STRATIGRAPHY AND STRUCTURE OF THE JULIAN ALPS IN NW SLOVENIA

STRATIGRAFIJA IN STRUKTURA JULIJSKIH ALP V SEVEROZAHODNI SLOVENIJI

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ABSTRACT

Stratigraphy and structure of the Julian Alps in NW Slovenia

The Julian Alps belong to the eastern Southern Alps where the South-Alpine and the Dinaric structures now overlap. In Mesozoic times, this area was part of the northeastern Adriatic continental margin, which was facing the Neotethys Ocean but was also close to the Alpine Tethys. The Mesozoic distribution of basins and swells on the continental margin determined variations in the stratigraphic record and also controlled the structural evolution of the later thrust belt. The most general tectonic subdivision in the Julian Alps is the distinction between the Tolmin nappes derived from the Slovenian Basin and the Julian nappes derived from the Julian High and its surroundings. This paper focuses on the Julian nappes. The Mesozoic stratigraphic record is linked with the available structural data to propose a robust subdivision in four nappes that were emplaced in the early Paleogene. From bottom to top these nappes and their corresponding paleotopographic units are: The Tamar Nappe (Tarvisio Basin), the Krn Nappe (western part of the Julian High) with the overlying Travnik Thrust Sheet (Bovec Basin), the Jelovica Nappe together with the Zlatna Klippe and the equivalent smaller klippen (eastern Julian High) and the Pokljuka Nappe (Bled Basin).

The second part of the paper deals with the description of field-trip stops. The panoramic view from the mountain ridge south of Lake Bohinj is presented to explain the general structure of the Julian Alps. The second half of the field-trip is devoted to the Jurassic and Cretaceous stratigraphy of the Bled Basin as the paleogeographically most internal unit with clear affinities with the central Dinarides.

Key words: Mesozoic, Cenozoic, Southern Alps, Dinarides, stratigraphy, nappe structure

IZVLEČEK

Stratigrafija in struktura Julijskih Alp v severozahodni Sloveniji

Julijske Alpe so del vzhodnih Južnih Alp, kjer se danes križajo južnoalpske in starejše dinarske strukture. V mezozoiku je bilo ozemlje del severovzhodnega kontinentalnega roba Jadranske plošče med Neotetido na vzhodu in Alpsko Tetido na zahodu. Razporeditev globokomorskih bazenov in relativno dvignjenih planot na mezozojskem kontinentalnem robu se odraža v raznolikem stratigrafskem zapisu, od mezozojskih prelomov in razlik v stratigrafskih zaporedjih pa je bil odvisen tudi nadaljnji strukturni razvoj ozemlja. Generalno so Julijske Alpe razdeljene na Tolminske in na Julijske pokrove. Stratigrafska zaporedja Tolminskih pokrovov so bila paleogeografsko del Slovenskega bazena, v Julijskih pokrovih pa so ohranjena zaporedja Julijskega praga in bazenov, ki so ga obkrožali. Poudarek članka je na Julijskih pokrovih. Na osnovi mezozojske stratigrafije in obstoječih strukturnih podatkov predlagamo grobo delitev Julijskih pokrovov na štiri pokrove iz Dinarskega faze narivanja, tako da vsakemu pokrovu ustreza določena mezozojska paleotopografska enota. Najnižji je Tamarski pokrov z zaporedji Trbiškega bazena. Sledi Krnski pokrov (zahodni del Julijskega praga) s Travniško lusko oziroma zaporedjem Bovškega bazena. Nad Krnskim pokrovom je Jelovški pokrov (vzhodni del Julijskega praga), ki mu pripadajo še Zlatenska plošča in nekaj manjših tektonskih krp. Strukturno najvišji je bil v paleogenu Pokljuški pokrov, sestavljen iz kamnin Blejskega bazena.

V drugem delu članka so opisane ogledne točke ekskurzije. Razgled z Vogla in Šije smo uporabili za razlago generalne strukture Julijskih Alp. Druga polovica ekskurzije je posvečena stratigrafiji jurskih in krednih plasti Blejskega bazena, ki je bil paleogeografsko relativno interna enota, po stratigrafiji primerljiva z enotami centralnih Dinaridov.

Ključne besede: mezozoik, kenozoik, Južne Alpe, Dinaridi, stratigrafija, pokrovna zgradba

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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 (Figure 1). Westwards, in northern Italy, an overlap of South-Alpine and Dinaric structures has been established (Doglioni 1987; Doglioni & Siorpaes 1990) and a strong influence of Mesozoic stratigraphy on the structural evolution of the thrust belt has been demonstrated (Doglioni 1992; Doglioni & Carminati 2008, and references therein). An overlap of the Dinaric and younger Alpine structures was also confirmed at the boundary between the Southern Alps and the Dinarides in Slovenia (Placer & 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) (Figure 2a). The Mesozoic successions consist of a variety of facies ranging from platform carbonates to deep-marine radiolarian cherts. Due to extensive stratigraphic research, the local basin-and-swell configuration of the continental margin through the Mesozoic is now relatively well known (Goričan et al. 2012a with references; Gale et al. 2015; Goričan et al. 2018). On the other hand, the complex structure and the polyphase deformation history of the area have not been sufficiently explored yet. Although several thrust faults have been recognized by early researchers (e.g. Kossmat 1913; Winkler 1923) and confirmed during the systematic geological mapping at scale 1:100,000 (Jurkovšek 1986; Buser 1987), a clear differentiation between the Paleogene (Dinaric) and younger structures is still missing.

The aim of this paper is to relate the well-established Mesozoic stratigraphy to the present-day structure and to propose a subdivision in which each Mesozoic paleotopographic unit (basin or swell) corresponds to a separate thrust sheet of the initial Dinaric nappe stack. The field trip will start south of Lake Bohinj at Mt. Šija (1880 m altitude), which offers a nice view of the general nappe structure in the Julian Alps. In the afternoon, the

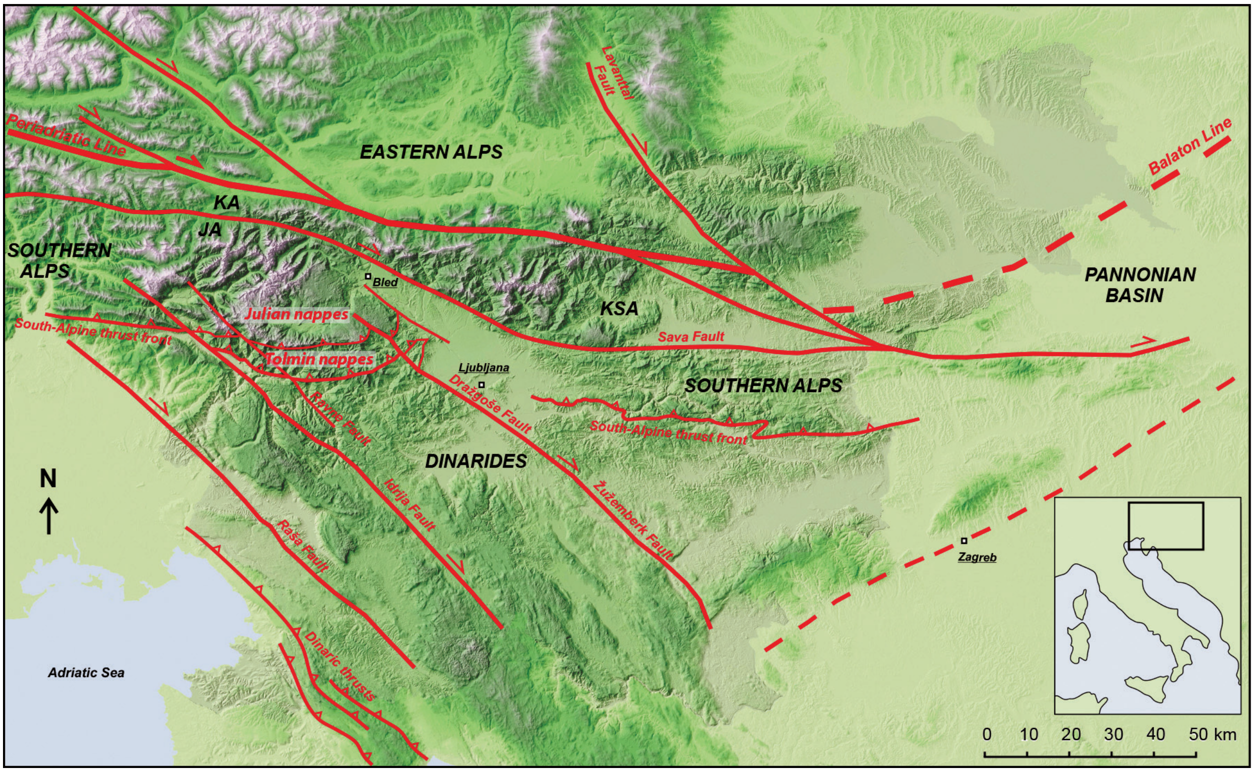

Figure 1: Eastern Southern Alps and adjacent tectonic units with the location of the Julian and Tolmin nappes. Abbreviations: KA Karavanke Mountains, JA Julian Alps, KSA Kamnik–Savinja Alps.

Jurassic – Cretaceous stratigraphy of the highest nappe, the Pokljuka Nappe, will be visited. This stratigraphic succession defines the Bled Basin, which occupied the most internal position in the area and is characterized by Lower Cretaceous ophiolite-bearing flysch-type deposits correlative to the Bosnian Flysch in the central Dinarides.

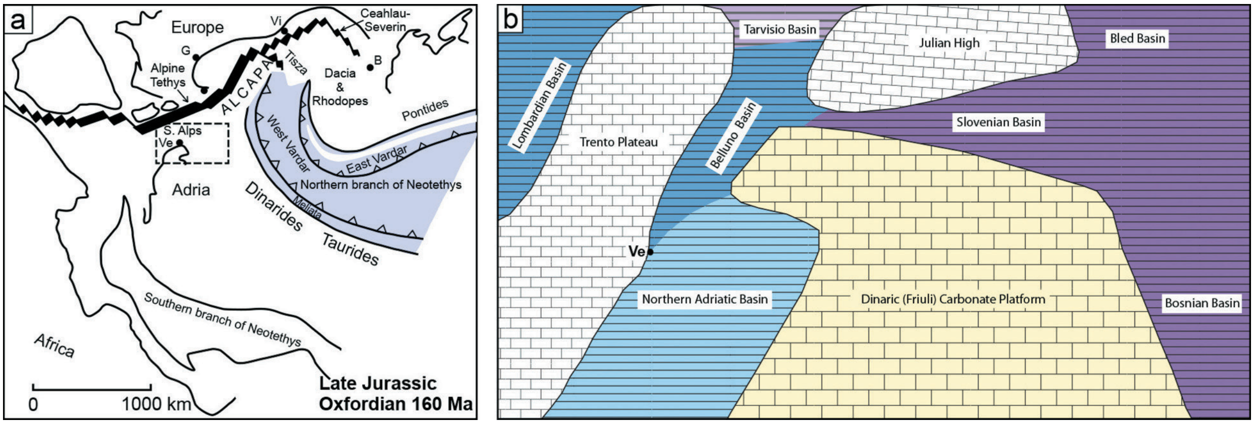

Figure 2a: Paleogeographic map in the Late Jurassic (after Schmid *et al. 2020). The dashed rectangle indicates the location of the map on the right (Ve = Venice).*
2b: Local configuration of the Adriatic continental margin (Belluno Basin and Northern Adriatic Basin simplified according to Masetti *et al. 2012). The colors in 2b correspond to the time of basin formation. The Bled, Slovenian and Bosnian basins formed in the Middle Triassic and the Tarvisio Basin in the Late Triassic. The Belluno Basin subsided in the Hettangian and the Northern Adriatic Basin around the Sinemurian–Pliensbachian boundary (*Masetti *et al. 2012).*

REGIONAL 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 (Figure 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; Figure 1). Since both consist of several nappe units, it is preferable to use 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 deeper marine (shale, chert, pelagic limestone, carbonate turbidites) from a Middle Triassic volcano-sedimentary succession up to Campanian-Maastrichtian flysch. The Mesozoic successions of the Tolmin nappes exhibit a considerable thermal overprint (Rainer et al., 2002, 2016).

The Julian nappes are stratigraphically more complex and structurally less well known. The area is now dominated by Triassic platform carbonates but deep-water Jurassic–Cretaceous and also Upper Triassic sediments also exist. Significant lateral variations in thickness and facies types indicate that the Julian nappes originated from several paleotopographic units. The Julian Carbonate Platform that in the Jurassic evolved to submerged submarine high, the Julian High (Buser 1996), and remnants of the surrounding basins are preserved.

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 (Figure 3) is well differentiated and the sub-horizontal contact with the underlying nappe is preserved. In remaining portions of the Julian Alps, the nappe structure is strongly obliterated by younger deformation. The area is dissected by a set of NE-SW striking faults (Jurkovšek 1986; Buser 2009; Goričan et al.

Figure 3: Aerial view of the central Julian Alps towards south. The Zlatna Klippe is outlined in red.

2018). Some of these faults have a prominent reverse-slip component. Well-exposed normal faults with the same orientation have also been observed.

The NE-SW striking faults are cross-cut by subvertical NW-SE oriented faults; some are evidently still active as dextral strike-slip faults (Kastelic et al. 2008; Atanackov et al. 2021). The most prominent of these is the Sava Fault whose right lateral displacement is estimated at 30–60 km (Vrabec & Fodor 2006) or even 70 km (Placer 1996). These young faults are well-marked on satellite and digital relief images and are directly linked to the system of NW-SE dextral faults in the External Dinarides (the Raša, Idrija, Ravne and Dražgoše–Žužemberk faults in Figure 1).

MESOZOIC STRATIGRAPHY OF THE JULIAN ALPS

An overview of the stratigraphic successions characteristic of different paleogeographic units in the area is presented graphically (Figure 4). Only the most distinctive formations are highlighted in the text but sufficient references are cited to provide the relevant source of more detailed information.

Since the study area was part of a continental margin between the Alpine Tethys and the Neotethys (Figure 2a), the correlative stratigraphic units exist in the Southern Alps in Italy, in the Northern Calcareous Alps in Austria, in the Transdanubian Range in Hungary and in the Dinarides. For a Triassic to end Cretaceous correlation of the Julian Alps with the neighboring units in the Southern Alps (Trento Plateau and Belluno Basin in Figure 2b) the reader is referred to Goričan et al. (2012a) and references therein. More recent studies (Goričan et al. 2018) focused on correlation with the other three mountain chains that preserve stratigraphic successions of Neotethyan affinity.

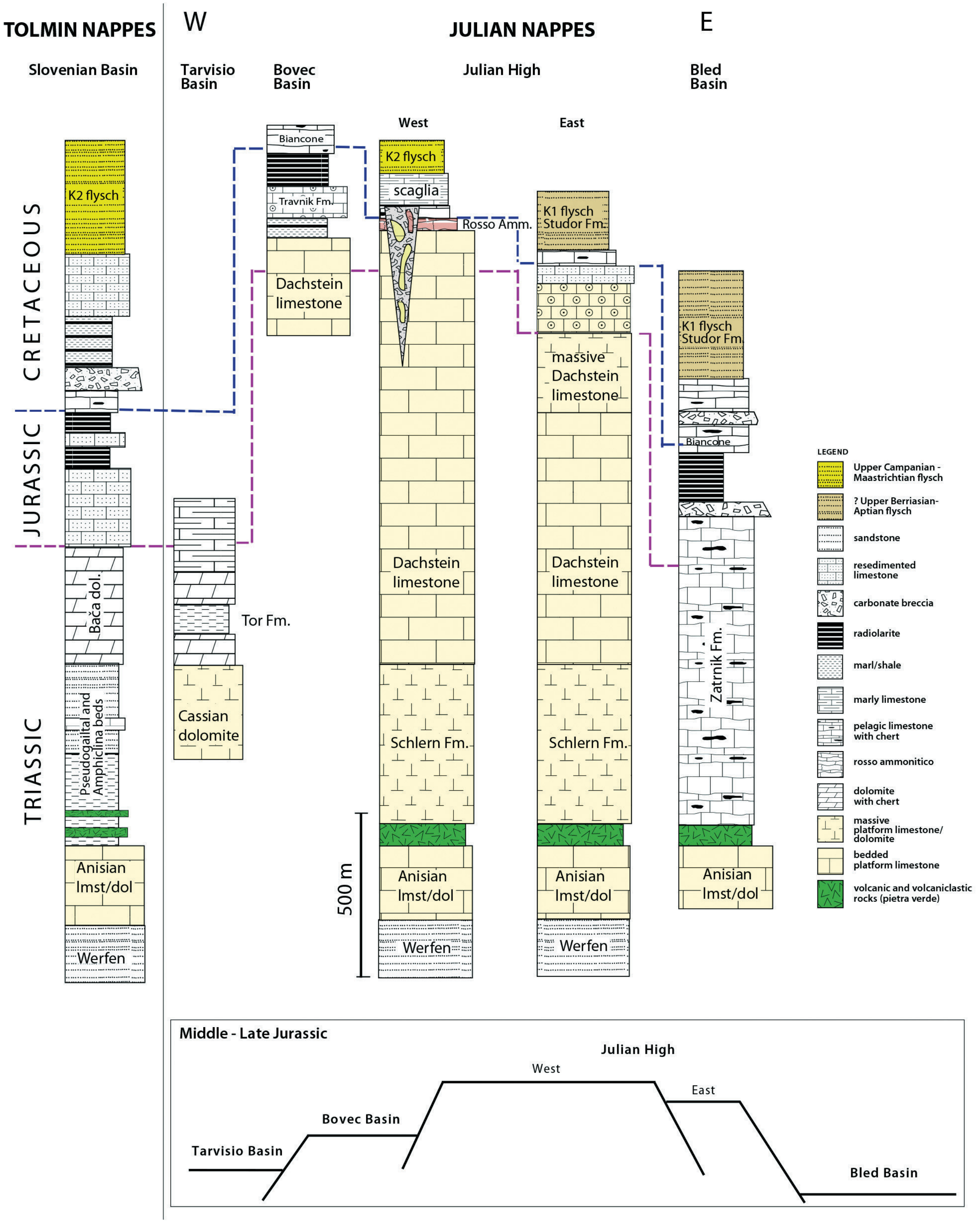

Figure 4: Stratigraphic overview of different tectonic/paleogeographic units in the Julian Alps. The Tolmin nappes are represented by a single synthetic log because the successions of different thrust sheets are basically identical; only the thickness of individual formations varies in relation to proximity of adjacent carbonate platforms. The Julian nappes, on the other hand, show great variations in the stratigraphic record suggesting a complex topography of a submarine high surrounded by deeper basins (a simple 2D sketch is presented below the stratigraphic logs). References to stratigraphy are given in the text.

Three main paleotopographic units with their distinct stratigraphic record have been differentiated in the Julian nappes (Figures 2b, 4) – the Tarvisio Basin, the Julian High and the Bled Basin.

The sediments of the Tarvisio Basin are now exposed in the Carnic Alps (NE Italy), in the NW Julian Alps, and in the Southern Karavanke Mountains. The most distinctive units of this stratigraphic succession are the uppermost Julian–lower Tuvalian carbonate-siliciclastic Tor Formation (formerly known as the Raibl beds) and the upper Tuvalian to Rhaetian carbonates rich in organic matter and chert nodules (Gale et al. 2015). Lower Jurassic rocks of this basin consist of a thick pile of thin-bedded lime mudstone and are exposed only in the Karavanke Mountains (Krystyn et al. 1994). The Tarvisio Basin formed in the Carnian apparently as a west-east oriented intraplatform basin (Gale et al. 2015). In the Jurassic it may have been connected to the Belluno Basin, which subsided in the Hettangian (Masetti et al. 2012).

The sediments of the Julian High rest upon a thick pile of Upper Triassic to Lower Pliensbachian platform limestones that constitute the core of the Julian nappes. The post-Pliensbachian sections are all composed of deeper-water facies but differ in thickness and the degree of condensation.

Three characteristic successions are distinguished. The most continuous succession, best exposed in the Travnik structural unit at Mt. Mangart saddle, pertained to the deeply subsided block of the former carbonate platform; the term Bovec Basin designates this paleogeographic unit (Cousin 1981). The succession shows first a gradual transition from shallow to deeper-marine facies through the Pliensbachian and Lower Toarcian that ends with a discontinuity surface. Black shales with interbedded radiolarian-rich siliceous limestone characterize the Lower Toarcian (Goričan et al. 2003; Šmuc & Goričan 2005; Sabatino et al. 2009). This lower part is overlain by typical basinal deposits ranging in age from the Bajocian to the Early Hauterivian (Šmuc 2005; Šmuc & Goričan 2005). The most distinguishing Jurassic facies are oolitic megabeds (Member 2 of the Travnik Formation) evoking the Vajont Limestone of the Belluno Basin in northern Italy (e.g. Bosellini et al. 1981).

The strongly condensed Middle to Upper Jurassic sections consist of Rosso Ammonitico type limestone (the Prehodavci Formation) that does not exceed 20 m in thickness; ferromanganese mineralisations are common and mark distinctive discontinuity sufaces at certain stratigraphic levels (Šmuc 2005; Šmuc & Rožič 2010). The overlying Biancone limestone also is a thin (only a few meters thick) pelagic sequence. The condensed Rosso Ammonitico type limestone was widely deposited but is now poorly preserved with laterally continuous exposures occurring only in the Triglav Lakes Valley just below the thrust-fault contact with the Zlatna Klippe.

The condensed Jurassic sections are in places associated with up to several hundred meters deep neptunian dykes filled with chaotic blocky breccias. Such breccias are well known on Mt. Mangart (Šmuc 2005; Črne et al. 2007) and at Lužnica Lake (Babić 1981; Cousin 1981) but have been also mapped in other localities west of the Zlatna Klippe (Jurkovšek 1986; Jurkovšek et al. 1990). The Scaglia variegata of Albian age directly overlies the breccias in places (Cousin 1981; Goričan & Šmuc 2004) and provides good age control on the formation of these deep neptunian dykes. The Scaglia variegata is followed by Turonian to Senonian red pelagic limestone (Scaglia rossa) and by upper Campanian – Maastrichtian flysch (Cousin 1981; Jurkovšek 1986; Buser 1987; Kocjančič et al. 2022).

The stratigraphy of the Julian High at its eastern border is fundamentally different. The post-Pliensbachian succession is extremely thin, reduced to a few meters of the Biancone limestone (Rožič et al. 2014) and is overlain by Lower Cretaceous mixed carbonate-siliciclastic flysch-type deposits of the Studor Formation (Goričan et al. 2018). This stratigraphically incomplete succession and the age of flysch indicate the transition to the Bled Basin.

The Bled Basin (Cousin 1981) formed during the Middle Triassic rifting event. The entire upper Anisian to Lower Cretaceous succession consists of deep-water sediments. The more than 600 m thick Zatrnik Limestone spans the long stratigraphic interval from the Ladinian to the Lower Jurassic and consists mostly of bedded micrite with chert nodules (Cousin 1981; Goričan et al. 2018; Gale et al., 2019, 2021). The limestone is generally light gray, rarely reddish in color. This limestone clearly contrasts with the time equivalent formations of the Tarvisio Basin that are darker (bituminous) and usually dolomitized. The Zatrnik Limestone is overlain by Pliensbachian carbonate breccia, Upper Bajocian to Lower Tithonian bedded radiolarian cherts and shales, Upper Tithonian–Berriasian Biancone limestone ending with carbonate breccia and calcarenite (the Bohinj Formation), marly limestone with scarce siliciclastic admixture, and finally Berriasian?–Hauterivian mixed carbonate-siliciclastic turbidites with ophiolite debris (the Studor Formation) (Goričan et al. 2018, with references). It is well established that the Lower Cretaceous flysch of the Julian Alps corresponds to the Bosnian Flysch (Cousin 1981; Kukoč et al. 2012). Moreover, the entire succession is in good agreement with that of the median Bosnian Zone in the central Dinarides (Goričan et al. 2018).

The Mesozoic stratigraphy of the Tolmin nappes is typical of a deep basin that also formed in the Middle Triassic and persited until the end of the Cretaceous. The Triassic to Cretaceous stratigraphy and sedimentary evolution have been described in great detail in several recently published papers (Rožič 2009; Rožič et al. 2009, 2017, 2018; Gale 2010, Gale et al., 2012; Goričan et al. 2012a, b). Paleogeographically, the area belonged to the Tolmin Basin, which was located between the Julian Carbonate Platform / Julian High and the Dinaric Carbonate Platform. The Tolmin Basin is regarded as the western part of the Slovenian Basin (*sensu* Cousin 1970 and Buser 1989), which is now exposed in a longer facies belt running in W-E direction through all of central Slovenia. In the Tolmin Basin, the onset of flysch-type deposits is, similar to the western Julian High, dated upper Campanian to Maastrichtian (Caron & Cousin 1972; Cousin 1981; Buser 1987). In the underlying succession, we note the upper Aptian to Turonian Lower flyschoid formation, which is composed of basal calcareous breccia, shale, marl, and limestone turbidites but devoid of sand-sized siliciclastic material and cannot be considered flysch in the proper sense (Caron & Cousin 1972).

In summary, we can emphasize that flysch deposits of the Julian Alps are clearly related to two separate orogenic phases. Their distribution allows us to distinguish a relatively internal Dinaric sector with Lower Cretaceous flysch and a more external sector where the oldest flysch is Campanian-Maastrichtian in age (Figure 4). The two orogenic phases have been well documented throughout the Dinarides and Hellenides (Schmid et al. 2020, with references). The first phase started with emplacement of ophiolites on the Adriatic continental margin; deep-sea foreland basins were then created in front of the obducted ophiolite nappes and filled with flysch-type deposits from the Tithonian–Berriasian (Mikes et al. 2008). The second phase was related to the Late Cretaceous – Paleogene continental collision of the African and Eurasian plates. The widespread flysch sedimentation of Campanian age in all the internal Dinarides marks the beginning of this tectonic phase (Nirta et al. 2020; Schmid et al. 2020) with deformation that propagated towards SW and continued to the Eocene.

MAIN STRUCTURAL ELEMENTS

The initial nappe structure related to the Dinaric thrusting phase was strongly controlled by inherited Mesozoic normal faults and facies variations across these faults. Based on the compiled stratigraphic data and available structural evidence we present a generalized tectonic map and a profile perpendicular to the NE-SW trending faults (Figures 5a, b). A tentative reconstruction of the Dinaric-phase nappe emplacement is also presented (Figure 6).

The present-day morphology of the Julian nappes is mainly determined by the deformation along steep reverse and normal faults. Except for the central part of the study area and a few other exceptions (Figure 5a) the initial nappe contacts are located below surface and the boundaries among different nappes in map-view now coincide with the post-nappe faults. The structural elements of the South-Alpine contraction phase are clearly differentiated from the first-phase nappe contacts and are generally easy to recognize in the field, especially when well-bedded lithologies (e.g. the Dachstein limestone) are involved. Some typical examples are illustrated in Figures 7 to 9. A well-defined distinction among different stratigraphic successions as shown in Figure 4 is also of prime importance to map the nappes.

The Pokljuka Nappe is the highest of the Julian nappes but is now preserved only in a relatively subsided block, separated by steep boundary faults from the originally underlying nappe (Goričan et al. 2018). Goričan et al. (2018) suggested that the previously defined Krn Nappe (Buser 1986) 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. Here we retain this distinction but, instead of the “eastern Krn Nappe”, we use the name Jelovica Nappe, a name that was previously applied to the southeastern part of this structural unit (Grad & Ferjančič 1976; Demšar 2016).

The Zlatna Klippe was possibly connected to the Jelovica Nappe as suggested by its structural position on top of the Krn Nappe (Figure 5a). Stratigraphically it is less distinctive because it is composed almost exclusively of the upper Ladinian–Carnian massive carbonates of the Schlern Formation; only at Begunjski vrh along the northern contact of this klippe, some meters of heavily folded older Ladinian rocks (bedded limestone, sandstone and tuff) occur (Ramovš 1990). Smaller Zlatna-type klippen, composed only of the Schlern Formation are present west of the Zlatna

Klippe (two are rather clear and are indicated in Figure 5a; one is illustrated in Figure 9a). The Viševnik Klippe (Jurkovšek 1987), which now constitutes a footwall syncline below a steep SE vergent reverse fault (Figures 8a, b) can be also related to the Zlatna Klippe. The oldest rocks of this klippe are Lower Triassic brownish-gray fossiliferous marly limestones (Kolar-Jurkovšek et al. 2013), in classical stratigraphy of the Southern Alps known as the Campil beds of the Werfen Formation. The well-exposed contacts of

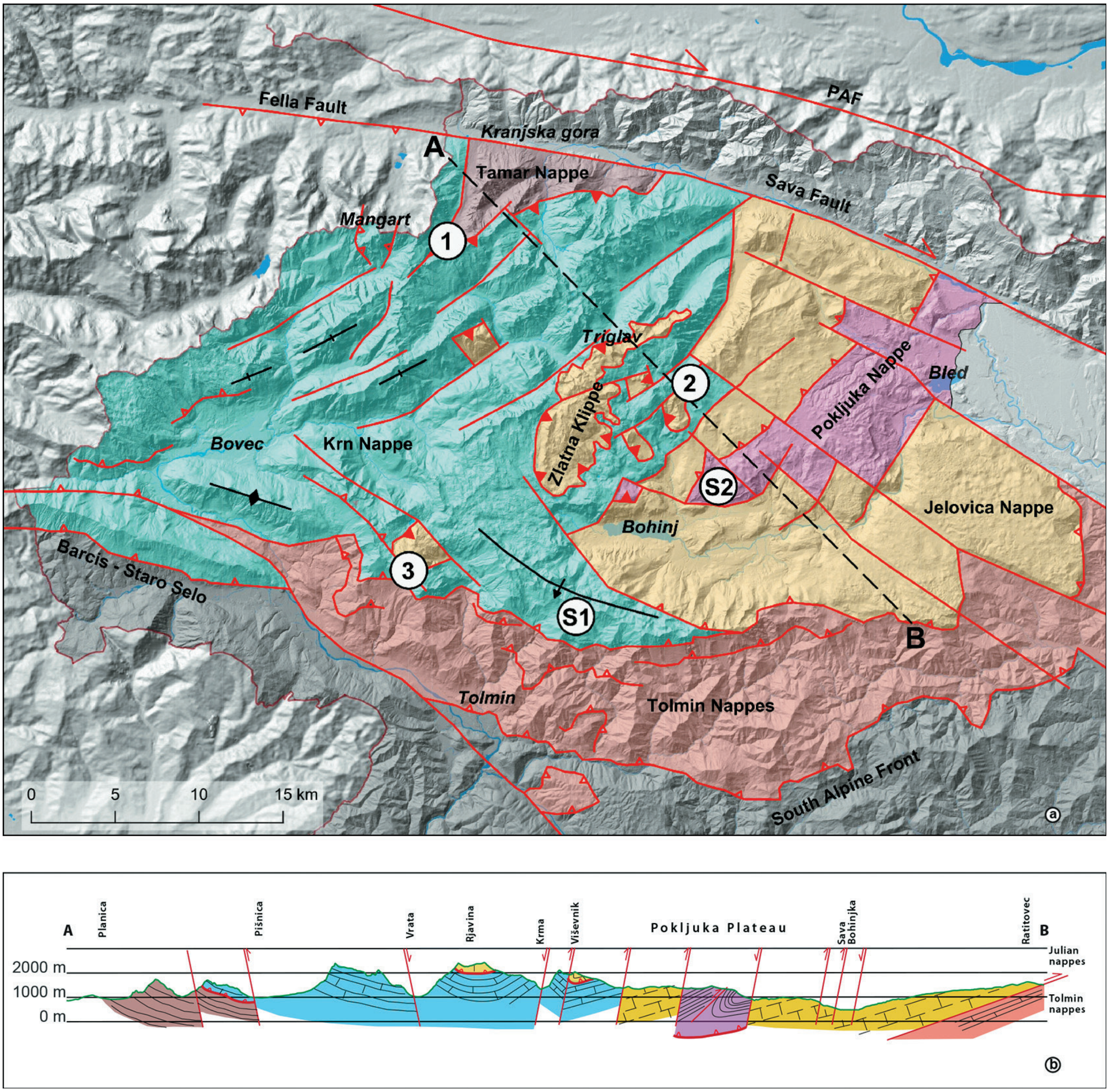

Figure 5a: Generalized tectonic map with emphasis on subdivision into Dinaric-phase nappes (solid triangles – Dinaric-phase nappe contacts; empty triangles – high- and low-angle reverse faults of the South-Alpine phase). The numbers in circles correspond to localities shown in Figures 7 to 9 (1 = Tamar Valley, 2 = Viševnik, 3 = Jezero v Lužnici-Rdeči rob) and to the field-trip stops (S1 and S2).
5b: Profile AB perpendicular to the NE-SW trending post-nappe faults. Note that the reverse faults are doubly-verging: they are directed towards SE to S in the eastern part of the study area and have the opposite direction NW of the Zlatna Klippe.
Based mainly on Geological Map of Slovenia 1:250,000 (Buser 2009). The Pokljuka Nappe in Figure 5a and the south-eastern half of the profile in Figure 5b are from Goričan et al. (2018).

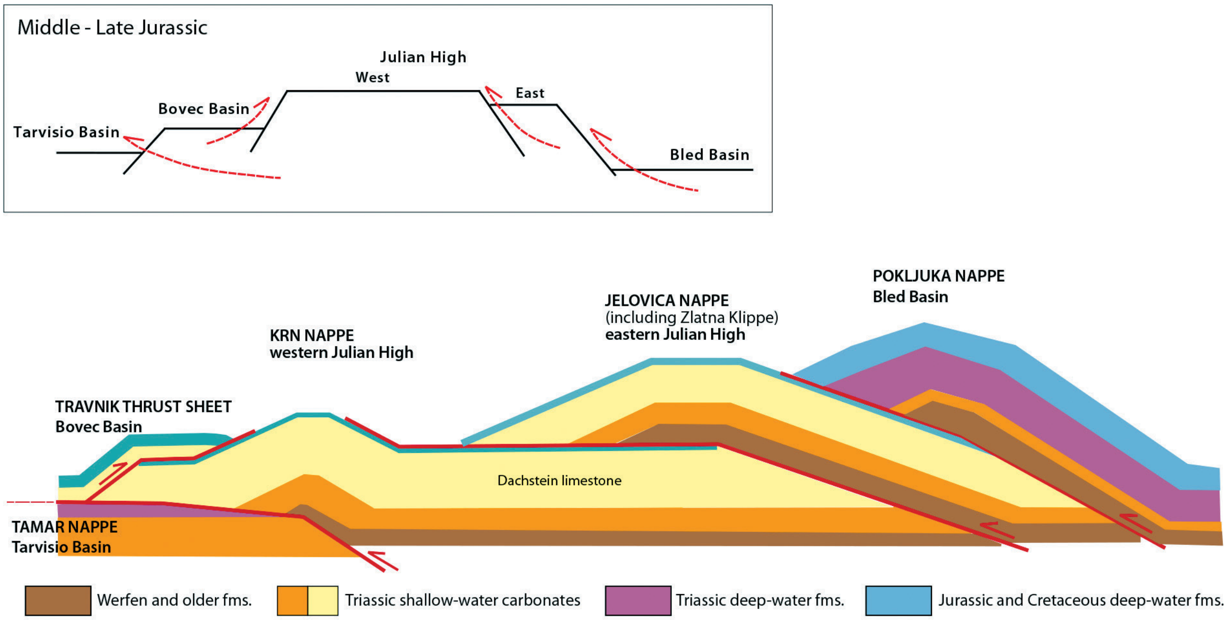

Figure 6: Tentative reconstruction after the Dinaric-phase nappe emplacement and its relation to pre-orogenic topography. The back-thrusting of the Travnik thrust sheet (the type locality of the Bovec Basin stratigraphy) is suggested by its position on top of the condensed succession of the western Julian High as demonstrated on Mt. Mangart (Šmuc 2005; see Figure 5a for the location of Mt. Mangart). The contact between the Krn and Tamar nappes is visible in the entire SE wall of the Tamar Valley (Figure 7a, see also Figure 8 in Celarc et al. 2013); the incompetent terrigenous sediments of the Raibl Group and the Norian-Rhaetian marly carbonates were the main horizon allowing for the displacement along thrust fault that cut through the inherited Mesozoic normal faults.

the Zlatna Klippe and its equivalents thus suggest a hanging-wall ramp position for the central Julian Alps. The ramp cuts through the Lower Triassic to Ladinian – Carnian succession of the upper nappe whereas the underlying Krn Nappe in this central area is quasi complete, preserved to the top of the Dachstein limestone or even to the Jurassic-Cretaceous condensed facies.

The contact of the Krn Nappe with the underlying structural unit is well exposed in the Tamar Valley (Figure 7a) where the upper Tuvalian to Rhaetian deep-water sediments of the Tarvisio Basin are thrust by the Dachstein limestone (Celarc et al. 2013). This north-verging thrust was first interpreted as a possible continuation of the Val Resia–Val Coritenza backthrust (Celarc et al. 2013; Gale et al. 2015), known from the Italian part of the Julian Alps as an E-W striking Alpine-phase backthrust (Venturini & Carulli 2002; Merlini et al. 2002; Ponton 2002). The completely different Upper Triassic facies below and above the thrust plane in the Tamar Valley (basin vs. carbonate platform, Figure 7a) indicate a different paleogeographic location of the two thrust blocks in the Mesozoic and suggest that this thrust belongs to the group of pre-existing Dinaric thrusts. The Dinaric thrust could then have been steepened and probably dextrally rotated during the later Alpine phase.

The stratigraphic succession of the Bovec Basin overlying the Julian Platform (see the 3rd column in Figure 4) is limited to a tectonically complicated area near the Slovenian-Italian border (Figure 5a). On Mt. Mangart, this succession forms a separate Travnik Thrust Sheet on top of the massive Dachstein limestone (Šmuc 2005). The plausible explanation for this tectonic superposition is a Dinaric-phase backthrust along an inverted Mesozoic normal fault that was dipping opposite to the dip of normal faults in the eastern part of the Julian High (Figure 6). This original geometry was cross-cut by steep reverse faults and was heavily folded during the Alpine contraction (for photographs of folds and a detailed map see Šmuc 2005).

The Tolmin nappes (paleogeographically the Slovenian Basin) are a composite south-verging tectonic unit between the External Dinarides below and the Julian nappes above (Figures 1, 5a). Individual nappes within this system are largely discontinuous laterally but allow a general subdivision into three superposed units. From bottom to top these are the Podmelec Nappe, the Rut Nappe and the Kobla Nappe (Buser 1986, 1987). The generally E-W striking thrust faults

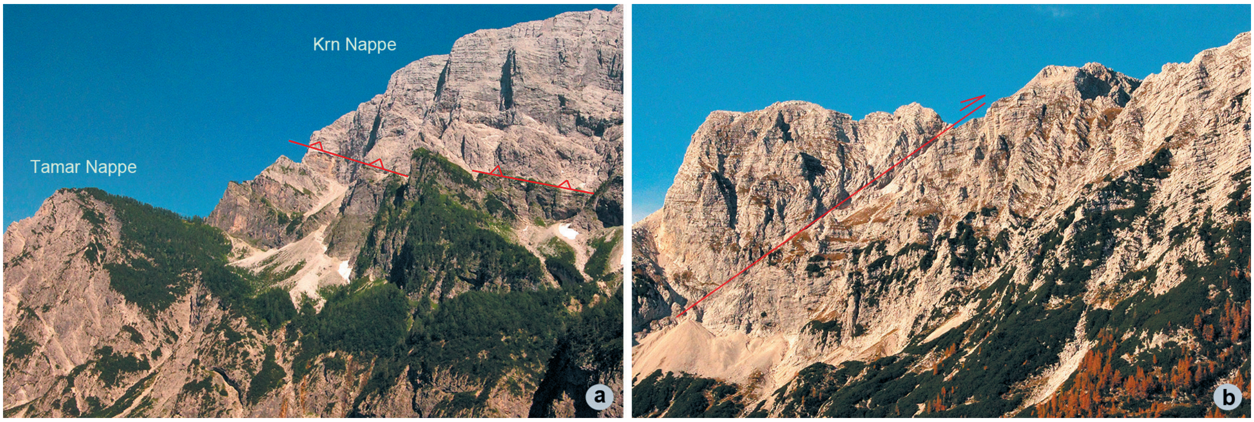

Figure 7: Dinaric and South-Alpine deformation in the Tamar Valley, locality no. 1 in Figure 5a.
7a: Dinaric-phase thrust contact between the deep-water Norian-Rhaetian limestone of the Tamar Nappe and the Dachstein limestone of the Krn Nappe; SE wall of the Tamar Valley. 7b: Post-nappe north vergent reverse fault in the Dachstein limestone of the Krn Nappe; W wall of the Tamar Valley.

Figure 8: Viševnik Klippe, locality no. 2 in Figure 5a.
8a: Panoramic view of the Dinaric thrust plane; the Werfen Formation lies on top of the Dachstein limestone. This thrust plane was bent during the South-Alpine shortening along steep SE directed reverse faults.
8b: The same locality seen from NW to SE. The thrust plane separating the Werfen and the Dachstein formations is easily visible.

(Buser 1986) indicate that the Tolmin nappes mainly resulted from the N–S, i.e. South-Alpine shortening. Further structural analysis could unravel an older deformational phase but has not been carried out yet.

TIMING OF TECTONIC EVENTS

The nappe emplacement can be broadly attributed to the Maastrichtian to Eocene top-to-SW thrusting phases observed throughout the Dinarides (Tari 2002; Ilić & Neubauer 2005; Schmid et al. 2008, 2020; Žibret & Vrabec 2016). Considering the striking similarity in stratigraphy and facies between the Bled Basin and the Bosnian Basin, a pre-Maastrichtian emplacement of the Pokljuka Nappe is unlikely although the Upper Cretaceous deposits are actually missing. The Upper Campanian – Maastrichtian flysch deposits of

Figure 9: Jezero v Lužnici – Rdeči rob, locality no. 3 in Figure 5a.
9a: Panoramic view showing 3 phases of deformation: 1= Dinaric thrust (Schlern Formation on top of the Dachstein limestone); 2 = steep reverse fault of the South-Alpine phase; 3 = younger normal fault.
9b: Enlargement of the fold in the Scaglia rossa; 2nd deformation phase.
9c: C-S structures in the Scaglia rossa indicate top-to-the-south sense of shear that is compatible with the thrusting direction of the Julian nappes over the Tolmin nappes (see Figure 5a).

the Julian High and the Slovenian Basin (Figure 4) were not necessarily shed coevally with the emplacement of the Pokljuka Nappe but may have originated from a more internal part of the Dinarides. The upper age limit for the emplacement of the Julian nappes is provided in the Southern Karavanke Mountains by middle Eocene molasse-type deposits with abundant mollusks (Mikuž 1979).

The first post-nappe contraction, reflected in NE-SW striking reverse faults can be attributed to the late Oligocene–early Miocene southward to SE-ward South-Alpine thrusting (Doglioni 1987; Doglioni & Siorpaes 1990; Fodor et al. 1998; Castellarin & Cantelli 2000; Bartel et al. 2014; van Gelder et al. 2015). South and east of the Zlatna Klippe the faults of this group are associated with S to SE vergent folds, whereas the folds and the steepened beds west and north of the Zlatna Klippe have the opposite vergence (Figures 5a, b; 7b). South of Bohinj, closer to the Tolmin nappes, the faults are NW-SE trending and the associated folds are S to SSW vergent. This pattern suggests an overall pop-up structure and probably CW rotation of internal smaller-scale fault blocks. The style of deformation within the Julian nappes is predominantly brittle, determined by the thick pile of platform carbonates. 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.

The South-Alpine thrusting is generally thought to have been associated with dextral transpression concentrated on the Periadriatic (Insubric) Lineament (Doglioni 1987; Fodor et al. 1998; Bartel et al. 2014). The shear zone in the study area encompasses the Julian nappes but most probably also includes the Tolmin nappes. This zone between the Sava Fault and the South-Alpine Front has a lenticular outline (Figure 5a) and is comparable to the adjacent Sava-PAF "shear lens" (Vrabec & Fodor 2006), which is composed of the Southern Karavanke Mountains and the Kamnik-Savinja Alps (Figure 1).

The subsequent short-lasting extension is evidenced by normal faults, which were documented at several locations (e.g., Celarc & Herlec 2007; Goričan et al. 2018) but the overall pattern of the extensional structures throughout the Julian Alps has not been determined. It is thus not yet clear to what extent the normal faults were determined by the structures inherited from the preceding contraction stage. The event is ascribed to the Early-Middle Miocene extension widely documented in the Dinarides and classically interpreted in relation to the formation of the Pannonian Basin (Ilić & Neubauer 2005; van Gelder et al. 2015; Žibret & Vrabec 2016). The extension was followed by a renewed shortening, which started in the latest Miocene and is still active. The last stage of deformation in the Julian Alps is the strike-slip reactivation of both sets of pre-existing faults (Goričan et al. 2018). This deformation fits well into the recent inversive/transpressive tectonic phase, documented in a wider South-Alpine – NW Dinarides territory (Tomljenović & Csontos 2001; Bartel et al. 2014; Žibret & Vrabec 2016).

DESCRIPTION OF STOPS

Stop 1. General view on the Julian Alps from Mt. Šija

(Location: N 46°14'19.23", E 13°50'2.45, altitude 1880 m, Figure 10)

Mt. Šija is part of the Lower Bohinj Ridge, a high mountain ridge south of Lake Bohinj. Its western part belongs to the Krn Nappe (Figure 5a). The overall structure of this ridge is a south-verging monocline, which formed as a fault-propagation fold above the thrust over the Tolmin nappes.

The upper Vogel cable car station offers a magnificent view to the north to the Bohinj area and to the central Julian Alps with Triglav and other mountains of the Zlatna Klippe (Figure 11). On a walk towards the top of the ridge we will cross first the gently north dipping beds of the Dachstein limestone and then the steeply south dipping beds of the southern limb of the anticline. From the top of Mt. Šija almost the entire ridge is visible (Figures 12, 13, 14). The morphological contrast with vegetated low hills of the Tolmin nappes is also apparent (Figure 13).

Stop 2. Jurassic and Cretaceous of the Bled Basin

The stratigraphy of the Bled Basin will be visited at three nearby outcrops located north of Srednja Vas and Studor, between the Ribnica Valley and the road to Uskovnica (Figures 10, 15a, b).

Stop 2.1 – The Ribnica Valley (Pliensbachian to Tithonian) (Location: N 46° 18.190’, E 13° 54.821’)

General description: The Lower Jurassic Ribnica Breccia and the overlying Middle to Upper Jurassic radiolarian cherts (Figure 15a) are best exposed at the first waterfall in the Ribnica Valley. The lowermost part of the section is composed of calcarenite with more than 50% echinoderms and rare foraminifers. The calcarenite is followed by a 0.5 m thick layer of greenish marly limestone and a 20 cm thick layer of reddish filament-bearing limestone, which also contains echinoderms and foraminifers.

The Ribnica Breccia (Cousin 1981; Kukoč 2014) consists of several beds. The first is 1 m thick and con-

Figure 10: Topographic map 1:50,000 of the Julian Alps around Lake Bohinj with location of field-trip stops S1 and S2.

Figure 11: Panoramic view from the upper Vogel cable car station to Lake Bohinj and the central part of the Julian Alps. The red line indicates the contact between the Krn Nappe and the Zlatna Klippe. Dashed line means that the contact runs behind the hills in foreground.

Figure 12: View from Mt. Šija towards west. The mountains in the foreground belong to the western part of the Bohinj Ridge (see Figures 5a and 10 for location). The Dachstein limestone beds along the ridge are dipping steeply towards south to south-west and constitute the forelimb of a larger fault-propagation fold, which was formed during the South-Alpine thrusting phase.

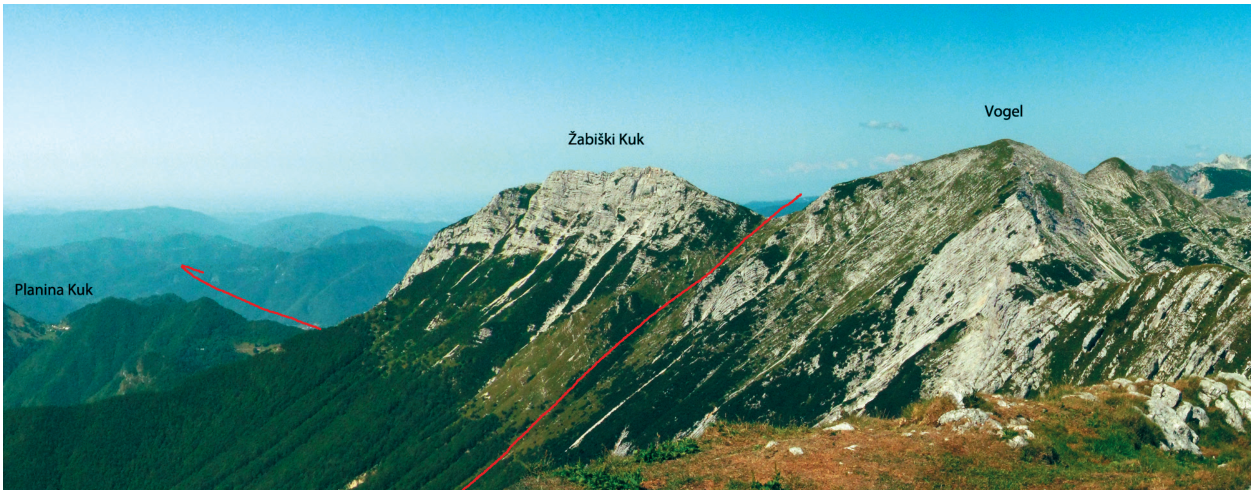

Figure 13: View from Mt. Šija towards southwest (left of Figure 12). The difference between the Krn Nappe and the underlying Tolmin nappes is well expressed in the landscape. Note the change in dip of the Dachstein limestone across the steep fault. The beds are dipping towards south on Mt. Vogel and towards NW on Mt. Žabiški Kuk. This deviation can be ascribed to the transpressive dextral shear that accompanied the general N–S directed shortening during the South-Alpine phase.

Figure 14: Oblique view from SE to the fault-propagation fold in the Dachstein limestone at the southern edge of the Krn Nappe. The thrust contact with the Tolmin nappes below is indicated but is actually located just below the view of the photograph. The change from SSW dipping beds on Mt. Vrh nad Škrbino to almost horizontal bedding is marked by a shelf (the hinge of the syncline is indicated with a dashed red line). The opposite side of Vrh nad Škrbino is illustrated in Figure 12.

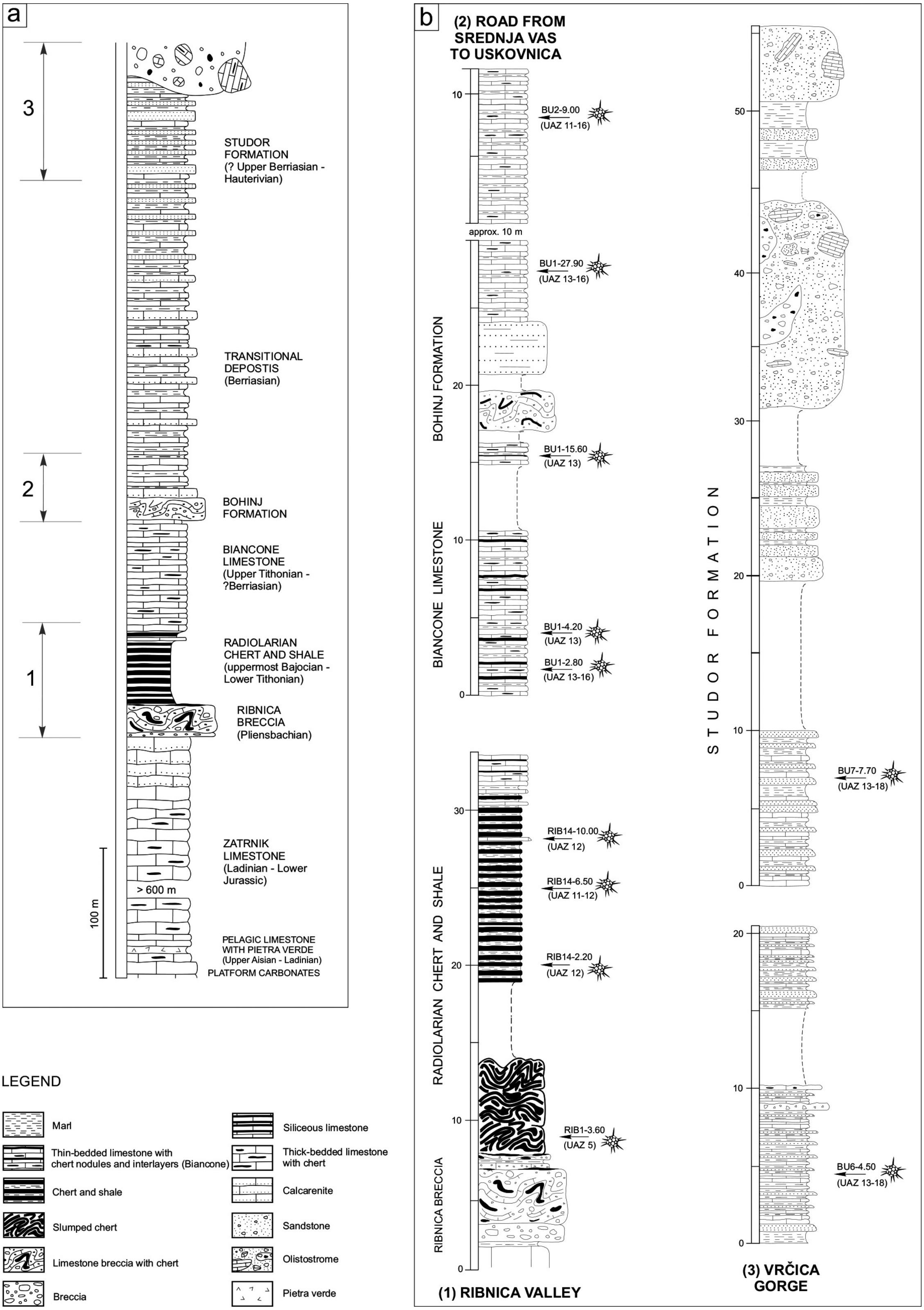

Figure 15a: General stratigraphy of the Bled Basin. The stratigraphic position of stops 2.1, 2.2 and 2.3 is indicated. 15b: Detailed stratigraphy of the three stops with position of radiolarian samples and their assignment to UA Zones of Baumgartner *et al. (1995).*

tains limestone clasts up to 40 cm in size, but no chert. The overlying bed is thinner (0.5 m) with smaller limestone clasts. The upper part of the Ribnica Breccia is an approximately 5 m thick chaotic bed containing large limestone and chert clasts, and also irregularly shaped folded layers of chert up to 1 m in size. The upper bedding plane is in places silicified and covered by a 10 cm thick horizon of gray marl. The topmost breccia bed is 0.5 m thick and contains a high amount of chert (app. 50%) in the form of folded nodules and layers.

The most common microfacies of the breccia clasts is bioclastic wackestone-packstone with abundant echinoderms and foraminifers (e.g., *Involutina liassica* (Jones)). Ammonite and gastropod shells also occur. Some clasts are wackestones with radiolarians and sponge spicules. Glauconite grains are rare but present throughout the Ribnica Breccia.

The overlying succession is dominated by radiolarian chert (Figure 15b). It starts with a 6 m thick slumped interval of dark-green bedded chert. The shale interlayers constitute less than 10% of the sequence. The transition to the overlying bedded chert is not exposed; presumably mostly shales occur in this covered interval. The upper part of the succession consists of dark-brownish-red bedded chert and shale. The content of shale in this part of the succession is high and reaches up to 60%. Individual chert beds are 3 to 5 cm thick and generally laminated. In places, normal grading and channel structures clearly indicate that the chert beds were deposited as low-density turbidites. In the upper part of the section carbonate content increases again. Gray laminated siliceous-limestone beds, up to 10 cm thick, are intercalated in the dark-gray shale. Limestone microfacies is wackestone-packstone with radiolarians and sponge spicules. Parallel lamination and normal grading again indicate deposition as low-density turbidites. The content of shale decreases upsection and the succession ends with thin-bedded laminated siliceous radiolarian-bearing limestones. The entire thickness of the laminated limestones is estimated to 50 m but is not visible at this outcrop.

Age: The diagnostic foraminifer *Involutina liassica* (Jones) in the breccia clasts indicates an Early Jurassic age. The maximum range of this species is from the Upper Norian to the lowermost Toarcian (Bassoullet 1997). Based on regional stratigraphic correlations, the Pliensbachian is the most probable age of the Ribnica breccia. The slumped cherts above the breccias yielded a latest Bajocian to early Bathonian radiolarian assemblage (UA Zone 5 of Baumgartner et al. 1995) based on the occurrence of *Hemicryptocapsa tetragona* (Matsuoka). These two age constraints suggest that a significant stratigraphic gap occurs between the Ribnica Breccia and the overlying radiolarian cherts. The upper part of the chert/shale succession in the Ribnica Valley is dated as early to early late Tithonian (UA Zone 12) based on co-occurrence of *Protunuma japonicus* Matsuoka & Yao and *Eucyrtidiellum pyramis* (Aita).

Stop 2.2 – Along the road from Srednja vas to Uskovnica (Tithonian and Lower Cretaceous)
(Location N 46° 17.992‘, E 13° 55.069‘)

General description: An approximately 40 m thick section of pelagic limestones, including carbonate gravity-flow deposits (Figure 15b), is exposed along the road from Srednja Vas to Uskovnica. This section is subdivided into three lithostratigraphic units: 1) the Biancone limestone; 2) carbonate gravity-flow deposits (the Bohinj Formation); and 3) siliceous limestone with marl.

The Biancone limestone is characterized by thin- to medium-bedded light gray to white limestone with individual beds up to 20 cm thick; up to 5 cm thick discontinuous beds of dark-gray chert and irregularly shaped chert nodules are common. Intercalations of marl are also present. The predominant microfacies are radiolarian-rich wackestone and packstone with parallel lamination in some layers. In some places, normally graded calcarenites occur as several centimeters thick intercalations in micrite beds and contain up to 5 mm large intraclasts of wackestone with radiolarians and chert clasts in the basal part.

The second lithostratigraphic unit is the Bohinj Formation (Kukoč et al. 2012). At the type locality, the Bohinj Formation consists of 3 m of carbonate breccia and 4 m of calcarenite. Slump folds are present in the breccia. The calcarenite is massive and shows no internal folding or bedding.

The third lithostratigraphic unit is reddish siliceous limestone similar to the Biancone limestone, but with a higher proportion of marl and red color. At this section the transition into overlying deposits is covered.

Composition of the breccia and calcarenite: The breccia consists primarily of matrix-supported angular to subangular shallow-water carbonate clasts up to 2 cm in diameter. The matrix is radiolarian-rich lime mudstone with sponge spicules and scarce calpionellids. Most limestone clasts are bioclastic grainstones and bioclastic-peloidal packstones. The skeletal grains in these clasts are miliolid and textulariid foraminifers, echinoderm fragments and algal fragments. Clasts of algal wackestone and oncoid packstone are also present but rare. The dasyclad algae *Clypeina jurassica* Favre, characteristic of the upper Kimmeridgian to lowest Berriasian, is found both in the clasts of algal wackestone and in the form of isolated fragments. Intraclasts of pelagic calpionellid wackestone with sponge spicules and rare planktonic foraminifers are also present. Callpionellid species *Calpionella alpina* Lorenz, ranging from the late Tithonian to earliest Valanginian has been recognized. Single bioclasts are common and include fragments of *Clypeina jurassica* Favre, the green algae *Cayeuxia*, and fragments of sponges, bryozoans, echinoderms and thick-shelled bivalves. Well-developed concentric and radial ooids and oncoids are present as isolated grains. Rare chert grains and lithic grains of igneous origin, including basalt, also occur in the breccia.

Calcarenite is predominantly composed of shallow-water skeletal fragments and lithoclasts similar to those found in the breccia. Lithic grains of igneous origin, grains of chert and opaque grains are present but are less abundant than carbonate components.

The microfacies analysis reveals that the main source area of the resedimented limestone was a penecontemporaneous carbonate platform. Limestone clasts and isolated grains from the outer platform prevail, but lagoonal facies (algal wackestone) is also present. Grains of basalt indicate ophiolitic origin.

Age: Radiolarians from the Biancone limestone below the Bohinj Formation indicate a latest Tithonian to earliest Berriasian age (UA Zone 13) based on cooccurrence of *Eucyrtidiellum pyramis* (Aita) with *Hiscocapsa kaminogoensis* (Aita), *Parapodocapsa furcata* Steiger and *Praeparvicingula columna* (Rüst). Radiolarians in samples above the Bohinj Formation may range into the early Valanginian, with *Fultacapsa tricornis* (Jud) having the shortest range (UA Zones 13-16). Typical genera first appearing in the late Valanginian (e.g. *Cana*, *Crolanium* and *Pseudocrolanium*) have not been found.

Significance for local paleogeography: The Bohinj Formation provides evidence of a carbonate platform that must have been located more internally but is now not preserved. This inferred platform (named the Bohinj Carbonate Platform by Kukoč et al. 2012) may have developed on top of a nappe stack that formed during the early emplacement of the internal Dinaric units onto the continental margin. The platform correlates regionally with genetically similar isolated carbonate platforms of the Alpine – Dinaride – Carpathian orogenic system, e.g., with the Plassen Carbonate Platform in the Northern Calcareous Alps (Gawlick & Schlagintweit 2006) and the Kurbnesh Carbonate Platform in Albania (Schlagintweit et al. 2008).

Stop 2.3 – Along the road from Srednja vas to Uskovnica – Vrčica Gorge (Lower Cretaceous)

(location N 46° 17‘50.51“, E 13° 54‘49.48“)

General description: Mixed carbonate-siliciclastic deposits of the Studor Formation (Kukoč 2014, Goričan et al. 2018; Figure 15b) are exposed in the Vrčica Gorge. By its lithological characteristics the Studor Formation represents a unique and easily distinguishable lithostratigraphic unit in the wider area. The formation starts with 5–10 cm thick beds of light gray radiolarian wackestone/packstone intercalated with thin-bedded sandstone, which is less frequent in the lower part of the formation. Calcarenite beds are rare. Micrite beds in places contain chert. In the upper part of the formation the proportion of marl is higher and micrite and calcarenite beds are subordinate to sandstone. Thickness of sandstone beds in this part reaches up to 1 m. Horizontal and cross lamination is observed. The uppermost part of the formation is composed of two olistostrome layers composed of centimeter- to meter-sized blocks of different litologies in a dark gray sandy matrix. Laminated micritic limestone with radiolarians (Biancone facies) prevails among these olistolithes. Carbonate breccia with limestone and chert clasts is also present as well as smaller, decimeter-sized clasts of dark green and red chert.

Composition of sandstone: Carbonate lithic grains prevail in sandstone (approximately 40% of all lithic grains). Most are small micrite grains, however larger grains of peloidal and bioclastic grainstone and packstone also occur. Isolated bioclasts and echinoderm fragments are rare. Non-carbonate components include predominantly fragments of mafic rocks. Grains of basalts with intersertal and spherulitic texture predominate. Grains of serpentinite, chert, amphibolite, phyllites, quartzite, granitoid rocks and grains of quartz sandstone are also present. Quartz grains represent approximately 10–20% of grains and are mostly monocrystalline, however polycrystalline quartz of metamorphic origin also occurs. Heavy minerals make up less than 10% of all grains. The sandstone matrix is micritic with admixture of clay component.

Sandstones of the Studor Formation were deposited by turbidity currents. Composition of sandstone indicates a composite source of material. Shallow-water carbonate clasts, specially isolated bioclasts indicate proximity of an active carbonate platform while siliciclastic admixtures indicate erosion of ophiolites and underlying metamorphic soles. Olistostromes were deposited as a debris-flow.

Age: Radiolarian samples from the lower part of the Studor Formation yielded poorly preserved radiolarian faunas assigned to a relatively broad range from the latest Tithonian–earliest Berriasian (UAZ13) to the latest Valanginian–earliest Hauterivian (UAZ18) based on the occurrence of *Svinitzium depressum* (Baumgartner). Similar as below, typical genera first appearing in the late Valanginian have not been found. This may indicate that the lower part of the Studor Formation is of late Berriasian to early Valanginian age. Valanginian-Hauterivian age of the Studor Formation was previously obtained with nannoplankton (Buser et al. 1979).

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