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ORIGINAL PAPER

Formation of a Late Jurassic carbonate platform on top of the obducted Dinaridic ophiolites deduced from the analysis of carbonate pebbles and ophiolitic detritus in southwestern Serbia

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Abstract

In the Inner Dinarides of southwestern Serbia, Tithonian polymictic carbonate turbidites, deposited in a deep-water foreland basin below overthrust ophiolites, contain Kimmeridgian–Tithonian shallow-water clasts, Triassic open-marine limestone and radiolarite clasts, and chrome spinels of a harzburgitic source (suprasubduction and MOR ophiolites). The results from the component analysis of these Tithonian polymictic carbonate turbidites constrain a Middle to Late Jurassic orogeny in the Western Tethys realm with following geodynamic evolution: (1) The closure of the western part of the Neo-Tethys Ocean caused west- to northwestward-directed ophiolite obduction onto the wider Adriatic shelf from Middle Jurassic times onwards. The former Triassic–Middle Jurassic outer passive continental margin of the Neo-Tethys imbricated and a nappe stack in lower plate (wider Adriatic) position was formed in front of the propagating obducting ophiolites. (2) During a period of relative tectonic quiescence, formation of a Late Jurassic carbonate platform started around the Oxfordian/Kimmeridgian boundary on top of the obducted ophiolites. This detection of a Late Jurassic carbonate platform formed above the obducted Dinaridic ophiolites close an important gap in knowledge about the geodynamic evolution of the Inner Dinarides. (3) From the Kimmeridgian/Tithonian boundary onwards uplift of the imbricated rocks below the obducted ophiolites triggered unroofing. During Tithonian times the obducted ophiolites were transported west-directed along low-angle fault plains near to its present position in the Dinarides. Mountain uplift and unroofing caused the partly erosion of the Late Jurassic carbonate platform, the underlying ophiolites and the Triassic–Jurassic nappe stack consisting of outer shelf sedimentary rocks.

Keywords Western Tethys · Dinarides · Provenance analysis · Stratigraphy · Basin evolution

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Introduction

Until today, there is only little consensus on the Triassic–Jurassic regional plate tectonic development of the eastern Mediterranean orogenic belt. Palaeogeographic reconstructions and the arrangement of one or more oceanic domains and assumed continental blocks ("terranes") in the Western Tethys realm contrast significantly (Stampfli and Kozur 2006; Schmid et al. 2008, 2020; Gawlick et al. 2008; Robertson 2012; Gawlick and Missoni 2019; van Hinsbergen et al. 2019). For the Dinarides and adjacent areas, one crucial problem is the not fully understood stratigraphic and facies evolution of the Triassic and Jurassic shelf and oceanic sedimentary sequences, very often only preserved as pebbles and blocks in mélanges or as resediments in the underfilled foreland basins. However, there is progress in the reconstruction of:

- the age dating and microfacies characteristics of the Mesozoic sedimentary sequences,
- the age of lost oceanic domains, and
- the understanding of geodynamic processes in the Western Tethys realm, especially in the Dinarides.

In the Inner Dinarides the sedimentary successions and mélanges below the obducted ophiolites (Dinaridic Ophiolite Belt: Dimitrijević 1997; Western Vardar ophiolites: Schmid et al. 2008; Dinaridic Ophiolite nappes: Gawlick et al. 2016; and their equivalents in the Albanides or Hellenides) play a crucial role for understanding the geology of the Dinarides and adjacent areas (Fig. 1). These ophiolites, their provenance and original palaeogeographic position experienced controversial interpretations. Various models were proposed to interpret the complex and polyphase tectonic history (see Gawlick et al. 2016 for a review). In general, today two main contrasting interpretations/models remain about the existence and number of lost oceanic domains in the Dinaridic–Albanide–Hellenide mountain chain (compare Cvetković et al. 2016):

1. Multi-Ocean reconstructions: an autochthonous model with several oceanic domains between continental blocks (Charvet 1978) ("terranes" in other nomenclature). In this model the Dinaridic ophiolites are seen as a remnant of the Pindos-Mirdita-Dinaridic Ocean between Adria to the west and Drina-Ivanjica as northern part of the Pelagonian microcontinent. In most previous literature the Dinaridic ophiolites are interpreted as northward continuation of the Pindos-Mirdita Ocean (e.g., Kossmat 1924; Stampfli and Kozur 2006; Karamata 2006; Robertson et al. 2009; Dilek and Furnes 2011).
2. One-ocean reconstructions: an allochthonous model which interprets the Dinaridic ophiolites as overthrust ophiolitic nappe stack (or single ophiolite sheet) from one oceanic domain to the east with different names in the literature: e.g., Vardar Ocean, Maliac Ocean, and Neo-Tethys Ocean. According to the one-ocean model the Dinaridic ophiolites are the remnant of an ophiolitic nappe stack (or single ophiolite sheet), which obducted in west/northwestward direction (e.g., Schmid et al. 2008; Gawlick et al. 2008, 2016; Kilias et al. 2010). In this view the Drina-Ivanjica Unit represents a tectonic window below the obducted ophiolitic nappe and is, therefore, part of the same continental realm.

In addition, the onset of ophiolite obduction onto wider Adria and the timing of the west/northwest-directed transport are discussed controversially as latest Jurassic to earliest Cretaceous or Middle Jurassic (see Schmid et al. 2008, 2020, Gawlick and Missoni 2019 with references therein).

Component analyses of mass transport deposits or turbidite beds are a common tool to determine the sedimentary provenance of the re-sedimented rocks and hinterland reconstructions (Blatt 1967; Zuffa 1980, 1985; Lewis 1984). Data from such components can play a critical role in. e.g., palaeogeographic reconstructions, constraining lateral displacement in orogens, characterizing crust which is eroded or no longer exposed, and testing tectonic models for uplift at orogenic scale (Haughton et al. 1991). Most of the studies concern provenance analysis of siliciclastic material, but provenance analyses of carbonate or radiolarite components remain rare (Krische et al. 2014; Gawlick and Missoni 2015). For reliable results, the macroscopic description of the clasts has to be combined with microfacies analysis (Flügel 2004) and biostratigraphic age dating, e.g., by their microfossil content. The early erosional products resedimented in adjacent basins near to uplifting orogens, which underwent unroofing, were only rarely identified (Haughton et al. 1991). They are rarely preserved below slivers (nappes) transported to the foreland in the frame of tectonic erosion during late orogenic extension.

In this paper we present the analyses of Late Jurassic (Tithonian) polymictic calcareous turbidites from the western Inner Dinarides: Late Jurassic shallow-water material resedimented together with various older radiolarite and carbonate clasts, and chrome spinel of ophiolitic detritic material. This is the first proof in the Inner Dinarides for the formation of a Late Jurassic shallow-water platform on top of the obducted ophiolites. The age of platform formation, their subsequent erosion and the overthrust of the studied parautochthonous sequences around the Jurassic/

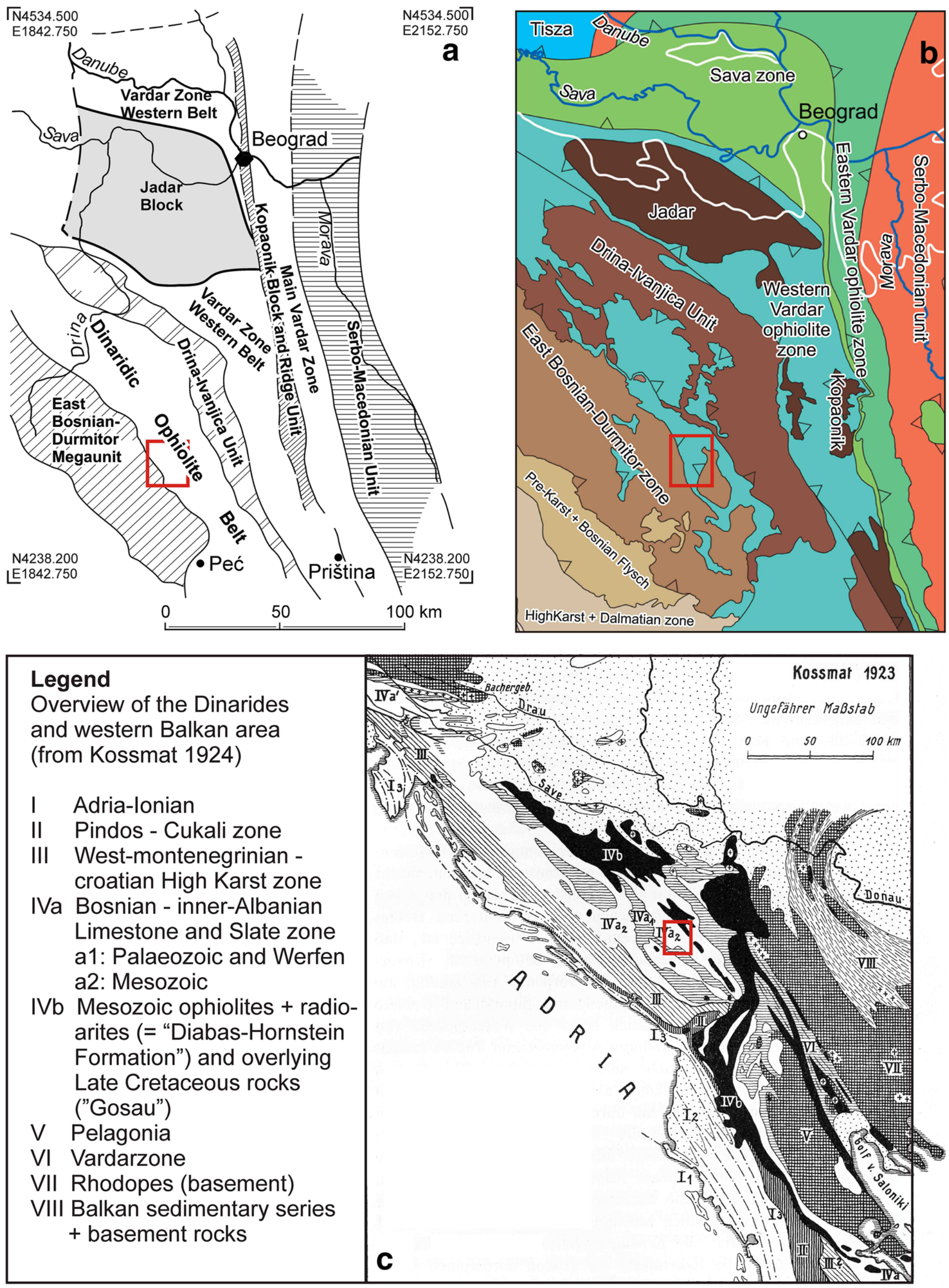


Fig. 1 Area of the studied Late Triassic to Late Jurassic localities in the Inner Dinarides (for geographic details see Fig. 2). **a** Tectonic units and terranes of the central Balkan Peninsula in the sense of Karamata (2006), based on Kossmat (1924). For details, e.g., Aubouin 1973; Dimitrijević 1997; Karamata 2006. **b** Tectonic units of the central Balkan Peninsula from Schmid et al. (2008), modified. For detailed explanation see Schmid et al. (2008). **c** Map of the geological units in the Dinarides and western Balkan areas from Kossmat (1923) (in Kossmat 1924). Legend translated by the authors

Cretaceous boundary by ophiolites contributes essentially to a reconstruction of the west/northwestward transport of the obducted ophiolites in time and space. The results are important for the timing of the different orogenic movements and the reconstruction of the thrusting process in Middle to Late Jurassic time in the Western Tethys realm. They close a gap of knowledge in the Dinarides and show the strong connection between the Eastern Alps on one hand and the Hellenides on the other.

Geological setting

The study area is located in southwestern Serbia and northeastern Montenegro (Fig. 2) and belongs to the Dinaridic Ophiolite nappe and their underlying Triassic–Jurassic parautochthonous sequences (East Bosnian–Durmitor Megaunit).

The Dachstein Carbonate Platform evolution formed during optimum climatic and geodynamic conditions in the

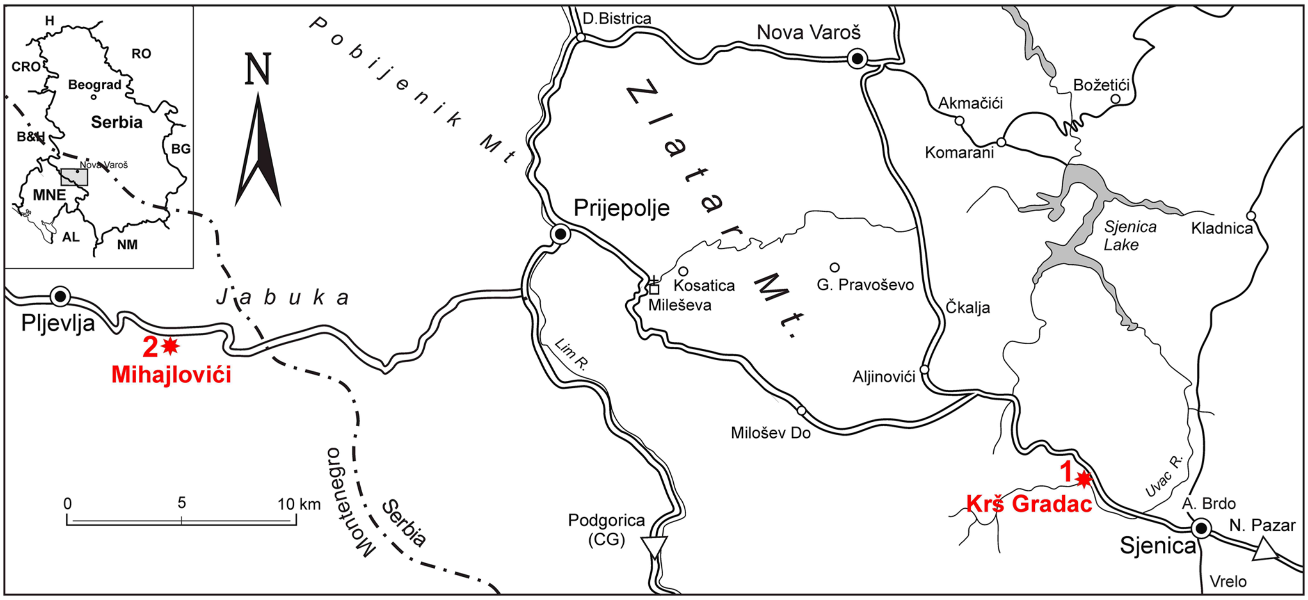


Fig. 2 Studied localities in southwestern Serbia and northern Montenegro: 1 Krš Gradac in Serbia, 2 Mihajlovići in Montenegro. *H* Hungary, *RO* Romania, *BG* Bulgaria, *NM* Northern Macedonia, *AL* Albania, *MNE* Montenegro, *B&H* Bosnia and Herzegovina, *CRO* Croatia

Norian and Rhaetian (Fig. 3). At the Triassic/Jurassic boundary, the carbonate production rate decreased significantly. This occurred in connection with an environmental crisis that caused a mass extinction accompanied by a sea-level drop (compare Sepkoski 1996; Ogg 2004a, b), followed by a warming event and long-term sea-level rise in the Hettangian (Guex et al. 2004; Ogg 2004b). The sea-level drop at the end of the Triassic led to emergence of the Dachstein Carbonate Platform resulting in a stratigraphic gap (Fig. 3). The subsequent sea-level rise during the Hettangian is marked in the study area by the onset of deposition of deeper-water micro-oncoidal sedimentary rocks with ammonoids, followed by the deposition of Ammonitico Rosso (Krš Gradac Formation: Ljubović-Obradović et al. 1998; Radovanović 2000; Radovanović et al. 2004; Fig. 3). An increasing pelagic influence was manifested in the late Early to Middle Jurassic sediments. In the early Middle Jurassic a thin series of *Bositra/Protoglobigerina* red nodular limestone and red clayey limestone deposited widespread (Fig. 3). In some areas (distal shelf) deposition of radiolarites started (Zlatar Formation: Fig. 3). Anyhow, from the Bathonian onwards radiolarites can be traced widespread in the Western Tethyan realm, because in Middle Jurassic times the palaeogeographic situation changed generally due to the partial closure of the Neo-Tethys Ocean and the west/northwest-directed obduction of the ophiolitic nappe stack (Fig. 3). Concerning the active margin, the Dinaridic domain attained a lower plate position. The tectonic motions during this time span were characterized by a propagating thrust belt in front of the overriding ophiolite nappe stack and imbrication of the former Adria shelf.

Middle Jurassic west-directed thrusting caused the formation of deep-water trench-like foreland basins in front of the propagating nappes which in parts obliquely cut through former Triassic to Early/Middle Jurassic facies belts. Deposition of radiolarites and siliceous–argillaceous sediments with mass transport deposits (Gawlick and Missoni 2019) dominated in the newly formed trench-like foreland basins. The ocean floor with its sedimentary cover rocks and the sedimentary rocks from the former distal passive margin (Fig. 3) were incorporated from the Bajocian onwards into the nappe stack. The ophiolitic mélange, with blocks derived from the oceanic domain and the distal continental slope, was formed in the Bajocian to Callovian timespan. Above the radiolarites of the Zlatar Formation the Pavlovića Ćuprija Formation (= Hallstatt Mélange: Gawlick et al. 2017a, c, 2018), exclusively consisting of blocks from the outer shelf (Hallstatt Limestone) facies zone, was formed in the (Late) Bathonian/Callovian to ?Early Oxfordian (Fig. 3). The Sirogojno Mélange (Gawlick et al. 2017a, b), consisting of blocks deriving from the Late Triassic reef rim facies zone, was formed in ?Middle/Late Callovian to Oxfordian times (Fig. 3). The radiolarites of the Ljubiš Formation (Fig. 3; Gawlick et al. 2016, 2017a) were deposited from the Bathonian onwards (Bragin and Djeric in press), and resedimented material from the Drina–Ivanjica Unit indicate a Middle Jurassic relief formation. Sedimentary mélange formation, i.e. formations with mass transport deposits in deep-water trench-like foreland basins, indicate therefore quite clearly

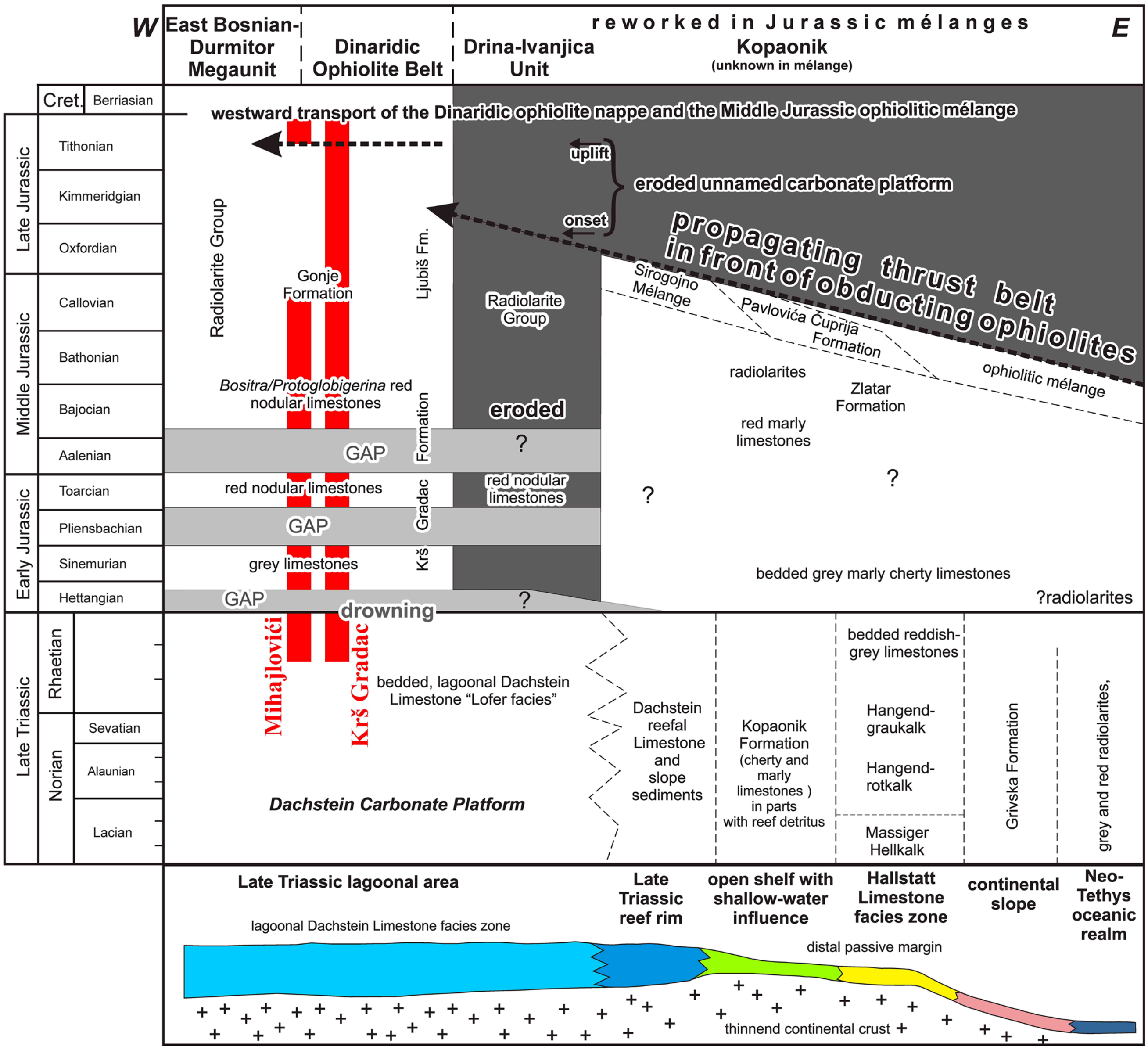
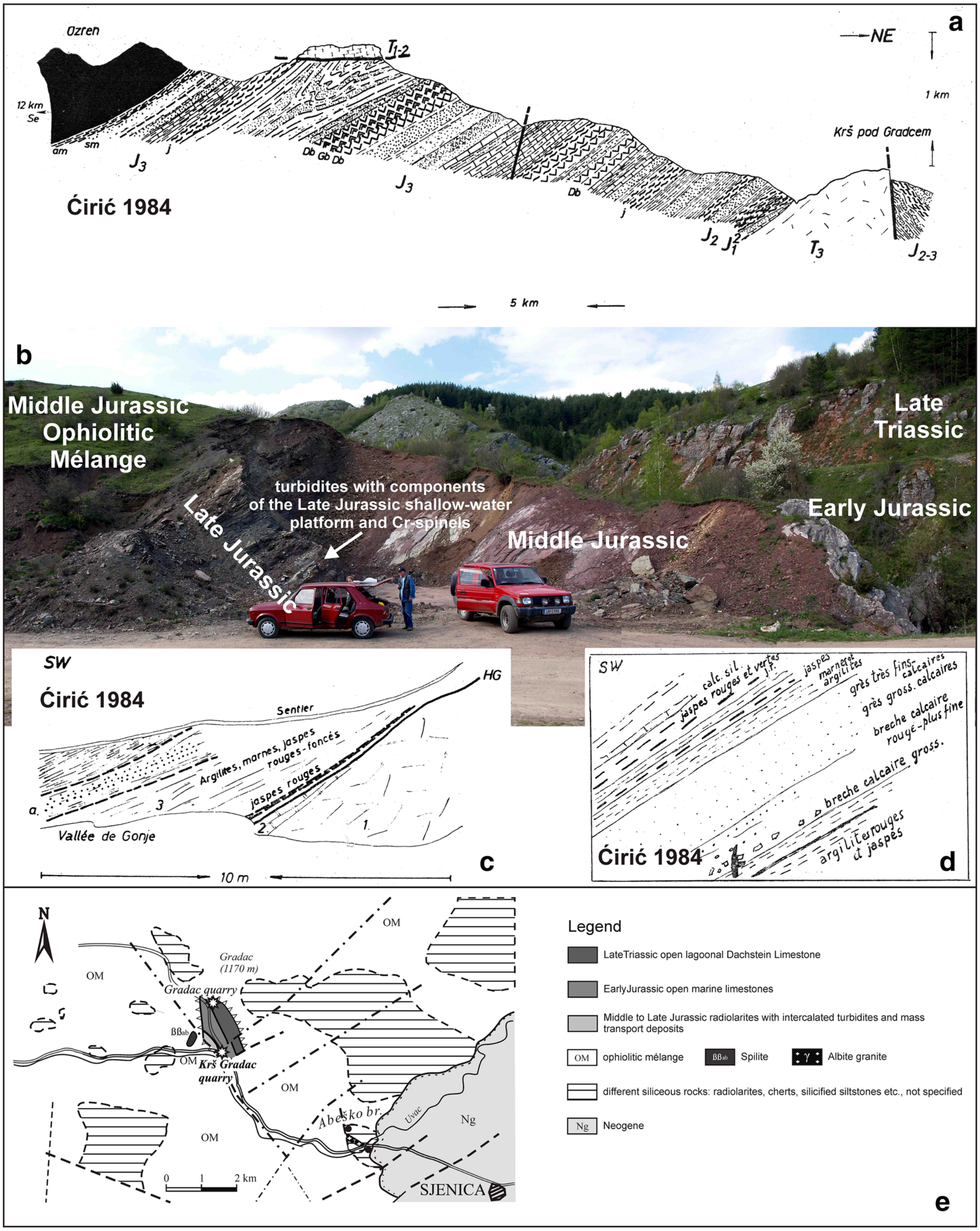


Fig. 3 Stratigraphic table for the Late Triassic to Jurassic of the Inner Dinarides and position of the studied sections marked in red by vertical bars. Jurassic mélanges after Gawlick et al. (2009b, 2016); Gawlick and Missoni (2019). Drina-Ivanjica Unit (in parts after Dimitrijević (1997); Kovács et al. (2010, 2011, 2014); Sudar et al. (2013). Dinaridic Ophiolite Belt after Dimitrijević (1997); Kovács et al. (2010, 2011, 2014); Missoni et al. (2012); Sudar et al. (2013). East Bosnian–Durmitor Megaunit after Dimitrijević (1997); Schmid et al. (2008); Haas et al. (2010, 2011, 2014). For description, definition and emendation of several formations see Gawlick et al. (2017a)

the westward propagation of the nappe stack (Gawlick and Missoni 2019 and references therein).

Tectonic shortening decreased in early Late Jurassic time. In contrast to the Triassic evolution, shallow-water carbonates are generally missing in the Dinaridic domain during most time of the Jurassic until the ?Late(st) Oxfordian/Kimmeridgian (except the Outer Dinarides, where the Adria Platform was formed: Vlahović et al. 2005). New shallow-water carbonate ramps and platforms, described here for the first time established on top of the obducted ophiolites and sealed the main tectonic shortening structures. They existed until the latest Jurassic or Early Cretaceous but started to be eroded in the Tithonian. Due to erosional processes, this newly described and at present unnamed shallow-water carbonate platform is not preserved in the Inner Dinarides. Mountain uplift started from the Kimmeridgian/Tithonian boundary onwards and unroofing caused further westward transport of the Dinaridic Ophiolite nappe and the mélanges (Fig. 3) with contemporaneous erosion of the Late Jurassic carbonate platform and the ophiolites below.



Material and methods

One sample (SRB 515–3; 30 kg) from the polymictic carbonate turbidites, containing heavy minerals and Triassic open-marine limestone and radiolarite clasts, was dissolved for their provenance analysis and conodonts. Heavy fraction from the sample was separated by heavy liquids (bromoform, polytungstate, with densities of about 2.8). In these polymictic carbonate turbidites, the content of conodonts, siliciclastic admixture and its heavy fraction, is very low. Only detritic chlorites and Cr-spinels were identified; the latter was subjected to chemical microanalysis. Spinel grains were hand-picked, embedded in epoxy resin, polished, coated by carbon and measured in micro-analyzer. Chemical composition was determined on JEOL JXA-8530FE microprobe (Earth Science Institute of the Slovak Academy

◂**Fig. 4** The Upper Triassic to Upper Jurassic sedimentary succession in the abandoned Krš Gradac quarry (see Radoičić et al. 2009 for details). **a** Whole Triassic to Jurassic sedimentary succession in Gonje valley according to Ćirić (1984). Ćirić (1954, 1984) assumed a thick complete succession including also the overthrust ophiolitic mélange (indicated by Db = Diabase and Gb = Gabbro in the succession) and the ophiolites to the succession. **b** Showing the outcrop situation of the abandoned Krš Gradac quarry in the year 2007 with indication of the ages in the outcrop. The Upper Triassic to Upper Jurassic sedimentary succession belongs to the parautochthonous sequence in a window below the overthrust Middle Jurassic ophiolitic mélange and ophiolites. Kimmeridgian-Tithonian part of the succession and studied intercalated polymictic calcareous turbidites with clasts from the Kimmeridgian-Tithonian shallow-water platform, Upper Triassic open-marine limestone clasts, radiolarite clasts, and Cr-spinels. Photo from Gawlick et al. (2009b, modified). **c** and **d**. From Ćirić (1984). Rhaetian Dachstein Limestone in lagoonal facies (1), topped by a hardground (HG), followed by Early-Middle Jurassic micro-oncoidal packstone and Ammonitico Rosso (Krš Gradac Formation) (2). Above the Ammonitico Rosso follows a Bathonian to ?Tithonian radiolaritic sequence, in the uppermost part with mass transport deposits and turbidites (Gonje Formation). **e** Modified geological sketch map of the Republic Serbia 1:50.000, Prijepolje 2 (Radovanović et al. 2004) with the Krš Gradac window west of Sjenica, modified after Gawlick et al. (2009b). The star indicates the studied section

of Sciences in Banská Bystrica, Slovakia) at following conditions: accelerating voltage 15 kV, sample current 20 nA, probe diameter 2–5 µm, counting time 10 s—peak and 5 s for background, ZAF correction. Used standards, lines and detection limits (in ppm) are: Ca (Kα, 19–21)—diopside, Mn (Kα, 49–62)— rhodonite, Si (Kα, 45–50)—quartz, Mg (Kα, 35–37)—olivine, F (Kα, 112–294)—fluorite, Na (Kα, 31–36)—jadeite, Al (Kα, 38–40)— kyanite, K (Kα, 29–38) – orthoclase, Fe (Kα, 43–57) – hematite, Ti (Kα, 35–38)—rutile, Cr—(Kα, 71–130)—Cr_2O_3, Cl (Kα, 27–34)—tugtupite. For microfacies analysis and biostratigraphic age dating around 30 thin sections were prepared.

Studied sections

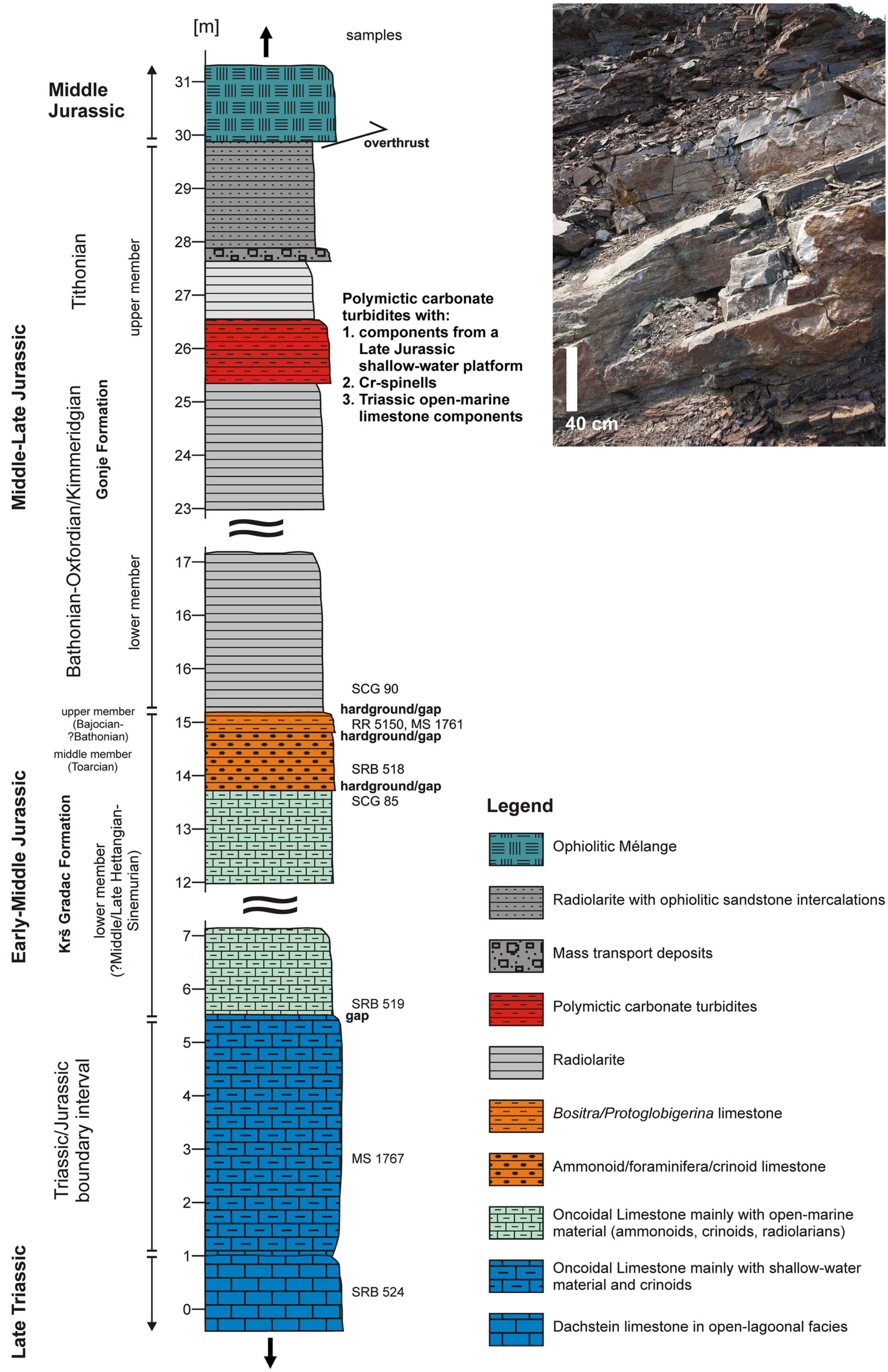
Krš Gradac section in southwestern Serbia

The abandoned quarry (N 43°17′21.6′′ E 19°56′21.6′′; Figs. 2, 4) is located on the northern side of the river Uvac at the beginning of the local road to Donje and Gornje Gonje villages and to the Jadovnik Mt. An Upper Triassic to uppermost Jurassic sedimentary succession of the parautochthonous East Bosnian–Durmitor Megaunit and the overthrust ophiolitic mélange is exposed (Fig. 5). Ćirić (1954, 1984) mentioned the section as an outcrop in the Gonje valley and interpreted it as a continuous succession (Fig. 4a). Accordingly. the tectonically overlying ophiolitic mélange was thought to be of Late Jurassic age. Recent dating of the underlying radiolarite as Bathonian to ?Tithonian by Vishnevskaya et al. (2009) (Gonje Formation: Gawlick et al. 2017a; Fig. 3) proved clearly an overthrust of the late Middle to early Late Jurassic ophiolitic mélange (Grubić 1980; Gawlick et al. 2009b).

The sedimentary succession in the Gradac area starts with Norian Dachstein Limestone in typical Lofer facies (Fischer 1964, Richoz et al. 2012 with references therein), exposed in the Gradac quarry (Fig. 4) (see Gawlick et al. 2017a for details). Along the road in direction to the Krš Gradac quarry the transition to the Rhaetian Dachstein Limestone in open lagoonal facies is located. The uppermost part of the Rhaetian Dachstein Limestone consists of bioclastic pack- and grainstones (Fig. 6a), in cases with coral fragments. Without any significant unconformity micro-oncoidal grapestones (Fig. 6b) were deposited directly on top of the "typical" Dachstein Limestone. The microfacies of this roughly 4 meter-thick part of the sequence is similar to the "Lorüns–Oolith" exposed in the Lorüns quarry in Vorarlberg (Austria), where it was assigned originally to the earliest Jurassic (Furrer 1993). According to the actual definition of the Triassic/Jurassic boundary it represents the topmost Triassic (compare Hillebrandt and Ulrichs 2008; Richoz et al. 2012). In the Inner Dinarides there is no proof by ammonites regarding the exact age of this type of micro-oncoidal facies. We assign this part of the section as deposited around the Triassic/Jurassic boundary.

Above occurs a roughly 8-meter-thick sequence of gray-reddish thick bedded nodular limestones with micro-oncoids, ammonoids, ostracods, rare radiolarians, benthic foraminifera and crinoids (Fig. 6c, d) of a ?Middle/Late Hettangian to Sinemurian age. However, this stratigraphic gap (at least Early–?Middle Hettangian) on top of the shallow-water micro-oncoidal limestone and below this open-marine influenced facies is related to a sea-level drop around the Triassic/Jurassic boundary as known everywhere in the Western Tethys realm, where the Dachstein Carbonate Platform is overlain by open-marine red nodular limestones (Gawlick et al. 2009a with references therein). The upper boundary of the open-marine micro-oncoidal limestone is a hardground, dated by ammonites as Early Toarcian (Ćirić 1954). Even the lower part of the red nodular Toarcian limestones (Fig. 6e), close above this hardground (gap) is characterized by the micro-oncoidal grapestone facies. The microbial rim around the nucleus of the micro-oncoidal grains is here much thinner as in the sequence below. Upsection, radiolarians, ostracods, crinoids and ammonoids are dominant in the red nodular limestone indicating a deepening trend. Micro-oncoids are missing now. Clasts from reworked hardgrounds are common.

Between the Toarcian ammonoid/crinoidal/foraminifera limestones and the Middle Jurassic *Bositra/Protoglobigerina* red nodular limestone also a hardground with a long-lasting gap is verified. Most probably the Aalenian and parts of the


[m]
samples
Middle Jurassic
overthrust
Middle-Late Jurassic
Tithonian
upper member
Bathonian-Oxfordian/Kimmeridgian
Gonje Formation
lower member
Polymictic carbonate turbidites with:
1. components from a Late Jurassic shallow-water platform
2. Cr-spinells
3. Triassic open-marine limestone components
40 cm
SCG 90
hardground/gap
RR 5150, MS 1761
hardground/gap
SRB 518
hardground/gap
SCG 85
upper member (Bajocian-?Bathonian)
middle member (Toarcian)
Early-Middle Jurassic
Krš Gradac Formation
lower member (?Middle/Late Hettangian-Sinemurian)
SRB 519
gap
Triassic/Jurassic boundary interval
MS 1767
Late Triassic
SRB 524
31
30
29
28
27
26
25
24
23
17
16
16
15
14
13
12
7
6
5
4
3
2
1
0
Legend
Ophiolitic Mélange
Radiolarite with ophiolitic sandstone intercalations
Mass transport deposits
Polymictic carbonate turbidites
Radiolarite
Bositra/Protoglobigerina limestone
Ammonoid/foraminifera/crinoid limestone
Oncoidal Limestone mainly with open-marine material (ammonoids, crinoids, radiolarians)
Oncoidal Limestone mainly with shallow-water material and crinoids
Dachstein limestone in open-lagoonal facies

◂**Fig. 5** Uppermost Triassic to Upper Jurassic sedimentary succession of the abandoned Krš Gradac quarry with position of the described samples and photograph of the calcareous polymictic turbidites with Upper Jurassic shallow-water clasts, open-marine Upper Triassic limestone clasts, radiolarite clasts, and Cr-spinels from the obducted Neo-Tethys ophiolites. Thickness of the Lower-Middle Jurassic part of the succession according to Radoičić et al. (2009). For detailed description see text

Bajocian are missing. The age of this 30 centimeter-thick *Bositra/Protoglobigerina* limestone (Fig. 6f, g) is assumed to be (Late) Bajocian to (Early) Bathonian as proven by radiolarian dating above (Gawlick et al. 2017a).

Radiolarite deposition started in the Bathonian with dark-gray slightly bioturbated radiolarian wackestones to packstones (Fig. 6h). In the higher parts of the radiolarites (Fig. 5) intercalated polymictic calcareous turbidites appear, followed by mass transport deposits. Below the overthrust ophiolitic mélange occur sandstone turbidites consisting of reworked ophiolitic material.

The younger part of the sedimentary succession in the Krš Gradac quarry (Rampnoux 1974) was recently reinvestigated by Vishnevskaya and Djerić (2009), Vishnevskaya et al. (2009), Radoičić et al. (2009) and Gawlick et al. (2009b). According to Vishnevskaya et al. (2009) the radiolaritic deposition started on base of badly preserved radiolarian faunas in the ?Late Bathonian to Early Callovian, directly above an hardground on top of the condensed red nodular limestone (*Bositra/Protoglobigerina* limestone) and continued until the Middle Oxfordian to Early Tithonian. In contrast, Vishnevskaya and Djerić (2009) assigned a Callovian-Oxfordian age for the various colored cherty limestones directly below the reddish clayey radiolarites and an age not younger than Middle Oxfordian for the radiolarite 8–9 meters above the red cherty limestones. Gawlick et al. (2017a) dated on base of well-preserved radiolarian faunas the onset of radiolarite deposition as Bathonian, but the age of the whole radiolaritic succession (Gonje Formation—Fig. 3) is still not exactly dated, especially in the upper part of the sequence. Until now, the bad preservation of the radiolarians (Vishnevskaya et al. 2009; Gawlick et al. 2009b) prevented an exact age determination of the younger part of the radiolaritic succession. Anyhow, an early Late Tithonian age for the highest part of the radiolaritic succession above the intercalated mass flows and turbidites with reworked ophiolitic material seems most likely. This assumption is confirmed by shallow-marine organisms (calcareous algae and foraminifera) in the mass flows and calcareous polymictic turbidites (Radoičić et al. 2009).

Polymictic calcareous turbidites: Component analysis

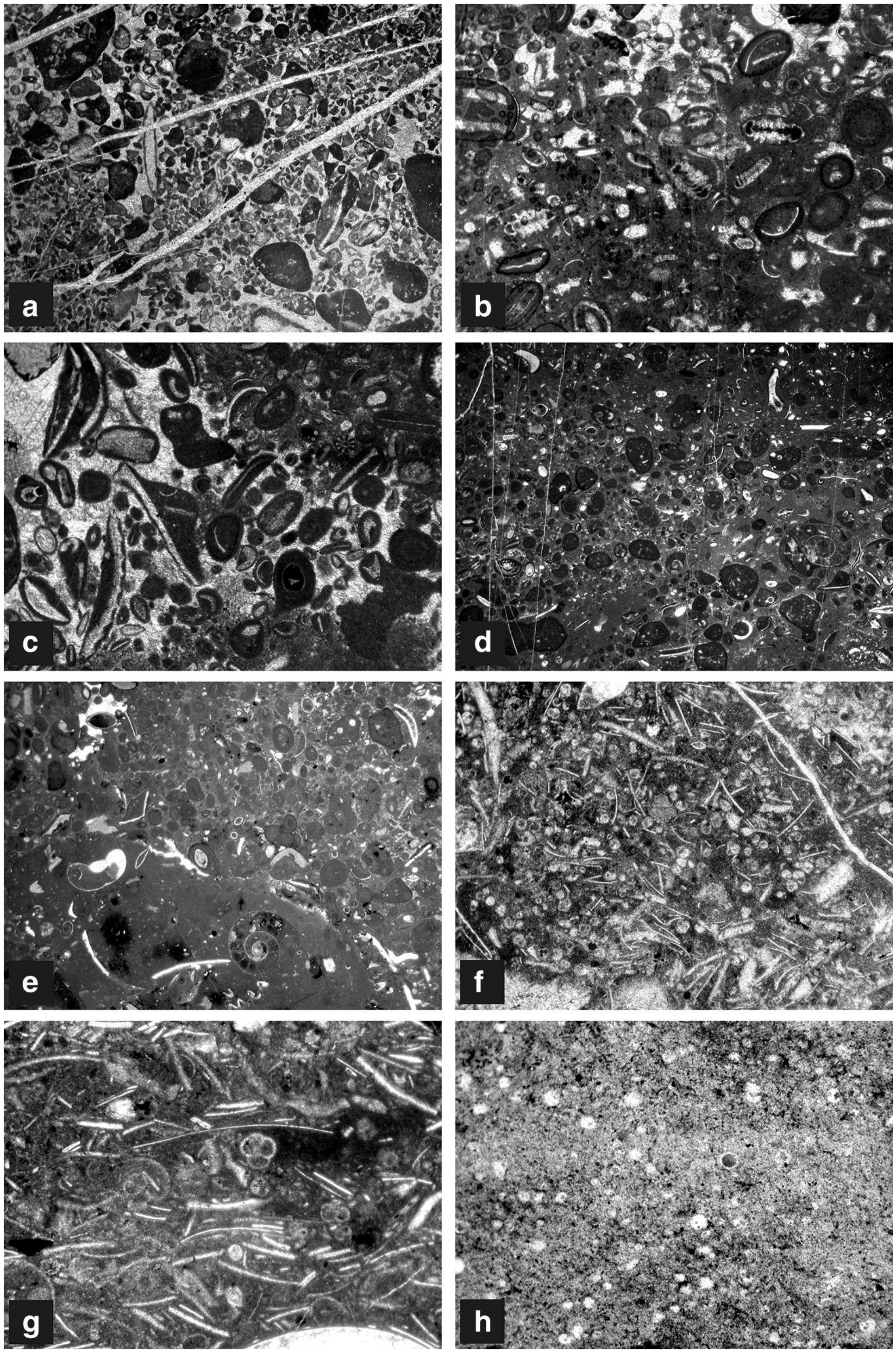
The polymictic calcareous turbidites in the higher part of the radiolarite (Fig. 5) contain various limestone clasts of different age and scattered heavy minerals. The mass transport deposits and fine-grained sandstone turbidites in the highest part of the section lack any limestone clasts. They consist of reworked material from the advancing ophiolites and the ophiolitic mélange: radiolarite clasts, clasts of basalt and mafic rocks, quartz grains. This component spectrum and the general coarsening-upward trend of the succession indicate the onset of the overthrust of the ophiolites above this parautochthonous succession.

Ophiolitic detritus

The ophiolitic detritus consists of Cr spinel grains which were mostly fragmented; their roundness is low and the grains are mostly subangular. The analyzed grains display no zonation, alteration rims or inclusions of other minerals. On the basis of the spinel prism (Fig. 7a) for the solid solution spinel-hercynite-chromite-magnesiochromite-magnesioferrite-magnetite, two chemical variation diagrams were constructed according to Gargiulo et al. (2013) with the projections on the triangular face “B” of the spinel prism (Fig. 7b) and the compositions on the left-lateral face “C” of the prism (Fig. 7c). The diagrams were constructed on the base of previously published diagrams of Stevens (1944), Haggerty (1991), and Deer et al. (1992). In the triangular Fe^{3+}-Cr-Al diagram (Fig. 7b), the analyzed spinels plot mostly in the Al-chromite and picotite field and some in the chromite field. In the binary diagram (Fig. 7c), most of the grains plot in the pleonaste field, a few also in ferrian pleonaste and one in the ferrian picotite field.

For the provenance of spinels, their chemical variability is used, mainly the most important elements, such as Mg, Fe, Cr, Al, and Ti (Table 1). Two types of diagrams are widely used for this purpose: 1) $Mg/Mg+Fe^{2+}$ vs. $Cr/Cr+Al$ and 2) Al_2O_3 vs. TiO_2. The first diagram after Dick and Bullen (1984) distinguishes three fields:

(1) Type I ophiolites which correspond to peridotites for which $Cr/(Cr+Al)$ in spinels does not exceed 0.60. Such peridotites evolved in mid-oceanic ridge settings.
(2) Type III ophiolites representing peridotites bearing spinels with $Cr/(Cr+Al)$ above 0.60, which are related to the early stages of arc formation on oceanic crust.
(3) Type II ophiolites bearing spinels with a wide range of $Cr/(Cr+Al)$, representing transitional types.



Based on this, Pober and Faupl (1988) discriminated spinels deriving from harzburgite and lherzolite rocks, complemented by fields of podiform chromitites and cumulates. Two grains outside the defined fields were likely affected by alteration (Fig. 8).

The second diagram (TiO_2 vs. Al_2O_3) was designed to distinguish the spinels derived from peridotites and volcanics (Lenaz et al. 2000; Kamenetsky et al. 2001). More than 95% of spinel from mantle rocks have TiO_2 lower than 0.2 wt%, and volcanic spinels with TiO_2 lower than 0.2 wt% are uncommon, the boundary between peridotitic and volcanic spinels was set at a TiO_2 value of 0.2 wt% (for overview see Lenaz et al. 2009).

◂**Fig. 6** Microfacies characteristics of the latest Triassic shallow-water limestones to Middle Jurassic radiolarites of the different formations in the Krš Gradac section. **a** Microfacies of the uppermost Triassic (Rhaetian) Dachstein Limestone. Bioclastic grainstone composed of algae fragments, foraminifera and aggregate grains. Open lagoonal limestone originated from a back-reef environment. Sample SRB 524. Width of the photograph: 1.4 cm. **b** Well sorted micro-oncoidal packstone from the Triassic/Jurassic boundary interval. Shell fragments, ostracods, crinoids, and foraminifera (mainly *Involutina liassica* (Jones)) are common and form the nucleus of the oncoidal framework. Sample MS 1767. Width of the photograph: 0.5 cm. **c** Basal part of the micro-oncoidal Lower Jurassic Krš Gradac formation: Micro-oncoidal pack- to grainstone with shell fragments, crinoids, echinoderm spines and in cases small ammonoids form the core of the micro-oncoidal framework. Sample SRB 519. Width of the photo: 0.5 cm. **d** Micro-oncoidal packstone from the upper part of the lower member of the Krš Gradac formation with open-marine matrix containing small ammonoids, ostracods and radiolarians. The rims of the micro-oncoidal fabrics around the organisms are much smaller as in the sequence below. Sample SCG 85. Width of the photograph: 1.4 cm. **e** Early Toarcian hardground with ammonoids, micro-oncoidal fabrics, ostracod shells, crinoids and involutinid foraminifera. Some clasts are encrusted by Fe/Mn-crusts indicating hardground formation. Sample SRB 518. Width of the photograph: 1.4. cm. **f** *Bositra*-shell packstone with small ammonoids and *Protoglobigerina* from the Bajocian-Bathonian part of the Krš Gradac formation. Sample RR 5150. Width of the photograph: 0.5 cm. **g** Protoglobigerinid-packstone with some *Bositra* shells. Sample MS 1761. Width of the photograph: 0.25 cm. **h** Slightly bioturbated dark-gray radiolarian wacke- to packstone from the lower part of the Gonje formation. Most radiolarians are recrystallized to microquartz and show a poor preservation. In some cases the radiolarian tests are well to moderately preserved. Sample SCG 90. Width of the photograph: 0.25 cm

In the $Mg/Mg + Fe^{2+}$ vs. $Cr/Cr + Al$ diagram, distribution of the spinels match best the fields of harzburgites and cumulates (Fig. 8) of Pober and Faupl (1988).

In the TiO_2 vs. Al_2O_3 diagram of Lenaz et al. (2000) and Kamenetsky et al. (2001), most of the fresh spinel grains fall into peridotite fields (with TiO_2 of less than 0.2 wt%); only one measured value had higher TiO_2 values, falling into the field of ocean-island or island-arc basalts (Fig. 9). The peridotitic spinels have mostly lower Al_2O_3 values, which match the supra-subduction zone field.

Upper Triassic open-marine limestone clasts

Beside the rare Cr-spinels and the Upper Jurassic shallow-water carbonate clast several other, mainly Upper Triassic open-marine limestone components appear in the component spectrum of the polymictic turbidites. Important is the occurrence of different Upper Triassic open-marine limestone clasts: radiolarian-bearing wackestones with fragments of thin-shelled bivalves and well-sorted grainstones with shallow-water debris (grains and bioclasts) and fragments of thin-shelled bivalves are common (Fig. 10). Some clasts could be dated on base of the conodont *Paragondolella* cf. *polygnathiformis* (Budurov and Stefanov) as Carnian, most probably Late Carnian. Other clasts show the typical microfacies characteristics of Norian limestones from the reef rim to the adjacent deeper water facies with its intercalated radiolarian wacke- to packstones. All these components derive from a reef-near facies belt (Fig. 3) of the Upper Triassic carbonate platform configuration.

Upper Jurassic redeposited clasts and microfossils

The existence of a Late Jurassic shallow-water carbonate platform is evidenced mainly by resedimented bioclasts: (large) benthic foraminifera, dasycladaleans, and microproblematica. Typical foraminifera associations of outer platform shoal include *Protopeneroplis striata*, Weynschenk (Fig. 11a, e), *Labyrinthina mirabilis*, Weynschenk (Fig. 11f) and coarsely agglutinated lituolids (Fig. 11g) (e.g., Pelissié et al. 1984; Schlagintweit et al. 2005). Taxa like *Parurgonina caelinensis*, Cuvillier, Foury & Pignatti (Fig. 11c) or the dasycladale *Aloisalthella sulcata*, (Alth) (Fig. 11i) indicate the presence of lagoonal facies. The microencruster incertae sedis *Radiomura cautica*, Senowbari-Daryan (Fig. 11k) refers to (fore-) reefal facies (e.g., Senowbari-Daryan and Schäfer 1979; Schlagintweit and Gawlick 2008). The occurrence of *L. mirabilis* and *P. caelinensis* indicate a latest Oxfordian to earliest Tithonian age (Bassoullet 1996). The coarse-grained polymictic carbonate turbidites contain several lithoclast types (e.g., grainstones) derived most likely from this Late Jurassic carbonate platform. The small size of these clasts however does not allow an identification of any age-diagnostic microfossils. Beside these determinable organism, crinoids are common Fig. 12.

The occurrence of clasts derived from the open lagoon, the outer platform shoals, the reefal and fore-reefal depositional realm indicate the existence of a fully evolved rimmed carbonate platform of Late Jurassic (?latest Oxfordian to Early Tithonian) age. Most of the determinable organisms occur in the matrix of the clasts and indicate, therefore, an Early Tithonian age of the polymictic calcareous turbidites. In the Early Tithonian the platform was still productive, but the erosional products from the underlying ophiolites, the ophiolitic mélange and the imbricated Triassic outer shelf sedimentary rocks indicate uplift in the hinterland.

Radiolarite clasts

Radiolarite clasts from different sources complete the component spectrum (Fig. 13). Beside Jurassic radiolarite clasts, which may derive from the Middle Jurassic sedimentary cover of the youngest ophiolites, Middle Triassic radiolarites with relatively big radiolarian tests are quite common components. These Middle Triassic radiolarites derive most probably from the same Middle to Upper Triassic sedimentary sequence as the Upper Triassic open-marine limestone clasts (compare Fig. 3), but a provenance from

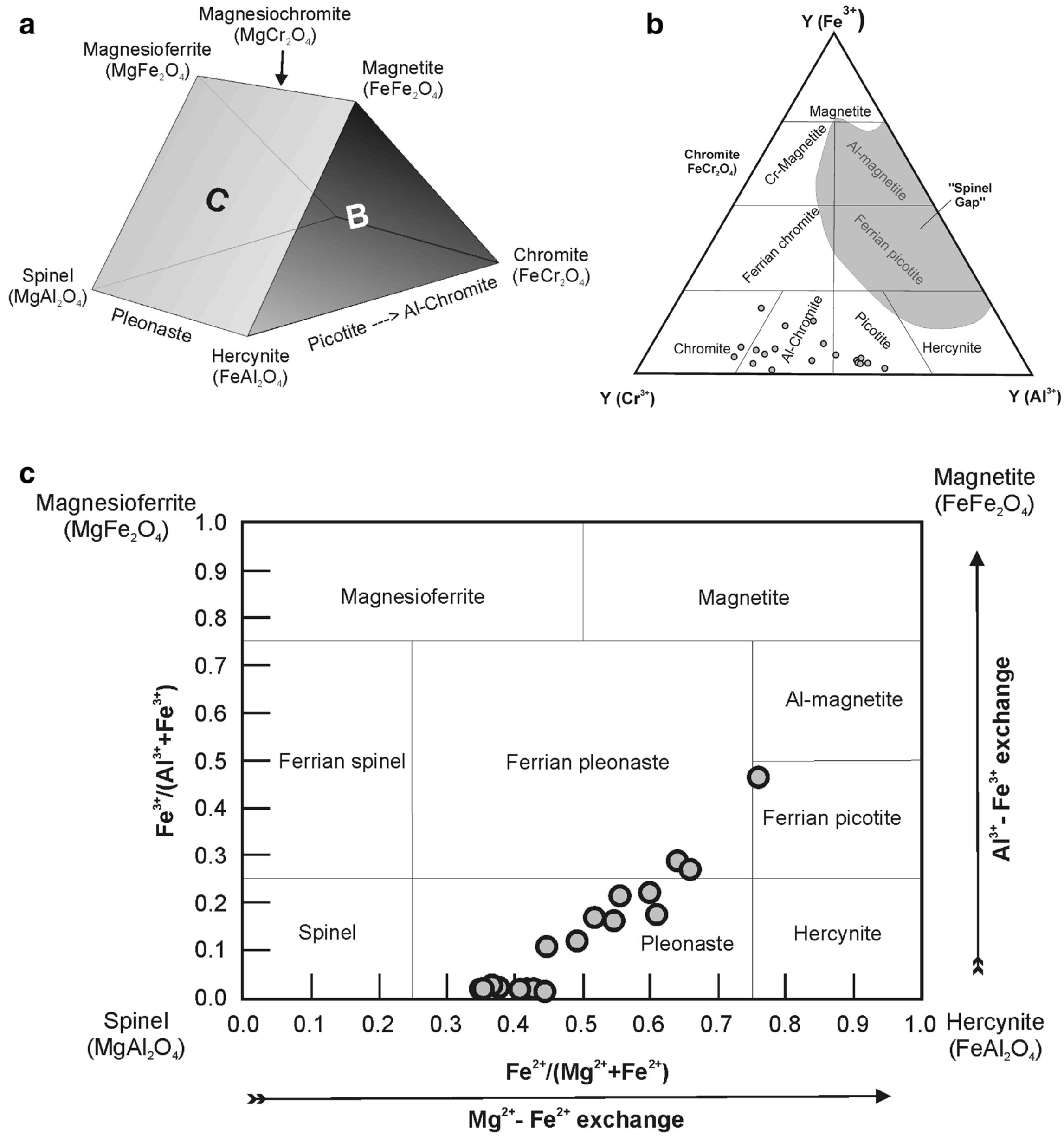


Fig. 7 Chemical classification diagrams (see Gargiulo et al. 2013) for the spinel group minerals of the studied locality. **a** Spinel prism for the multi-component system: spinel-hercynite-chromite-magnesiochromite-magnesioferrite-magnetite (after Deer et al. 1992). The projections of the triangular-front face and the lateral-left face of the prism represent the diagrams in b and c. **b** Triangular classification diagram (Cr^{3+}-Fe^{3+}-Al^{3+}). "Spinel gap" field from Barnes and Roeder (2001). **c** Binary classification diagram considering the Mg^{2+}-Fe^{2+} exchange in the structural site "X": $Fe^{2+}/(Mg^{2+}+Fe^{2+})$

the sedimentary cover of the Neo-Tethys ocean floor cannot be excluded.

Mihajlovići section in northeastern Montenegro

This section (Fig. 14) in northeastern Montenegro is located around 10 km east–southeast from the town Pljevlja below the hill Mihajlovica or Mijajlovica (1411 m) (1:50,000, sheet Pljevlja 2, 1967; 1:25,000, sheet Otilovići, 1974), and the road Pljevlja-Jabuka-Prijepolje (Fig. 2; N 43°20´32.5´´ E 19°26´19.2´´). The locality was first described by Živković and Milojević (1934) with the name Mihajlovići which we also use. In the literature the names Mihajlovići or Mihailovići are used (Radoičić-Brstina 1956; Nöth 1956; Mirković 1970; Rampnoux 1974; Rabrenović et al. 2012; Metodiev et al. 2013; Ostojić and Milić 2014).

Similar to for the Krš Gradac section in the early stages of investigations the ammonoid fauna of Mihajlovići was

Table 1 Representative microprobe analyses of the spinels (in wt.%). Formula is based on three cations

Analysis No	Peridotite spinels					Volcanic spinel
	3	6	8	25	27	18
SiO_2	0.00	0.00	0.00	0.00	0.00	0.00
TiO_2	0.27	0.05	0.16	0.30	0.22	1.31
Al_2O_3	11.45	18.80	14.91	30.22	13.65	17.05
Cr_2O_3	50.98	50.90	52.34	35.74	49.85	43.80
FeO	29.11	17.12	20.83	19.62	26.95	27.20
MnO	0.48	0.45	0.44	0.35	0.42	0.45
MgO	6.77	11.70	10.43	12.98	7.96	9.25
Sum	99.06	99.02	99.11	99.20	99.04	99.06
Si	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.01	0.00	0.00	0.01	0.01	0.03
Al	0.46	0.70	0.57	1.07	0.53	0.65
Cr	1.36	1.28	1.34	0.85	1.31	1.12
Fe^{2+}	0.65	0.43	0.48	0.41	0.59	0.54
Fe^{3+}	0.18	0.02	0.08	0.08	0.15	0.20
Mn	0.01	0.01	0.01	0.01	0.01	0.01
Mg	0.34	0.55	0.50	0.58	0.39	0.45
Sum A	1.00	1.00	1.00	1.00	1.00	1.00
Sum B	1.82	1.98	1.92	1.92	1.85	1.80
$Mg/(Mg+Fe^{2+})$	0.35	0.56	0.51	0.58	0.40	0.45
$Cr/(Cr+Al)$	0.75	0.64	0.70	0.44	0.71	0.63

assigned to the Upper Triassic (Živković and Milojević 1934). Later, other authors revised the age of this succession as Jurassic, Upper Liassic and lower parts of Middle Jurassic (Radoičić-Brstina 1956; Nöth 1956; Mirković 1970; Rampnoux 1974). In the more recent literature (Rabrenović et al. 2012; Metodiev et al. 2013) the whole sequence was biostratigraphically dated according to foraminifera and ammonites as Sinemurian, Toarcian and Bajocian with two major sedimentary gaps (missing the Pliensbachian-basal Toarcian, and the Aalenian) and two minor gaps (within the Sinemurian and probably around the Lower–Upper Toarcian transition: Metodiev et al. 2013, p. 68). Ostojić and Milić (2014) described ammonites only from the Early Jurassic part of the section.

The contact between the thick bedded to massive gray Rhaetian shallow-water Dachstein Limestone, with recrystallized foraminifera (including *Triasina* sp.) and in some cases with large gastropods and tempestites with crinoids, and the Early Jurassic is located some 50 meters southwest of the main section forming the small hill north of the village Vijenac. Here the Triassic/Jurassic boundary is exposed in a fresh artificial outcrop near a restaurant.

The Early Jurassic starts with a thick bedded to massive gray micro-oncoidal limestone (Fig. 15). The exact thickness of the micro-oncoidal limestone cannot be estimated (covered by the road). At the section Mihajlovići itself this facies is about 4–5 meter-thick and overlain by a reddish limestone with micro-oncoids, crinoids and foraminifera (Fig. 15), and an ammonoid-rich hardground on top of red nodular marly limestones. Upwards, the section is mainly covered by bushes and grassland. Small outcrops above the ammonoid-bearing horizon consist again of red nodular limestones with *Bositra* shells (Figs. 14, 15). A dark-gray radiolarite in the highest part of the section is preserved below the ophiolitic mélange, best outcropping north of the road. The tectonic contact between the underlying Jurassic succession and the ophiolitic mélange is covered today, but was described by Nöth (1956). In the vicinity of Mihajlovići very often ophiolitic sandstones with polymictic mass transport deposits (with material from the whole ophiolite suite including the sedimentary cover) are outcropping. Such reworked material from the advancing ophiolitic nappe stack is also visible in the Krš Gradac section, but in covered areas like in the surroundings of Mihajlovići it cannot be easily distinguished from the ophiolitic mélange sensu stricto.

The Late Triassic to Late Jurassic parautochthonous succession

The parautochthonous Norian to Tithonian succession of the East Bosnian-Durmitor Megaunit (Figs. 1, 3) below the western part of the Dinaridic Ophiolite nappe subdivided to the following formations:

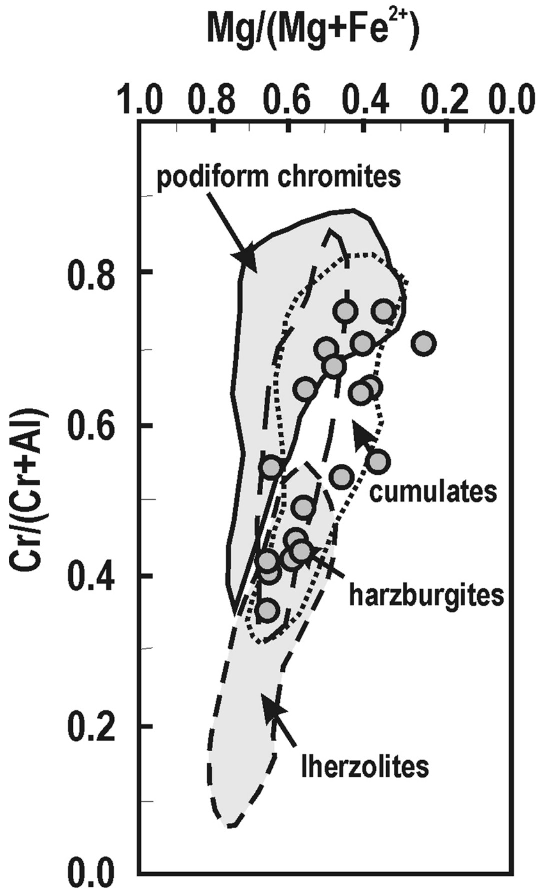


Fig. 8 Spinels plotted in the Cr/(Cr+Al) vs. Mg/(Mg+Fe^{2+}) diagram with fields distinguished by Pober and Faupl (1988). The vertical distribution of the points matches best to the fields of harzburgites and cumulates

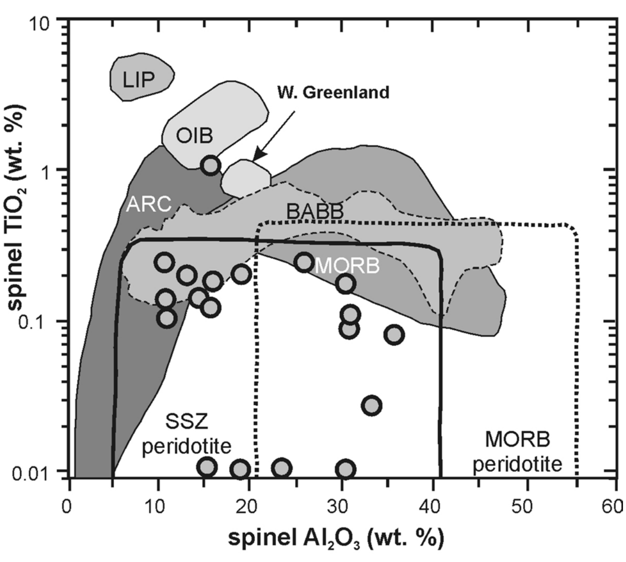


Fig. 9 Analyzed spinels plotted in the TiO_2 vs. Al_2O_3 diagram of Lenaz et al. (2000) and Kamenetsky et al. (2001). Explanations: *LIP* large igneous provinces, *OIB* ocean island basalts, *ARC* island-arc magmas, *BABB* back-arc basin basalts, *MORB* middle ocean ridge basalts, *SSZ* supra-subduction zone peridotites

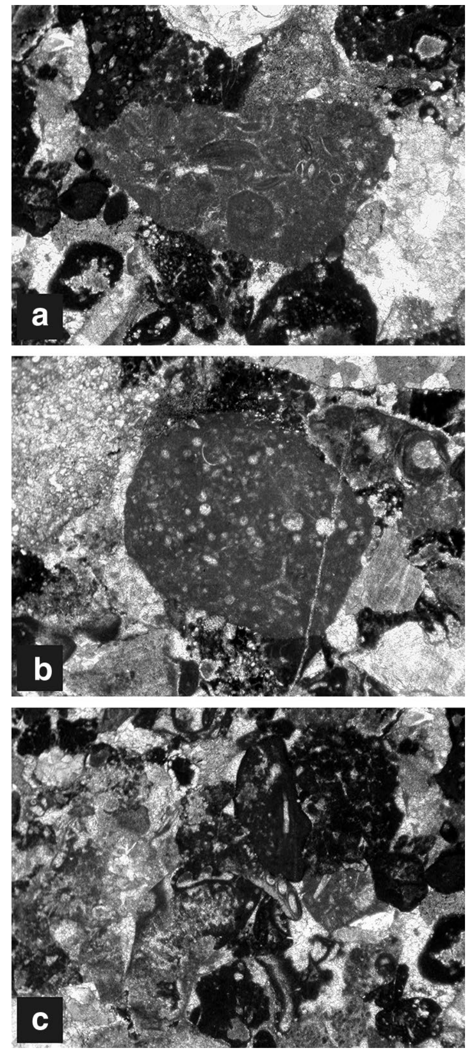


Fig. 10 Microfacies of the Upper Triassic open-marine limestone components from the polymictic calcareous turbidites (Fig. 5). **a** Roughly 1 cm big subrounded Upper Triassic clast with encrusted shallow-water grains, ostracods and filaments. This Upper Triassic (most probably Norian) clast derives from the open shelf with shallow-water influence from the reef rim. Sample SRB 515–1. Width of the photograph: 1.4 cm. **b** Roughly 3 mm big Upper Triassic radiolarian-filament wacke- to packstone. Sample SRB 515–1. Width of the photograph: 0.5 cm. **c** Jurassic and Upper Triassic limestone components together with *Mohlerina basiliensis* (Mohler) in the matrix (Fig. 11: **b**. Sample SRB 515–1. Width of the photograph: 0.5 cm

(1) Norian–Rhaetian Dachstein Limestone in both units in open lagoonal facies (Fig. 6a) (= Upper Triassic lagoonal area in Fig. 3).
(2) Lower-Middle Jurassic Krš Gradac Formation (Fig. 6b–g, Fig. 15a–g) in the sense of Ljubović-Obradović et al. (1998); Radovanović (2000); Radovanović et al. (2004).

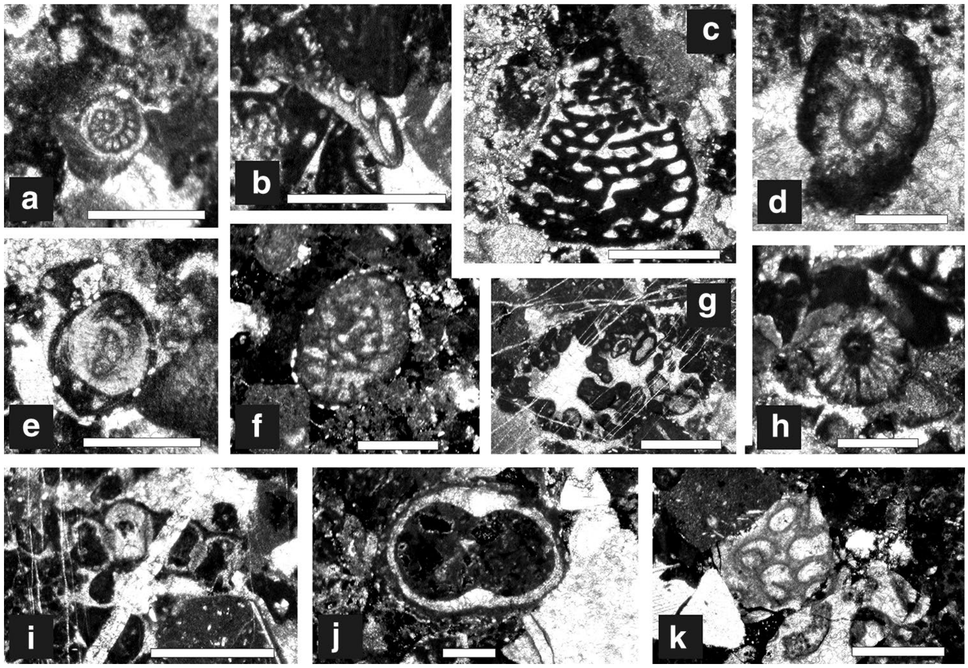


Fig. 11 Upper Jurassic resedimented microfossils from the polymictic calcareous turbidites of the Krš Gradac section (Fig. 5). **a**, **e** *Protopeneroplis striata* Weynschenk. Samples MS 2058 and RR 5154. **b** *Mohlerina basiliensis* (Mohler). Sample SRB 515–1. **c** *Parurgonina caelinensis* Cuvillier, Foury & Pignatti. Sample RR 5151. **d**, **h** Dasycladale indet. (?*Salpingoporella*). Samples SRB 515–1 and 515–2. **f** *Labyrinthina mirabilis* Weynschenk. Sample MS 2054. **g** Lituolidae indet (?*Reophax*, ?*Sievoides*). Sample MS 2053. **i** Dasycladale *Aloisalthella sulcata* (Alth). Sample MS 2053. **j** Problematic crustacean remain *Carpathocancer*? *plassenensis* Schlagintweit & Gawlick. Sample MS 2054. **k** Microproblematicum (sponge?) *Radiomura cautica* Senowbari-Daryan. Sample MS 2054. Scale bars 0.5 cm

(3) Bathonian to Tithonian Gonje Formation (Fig. 3: radiolarite succession, in the upper part with mass transport deposits and polymictic calcareous turbidites.

Krš Gradac Formation

Based on the microfacies characteristics and the age we differentiate the Krš Gradac Formation (Ammonitico Rosso sequence, compare Radoičić et al. 2009) situated between the Dachstein Limestone s. str. and the radiolarite of the Gonje Formation in three different members with long lasting gaps.

?Middle/Late Hettangian—Sinemurian

In the Mihajlovići section the 36 meter-thick ?Middle/Late Hettangian to Sinemurian gray-reddish thick bedded nodular limestone sequence consisting of micro-oncoids, ammonoids, ostracods, rare radiolarians, benthic foraminifera and crinoids is assigned to be exclusively of Sinemurian age (Rabrenović et al. 2012), but the lowermost part could not be dated. In the Krš Gradac section this part of the Krš Gradac Formation is only 14 meters thick. However, above the Triassic/Jurassic boundary at least the Early/?Middle Hettangian is missing (for a review see Gawlick et al. 2009a). On top of this micro-oncoidal limestone occur a hardground, dated by ammonites as Early Toarcian (Ćirić 1954 for Krš Gradac; Rabrenović et al. 2012; Metodiev et al. 2013; Ostojić and Milić 2014 for Mihajlovići). Neptunian dykes in the upper part of the gray-reddish limestones are filled with Toarcian red nodular limestone and breccias (Gawlick et al. 2017a). Based on the described organisms, the microfacies characteristics and the overall Early Jurassic evolution in the Western Tethys, the age of this member of the Krš Gradac Formation is most probably ?Middle/Late Hettangian to Late Sinemurian. A long-lasting time gap of ?Latest Sinemurian to the Pliensbachian/Toarcian boundary is proven in Mihajlovići (Rabrenović et al. 2012).

Similar Hettangian to Sinemurian shallow subtidal successions are known and well investigated in the Southern Alps (Calcari Grigi Group and equivalent formations: Jadoul et al. 2005; Jadoul and Galli 2008; Masetti et al. 2017) or Apennines (Mancinelli et al. 2005). The drowning of these Hettangian–Sinemurian “carbonate platforms” was dated by Masetti et al. (2017) as Early Sinemurian, followed by a crinoid-rich and ammonite-bearing interval of Early to Late Sinemurian. This fits to the microfacies characteristics of the micro-oncoidal limestone member with more open-marine influence in its upper part (Figs. 6, 15).

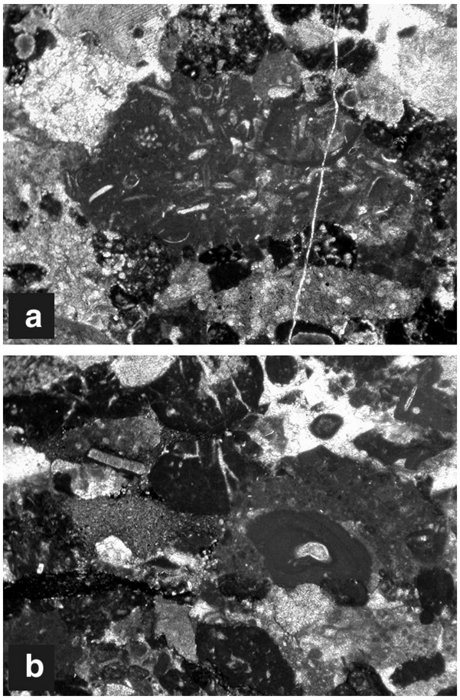


Fig. 12 Microfacies of the polymictic calcareous turbidites. **a** Various undeterminable and in parts recrystallized carbonate clasts and a large clast of the lagoonal depositional environment. Sample SRB 515. **b** Various Upper Jurassic angular clasts and microprobleematicum "*Tubiphytes*" sp. Sample SRB 515. Width of the photographs: 1.25 cm

Toarcian

The roughly one (Krš Gradac) to three (Mihajlovići) meters thick red limestone sequence directly above the Toarcian hardground contains in the lowermost part still micro-oncoids beside open-marine organisms like ammonoids (Krš Gradac – ?*Phylloceras* sp.: Ćirić 1954; Mihajlovići – Rabrenović et al. 2012) (Figs. 5, 14). This microfacies corresponds roughly to the Enzesfeld Formation or Schnöll Formation of the lower Adnet Group in the Northern Calcareous Alps (Böhm 1992; Ebli 1997; Gawlick et al. 2009a for a review) but is younger here in the Dinarides, according to ammonite dating. Another difference is the occurrence of micro-oncoids in the hardground with ammonites at the base.

Bajocian-?Bathonian

The upper red nodular limestones with *Bositra* shells and protoglobigerinids (Figs. 6, 14) has a thickness of approximately 30 centimeters in Krš Gradac, and a thickness of roughly three meters in Mihajlovići (Figs. 5, 14). In the Mihajlovići section this red nodular limestone is dated as Bajocian based on planktonic and benthic foraminifera (Rabrenović et al. 2012). In the section Krš Gradac the radiolarite directly above this is *Protoglobigerina–Bositra* limestone is biostratigraphically dated with radiolarians as Bathonian (Gawlick et al. 2017a). Also this Bajocian-?Bathonian Ammonitico Rosso was believed to be Early Jurassic in section Krš Gradac (e.g., Vishnevskaya et al. 2009; compare Ćirić 1984).

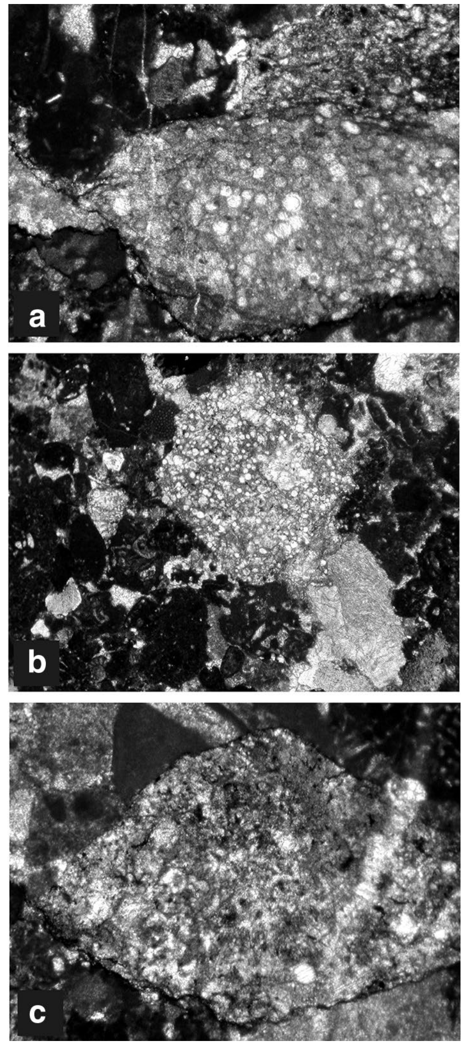


Fig. 13 Radiolarite components from the polymictic calcareous turbidites of the Krš Gradac section (Fig. 5). **a** Middle Triassic radiolarian wackestone with big recrystallized radiolarians. Sample SRB 515–1. Width of the photograph: 0.25 cm. **b** Middle Jurassic radiolarian packstone with small recrystallized radiolarians. Sample MS 2059. Width of the photograph: 0.5 cm. **c** Silicified Middle Triassic radiolarite with some filaments. Sample SRB 515–2. Width of the photograph: 0.5 cm

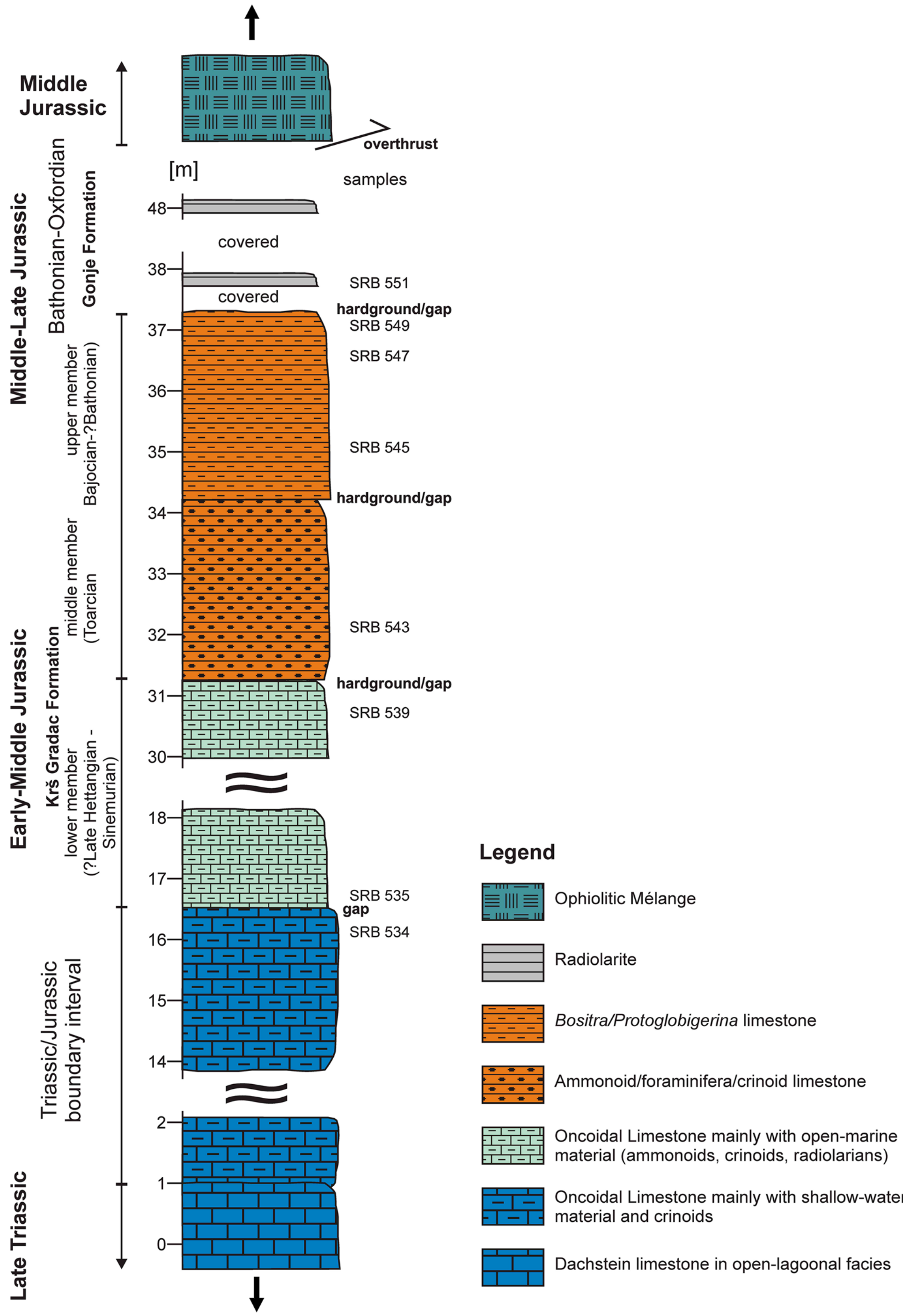


Fig. 14 Uppermost Triassic to Middle-(?Upper) Jurassic sedimentary succession in Mihajlovići and position of the described samples. Thickness of the Sinemurian to Bajocian part of the succession according to Rabrenović et al. (2012). Thickness of the radiolarite below the ophiolitic mélange according to Nöth (1956). The part between the radiolarites on top of the *Protoglobigerina* limestone and the overlying ophiolitic mélange is covered by grassland with bushes and the road. The tectonic contact between the radiolarites and the ophiolitic mélange was visible in the year 1955 near the road (Nöth 1956), meaning that the upper part of the Gonje Formation with its calcareous turbidites was tectonically eroded. For detailed description see text

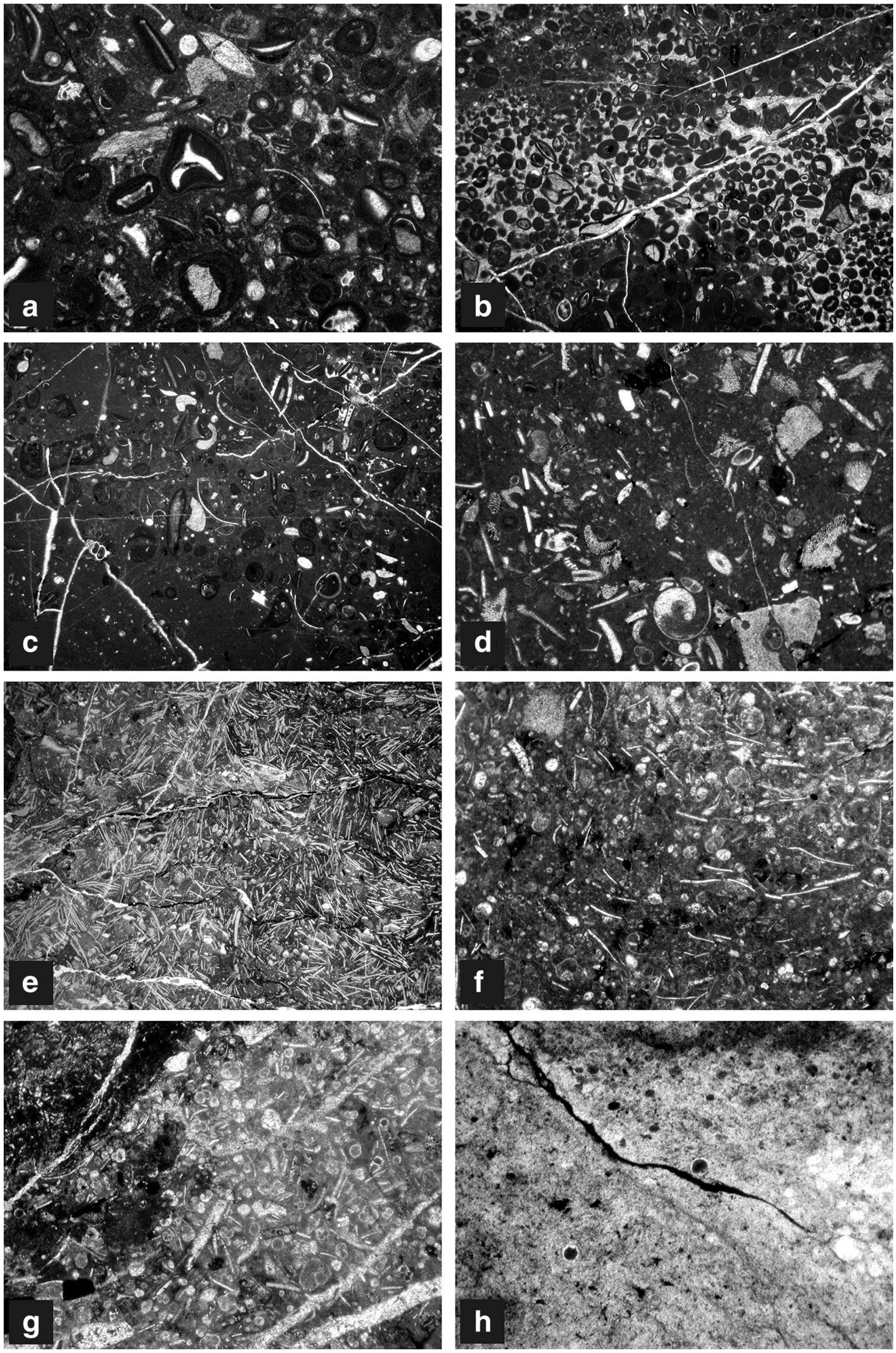
Gonje Formation

Bathonian to Tithonian radiolarite succession, in the upper part with mass transport deposits and polymictic calcareous turbidites: Gonje Formation, in the Krš Gradac section subdivided in two members. The Kimmeridgian-Tithonian part of the formation is completely missing in the Mihajlovići section due to tectonic erosion of the overthrust ophiolitic mélange.

Bathonian–Oxfordian/Kimmeridgian

In the Krš Gradac section roughly 20 meter-thick radiolarite sequence without mass transport deposits (Fig. 5). This part of the Gonje Formation is also preserved in the Mihajlovići section, but mainly covered.

This part of the Gonje Formation corresponds to the Ljubiš Formation to the east (Fig. 3), but the radiolarites of the Gonje Formation were deposited in the distal parts of the



Ljubiš Basin (Fig. 16b). In contrast to the radiolaritic Ljubiš Formation the Gonje Formation contains no turbidites or fine-grained mass transport deposits in this stratigraphic level.

?Late Kimmeridgian—Tithonian

The higher part of the radiolaritic sequence of the Gonje Formation with intercalated mass transport deposits and turbidites is ?Late Kimmeridgian to Early Tithonian according

◂**Fig. 15** Microfacies characteristics from lowermost Jurassic shallow-water limestone to Middle Jurassic radiolarites of the different formations of the Mihajlovići section. **a** Well sorted micro-oncoidal packstone from the Triassic/Jurassic boundary interval. Shell fragments, foraminifera (mainly *Involutina liassica* (Jones), and crinoids form the nucleus of the micro-oncoidal framework. Sample SRB 534. Width of the photograph: 0.5 cm. **b** Basal part of the micro-oncoidal Early Jurassic Krš Gradac formation: Micro-oncoidal pack- to grainstone with shell fragments, crinoids, and foraminifera as nucleus of the micro-oncoidal framework. Sample SRB 535. Width of the photo: 1.4 cm. **c** Micro-oncoidal packstone with open-marine matrix containing small ammonoids, crinoids, ostracods, and radiolarians. The rims of the micro-oncoidal fabrics around the grains are much smaller as in the sequence below. Upper part of the lower member of the Krš Gradac formation. Sample SRB 539. Width of the photograph: 1.4 cm. **d** Early Toarcian hardground with ammonoids, ostracods shells, crinoids and few involutinid foraminifera. Some clasts are encrusted by Fe/Mn-crusts indicating hardground formation. Sample SRB 543. Width of the photograph: 0.5. cm. **e** Bositra-shell packstone with crinoids from the Bajocian-Bathonian part of the Krš Gradac formation. Sample SRB 545. Width of the photograph: 1.4 cm. **f** *Protoglobigerina*-packstone with some *Bositra* shells. Sample SRB 547. Width of the photograph: 0.5 cm. **g** Top of the *Protoglobigerina* limestone with characteristic microbial hardground formation. Sample SRB 549. Width of the photograph: 0.5 cm. **h** Slightly bioturbated and massive silicified dark-gray radiolarian wacke- to packstone from the lower part of the Gonje formation. Most radiolarians are recrystallized to microquartz with poor preservation. In some cases the radiolarian tests are filled with mud showing a moderate preservation. Sample SRB 551. Width of the photograph: 0.25 cm

to the age of the matrix radiolarite and the shallow-water organisms in the mass flows (compare Radoičić et al. 2009).

The component spectrum in the intercalated fine-grained mass transport deposits and calcareous turbidites of the Ljubiš Formation to the east contrasts significantly the component spectrum of the higher Gonje Formation and its redeposition is older. In the Ljubiš Formation the allochthonous material consists exclusively of reworked clasts from the Upper Triassic to Middle Jurassic sedimentary succession of the Drina–Ivanjica Unit to the east: Norian-Rhaetian lagoonal Dachstein Limestone, earliest Jurassic micro-oncoidal limestones, Early Jurassic open-marine red nodular limestones, Middle Jurassic *Bositra*-limestone, and Middle Jurassic gray carbonatic radiolarites with *Bositra*-shells. In the higher part of the Ljubiš Formation, just below the overthrust ophiolitic mélange first resedimented carbonate material shed from the Kimmeridgian–Tithonian shallow-water platform appear (Fig. 16c; Gawlick et al. 2017a).

The topmost part (?Late Tithonian) of the sequence contains more and more fine-grained sandstone layers, which consist of quartz grains, heavy minerals and ophiolitic detritus. The matrix is still radiolaritic, but also spicula-rich layers occur. Thin mass transport deposits contain beside reworked radiolarite clasts (?from the ophiolitic mélange) also ophiolite clasts. The topmost part shows an increase in siliciclastic material and a coarsening-upward trend. This series is overthrust by the Middle Jurassic ophiolitic mélange (Gawlick et al. 2009b) (Fig. 5).

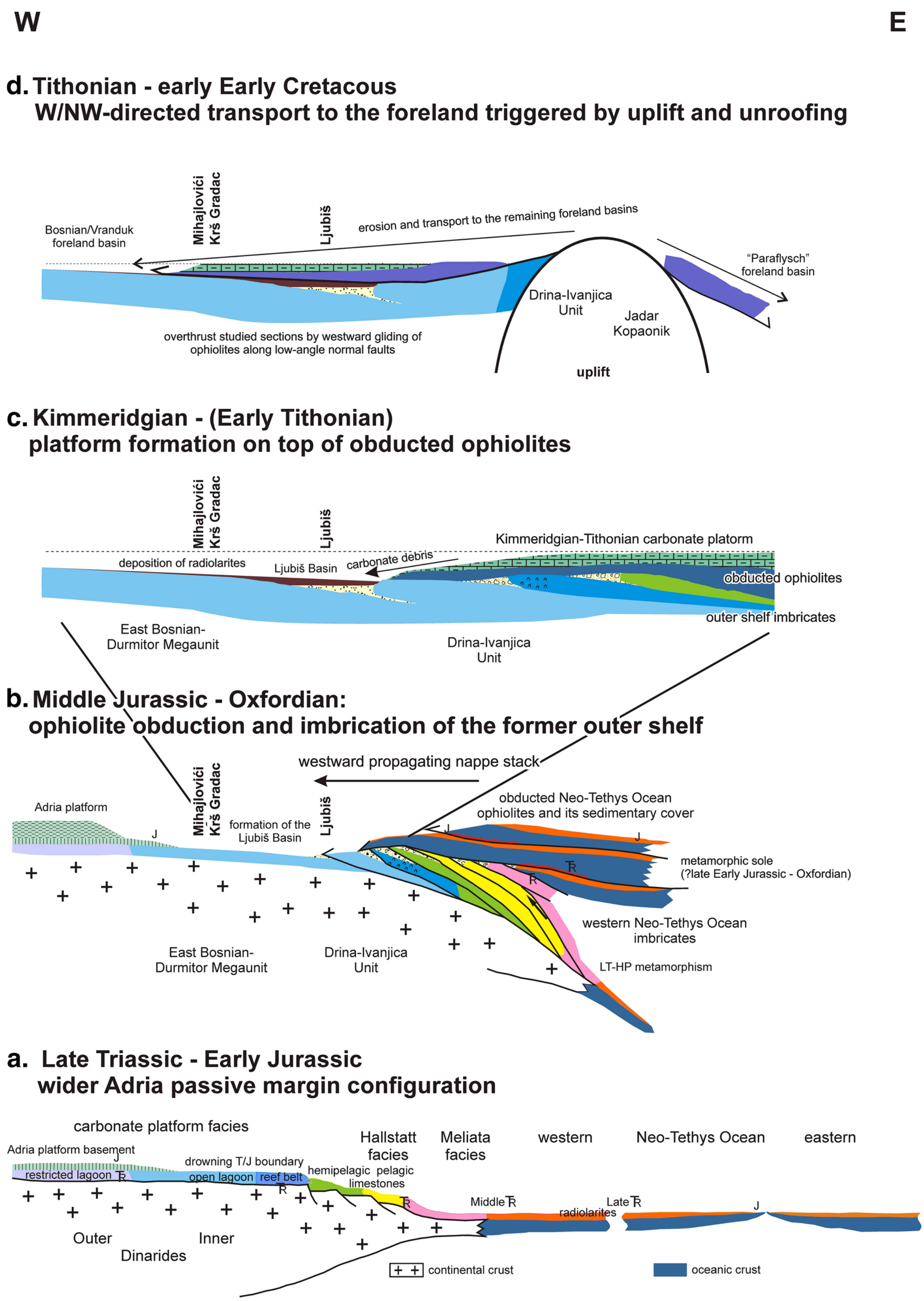
Southeast of our studied sections Haas et al. (2019) described in the Trijebinska Reka valley section calcareous turbidites of Middle Jurassic age (Bajocian-Bathonian). Our radiolarian samples with the age diagnostic radiolarian taxa *Williriedellum carpathicum* (Ozvoldova) instead indicate Callovian-Oxfordian. In the higher part of the radiolarite succession intercalated calcareous turbidites contain shallow-water organism and Cr-spinels (Haas et al. 2019) below the overthrust ophiolites.

Discussion

The current controversial discussions about the provenance and the tectonic interpretation of the Dinaridic-Hellenic ophiolites (see Gawlick and Missoni 2019; Schmid et al. 2020 for recent reviews) show a lack of data from the sedimentary rocks in contact to the ophiolites. In the Dinarides the existence and palaeogeographic position of a shallow-water carbonate platform above the ophiolitic nappe stack can only be reconstructed by pebble analysis from mass transport deposits and turbidites accumulated in adjacent foreland basins. Comparisons with other similar platforms in the Dinaridic-Hellenic and the East-Alpine/Carpathian realms increase the understanding of the Jurassic palaeogeography and geodynamic evolution.

In late Middle to early Late Jurassic times the Dinaridic Ophiolite nappes were already emplaced on top of the inner units of the Dinarides (Kopaonik, Jadar, Drina-Ivanjica) (Gawlick et al. 2016, 2017a; Porkoláb et al. (2019);.

The Late Triassic to Late Jurassic sedimentological evolution and tectonostratigraphy from the Drina-Ivanjica Unit in the east to the East Bosnian–Durmitor Megaunit in the west, i.e. the successions deposited in the area situated today below the Dinaridic Ophiolite nappe can be compared with age equivalent successions in the Circum-Pannonian realm (for the Triassic: Kovács et al. 2011 and references therein; for the Jurassic: Haas et al. 2011 and references therein). The age and microfacies of the Norian-Rhaetian Dachstein Limestone correspond to the microfacies of the Dachstein Limestone elsewhere. The Early-Middle Jurassic Krš Gradac Formation corresponds stratigraphically in its lower parts (micro-oncoidal limestone) to the Calcari Grigi Group and equivalent formations in the Southern Alps or Apennines. The Toarcian to Bajocian condensed red nodular limestones can be compared with the red nodular limestones of the Adnet Group in the Eastern Alps. The *Bositra*- and *Protoglobigerina*-limestones are similar elsewhere in the Circum-Pannonian realm. The Bathonian to Tithonian radiolarite sequence was deposited in the newly formed Ljubiš Basin (Fig. 16b) and is roughly contemporaneous with the



widespread onset of radiolarite deposition in the Eastern and Southern Alps, Western Carpathians or Dinarides/Albanides/Hellenides.

Late Jurassic platform

A today eroded and so far unknown Late Jurassic carbonate platform formed on top of the ophiolites in the Inner

◂**Fig. 16** General geodynamic evolution of the Late Triassic to earliest Cretaceous geodynamic evolution of the Dinarides with emphasis on the Inner Dinarides. **a** Late Triassic to Early Jurassic passive continental margin configuration of the wider Adria shelf. The opening of the Neo-Tethys started at the Middle/Late Anisian boundary (Gawlick et al. 2008 with references therein) and from this time onwards throughout the entire Middle Triassic to Early Jurassic a carbonate dominated passive continental margin evolved. Whereas in the distal part of the shelf shallow-water carbonate production stopped at the Triassic/Jurassic boundary and open-marine hemipelagic limestones were deposited (Fig. 3) the more proximal parts of the shelf (Outer Dinarides) are characterized by the formation of shallow-water carbonates (Adria platform basement: Vlahović et al. 2005). **b** Around the Early/Middle Jurassic boundary to the early Middle Jurassic intra-oceanic subduction started in the Neo-Tethys Ocean with formation of metamorphic soles (Karamata 2006; Schmid et al. 2020 and references therein) and ophiolitic mélanges in the oceanic realm. From Bajocian onwards obduction started, proven by the tectonic incorporation of continental slope derived blocks into the sub-ophiolitic mélange and imbrication of the Middle Triassic to Middle Jurassic outer passive continental margin (Gawlick and Missoni 2019 and references therein). Formation and position of the plagiogranites according to Michail (2016). **c** Onset of a new shallow-water carbonate platform cycle from the latest Oxfordian onwards on top of the obducted ophiolites (compare Schlagintweit et al. 2008) during a period of relative tectonic quiescence. The carbonate debris of this platform was shed into the foreland basin. The studied sections Krš Gradac and Mihajlovići were located at this time relatively far on the slope of this foreland basin. **d** Mountain uplift and unroofing started in the Early Tithonian and resulted in westward and eastward gliding of the obducted ophiolites and the shallow-water platform above. Still in the Tithonian the studied sections Krš Gradac and Mihajlovići were overthrust by the arriving ophiolites. Their erosional products including the overlying shallow-water carbonates deposited in the Bosnian/Vranduk foreland basin from that time onwards (e.g., Mikes et al. 2008; Hrvatović 2006). Position of the "paraflysch" according to Dimitrijević and Dimitrijević (1987, 2009)

Dinarides of SW Serbia. It was detected by the analysis of Tithonian polymictic calcareous turbidites in the eastern East Bosnian-Durmitor Megaunit. The stratigraphic interpretation and the facies distribution of the platform carbonates are based on calcareous algae, benthic foraminifera, and other organisms. A detailed platform reconstruction trough space and time is not possible at the moment due to the lack of appropriate material. However, on the basis of biostratigraphic data and the microfacies of other clasts, it can be directly correlated with equivalent platform carbonates known from other areas in the eastern Mediterranean mountain ranges. Comparable and well preserved Late Jurassic carbonate platforms formed in a similar position in the Northern Calcareous Alps (Plassen Carbonate Platform: Gawlick and Schlagintweit 2006; Auer et al. 2009; Gawlick et al. 2009b), NW Slovenia (Turnšek et al. 1981; Kukoč et al. 2012), Albania (Kurbnesh Carbonate Platform: Schlagintweit et al. 2008) and Greece (Dragastan and Richter 1999; Carras 1995; Carras et al. 2004).

Provenance of the components

The chemistry of spinels indicate that they derived from cumulate and/or harzburgitic ophiolite sources (both sources slightly differ in Mg content). Spinels indicating pure lherzolitic (MORB) source having values of Cr/Cr + Al below 0.3 and Al_2O_3 above 40 are missing. This means that most of our spinels derived from the oceanic crust originating rather in an arc to back-arc or supra-subduction ophiolite (SSZ) than in a mid-oceanic ridge setting. Spinels from harzburgitic sources, which match the Krš Gradac sample, predominate in most of the Cretaceous synorogenic foreland basin fills all over the Alpine–Carpathian–Dinaridic belt (Pober and Faupl 1988; Wagreich et al. 1995; Árgyelán 1996; von Eynatten and Gaupp 1999; Jablonský et al. 2001; Lužar-Oberiter et al. 2009; Bellová et al. 2018). However, the same is true for the spinels from the earliest, Jurassic detritic input from the obducting Neo-Tethys oceanic crust, recorded in the Jurassic sediments of the Transdanubian Central Range (Árgyelán and Császár 1998) and Kimmeridgian of the Northern Calcareous Alps (Gawlick et al. 2015).

On the other hand, presently outcropping primary ophiolitic rocks of the Meliatic and Penninic provenance show mostly lherzolitic origin (Mikuš and Spišiak 2007) and their spinel chemistry is mostly off the range of the sample from Krš Gradac.

Reconstruction of the Kimmeridgian to Tithonian tectonic evolution

The occurrence of Late Jurassic carbonate platform clasts together with spinels of a back-arc or supra-subduction setting and Upper Triassic open-marine limestone clasts and Triassic-Jurassic radiolarite clasts in Early Tithonian deep-water sedimentary rocks indicate clearly uplift of the imbricated Triassic to Middle Jurassic wider Adria outer shelf (Fig. 3, Fig. 16) with the overthrust ophiolites from the Kimmeridgian/Tithonian boundary onwards (~ 152 Ma). During west-directed obduction of the ophiolitic nappe stack on Adria since Middle Jurassic times (Gawlick et al. 2016; Gawlick and Missoni 2019 with references therein; Fig. 16) the underthrust Adriatic margin became imbricated and a thin-skinned orogen was formed in front of the obducting ophiolites.

A Middle Jurassic onset of ophiolite obduction is still doubted (Nirta et al. in press; Schmid et al. 2020 and references therein), mainly based on arguments against matrix ages coming from subophiolitic mélanges. But, a late Middle to early Late Jurassic formation of a thin-skinned orogen is proven by the creation of Bathonian to Oxfordian deep-water radiolaritic foreland basins formed in sequence in front of the advancing nappes pushed to the foreland by the obducting ophiolites (e.g., Gawlick and Missoni 2019 and references therein). These basins were filled by the erosional products of the deformed outer shelf (Figs. 3, 16) and indicate shortening by thrusting.

However, the obducting ophiolites arrived in the area of the Drina-Ivanjica Unit (Fig. 1) in the Late Middle to early Late Jurassic. This is proven by A) the formation of a deep-water trench-like basin in front of the Drina–Ivanjica thrust sheet (Gawlick et al. 2017a) and B) by the known greenshist facies conditions (Djoković 1985) and the recently investigated deformation phases in the Drina–Ivanjica Unit (Trivić et al. 2010; Porkoláb et al. 2019). In addition, Conodont Colour Alteration Index (CAI) values of CAI 5.5 from Middle Triassic open-marine limestones confirm this thermal overprint (Sudar et al. 2013). According to Trivić et al. (2010), the metamorphic mineral phases of the D1 phase developed at 350 °C and around 0.05 GPa (Milovanović 1984) indicating a Middle to early Late Jurassic high-temperature low-pressure metamorphic event in the Drina-Ivanjica Unit. K/Ar ages for D1-metamorphism are in a range between 179 and 160 Ma according to Milovanović (1984). Recently Porkoláb et al. (2019) were able to distinguish two clusters of metamorphic age data from the Drina-Ivanjica Triassic, one early overprint of 162–153 Ma (~ Oxfordian-Kimmeridgian) and a younger age cluster of 141–136 Ma (Berriasian). This is in line with K/Ar ages in the range from 139–129 (Early Cretaceous; Lovrić in Chiari et al. 2011) for the D2 phase. According to these data, we interpret the first cluster of these age data as nappe stacking and overthrust by the ophiolites and the second cluster of age data represent later stages of uplift. The closing temperatures of the K/Ar-system were reached in the earliest Cretaceous. Therefore, uplift and unroofing of Drina–Ivanjica started slightly early, most likely around the Kimmeridgian/Tithonian boundary.

During the first stages of uplift eroded the highest parts of the nappe stack with its overlying sedimentary cover, i.e. the Kimmeridgian–Tithonian carbonate platform on top of the highest ophiolite nappes, composed of supra-subduction ophiolites (Fig. 16). Uplift of the Drina–Ivanjica (and related units) metamorphic core complex, i.e. the imbricated wedge resulted in the successive collapse, unroofing and erosion of parts of the highest nappe stack. During this process several mélanges and ophiolite bodies glided east- and westward (Fig. 16) along low-angle plains in latest Jurassic to Early Cretaceous time. This explains the Late Jurassic (Kimmeridgian) to earliest Cretaceous (Berriasian) age of the youngest sedimentary rocks found below the ophiolites east of the uplifted units rather better than Kimmeridgian to Berriasian obduction (Schmid et al. 2020 and references therein).

First indication of uplift of the imbricated wedge are the Early Tithonian polymictic calcareous turbidites in the studied Krš Gradac section, located far to the west in the foredeep of the Middle to early Late Jurassic orogen (Neotethyan Belt: Missoni and Gawlick 2011a). Westward gliding of the ophiolitic nappe stack from the position of the Drina–vanjica Unit over the parautochthonous sequences (East Bosnian–Durmitor Megaunit) can be traced by additional remains of the Late Jurassic platform south of the village Ljubiš (for exact locality and description see Gawlick et al. 2016): here the ophiolitic mélange overthrust calcareous radiolarites of the Ljubiš Formation (Fig. 3). Along the shear zone with west-directed fold axis between the Bathonian–Kimmeridgian Ljubiš Formation and the overthrust Bathonian/Callovian (to Middle Oxfordian) ophiolitic mélange blocks from the higher Ljubiš Formation with Upper Jurassic shallow-water material are incorporated (Gawlick et al. 2017a: Fig. 56b). In latest Jurassic times or latest around the Jurassic/Cretaceous boundary the section Krš Gradac became overthrust by the arriving ophiolitic mélange and ophiolites (Fig. 16). This scenario fits to the Late Jurassic geodynamic evolution as described for the southern Northern Calcareous Alps (Missoni and Gawlick 2011b), or the Inner Western Carpathians (Plasienka 2018), or the conclusions which were reached for the Vardar–Axios zone in northern Greece by Kostaki et al. (2013).

Conclusions

The detection of reworked Upper Jurassic shallow-water carbonate clasts together with ophiolitic detritus and Upper Triassic open-marine components in an Upper Jurassic sequence, overthrust by the ophiolitic mélange and the ophiolites on top in the western Inner Dinarides allows a better reconstruction of the latest Jurassic geodynamic evolution of the Neotethyan Belt.

Thrusting on the distal Adria margin started in the Middle Jurassic with the onset of ophiolite obduction. In Oxfordian time the ophiolite thrust front reached the Drina–Ivanjica Unit. Around the Oxfordian/Kimmeridgian boundary a period of relative tectonic quiescence began and a shallow-water carbonate platform established on top of the obducted ophiolites. The imbricated wedge uplifted from the Kimmeridgian/Tithonian boundary onwards and subsequent unroofing foster erosion of parts of the platform and underlying ophiolites. Unroofing triggered also the process of northwest- to westward gliding of several mélanges and ophiolite bodies in latest Jurassic to earliest Cretaceous time along low-angle plains. This is proven by the overthrust of the ophiolitic mélange on top of the studied sections in the western part of the Inner Dinarides in southwestern Serbia and northern Montenegro.

Erosion of the shallow-water carbonate platforms, formed on top of the obducted ophiolites (e.g., Mirdita ophiolites in Albania: Schlagintweit et al. 2008; Vourinos ophiolite in Greece: Carras et al. 2004), started in the Early Tithonian and therefore earlier as formerly believed on base of the analysis of different foreland basin fills, e.g., the Bosnian "Flysch" (Mikes et al. 2008) and the Vranduk "Flysch" (Hrvatović 2006) in the Dinarides, the Firza "Flysch" in the Albanides (Schlagintweit et al. 2008), and the Boeotian "Flysch" in the Hellenides (Nirta et al. 2018). These basin fills can be compared with the Rossfeld foreland basin fill in the Eastern Alps (Krische et al. 2014). Later, in the Early Cretaceous, most of these platforms formed on top of the obducted ophiolites eroded and their material was transported to the underfilled deep-water foreland basins (Bosnian, Vranduk, Firza, Boeotian or Rossfeld Basins).

The Jurassic geodynamic evolution of the Inner Dinarides is well comparable with other mountain ranges (Eastern and Southern Alps, Inner Western Carpathians, Albanides-Hellenides) in the eastern Mediterranean: Middle to Early Late Jurassic ophiolite obduction and formation of a thin-skinned orogen in lower plate position, a Kimmeridgian–Tithonian shallow-water evolution with formation of platforms also on top of obducted ophiolites, and mountain uplift from the latest Jurassic onwards with subsequent west-directed transport of the nappes is time-equivalent everywhere. The Inner Dinarides were located relatively in the central part of the orogen, named Neotethyan Belt by Missoni and Gawlick (2011a), and their evolution proves clearly the one-ocean model (Gawlick et al. 2008; Schmid et al. 2008, 2020; Gawlick and Missoni 2019) rather than a multi-ocean concept.

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