Rožič et. al. *Swiss Journal of Geosciences* (2024) 117:3
https://doi.org/10.1186/s00015-023-00449-w

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Swiss Journal of Geosciences

ORIGINAL PAPER

Open Access

Architecture and sedimentary evolution of the Ladinian Kobilji curek basin (External Dinarides, central Slovenia)

Boštjan Rožič[1*], Anja Kocjančič[2], Luka Gale[1,3], Nina Zupančič[1,2], Tomislav Popit[1], Primož Vodnik[4], Tea Kolar-Jurkovšek[3], Rok Brajkovič[3] and Petra Žvab Rožič[1]

Abstract

The study area is located in cental Slovenia, and geologically located at the junction between the Alps and the Dinarides. The Middle Triassic of this region is characterised by intense rifting manifested by differential subsidence and volcanism. This led to a major paleogeographic reorganisation of the region, where three paleogeographic domains formed in the Upper Triassic: The Julian Carbonate Platform in the north, the intermediate Slovenian Basin, both parts of the Southern Alps, and the Dinaric (Adriatic, Friuli) Carbonate Platform in the south, which today is a part of the External Dinarides that host the area of investigation. Prior to the installation of the Dinaric Carbonate Platfrom, i.e. in the Ladinian, the entire area of the preset-day External Dinarides broke up into numerous tectonic blocks that were exposed to either erosion or continental, shallow-marine, and deep-marine sedimentation. In this study, we analyse at small scale a complex transitional area between a local carbonate platform and the Kobilji curek basin (depositional area dominated by deeper marine sediments), located in the Rute Plateau in central Slovenia south of Ljubljana. During enhanced subsidence, the basin was filled with volcanic material (tuffs and volcanogenic clays and subordinate extrusive material), while the adjacent platform aggraded. The slope was positioned above active paleofaults. During relative sea level lowstand, the platform prograded across the basin. The study area is divided into four major tectonic paleoblocks. The NW paleoblock experienced the most enhanced subsidence, and the platform prograded twice in this area and was submerged again by the rejuvenated subsidence and/or sea-level rise. The second and third paleoblocks subsided only during discrete major subsidence events, and the carbonates of the platform and slope were soon reinstated therein. In the fourth paleoblock to the east the platform persisted during the Ladinian. In the Carnian, the entire study area became emerged, and continental clastics were deposited. These were then replaced by a uniform shallow marine/intertidal Hauptdolomit (Dolomia Principale) formation at the onset of the Norian. This study provides the first detailed reconstruction of the sedimentary evolution of small-scale Ladinian basin and platforms system in the northern External Dinarides.

Keywords External dinarides, Ladinian, Rifting, Basin evolution, Platform progradation

Editorial handling: Stefan Schmid

*Correspondence:
Boštjan Rožič
bostjan.rozic@ntf.uni-lj.si
[1] Department of Geology, NTF, UL, Aškerčeva c. 12, 1000 Ljubljana, Slovenia
[2] Ivan Rakovec Paleontological Institute, ZRC SAZU, Novi trg 2, 1000 Ljubljana, Slovenia
[3] Geological Survey of Slovenia, Dimičeva ul. 14, 1000 Ljubljana, Slovenia
[4] ELEA iC, Dunajska c. 21, 1000 Ljubljana, Slovenia

1 Introduction

The Middle Triassic tectonic and paleogeographic evolution of the present-day Southern Alps, Dinarides, Northern Calcareous Alps, and Transdanubian Range was strongly influenced by crustal extension associated with the opening and spreading near the western end of the Neotethys (Meliata) Ocean preceeding the opening of the Alpine Tethys during the Jurassic farther north and northwest (e.g. Schmid et al., 2008, 2020; Kovács et al., 2011). As a result, several deeper marine basins formed, mainly between the Late Anisian and Early Ladinian (e.g. Buser, 1989; Haas & Budai, 1999; Budai & Vörös, 2006; Berra & Carminati, 2010; Stefani et al., 2010; Velledits et al., 2011; Gawlick et al. 2012; Celarc et al., 2013; Smirčič et al. 2020). Paleotectonic activity was locally accompanied by volcanism that resulted in the deposition of volcaniclastics and/or volcanic rocks, especially in basinal areas (Buser 1989; Bosellini et al., 2003; Storck et al., 2018; Slovenec et al., 2023). The spatial relationships between the Middle Triassic platforms and the basins were, to a large extent, reconstructed in the Italian part of the Southern Alps, especially in the Italian Dolomites (e.g. Blendinger, 1986; De Zanche et al., 1993; Brack et al., 1996; Emmerich et al., 2005; Gianolla et al., 2010, 2021).

On the territory of Slovenia, which structurally lies at the junction of the easternmost Southern Alps and the northernmost External Dinarides (Fig. 1), the lack of continuous outcrops at the scale of seismic profiles generally precludes direct observation of basin morphology. Rare exceptions with good outcrop consitions include the small-scale half-grabens described by Petek (1997), Celarc et al. (2013), and Gale et al. (2023). Laterally, the most extensive (Upper Anisian?) Ladinian basinal deposits belong to the informal "Pseudozilje (Pseudogailtal) Formation", composed mainly of shale, lithoclastic sandstone, and tuff, with local extrusions of rhyolitic volcanics in the lower part of the formation (Teller, 1898; Rakovec, 1950; Buser, 1986; Demšar, 2016). The "Pseudozilje Formation" represents the lowest unit in the succession of the Slovenian Basin, a major deep-marine paleogeographic unit, which persisted until the end of the Cretaceous. Today this basin forms the Tolmin Nappe, i.e. the lowest thrust unit of the easternmost Southern Alps, but it also occurs as tectonic klippen within northeastern Dinarides (Buser, 1989; Buser et al., 2008; Rožič, 2016), i.e. north and east

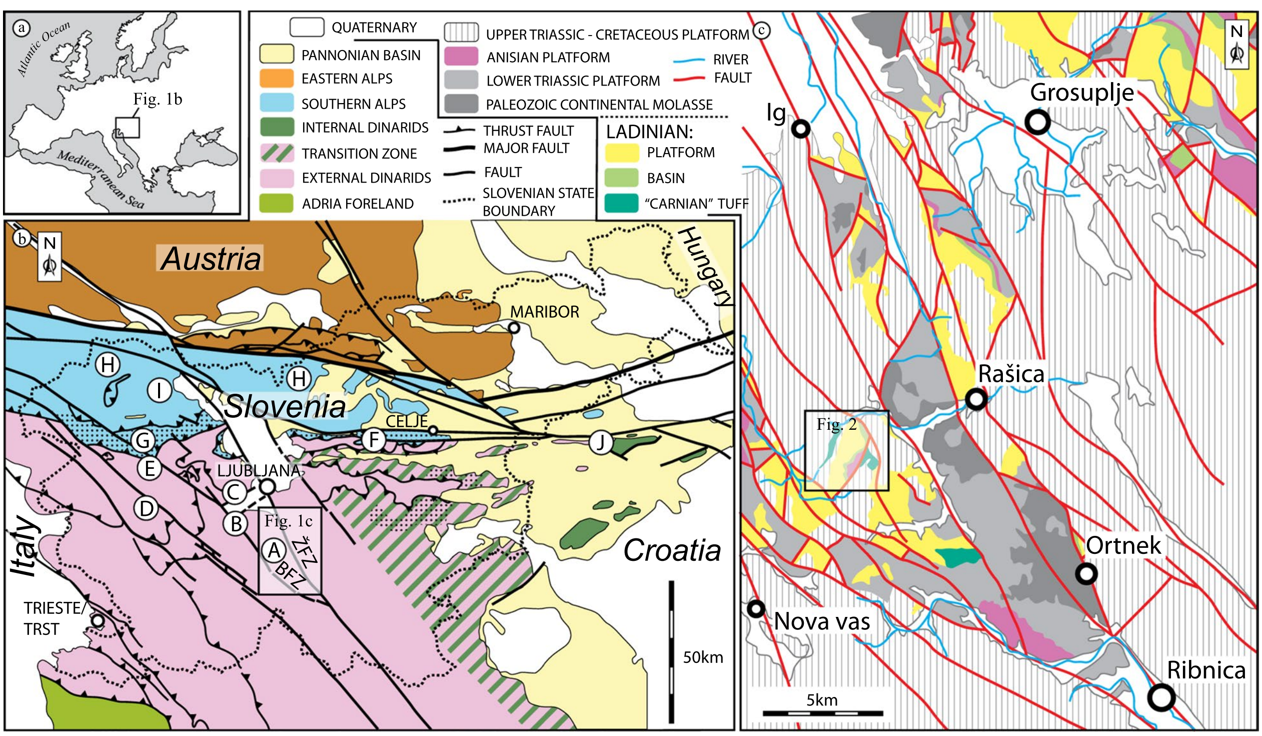

Fig. 1 Geological setting of the study area: **a** location within Europe (the framed area is enlarged in **b**. **b** geotectonic subdivision of the Alps-Dinarides junction with location of the study area referred to as the Kobilji curek basin (circled capital letters mark the locations of logs shown in Fig. 6, dotted area marks the outcrops of the Slovenian Basin—largest Mesozoic deep marine unit originating in Ladinian; framed area—enlarged in **c**, *BFZ* Borovnica fault zone, *ŽFZ* Želimlje fault zone) (after Placer, 2008; Rožič, 2016). **c** Simplified geological map of the area with outcrops of Anisian platform carbonates (purple), Ladinian platform carbonates (yellow) and Ladinian basinal successions (green) marked (after Buser, 1968)–the framed area marks the location of the Kobilji curek basin (see Fig. 2 for details)

of our study area. Other occurrences of Middle Triassic basinal successions are much smaller in extent. Although they are numerous (e.g. Kühn & Ramovš, 1965; Ramovš & Jurkovšek, 1983; Kolar-Jurkovšek, 1983; Goričan & Buser, 1988; Buser et al., 2008; Dozet & Buser, 2009; Kolar-Jurkovšek & Jurkovšek, 2019) they have remained poorly investigated.

In this paper, we present the first detailed sedimentary study of Middle Triassic deeper marine basin and carbonate platform deposits preserved in the northern External Dinarides. The study area is located on the Rute Plateau, about 25 km south of Ljubljana. The detailed geological map illustrates the complex architecture of the platform-basin transition defined by structural segmentation of the area, which is evident from the rapid lateral facies changes along several synsedimentary faults (bolded in Figs. 2, 4). For the deeper marine deposits, we use the informal term "Kobilji curek basin" after a well-known waterfall in the study area (see Fig. 1c). We note that in the current paper the term basin is used for relatively deep marine depositional environments formed over paleotectonic blocks of accelerated subsidence. However, in the study area, coeval shallow-marine carbonate platfrom deposits are also found. The spatial transition between platform and basin is complex and determined by a system of paleofaults; moreover, it changes over time. We emphasise that even in the paleotectonic block characterised by the greatest subsidence (i.e. in the central basin area), the deeper marine deposits are interlayered twice by shallow-marine carbonates, indicating a relatively low platform-basin relief.

The uppermost part of the stratigraphic succession in the Kobilji curek basin was previously described as the two lower members of the Mohorje Formation, namely the Boštetje and Borovnik members (Dozet, 2009; Kralj & Dozet, 2009), which were questionably assigned to the Carnian on the basis of macroscopic lithological similarity to the Carnian (Julian) Lesno Brdo limestone (Jelen, 1990; Dozet, 2009). In addition, the dasycladalean algae Diplopora annulata from the platform limestone that underlies the Mohorje Formation has traditionally been incorrectly assigned to the Cordevolian (Lower Carnian) in Slovenia (see Celarc, 2004, 2008). Our study has shown that the evolution of the Kobilji curek basin is far more complex and that the Boštetje and Borovnik members form only the uppermost part of a Ladinian succession characterised by alternating basin/platform deposits. This work provides the first detailed description of the small-scale basin/platform system and highlights the interplay of subsidence pulses, volcanic activity, and platform progradation. In contrast to the small, fast-filling half-grabens of the eastern Southern Alps, or the large Slovenian Basin at their southern front, the Kobilji curek basin of the External Dinarides clearly reflects the complex and repetitive interplay of these tectono-sedimentary events. The interpretation is based on detailed geological mapping, section logging, microfacies analysis, clay mineralogy, and biostratigraphy (conodont data).

2 Geological setting

The Rute Plateau is a hilly area located about 25 km south of Ljubljana and 10 km west of the village of Rašica (Fig. 1c). Structurally, the study area belongs to the External Dinarides. According to Placer (1999) it is part of the Hrušica Nappe, but it could also lie within the Snežnik Thrust sheet located northeast of the Snežnik frontal thrust (Schmid, pers.comm.; see also Placer et al. 2010). The latter is a Dinaric thrust sheet that can be laterally connected to the Velebit thrust sheet in Croatia that represents a frontal part of the High Karst unit (Fig. 1; Schmid et al., 2020, Balling et al., 2021). The stratigraphic sequence is displaced by post-thrusting NW–SE trending strike-slip fault zones: the Želimlje fault zone to the east and the Borovnica fault zones to the west (Placer, 2008). The area is further disected by differently oriented connecting faults (Buser, 1968).

The succession of the Rute Plateau wider area begins with predominantly continental Variscan clastic mollase-type deposits (Ramovš & Kochansky-Devidé, 1965). Above the unconformity, it is overlain by the Lower Triassic mixed siliciclastic/carbonate shallow shelf deposits (Werfen Formation) that pass into a pure Anisian carbonate succession (mainly dolomite). In the northern and southeastern parts of the Rute Plateau wider area, the latter is not preserved due to unconformity (Fig. 1c) (Buser, 1968).

The Ladinian succession shows a laterally diverse development that largely occurs as massive dolomite or subordinate limestone overlying the Anisian carbonates or unconformably overlying the Lower Triassic succession. Locally, the Ladinian carbonates alternate laterally and vertically with deeper marine volcaniclastics, fine clastics (clays), and thin-bedded dark limestones (Buser, 1968; Dozet, 2009). In the region, the Ladinian succession generally terminates with shallow marine carbonates, whereas only on the Rute Plateau does the succession end with deeper marine limestones that are succeeded by volcaniclastics. In previous publications, this uppermost deeper marine succession was already considered to be of Carnian age on the basis of superposition and lithological similarities with the well-dated lagoonal black limestones west of Ljubljana (Jelen, 1990; Dozet, 2009; Kralj & Dozet, 2009).

Due to subaerial exposure and associated erosion, a levelled topography came into being in the Early Carnian that was overlain by alluvial sediments. Towards the

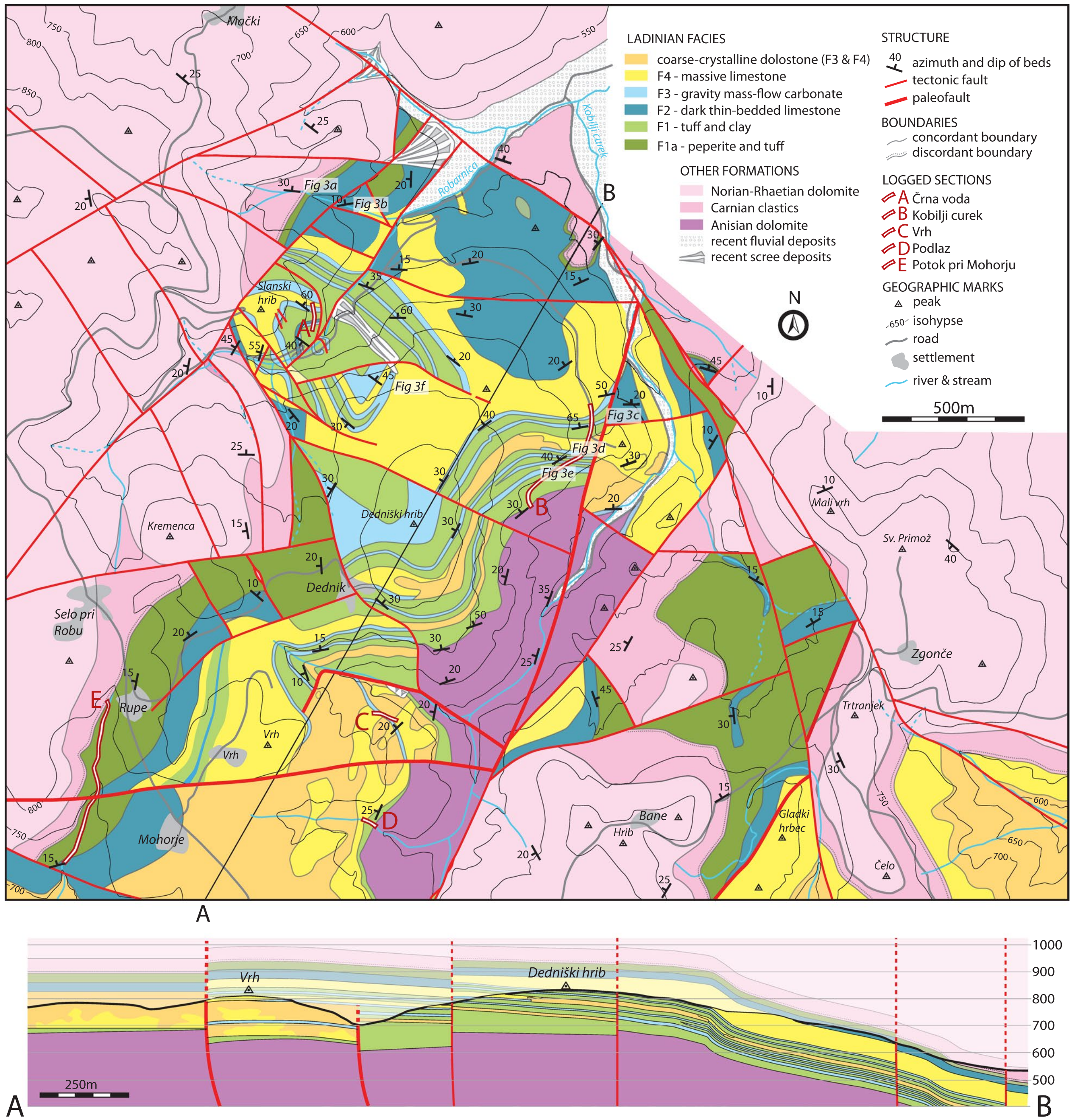

Fig. 2 Geological map and cross-section of the Rute Plateau area: Ladinian basinal succesions (green and blue colors) are located in the northwestern part of the area, while the eastern and southern parts are dominated by platform carbonates (yellow and orange colors). The transition between the sedimentary environment end members is characterized by paleotectonic blocks dominated by platform carbonates, but also containing intervals of basinal deposits. Facies transitions are rapid and occur along faults (bolded) considered to be synsedimentary

north, these continental deposits alternate with the shallow-marine carbonates characteristic of very restricted intertidal/lagoonal environments (Jelen, 1990; Buser, 1996; Celarc, 2004, 2008; Čar, 2010; Gerčar et al., 2017). Due to a new transgression in the late Carnian, the formation of the Norian-Rhaetian Hauptdolomit gradually began, thus forming the large-scale Dinaric (Adriatic, Friuli) Carbonate Platfrom, which connected in the west with the extensive carbonate shelf of the Southern Alps, the Transdanubian Range, and the Northern Calcareous Alps (e.g. Haas, 2002; Vlahović et al., 2005; Buser et al., 2007; Caggiati et al., 2018).

3 Methods

Geological mapping was carried out at a scale of 1:5000, combined with a shaded digital elevation model with a spatial resolution of 1 m obtained from LIDAR scanning in 2014–2015 (available from the Environmental Agency of the Republic of Slovenia). A combination of two mapping approaches was used to create the detailed geological map: (A) Analysis of all outcrops (including description of lithology and structural elements) and B) tracing of geological boundaries.

Five sedimentological sections were logged at scales of 1:100 and 1:50, namely one 233 m section of Kobilji curek and four separate sections of different stratigraphic lengths belonging to different tectonic blocks (section Črna voda—52.20 m; section Podlaz—41 m; section Vrh—42.5 m; section Potok pri Mohorju—86.45 m).

In total, 144 samples were taken from various lithological units. Of these, 126 petrographic thin sections were prepared, representing mostly carbonates and, to a lesser extent, clastics and volcaniclastics. The thin sections are kept in the Department of Geology of the Faculty of Natural Sciences and Engineering of the University of Ljubljana. Microscopic determination of carbonates was based on the standard classification of carbonate rocks (Dunham, 1962), with modifications by Embry and Klovan (1971). Additional literature on carbonate microfacies (Flügel, 2004) was used to compare microfacies. The volcaniclastic rocks were described and classified according to Schmid (1981), taking into account previous descriptions from the studied area (Kralj & Dozet, 2009). The following terms were used in the description of the carbonate rocks: micrite for lithified microcrystalline calcareous mud or matrix; sparite for relatively coarse-grained calcite or dolomite cement, calcisiltite for carbonate rocks with detrital silt-sized carbonate grains (up to 0.063 mm), calcarenite for carbonate rocks composed predominantly of sand-sized grains (from 0.063 mm to 2 mm), and carbonate or limestone breccia for rocks with grain size greater than 2 mm.

Biostratigraphy is based on conodonts. Composite samples were taken for the study of conodonts. Samples with an average weight of 2 kg were treated in acetic acid and then separated with heavy liquid. The recovered microfossil material is housed at the Geological Survey of Slovenia.

The mineral composition of 12 fine-grained samples of clays and tuffs was analysed using powder X-ray diffraction (XRD). Measurements were performed using a Phillips PW3710 diffractometer at the Department of Geology, Faculty of Natural Sciences and Engineering, University of Ljubljana. The XRD acquisition was produced with CuKα radiation at a voltage of 10 kV and a current of 10 mA. The recording speed was 3°2θ/min in an angular range between 3° and 70°. The type of clay mineral was determined in <2 µm clay fraction in oriented samples solvated with ethylene glycol. Montmorillonite was confirmed by the presence of a characteristic 15 Å peak in the oriented sample, which shifted to 16.9 Å in the glycolized sample. Kaolinite and chlorite were separated by the presence of peaks at 14.2 Å and 4.74 Å, accompanied by a characteristic peak at 7.1 Å for both.

4 Results

The lowest and oldest stratigraphic unit in this area is the indistinctly bedded Anisian dolomite (Figs. 2, 4). Stromatolites and fenestrae are visible in this dolomite, indicating a shallow-water origin for this formation. During geological mapping a 10 m thick interval of dark, thin-bedded dolomite with shale/marl interlayers was found within massive dolomite, probably as the result of a minor deepening episode. Anisian dolomite is followed by a highly variegated Ladinian succession of volcaniclastics and carbonates (described in detail below). This succession is unconformably overlain by red fluvial sandstone and conglomerate (the Rupe Member of the Mohorje Formation in Dozet, 2009), which is equivalent to the Carnian Travenanzes Formation in the Southern Alps; Breda & Preto, 2011; Gerčar et al., 2017). The unconformable position of the Carnian clastites can be inferred from the sudden change from basinal/platform facies to fluvial deposits, and especially from the fact that the red clastics lie indiscriminately on top of different facies associations. The red clastics are followed by peritidal dolomite and marlstone (the Selo Member of the Mohorje Formation in Dozet, 2009), which gradually pass into the Hauptolomit Formation at the beginning of the Norian.

4.1 Facies of the Ladinian succession

The Ladinian succession is highly variable, but within the succession four main facies associations can be distinguished: volcaniclastics and clays (facies F1), dark thin-bedded limestone (facies F2), carbonate mass flow deposits (facies F3), and massive limestone and

Fig. 3 Ladinian facies: **a** alternating tuff layers with different grain sizes (F1), **b** dark, thin-bedded limestone (F2), **c** pumice clasts (arrows) in thin-bedded limestone with bent laminae in underlying filament packstone (F2), **d** coarse limestone breccia at the base of platform limestone (F3), **e** fold formed by slumping in gravity mass flow carbonates (F3), **f** massive platform limestone (F4)

dolostone (facies F4). These facies types alternate laterally across paleofaults but may also repeat vertically several times within a single section. In this chapter, we describe the facies and associated microfacies and their sedimentary processes, which serves as a basis for understanding the complex spatial and chronological platform-basin relationships described in the following chapters.

4.1.1 F1: Volcaniclastic and clay facies

Facies description: Various rock types of pyroclastic origin ("pietra verde tuffs") and the intercalated clay layers are assigned to this facies. It alternates vertically with all other facies types, but most frequently with facies F2 and F3. The F1 facies consists of massive or laminated green to light brown clays, fine- to coarse-grained tuffs (Fig. 3a), and dacite/rhyolite peperites. Indistinct gradation is observed in some parts of the succession. Based on grain size and the presence of crystals and lithic material, we recognised three lithotypes: vitroclastic, vitrocrystalloclastic, and crystalloclastic tuffs (Table 1). In addition, peperites of dacite/rhyolite-siltstone were described in the uppermost part of the Ladinian succession by Kralj and Dozet (2009). This part has been formalised as the Borovnik Member of the Mohorje Formation, supposedly Carnian in age (Dozet, 2009). We did not detect it in our Potok pri Mohorju section but observed some potential outcrops of this lithotype during geological mapping. In the geological map (see below), we delineate this

Table 1 Lithotypes of volcaniclastics facies (for micrographs see Additional file 2)

MICROFACIES	COMPOSITION	DIAGENESIS/OTHER FEATURES
Fine-grained rhyolitc vitroclastic tuff (F1-A)	**Matrix:** 60–80% fine-grained glassy sherds of indistinguishable shape, rarely arcuate and y-shaped; in some parts 0–20% rounded pumice litoclasts up to 8 mm in size. **Clasts:** 10 % crystalloclasts; 50 % anhedral quartz (0.04 mm) and 50 % euhedral feldspars, (0.07 mm). Scarce lithoclasts. Accessory minerals are zircon and pyrite.	Partially recrystallized and chloritized matrix. In some parts of the profile intensely weathered to bentonitic clay.
Medium-grained rhyolitc/dacitic vitrocrystalloclastic tuff (F1-B)	**Matrix:** 70–80% medium sized arcuate, platy and Y-shaped recrystallized glass sherds and elongated pumice fragments up to 2 cm long (average 0.6 mm). **Clasts:** 20–30 % crystalloclasts; 20-50 % anhedral quartz (0.8 mm), 20–40 %, euhedral to subhedral and generally fragmented zoned, polysynthetic twinned plagoclases (1 mm). In some samples, 15 % of euhedral sanidine and orthoclase (0.4 mm) in other 25 % of subhedral biotite (0.5 mm). Zircon and pyrite are accessory.	Matrix is chloritized and carbonatised, orthoclase sericitized.
Coarse-grained rhyolitc/dacitic crystalloclastic tuff (F1-C)	**Matrix:** coarse grained recrystallized vitric matrix. **Clasts:** 50–80 % crystalloclasts; 10–30 % cracked anhedral quartz (0.4 mm), 40–70 % euhedral to subhedral fragmented and cracked polysynthetic twinned and zoned plagioclases (1 mm), 20 % subhedral to anhedral orthoclase (1.3 mm). In some samples 20 % of subhedral biotite (1 mm), other scarce euhedral hornblende (0.5 mm). Accessory minerals are rutile, sphen, zircon, and pyrite.	Matrix and lithic clasts are chloritized, carbonatised and limonitised, orthoclase sericitized.
Dacite/riolite-siltstone peperites (F1-D)	Fluidal texture with alternating glassy lava and siltstone **Matrix:** glassy **Phenocrysts:** zoned and twinned plagioclases (up to 3 mm) and K-feldspars, prevailingly sanidine.	Matrix is chloritized, limonitised, carbonatised, epidotised and albitised, feldspars sericitized.
Clays (F1-E)	Clays comprised of quartz, feldspars and clay minerals. In oriented and glycolised samples, we confirmed illite and montmorillonte or mixed layer mineral of illite/montmorllonite type. In some samples, we also determine kaolinite and chlorite group mineral.	

uppermost part of the sequence as a specific subtype of the volcaniclastic facies (F1a).

Facies analysis: According to mineral composition, pyroclastic rocks are of rhyolitic to dacitic composition. They are usually the product of several successive explosive volcanic eruptions and, rarely, effusive lava flows (cf. Kralj & Dozet, 2009). The intensity of the eruptions varied but depending on the grain size of the material most of the pyroclastic material was deposited by pyroclastic density flows and surges and were submerged when entering the basinal area (cf. Lockwood and Hazlett, 2014). Ashfall from more distant sources settling through a water column and redeposition from a platform slope (cf. Brack and Muttoni, 2006) are possible for some parts of the succession. The presence of montmorillonite and/or mixed layer clay mineral of I/S-type indicates that the clays are a product of recrystallization (Christidis et al., 1995; Velde, 2010) and submarine weathering of volcanic glass (Pellenard et al., 2003).

4.1.2 F2: Dark thin-bedded limestone facies

Facies description: This facies alternates laterally and vertically with the F1 and F3 facies. The F2 facies consists mainly of dark, thin-bedded, laminated or homogeneous black (organic-rich) limestone (mudstone to wackestone) (Fig. 3b). Distinct laminae of filament (thin-shelled bivalves)-rich packstone are present in some beds, and sometimes stand out due to selective silicification of bioclasts. Rare chert nodules are present. Thin interlayers of marlstone often separate limestone beds. Locally, slumps were recognized, which developed into a mud-supported breccia with clasts of light grey micritic limestone several centimetres in size. In an outcrop (not logged), pumice clasts up to 4 cm in size are embedded in the laminated limestone. The laminae beneath the clasts are unbroken but bent and deformed (Fig. 3c). Within this facies, four microfacies types are distinguished (Table 2).

Facies analysis: The frequent presence of radiolarians and filaments in the samples indicates open-marine

Table 2 Microfacies of dark thin-bedded limestone facies

MICROFACIES	COMPOSITION	DIAGENESIS/OTHER FEATURES
Radiolarian M to W (F2-A)	**Structure:** occasional bedding-parallel lamination **Matrix:** micrite **Main comp.:** radiolarians, peloids **Subordinate comp.:** filaments (thin-shelled bivalves), bioclastic debris. Rare pyrite and monocrystal quartz grains and opaque bituminous matter.	Very rare bioturbation, dissolution seams
Filament W to P (F2-B)	**Structure:** bedding-parallel lamination and orientation of elongated grains, grading to radiolarian W (F2-A) **Matrix:** micrite **Main comp.:** filaments **Subordinate comp.:** peloids, radiolarians, ostracods, echinoderm fragments, monocrystal quartz grains, pumice fragments, bituminous matter	Strongly recrystallized horizons of calcite cement between bivalve shells (occasionally almost complete recrystalisation); dissolution seams
Bioturbated fine P (F2-C)	**Structure:** chaotic or with borings **Matrix:** micrite with reddish argillaceous component **Main comp.:** peloids, fine bioclastic debris **Subordinate comp.:** tiny biotite and monocrystal quartz.	Bioturbation, dissolution seams; locally slightly silicified parts
Fine-grained bioclastic W to P (F2-D)	**Structure:** indistinct lamination, poor sorting **Matrix:** micrite **Main comp.:** peloids, unrecogmisable bioclastic debris, **Subordinate comp.:** filaments (fragmented), sponge spicules foraminifera *Nodosaria ordinata*, echinoderm (crinoid) fragments, dasycladalean fragments, radiolarians, ostracods, *Tubiphytes*, rare gastropods, and juvenile ammonites.	Rare rhombic euhedral crystals of dolomite inside matrix

P packstone, *G* grainstone, *R* rudstone, *F* floatstone, *B* boundstone, *Bi* bindstone) (for micrographs see Additional file 2) sedimentation in a relatively deep marine environment. Hemipelagic/pelagic deposition of the material was sporadically redeposited by diluted turbidites, from which graded filament wackestone-packstone was deposited. Small-scale synsedimentary slumps indicate an inclined seafloor. Slumps occasionally developed into dilute debris flows (mud-supported breccias with rare micritic clasts). Pumice clasts in micritic limestone indicate lapilli derived from a nearby explosive eruption or the sinking of pumice fragments after floating away from a more distant source. Thinly laminated, organic-rich limestone beds indicate deposition predominantly under oxygen-depleted conditions. In contrast, one micritic microfacies is lighter in colour and exhibits bioturbation (F2-C), which was found in an association typical of a lower slope environment. Another micrite-rich microfacies has diverse benthic organisms (F2-D), indicating well-oxygenated bottom waters. Dasycladalean fragments (F3-D) point to partial redeposition of material from the adjacent shallow marine environment. We emphasise that the last microfacies is found only in the basal part of the Ladinian succession, documenting the initial phase of the Anisian platform drowning.

4.1.3 F3: Gravity mass flow carbonate facies

Facies description: This facies alternates vertically with facies F1 and passes laterally and vertically into facies F2 and F4. It consists of thin- to medium-bedded, graded, and laminated calcarenite and limestone microbreccia, and layers of coarse limestone breccia up to several meters thick, often with meter-scale olistoliths of massive platform limestone (Cipit boulders) (Fig. 3d). Slumps are present (Fig. 3e). In intervals, where this facies is overlain by the massive (platform) carbonates (F4), it is characterized by coarse-grained breccia. The clasts are often meters in size, and the delineation between the breccia and the massive carbonates is unclear.

Calcarenites and microbreccia layers, mostly of the packstone to rudstone type, contain a variety of grains derived from the shallow water environment, as well as shallow and deeper marine lithoclasts. Five microfacies types were recognized within this facies, and two additional microfacies types were described from the Cipit boulders (Table 3). Sporadic silicification occurs in calcarenite in the form of chert laminae and nodules.

Facies analysis: The described lithologies are interpreted as gravity mass flow deposits. Calcarenites and microbreccias are calciturbidites, coarse limestone breccias are high-density turbidites and debris-flow deposits. These resedimented carbonates originated from the platform margin. The latter is inferred from the smaller grains typical of platform sediments (various bioclasts, intraclasts, peloids). Erosion of the lithified platform margin carbonates is evident by lithoclasts, including meter-scale Cipit boulders (clasts with oncoids and fenestral porosity, microbial boundstone, dasycladalean grainstone). From the lithoclasts, which correspond in composition to the facies F2, it can be inferred that eroded slope and basinal deposits were incorporated in the gravity mass flows.

The depositional environment of this facies was the base of the slope and the basin floor. When underlying the platform limestone (F4), this facies probably formed on the slope of [a/the] prograding platform. The inclination of the seafloor is indicated by slumps. Upward, this facies gradually passes into the slope/platform margin, while towards the inner parts of the basin it begins to interfinger with the facies F1 and F2.

4.1.4 F4: Massive limestone and dolostone facies

Facies description: We emphasise that this facies has been studied in detail only in sections logged in the valleys surrounding the Rute Plateau, where it exchanges with other facies types (Figs. 2, 4). Detailed studies on the plateau (SE part of the mapped area, where this facies is predominant) are not possible because of the strong dolomitization and low relief, resulting in poor outcrops.

The predominant lithology is massive, light grey limestone. Some layers are rich in dasycladalean algae or sponges. Horizons and lenses with reef-derived bioclasts and intraclasts are interbedded. Rarely, oncoidal limestone was observed. The limestone was locally affected by late diagenetic dolomitization that completely or partially destroyed the original sedimentary fabric. Seven microfacies types were recognised within this facies (Table 4).

In microbreccia, silica selectively replaces particular grains (mostly bioclasts). Selective silicification of bioclasts is also observed in Cipit boulders. Dolomitization occurs in this facies. Occasionally, the primary composition is still visible, but often it is coarse-crystalline dolomite whose primary structure and composition is completely obliterated (microfacies F4-G, described within the platform microfacies types in Table 4).

Facies analysis: The absence of bedding, the presence of photic zone fossils (dasycladalean algae), the absence of open marine organisms, and the presence of in-situ preserved sponge-microbial boundstone suggest sedimentation on the platform top, margin, and slope, mostly within the photic zone. In seismic-scale outcrops in the Southern Alps, dasycladalean-rich facies comparable to F4-B, F4-E, and F4-F described above characterise the back-reef lagoon, while microbialite and "*Tubiphytes*" boundstones characterise the reef margin and slope (e.g. Biddle, 1981; Boni et al., 1994; Rüffer & Zamparelli, 1997;

Table 3 Microfacies of gravity mass flow carbonate facies

MICROFACIES	COMPOSITION	OTHER FEATURES/ DIAGENESIS
Fine-grained P to G (F3-A)	**Structure:** well-sorted, often chaotic (bioturbation) **Matrix:** micrite and microsparite with argillaceous component **Main comp.:** Peloids (pellets), tiny unrecognisable bioclasts, in micritic parts radiolarians and fragmented filaments **Subordinate comp.:** monocrystalline quartz grains; rare foraminifera, biotite, and framboidal pyrite.	Bioturbation, frequent laminae couplets and dissolution seams
Intra - peloid G (F3-B)	**Structure:** medium- to well-sorted, bedding-parallel even lamination **Matrix:** microsparite and sparite, rarely micrite **Main comp.:** peloids, micritic intraclasts **Subordinate comp.:** small lithoclasts, foraminifera (*Pseudonodosaria, Grillina, Reophax rudis*), bivalve, echinoderms and *Tubiphytes* fragments, filaments, in some samples angular monocrystalline quartz grains (in one sample abundant – 20 % of all grains).	Drusy mosaic cement, syntaxial echinoderm overgrowths, selectively silicified bioclasts
Bio-intraclastic P to R with larger lithoclasts (F3-C)	**Structure:** poorly-sorted, common angular clasts **Matrix:** microsparite and sparite **Main comp.:** micrite intraclasts, peloids, *Tubiphytes* and calcimicrobial/microbialite grains, lithoclasts of hemipelagic (radiolarian and/or filament W), slope (bioclastic W) and platfrom origin (peloidal P, bio/intaclastic cortoid P/G, microbialite *Tubiphytes* Bi, fenestral M/Bi) **Subordinate comp.:** calcareous sponges, bivalve, echinoderm and dasycladalean fragments, terebellid tubes, oncoids, foraminifera (*Endothyranella* sp., *Glomospirella irregularis*), rare chert lithoclasts, monocrystalline quartz grains	Dissolution seams around clasts, drusy mosaic, syntaxial and intragranular calcite cement. Chalcedony in replaced bioclasts. Rare inequigranular, xenotopic dolomite texture in matrix
Lithoclastic R/ limestone breccia (F3-D)	**Structure:** clast-supported, subangular to angular clasts **Matrix:** micrite or sparite, often not present (dissolution or dolomitization) **Main comp.:** lithoclasts: mainly platfom origin (calcimicrobial/microbialite Bi, fenestral M/Bi, oncoid R, sponge B, algal cortoid and/or *Tubiphytes* G, intra/bioclastic cortoid G, intraclast *Tubiphytes* P, peloid P, *Baccanella* W), rare basinal origin (radiolarian M, filament W, intraclast-filament G), possible slope origin (bioclastic peloid W) **Subordinate comp.:** peloids, micrite intraclasts, bioclasts (*Tubiphytes*, bivalves), monocrystalline quartz grains	Dissolution seams and often stylolithic contacts, fibrous and drusy mosaic calcite cement, rare silification of lithoclasts or bioclasts within particular lithoclasts, dolomitization of matrix and particular lithoclasts (occasionally in the form of large ferro-dolomite crystals)
Algal peloidal F (F3-E) (Cipit boulder)	**Structure:** poorly-sorted, large dasycladalean alga in finer sediment **Matrix:** sparite, localy micrite **Main comp.:** large dasycladalean fragments, pelets, cortoids, *Tubiphytes grains* **Subordinate comp.:** micrite intraclasts, microproblematica *Bacinella irregularis*, foraminifera (*Duostomina* sp, *Endotriadella wirtzi*), Terebellida tubes, echinoderm fragments	Radiaxial and mosaic calcite cement between grains, geopetal infills of algae, fenestrae with drusy mosaic and granular calcite cement
Microbial Bi (F3-F) (Cipit boulder)	**Structure:** laminated (stromatolitic) **Matrix:** micrite to microsparite **Main comp.:** alternating microbial crusts (stromatolites), occasionaly with visible calcimicrobial filaments, peloid laminae with occasional Tubiphytes and intraclasts, large cavities within primary framework are filled with peloidal P. **Subordinate comp.:** foraminifera, oncoids, terebellid tubes	Fenestrae filled with fibrous rim and drusy mosaic cements. Some laminae almost completely recrystallized.

P packstone, *G* grainstone, *R* rudstone, *F* floatstone, *B* boundstone, *Bi* bindstone) (for micrographs see Additional file 2)

Table 4 Microfacies of massive limestone and dolostone facies

MICROFACIES	COMPOSITION	DIAGENESIS/OTHER FEATURES
Peloidal-bioclastic W to P (F4-A)	**Matrix:** micrite **Main comp.**: peloids **Subordinate comp.**: bioclasts (echinoderms fragments, bivalve, algae (*Dendronella articulata*), microproblematica (*Plexoramea cerebriformis*, *Plexoramea gracilis, Bacinella irregularis*, *Thaumatoporella, Radiomura cautica)*, foraminifera (*Endotriadella*, *Earlandia, Endotriada, Variostoma exile),* larger Terebellida tubes	Dissolution seams, terebellid geopetal infills, syntaxial echinoderm overgrowths, rarely fenestrae.
Intraclastic-bioclastic G (F4-B)	**Structure:** medium-sorted, orientation of long grains parallel to bedding **Matrix:** microsparite to sparite **Main comp.**: angular micrite intraclasts, dasycladalean algae, *Tubiphytes*- like microproblematica, cortoids, peloids **Subordinate comp.:** ostracods, echinoderm fragments, calcimicrobial/microbialite grains, foraminifera (*Earlandia, Endotriadella wirzi, Grillina* sp., Duostominidae), gastropods, bivalves	Similar to F4-A; fibrous rim, intergranular mosaic calcite cement, syntaxial echinoderm overgrowths
Sponge-microbial B (F4-C)	**Structure**: primary growth of encrusters with W, P and G sediment fill of cavities within the bioconstruction framework **Matrix:** micrite and sparite (in cavities) **Main comp.:** framework of sponges and subordinate calcimicrobial/microbialite crusts, T*ubiphytes, Baccanella floriformis, Dendronella articulata.* **Subordinate comp.:** pellets and intraclasts (in cavities)	Strong recrystallization of bioclasts (especially sponges)
Microbialite and Tubiphytes-like microproblematica boundstone	**Structure**: boundstone **Matrix:** / **Main comp.:** *Tubiphytes*-like microproblematica and microbialite (rarely visible calcimicrobial filaments)	Dense network of fenestrae filled with radial fibrous and drusy mosaic calcite cement
(F4-D)	**Subordinate comp.:** foraminifera, ostracods, Terebellida tubes.	
Oncoid R (F4-E)	**Structure**: bimodal grain size **Matrix:** micrite to sparite **Main comp.:** large oncoids, fragments of dasycladalean algae (and mollusks?) **Subordinate comp.:** *Tubiphytes*-like microproblematica, foraminifera, micrite intraclasts, Terebellida tubes	Recrystallization of dasycladalean/mollusk fragments
Dasycladalean P to R (F4-F)	**Structure**: bimodal grain size **Matrix:** originally micrite (only locally preserved) **Main comp.:** dasycladalean algae (fragmented, often with thin microbial overgrowths), small pellets **Subordinate comp.:** *Tubiphytes,* calcimicrobes, micrite intraclasts, foraminifera, bivalves, Terebellida tubes	Dasycladalean algae and bivalves replaced by granular calcite spar; matrix largely replaced by bladed rim and drusy mosaic cements
Dolosparstone (F4-E)	**Matrix:** dolosparstone with dolomicrosparstone,	Inequigranular xenotopic dolomite, dissolution seams

W wackestone, *P* packstone, *G* grainstone, *B* boundstone) (for micrographs see Additional file 2)

Seeling et al., 2005; Maragnon et al., 2011, Gianolla et al., 2021). A similar association of microfacies types has been noted in Ladinian olistoliths in Slovenia (Gale et al., 2020) and in Carnian massive limestone in central Slovenia (Gale et al., 2018).

4.2 Paleotectonic blocks

Based on the lateral differences in the Ladinian succession that lies between the uniform Anisian dolomite and the red Carnian clastics, four major Ladinian paleotectonic blocks were distinguished (Fig. 4). Within individual paleoblocks the Ladinian successions are uniform, whereas they change rapidly along faults, which are consequently considered synsedimentary.

Paleoblock 1 is located in the NW part of the mapped area and has the most variegated Ladinian succession. It is characterized by three intervals of deeper marine sediments (facies F1, F2 and F3), with the first two intervals succeeded by platform carbonates (F4). Most of the succession was logged in the Kobilji curek section, and the middle part additionally in the Črna voda section (Fig. 4; Additional file 1).

In the Kobilji curek section, fine-clastic sediments (clays, fine tuffs) (F1) dominate in the first 55 m above the Anisian platform dolomite, while thin-bedded limestone (F2) and generally fine-grained gravity mass flow deposits (F3) are subordinate. In the next 40 m, carbonate resediments (F3) become coarser and thicker, forming intervals up to 10 m thick. Slumping is present (on 75 m of the Kobilji curek section; Fig. 3e). This interval was logged also in the Črna voda section and is similar in composition, but gravity mass flow deposits (F3) are generally thinner.

The transition to the lower platform limestone is initially characterized by calcarenites and limestone microbreccias that grade upward into coarse limestone breccias (F3) and then into the massive (platform) limestone (F4). In the Kobilji curek section, this interval dominated by massive limestone is 50 m thick. The limestone passes laterally into coarse crystalline dolomite. We note that outcrops in this area are limited and that the massive limestone could alternatively (but less likely) be a limestone breccia consisting of extremely large platform boulders. In the Črna voda section, only the transition to the lower massive limestone interval was logged. It consists of alternating marl (F1) and calcarenite (F3), which show synsedimentary slumping and contain limestone boulders (Cipits) up to 3.5 m thick.

The second deeper marine interval in the Kobilji curek section is 45 m thick and dominated by tuffs (F1), which are generally coarser than the tuffs of the first interval. In the middle part of this interval, carbonate resediments (F3) occur in thicknesses of 9 m in the form of calcarenite and microbreccia, and two thick limestone breccia beds (1.2 and 4 m) containing Cipit boulders.

Transition to the upper massive limestone interval starts like the first one, i.e. with carbonate resediments (F3), which progressively become coarser and rapidly change into the massive platform limestone (F4). In the Kobilji curek section, the carbonate resediments are 10.5 m thick. These strata are followed by a transition interval 7 m thick dominated by massive limestone (F4), but still containing two limestone breccia beds (1.4 and 0.45 m thick). Above, massive limestone was logged for another 23 m, but the entire interval is about 100 m thick.

The third, deeper marine interval overlies the massive limestone with sharp contact. It begins with a dark, thin-bedded and laminated limestone (F2) that is about 20 m thick. In its basal part, subordinate calcarenite and limestone microbreccia beds (F3) occur. Thin coquina beds of Bositra sp. pelagic bivalves were found in several places. With a sharp contact, the thin-bedded limestone passes upward into an interval composed predominantly of tuffs up to 30 m thick (F1). Compact rhyolite, which may be part of the in-situ volcanic rocks, was also noted in several isolated outcrops during geological mapping.

Paleoblock 2 contains massive (platform) carbonates with thin intervals of deeper marine strata. The Anisian dolomite is followed by dark, thin-bedded limestones (F2) and volcaniclastic layers (F1). The thickness of this interval varies laterally between 10 and 25 m over a distance of 300 m, indicating block tilting. This is followed by massive limestone and dolomite (F4) some 50 m thick. This is in turn overlain by carbonate resediments (F3) (logged in the Vrh section; Fig. 4, Additional file 1), about 10 m thick and dominated by graded microbreccia and coarse calcarenite. However, bioturbated micritic limestone (F2-C) was also documented. Upwards, another massive carbonate interval (F4) with a thickness of 80 m follows. Further up, a thin (up to 2 m) layer of thin-bedded dolomite (presumably resediments—F3) was mapped near the paleofault between paleoblocks 1 and 2. It is overlain by massive limestone (F4) that continues directly (without faulting) into the lower massive limestone of paleoblock 1, sealing the paleofault between these two paleoblocks. The following succession is almost identical to that observed in paleoblock 1. The most notable difference is in the thickness of the upper massive limestone (F4), which is much thinner in this paleoblock, only reaching a thickness of less than 20 m.

Paleoblock 3 begins with a deeper marine succession corresponding to that at the base of paleoblock 2 (facies F1 and F2). It was logged in a Podlaz section (Fig. 4, Additional file 1), where it reaches a thickness of 20 m but thins laterally. The transition to the overlying massive carbonates (F4) is characterised by thin-bedded

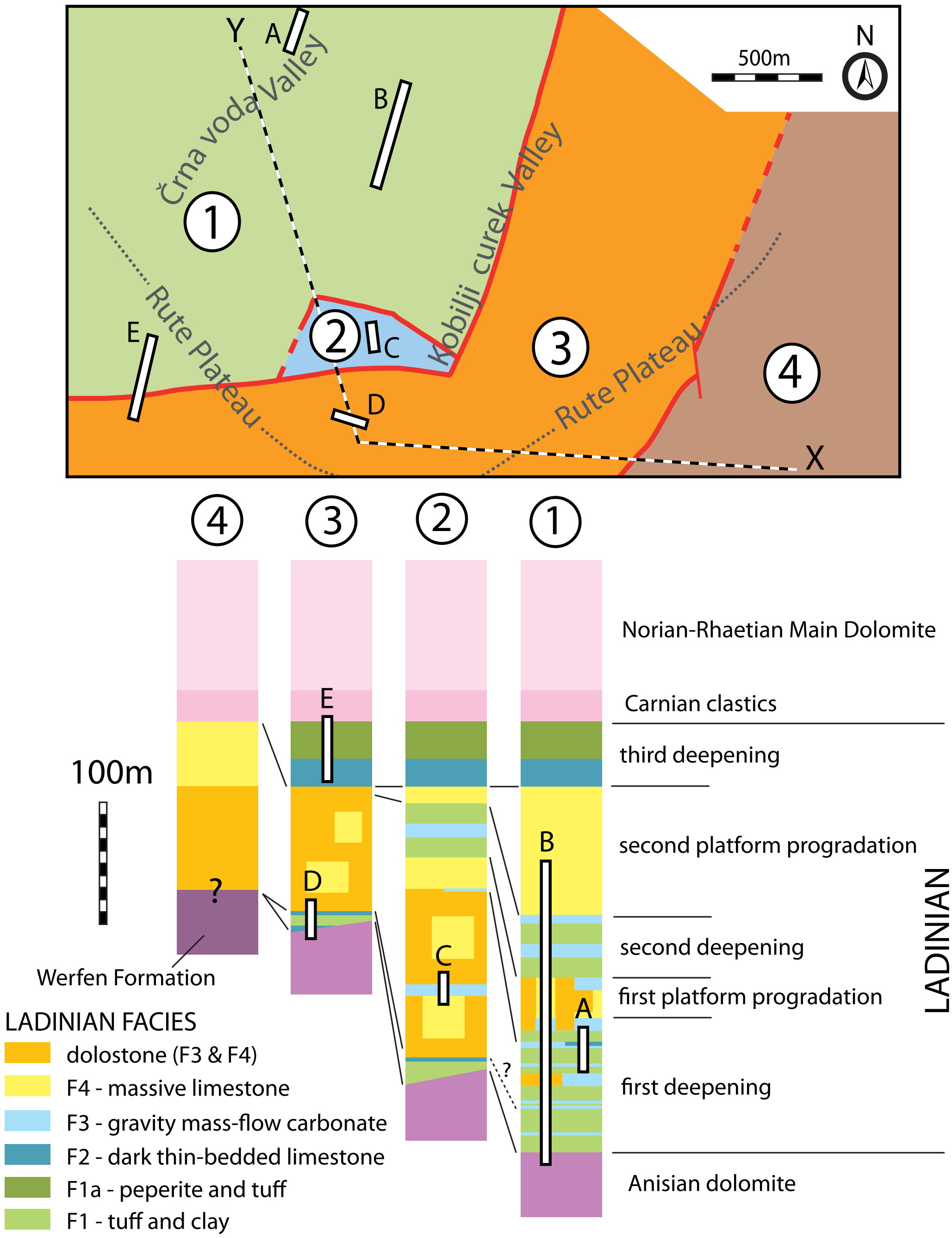

Fig. 4 Spatial distribution of the four tectonic paleoblocks (top) with generalized successions (bottom), and location of the detailed sedimentological logs (A—Črna voda, B—Kobilji curek, C—Vrh, D—Podlaz, E—Potok pri Mohorju – for details see Additional file 1). Paleoblock 1 is in the NW is dominated by basinal facies (F1, F2 and F3) with two intervals of platform carbonates (F4), paleoblocks 2 and 3 are dominated by platform carbonates (F4) with intervals of basinal facies (F1, F2 and F3), while paleoblock 4 in the SE contains exclusively platform carbonates (F4) (Line X–Y marks the position of Fig. 5 schematic cross-sections)

dolomites, presumably dolomitized resediments (F3). This is followed by a platform succession approximately 100 m thick (F4). It consists in the lower half of laterally alternating limestone and dolomite and in the upper part exclusively of dolomite. Like paleoblocks 1 and 2, the uppermost part of paleoblock 3 ends with a deeper marine succession (logged in a Potok pri Mohorju section, Fig. 4, Additional file 1), i.e. first with an interval of thin-bedded limestone (F2) with sporadic coarser calciturbidites (F3), followed by tuffs (F1a). At this locality, Kralj and Dozet (2009) described dacite/riolite-siltstone peperites.

Paleoblock 4 consists entirely of platform carbonates (F4). The thickness of this formation cannot be estimated in the mapped area but varies from 50 to 400 m in the wider area and probably lies directly above the Lower Triassic Werfen Formation (Buser, 1968). The sequence is dominated by coarse crystalline dolomite, but limestone occurs mainly in the upper part of the sequence below the contact with the red Carnian clastics.

Post-Ladinian tectonic deformation includes reactivation of some paleofaults, such as the NNE-SSW trending faults between paleoblocks 1 and 3, and paleoblocks 3 and 4 (the E blocks are structurally lowered). Minor reactivation is also observed for the E-W trending paleofault between paleoblocks 2 and 3 (the N block is slightly lowered). In the NE part of the mapped area, a NW–SE striking fault system is evident. It is part of the neotectonic (cf. Placer, 2008) Mišji dol strike-slip fault system located further in the NE of the mapped area (Fig. 1c). Apart from it, a rather dense network of NNE-SSW, E-W, NW–SE and NE-SW trending tectonic faults has developed. They occur within paleoblocks, but there are no obvious differences in the Ladinian strata across these faults. The major anticline of the Ladinian basinal strata that precedes the displacements along the vertical tectonic faults is observed in paleoblock 1. It is related to the Dinaric (SW directed) thrusting, but shows an opposite direction. The fold is more extensive in the western part, where the basinal strata are cut off from the basement by a thrust fault that changes to a reverse fault to the east and finally vanishes. We interpret it as a backthrust in the wedge between the SW trending compression and the E-W paleofault that separated the platform-dominated paleoblocks 2 and 3 and the "deformable" paleoblock 1 (characterised by deeper marine deposits).

4.3 Biostratigraphy

Biostratigraphic data is crucial to the identification and interpretation of the Kobilji curek basin. Based on its macroscopic similarity to the black limestone of Lesno Brdo (Jelen, 1990), Dozet (2009) assigned the dark, thin-bedded limestone beneath the Carnian red clastites to the Carnian. Subsequently, Dozet (2009) interpreted the volcanics and volcaniclastics, which he suggested were stratigraphically intermediate between the aforementioned limestone and the Carnian red clastites, as Carnian as well. However, as described above, the dark, thin-bedded limestone, volcanics and volcaniclastics, and gravity mass flow carbonates, which were not mentioned at all by Dozet (2009), grade into each other laterally and vertically (Fig. 4), and this bed-set is truncated by a major unconformity.

To determine the age of the succession lying between the Anisian platform dolomite and the Carnian red clastites, foraminifera, pelagic bivalves, dasycladalen algae, radiolaria, and conodonts were analysed. However, only a few of the conodont samples yielded age-diagnostic fossils. Samples from micritic limestone 15.7 m above the top of the Anisian dolomite in the Kobilji curek section (paleoblock 1) contained conodont elements *Paragondolella trammeri* (Kozur), *Neogondolella* sp. and ?*Budurovignathus* sp.. The same conodonts were also found in the thin-bedded limestone above the Anisian dolomite in the Podlaz section (paleoblock 3).

The sample from the limestone beds at the 195 m point of the Kobilji curek section (directly below the upper massive limestone) contained the conodonts *P.* cf. *trammeri* (Kozur) and *Budurovignathus* cf. *hungaricus* (Kozur & Vegh). The stratigraphic range of *P. trammeri* extends from the Late Anisian to early Late Ladinian, whereas *Budurovignathus* first appears in the Early Ladinian (Buser et al., 2008). Therefore, the most probable age for the entire succession between the Anisian dolomite and the Carnian red clastics is Ladinian, with the lower massive limestone (F4) within the first paleoblock probably Early Ladinian and the upper massive limestone already Late Ladinian.

5 Discussion

5.1 Basin evolution

The variegated Ladinian succession of the Rute Plateau area reflects the complex sedimentary evolution of a small-scale marine basin. The interpretation relies on a conceptual model based on the spatiotemporal platform-basin relationships observed in the Southern Alps (Blendinger, 1986; Harris, 1994; Maurer, 2000; Emmerich et al., 2005; Preto et al., 2011). The model predicts two end-member sedimentary conditions. First, there are periods of increasing accommodation space within the basin. Since the platform/basin facies changes abruptly along the paleofauts, we attribute it to the intense differential subsidence. Because major paleofaults occur at an angle of approx. 70° to each other (forming romb-shapped blocks), this indicates a possible transtensional tectonic pattern (partially inverted during the Cenozoic). Similar tectonic conditions are described also from the Dolomites (e.g. Abbas et al., 2018; Gianolla et al., 2021).

Subsidence may have been accompanied by eustatic sea level rises recognised during the latest Anisian/earliest Ladinian, early Late Ladinian, and latest Ladinian of the Southern Alps (de Zanche et al., 1993; Gianolla et al., 1998, 2021). In the Rute Plateau area, tectonic activity was accompanied by volcanism. Under such conditions, the basin was filled with terrigenous and/or volcanogenic clay and volcanic sediments (F1). During these periods, the production of carbonate on the adjacent platform (located above the footwall) may have been hindered by the influx of volcanic material (cf. Wilson, 2000; Caron et al., 2019; Courgeon et al., 2016; Lokier, 2023). Although poor outcrops of platform carbonates do not allow for detailed studies, we propose that the platform aggraded (F4) during these periods, as observed in the Dolomites during relative sea-level rise (TST and early HST) (Maurer, 2000; Franceschi et al., 2020; Gianolla et al., 2021).

The second end-member of sedimentary conditions is marked by overall progradation of the carbonate platform. In the Southern Alps and the Transdanubian Range, a change from platform aggradation to progradation is attributed to relative sea-level changes, more specifically to the HST dated to the late Early Ladinian and late Late Ladinian (Gianolla et al., 1998; Haas and Budai, 1999; Budai and Vörös, 2006; Stefani et al., 2010; Haas et al., 2014). As shown by Gianolla et al. (2021), pronounced progradation can also occur during a sea-level lowstand, when the interior of the platform becomes subaerially exposed, but carbonate production continues on the platform margins and slopes. We can implement a similar scenario for the Rute Plateau area, but the decrease in accommodation space is certainly (also) related to the deceleration of tectonic and volcanic activity. It is evident from the fact that progading platform carbonates sealed a paleofault along which the main lateral platform/basin facies change is observed in the Early Ladinian.

The Ladinian successions are divided into four tectonic paleoblocks that are attributed to different positions at the transition between the platform area (represented by paleoblock 4) and the basin (paleoblock 1). The lack of good biostratigraphic markers does not allow for accurate dating of specific sedimentation events. However, detailed facies analysis (including logging of key sections) and detailed geological mapping (with spatial tracing of prominent strata) allow for the following interpretation of basin evolution, which can be divided into five stages.

5.1.1 1. Stage

First deepening of the Kobilji curek basin occurred during the early Ladinian, probably beginning during the Anisian-Ladinian boundary. The basin formed after a major tectonic differentiation of the paleotopography (accompanied by volcanism), which followed the deposition of the Anisian platform carbonates. The Anisian dolomite in the paleoblocks 1, 2, and 3 is overlain by volcaniclastics (F1) and carbonate resediments (F2), indicating subsidence of these paleoblocks. In paleoblock 4 (footwall), however, only the shallow marine carbonates were deposited.

During the initiation of differential subsidence, the footwall (later the central platform area) may have been subaerially exposed. The latter is inferred from a wider area because the lower contact of the Ladinian platform carbonates is not exposed in the mapped area. However, the Ladinian platform carbonates unconformably overlie the Early Triassic Werfen Formation about 2 km further SE (Fig. 1c; Buser, 1968). This indicates the erosion of Anisian platform carbonates prior to the installation of the Ladinian platform (Fig. 4). Subaerial exposure of the Anisian platforms in the footwall blocks is reported from the Southern Alps and the Transdanubian Range (de Zanche et al., 1993; Gianolla et al., 1998, 2021; Hass and Budai, 1999; Budai and Vörös, 2006; Stefani et al., 2010; Haas et al., 2014).

After the initial tectonic segmentation of the area, the platform was reinstalled and prograded over paleoblocks 2 and 3 (Fig. 5a). We note that the differences in the lateral thickness of the deeper marine deposits of these two paleoblocks point to their tilting during the initial subsidence. At the same time, the area above paleoblock 1 remained deeper marine. This indicates a paleofault between paleoblocks 1 and 2 (and the NNE-SSE paleofault between paleoblocks 1 and 3) as the most active during this stage. The slope area between the platform and basin was narrow and located above paleoblock 2, as massive limestone is often interbedded with carbonate resediments (logged in the Vrh section). The platform-basin relief was not as agitated as in the Southern Alps, which can be inferred from the relatively low thickness (up to 400 m) of the total Ladinian deposits in this part of the External Dinarides (Buser, 1968). However, the relief was high enough to produce carbonate gravity mass flow deposits that extend into the central basinal area. These deposits become more frequent and coarser upsection, which indicates a gradual transition to the second stage of basin evolution, i.e. platform progradation. In the carbonate sequence stratigraphy, this upward coarsening trend can be attributed to the early HST. On closer examination, the carbonate resediments are grouped into several intervals divided by volcaniclastic material and clays. Such alternation could be the consequence of several processes, e.g. high-frequency sea-level fluctuations, alternating volcanism and bioproductivity, and the instability of the slopes caused either by subsidence or increased bioproductivity.

5.1.2 2. Stage

First platform progradation is documented over the entire mapped area (Fig. 5b). In paleoblock 2, the massive (platform) limestone overlies a few beds of resedimented

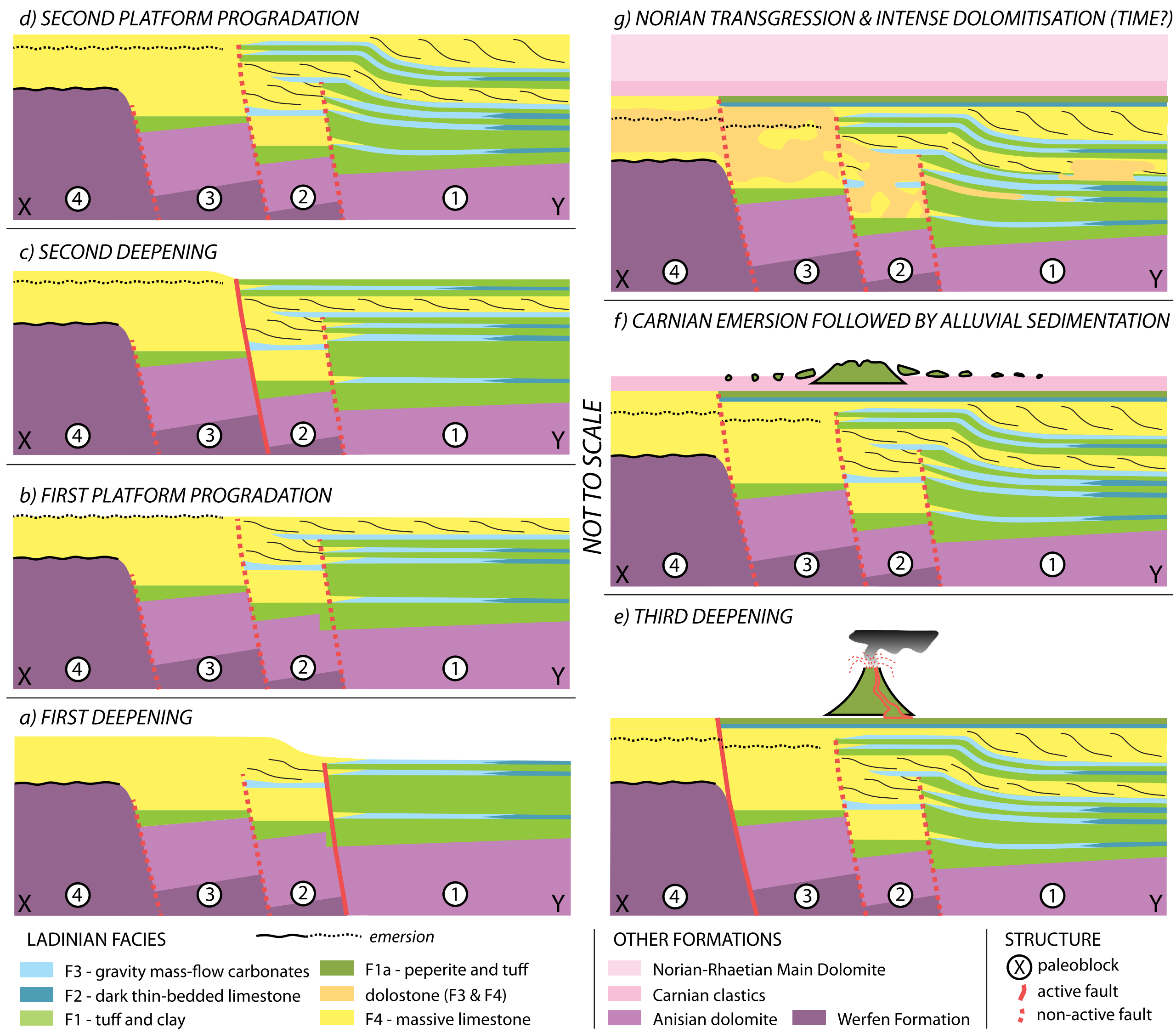

Fig. 5 Sedimentary evolution of the Kobilji curek basin during the Ladinian, divided into five stages (column on the left-hand side and bottom of the column on the right hand side) and evolution during the Carian and Norian (for the position of cross-section see Fig. 4.): **a** The first deepening involves paleoblocks 1, 2 and 3, while the less subsided area represemted by paleoblock 4 probably remains emerged. After this initial phase and the platform re-establishes itself over paleoblocks 2, 3 and 4, which indicates a main componenet of subsidence taking place during the rest of this stage along the paleofault located between paleoblocks 1 and 2. **b** During the second stage the platform progrades across the entire area and seals the fault between paleoblocks 1 and 2. **c** The second deepening (third stage) affects paleoblocks 1 and 2, indicating a tapered but slightly reorganized subsidence. d) The fourth stage is represented by a second overall platform progradation that again levels the entire area. **e** The following third deepening (fifth stage) is accompanied by nearby volcanism and certainly involves paleoblocks 1, 2 and 3. **f** During the Carnian, the surface of the area is flattened and is subsequently covered by continental fluvial sedimentation. **g** This is followed by general marine transgression in the Norian. Late diagenesis alters the thicker Ladinian limestone intervals (F3 and F4 facies)

carbonates. In the basinal succession (paleoblock 1), it begins with resediments (F3) that become progressively coarser upward, including the large Cipit boulders. Above this, the shallow marine carbonates (F4) are deposited throughout the area. Oncoidal rudstone from the topmost part of this interval might even indicate platform top deposits (e.g. Mercedes-Martín et al., 2013; Gianolla et al., 2021). Unfortunately, the exact direction of platform progradation could not be determined from the available data. It could be from the south, but also from the east, where paleoblocks 1 and 3 are in direct contact. Progradation from the north and west, where

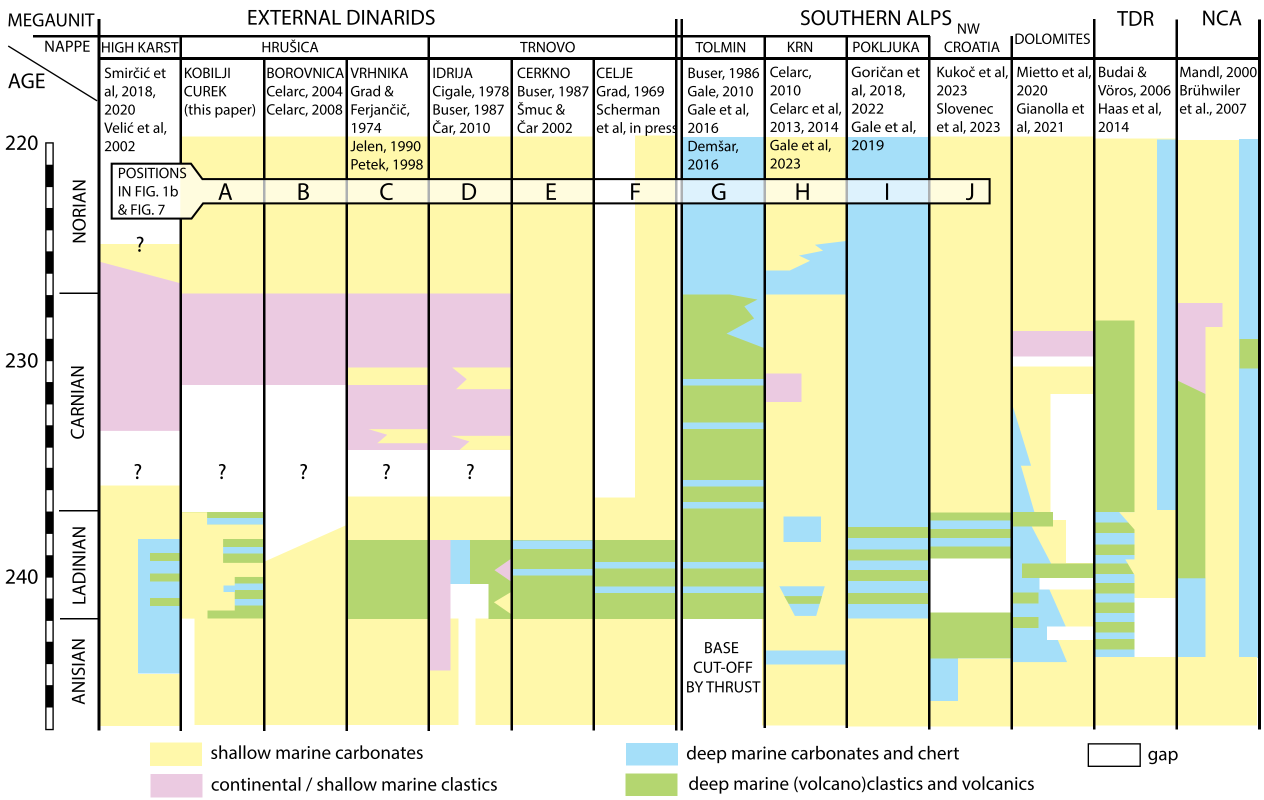

Fig. 6 Correlation of selected areas of the External Dinarides, Southern Alps, Northern Calcareous Alps (NCA) and Transdanubian Range (TDR): the Middle Anisian and Ladinian rifting event resulted in differential subsidence associated with volcanic activity over the entire NW part of the Adria microplate. In the northern part of the External Dinarides, the main tectonic activity is considered Ladinian in age (time scale after Cohen et al., 2013, updated)

the transition between the basin and the platform is not exposed, cannot be excluded. Considering the limited size of the basin, progradation from different directions also seems possible. The timing of progradation is probably end-Early Ladinian and thus correlates with the An5/La1 SB (Mietto et al., 2020; Gianolla et al., 2021). It could document the late HST phase (e.g. Maurer, 2000; Budai and Vörös, 2006; Stefani et al., 2010; Preto et al., 2011; Haas et al., 2014), but it seems possible that major platform progradation occurred during the sea-level lowstand, but was even more enhanced than described by Gianolla et al. (2021). During the lowstand, the interior of the platform would emerge. Unfortunately, this cannot be confirmed due to poor outcrops on the Rute Plateau. As mentioned above, the paleotopography of the Rute Plateau area was probably mild. During LST, the basinal area would have shallowed, possibly reaching even the photic zone. Together with the drastically reduced accommodation space, this would lead to the rapid progradation of the platform throughout the Rute Plateau area. As mentioned earlier, we do not completely exclude the possibility that this massive limestone interval could represent a 50 m thick breccia megabed, which would consist of huge limestone boulders in the upper part.

5.1.3 3. Stage

Second deepening is marked by a reorganisation of the fault system at the transition between the platform and the basin. The platform carbonates of the first progradation continue directly from paleoblock 2 to paleoblock 1, sealing the Lower Ladinian paleofault between these two blocks. Thereafter, the main differences in facies are observed between paleoblocks 2 and 3 (Fig. 5c). Platform carbonates (F4) continued to be deposited in paleoblock 4, while the slope was positioned within paleoblock 3. At the same time, in paleoblocks 1 and 2, we observe the identical basinal strata characterised by two intervals of volcaniclastics (F1) interbedded with an interval of coarse carbonate resediments (F3). The alternation can be explained by the same high-frequency sedimentary changes as before. In general, however, the tuffs are coarser than in the first deepening stage, most likely indicating that the volcanic sources were closer to the Kobilji curek basin. This deepening may be consistent with the TST of the La1 sequence of the Southern Alps (Mietto

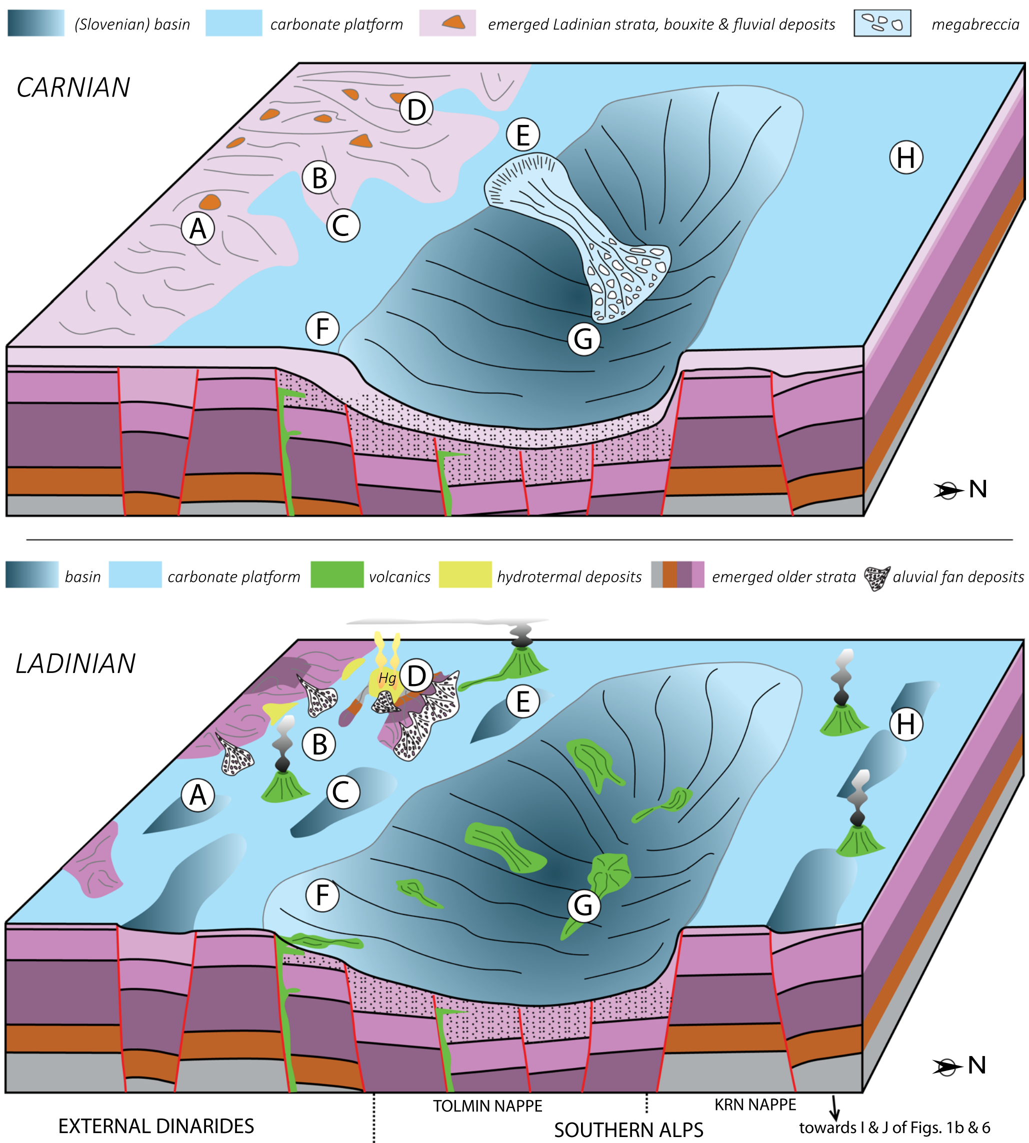

Fig. 7 Simplified paleogeographic reconstruction of the future Alps-Dinarides junction area (view is from the east and the Bled Basin succession in the Pokljuka Nappe (highest thrust-unit of the eastern Southern Alps) is not included in the figure): In the Ladinian the entire area was subjected to differential subsidence and accompanied by volcanic activity. In the south (present day Dinarides), lateraly diverse sedimentary environments developed, including subaerially exposed ares, platforms, and small-scale basins. The greatest subsidence occurred in the central area (present day Tolmin Nappe of the Southern Alps); to the north (present day Krn and Slatna Nappes of the Southern Alps); however, carbonate platforms dominated. In the Carnian, the southern and northern areas were levelled, while the central area remained deep (see also Additional file 3), thus forming the largest and long-lived deep marine paleogeographic unit known as the Slovenian Basin, which pinched out towards the west

et al., 2020; Gianolla et al., 2021). Rapid facies changes along the paleofault between paleoblocks 2 and 3 suggest that the deepening was governed by a rejuvenated subsidence. Increased tectonic subsidence at the base of the La1 sequence was recognized also in the Transdanubian Range, particularly in the Veszprém area, where a similar vertical alternation of the platfrom-basin sediments has been documented (Haas and Budai, 1999; Budai and Vörös, 2006). Increased early Upper Ladinian subsidence and volcanism are reported also from the Dolomites (Abbas et al., 2018, Gianolla et al., 2021).

5.1.4 4. Stage

Second platform progradation follows, again covering the entire area and resembling the first progradation (Fig. 5d). Namely, in the basinal succession (paleoblocks 1 and 2), it starts with coarse resediments (F3), which pass over boulder-bearing breccias into massive platform limestone/dolostone (F4). As with the first progradation, the direction of progradation is not univocal. The thickness of this platform limestone increases basinward and is greatest in the Kobilji curek section, where it reaches 100 m. We interpret this to be related to the filling of the existing paleotopography, but it could also be related to the compaction of the underlying clay-rich basinal strata of paleoblock 1, which increased the accommodation space in this tectonic block. The time of the progradation is probably the Late Ladinian and correlates with the HST intervals of the La1 sequence of the Southern Alps (Stefani et al., 2010; Gianolla et al., 2021) and the Transdanubian Range (Budai and Vörös, 2006).

5.1.5 5. Stage

Third deepening is documented throughout most of the area, and in fact the succession is uniform in paleoblocks 1, 2, and 3 (Fig. 5e). This starts with thin-bedded limestone (F1), which still contains some carbonate resediments (F3) in the basal part but becomes very micritic towards the top (distal). Further up, coarse tuffs and probably also rhyolite layers are overlain. These, together with lapilli/pumice clasts in the uppermost part of the thin-bedded limestone, indicate volcanic activity at the gates of the Kobilji curek basin.

In paleoblock 4 the Ladinian is represented exclusively by platform carbonates (F4). Again, the facies change along the paleofault between paleoblocks 3 and 4 is abrupt. However, it is not clear whether the sedimentary environment above this paleoblock did not deepen along with the rest. Namely, the fault could also be activated later in the Carnian, and erosion would remove the uppermost part of the succession prior to the deposition of the red alluvial clastites (Fig. 5f) and the following Hauptdolomit (Fig. 5g). The age of the third deepening stage is not resolved (see next chapter for further discussion), but probably corresponds to the TST of the La2 sequence dated to the latest Ladinian in the Southern Alps (Mietto et al., 2020; Gianolla et al., 2021).

5.2 Regional correlation

In the past, all Ladinian deeper marine successions in Slovenia were considered part of the Slovenian Basin, leading to somewhat simplified paleogeographic reconstructions of the area (Buser, 1989; Buser et al., 2008). The Ladinian of the Slovenian Basin is characterized by the Pseudozilje (Pseudogaital) formation, which consists of shales, volcaniclastics, volcanites, hemipelagic limestone, and coarse carbonate gravity flow deposits (Teller, 1885, 1889; Kossmat, 1913; Rakovec, 1950; Demšar, 2016). Although a similar succession is observed also in the deeper marine intervals of the Kobilji curek basin, there is a crucial difference in the overall succession. While in the Slovenian Basin the deep marine strata continue to be deposited until the end of the Cretaceous, in the Kobilji curek basin they alternate with platform carbonates and are overlain by Carnian red clastics. (Fig. 6). This defines the Kobilji curek basin as a relatively small intraplatform basin, formed at the beginning of the Ladinian and filled before the middle Carnian. It was one of the small-scale basins formed within the laterally highly diverse Ladinian continental and marine sedimentary environments, and the large uplifted, subaerially exposed areas of the present-day northern External Dinarides (Fig. 7). With the exception of the Kobilji curek basin, all other basins are covered by Late Ladinian carbonate platform deposits (Fig. 6) (Buser, 1986, 2010; Šmuc & Čar 2002; Čar, 2010); but all, including the Kobilji curek basin, are overlain by Carnian continental clastics. The latter start to interfinger with shallow marine carbonates to the north (Cigale, 1978; Jelen 1990; Buser and Dozet, 2009), while in the Sava Folds (northwestern External Dinarids) the Ladinian platform carbonates continue into the Carnian, or are characterized by major unconformity (Fig. 7; Additional file 3) (Buser, 2010; Scherman et al., in press).

Further north, i.e. beyond the Southalpine thrust front (and in klippen in the eastern Sava Folds), the Carnian is characterized by the deep marine "Amficlina beds" of the Slovenian Basin. This formation resembles the Pseudozilje formation, but does not contain synsedimentary volcanics (Buser, 1989, Demšar, 2016, Gale et al., 2016, 2017). Short-lived, laterally discontinuous (Upper Anisian and) Ladinian basins similar to those of the External Dinarides are also known from the Krn Nappe of the eastern Southern Alps, otherwise dominated by Julian Carbonate Platfrom deposits (Jurkovšek, 1984; Celarc, 2010; Celarc et al., 2013; Gale et al., 2023). In this context, we also mention the continuous Ladinian-Early Cretaceous deep marine succession of the Bled Basin located within the Pokljuka Nappe (highest thrust-unit of the eastern Southern Alps). This succession was positioned on the ocean side of the Julian Carbonate Platfrom and is dominated with (hemi) pelagic and resedimented limestones with volcaniclastic intercalations in the Ladinian (Goričan et al., 2018, 2022; Gale et al., 2019).

In the Alps-Dinarides region, the Kobilji curek succession correlates with the Buchenstein Formation in the Southern Alps (Brack et al., 2000; Brack et al., 2005, 2007; Celarc et al., 2013; Wotzlaw et al., 2017; Storck et al., 2018; Lustrino et al., 2019) and the Balaton Highland (Budai & Vörös, 1992), the Vászoly and Buchenstein Formations in the Transdanubian Range (Budai & Vöros, 1993, 2006; Karadi et al., 2022), the volcano-sedimentary deposits in NW Croatia in the southernmost part of the Southern Alps (Goričan et al., 2005; Slovenec et al., 2023; Kukoč et al., 2023), the volcano-sedimentary deposits in the External Dinarides (Jurkovšek, 1984; Skaberne et al., 2003; Smirčić et al., 2018, 2020), and to some extent with the upper part of the Reifling Formation in the Northern Calcareous Alps (Brühwiler et al., 2007). In contrast to these examples, the succession of the Kobilji curek basin shows a successive repetition of basin deepening followed by complete platform progradation, indicating a rather small-scale and low relief basinal area.

The scarcity of biostratigraphic data makes the correlation with the bio-chrono-stratigraphic scheme of the Middle Triassic succession of the Southern Alps (Gianolla et al., 1998; 2021; Mietto et al., 2020) more ambiguous. However, the working hypothesis is that the first platform progradation corresponds to the progradation of the Sciliar (Schlern) Formation during the Fassanian (depositional sequence An5; *Eoprotrachyceras* and lower part of the *Protrachyceras* ammonoid zones in Mietto et al., 2020), while the second platform progradation matches the progradation of the Sciliar (Schlern) Formation during the Longobardian (depositional sequence La1; *A. neumayri* subzone of the *Protrachyceras* ammonoid zone in Mietto et al., 2020).

The age of the third subsidence and volcanism in the Kobilji curek basin is not constrained, but the facies characteristics of the thin-bedded limestone with abunadant *Bositra* (formerly *Posidonia*) sp. shells could still point to the Ladinian, as such facies is characteristic of this stage (Jurkovšek, 1984; Buser, 1996; Čar, 2010; Dozet & Buser, 2009). It could correspond to the latest Ladinian onset of sedimentation of the Wengen Formation in the Dolomites (depositional sequence La2; initiating within the *"F." regoledanus* of the *Protrachyceras* ammonoid zone in Mietto et al., 2020). The possible corresponding deepening of the sedimentary environment (subsidence) is documented in thin-bedded dolomites occurring above massive carbonates of the Schlern Formation in the Idrija region in Dinarides (Čar, 2010) as well as in the platy limestone of the Korošica Formation from the eastern Southern Alps (Jurkovšek, 1984; Celarc, 2010). The age of the volcanism overlying the thin-bedded limestone in the Kobilji curek basin is also not yet clear. In the Dinarides, Triassic volcanism is generally considered to be Ladinian in age (Buser, 1996; Smirčić et al., 2018; Gianolla et al., 2019), but some geochronological data from the Alps, Transdanubian Range, and Dinarides also suggests Upper Triassic activity (Neubauer et al., 2014; Kövér et al., 2018, Dunkl et al., 2019). The potential geochronological dating of tuffs from the Kobilji curek basin would therefore consolidate the chronostratigraphic framework of certain developmental stages of the basin.

6 Conclusions

The Kobilji curek basin formed at the beginning of the Ladinian through a rifting event associated with the opening of the Neothetys Ocean. In the studied area, the transition from the carbonate platform to the deeper marine basin could be documented. During periods of intense subsidence, the basin was filled with volcanogenic sediments (tuffs and clays) and hemipelagic limestone, while laterally the massive platform carbonates were deposited. Gravity mass flow carbonates were shed from the platform margin and slope and can be traced throughout the basin. Twice, during pronounced reduction of accommodation space (subsidence deceleration and/or sea-level lowstand), the platform prograded across the entire area (probably correlating with the An5/La1 and La1/La2 SBs of the Southern Alps). However, the basin area deepened again during rejuvenated subsidence (probably accompanied by sea-level rise).

Four tectonic paleoblocks were defined in the study area. To the NW was the main basin (paleoblock 1), which transitioned to the carbonate platform (to the E and S–paleoblock 4) via two paleoblocks dominated by platform carbonates but also exhibiting slope characteristics. During the first deepening stage, the most prominent facies change occurred along the paleofault between paleoblocks 1 and 2. During the second deepening stage, it shifted towards the central platform area, along the paleofault between paleoblocks 2 and 3, indicating partial tectonic reorganisation of the platform-basin system. The third deepening is uniform almost throughout the study area and follows the trend of long-term platform retreat described above. During the Carnian, the entire area was uplifted and continental clastics sedimented, levelling the paleotopography, and after transgression at the beginning of the Norian the Hauptdolomit formation began to be deposited throughout the region.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s00015-023-00449-w.

Additional file 1. Detailed sedimentological sections of the Kobilji curek basin.

Additional file 2: Micrographs of particular microfacies.

Additional file 3: Geological map of Slovenia with Ladinian—Carnian strata and major structural elements

Acknowledgements

The research was financially supported by the Slovenian Research Agency (research core funding No. P1-0195 and No. P1-0011). are thanked for their thorough review of the manuscript. Christopher McRoberts is acknowledged for the cross-check of pelagic bivalves. We thank Jeff Bickert for his copy edit of the text. Students of the Department of Geology, University of Ljubljana, are acknowledged for their assistance during the geological mapping. This paper is dedicated to our deceased collegues Bogomir Celarc, who encouraged the research and student Klavdija Prašnikar, who was involved in the mapping campaign.

Author contributions
BR: geological mapping, geological map interpretation, section logging, microfacies analysis, main writing. Anja KPV: geological mapping, section logging, microfacies analysis LG: geological mapping, section logging, microfacies analysis, determination of foraminfera. NZ: microfacies of volcaniclastic material. TKJ: determination of conodonts. Tomislav Popit, PŽR, RB: geological mapping.

Funding
The research was financially supported by the Slovenian Research Agency (research core funding No. P1-0195 and No. P1-0011.

Availability of data and materials
All data is available on request, materias are stored at the Department of geology, Faculty of Natural Sciences and Engineering, University of Ljubljana (thin sections, samples), and Geological survey of Slovenia (conodonts).

Declarations

Ethics approval and consent to participate
There is no ethics problem about our researc and we consent to paricipate.

Consent for publication
We consent for publication.

Competing interests
There are no competing interests.

Received: 5 June 2023 Accepted: 12 December 2023
Published online: 08 March 2024

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