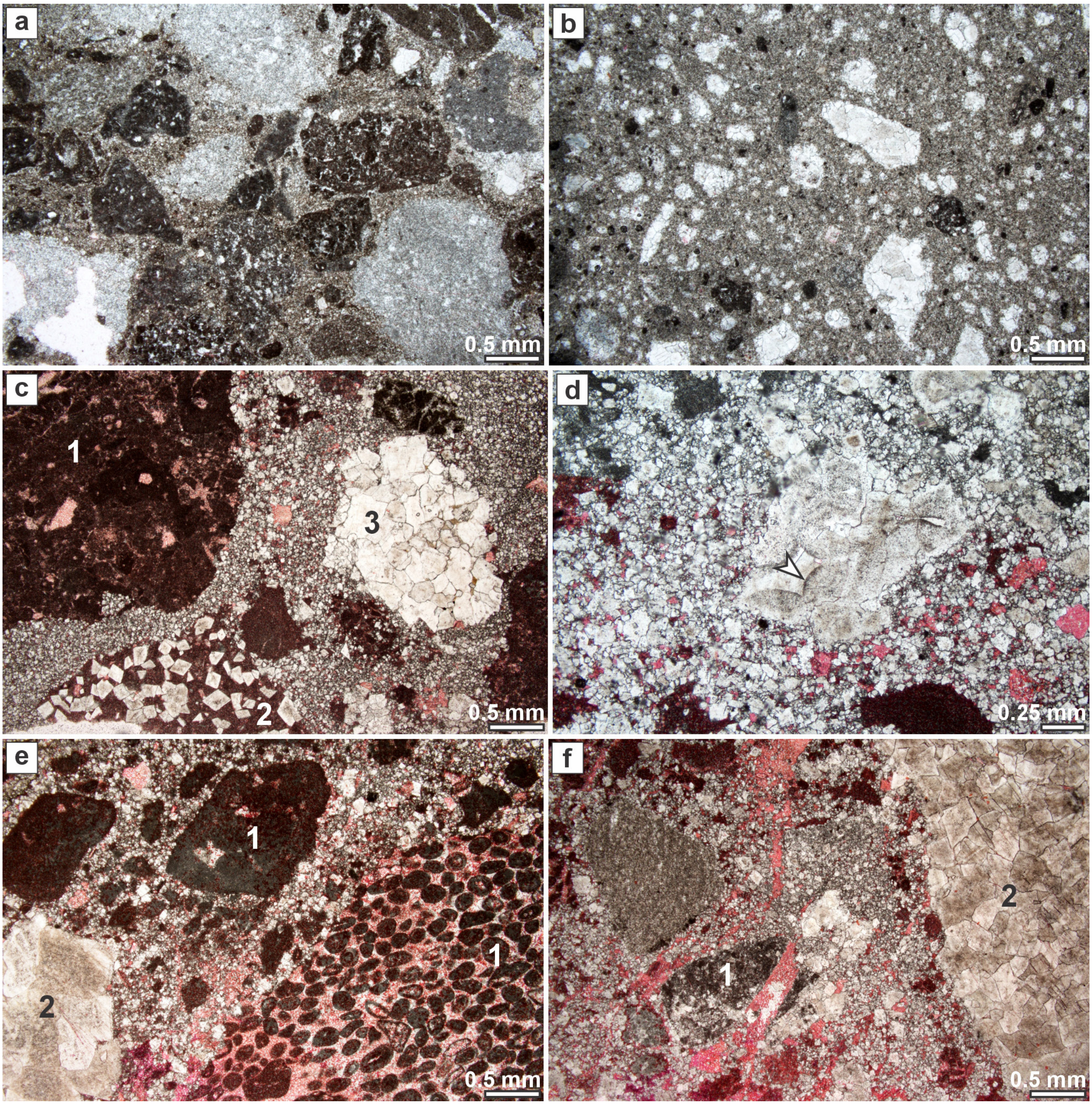

Fig. 7. Dolomitization of Lower Jurassic breccias. All pictures are from the stained parts of the thin sections. **a:** Pervasive dolomitization of clasts and matrix. Thin section 1903; outcrop 3; Sinemurian. **b:** Pervasive dolomitization of clasts and matrix. Most dolomite in the clasts is non-mimic, subhedral. Thin section 1906; outcrop 3; Sinemurian. **c:** Different degrees of dolomitization of breccia. Some clasts are undolomitized (1), others partly dolomitized with euhedral rhomboidal dolomite (2), and some non-mimically replaced by subhedral dolomite (3). The breccia matrix is mostly dolomitized. Thin section 1921; outcrop 4 (upper); Toarcian. **d:** Mimical dolomitization of oolitic grainstone. Outlines of ooids is indicated by the arrowhead. Thin section 1915; outcrop 4 (upper); Toarcian. **e:** Partial dolomitization of breccia, with undolomitized (1) and completely dolomitized clasts (2). Thin section 1916; outcrop 4 (upper); Toarcian. **f:** Partial dolomitization of breccia. Mimical (1) and non-mimical (2) dolomitization of clasts. Thin section 1916; outcrop 4 (upper); Toarcian.

In contrast, Toarcian breccia shows only partial dolomitization (Fig. 7c–f). Some of the clasts are completely devoid of dolomitization or are only partly dolomitized. These are calcimudstone (partially dolomitized clasts show non-mimical growth of euhedral, rhombic dolomite crystals), peloidal packstone, and bioclastic wackestone. Oolitic grainstone is present in a non-dolomitized as well as completely dolomitized variety. The latter comprises mimical replacement by coarse subplanar dolomite. Completely dolomitized clasts include non-mimical, unimodal, subhedral dolomite, and polymodal, non-mimical subhedral dolomite. The matrix of the breccia is partially or completely dolomitized, non-mimically replaced by euhedral crystals of dolomite of different sizes (polymodal), or by both, subplanar and euhedral crystals of dolomite.

Discussion

Interpretation of described outcrops

The outcrops described above contain two types of sedimentary bodies that are here interpreted as evidence for extensional tectonics: (1) neptunian dykes, and (2) breccias associated with palaeofaults.

Neptunian dykes are "sedimentary dykes and sills formed by sediment filling of submarine fissures or cavities" (Lehner, 1991, p. 593). They can be "caused by extensional movement of lithified and indurated sediment due to gravitational mass movement or differential tectonic movement" (Lehner, 1991, p. 593). Alternatively, open spaces could be created by dissolution by meteoric waters during the emergence of the platform (Winterer et al., 1991). Early Jurassic tectonics was advocated as a possible cause for the formation of the neptunian dykes cutting through the shallow platform deposits of the former Trento Platform in the Sasso Rosso region in Trentino, northern Italy (Lehner, 1991), and for the dykes transecting the Upper Triassic and Lower Jurassic peritidal facies of the Julian Carbonate Platform in the Julian Alps, Slovenia (Babić, 1981; Šmuc, 2005; Črne et al., 2007). These last are dated as probably Pliensbachian in age (Črne et al., 2007). Small-scale neptunian dykes have also been recognized in Sinemurian limestone from the vicinity of Ig, but they are filled with intraclastic-bioclastic packstone containing Upper Jurassic microfossils (Rožič et al., 2018). Evidence of neptunian dykes and sills is unambiguous in outcrop 1. No fossils were found in the infill of neptunian dykes at Pijava Gorica. Based on locally derived clasts that are barely detached from the sides of the dykes and sills, we assume that their age is similar to that of the host rock, i.e. Hettangian – ?Sinemurian in age.

In the case of outcrops 2 and 3, it seems that breccia deposited along fault-scarps. Combining the existence of paleo-scarps and the large thickness of the breccia in outcrops 2 and 3, interpretation of this as intraformational breccia related to subaerial exposures and the Lofer cycle-type of sedimentation can be excluded. Instead, breccias deposited at the base of the scarp, which itself was created by a normal fault in the form of submarine talus (see Mišík et al., 1994; Ruiz-Ortiz et al., 2004; Aubrecht & Szulc, 2006; Ortner et al., 2008). The matrix-supported nature of the breccia suggests deposition from submarine debris flows (Fig. 2 in Ribes et al., 2019), rather than via collapse of the footwall (Ortner et al., 2008). As described above, the breccia from outcrop 2 is of Sinemurian age or slightly older. Seemingly the same miliolid foraminifera were found in the clasts and matrix of breccias from outcrops 2 and 3, so Hettangian – Sinemurian age is also assumed for the latter too. In the section below the summit of Mt. Krim (outcrop 4), carbonate breccias occur below as well as above the Lithiotid Limestone Member. The first breccia is lithologically identical to the breccia recorded in outcrops 2 and 3, but the geometry of the breccia could not be determined, nor were any palaeofaults identified.

The breccia overlying the Lithiotid Limestone Member clearly differs from the above mentioned breccias in age, in the composition of the clasts and matrix, in the manner of dolomitization, and in their being under- and overlain by subtidal carbonates. Here also, the geometry of the breccia body is not determined due to the vegetative cover of the area. However, the variety of clasts, which are mixed with ooids, sponge and coral fragments, derived from an active carbonate platform suggests that this too could be scarp breccia.

The late Pliensbachian – Toarcian extension is clearly manifested in the partial disintegration of the north-eastern margin of the Southern Tethyan Megaplatform margin (Dragičević & Velić, 2002), the deepening of some other areas of the same platform (Masetti et al., 2012; Sabatino et al., 2013; Ettinger et al., 2021), and the break-up and partial subsidence of the Julian Carbonate Platform (Šmuc, 2005; Šmuc & Goričan, 2005; Rožič et al., 2014; Gale et al., 2021). The effects of the earlier, Hettangian–Sinemurian extensional tectonics on the Southern Tethyan Megaplatform, are less clear, since the tectonics coincide with eustatic sea-level changes (Haq et al., 1988; Hallam, 2001), as well as the recovery of skeletal-carbonate producing biota after the biotic crisis at the Triassic/Jurassic boundary (Hallam, 1996; Barattolo & Romano, 2005; Damborenea et al., 2017). Nevertheless, we hypothesise that the extensional tectonics, through the establishment of rugged palaeotopography, played an important role in the recorded facies changes (see Ruiz-Ortiz et al., 2004; Lachkar et al., 2009). This tectonic phase may potentially coincide with the subsidence of the margin, the increased sedimentation of the slope sediments, and the tilting of tectonic blocks in the Slovenian Basin (Rožič et al., 2017).

Timing and style of dolomitization

Despite the differences in the completeness of dolomitization (pervasive dolomitization of the Hettangian-Sinemurian breccia, and the partial dolomitization of the Toarcian breccia), subhedral and euhedral dolomite textures predominate in both cases. Planar dolomite forms early during diagenesis at temperatures below 50 °C (Gregg & Sibley, 1984; Warren, 2000), so an early diagenetic dolomitization is assumed for both types of breccia.

Early, even penecontemporaneous dolomitization has been postulated for the lowermost Jurassic peritidal dolomites of the Mt. Krim area (Ogorelec, 2009), as well as for analogous Upper Triassic dolomites from Slovenia and Hungary (Ogorelec & Rothe, 1993; Haas & Demény, 2002; Haas et al., 2015). For the peritidal facies of the Krka Member, microbially induced precipitation of the Ca–Mg carbonate precursor to dolomite is assumed, coupled with penecontemporaneous mimetic dolomitization via evaporative pumping or seepage influx. In contrast, dolomitization via reflux of slightly evaporated seawater after deposition of the sediment was suggested for the subtidal facies (Haas et al., 2015).

In the case of the Hettangian-Sinemurian breccia, we thus assume that some of the clasts were dolomitized already prior to brecciation, and that pervasive dolomitization of the rest of the clasts, as well as the matrix of the breccia, took place via the reflux of seawater after the deposition of the breccia and its subsequent burial by younger peritidal deposits. The variations in dolomite textures between different clasts and matrix could be explained by precursor grain size and mineralogical composition, and/or differences in concentrations of Mg ions in dolomitizing fluids (see Sibley & Gregg, 1987). The coarse-grained dolomite fabrics observed in some clasts, probably formed during later stages of diagenesis from finer-grained precursors (Warren, 2000; Haas & Demény, 2002; Ogorelec, 2009).

A similar early diagenetic dolomitization is assumed for the Toarcian breccia. However, due to deposition in a completely subtidal environment, it is possible that some other mechanism of dolomitization should be applied, such as one of the normal marine dolomite models (see Warren, 2000, fig. 10).

Conclusions

Early Jurassic extensional tectonics is manifested in the northern sector of the Southern Tethyan Megaplatform of the central Slovenia in the presence of neptunian dykes and sills cutting through the peritidal dolostone, and in possible scarp breccias. The latter occur at two stratigraphic levels. The Hettangian – Sinemurian breccias are pervasively dolomitized. Clasts are poorly sorted and matrix supported. Their occurrence could be related to the “diffused rifting stage” recognized across the western and central Southern Alps at the beginning of the Jurassic. The younger breccias some metres thick are Toarcian in age. They are matrix-supported with poorly sorted clasts. Limestone clasts predominate over dolomitic ones and are more variable in texture. Radial ooids, coral and sponge fragments occur within the matrix.

Extensional tectonics had a significant effect on the architecture of the Southern Tethyan Megaplatform in the Early Jurassic. While the late Pliensbachian – Toarcian extension had a regional impact, leading to the breaking-up of the Southern Tethyan Megaplatform, the earlier extension may have governed the Hettangian – Pliensbachian transition from peritidal facies towards the predominantly subtidal lagoon and shoal facies observed within the Podbukovje Formation.

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