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ORIGINAL PAPER

Stratigraphic correlation and structural position of Lower Cretaceous flysch-type deposits in the eastern Southern Alps (NW Slovenia)

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Abstract

Lower Cretaceous syn-orogenic sediments derived from the obducted ophiolites of the Meliata–Maliac–Vardar (Neotethys) Ocean are typically found in the Dinarides and the Austroalpine units. Correlative flysch-type deposits linking both regions through the Southern Alps had been reported from the Bohinj area (NW Slovenia), but their stratigraphic and structural framework remained poorly known. Our research focused on stratigraphic and structural field studies in a 50 km^2 area between Lake Bled and Lake Bohinj in the Julian Alps. The mixed carbonate–siliciclastic sediments, informally named the Studor formation, range in age from the Valanginian (possibly late Berriasian) to the Aptian. They occur on top of two different stratigraphic successions, which we assign to two separate nappes. The first succession consists of deep-water Middle Triassic to Lower Cretaceous deposits of the Bled Basin and belongs to the Pokljuka Nappe, which is the uppermost nappe of the Julian nappe stack. The second succession consists of Upper Triassic to Lower Jurassic platform carbonates and a thin Jurassic–Cretaceous deep-water sequence. This succession was deposited in the marginal area of the Julian Carbonate Platform/Julian High and now belongs to the underlying Krn Nappe. The original (Dinaric) thrust contacts between the Pokljuka and Krn nappes are obliterated by younger deformations. The present-day boundaries between these two nappes are steep NE–SW and younger NW–SE trending faults. The post-nappe deformation sequence characterizing the Alps–Dinarides transition zone has been recognized: (1) Oligocene–Early Miocene NW–SE contraction; (2) Early–Middle Miocene extension; and (3) Late Miocene to recent inversion and transpression.

Keywords Alps–Dinarides transition zone · Mesozoic stratigraphy · Geological map · Julian nappes · Post-nappe tectonics

Introduction

The eastern Southern Alps (including the Julian Alps in NW Slovenia) are part of a complex, more than 300 km long transition zone between the Alps and the Dinarides (Fig. 1). An overlap of the Dinaric and younger Alpine structures was first recognized westwards in the eastern Southern Alps of northern Italy (Doglioni and Siorpaes 1990) and then also confirmed at the boundary between the Southern Alps and the Dinarides in Slovenia (Placer and Čar 1998). Recent studies revealed that the zone of interference extends far eastwards to the Internal Dinarides in northern Croatia (van Gelder et al. 2015). The nappe system in the research area was derived from the continental margin of the Adriatic microplate. In the Middle and Late Jurassic, this part of the margin was located between two oceanic domains: the Alpine Tethys and the Meliata–Maliac–Vardar branch of the Neotethys (in the sense of Schmid et al. 2008). In complex transition zones, key segments with a solid stratigraphic and structural framework may help considerably in understanding the broader area.

The primary aim of this study is to clarify the structural position and hence tectonic emplacement of Lower Cretaceous flysch-type deposits that occur in the eastern Julian Alps. Time-equivalent syn-orogenic sediments are common

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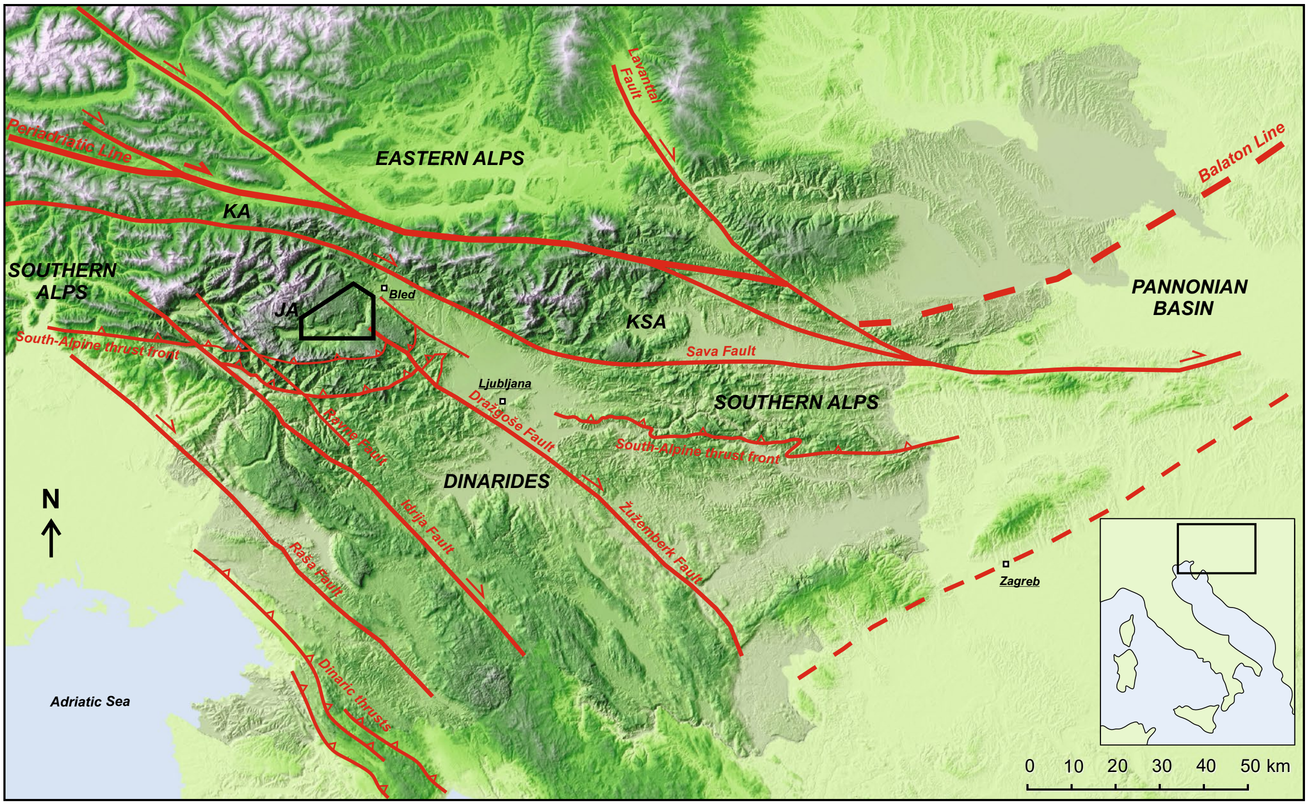

Fig. 1 Eastern Southern Alps and adjacent tectonic units (based on Placer 1999, 2009; Vrabec and Fodor 2006). The area west of Bled is enlarged in Fig. 2a, the framed polygon marks the location of the map in Fig. 4. *KA* Karavanke Mountains, *JA* Julian Alps, *KSA* Kamnik–Savinja Alps

in the Northern Calcareous Alps and in the Dinarides. In the eastern Southern Alps, except for the study area, the onset of flysch is Campanian–Maastrichtian and gets progressively younger westwards. In the Bohinj area, the Lower Cretaceous mixed carbonate–clastic turbidites with ophiolite debris have long been known (Budkovič 1978; Cousin 1981; Buser 1986, 1987; Kukoč et al. 2012). The areal extent of these deposits is limited to a few km^2, but their occurrence is important for paleogeographic and geodynamic reconstructions because in the Southern Alps these are the only sediments that undoubtedly originated from the relatively distal continental margin, facing the Neotethys (Kukoč et al. 2012; Kukoč 2014).

Previous publications emphasized the age of these flysch-type deposits and their affinity to the Bosnian Flysch in the central Dinarides but little was known about their structural position. The area was mapped early in the last century (Härtel 1920) and, after that, as part of the Basic Geological Map 1:100,000 in the 1980s (Buser 1986, 1987). Buser (1986) assumed that the Jurassic–Cretaceous deep-water sediments of the Bohinj area occur in the footwall of the Pokljuka Nappe and may be a separate second-order unit within the Krn Nappe (see Fig. 2a for a general structural map). He also discussed the possibility that they represent a window of the Tolmin Nappe (the Slovenian Basin) but presented reliable evidence against this interpretation. Yet in some recent publications, the window interpretation was accepted and, for example, used in explanation of regional thermal maturity patterns (e.g., Rainer et al. 2002, 2016).

We carried out detailed geological mapping of the area between Lake Bohinj and Lake Bled (Fig. 2a). In this paper, we present stratigraphic and structural data showing that the Lower Cretaceous flysch-type deposits are part of the Pokljuka and Krn nappes, which belong to the upper nappe units of the Julian Alps. The Middle Triassic to Cretaceous successions are correlated with similar successions of the Dinarides, the Northern Calcareous Alps and the Transdanubian Range. Some previous considerations about the local tectonic history are discussed and the need for further systematic structural investigations in the Julian Alps is pointed out.

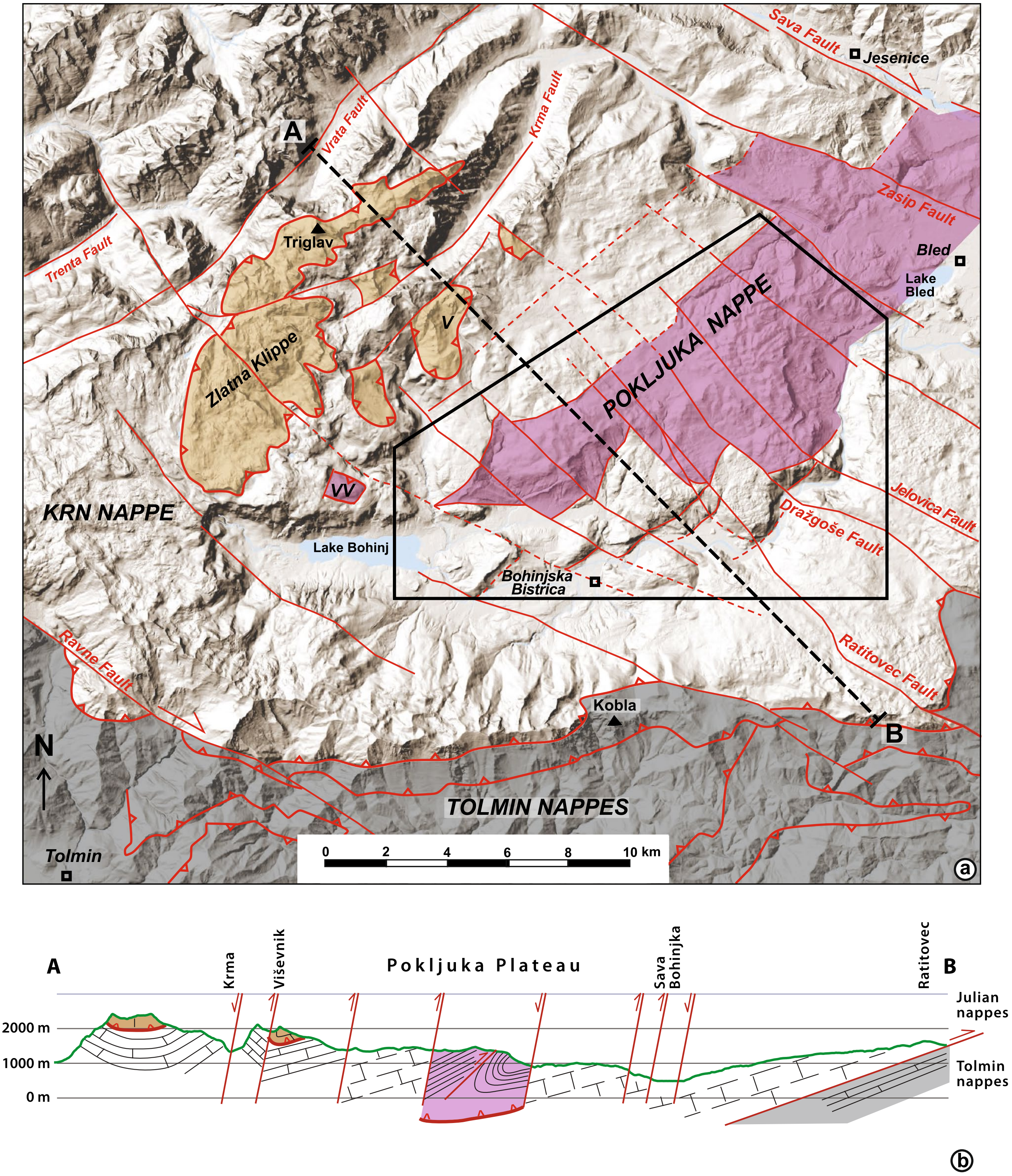

Fig. 2 **a** Generalized structural map of the eastern Julian Alps showing the location of the map in Fig. 4 (framed polygon). **b** Schematic cross-section A–B showing the role of high-angle faults in defining the present-day map-view distribution of different nappes. Data outside the study area based on Basic Geological Map 1:100,000 (Grad and Ferjančič 1974; Buser and Cajhen 1977; Jurkovšek 1986; Buser 1987) and on Geological Map of Slovenia 1:250,000 (Buser 2009). *V* Viševnik Klippe, *VV* Vodični vrh Klippe

Geological setting

The Southern Alps are bounded to the north by the Periadriatic Fault and extend southwards to the South-Alpine front, where they are in direct thrust contact with the External Dinarides (Fig. 1). The Sava Fault, a branch of the Periadriatic fault system, internally separates the Julian Alps from the South Karavanke Mountains and the Kamnik–Savinja Alps.

The Julian Alps are traditionally subdivided into the Tolmin Nappe and the overlying Julian Nappe (Placer 1999; Fig. 2a). Since both consist of several nappe units, here we propose using the names Tolmin nappes and Julian nappes as collective plural terms.

The Tolmin nappes are composed of several superposed E–W trending south-vergent second-order nappes (Cousin 1981; Buser 1986, 1987). The stratigraphic successions of these nappes are ascribed to the Tolmin Basin (Cousin 1981) which represents the western part of the Slovenian Basin (in the sense of Buser 1989). The sediments are typically deep marine (shale, chert, pelagic limestone, carbonate turbidites) from the Middle Triassic volcano-sedimentary succession up to the Campanian–Maastrichtian flysch.

The rocks forming the high mountains of the Julian Alps were defined as the Julian Nappe (Placer 1999). Within this unit, several thrust faults have been observed and a nappe structure was long ago recognized in regional studies (e.g., Kossmat 1913; Winkler 1923; Buser 1986; Jurkovšek 1987), but the entire nappe pile is still not satisfactorily reconstructed. As suggested by the stratigraphic record, remnants of various Mesozoic paleogeographic units (basins and swells) are now preserved in the Julian Alps. From west to east, these units are the Tarvisio Basin, the Bovec Basin, the Julian High (the Julian Carbonate Platform prior to drowning in the Early Jurassic), and the Bled Basin (for a general overview, see Goričan et al. 2012; for details on the stratigraphic evolution of individual basins, see Šmuc 2005; Kukoč et al. 2012; Kukoč 2014; Rožič et al. 2014; Gale et al. 2015). The stratigraphic results indubitably indicate that the area is a complex nappe stack that may include far traveled allochthonous units. Hence, we use the name Julian nappes when referring to the entire nappe stack.

The overall shape of the Julian nappes is an approximately E–W oriented dish-like synform (Placer 2009). The Zlatna Klippe [Zlatnaplatte of Kossmat (1913)] in the central, highest part of the Julian Alps around Mt. Triglav (Fig. 2a, b) is well-differentiated and the sub-horizontal contact with the underlying nappe is preserved. Some smaller klippen of the same nappe occur in the area. This nappe is composed of Lower Triassic to lower Upper Triassic shallow-water carbonates.

The underlying Krn Nappe has the largest areal extent and is characterized by a thick pile of the Dachstein limestone overlain by a more or less condensed succession of Jurassic and Cretaceous pelagic rocks. To the south it directly overlies the Tolmin nappes (Fig. 2a, b). The Krn Nappe was named by Buser (1986), but Jurkovšek (1987) used the name Julian Nappe for the same tectonic unit. We use the name Krn Nappe to avoid confusion with the group name Julian nappes.

The Pokljuka Nappe, which occupies the major part of our study area (Fig. 2a), was defined 30 years ago (Buser 1986) but since then has been largely ignored in geological literature, because its structural position was ambiguous and the contacts with adjacent tectonic units were not clearly established. As originally defined by Buser (1986), the Pokljuka Nappe is composed of several 100 m thick Middle to Upper Triassic bedded cherty limestone that overlies the Dachstein limestone of the Krn Nappe. The nappe was described in the frame of geological mapping at 1:100,000 and its areal extent was considered for the investigated sheet (Sheet Tolmin and Videm) only. In his compiled geological map of Slovenia at a scale of 1:250,000, Buser (2009) revised the lateral extent of the Triassic cherty limestone but did not attempt to clarify the structural position of this lithostratigraphic unit. Moreover, he considered Jurassic pelagic sediments as well as Lower Cretaceous flysch-type deposits between Lake Bohinj and Bohinjska Bistrica as a separate tectonic unit underlying the Pokljuka Nappe.

In contrast, Cousin (1981) regarded the Triassic cherty limestone, which he named the Zatrnik limestone, and the Cretaceous flysch-type deposits as part of the same stratigraphic succession and introduced the name Bled Basin for the corresponding paleogeographic unit. In more recent studies (Kukoč et al. 2012; Kukoč 2014), this stratigraphic continuity is confirmed, implying that the entire succession was, during the initial nappe stacking, part of the same tectonic unit. The Ladinian to Lower Cretaceous succession is thus entirely of deep-water origin and, as such, significantly different from the surrounding area that is dominated by Triassic platform carbonates.

A small klippe north of Lake Bohinj (the Vodični vrh Klippe, Fig. 2a) composed of Upper Triassic bedded cherty limestone was ascribed to the Pokljuka Nappe (Buser 1986; Rman and Brenčič 2008). Its position on top of the Krn Nappe is the same as for the Zlatna Klippe. However, as suggested by their entirely different stratigraphy, these two klippen originally belonged to two different nappes.

The Julian nappes are dissected by a set of NE–SW striking faults (Fig. 2a, b). Some of these faults have a prominent reverse-slip component with SE vergence. For example, the Viševnik Klippe (Jurkovšek 1987) above the Krma Valley (Fig. 2b) constitutes a footwall syncline below one of these steep reverse faults with SE vergence. Well-exposed normal faults with the same orientation have also been observed (e.g., the Krma Fault in Fig. 2a, b).

The NE–SW faults are cross-cut by sub-vertical NW–SE oriented faults; some are evidently active as dextral strike-slip faults (e.g., Kastelic et al. 2008). The most prominent of these is the Sava Fault whose right lateral displacement is estimated at 30–60 km (Vrabec and Fodor 2006) or even 70 km (Placer 1996). The Dražgoše and Ratitovec faults, also well-visible on satellite and digital relief images (Fig. 2a), are the well-marked faults of this group in our study area. The NW–SE faults of the Julian Alps are directly linked to the system of NW–SE dextral faults in the External Dinarides (the Raša, Idrija, Ravne and Dražgoše–Žužemberk faults in Fig. 1).

Study area and research methods

Geological mapping at a scale of 1:5,000 and systematic structural field measurements were carried out in an area of approximately 50 km^2 between Lake Bled and Lake Bohinj (Fig. 2a). The largest part of the mapped area is the flat and vegetated Pokljuka Plateau at an elevation of 1000–1400 m above sea level. Good outcrops are available along forest roads, in narrow gorges and on steep southern and eastern slopes of the plateau. Detailed mapping was performed in key areas with exposed Jurassic and Cretaceous rocks. A more general mapping survey was carried out in the interior of the Pokljuka Plateau where only Triassic cherty limestone is exposed. The following structural elements were systematically measured: bedding orientation and polarity, fault plane orientation, fault striation, and kinematic criteria.

The stratigraphy of the mapped units is mainly based on the existing literature including our recent studies on Jurassic and Cretaceous deposits of the Bled Basin (Kukoč et al. 2012; Kukoč 2014). An additional 130 rock samples were collected in localities that were not covered by our previous research. 145 standard thin sections were made from carbonate and sandstone samples and examined under a petrographic microscope. Selected sandstone thin sections were roughly polished and analyzed uncoated on a JEOL JSM-IT100 scanning electron microscope using backscattered electron imaging and EDS microanalysis in a low-vacuum mode. Fifteen samples of fine-grained mixed carbonate–siliciclastic sediments were prepared with diluted acetic (10%) and hydrofluoric (5%) acid to extract radiolarians.

Stratigraphic overview of the mapped units

Lithostratigraphic units of the Pokljuka Nappe

The oldest unit in the study area are Middle Triassic (probably Upper Anisian) green volcanic and volcaniclastic rocks ("pietra verde") associated with bedded limestone with rare chert nodules (Fig. 3). The underlying rocks, not exposed in the study area, are carbonate breccias and massive Anisian dolomite (Buser 1980).

The Zatrnik limestone (Cousin 1981) is a more than 600 m thick succession of bedded limestone that covers a large southeastern part of the Pokljuka Plateau (Fig. 4). The limestone is mostly light-gray, rarely reddish micrite; chert nodules are common. Bed thickness mainly varies between 10 and 50 cm; thicker packages containing up to 1 m thick beds are present. The most common microfacies is wackestone with radiolarians and thin-shelled bivalves. Coarser facies is wackestone to packstone with echinoderms, bivalves, gastropods, brachiopods, and benthic foraminifers. Various bioclasts are generally well-sorted. Parallel lamination and normal grading, suggesting deposition by turbidity currents, are observed in places.

The upper part of the formation, some tens of meters thick, is composed of grainstone dominated by echinoderm fragments. Subordinately, peloidal packstone and pelagic wackestone with foraminifers, ostracods and fragments of bivalve shells occur. The echinoderm-rich cherty limestone is easily recognizable in the field. However, we mapped it as a separate unit (Figs. 3, 4) only where field relationships clearly indicated that the echinoderm limestone belonged to the uppermost part of the Zatrnik limestone. Since this thick formation has never been systematically logged for stratigraphic and sedimentological studies, we cannot exclude the possibility that other echinoderm-rich units occur within the formation.

The Zatrnik limestone spans a long stratigraphic interval from the Ladinian to the Lower Jurassic. In the frame of geological mapping, Ladinian, Carnian, and Norian stages were documented with conodonts (Kolar-Jurkovšek et al. 1983; Buser 1986). Rhaetian–Hettangian foraminifers were found previously (Cousin 1981). Buser (2009) used the name Pokljuka limestone for the Triassic part of this formation. Here we use the older name Zatrnik limestone (Cousin 1981) for its priority and also for a more adequate definition, which includes the lithologically indistinguishable Lower Jurassic beds.

The overlying Ribnica Breccia (Cousin 1981; Kukoč 2014) is, at the type locality, a conspicuous 7 m thick unit composed of several chaotic breccia levels containing various limestone clasts (up to 40 cm in size) and chert. The most common are clasts of bioclastic wackestone/packstone with abundant echinoderms and foraminifers, less common are clasts of wackestone with radiolarians, sponge spicules, and ammonite and gastropod shells. The matrix is composed of packstone with filaments, foraminifers and ostracods. The breccia, interpreted as a debris-flow deposit, only occurs along the Ribnica creek in the western part of the mapped area (Fig. 4). Away from the Ribnica creek, the entire unit

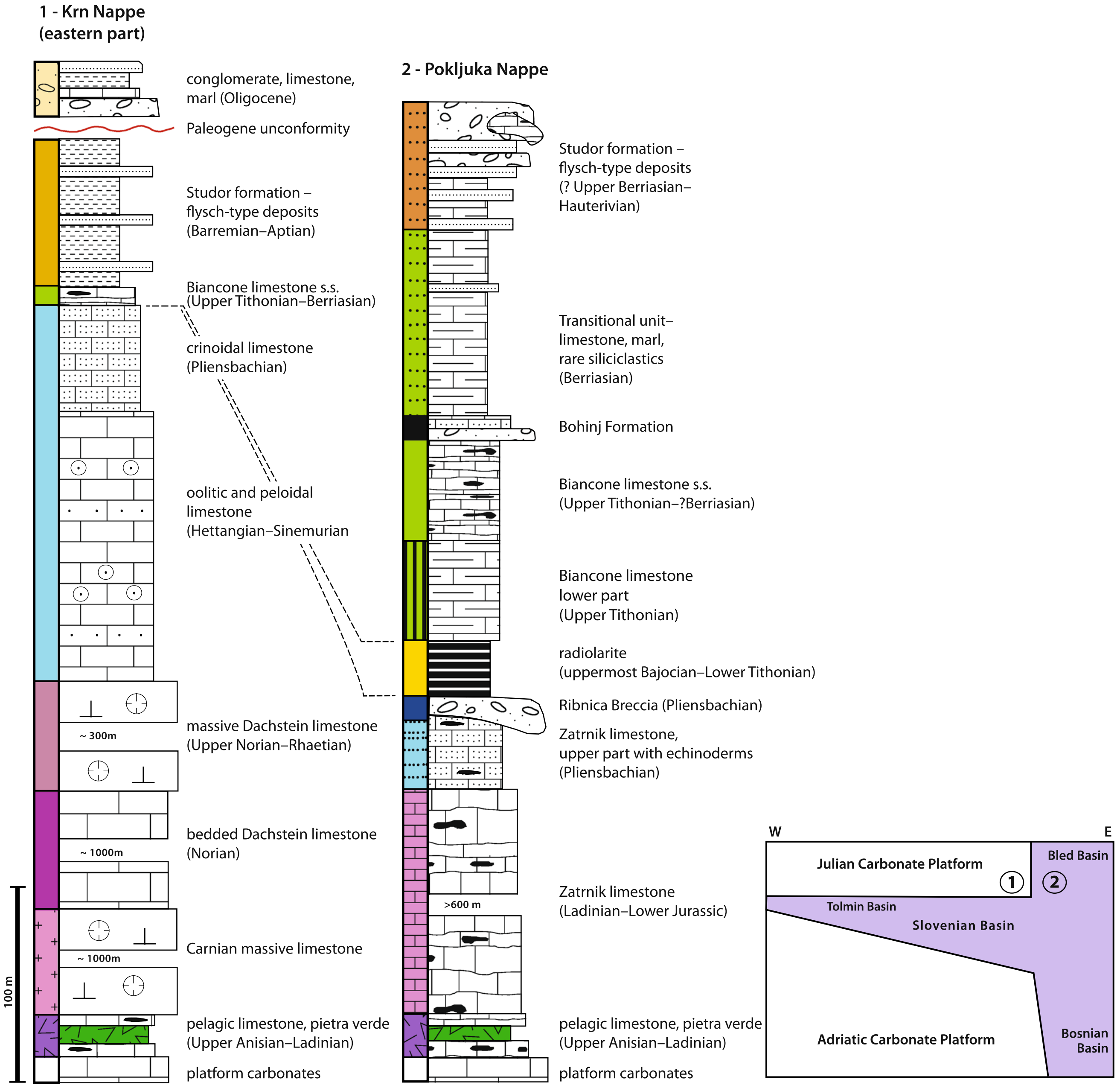

Fig. 3 Synthetic stratigraphic columns for the mapped area in the Julian Alps. Colored patterns of each stratigraphic unit correspond to the symbols in the map (Fig. 4). Inset figure: local paleogeographic sketch for the Late Triassic with location of columns 1 and 2

is less than 2 m thick, composed of dark-red, fine-grained breccia and calcarenite. Based on foraminifers and regional correlation, the Ribnica Breccia is assigned to the Pliensbachian (Kukoč 2014).

The next unit, an approximately 20 m thick radiolarite, occurs between the Ribnica Breccia and the Biancone limestone. The succession is composed of dark-green and upsection dark-red, thin-bedded (3–5 cm) radiolarian chert alternating with shale. The proportion of shale varies from less than 10% in the lower part to more than 60% in the upper part of the formation. Throughout the formation, the chert beds contain some dispersed carbonate (up to 30%) but the succession is devoid of carbonate turbidites. The contact with the underlying Ribnica Breccia is sharp and well-exposed in the Ribnica creek where the formation starts with a 6 m thick slumped interval of dark-green, bedded chert. Radiolarian analysis (Kukoč 2014) revealed a latest Bajocian to early Bathonian age (Unitary Association Zone (UAZ) 5 of Baumgartner et al. 1995) in the lowermost chert beds. A considerable stratigraphic gap comprising the

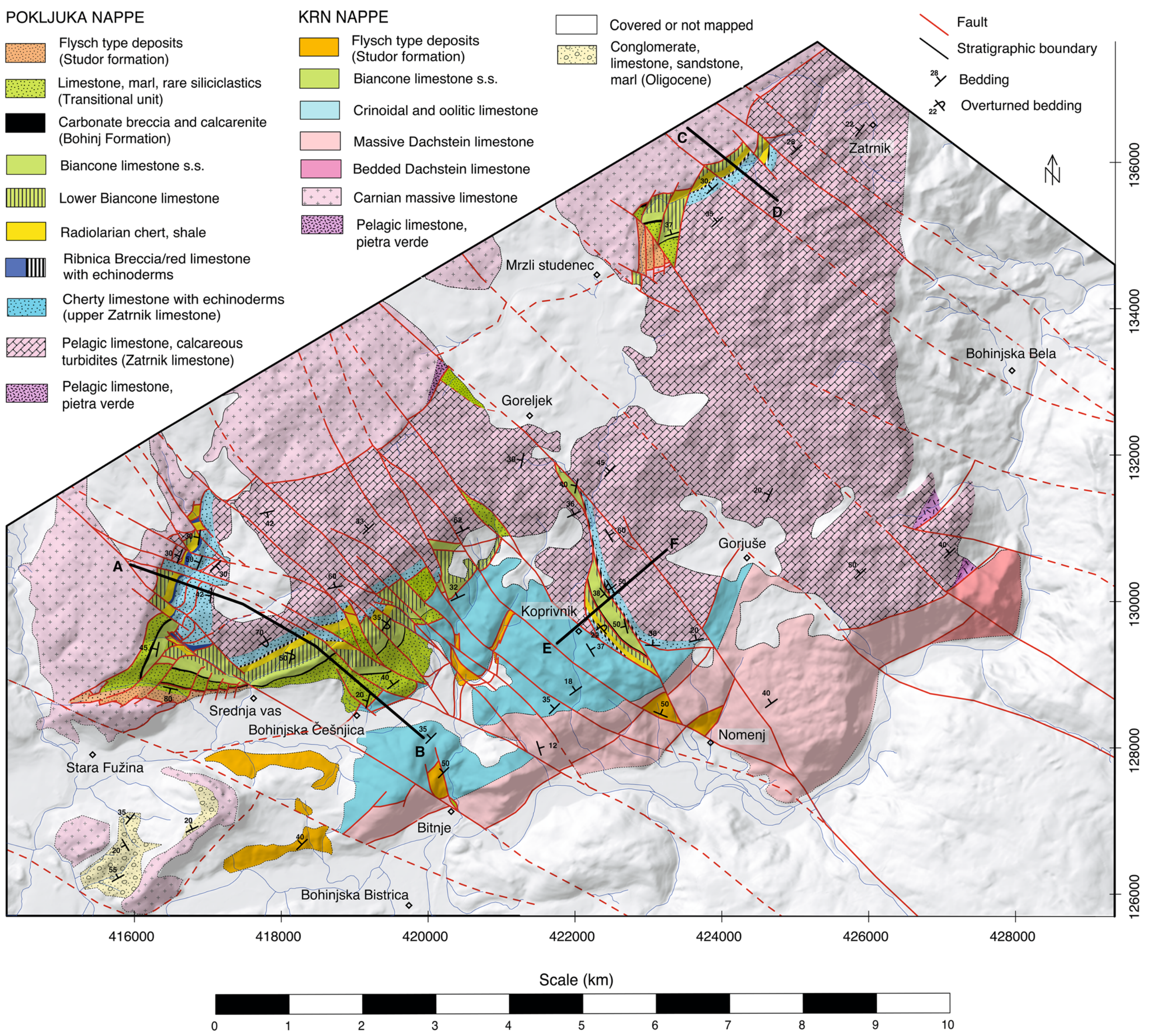

Fig. 4 Geological map of the study area (referenced in the Slovenian Gauss Krüger coordinate system). A–B, C–D and E–F refer to cross-sections in Fig. 9. For an easier distinction between the Pokljuka and Krn nappes, see electronic supplementary material

Toarcian, Aalenian and part of the Bajocian is thus documented between the Ribnica Breccia and the overlying radiolarian cherts. The upper boundary is gradual, marked by an increase in carbonate content and by a change to light-beige color, typical of the Biancone limestone. An Early to early Late Tithonian age (UAZ 12 of Baumgartner et al. 1995) was determined near the top of the formation (Kukoč 2014).

The Biancone limestone is approximately 100 m thick. The lower part, representing the transition from radiolarian chert and shale, consists of gray laminated siliceous marly limestone. The Biancone limestone sensu stricto is characterized by thin- to medium-bedded light-gray to white radiolarian-rich wackestone and packstone with individual beds up to 20 cm thick. Discontinuous beds and irregularly shaped nodules of dark-gray chert are common. In places, normally graded calcarenite to microbreccia occurs as a few centimeters thick intercalations. Radiolarians indicate a latest Tithonian to earliest Berriasian age [UAZ 13 of Baumgartner et al. (1995) according to Kukoč (2014)]. A late Tithonian to Berriasian age was also determined with calpionellids (Buser et al. 1979; Buser 1986; Cousin 1981).

The Bohinj Formation (Kukoč et al. 2012) overlying the Biancone limestone is a few meters thick unit composed of carbonate breccia and massive calcarenite. This unit is very characteristic as it contains shallow-water limestone clasts and isolated grains (algae, benthic foraminifers, calcareous sponges, ooids and oncoids) that originated from a penecontemporaneous carbonate platform. Clasts of the Biancone limestone and small clasts of chert are also common. Importantly, clasts of basalt were found in coarse-grained facies of the Bohinj Formation. The age is latest Tithonian to Berriasian, according to *Clypeina jurassica* Favre found in breccia and radiolarian assemblages extracted from limestone beds below and above (Kukoč et al. 2012; Kukoč 2014).

The overlying succession, provisionally named the Transitional unit, is predominantly composed of thin-bedded, light-gray to white limestone with radiolarians and sponge spicules, similar to the Biancone facies, intercalated with marl interlayers and thin beds (up to 15 cm) of calcarenite. Calcarenites are predominantly composed of shallow-water carbonate debris but also contain non-carbonate grains, mostly quartz. The ratio of siliciclastic to carbonate component progressively increases up-section. However, siliciclastic components are never dominant. The measured section in the Transitional unit is 120 m thick [section BU 3 of (Kukoč 2014)].

The following unit, informally described as the Studor formation (Kukoč 2014), is characterized by flysch-type deposits (Fig. 3). The lower boundary is arbitrarily set where sandstone beds become dominant and the proportion of carbonate beds decreases (Fig. 5a–f). The thickness of these mixed carbonate–siliciclastic turbidites exceeds 100 m in the mapped area but the succession is not complete. In the lower part of the formation, 5–10 cm thick beds of calcareous mudstone alternate with thin-bedded sandstone, whereas up-section the proportion of sandstone increases and the beds are up to 1 m thick. The sandstones (lithic arenites and graywackes) are composed of poorly sorted angular to rounded grains in a calcareous mudstone matrix. Carbonate clasts prevail; some isolated bioclasts are present. Non-carbonate lithic grains are chert, basalt, serpentinite, amphibolite, and granitoid rocks. Quartz grains are mostly monocrystalline. Chrome spinel and other heavy minerals are present. An olistostrome with meter-sized blocks (mostly of Biancone limestone) occurs within the thick-bedded sandstone unit. On the basis of nannoplankton, a Valanginian–Hauterivian age was inferred for this formation (Buser et al. 1979). Recent radiolarian studies indicate that the base of the formation could be as old as the Berriasian (Kukoč 2014).

Lithostratigraphic units of the eastern Krn Nappe

Within the Krn Nappe, which is a large and complex tectonic unit (Fig. 2a), at least two fundamentally different stratigraphic successions have been recorded (see the "Discussion" below). The description in this chapter refers only to the lithostratigraphic units that are exposed in the study area (Figs. 2a, 4) and in direct contact with the rocks of the Pokljuka Nappe. Middle Triassic and Carnian rocks occur along the NW contact with the Pokljuka Nappe whereas Norian to Cretaceous rocks are exposed SE of the Pokljuka Nappe (Fig. 4).

Middle Triassic thin-bedded cherty limestone with interlayers of tuff and tuffite (Fig. 3) is limited to a small, 20 m thick outcrop below the Carnian massive limestone near the Hotel Šport (Goreljek) on the Pokljuka Plateau (Fig. 4, Jurkovšek 1986). Wackestone with radiolarians and thin-shelled bivalves occurs in the lower part of this section, calcarenite with echinoderms is interstratified in the upper part; the Ladinian age of this section was determined with radiolarians and conodonts (Kolar-Jurkovšek 1990).

The Carnian massive limestone is approximately 1000 m thick (Buser 1986) and contains various reef-building fossils (corals, chaetetids, stromatoporoids, algae) and oncoids. Cordevolian, Julian, and Tuvalian stages were differentiated in reef communities of the NW Pokljuka Plateau (Turnšek and Buser 1989; Turnšek 1997).

The bedded Dachstein Limestone, which is the thickest and most widely expanded formation of the Krn Nappe, only occurs in the SE corner of the study area (Fig. 4). Norian–Rhaetian foraminifers were previously found in this locality (Grad and Ferjančič 1976).

The overlying massive Dachstein limestone forms the steep southern slopes of the Pokljuka Plateau (Fig. 4) and attains an approximate thickness of 250–300 m. Several localities in this area were studied for corals and other reef organisms, and a Late Norian–Rhaetian age was inferred (Turnšek and Buser 1991; Turnšek 1997).

This massive limestone passes upwards into bedded bioclastic crinoidal limestone (Fig. 3). Beds of oolitic grainstone occur in places. The light-gray to white, in places yellowish limestone is easily distinguished from the underlying massive Dachstein limestone by its well-marked bedding. In the study area, a complete succession of this bedded limestone has not been restored but a recently studied section of the northern slope of Mt. Kobla (Rožič et al. 2014; for the location of Mt. Kobla, see Fig. 2a) can be regarded as a reference section. On Mt. Kobla, the formation is 250 m thick. Peloidal and ooid limestone prevails in the lower two-thirds of the section, whereas echinoderms are dominant in the upper part. Sponge spicules, filaments, ostracods, benthic foraminifers, juvenile ammonites, brachiopods and calcareous sponges are also common in the upper part. Late Pliensbachian ammonites were found near the top of the formation (Rožič et al. 2014). Abundant finds of middle Liassic brachiopods and ammonites were reported from the area between Bohinjska Češnjica and Bitnje (Fig. 4) a century ago (Härtel 1920), but in subsequent studies the precise location of these fossiliferous sites could not be determined.

The upper part of the formation is characterized by abundant crinoids and resembles the upper part of the Zatrnik

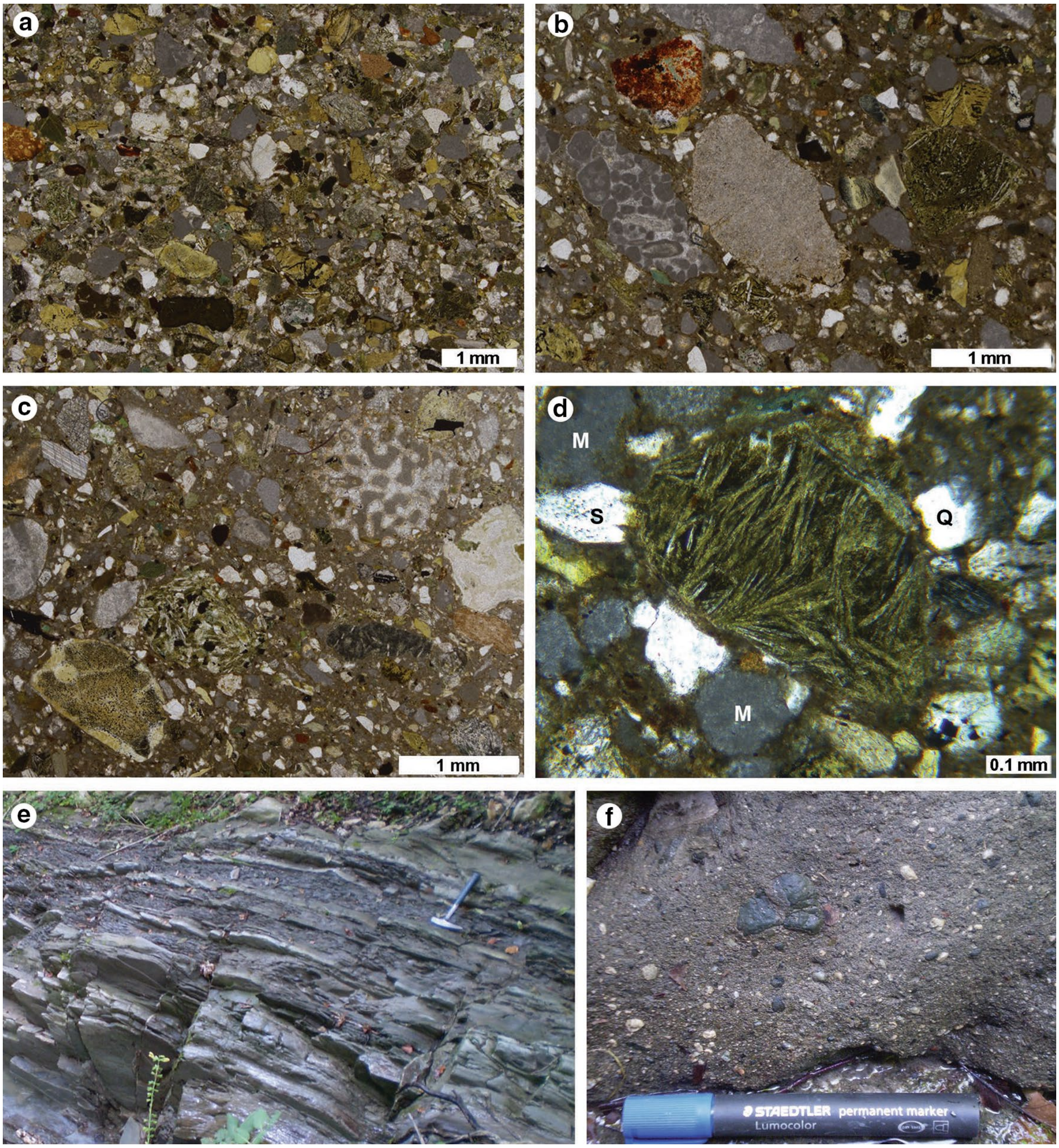

Fig. 5 Lower Cretaceous flysch-type deposits (Studor formation) of the Pokljuka Nappe. **a** Sandstone microfacies: carbonate clasts and lithoclasts of various igneous and metamorphic rocks. **b** Clast of peloidal grainstone with benthic foraminifer in the sandstone. **c** Isolated bioclast (calcareous sponge) within the sandstone. **d** Clast of mafic volcanic rock with branching augite crystals together with grains of quartz (Q), serpentinite (S) and calcimudstone (M). **e** Alternation of micritic limestone, marl and sandstone. **f** Green and red chert clasts and light-gray to white carbonate clasts within a sandy matrix

limestone. However, as stated by Rožič et al. (2014) and also observed in our study area (Fig. 4), this crinoidal limestone is devoid of chert, whereas chert nodules and layers are common in the Zatrnik limestone. The presence/absence of chert can be used as a simple field criterion to distinguish these two formations. In previously published maps (Härtel 1920; Buser et al. 1979; Buser 1987), the crinoidal limestones of both formations were treated together as a single lithostratigraphic unit.

In the Mt. Kobla section, the crinoidal limestone is overlain by a 0.5 m thick marl, presumably of Toarcian age, followed by a few meters of Biancone-type limestone, i.e., thin-bedded mudstone/wackestone with chert nodules (Rožič et al. 2014).

In the study area east of Lake Bohinj (Fig. 4), the upper stratigraphic contact of the crinoidal limestone is not exposed. Only a very small, about 1 m thick outcrop of the Biancone limestone was found in a heavily tectonized zone north of Bitnje (Fig. 4). The following Cretaceous mixed carbonate–siliciclastic turbidite deposits are more expanded but their contacts with underlying rocks are either tectonized or covered by vegetation. Although the field conditions do not allow us to determine the thickness of the Biancone limestone, it seems likely that the Biancone limestone of the Krn Nappe is extremely reduced, especially when compared with the Pokljuka Nappe where the Biancone limestone together with the overlying, carbonate-dominated Transitional unit attains a thickness of more than 200 m. Similarly, as also suggested by the Kobla section (Rožič et al. 2014), the Middle and Upper Jurassic radiolarites are entirely missing; their time interval is comprised in a stratigraphic gap.

The mixed carbonate–siliciclastic turbidite deposits occur at several localities (Fig. 4). Only minor differences exist between the flysch-type deposits of the Pokljuka and of the Krn Nappe; hence, we use the same name, the Studor formation, for both areas. In comparison with the Studor formation of the Pokljuka Nappe, the proportion of fine-grained rocks (shale, mudstone) is higher here (Fig. 6a). Qualitative estimates in coarser-grained rocks reveal that carbonate grains (calcimudstone and bioclastic packstone lithoclasts, abundant echinoderm fragments, rare planktonic and benthic foraminifera) generally predominate and the matrix is also carbonate-rich (Fig. 6b–d, f, g). Beds of radiolarian "packstone" (Fig. 6a, b) with clayey-carbonate matrix are common. In places, centimeter-sized breccia beds with angular limestone clasts are interstratified (Fig. 6d). Calcareous sandstones with a higher proportion of siliciclastic material contain abundant radiolarian chert and siliceous shale clasts, mono- and polycrystalline quartz grains (Fig. 6e, f), common chrome spinel (Fig. 6e), and rare feldspar, mica and chlorite. Lithic grains of igneous origin are common, mostly composed of serpentinitized pyroxene- and olivine-rich lithologies.

The age assignment is based on rare findings of diagnostic microfossils. Planktonic foraminifers and orbitolinids (Fig. 6f, g) were found in the SW part of the study area (south of Srednja vas in Fig. 4). *Globigerinelloides algerianus* Cushman and ten Dam (Fig. 6f), which has its total range in the Upper Aptian *Globigerinelloides algerianus* zone (Verga and Premoli Silva 2003) has been identified. Several samples were treated with diluted acetic and hydrofluoric acid to extract radiolarians. In the residues, radiolarian skeletons are abundant but poorly preserved. The prevailing radiolarians are dissolution-resistant multisegmented nassellarians (*Archaeodictyomitra, Dictyomitra, Thanarla*) and undeterminable spherical forms, most of which probably belong to cryptocephalic nassellarians. Identification at species level was possible in one sample only. According to Dumitrica et al. (1997), the assemblage of this sample (Fig. 7) is assignable to the Barremian. The diagnostic species are *Pseudodictyomitra recta* Vishnevskaya (determined as *Pseudodictyomitra conicostriata* Dumitrica by Dumitrica et al. 1997), which occurs in the Barremian to lower Aptian, and *Clavaxitus clava* (Parona), which is known from the Hauterivian and Barremian. We note that no age data were obtained for the base of the Studor formation, which might thus be older than the Barremian.

The Mesozoic rocks are unconformably overlain by a middle Oligocene succession composed of basal coarse-grained limestone conglomerate (up to 200 m thick), laminated thin-bedded limestone with characeans, and an alternation of sandstone and clayey marl (Buser 1986). The Oligocene deposits occur directly on top of Triassic massive limestone in the SW part of the study area (Fig. 4).

Structural elements in the study area

Geological mapping demonstrated that the NE–SW striking, approximately 13 km long and 5–7 km wide belt of deep-water lithological units of the Pokljuka Nappe, is surrounded by the Krn Nappe carbonate platform units (Fig. 4). The present-day contacts between the two nappes are steep ENE–WSW to NE–SW faults and locally also younger NW–SE striking faults (see the faults near Koprivnik and Gorjuše in Fig. 4).

The juxtaposition of the contrasting lithologies along a fault is generally well-discernible in topography and in places visible in outcrop (Fig. 8c) but reliable criteria to determine the sense of the dip slip are rare. On both sets of faults, sub-horizontal striation is relatively common (Fig. 8a, b). Where two generations of fault striation occur on the same fault plane, the horizontal striation is always better preserved than the vertical one (Fig. 8a), and thus probably younger. Only in a few cases could the sense of dip slip be determined on the fault plane (Fig. 8d). As suggested by cross-sections (Fig. 9a, b) and parallel faults in the vicinity (Fig. 2a, b), reverse as well as normal NE–SW trending faults are present.

The lateral displacement of NE–SW trending faults and stratigraphic units along the subsequent NW–SE trending faults is best visible where the relatively thin deep-water Jurassic and Cretaceous formations are exposed, e.g., north of Srednja vas and east of Mrzli studenec (Fig. 4). The offset generally does not amount to more than 100 m. In some cases, the apparent lateral displacement of lithostratigraphic units is much greater, e.g., along the faults near Koprivnik and Gorjuše (Fig. 4). A similar example was mapped NE of the study area between the Zasip Fault and an unnamed fault on both sides of Lake Bled (Fig. 2a). These anomalously long offsets can be ascribed to normal faults and not to strike-slip movements.

Mapping of the stratigraphic units and systematically documented bedding orientation/polarity and fault plane

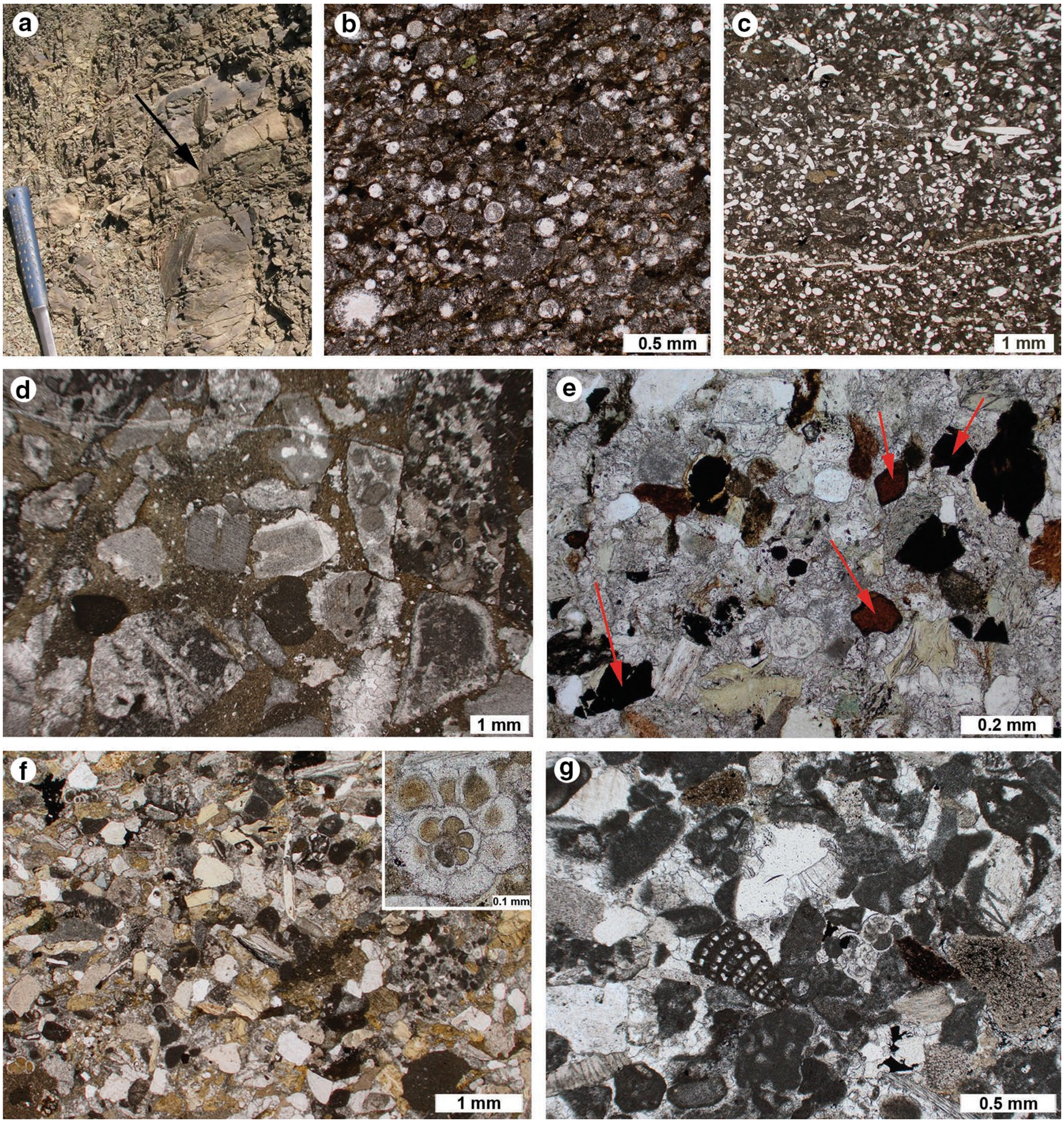

Fig. 6 Lower Cretaceous flysch-type deposits (Studor formation) of the eastern Krn Nappe. **a** Alternation of a few centimeter thick arenite beds and mudstone. The microfacies of the marked bed is figured in **b**. **b** Densely packed radiolarians (partly calcified) in a clayey-carbonate matrix (thin-section of the bed in **a**). **c** Concentration of sponge spicules in a limestone bed. **d** Microbreccia with angular clasts of various types of limestone and isolated echinoderm fragments. **e** Sandstone containing abundant chrome spinel grains (red arrows) and Fe–Ti heavy minerals (opaque grains). Mineral identification is based on EDS elemental analysis. PPL photomicrograph. **f** Calcareous sandstone with planktonic foraminifers in the matrix. *Globigerinelloides algerianus* Cushman and ten Dam is enlarged (sample coordinates 417527N, 126418E). Non-carbonate grains are mostly monocrystalline quartz. **g** Calcarenite including isolated planktonic foraminifers and orbitolinids

characteristics allowed us to reconstruct map-scale folds associated with both the NE–SW and NW–SE faults (Fig. 9a–c). The A–B profile cutting across two main NE–SW faults (Figs. 4, 9a) shows the deep-water succession of the Pokljuka Nappe as the central subsided block and the steep fault contacts with the platform carbonates of the Krn Nappe on both sides. A conspicuous overturned syncline, recognized already by Härtel (1920), occurs in the interior of the Pokljuka Nappe. The existence of this fault-propagation fold structure with a NE–SW trending fold axis (Fig. 9a) is supported by asymmetrically folded flyschoid lithologies, which could represent a tri-shear zone of a fault-propagation fold, and overturned bedding in the forelimb area. Approximately, 30°NW dipping beds of normal polarity in the west could represent the back-limb of the fault-propagation fold. The NE–SW striking

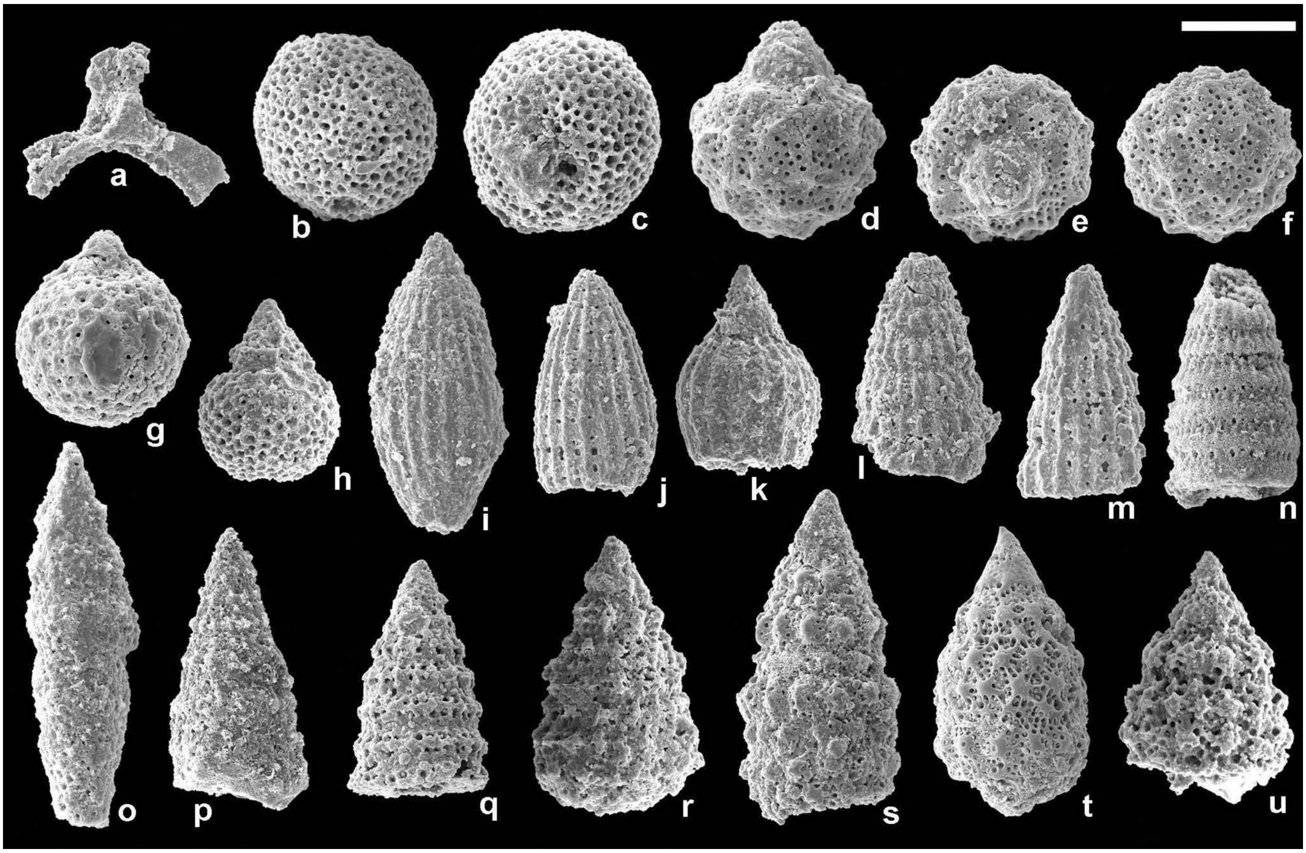

Fig. 7 Barremian radiolarians from the Studor formation of the eastern Krn Nappe. **a** *Dicerosaturnalis trizonalis* (Rüst). **b, c** *Holocryptocanium barbui* Dumitrica, apical (**b**) and antapical (**c**) view of the same specimen. **d–f** *Arcanicapsa* sp., lateral (**d**), apical (**e**) and antapical (**f**) view of the same specimen. **g** *Hemicryptocapsa* sp. **h** *Crococapsa uterculus* (Parona). **i** *Archaeodictyomitra lacrimula* (Foreman). **j** *Archaeodictyomitra* sp. **k** *Thanarla pacifica* Nakaseko and Nishimura. **l, m** *Dictyomitra communis* (Squinabol). **n** *Pseudodictyomitra recta* Vishnevskaya. **o** *Pseudoeucyrtis* sp. **p** *Crolanium* sp. **q** *Pseudocrolanium* cf. *puga* (Schaaf). **r** *Clavaxitus clava* (Parona). **s, t** *Xitus* sp. **u** *Xitus normalis* (Wu and Li). All specimens are from sample VZ 76 (sample coordinates 420373N, 129154E). Scale bar 100 µm for **a–c, h–m, p–t**; 75 µm for **n, o, u**; 60 µm for **d–g**

overturned succession of the Upper Triassic to Cretaceous formations is well-visible in the field and can be traced over a distance of 3 km (Fig. 4). This large-scale asymmetric fold provides good evidence of a SE-directed thrusting event.

In the NE part of the study area, the Pokljuka Nappe terminates against the steep boundary fault with gently NW dipping beds of normal polarity (cross-section C–D in Figs. 4, 9b). Here, a NE–SW fold has not been detected in the interior of the Pokljuka Nappe.

In the central part of the study area (cross-section E–F in Fig. 4), a NW–SE striking overturned succession of the Pokljuka Nappe has been mapped and interpreted as part of a contraction duplex (Fig. 9c). The map-view lenticular shape (Fig. 4) suggests that this duplex represents a positive flower structure formed along a NW–SE oriented fault.

According to what is mentioned above, we propose the following sequence of post-nappe deformational phases:

1. The oldest NW–SE contraction event was responsible for reverse faulting along steep NE–SW faults and for the parallel fault-propagation fold in the interior of the Pokljuka Nappe.
2. A younger extensional event in the same direction is evidenced by normal slips on NE–SW striking fault planes and also suggested by parallel normal faults documented in the vicinity of the study area (e.g., the Krma Fault in Fig. 2a, b).
3. A subsequent NE–SW contraction was responsible for the NW–SE oriented overturned fold in the central part of the Pokljuka Nappe. Dip-slip displacements (reverse and normal) along the NW–SE faults can be deduced from the geological map (Fig. 4, also see Fig. 2 a) but have not been directly documented on the fault planes.
4. The strike-slip event is probably the youngest and is reflected in a well-preserved horizontal striation on both NE–SW and NW–SE striking fault planes.

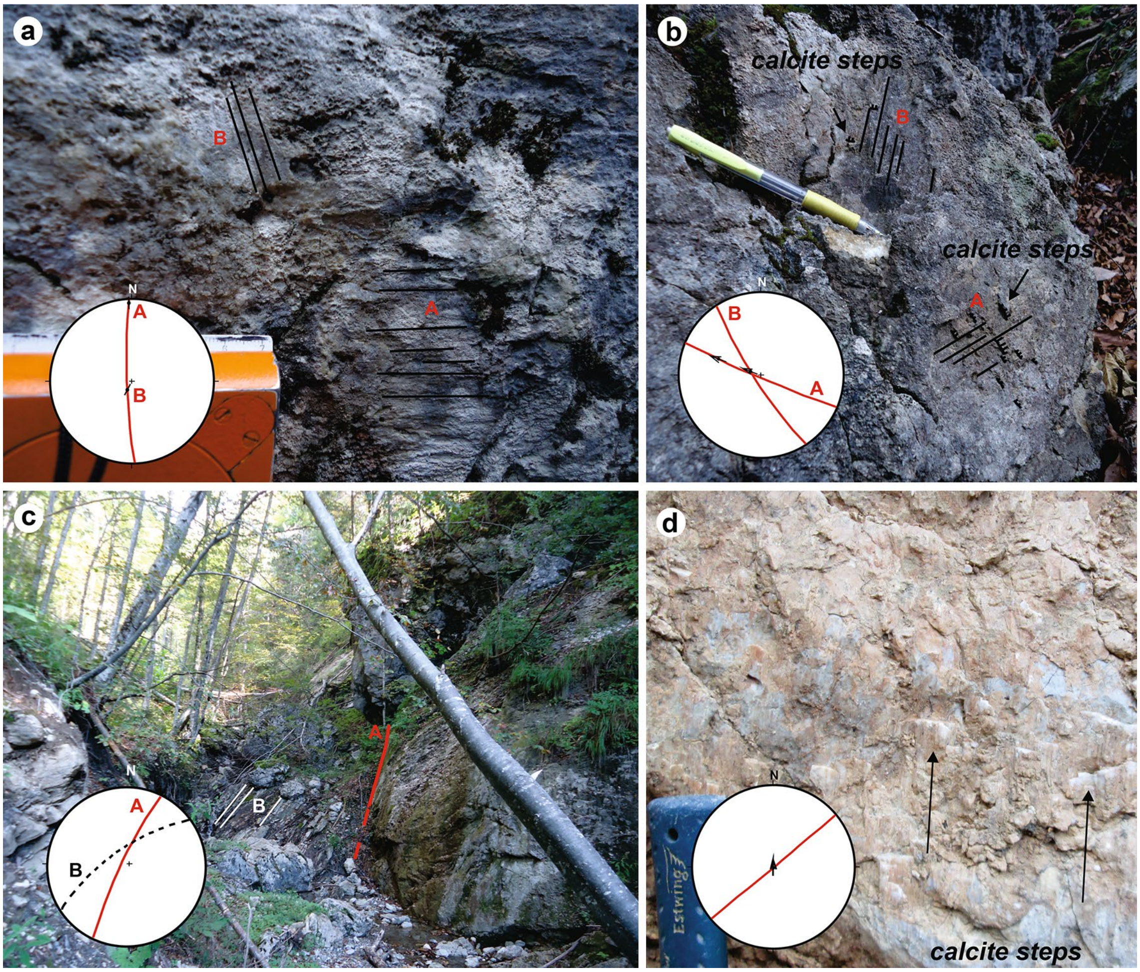

Fig. 8 Indicators of polyphase deformations along high-angle faults. **a, b** Two generations of fault striation observed on the same fault plane. Location coordinates 421741N, 128782E. **c** Sub-vertical fault separating the Biancone limestone of the Pokljuka Nappe (left) and the Lower Jurassic crinoidal limestone of the Krn Nappe (right). Location coordinates 420927N, 130752E. **d** Sub-vertical fault at the SE boundary between the Pokljuka Nappe and the Krn Nappe. Calcite steps indicate normal slip of the preserved block (the Zatrnik limestone of the Pokljuka Nappe). Location coordinates 427652N, 130944E. Red lines on stereograms are fault planes; the dotted black line is the bedding

Discussion

Stratigraphic correlations

The Lower Cretaceous flysch-type sediments between Lake Bled and Lake Bohinj record the early orogenic history of the present-day eastern Southern Alps. The chronostratigraphic correlation (Fig. 10) emphasizes the timing of the flysch deposition and allows us to link the study area with certain units in the Dinarides and in the Northern Calcareous Alps that were subjected to coeval orogenic processes. On the other hand, the locally diachronous onset of flysch deposition recorded in superposed units of the Julian Alps helps us to distinguish several orogenic pulses in the study area and provides important information for reconstructing the initial Dinaric nappe stack.

The local stratigraphic correlation within the Julian Alps (Fig. 10) shows flysch-type deposits of two different ages, the Early Cretaceous and the late Campanian–Maastrichtian that roughly divide the Julian Alps into eastern and western sectors (see Fig. 2a for the present-day position of the tectonic units and Fig. 11 for the paleogeographic location). The most striking feature is that the Julian High (i.e., the subsided Julian Carbonate Platform), supposedly quite a uniform submarine high from the late Early Jurassic, is split into two parts with significant differences in the stratigraphic record. The western part of the Julian High is characterized by condensed upper Bajocian to Tithonian Rosso Ammonitico type limestone of the Prehodavci Formation (Šmuc 2005), Upper Tithonian to Neocomian Biancone limestone, Albian to Cenomanian Scaglia variegata, Turonian to Campanian Scaglia rossa and Upper Campanian to

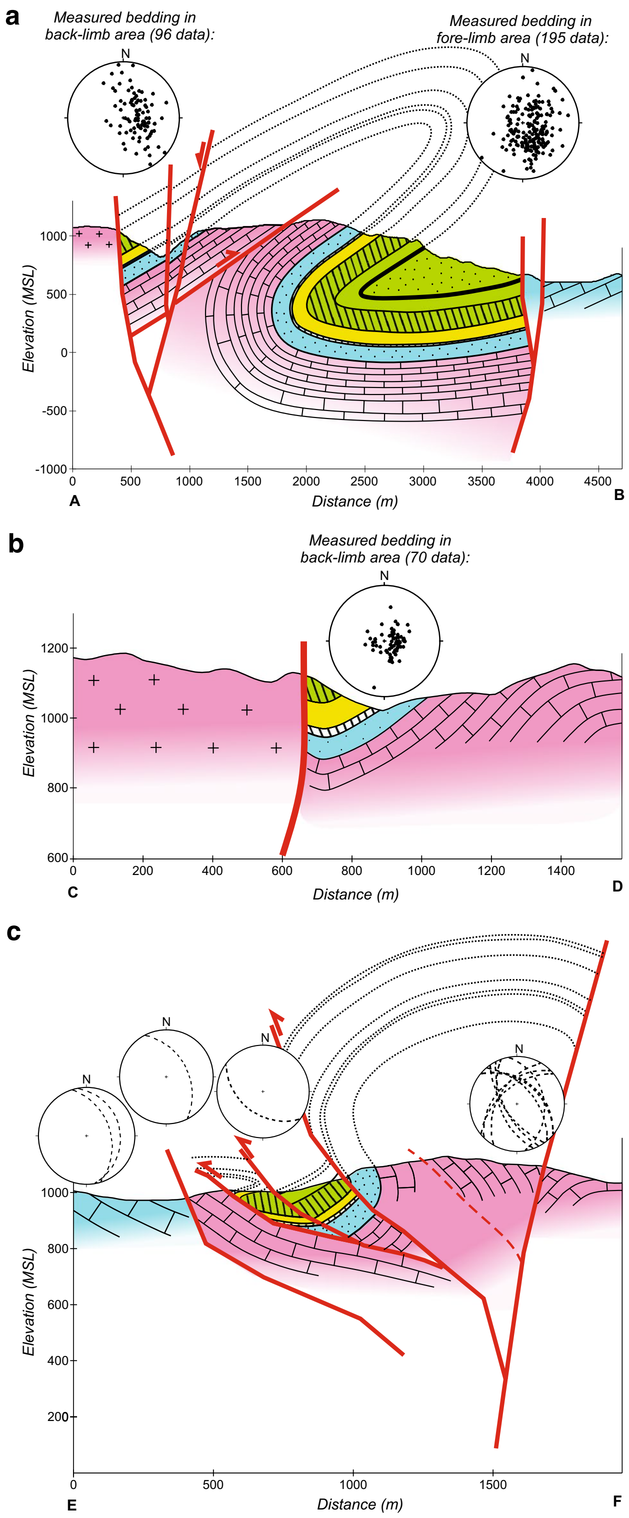

Fig. 9 Cross-sections showing fault boundaries between the Pokljuka and Krn nappes. **a, b** Geometries at NE–SW striking boundary faults. **c** Contraction duplex geometry at a NW–SE striking fault. Locations of cross-sections AB, CD and EF are marked in Fig. 4. Stereograms show measured bedding at several localities along the same structure. The legend for the lithostratigraphic units is the same as in Fig. 4

Maastrichtian flysch (Cousin 1981; Buser 1986; Jurkovšek 1987; Šmuc 2005). Locally, several hundred meters deep neptunian dykes filled with carbonate blocky breccia and sealed with the Lower Albian Scaglia variegata occur (Buser 1986; Goričan and Šmuc 2004). In the Tolmin Basin, also belonging to the western sector (Fig. 10), the onset of flysch-type deposits is, similar to the western Julian High, dated to upper Campanian to Maastrichtian (Caron and Cousin 1972; Cousin 1981; Buser 1986). In the underlying succession (Fig. 10), we note the upper Aptian to Turonian Lower flyschoid formation, which is composed of basal calcareous breccia, shale, marl, and limestone turbidites but is devoid of sand-sized siliciclastic material and cannot be considered flysch in the proper sense (Caron and Cousin 1972). The foreland sediments of the Julian Alps were thus clearly related to two separate orogenic phases. Importantly, the flysch-type deposits of the eastern sector, the Studor formation, at least partly overlap in time with extension-related features in the west, that is, with the formation of large neptunian dykes on the Julian High, and with an erosional event and the deposition of basal breccia in the Tolmin Basin (Fig. 10). This correlation allows us to integrate the Early Cretaceous basins of the Julian Alps into a foreland-basin system with flysch deposition in the eastern, internal area and extensional faulting in the western, external zones (Fig. 11).

It is well-established that the Lower Cretaceous flysch of the Julian Alps corresponds to the Bosnian Flysch in the central Dinarides (Cousin 1981; Kukoč et al. 2012). The Bosnian Flysch (Blanchet et al. 1969) is subdivided into the lower, predominantly siliciclastic Vranduk Formation, and the upper carbonate-dominated Ugar Formation (Hrvatović 2006; Mikes et al. 2008). The transition to carbonate facies occurs around the Cenomanian–Turonian boundary but is rarely found in a continuous succession (e.g., Charvet 1978). Measured sections through the Vranduk Formation are rare (e.g., Rampnoux 1974; Cadet 1978). For the correlation (Fig. 10), we selected two sections published by Cadet (1978) that include the underlying stratigraphic units. The first section (Cadet 1978, p. 42), representing the external part of the Bosnian Zone, is an approximately 250 m thick succession of mostly dark-gray mudstone, and subordinate fine-grained sandstone, silty limestone and some breccia beds. Planktonic foraminifera indicate a Barremian–Aptian age at the base and a Cenomanian age in the upper part of the succession. The underlying section consists of massive dolomite (possibly Lower Jurassic), some 20 m of bedded limestone, a few meters of black chert, and a Tithonian–Berriasian breccia. This succession compares well with the reduced succession of the eastern Julian High (Fig. 10). The second section (Cadet 1978, p. 43) is situated in the median Bosnian Zone and represented by a more than 1000 m thick flysch series, which is subdivided into three units—gray (Berriasian to Barremian–lower Aptian),

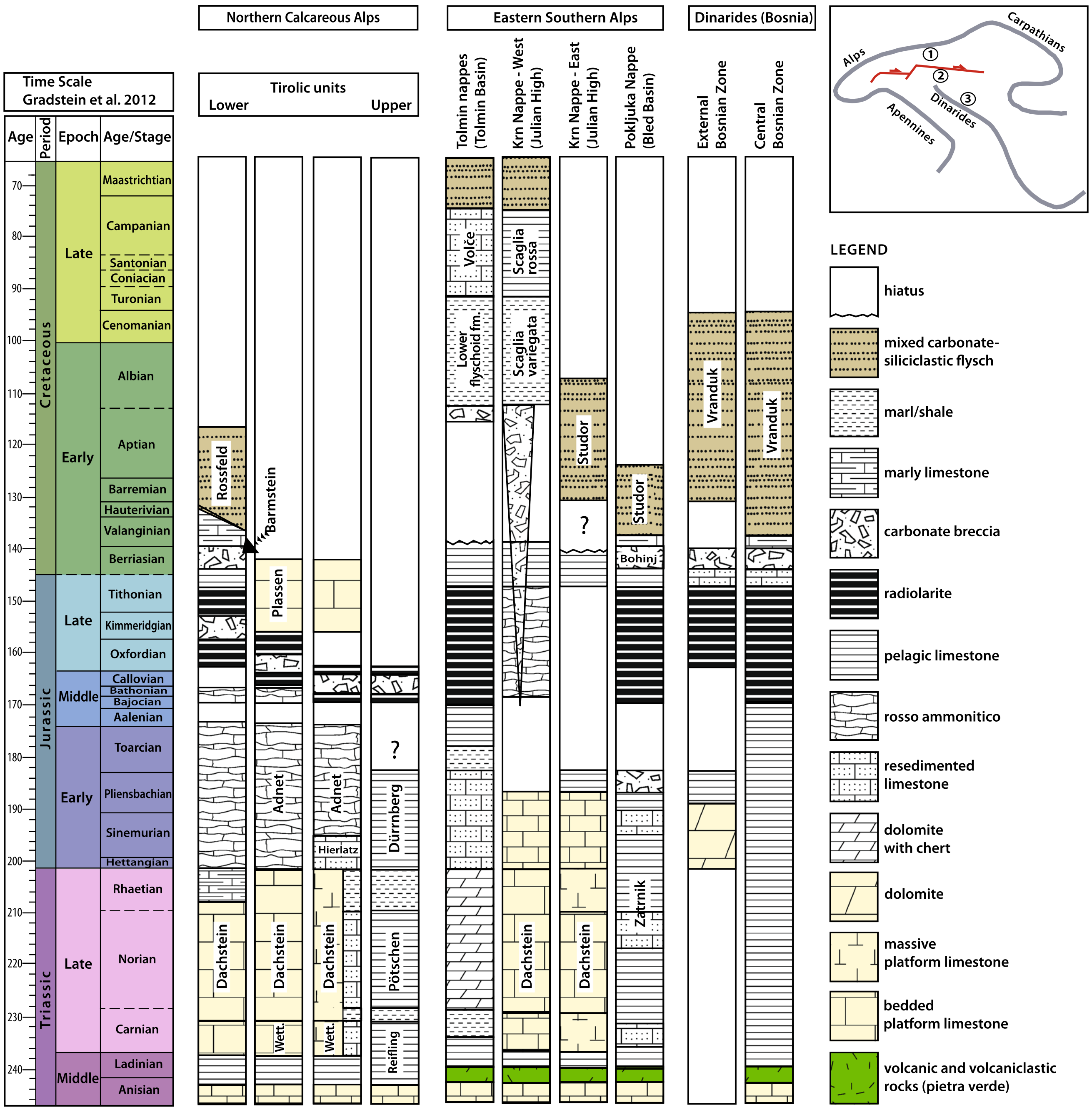

Fig. 10 Chronostratigraphic overview of Middle Triassic to Cretaceous formations in the Julian Alps (see Figs. 2a, 11 for the location of tectonic and paleogeographic units) and correlation with selected successions in the Northern Calcareous Alps and Dinarides. The Northern Calcareous Alps compiled according to Faupl and Wagreich (2000), Mandl (2000) and Missoni and Gawlick (2011a, b). The Tolmin Basin and the western Julian High according to Cousin (1981), Buser (1986), Šmuc (2005) and Rožič (2009). The eastern Julian High and the Bled Basin: this study with references. The Bosnian Basin: Cadet (1978). Inset figure: location of the correlated areas on a schematic orographic map. 1 = Northern Calcareous Alps, 2 = Julian Alps, 3 = Bosnian Zone

black (Aptian–Albian) and white (Cenomanian) flysch units. Clasts originating from ophiolites are common in the gray and black units. The white unit contains less sandstone and the proportion of pelagic limestone increases towards the top of the flysch sequence. The underlying Triassic to Jurassic succession is fully of deep-water origin from the Ladinian onwards (Cadet 1978). The entire Mesozoic section is in good agreement with the succession of the Bled Basin. The Vranduk Formation of this section is complete and allows us to assume that the original flysch sequence of the Bled

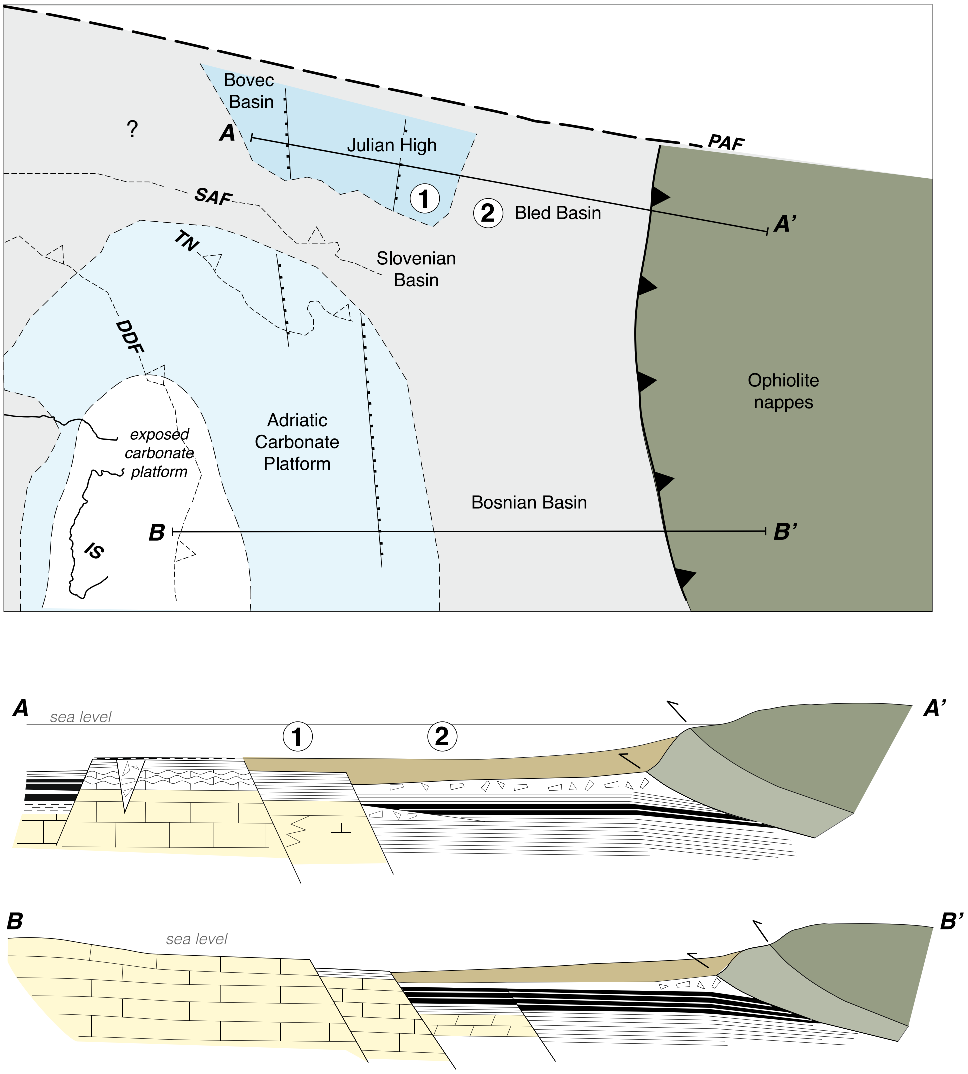

Fig. 11 Aptian–Albian paleogeographic sketch of a broader study area based on map restoration data of the Alpine–Dinaric system of Ustaszewski et al. (2008) and the nappe-related shortening estimates in SW Slovenia of Placer (1981). Palinspastic restoration is indicated by major tectonic boundaries (*PAF* Periadriatic Fault, *SAF* South-Alpine front, *TN* Trnovo Nappe, *DDF* deformation front of the External Dinarides) and the present-day outline of the Istrian peninsula (*IS*). Numbers in circles on map and in cross-section A–A′ indicate sedimentary domains discussed in the text: (1) eastern Krn Nappe; (2) Pokljuka Nappe. Cross-section B–B′: representative composite profile through the northern part of the Bosnian Basin based on Cadet (1978) and Lužar-Oberiter et al. (2012). Lithologic patterns correspond to key in Fig. 10

Basin was deposited over the same time span and attained a comparable thickness.

In the Dinarides, the northernmost equivalent of the Vranduk Formation occurs on Mt. Ivanščica in northern Croatia. These mixed carbonate–siliciclastic turbidites, the Oštrc Formation, are Hauterivian to Albian in age, and overlie a succession composed of Upper Triassic shallow-marine carbonates, Jurassic pelagic limestones and cherts, and Tithonian–Valanginian Aptychus (Biancone) limestones (Babić and Zupanič 1978). Recent provenance studies clearly show the predominant ophiolitic origin of the clastic material in the Oštrc Formation (Lužar-Oberiter et al. 2009, 2012).

Regional stratigraphic correlation (Fig. 10) also reveals the close resemblance of the study area in the Julian Alps and the upper nappes (the Tirolic units) of the Northern Calcareous Alps in Austria. The Triassic to Lower Jurassic stratigraphic evolution is practically identical to that inferred for the Dachstein reef-rimmed carbonate platform and its ocean-ward transition to a deep shelf (Mandl 2000; Missoni and Gawlick 2011a, b with references). The equivalents of the Wetterstein and Dachstein reefs occur at the margin of the Julian Carbonate Platform. The Zatrnik limestone is similar to the deep-water Reifling and Pötschen formations but is much thicker and contains abundant platform-derived detritus. The Zatrnik limestone thus best compares with the slope equivalents of these deep-marine formations, namely with the Raming Limestone and the Gosausee Limestone (or Pedata Schichten) of Mandl (2000).

Lower Jurassic deposits show a distinction between the two areas due to a different platform drowning timing. In the Austroalpine realm from the late Hettangian, condensed red limestones of the Adnet Group including coarser-grained Hierlatz Limestone Member were deposited on the margin of the drowned platform, and the hemipelagic Dürrnberg Formation characterized the adjacent deeper-water basin (Gawlick et al. 2009; Missoni and Gawlick 2011a, b). In the Julian Alps, the subsidence of the carbonate platform was delayed. Crinoidal limestone with ammonites and brachiopods on the margin of the Julian Carbonate Platform/Julian High, and fault-related breccias in the Bled Basin started to accumulate as late as in the Pliensbachian (Fig. 10).

A major difference between the Julian Alps and the Northern Calcareous Alps is recorded in the Middle and Upper Jurassic. The Tirolic units are characterized by time-transgressive (upper Bajocian to Oxfordian) polymictic mass-flow deposits (the Sandlingalm, Strubberg and Tauglboden formations) interstratified in a succession of radiolarian cherts; these mass-flow deposits form an up to 2000 m thick sediment fill of trench-like basins that were created in front of a propagating thrust belt (Gawlick 1996; Gawlick et al. 1999; Missoni and Gawlick 2011b). Contrary to this, the coeval radiolarites of the Bled Basin are only 20 m thick and devoid of any coarse-grained extra-basinal material, implying that the Bled Basin was located at a greater distance from the Jurassic thrust front.

The next step in the tectonostratigraphic evolution of the Northern Calcareous Alps was the development of carbonate platforms (the Plassen Formation and equivalents) on top of the newly formed nappe stack (Gawlick et al. 2009; Missoni and Gawlick 2011a, b with references). In the Bled Basin, erosional remnants of such an internal platform, named the Bohinj Carbonate Platform by Kukoč et al. (2012), characterize the Bohinj Formation. The Bohinj Formation represents the time and facies equivalent of the Barmstein Limestone, containing clasts of the Plassen Formation (Kukoč et al. 2012).

Finally, the Lower Cretaceous mixed carbonate–siliciclastic flysch-type turbidites correspond to the Valanginian to Aptian Rossfeld Formation (e.g., Gawlick et al. 1999; Faupl and Wagreich 2000; Missoni and Gawlick 2011a) of the Lower Tirolic units (Fig. 10). Similar flysch-type deposits of the same provenance continue into the Aptian to Albian Lech Formation of the upper Bavaric nappes (von Eynatten and Gaupp 1999) and the Lavant Formation of the Drau Range (Faupl and Wagreich 2000). The evolution of both areas is thus in good agreement, with the main difference being the location of the foreland basins with respect to the underlying Triassic carbonate platforms. In the eastern Julian Alps, the Lower Cretaceous foreland sediments were deposited around the former (Late Triassic/Early Jurassic) platform-to-basin boundary, whereas in the Northern Calcareous Alps, the Jurassic and Lower Cretaceous syn-orogenic sediments reached well into the interior of the Late Triassic lagoon.

In Hungary, the well-known age and facies equivalent of the Rossfeld Formation is the ophiolite-derived coarsening-upward turbidite sequence that ends with channel-fill conglomerates (Sztanó 1990; Császár and Árgyelán 1994) of late Aptian age (Szives et al. 2018). This sequence is exposed in the Gerecse Mountains in the northeastern Transdanubian Range where the entire Upper Triassic, Jurassic and Cretaceous stratigraphic succession is strikingly similar to the Tirolic units of the Northern Calcareous Alps (see Császár et al. 2012 for details). The western part of the Transdanubian Range, on the contrary, shows close affinities with the Southern Alps (see Kazmer and Kovács 1985; Csontos and Vörös 2004; Csaszar et al. 2012; Fodor et al. 2013; Szives et al. 2018 for tectonic and paleogeographic implications). The overall stratigraphic correlation of our study area in the Julian Alps with the Gerecse Mountains is basically the same as that with the Northern Calcareous Alps. The individual Lower Cretaceous formations correlate as follows: the Bohinj Formation corresponds to the Felsővadács Breccia Member, the Transitional unit to the Bersek Marl Formation, and the Studor formation to the Lábatlan Sandstone Formation.

Implications for the tectonic history of the Julian Alps

The general structure of the Julian Alps is still poorly known, particularly the individual nappes and their areal extent have not been exactly determined yet. Our study proves that the Lower Cretaceous flysch-type deposits occur as part of two fundamentally different stratigraphic successions, implying that they belong to two separate nappes. The entirely deep-water succession of the Bled Basin belongs to the Pokljuka Nappe, which is the highest of the Julian nappes. The platform-to-basin succession deposited at the edge of the Julian Platform/Julian High belongs to the underlying Krn Nappe.

The structural position of the Pokljuka Nappe on top of the Krn Nappe cannot be directly proven in the study area but is evidenced about 10 km to the west by the Vodični vrh Klippe (Fig. 2a). In turn, the structural position of the Krn Nappe on top of the Tolmin nappes is visible in a well-exposed thrust plane and supported by the constant dip of bedding planes towards N to NW (Fig. 2b). The nappe structure in the Julian Alps is dissected by two sets of steep faults. The NE–SW oriented faults responsible for the characteristic present-day orientation of the Pokljuka Nappe are of prime importance (Fig. 2b). Cross-sections perpendicular to these faults (Fig. 9a, b) indicate that the Pokljuka Nappe is preserved in the central, relatively subsided block, whereas the side blocks expose the Krn Nappe at the surface.

As suggested by the stratigraphic differences between the western and eastern sectors of the Krn Nappe (Fig. 10), a further subdivision of the Krn Nappe can be expected. Since outcrops of Jurassic and Cretaceous rocks are rare, the main tectonic contact is to be searched for within Triassic shallow-water limestones that are practically identical in the western and eastern sector and cannot be distinguished by stratigraphic research alone. Systematic structural mapping would thus be essential to locate the contact between the western and the eastern, structurally higher, part of the

Krn Nappe. It is also tempting to connect the Zlatna Klippe, another unit of Triassic shallow-water carbonates, to the eastern Krn Nappe (Fig. 2a, b). This assignment would be in agreement with the position of the Zlatna Klippe directly on top of the Rosso Ammonitico, Biancone and Scaglia variegata facies (Jurkovšek 1986; Buser 1987) characteristic of the western Krn Nappe.

Vitrinite reflectance measurements have demonstrated the low thermal maturity of the Lower Cretaceous flysch-type deposits in the Bohinj area (Rainer et al. 2002, 2016). Consistent with these data, conodonts in the Zatrnik limestone are whitish-transparent (Buser 1986) and have a very low Conodont Alteration Index. On the other hand, Mesozoic successions of the Tolmin nappes (Fig. 2a, b) including their eastward continuation in central Slovenia, exhibit a considerable thermal overprint characteristic of deep diagenesis and locally anchizone metamorphism (Rainer et al. 2002, 2016). Rainer et al. (2002, 2016) explained this thermal maturity pattern by variations in the thickness of the overlying Upper Cretaceous to Eocene flysch deposits. One main reason they rejected the possibility of nappe stacking as the controlling factor was their assumption that the Lower Cretaceous flysch of the Julian Alps occurs as a window of the Slovenian Basin below the Julian nappes. Considering that this Lower Cretaceous flysch is in fact part of the structurally higher units of the Julian Alps reopens the question of interpretation. Southward thrusting of the Julian nappes over the Slovenian Basin offers a likely alternative to explain the elevated thermal maturity in an E–W oriented belt in central Slovenia (see Figs. 3, 4, 5, 6 in Rainer et al. 2016).

The polyphase tectonic history characteristic of the transition zone between the Alps and the Dinarides is well-manifested in our study area. Structural and stratigraphic relationships investigated during the geological mapping allowed us to obtain relative ages of the observed deformations. The determined deformational sequence was then correlated with published data on the timing of tectonic events in neighboring areas. In our study area, stratigraphic ages constraining the tectonic evolution are virtually missing. Except for the middle Oligocene shallow-marine to brackish sediments, that postdate the Dinaric nappe emplacement and predate the subsequent block faulting, no other Tertiary sediments occur in the Julian Alps.

The nappe emplacement can be broadly attributed to the Maastrichtian to Eocene top-to-SW thrusting phases observed throughout the Dinarides (Tari 2002; Ilić and Neubauer 2005; Schmid et al. 2008; Ustaszewski et al. 2010; Žibret and Vrabec 2016). Considering the striking similarity in stratigraphy and facies between the Bled Basin and the Bosnian Basin (Fig. 10), a pre-Maastrichtian emplacement of the Pokljuka Nappe is unlikely. The upper part of the Bosnian Flysch, the Ugar Formation, ranges in age up to the Maastrichtian or even Paleocene (Mikes et al. 2008 with references) implying that the Bosnian Basin remained in an under-filled stage throughout the Cretaceous. A similar situation can be inferred for the Bled Basin although the Upper Cretaceous deposits are actually missing.

The first post-nappe contraction, reflected in SE-directed reverse faults and overturned folds (Fig. 9a) can be associated with the late Oligocene–early Miocene southward to SE-ward South-Alpine thrusting (Doglioni and Siorpaes 1990; Fodor et al. 1998; Castellarin and Cantelli 2000; Bartel et al. 2014; van Gelder et al. 2015). The style of deformation within the Julian nappes is predominantly brittle, determined by the thick pile of platform carbonates. Low-angle thrusts were possible only in rheological weak zones like the basinal deposits of the Pokljuka Nappe (Fig. 9a). Larger-scale, low-angle thrusts were created in the Tolmin nappes where the Mesozoic sediments of the Slovenian Basin were overridden by the entire Julian nappe stack and internally dissected into several approximately E–W oriented thrust sheets (Fig. 2a, b). We also note that a contemporaneous early post-nappe compressional phase is missing in the External Dinarides (Žibret and Vrabec 2016) which is in agreement with the assignment of top-to-SE movements to a South-Alpine event.

According to the observed structural criteria, the NW–SE Oligocene–early Miocene contraction was followed by extension in the same direction. The Miocene extensional event is well-documented in the Dinarides and is classically interpreted in relation to the formation of the Pannonian Basin (Ilić and Neubauer 2005; Ustaszewski et al. 2010; van Gelder et al. 2015; Žibret and Vrabec 2016). We note that the orientation of the extension-related structures is not regionally uniform but varies significantly from one area to another and seems to be systematically determined by the structures inherited from the preceding contraction stage. Here we point out that our study area is relatively small and does not allow us to make further inferences before the overall pattern of the extensional structures is determined throughout the Julian Alps.

The next stage of deformation observed in our study area is NE–SW shortening accommodated by a reverse and possibly strike-slip displacement along NW–SE oriented faults (Figs. 4, 9c). We tentatively attribute this deformation to the widely documented inversion of extensional structures in the Pannonian Basin that started in the Late Miocene–Pliocene (Peresson and Decker 1997; Fodor et al. 1999; Vrabec and Fodor 2006; van Gelder et al. 2015). From the geological map (Figs. 2, 4), we also inferred the existence of normal NW–SE oriented faults but the relative age of the extension with respect to contraction across these faults could not be determined. We note that the NE–SW direction of shortening deviates from the directions documented in the neighboring areas. In the NW External Dinarides in Slovenia, an E–W Late Miocene compressional event has been recognized (Žibret and Vrabec 2016). For contraction phases in the Kamnik–Savinja Alps (see Fig. 1 for location) on the other hand, only NW–SE direction of shortening was inferred (Fodor et al. 1998). To interpret correctly the presumably Late Miocene NE–SW shortening in the study area, additional data on contraction phases are necessary from other parts of the Julian Alps including the Tolmin nappes from which systematic structural measurements are not yet available.

The last stage of deformation identified in our study area is the strike-slip reactivation of both sets of pre-existing faults. This deformation fits well into the recent inversive/transpressive tectonic phase, documented in a wider South-Alpine—NW Dinarides territory (Tomljenović and Csontos 2001; Bartel et al. 2014; Mladenović et al. 2015; Žibret and Vrabec 2016).

Conclusions

- Lower Cretaceous flysch-type deposits, the Studor formation, form the terminal sequence of two different stratigraphic successions. The first succession is entirely of deep-water origin from the Middle Triassic and was ascribed to the Bled Basin. The second succession consists of Upper Triassic to Lower Jurassic shallow-water carbonates overlain by a thin deep-water sequence and was located at the eastern margin of the adjacent Julian Carbonate Platform/Julian High. Practically identical Mesozoic successions are known from the Bosnian Zone in the central Dinarides and closely similar successions characterize the Tirolic units of the Northern Calcareous Alps in Austria and the northeastern Transdanubian Range in Hungary.
- The two stratigraphic successions are assigned to two superposed nappes. The succession of the Bled Basin belongs to the Pokljuka Nappe, which is the highest nappe of the original (Dinaric) nappe stack. The platform-to-basin succession is part of the underlying Krn Nappe.
- Today, the contacts between these two nappes are steep NE–SW striking fault segments cross-cut by younger NW–SE striking faults. A detailed geological map with representative cross-sections, bedding orientation and polarity, fault-slip microcriteria, in combination with data from the literature allowed us to recognize the following post-nappe deformation sequence: (1) Oligocene–Early Miocene NW–SE contraction; (2) Early–Middle Miocene extension; and (3) Late Miocene to recent inversion and transpression.
- The areal extent of the Pokljuka Nappe is larger than previously thought but, nevertheless, confined, limited to the blocks that underwent relative subsidence during the post-nappe block faulting. Most of the Pokljuka Nappe must have been completely removed by erosion.
- The Jurassic–Cretaceous stratigraphy of the Krn Nappe in the study area is significantly different from that in the western part of the same nappe. We suggest that the Krn Nappe could be subdivided into two nappes—the lower (western) Krn Nappe sensu stricto and the upper (eastern) Krn Nappe, which directly underlies the Pokljuka Nappe. We tentatively connect the Zlatna Klippe with the eastern Krn Nappe. Further structural research will determine the boundary between the two nappes elsewhere in the Julian Alps and allow a proper definition of the eastern Krn Nappe as a separate thrust unit.

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