GEOLOGIJA 67/1, 71-103, Ljubljana 2024

https://doi.org/10.5474/geologija.2024.005

Middle Triassic deeper-marine volcano-sedimentary successions in western Slovenia

Srednjetriasna globljemorska vulkansko-sedimentna zaporedja v zahodni Sloveniji

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Prejeto / Received 12. 2. 2024; Sprejeto / Accepted 7. 5. 2024; Objavljeno na spletu / Published online 11. 6. 2024

Key words: stratigraphy, carbonate-siliciclastic deposits, Slovenian Basin, Middle Triassic, Ladinian, Carnian, Pseudozilja formation, Amphiclina formation
Ključne besede: stratigrafija, karbonatno-siliciklastični sediment, Slovenski bazen, srednji trias, ladinij, karnij, psevdoziljska formacija, amfiklinska formacija

Abstract

A Ladinian – Carnian volcano-sedimentary succession from western Slovenia, paleogeographically belonging to the western Slovenian Basin, is presented in 17 sections. Except for the lowermost part, which is dominated by volcanics and volcaniclastics, most of the succession is dominated by shale, sandstone, and micritic limestone. Various authors use the name Pseudozilja and/or Amphiclina formation for this part, which is dominated by clastics, but they disagree on the differences between the formations. The lower Pseudozilja formation, represented by the Malenski Vrh section, comprises diabase, tuf and shale. No substantial differences in lithological composition have been observed between the upper Pseudozilja formation and the Amphiclina formation, which are predominantly composed of shale, sandstone, and limestone. The shale and sandstone are largely composed of quartz, feldspar, and lithic grains (especially volcanics), which vary in proportions. Limestone varieties comprise hemipelagic limestones and resedimented carbonates deposited by gravity-flows. Deposition of the Ladinian – Carnian volcano-sedimentary succession took place on or near the continental slope that was generally inclined to the S, with the direction of transport mainly from N to S.

Izvleček

V članku v 17 profilih predstavljamo ladinijsko – karnijsko vulkansko-sedimentno zaporedje zahodne Slovenije, paleogeografsko umeščeno v zahodni del Slovenskega bazena. Spodnji del psevdoziljske formacije, posnet na Melenskem vrhu, sestavljajo diabaz, tuf in laminiran muljevec. Zgornji del psevdoziljske formacije in amfiklinska formacija sta litološko identična. V večjem delu ju sestavljajo laminiran muljevec, peščenjak in apnenec. Glavne sestavine muljevca in peščenjaka so kremen, glinenci in litična zrna (predvsem predornin) v različnih razmerjih. Apnenec obsega hemipelagični apnenec in resedimentirane karbonate. Sedimentacija ladinijsko – karnijskega vulkansko-sedimentnega zaporedja je potekala na ali v bližini kontinentalnega pobočja z nagibom proti jugu. Transport sedimenta je v glavnem potekal od severa proti jugu.

Introduction

The time range and paleogeographic extent of the Slovenian Basin, a deeper marine sedimentary basin situated on the western Tethyan margin, is based on a succession of open-marine Mesozoic rocks, which today are exposed between Tolmin in western Slovenia and Neogene sediments of the Central Paratethys in eastern Slovenia (Buser, 1989, 1996; Buser et al., 2008). The lowermost/oldest rocks of the Slovenian Basin are volcanics (rhyolite, diabase, and basalt), tuffs, volcaniclastic sandstone, feldspar-quartz-lithic sandstone and shale with intercalations of conglomerate, muddy conglomerate and breccia, bedded hemipelagic limestone, and carbonate olistoliths (bioherms?) (Stur, 1858; Teller, 1885, 1889; Kossmat, 1901, 1910, 1913; Winkler, 1936; Rakovec, 1950; Ramovš, 1970; Grad & Ferjančič, 1976; Placer & Čar, 1977; Čar et al., 1981; Turnšek et al., 1982; Buser, 1986; Šmuc & Čar, 2002; Dozet & Buser, 2009;

Demšar, 2016; Gale et al., 2016; Čar et al., 2021). While some authors (e.g. Turnšek et al., 1982; Buser, 1986) distinguished between the Ladinian (informal) Pseudozilja (also Pseudozilian, Pseudogailtal) formation and the Carnian Amphiclina formation based on the presence or, respectively, absence of volcaniclastics, others argue that the entire succession should be treated as one, that is, as the Pseudozilja formation (e.g., Čar et al., 1981, 2021). We note here that although neither name follows modern stratigraphic standards, the International Stratigraphic Guide states that "traditional or well-established names /…/ should not be abandoned, providing they are or may become well defined or characterized" (Murphy & Salvador, 19.06.2023). The lower part of the volcano-sedimentary succession is relatively poorly dated. The succession rests unconformably on Lower Triassic shallow-water deposits or, more commonly, its base is tectonically cut-off. Rare fossil finds (bivalves) from tuff beds suggest that deeper-water sedimentation in the Slovenian Basin started in the Ladinian (Teller, 1889; Jurkovšek, 1984; Buser, 1986). However, the deepening could already have begun in the late Anisian during the regional extension of the crust and the formation of horst-and-graben relief (e.g. Buser, 1989; Gianolla et al., 1998a; Celarc et al., 2013; Smirčić et al., 2020).

The uppermost part of the investigated succession is represented by interchanging beds of dark limestone and shale dated with conodonts as late Carnian (Tuvalian) in age (Buser & Krivic, 1979; Kolar-Jurkovšek, 1982, 1990; Demšar, 2016). After a few meters, this transitional interval gives way to bedded dolostone with chert nodules known as the (also informal) Bača dolomite (i.e. dolostone) formation (Kossmat, 1901; Buser, 1986; Gale, 2010). In the more proximal settings, earlier (i.e. late Ladinian or early Carnian) transition to platform carbonates has been recorded (Čar et al., 2021).

With a combined thickness of 600 m (estimation based on profiles on geological maps; Buser, 1986; Demšar, 2016), the Pseudozilian/Amphiclina formations represent a notable zone of rheological weakness, along which important thrusting took place during the formation of the Alps (Placer & Čar, 1998; Placer, 1999; Placer et al., 2000). From the stratigraphic point of view, this succession is a sedimentary record of the early evolution of the Slovenian Basin, bearing information about the paleogeography, paleoclimate, and oceanographic conditions in this part of the Tethys during the Ladinian and Carnian. Due to the absence of data on the biostratigraphic and radiometric age, the lack of known and described sedimentary sections as well as abrupt lateral and vertical changes in lithologies, however, we have yet to find the key to access such information.

The purpose of the present paper is to show the lithological composition of the volcano-sedimentary succession lying below the Bača dolomite formation. Some of the sections end with the transition to the Bača dolomite formation and thus have a well-known stratigraphic position. For others, we have no biostratigraphic or other data to determine the age; these were stratigraphically positioned based on the geological map (Buser, 1987; Demšar, 2016).

Methods

The Middle – lower Upper Triassic volcano-sedimentary succession of the Slovenian Basin was logged in 17 sections from 13 localities. Sections were logged between the years 1982 and 1990 by authors D.S. and J.Č. at scales of 1:50, 1:100 and 1:500. Approximately 270 thin sections were made for more detailed investigation under a polarizing petrographic microscope. Carbonates were classified according to Dunham (1962), modified by Wright (1992), and Lokier and Junaibi (2016). The terminology of the volcanically derived deposits follows Di Capua et al. (2022). In addition to thin section analysis, 38 samples of fine-grained clastic rocks were investigated using a Philips X-Ray Diffractometer with vertical goniometer and monochromator with a Cu cathode, Cuαk-0,1542 nm, powered up to 40 kW and 20 mA.

Structural setting and stratigraphic position of the sections

The logged sections lie between Železniki in the east, Koritnica in the west, and Cerkno in the south (Figs. 1–2; Table 1). In addition, Figure 1 also shows the positions of previously documented sections at Vrh Bače (Gale, unpubl. 2012), Crngrob (Gale et al., 2017), and Martinj Vrh (Pristavec et al., 2021). Except for the Malenski vrh section, which structurally lies in the Trnovo Nappe that belongs to the External Dinarides, all the other presented sections belong to the Tolmin Nappe of the eastern Southern Alps, more precisely to the Podmelec subnappe (Table 1). The Vrh Bače, Crngrob, and Malenski Vrh sections are structurally positioned in higher Kobla and Rut subnappes of the Tolmin Nappe, respectively.

Both the External Dinarides and the Tolmin Nappe of the Southern Alps are marked by the NE to SW thrusting that took part approximately from the Oligocene to the early Miocene (Vrabec

& Fodor, 2006). Later in the Miocene, the area of the Southern Alps experienced N-S to SE-NW-directed compression, which additionally resulted in the formation of S- to SE-verging folds and thrusts (Vrabec & Fodor, 2006). On a more detailed level all of the mentioned nappes further contain inner thrust blocks and smaller inner thrust-sheets, particularly at the transition between the Southern Alps and the Dinarides (Placer & Čar, 1998; Čar et al., 2021). Younger tectonic deformations of the area include local extension along NW-SE-trending normal faults that were reactivated as dextral strike-slip faults that today displace both sets of older folds and thrusts (Fig. 3) (Placer & Čar, 1998; Vrabec & Fodor, 2006).

The stratigraphic position of the presented sections is taken after Demšar (2016) and/or the lithological composition of the sections. According to Demšar (2016), the lower part of the Ladinian – lowermost Carnian Pseudozilja formation consists of volcanics laterally and vertically passing into shale and tuff. Bedded limestone is subordinate and intercalated among volcanics. The higher part of the Pseudozilja formation is represented by volcanoclastic sandstone, shale, conglomerate, tuff, and subordinate bedded and massive limestone. The Carnian Amphiclina formation is defined by the same lithologies, except for the absence of tuff. In the upper part, the Amphiclina formation is mostly shale, sandstone, and quartz-carbonate lithic sandstone, with the addition of limestone, conglomerate, and breccia. The latter two locally contain abundant matrix. Nearing the transition into the Bača dolomite formation, the uppermost Amphiclina formation mostly comprises interchanging beds of limestone and shale (Demšar, 2016).

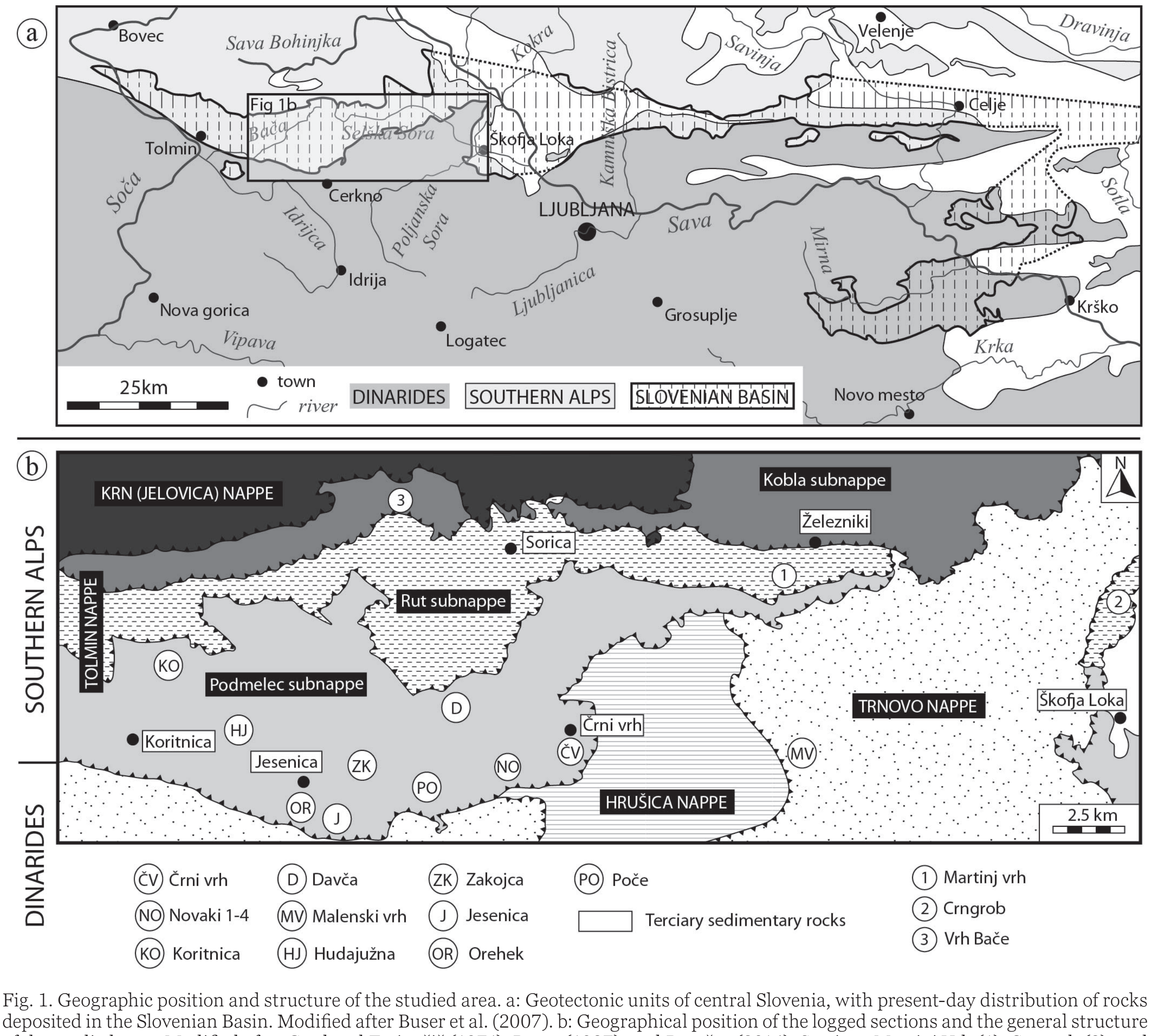

Fig. 1. Geographic position and structure of the studied area. a: Geotectonic units of central Slovenia, with present-day distribution of rocks deposited in the Slovenian Basin. Modified after Buser et al. (2007). b: Geographical position of the logged sections and the general structure of the studied area. Modified after Grad and Ferjančič (1974), Buser (1987), and Demšar (2016). Sections Martinj Vrh (1), Crngrob (2), and Vrh Bače (3) were previously investigated by Pristavec et al. (2021), Gale et al. (2017), and Gale (2012, unpubl.), respectively.

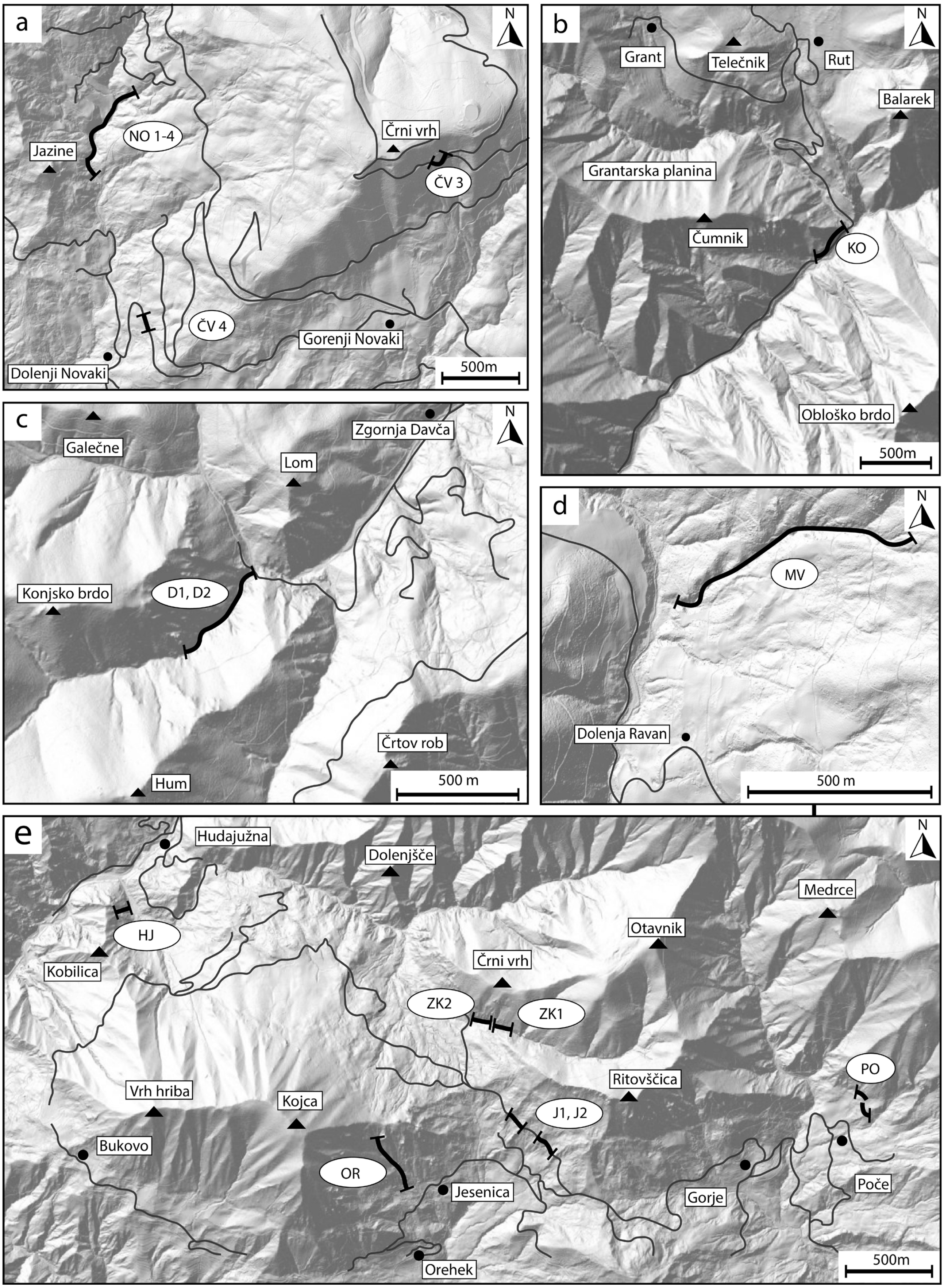

Fig. 2. Detailed position of the studied sections. **a:** Sections Novaki (NO 1–4), and Črni Vrh (ČV 3, ČV 4). **b:** Section Koritnica (KO). c: Sections Davča (D1, D2). d: Section Malenski Vrh (MV). e: Sections Hudajužna (HJ), Zakojca (ZK 1, ZK2, ZK 3), Jesenica (J1, J2), Orehek (OR), and Poče (PO). LIDAR digital model of the relief, 2015. Source: Slovenian Environment Agency. Accessed via portal Geopedia (Sinergise d.o.o.) in May 2023. For geographic coordinates see Table 1.

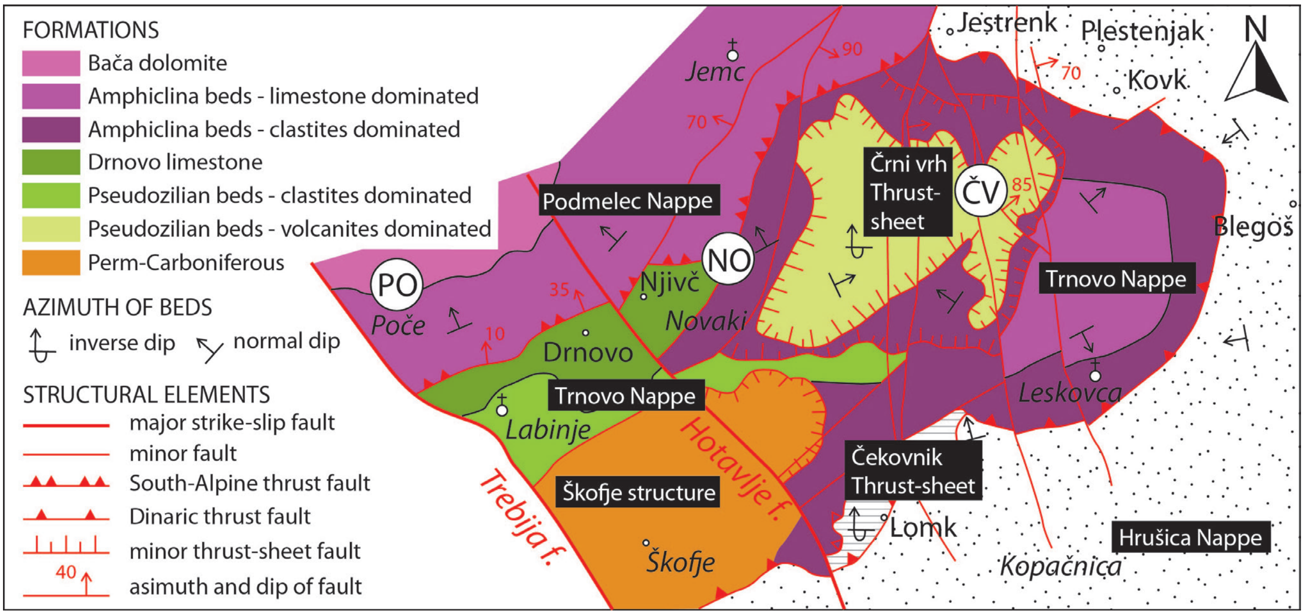

Fig. 3. Example of the minor thrust-sheet near Črni Vrh (coloured green) that is positioned just above the main South-Alpine Thrust Fault and characterized by partly overturned beds (for abbreviations of logged sections see Fig. 1). Note that in older publications (e.g., Placer & Čar, 1998; Placer, 1999, 2008) the structural unit marked here as the Trnovo Nappe was considered a thrust-sheet within the Hrušica Nappe.

Description of sections

Descriptions of logged successions are ordered according to their stratigraphic position (Table 1), starting with the lower part of the Pseudozilja formation and ending with the uppermost part of the Amphiclina formation sensu Demšar (2016). The stratigraphic position of the sections Jesenica 1 and 2 is ambiguous; they could represent either the upper part of the Pseudozilja formation or the lower part of the Amphiclina formation. Most of the sedimentary rocks of the Pseudozilja/Amphiclina formation are medium to dark grey, nearly black, so their colour will not be recorded in the subsequent description of the logged sections. The general aspect of the Pseudozilja/Amphiclina formations is shown in Figure 4.

Section	Stratigraphic position	Start of section	End of section	Structural position
Malenski Vrh	Lower & upper Pseudozilja fm.	46°9’18.41”N, 14°8‘30.84“E	46°9’23.54”N, 14°8‘58.73“E	External Dinarides (Malenski vrh klippe)
Črni Vrh 3 (in inverse position)	Upper Pseudozilja fm.	46°9’43.86”N, 14°3‘47.80“E	46°9’46.22”N, 14°3‘51.12“E	
Črni Vrh 4 (in inverse position)	Upper Pseudozilja fm.	46°9’43.86”N, 14°3‘47.80“E	46°9’46.22”N, 14°3‘51.12“E	
Jesenica 1	Upper Pseudozilja/lower Amphiclina fm.	46°9’14.49”N, 13°56‘58.45“E	46°9’10.96”N, 13°57‘2.76“E	
Jesenica 2	Upper Pseudozilja/lower Amphiclina fm.	46°9’8.57”N, 13°57‘10.45“E	46°9’3.30”N, 13°56‘41.89“E	
Novaki 1–4	Lower Amphiclina fm.	46°9’40.65”N, 14°2‘16.86“E	46°9’56.28”N, 14°2‘26.47“E	
Davča 1–2	Upper Amphiclina fm.	46°10’29.26”N 13°59‘59.93“E	46°10’19.30”N 13°59‘47.62“E	Southern Alps, Tolmin Nappe, Podmelec subnappe
Poče	Upper Amphiclina fm.	46°9’15.12”N, 13°59‘13.77“ E	46°9’21.29”N, 13°59‘7.99“E	
Zakojca 1	Upper Amphiclina Fm.	46°9’37.56”N, 13°56‘59.27“E	46°9´39.06”N, 13°56‘53.37“E	
Zakojca 2	Upper Amphiclina Fm.	46°9’39.24”N, 13°56°44.74“E	46°9’43.66”N, 13°56‘46.52“E	
Orehek	Upper Amphiclina fm.	46°8’52.23”N, 13°56‘19.35“E	46°9’7.67”N, 13°56‘7.68“E	
Hudajužna	Upper Amphiclina fm.	46°10’5.57”N, 13°54‘29.60“E	46°10’6.79”N, 13°54‘35.73“E	
Koritnica (in inverse position)	Upper Amphiclina fm.	46°11’43.41”N, 13°53‘41.82“E	46°11’36.44”N, 13°53‘31.32“E	

Table 1. Geographic coordinates, structural and stratigraphic position of the studied sections (see text).

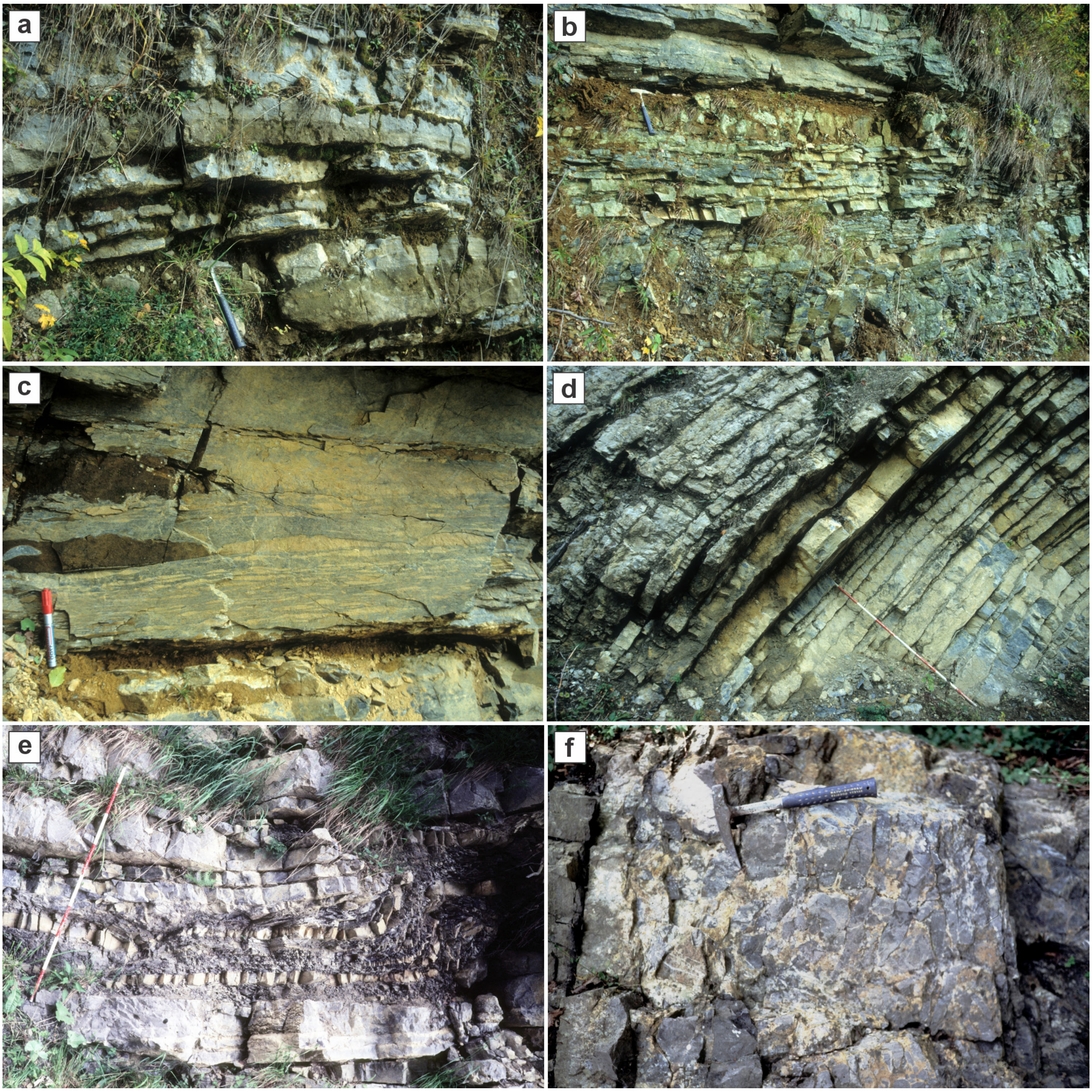

Fig. 4. Lithofacies of the Ladinian – Carnian volcano-sedimentary succession of the Slovenian Basin (Pseudozilja and Amphiclina formations sensu Demšar, 2016). **a:** Limestone interbedded with shale. Davča 1, 0.2–1.2 m. **b:** Interchange of shale-dominated heterolithic intervals with conglomerate and sandstone beds. Davča 1, 18.5 m. **c:** Lenticular bedding and ripple marks; sandstone interbedded in shale. Davča 1, 24.0 m. **d:** Transition from uppermost Amphiclina formation (right side of the picture) to the Bača dolomite formation (left side of the picture). Davča 2, 14.5–17.0 m. **e:** Sindepositional fold (slump). Interchange of calcarenite and shale. Koritnica 1, 45–46.3 m. **f:** Blocky limestone conglomerate. Koritnica 1, 33.0 m.

Pseudozilja formation (Malenski Vrh)

The Malenski Vrh section includes the lowermost part of the Pseudozilja formation and its clastics-dominated upper part. The entire volcano-sedimentary succession on the western slope of Malenski Vrh unconformably overlies Lower Triassic oolitic limestone (Fig. 5; also see Skaberne & Čar, 1986). The lowermost part of the Pseudozilja formation consists of 25 m of diabase with vacuoles filled by calcite and chlorite, followed by lithoclastic-crystalloclastic tuff with intercalations of diabase that is pyritized in places. The diabase and tuff unit is approximately 190 m thick and is 35 % covered. It is followed by a succession of siliciclastic and carbonate rocks 260 m thick. The lower part of this interval, approximately 170 m thick, is partly covered and shale dominated, with rare thin interlayers and lenses of sandstone and limestone (mostly wackestone, subordinate pack- and grainstone). Approximately 90 m from the start of the siliciclastic and carbonate unit, which is dominated by shale, a lens-shaped body of pebbly sand-

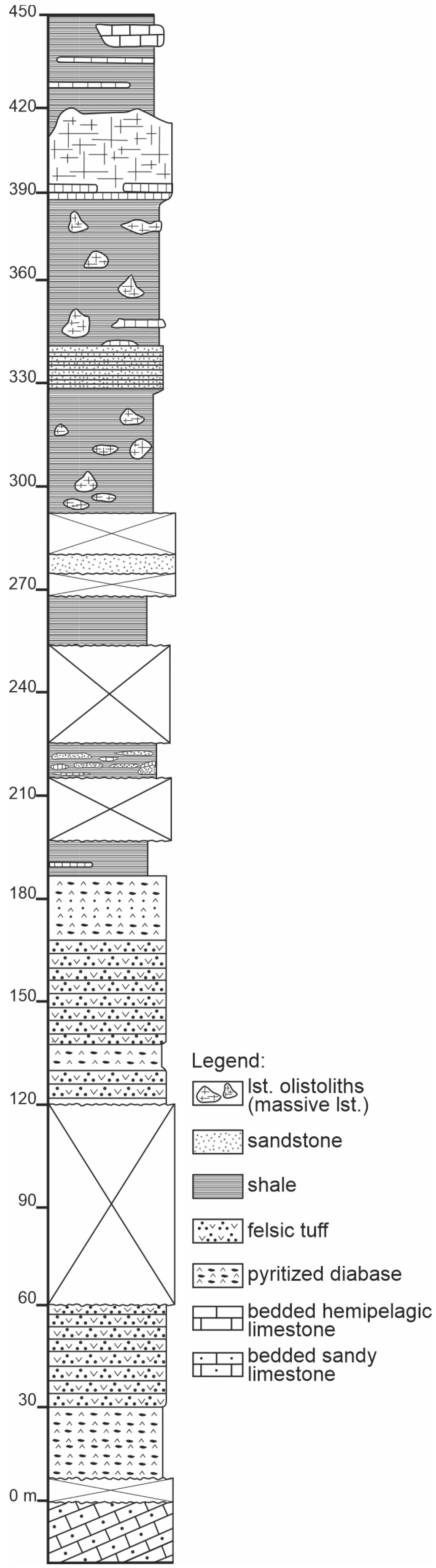

Fig. 5. Sedimentary log of the Malenski Vrh section. The section was logged schematically.

stone is recorded. It is characterised by a sharp, erosive lower boundary, and reaches up to 7 m in thickness. The sandstone consists mostly of feldspar, very altered volcanic lithic fragments, and quartz grains, with some chlorite and muscovite floating in quartz-sericite matrix and corrosion calcite cement. Approximately 160 m thick succession of shale follows. Locally, up to 25 m thick blocks of massive, in the lower part bedded limestone are present within the shale. No deformations around the massive limestone bodies were observed. Shale consists of 28–41 % of quartz, 6–15 % of feldspar, 19–34 % of muscovite /illite, 17–37 % of chlorite, and 0–26 % of calcite.

Upper Pseudozilja formation (Črni Vrh 3–4)

The sections Črni Vrh 3–4 are in overturned position. They are structurally situated in the Črni Vrh internal thrust sheet, in the tectonic zone between the Southern Alps and the External Dinarides. Approximately 12 m of the Pseudozilja formation recorded in the Črni vrh 3 section represent a fining-upward succession (Fig. 6). The lower part of the section displays normally graded sequences of conglomerate, upwards transitioning into coarse-grained sandstone with shale rip-up clasts. Conglomerates have erosive lower bedding planes. Pebbles in conglomerate are flattened, partly imbricated, and largely represented by rhyolites, felsic tuffs, and subordinate quartz grains. The last conglomerate bed overlies a 0.8 m bed of micritic limestone, laterally passing into shale. The top of the section is represented by sandstone, passing into shale. All coarser-grained beds are normally graded.

The Črni Vrh 4 section was logged in an abandoned quarry and stratigraphically lies above the Črni Vrh 3 section. The Črni Vrh 4 section comprises 43.6 m of the upper Pseudozilja formation, principally sandstone and conglomerate, intercalated with shale. Conglomerate mostly contains pebbles of rhyolites, felsic tuffs, subordinate quartz, and locally rip-up shale clasts. Several fining- and thinning-upward conglomerate-sandstone sequences can be recognized, each measuring 0.4–5 m in thickness. Sequences from the lower part of the section are thicker and are amalgamated or with thin intervals of shale in places. The sequences from the upper part of the section are finer-grained and thinner. The fine-grained part of sequences mostly consists of heterolithic intervals with 60–70 % of the interval consisting of fine-grained sandstone and 30–40 % shale.

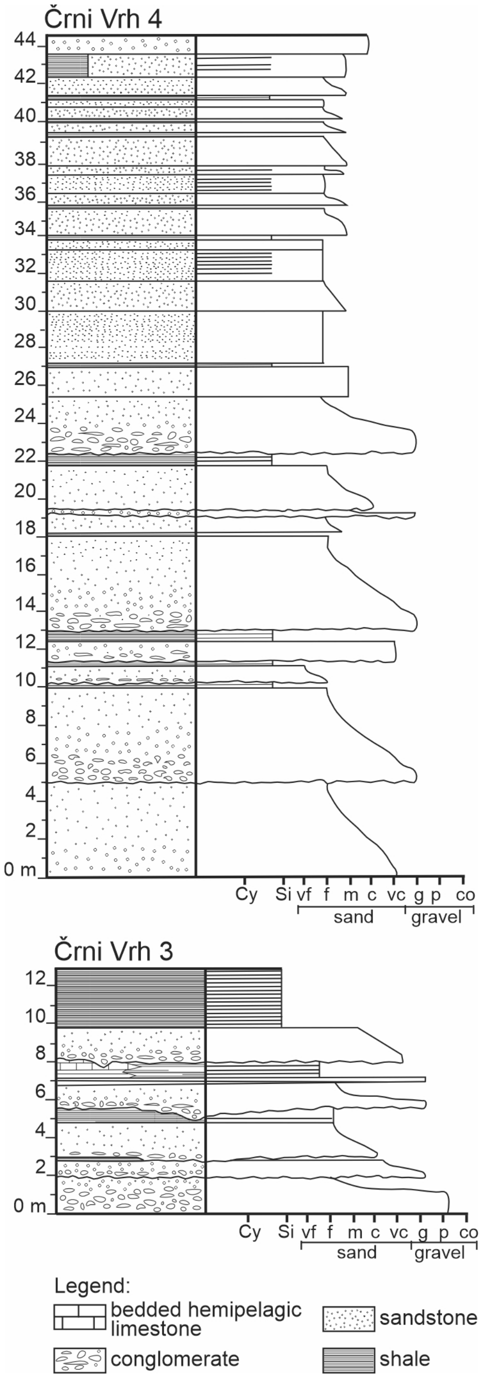

Fig. 6. Sedimentary log of the Črni Vrh sections. Right-side markings delineate grain sizes: Cy- clay, Si- silt, vf- very fine sand, f- fine sand, m- medium sand, c- coarse sand, vc- very coarse sand, g- granule, p- pebble, co- cobble.

Upper Pseudozilja formation and/or lower Amphiclina formation (Jesenica 1–2)

The Jesenica 1 section comprises 160 m of siliciclastic rocks, which are 50 % covered (Fig. 7). Even so, a coarsening-upward trend can be detected from the bottom to the top of the section. The lowermost 38 m of the section is shale-dominated. Approximately 15 % of this interval is represented by fine and very-fine sandstone that forms interchanging beds and lenses 2–20 cm thick. Sandstone is locally planar- and cross-laminated. After a 21 m thick gap, a 14.5 m thick heterolithic interval is exposed. Sandstone represents 30 % of the interval and is present in beds up to 10 cm thick. Small-scale slumps are present in the lower part of this interval. After another 13 m of covered interval, the next part of the section comprises a 13 m thick heterolithic interval, in which sandstone forms 50 % of the lithology, forming beds 5–40 cm thick. Lower bed boundaries are often erosional, and channelized, with scours running in a N–S direction. Load casts on lower bedding planes and ripple marks on upper bedding planes are common. Sandstone beds often contain rip-up clasts of shale in their lowermost parts, and display normal grading and planar and cross lamination in their upper parts. After another 19 m thick gap, a sandstone-dominated (60 %), interval 20 m thick follows. Sandstone beds are up to 50 cm thick and display the same characteristics as the underlying beds, with more pronounced cross lamination and ripple marks. Above a bed of normally graded pebbly to fine-grained sandstone, another heterolithic interval 3.4 m thick that is dominated by shale follows. Up to 20 cm thick, often normally graded and/or planar-laminated or normally graded beds of sandstone represent 20 % of this interval. Up to 3 m thick, matrix-supported conglomerate follows, bearing up to 30 cm large clasts of sandstone. The conglomerate is overlain by a heterolithic interval 1.5 m thick, which is dominated by shale. The next 12 m thick part of the section is covered. Matrix-supported muddy conglomerate approx. 5 m thick with large sandstone clasts up to 50 cm, follows. This is covered by a 5 m thick heterolithic, shale-dominated interval containing approx. 40 % of fine and very fine-grained sandstone.

The Jesenica 2 section, which measures 56 m in thickness (Fig. 8) lies in a slightly higher stratigraphic position than the succession described in the Jesenica 1 section. The first 39.6 m of the succession exhibits a coarsening-upward trend. This part is composed of heterolithic intervals comprising 60–90 % shale that is often bioturbated and in places contains calcite concretions and 10–40 % of sandstone in beds and lenses up to 10 cm thick. Shale-dominated heterolithic intervals from the upper half of the succession are interrupted by more sandy intervals, or by beds of conglomerate up to 60 cm thick, grading into sandstone showing planar and cross lamination. The conglomerate has erosive lower boundaries, with the proportion of coarser intervals increasing upwards. After a prominent bed of a matrix-supported conglomerate 5 m thick with sandstone and limestone clasts

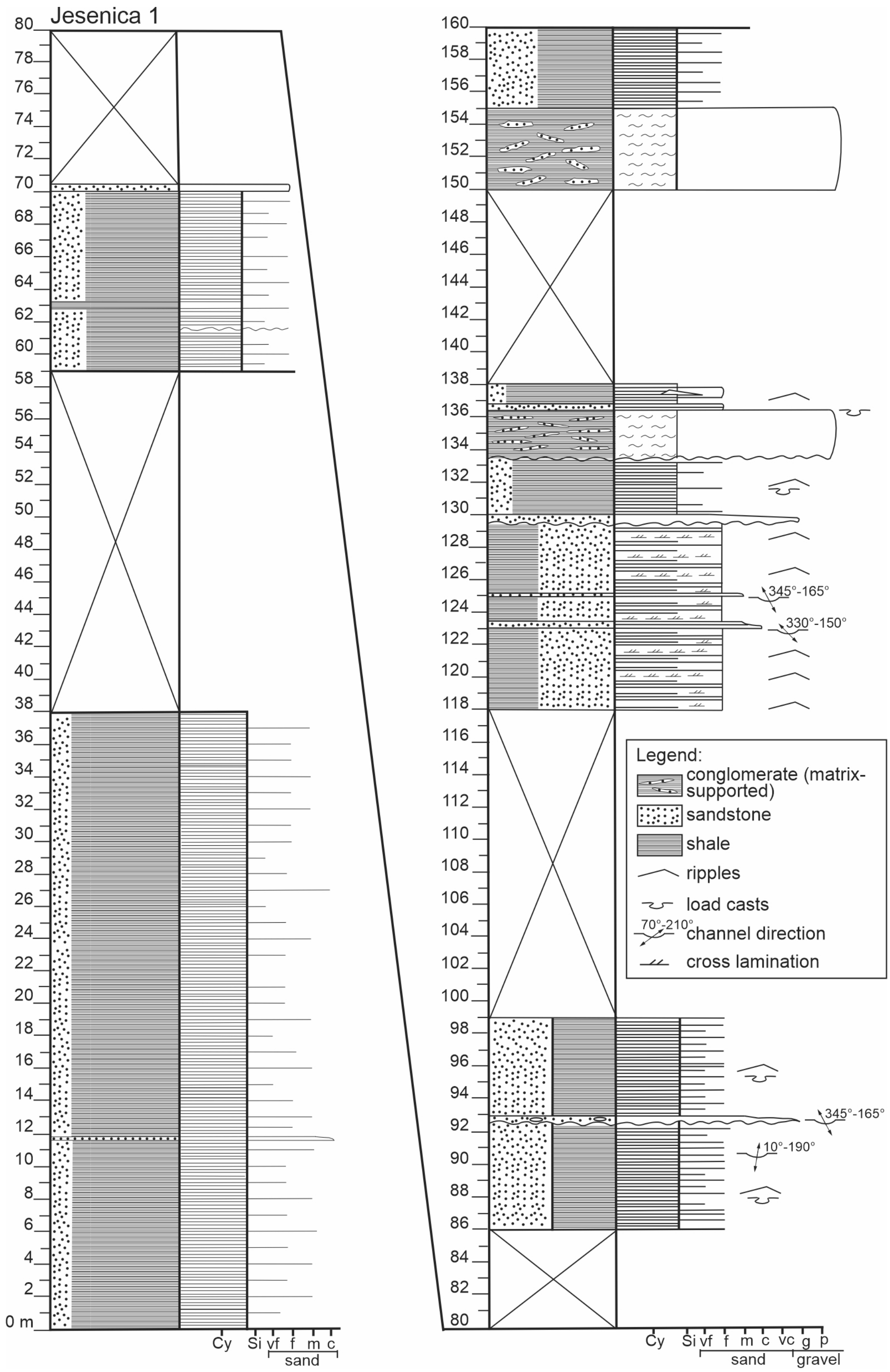

Fig. 7. Sedimentary log of the Jesenica 1 section. Right-side markings delineate grain sizes: Cy- clay, Si- silt, vf- very fine sand, f- fine sand, m- medium sand, c- coarse sand, vc- very coarse sand, g- granule, p- pebble.

up to 20 cm large, a finning-upward succession of shale 16.4 m thick follows. Shale is bioturbated, interbedded by normally graded conglomerate and thin sandstone beds with load casts. A single bed of micritic limestone is present near the top of the section.

Lower Amphiclina formation (Novaki 1–4)

The Novaki 1 section comprises a succession 39.6 m thick dominated by coarse- to fine-grained siliciclastic rocks (Fig. 9). The 1.5 m thick heterolithic, shale-dominated interval contains thin beds

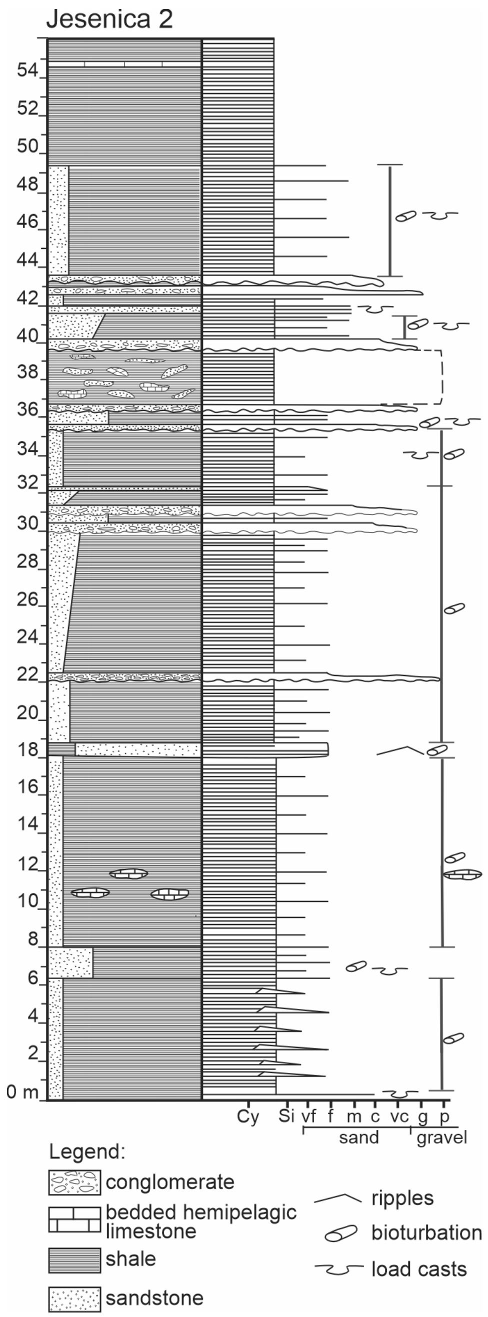

Fig. 8. Sedimentary log of the Jesenica 2 section. Right-side markings delineate grain sizes: Cy- clay, Si- silt, vf- very fine sand, f- fine sand, m- medium sand, c- coarse sand, vc- very coarse sand, g- granule, p- pebble.

and lenses of limestone (mudstone). It is overlain by an 11 m thick coarse-grained interval comprising normally graded, amalgamated beds of conglomerate and sandstone. The conglomerate beds contain mostly limestone pebbles and gradually pass to coarse-, medium- and fine-grained sandstone. The interval is overlain by 5 m thick shale, followed by 22 m of shale-dominated succession. Shale interchanges with calcareous conglomerate and siliciclastic sandstone. Sandstone is normally graded, planar-, and cross-laminated.

The Novaki 2 section reaches a thickness of 34 m (Fig. 9). It begins with a 10 m thick heterolithic interval consisting of shale and subordinate (25 %) beds of limestone (wackestone). A 4 m thick package of medium-grained massive sandstone follows, overlain by a 20 m thick succession comprising several sedimentary sequences. The lowermost sequences begin with conglomerate, containing mostly non-calcareous pebbles. Conglomerate gradually passes into sandstone. Other sequences begin with coarse- to medium-grained sandstone and are partly normally graded. Finer parts of the sequences mostly consist of heterolithic intervals in which shale prevails over thin sandstone beds.

The Novaki 3 section comprises 20.5 m of mostly sandstone and subordinate darker shale (Fig. 9). They are subdivided into several sedimentary sequences of different thicknesses. Sequences begin mostly with an erosional surface, followed by medium- to very coarse-grained sandstone, which is pebbly in the upper part of the section. The sandstone beds are 0.5–2.5 m thick, normally graded, and in some beds planar-laminated in the upper parts. The upper, fine-grained parts of the sequences are 1–1.8 m thick heterolithic intervals comprised of 60 % shale and 40 % sandstone in thin beds and lenses.

The Novaki 4 section measures 22.5 m in thickness (Fig. 9). The lower 6 m are represented by interchanging thin beds of shale and 20–30 cm thick beds of normally graded fine-grained sandstone. The remaining 16.5 m of the section are subdivided into 0.7–5.2 m thick sedimentary sequences. Sequences are dominated by sandstone and pebbly sandstone. Normally graded sandy conglomerate with erosional base is subordinate. Shale forms upper fine-grained parts 0.2–1 m thick of the sequences.

Upper Amphiclina formation (Davča 1–2, Poče, Zakojca 1–2, Orehek, Hudajužna, Koritnica)

The described sections are ordered according to their geographic position from E to W.

The Davča 1 section represents the upper 80 m of the Amphiclina formation (Fig. 10). The section starts with an 8.4 m thick fining-upward succession, comprising sequences of coarse-grained sandstone, pebbly sandstone, and conglomerate. These beds are mostly normally graded and gradually pass into limestone (wackestone), or heterolithic intervals composed of limestone (wackestone) interbedded with thin beds and laminae of shale (Fig. 4a). A bed of slumped pebbly mudstone approx. 2 m thick follows after a sharp erosive surface. Muddy matrix forms 80 % of this bed. Dispersed within the matrix of the pebbly mudstone are clasts of shale, sandstone, and limestone up

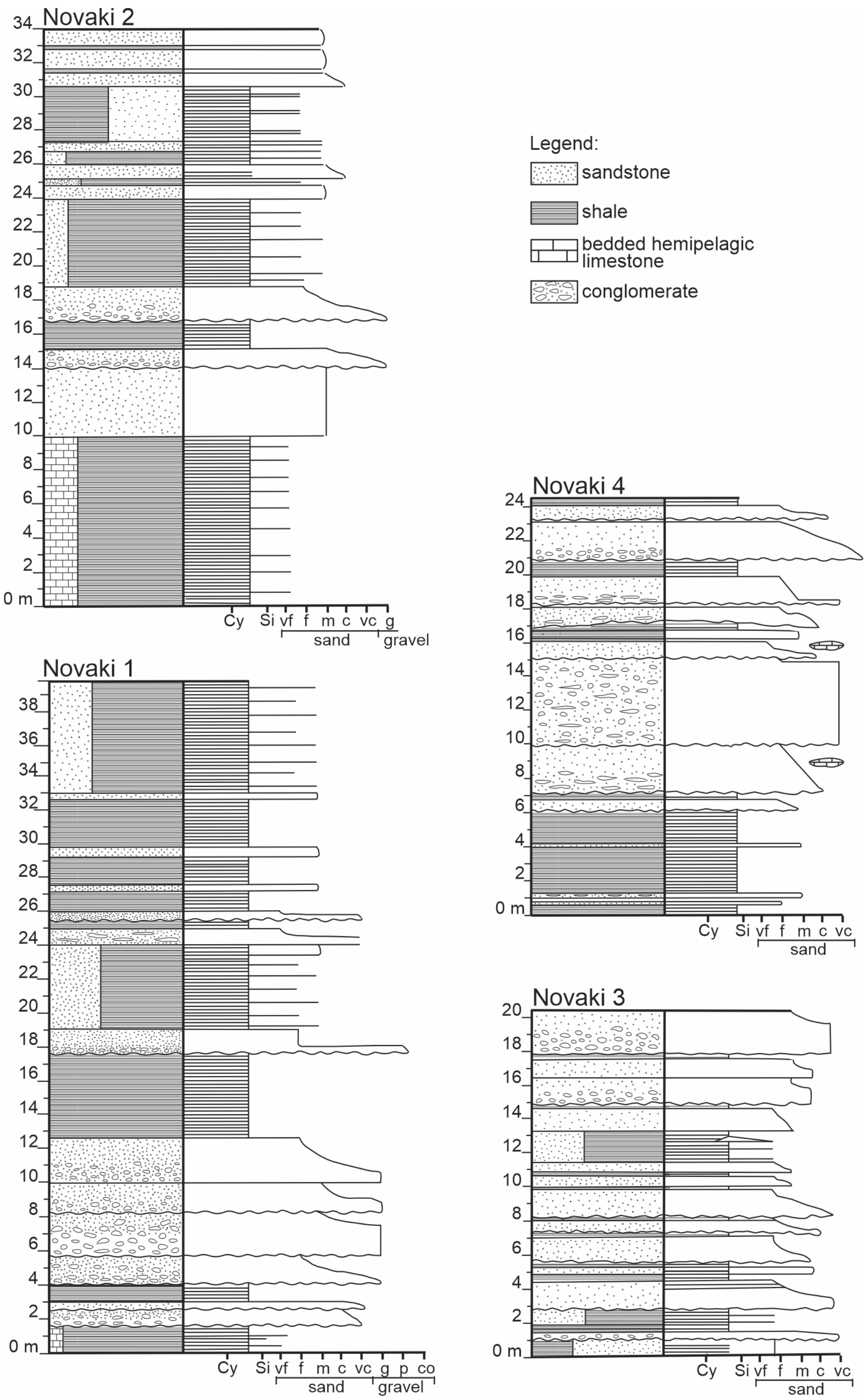

Fig. 9. Sedimentary log of the Novaki sections. Right-side markings delineate grain sizes: Cy- clay, Si- silt, vf- very fine sand, f- fine sand, m- medium sand, c- coarse sand, vc- very coarse sand, g- granule, p- pebble, co- cobble.

to 20 cm in size. The following 1.5 m of the section is covered. The covered interval is followed by a fining-upward succession 31 m thick. The lowermost 7.6 m of the interval is mostly sandstone, with subordinate locally bioturbated shale (Fig. 4b). Sandstone beds are up to 70 cm thick, with erosional, locally channelized bases and with cross, planar lamination, flaser bedding, and ripple marks on some of the upper bedding planes. Three sedimentary sequences were singled out in the next 25.4 m of the section (from approx. 18 m to 45 m in Fig. 10) and are 7.4 m, 9.6 m and 8.4 m thick. Each sequence begins with beds of normally graded of conglomerate up to 40 cm thick, transitioning to planar- and cross-laminated sandstone. This is followed by 40 cm to 3 m thick shale-dominated heterolithic intervals with 10-40 % thin beds, laminae, and lenses of fine-grained sandstone and thin beds of limestone (wackestone). Load casts are present on the lower bedding planes of sandstone, and ripple marks were observed on some of the upper bedding planes (Fig. 4c). Some upper parts of the sandstone beds are weathered and pass into brown mudstone some few cm thick. After a 13.4 m thick covered part of the section, a 16.2 m thick succession of heterolithic shale-dominated interval follows. Intercalations of thin beds, laminae, and lenses of cross-laminated fine-grained sandstone represent 15 % of the interval. Load casts are present on the lower bedding planes of sandstone beds. Ripple marks are present on the upper bedding planes. Shale is often bioturbated. The heterolithic clastic interval is followed by a predominantly calcareous, heterolithic interval 2 m thick containing 70–85 % of limestone (wackestone) in beds 10–15 cm thick, and 15–30 % of shale in thinner beds. The interval is overlain by 1 m of bedded fine crystalline dolostone. The section ends with a clastic heterolithic interval 1.4 m thick with the same characteristics as the underlying one.

The Davča 2 section spans 21.5 m of a carbonate-dominated succession (Fig. 10). The lower 10.2 m thick succession is characterized by increasing terrigenous component. The lowermost, 6 m thick part consists of limestone-dominated heterolithic intervals. Limestone (wackestone) in beds up to 20 cm thick forms 10–95 % of intervals and interchanges with thin beds of shale. Most of the contacts between the two lithologies are wavy. Heterolithic parts are interbedded by packages of bedded limestone (wackestone) 1 m thick. The lower part of the section ends with 4.2 m of shale, above which follow 5.8 m of calcareous-prevailing succession with heterolithic intervals containing 60–90 % of limestone (wackestone) interbedded by shale. Pyrite can be found in the lower part. Shale is locally bioturbated and ripple marks were observed on some bedding planes of limestone beds. Small chert nodules are present within the limestone in the upper part of the succession. The section ends with an interval of fine crystalline dolostone 5.6 m thick in beds 5–50 cm thick belonging to the lowermost part of the Bača dolomite formation (Fig. 4d). Dolostone often contains chert nodules and chert horizons up to 10 cm thick.

The Poče section represents the upper 128 m of the Amphiclina formation (Fig. 11). The section is interrupted by two covered parts that are 9 m and 25 m long respectively and is dissected by three minor faults. The section begins with a 14.6 m thick coarsening-upward siliciclastic-dominated succession. The lower, 11 m thick part consists of shale that is interbedded with fine-grained sandstone. The upper part comprises 0.7–1.3 m thick sequences composed of normally graded and partly planar-laminated sandstone, intercalated by beds of shale up to 30 cm thick. The next 5 m of the section consists of a heterolithic interval in its lower part. The heterolithic interval is composed of 75 % of shale and 25 % sandstone lenses. Upwards, the interval transitions into an interval of shale 4 m thick with a thin lenticular bed of limestone (mudstone). The next, 9 m thick part of the section is covered, and is followed by a predominantly shaly succession 22 m thick. In the lower part (4 m) is a heterolithic interval with 80 % shale, interbedded with fine-grained sandstone and thin beds and lenses of limestone (wackestone). The upper part of the interval consists of an interval of shale 18 m thick with two thicker beds of fine-grained sandstone. The succession is interrupted by a minor fault. Three heterolithic intervals follow, the first of which is 4 m thick, and consists of 85 % shale and 15 % limestone in lenses 2 cm thick. The second and third heterolithic intervals consist of 80–95 % locally bioturbated shale, interchanging with thin beds, laminae, and lenses of fine-grained sandstone. The section is interrupted by a covered interval 25 m thick. After the covered interval, a succession of bedded limestone (wackestone) 2.8 m thick follows. It is interbedded by a calcareous conglomerate with limestone and chert pebbles. This interval is overlain by a calcareous conglomerate 2 m thick with rip-up clasts of shale. The limestone pebbles are up to 7 cm in diameter, and on the outer side crusted in finely crystalline quartz. Clasts are partly imbricated. The conglomerate bed is followed by a package of beds of intra-bioclastic grainstone limestone that is cut by a minor fault. Above the fault, a 5 m thick interval of bedded limestone (wackestone) and heterolithic intervals follows. Heterolithic parts consist of 50–80 % of limestone (wackestone), interchanging with beds of shale up to 1 m thick. This limestone dominated interval is overlain by a 14 m thick clastic heterolithic interval consisting of shale (75 %) and sandstone (25 %) in thin, partly cross-laminated beds, laminae, and lenses. Load casts are often present on lower bedding planes. The heterolithic interval is followed by three thick sequences, each 2 m thick. Sequences start with heterolithic interval up to 1.4 m thick composed of 80 % bedded limestone (wackestone) and 20 %

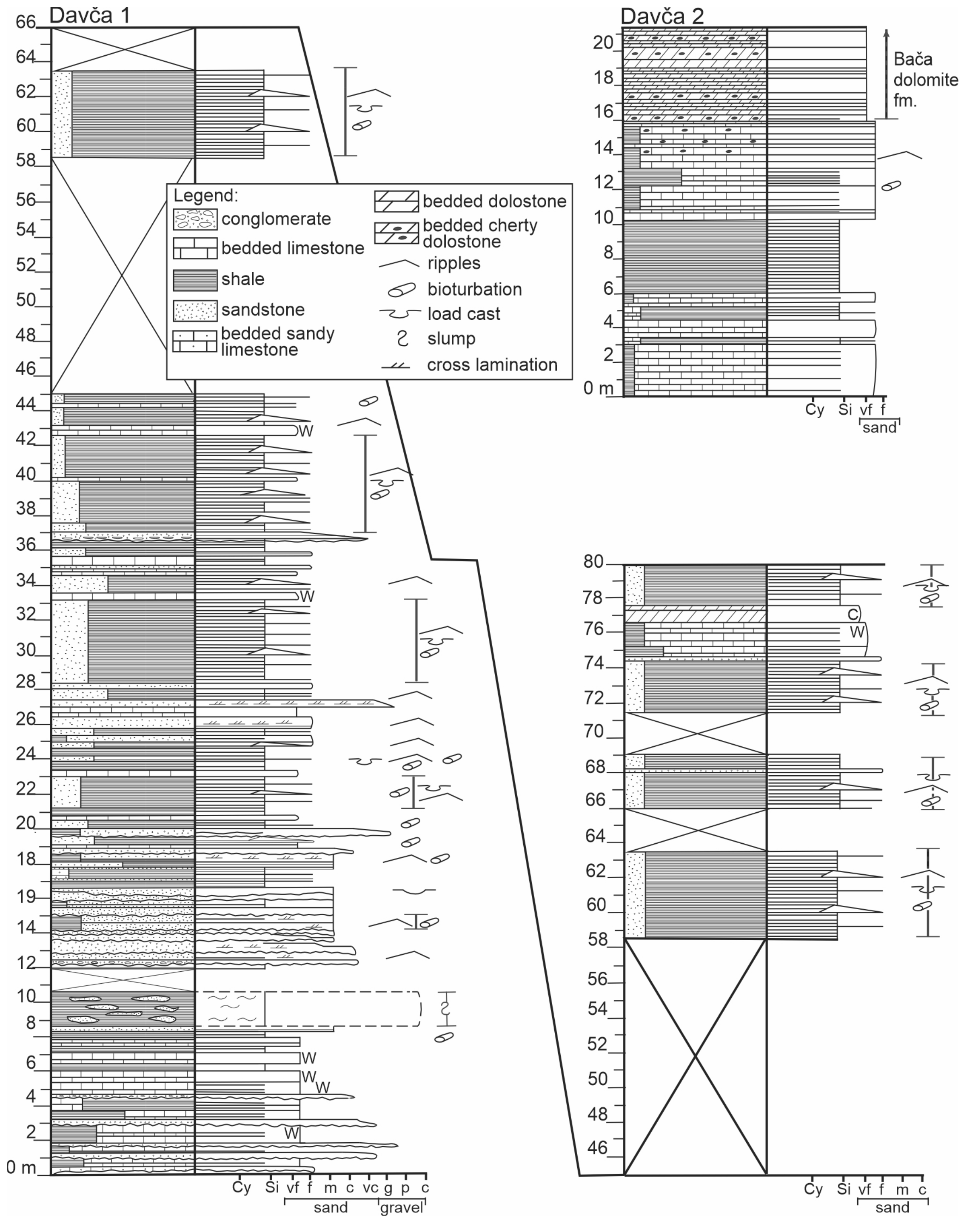

Fig. 10. Sedimentary log of the Davča sections. Right-side markings delineate grain sizes: Cy- clay, Si- silt, vf- very fine sand, f- fine sand, m- medium sand, c- coarse sand, vc- very coarse sand, g- granule, p- pebble, co- cobble. Letterings: W- wackestone, C- crystalline.

shale. The heterolithic parts are followed by clastic heterolithic intervals 0.8–1.4 m thick with 80–90 % of shale, interbedded with fine-grained sandstone in thin beds, laminae, and lenses. Load casts are present on some of the lower bedding planes. Ripple marks are present on the upper bed surfaces. Two more sequences follow, which are 1.6 m and 3 m thick, respectively. The lower one starts with bedded limestone (wackestone), followed by a heterolithic interval consisting of 80 % limestone (wackestone) and 20 % shale. A lens of calcareous conglomerate is present near the base. The upper interval is shale-dominated, with 15–50 % of the interval limestone (wackestone). The transition from the Amphiclina formation to the Bača dolomite formation lies within a heterolithic interval 2 m thick, containing 80 % of fine crystalline dolostone interbedded by 15 % of shale.

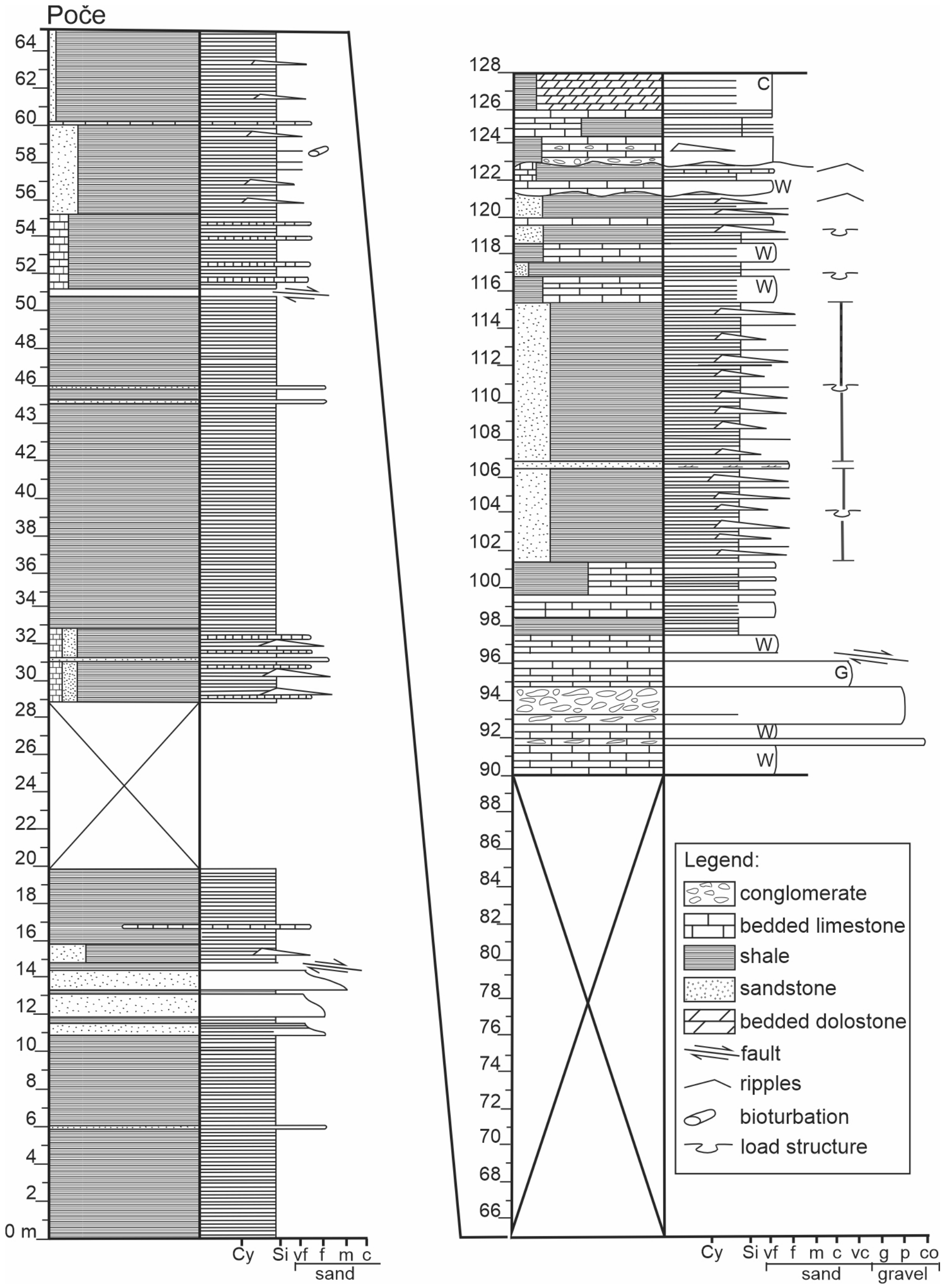

Fig. 11. Sedimentary log of the Poče section. Right-side markings delineate grain sizes: Cy- clay, Si- silt, vf- very fine sand, f- fine sand, m- medium sand, c- coarse sand, vc- very coarse sand, g- granule, p- pebble, co- cobble. Letterings: W- wackestone, G- grainstone.

The transition from the uppermost Amphiclina formation into the Bača dolomite formation in the surroundings of the village of Zakojca is exposed in two sections (Fig. 12).

The section Zakojca 1 represents a succession of sedimentary rocks 15 m thick. The lowest 12 m of the section consists of two sedimentary sequences with an upwardly increasing clastic component. The sequences are 7 m and 5 m thick, respectively. The lower parts contain heterolithic intervals 1–4.4 m thick with 60–70 % dark grey limestone (wackestone) in beds 5–25 cm thick interchanging with shale (30–40 %) in thin beds and laminae. The section continues with clastic, shale-dominated intervals 2.6–4 m thick with 70 % shale interchanging with 30 % fine-grained sandstone in thin beds and lenses. The uppermost part of this 3-m thick section is dominated by carbonate rocks. It begins with limestone (wackestone) followed by partly dolomitized limestone. The section ends with a heterolithic interval 1.6 m thick consisting of fine crystalline dolostone (85 %) in beds 10–20 cm thick with chert nodules up to 20 cm in size interbedded by thin beds of shale (15 %). This interval belongs to the lowermost part of the Bača dolomite formation.

Section Zakojca 2 is located 300 m to the west of the former section, separated from it by a strike-slip fault. It was logged in a thickness of 35 m. It begins with a heterolithic interval 60 cm thick dominated by limestone (wackestone), interbedded with thin beds of shale. It is overlain by a bed of calcareous breccia 2.4 m thick with limestone clasts up to 50 cm in diameter. Clasts are silicified at the margin and partly imbricated. This breccia is very similar in composition and structure to the limestone conglomerate bed in the Poče section. The breccia is succeeded by a heterolithic interval 7 m thick containing 75 % limestone (wackestone) in beds up to 50 cm thick interbedded with thin beds of shale and a bed of calcareous breccia. This interval was partly eroded by a 2 m thick matrix-supported very coarse breccia with limestone clasts up to 1.5 m in size. The breccia passes into a 1.8 m thick bed of inversely graded muddy conglomerate with limestone pebbles 4–5 cm in diameter. The amount of muddy matrix is lower than in the former breccia layer. Breccias are followed by a 2 m thick bed of inversely graded fine- to medium-grained calcarenite and a 1.6 m thick bed of calcareous breccia. The latter is overlain by a bed of matrix-supported limestone breccia 1.8 m thick with an erosional base. It is succeeded by a 1.4 m thick interval of medium-grained sandstone, limestone (wackestone) and shale. An erosional channel up to 30 cm deep is cut into the shale, and is filled with calcareous conglomerate with an admixture of smaller pebbles of quartz, rhyolites, chert, and sandstone. The conglomerate is followed by limestone (wackestone). Both are partly cut by matrix-supported breccia 4–5 m thick with clasts of sandstone and shale. The channel is oriented in a N–S direction. The muddy breccia is followed by 7 m of shale. The section ends with a heterolithic interval 2 m thick consisting of 85 % bedded, finely crystalline dolostone and 15 % shale belonging to the Bača dolomite formation.

The Orehek section is a heterogeneous succession approx. 430 m thick (Fig. 13). It starts with 5 m of shale with rare calcareous nodules. Above the erosional surface follows an approximately 15 m thick, matrix-supported blocky olistostrome breccia with deformational textures (from 5 m to 20 m in Fig. 13). Limestone clasts (olistoliths) are

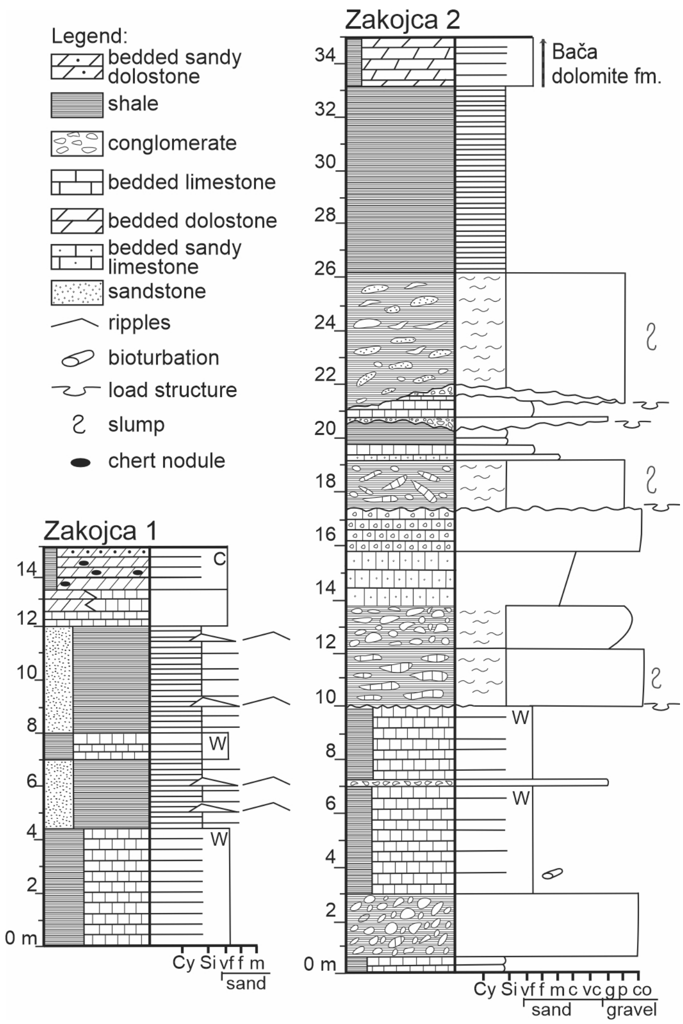

Fig. 12. Sedimentary log of the Zakojca sections. Right-side markings delineate grain sizes: Cy- clay, Si- silt, vf- very fine sand, f- fine sand, m- medium sand, c- coarse sand, vc- very coarse sand, g- granule, p- pebble, co- cobble. Letterings: W- wackestone, C- crystalline.

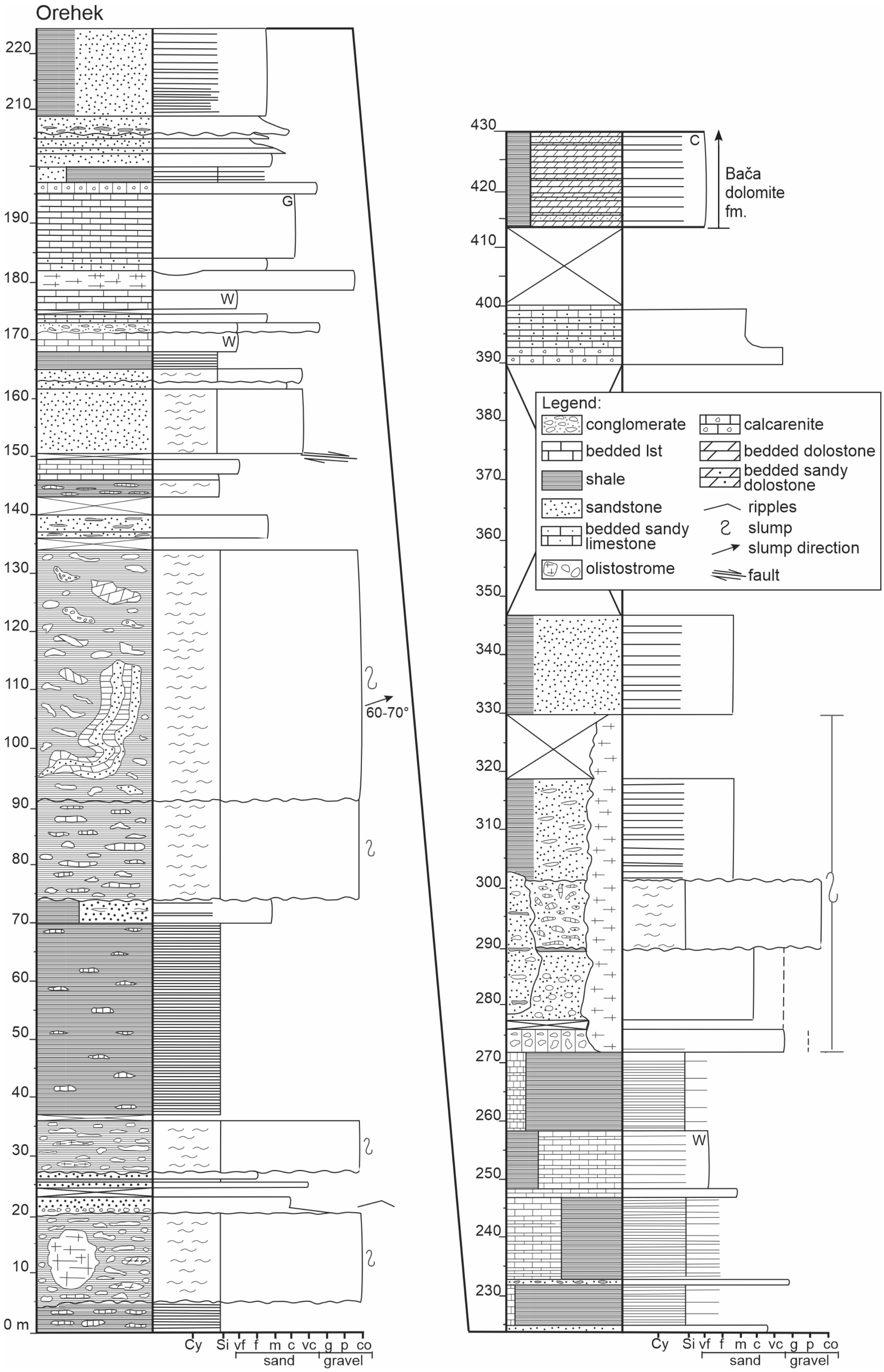

Fig. 13. Sedimentary log of the Orehek section. Right-side markings delineate grain sizes: Cy- clay, Si- silt, vf- very fine sand, f- fine sand, m- medium sand, c- coarse sand, vc- very coarse sand, g- granule, p- pebble, co- cobble. Letterings: W- wackestone, G- grainstone.

up to 10 m in size. The olistostrome passes upwards into calcareous breccia, which in turn passes into sandstone. Another 9 m thick olistostrome with an erosional base follows (from 27 m to 36 m in Fig. 13). It is overlain by 37 m of shale with rare calcareous nodules and a heterolithic interval consisting of 65 % sandstone and 35 % shale. The following two olistostromes, 17 m and 43 m thick, respectively, contain olistoliths up to 20 m in size. An internal deformational fold axis indicates slumping towards the E-NE. The second olistostrome is overlain by calcareous sandstone, sandy shale with calcareous nodules, and limestone (wackestone) in a partly covered, 16 m thick interval (from 134 m to 150 m in Fig. 13). Passing a smaller fault, the succession continues with an olistostrome 18 m thick with smaller clasts. Olistostrome intercalates with coarse-grained sandstone gradually passing into shale. This is overlain by a succession of limestone, interbedded with sandy limestone breccia and calcarenite 29 m thick (from 168 m to 197 m). This interval includes a limestone block (mud mound or olistolith?) 3.5 m thick covered by calcarenite and dark grey, locally laminated limestone (grainstone) in beds 3–40 cm thick passing into limestone breccia. The limestone-dominated interval is succeeded by a clastic succession 28 m thick containing a shale-dominant heterolithic interval at the base, followed by sandstone in mostly normally graded beds up to 3 m thick with planar lamination at the top. A sandy interval is followed by a heterolithic interval 15 m thick consisting of 65 % medium-grained sandstone interbedded with shale and topped by coarse-grained sandstone. The heterolithic interval is followed by 33.5 m of shale-dominated heterolithic intervals 7–18 m thick containing 30–90 % shale and 10–70 % dark grey limestone (wackestone), interbedded by beds of calcareous conglomerate and limestone (wackestone) 1 m thick. An olistostrome approx. 58 m thick follows (starts slightly below 272 m in Fig. 13) and is divided into four sections according to predominant lithology. The first section consists mostly of calcareous breccia with clasts of limestone (wackestone) up to 70 cm large containing echinoderms. The following interval consists of a sandy conglomerate with pebbles of quartz, rhyolite, chert, limestone (mudstone), shale, and coarse-grained sandstone. This interval is overlain by matrix-supported sandy breccia with an erosive base. Clasts within the breccia are predominantly dark grey limestone (mudstone), up to 1 m in diameter. Breccia is overlain by a heterolithic interval, consisting of 70 % sandstone and 30 % shale. The upper part is covered, except for 58 m of olistostrome breccia. The lower part of the breccia includes an olistolith 24 m thick composed of normally graded, planar-, and cross-laminated sandstone with shale intercalations. The olistostrome is covered by a heterolithic interval 17 m thick (from 330 m to 347 m) with 70 % sandstone and 30 % shale. Approximately 40 m of the section are poorly exposed. Shale and sandstone outcrop locally. An interval of limestone breccia approx. 9 m thick, passing into coarse-grained calcarenite follows. After 14 m of covered part the Bača dolomite formation follows.

The Hudajužna section reaches a thickness of 66 m. It is composed of carbonate-clastic deposits that represent the upper part of the Amphiclina formation. The top of the section lies approx. 15 m below the contact with the Bača dolomite formation (Fig. 14). Conodonts studied by Flügel and Ramovš (1970) from a section in the vicinity provided late Carnian, Tuvalian age. According to a prevailing lithology, the section can be divided into two parts: the lower part is 20 m thick and largely consists of heterolithic intervals up to 2 m thick. Each interval consists of 70–95 % limestone (wackestone), and 5–30 % shale, and is interbedded by beds of limestone (wackestone) 40–60 cm thick and two beds of calcareous conglomerate, 1.4 m and 0.4 m thick, respectively. The second part, some 46 m thick and consisting mostly of shale occupies the rest of the section. The succession is characterized by the increasing-upwards content of the calcareous component. The heterolithic intervals alternate between predominantly limestone and shale and form sequences ranging from 0.4 m to 11 m in thickness. Sequences most often start with heterolithic intervals that are 0.8–3.4 m thick, consisting of 40–95 % limestone (wackestone) and 5–60 % shale, or with beds of limestone (wackestone) 20–40 cm thick. The upper, clastic-dominated heterolithic intervals include 70–95 % of shale, interbedded with thin beds, laminae, and lenses of very fine- to fine-grained sandstone. Shale is partly bioturbated. Some sandstone beds are planar- and/or cross-laminated and have ripple marks on some of the upper bedding planes.

The Koritnica section is the westernmost logged section. Beds are in an overturned position, slightly folded in the lower third of the section, and intersected by a minor normal fault with a displacement of about 2 m. Both irregularities were restored, so the complete section is present. The section comprises a succession 89 m thick of a highly variegated exchange of lithology: shale, bedded limestone (texturally mostly wackestone, subordinate pack-

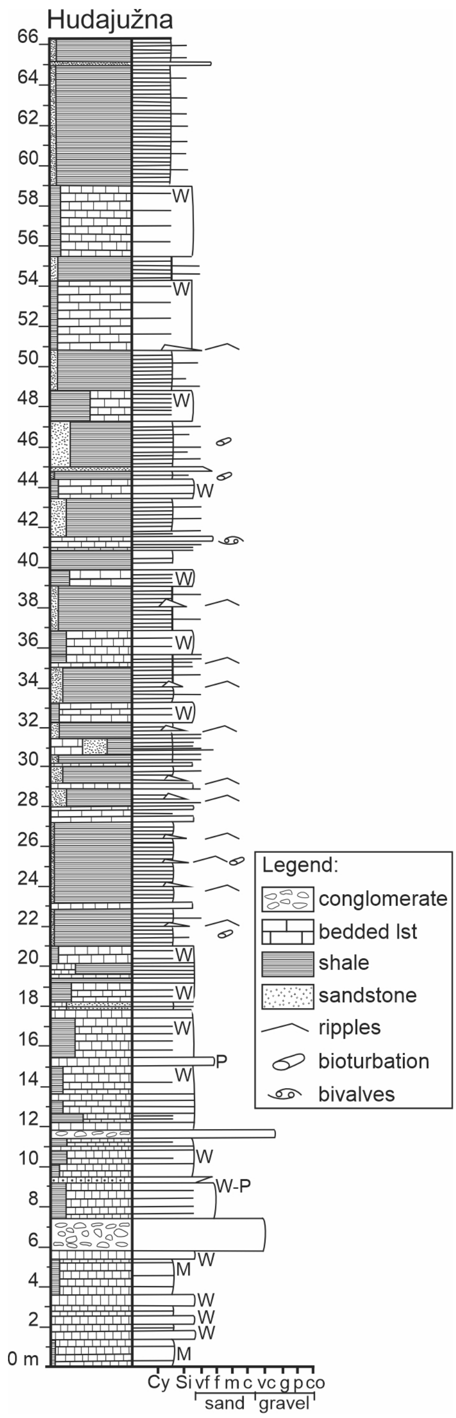

Fig. 14. Sedimentary log of the Hudajužna section. Right-side markings delineate grain sizes: Cy- clay, Si- silt, vf- very fine sand, f- fine sand, m- medium sand, c- coarse sand, vc- very coarse sand, g- granule, p- pebble, co- cobble. Letterings: W- wackestone, P- packstone.

stone, and grainstone), calcarenite, muddy breccia and conglomerate, and sandstone and dolostone with chert in the uppermost part of the section (Fig. 15). The complete succession was divided into ten intervals of different thickness and with specific characteristics. The first interval is 1.4 m thick and includes shale and limestone (mud- to wackestone). The second interval is 5.6 m thick and begins with muddy flat pebble calcareous conglomerate with erosional lower and upper bedding plane, followed by interchanging calcareous conglomerate, calcarenite, some normally graded, and heterolithic intervals with 20–70 % of shale interbedded with limestone (mud- and packstone). The third interval is 10.8 m in thickness (approx. 7 m to 17.8 m in Fig. 15). Limestone (wackestone) is dominant, composed mostly of heterolithic intervals 0.8–3 m thick with 70–80 % limestone, 20–30 % shale, and 20–100 cm thick packages of bedded limestone interbedded with calcareous conglomerate and calcarenite. The fourth interval (from 17.8 m to 31.6 m) is 13.8 m thick and clastic-dominated, containing beds of conglomerate 20–80 cm thick. Some beds are calcareous, muddy breccia, sandstone, and calcarenite, interbedded by a heterolithic interval 0.6–1.4 m thick with 50–70 % limestone (wackestone) and 30–50 % shale. In this interval, two sandstone beds with ripples indicate the N–S direction of the current (at 23.5 m and 25.5 m). The fifth interval (from 31.6 to 43.2 m) measures 11.6 m in thickness. It is also dominated by clastic components. Four fining-upward successions start (at 31.5 m in Fig. 15) with beds of breccia 40-80 cm thick with an erosional base (Fig. 4f), passing upwards into coarse- to medium-grained sandstone, usually normally graded, interbedded with thin limestone (wackestone) beds or heterolithic intervals up to 60 cm thick with 85 % limestone (wackestone) and 15 % shale. In one of them, a thin bed of finely crystalline dolostone was detected. The upper part of the succession comprises two heterolithic intervals consisting of 60–85 % bedded limestone (wackestone), and 15–40 % shale interbedded with calcarenite. The sixth interval (from 43.2 to 59.4 m) occupies 16.2 m of the section and shows the coarsening-upwards trend. The lower part of the succession consists of interchanging thin beds of calcareous breccia, subordinate siliciclastic conglomerates, limestone (wackestone), and heterolithic intervals, some of which are calcareous and some siliciclastic-dominant, and a thin bed of finely crystalline dolostone. Sedimentary slumps were observed in two intervals. It is important to mention a heterolithic interval 1.4 m thick with 60 % shale and 40 % sandstone in which beds are broken and folded around a block of bedded limestone (at app. 46 m in Fig. 15; Fig. 4e). The limestone block apparently slid from N to S, indicating slope inclination in the same direction. The upper part of the succession is composed of siliciclastic conglomerate and muddy breccia up to 1.4 m thick, both with erosional bases interbedded with limestone in thin lenses and filling small depressions on uneven upper bedding surfaces

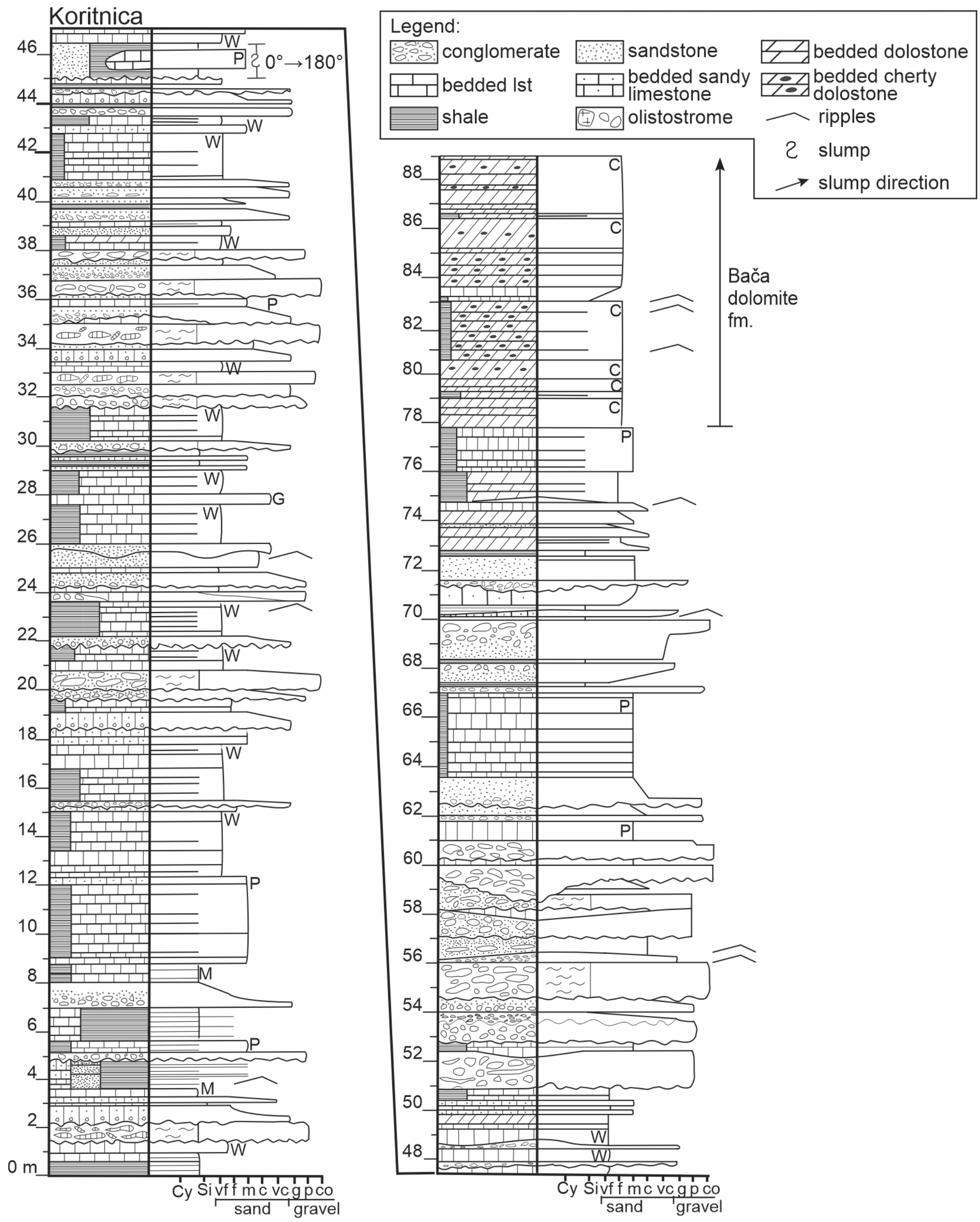

Fig. 15. Sedimentary log of the Koritnica section. Right-side markings delineate grain sizes: Cy- clay, Si- silt, vf- very fine sand, f- fine sand, m- medium sand, c- coarse sand, vc- very coarse sand, g- granule, p- pebble, co- cobble. Letterings: M- mudstone, W- wackestone, P- packstone, G- grainstone, C- crystalline.

of conglomerate, which are somewhere overlain by normally-graded sandstone or dunes with ripple marks. The seventh interval is 7.6 m thick with a fining-upward beds track. It begins with a channelized erosional surface cutting some 80 cm into underlying sediments (at app. 59 m in Fig. 15) and is overlain by two sequences with calcareous conglomerate with elongated, partly imbricated limestone clasts up to 50 cm in size, followed by sandstone or limestone (wackestone). The upper sequence also has a channelized erosional base. Channels run in the N–S direction. The succession ends with a heterolithic interval 3.4 m thick consisting of 90 % bedded limestone (packstone) and 10 % shale (from 63.5 m to 67 m in Fig. 15). The eight interval, which is 8 m thick, can be divided into two parts: the lower, 4.2 m thick, mostly contains inversely graded fine- to coarse-grained sandstone; the thickest bed at 2 m is inversely graded into siliciclastic conglomerate, which in the uppermost part is muddy and contains only limestone pebbles. The upper part is 3.8 m thick. It starts with channelized erosional surface (71 m in Fig. 15), overlain by a thin layer of conglomerate, followed by normally-graded coarse- to fine-grained sandstone, which is in the upper parts planar- or cross-laminated. Ripple marks are locally present. The sandstone is dolomitized. The ninth interval is 7.1 m thick, consisting of heterolithic intervals dominated by bedded dolostone or limestone. The heterolithic intervals are 1.2–2.6 m thick. They consist of 60–90 % bedded dolostone and 19–40 % shale. The limestone-dominated heterolithic interval, 1.8 m thick, consists of 80 % limestone (packstone) and 20% shale. The succession is capped by a lens of limestone (wackestone) with some ripple marks (75 m in Fig. 15). The tenth interval covers 11 m of the section and consists of bedded crystalline dolostone and a heterolithic interval 2.4 m thick dominated by dolostone with 10 % of shale. The dolostone contains nodules and thin, uneven beds of chert. This interval belongs to the Bača dolomite formation.

Microfacies

Table 2 lists microfacies varieties of clastic sedimentary rocks and limestone from the upper Pseudozilja and Amphiclina beds. Late diagenetic changes are omitted from the description. Volcanics and volcanoclastics of the Malenski Vrh section were already described by Skaberne and Čar (1986).

Selected microfacies types of limestones and coarser (sand- to gravel-size) clastic rocks are presented in Figures 16–18. Limestone comprises a variety of microfacies types. The most common is wackestone, dominated by thin-shelled bivalves, echinoderms, and radiolarians. Also common are carbonate mudstone and radiolarian wackestone, whereas other limestone types are less common. Sandstone is mostly dominated by quartz, feldspar, and lithic grains (mostly fragments of acidic volcanic rocks) in various proportions. Rare bioclasts, such as thin-shelled bivalves, and echinoderms, are found in sandstone. A single silicified foraminifera *Lamelliconus* ex gr. *ventroplanus* (Oberhauser) was found in one sample (Fig. 18c). The stratigraphic range of *L.* ex gr. *ventroplanus* extends from the Ladinian to the Carnian (Rettori, 1995; Pérez-López et al., 2005).

Table 2. Description of microfacies types from the Ladinian – Carnian volcano-sedimentary succession of the western Slovenian Basin.

Microfacies	Composition	Interpretation	Samples
Carbonate mudstone (Fig. 16a)	Less than 10 % of clasts (mostly bioclasts, small admixture of terrigenous grains); micritic matrix predominates. Different degrees of bioturbation. Elongated grains oriented parallel to the bedding (could be due to compaction). Rare samples show faint parallel lamination. Bioclasts: echinoderms, fragments of thin-shelled bivalves, sponge spicules. Terrigenous grains: include quartz, feldspar, mica.	Hemipelagic background sedimentation.	Hudajužna: 10.5, 17.4, 24.6, 38.5, 45.8, 62.0; Davča 1: 20.4; Davča 2: 18.9, 23.3; Jesenica 2: 1, 4, 5, 9; Poče: 1, 2, 9, 11, 15, 28, 37; Koritnica: 48.6, 59.4, 96.4.
Filament-echinoderm wackestone and packstone (Fig. 16b–c)	10–50% of grains (bioclasts, some samples with 0–2% of terrigenous grains), 50–90% of micritic matrix. Poorly to moderately sorted; elongated grains concordant to bedding. Possible bioturbations locally present. Locally interchanges with bioclastic packstone in laminae. Some samples with geopetal structures (umbrella-type porosity beneath valves, geopetal infillings of gastropods). Bioclasts: dominant thin-shelled bivalves (fragmented), echinoderms (often bored); subordinate radiolarians, sponge spicules, gastropods, ostracods, foraminifera. Terrigenous grains: poorly preserved, strongly carbonatized; feldspar, fragments of volcanics, quartz. Some samples contain very rare intraclasts.	Hemipelagic background sediment, mixed with allochthonous components; reworked by bioturbation and/or weak currents.	Hudajužna: 1.7, 3.2, 9.1, 9.6, 10.8, 12.5, 14.2, 15.7, 18.4, 19.5, 28.8, 41.1, 52.0, 56.7; Davča 1: 2.7, 5.5, 33.5, 94.7; Davča 2: 2.7, 3.5, 5.7, 10.3, 13.9, 15.3; Poče: 3, 9, 11, 12, 15; Zakojca 1: 2, 2a, 14, 20.6, 47; Koritnica: 11.6, 15.7, 39.5, 83.7.
Filament packstone (Fig. 16d)	80% of grains, 20% of microsparite and carbonate cement. Faint parallel lamination, caused by different amount of peloids. Thin-shelled bivalves are parallel to bedding, in long contacts. Grains: thin-shelled bivalves predominate (70% of rock); peloids and echinoderms together represent 10% of rock.	Reworked hemipelagic sediment.	Zakojca 2: 53; Koritnica: 57.4, 91.6, 95.8.
Radiolarian wackestone (Fig. 16e)	15–30% of grains (mostly bioclasts), 70–85% of micritic matrix. Grains are poorly sorted. Bivalves are oriented parallel to bedding. Umbrella-type porosity under the valves is present in some samples. Bioclasts: dominant radiolarians, followed by thin-shelled bivalves, gastropods, echinoderms, thick-shelled bivalves, ostracods, foraminifera. Terrigenous grains are rare, including grains of quartz and lithic grains. Lithoclasts of carbonate mudstone are also sporadically present.	Hemipelagic background sedimentation.	Hudajužna: 36.2; Davča 1: 2.3, 43.0, 75.0, 97.8; Davča 2: 0.7; Poče: 11, 24, 26; Zakojca 2: 17, 20.6; Koritnica: 12.0, 45.8, 80.8.
Bioclastic wackestone (Fig. 16f)	20% of grains, 80% of micritic matrix. Grains are well sorted, less than 0.5 mm in size. They comprise angular sparitic fragments of bioclasts.	Diluted gravity flow deposit (waning turbidite)?	Poče: 7.

Crinoid wackestone and packstone (Fig. 16g)	40% of grains, 40% of micritic matrix, 20% of syntaxial calcite cement. Grains are overall poorly sorted, but individual components show good sorting. Grains are matrix supported or are in point, rarely planar contacts. Grains: predominant are echinoderms predominate (30–35% of rock); subordinate are thin-shelled bivalves, fragments of brachiopods, lithoclasts (intraclasts?) of carbonate mudstone.	Diluted gravity flow deposit (waning turbidite)?	Poče: 8; Zakojca 2: 30; Koritnica: 83.7.
Peloid packstone (Fig. 16h)	50% of grains (peloids), 50% of recrystallized micritic matrix. Microfacies is very limited in extent, associated with carbonate mudstone. Peloids are very well sorted, rounded, in point contacts and elliptical in shape due to compaction. Fragments of thin-shelled bivalves and ostracods are rarely present.	Very diluted gravity flow deposit (waning turbidite)?	Poče: 2; Koritnica: 57.4.
Pelletal-bioclastic packstone	60% of grains (35% pellets, 15% bioclasts), 40% of micritic matrix, 10% of terrigenous grains. Poorly to moderately sorted. Locally weakly expressed parallel lamination indicated by a greater proportion of non-calcareous grains. Some samples are bioturbated. Bioclasts: dominantly thin-shelled bivalves; subordinate ostracods, radiolarians. Terrigenous grains: unequally distributed, angular; mostly feldspar, subordinate quartz, sericite. Cement: syntaxial rim.	Hemipelagic background sedimentat, mixed with allochthonous components; reworked by bioturbation and/or weak currents.	Hudajužna: 41.1; Poče: 9, 11; Koritnica: 39.5.
Bioclastic-intraclastic packstone (Fig. 17a)	60% of grains (50% bioclasts, 10% intraclasts), 5–35% micritic matrix, 5–35% calcite cement. Moderately sorted. Bioturbated, partly laminated. Bioclasts: dominant thin-shelled bivalves (concentrated in laminae, most fragmented), echinoderms; subordinate radiolarians, gastropods, foraminifera (***Nodosaria ordinata*** Trifonova, ***Endoteba*** sp.). Intraclasts:carbonate mudstone, 0.06–1.5 mm in size; subrounded, moderately sorted. Cement: granular and syntaxial rim.	Hemipelagic background sedimentat, mixed with allochthonous components; reworked by bioturbation and/or weak currents.	Hudajužna: 7.3; Zakojca 2: 3, 8, 5.1; Koritnica: 86.6, 90.5.
Intraclastic-bioclastic packstone	75% of grains (50% intraclasts, 20% bioclasts, 5% terrigenous grains), 20% of micritic matric, 5% of cement. Normal grading. Grain size 0.1–2 mm (dominant 0.2 mm), well sorted. Grains are in point, planar, rarely concavo-convex contacts. Elongated grains are oriented parallel to the bedding. Bioclasts: fragmented bivalves, echinoderms, foraminifera. Intraclasts are micritic, rounded. Terrigenous grains: subangular to subrounded; include quartz, feldspar, lithic grains (volcanics, chert). Cement: granular and syntaxial rim calcite cement.	Gravity flow deposit (turbidite?).	Koritnica: 16.5, 28.4, 51.4, 70.1.
Intraclastic-bioclastic grainstone (Fig. 17b, c)	50% of grains, 50% of carbonate cement. Grains are moderately sorted, of average size 0.4 mm. Intraclasts (carbonate mudstone, rarely peloidal grainstone) represent 30% of the rock. Bioclasts (echinoderms, foraminifera, bivalves) form 20% of the rock.	Gravity flow deposit (turbidite?).	Davča 1: 97.7; Zakojca 1: 7.9.
Bioclastic floatstone with bioclastic-intraclastic grainstone matrix (Fig. 17d)	50% of grains (40% of bioclasts, 10% of intraclasts), 50% of carbonate cement. Grains are poorly sorted, between 0.05 mm and 2 cm in size (the largest grain is a fragment of a solenoporacean algae, overgrown by a thin crust of microbialite). Average grain size is 0.75 mm. Larger grains are oriented parallel to bedding and elongated due to compaction. Bioclasts are dominated by sparitic particles (solenoporacean algae, but most are unrecognisable); echinoderms are rare.	Gravity flow deposit (turbidite?).	Poče: 6, 7.
Sandy mudstone (Fig. 17e)	Silt-sized grains predominate. Sand grains (up to 0.15 mm in size) represent app. 10% of the rock. They comprise quartz, feldspar, and opaque grains. Grains are somewhat rotated due to compaction; pseudo fluvial texture is visible. Some samples show parallel lamination.	Diluted gravity flow deposit.	Jesenica 2: 4; Poče: 2, 10, 14, 16, 21, 25, 27, 40, 43.
Fine-grained sandstone (Fig. 17f–h)	60–70% of grains, 25% of calcite cement, 5% of other cement, up to 20% of epimatrix. Locally interchanging in laminae with pebbly, sandy mudstone. Grains are 0.03–0.25 mm (mostly 0.07 mm) in size, angular to subrounded, isometric to elongated. They are in point, planar and concavo-convex contacts. Elongated grains are oriented parallel to the bedding. Grains: quartz, feldspar, lithic grains, biotite, heavy minerals (opaque minerals, zircon, rutile).	Gravity flow deposit.	Črni Vrh: 1, 1.3, 3, 4.5, 6, 8, 10; Davča 1: 85.5; Davča 2: 5.0; Jesenica 1: 2, 5, 6, 8; Novaki: 28.1, 40.0, 62.9; Poče: 2, 10, 14, 18, 21, 33, 37, 42; Zakojca 1: 5.4; Zakojca 2: 3.0; Koritnica: 26.6, 33.5, 41.1, 61.9, 69.0.

Medium-grained sandstone (Fig. 18a–c)	40–70% grains (10–20% quartz, 10–30% feldspar, 20–45% lithic grains), 25–60% cement, 1–5% epimatrix. Homogeneous structure or parallel lamination, caused by the difference in grain sizes or concentration in accessory heavy minerals. Some samples are graded. Elongated grains are oriented parallel to the bedding. Grains are poorly to moderately sorted; grain size 0.04–2 mm (dominant size 0.3–0.5 mm). Grain shape isometric to elongated, angular to rounded. Grains are in point, planar, concavo-convex or stylolitic contacts, rarely matrix-supported. The least abraded grains belong to quartz, often present as subhedral crystals. Grains: dominant (in different order) are feldspar (plagioclase and alkali feldspars), lithic grains (rhyolite and granitoids; very rare micritic limestone), quartz (mostly monocrystals, some with embayment structures); accessory are heavy minerals (zircon, rutile, titanite, opaque minerals) and mica (biotite, muscovite). Some samples with notable presence of carbonate mudstone lithoclasts (intraclasts). Very rare are bioclasts (fragments of bivalves, echinoderms, very rare fragments of thick-shelled bivalves). Cement: calcite, dolomite and feldspar.	Gravity flow deposit.	Črni Vrh 4: 0.7, 0.8, 1.6, 2, 2.5, 5, 12; Hudajužna: 22.0, 23.8, 31.8, 44.6, 64.8; Davča 1: 1.0, 8.9, 12.5, 13.8, 19.6, 27.5, 35.1, 38.9, 95.8; Novaki 1: 1, 3, 18, 84.7; Poče: 17, 18, 19, 22, 34, 36, 41; Koritnica: 43.9, 48.6, 63.7.
Coarse-grained sandstone (Fig. 18d)	60–80% of grains, 5–20% of epimatrix, 5–40% of carbonate cement. The amount of epimatrix increases with grain compaction. Grains are 0.15–2.5 mm in size, although most are in the range between 0.45 mm and 0.79 mm. They are poorly sorted, subangular to angular, isometric to slightly elongated. Planar contacts prevail, while point, concavo-convex and stylolitic contacts are locally present. Grains: quartz (monocrystals, rarely polycrystalline), feldspar, lithic grains (volcanics, mudstone); subordinate are opaque minerals and bioclasts (echinoderms, thin-shelled bivalves).	Gravity flow deposit.	Jesenica 1: 1, 7, 9; Jesenica 2: 3/1, 3/2, 6; Novaki: 10.3, 11.5, 18, 18.2, 27.5; Poče: 38; Zakojca 2: 18; Koritnica: 18.7, 33.5, 59.4.
Coarse-grained pebbly sandstone (Fig. 18e–f)	50–80% of grains (5–20% quartz, 10–30% feldspar, 30–50% lithic grains), 20–50% of matrix. Locally interchanging in laminae with fine-grained sandstone. 5–30% of grains larger than 2 mm, 40% of sand-sized grains, 50% of grains smaller than 0.03 mm. Grains are 0.03–7 mm in size, very poorly sorted. Larger grains are angular to well rounded. Smaller grains are mostly subangular to subrounded. Grains are isometric, rarely elongated. Most grains are supported by matrix; some are in point, planar, concavo-convex or stylolitic contacts. Grains: quartz (monocrystals, most with undulating extinction, some with embayment structures), feldspar (plagioclase and alkali feldspars), lithic grains (acidic volcanic rocks, basic volcanic rocks, tuff, chert), accessory are zircon, opaque minerals, mica (biotite). Matrix mostly ortho- and pseudomatrix, along cracks and grains illite-sericite epimatrix showing pseudofluidal texture around grains. Epimatrix prevails in tectonically-stressed samples.	Gravity flow deposit.	Črni Vrh: 4, 4.5; Davča 1: 9.5, 85.5; Davča 2: 5.0; Novaki: 1.0, 6.3, 14.0, 21.5, 33.3, 51.6, 57.4, 60.7; Koritnica: 23.2, 24.6, 33.2, 61.5, 73.5, 76.1.
Pebble breccia (lithoclastic rudstone) (Fig. 18g)	50% of clasts, 50% of carbonate cement. Clasts are poorly sorted. Their average size is 4 mm. The smallest grains measure 0.2 mm, while the largest grains measure 12 mm in size. Clasts are subangular to rounded. They comprise (not in order) carbonate mudstone, peloid packstone, filament mudstone, intraclastic-bioclastic wackestone-packstone, bioclastic grainstone, peloid grainstone, microbial boundstone, oncoids, bivalve shells, echinoderms, coral fragment, rhyolite lithoclasts, idiomorphic crystals of feldspar, quartz grains, and chert lithoclast.	Gravity flow deposit.	Poče: 4; Jesenica 2: 2, 7, 12; Koritnica: 15.7b, 55.3.
Cobble breccia/ conglomerate (Fig. 18h)	85% of grains larger than 2 mm, 8% of grains smaller than 2 mm, 7% of cement. Grains in concave-convex and stylolitic contacts. Grain size 0.5–15 cm, poorly sorted, angular to rounded, most subrounded, isometric to elongated in shape. Grains: dominantly limestone clasts (mostly bioclastic wackestone, followed by carbonate mudstone, pelletal-bioclastic packstone, and bioclastic-intraclastic packstone with rare ooids). Sand-sized grains are of the same composition. Bioclasts are presented by echinoderms. Selective silicification.	Gravity flow deposit.	Hudajužna: 6.8; Koritnica: 31.0.

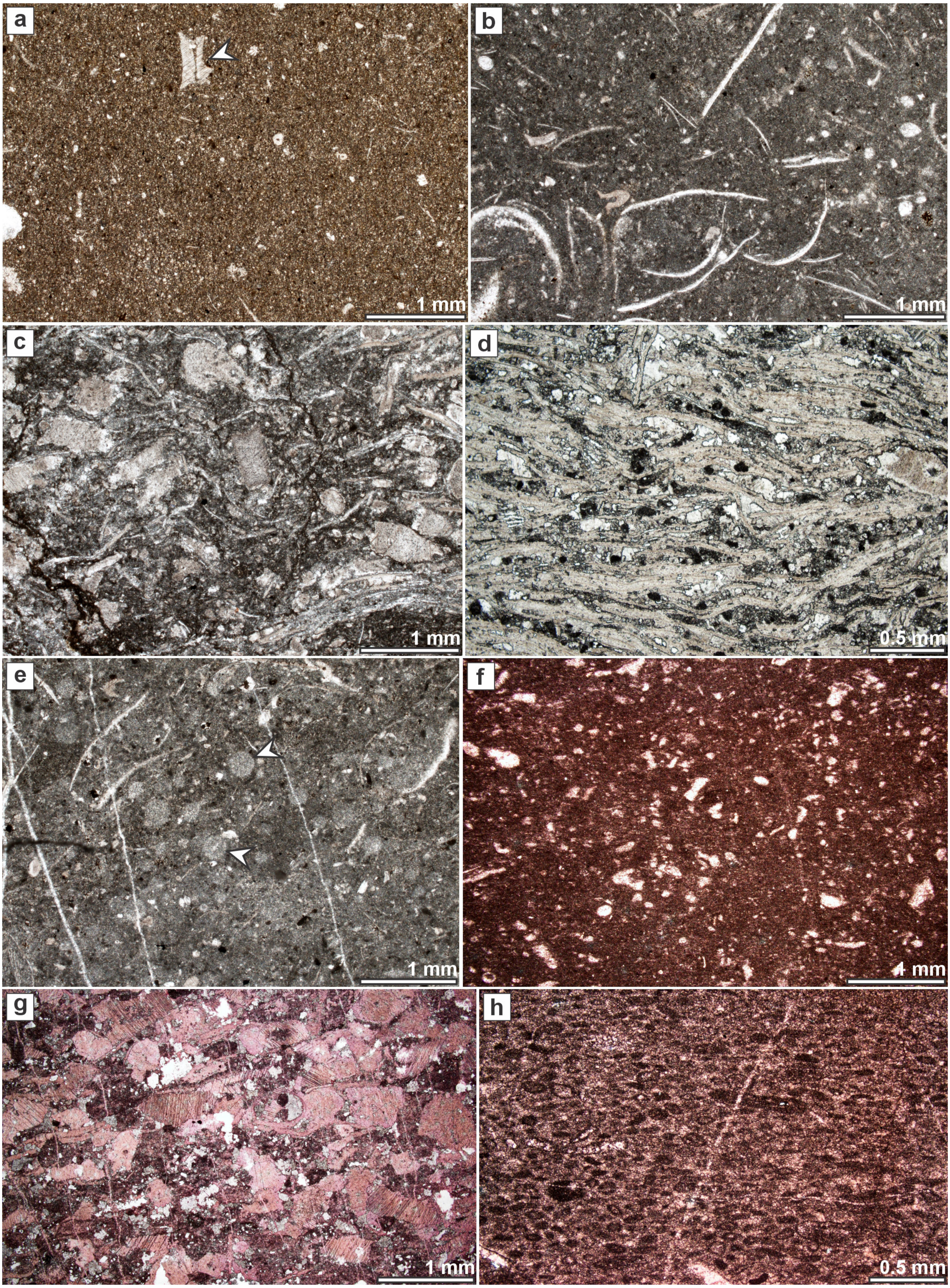

Fig. 16. Carbonate microfacies of the Ladinian – Carnian sedimentary succession of the Slovenian Basin (Pseudozilja and Amphiclina formations). **a:** Carbonate mudstone. Arrowhead points at the echinoderm. Sample Davča D1:23.3. **b:** Filament-echinoderm wackestone. Sample Hudajužna H19.5. **c:** Filament-echinoderm packstone. Sample Hudajužna H9.1. **d:** Filament packstone. Sample Zakojca ZK2:53. **e:** Radiolarian wackestone. Arrowheads point at calcified radiolarians. Note also the presence of filaments. Sample Hudajužna H36.2. **f:** Bioclastic wackestone. Sample Poče PO1:7. **g:** Crinoid packstone. Sample Zakojca ZK2:30. **h:** Peloid packstone. Sample Poče Po1:2.

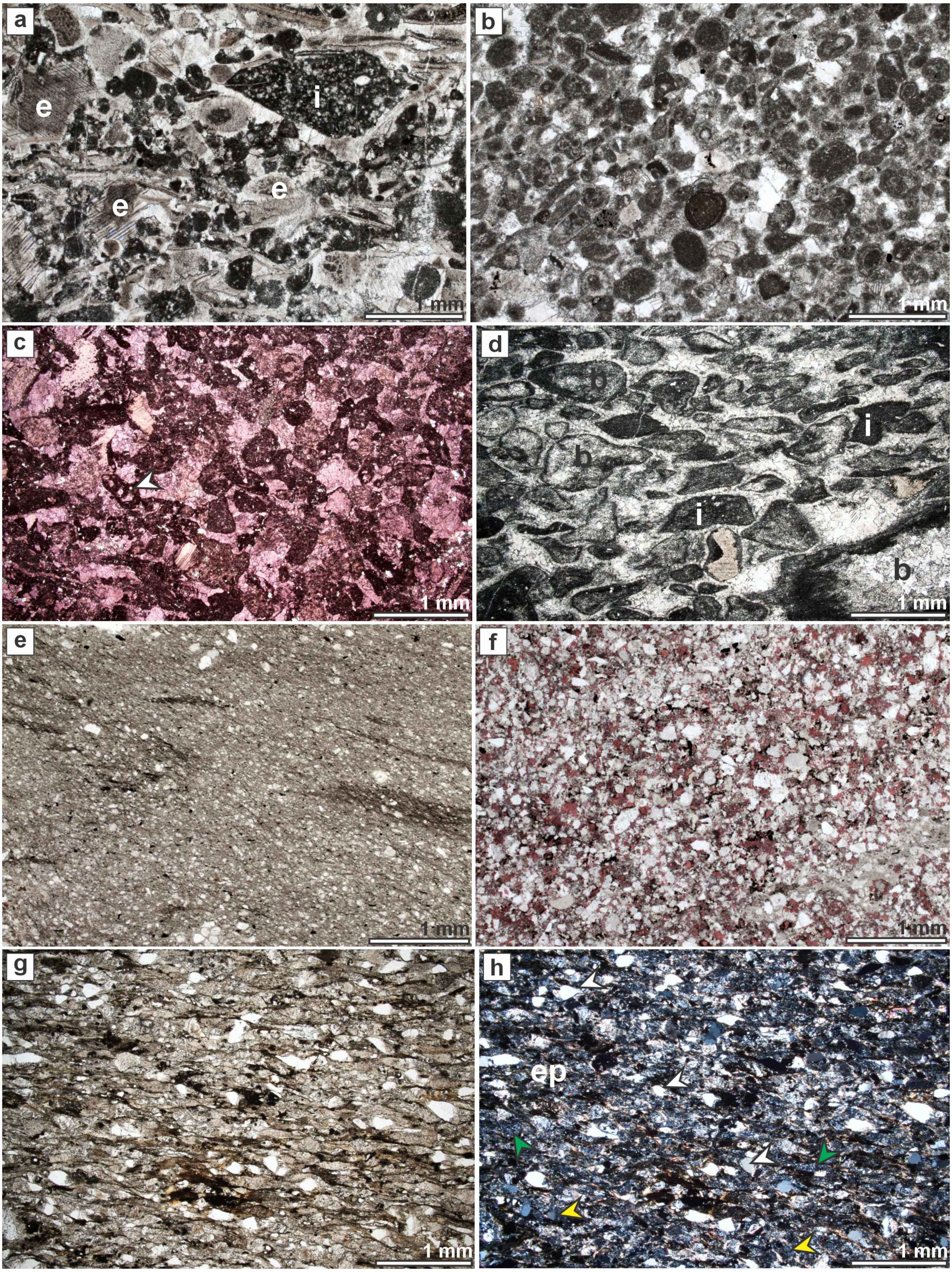

Fig. 17. Microfacies of the Ladinian – Carnian sedimentary succession of the Slovenian Basin (Pseudozilja and Amphiclina formations). **a:** Bioclastic-intraclastic packstone. Markings: e- echinoderm, i- intraclast. Sample Hudajužna H7.3. **b:** Intraclastic-bioclastic grainstone. Sample Davča D1:97.7. **c:** Intraclastic-bioclastic grainstone. Arrowhead points at the foraminifera. Sample Zakojca ZK1:7.9. **d:** Bioclastic floatstone with bioclastic-intraclastic grainstone matrix. Markings: b- bioclast, i- intraclast. Sample Poče Po:1.6. **e:** Sandy mudstone. White grains belong to quartz and felsic volcanic rocks. Sample Davča D1:85.5. **f:** Fine-grained sandstone. Sample Davča D1:85.5. **g:** Fine-grained sandstone. Sample Črni Vrh CV1:6. **h:** Same sample, crossed Nichols. White arrowheads point at quartz, green arrowheads point at grains of felsic volcanic rocks, yellow arrowheads point at feldspar. Quartz-sericite matrix is marked with “ep”.

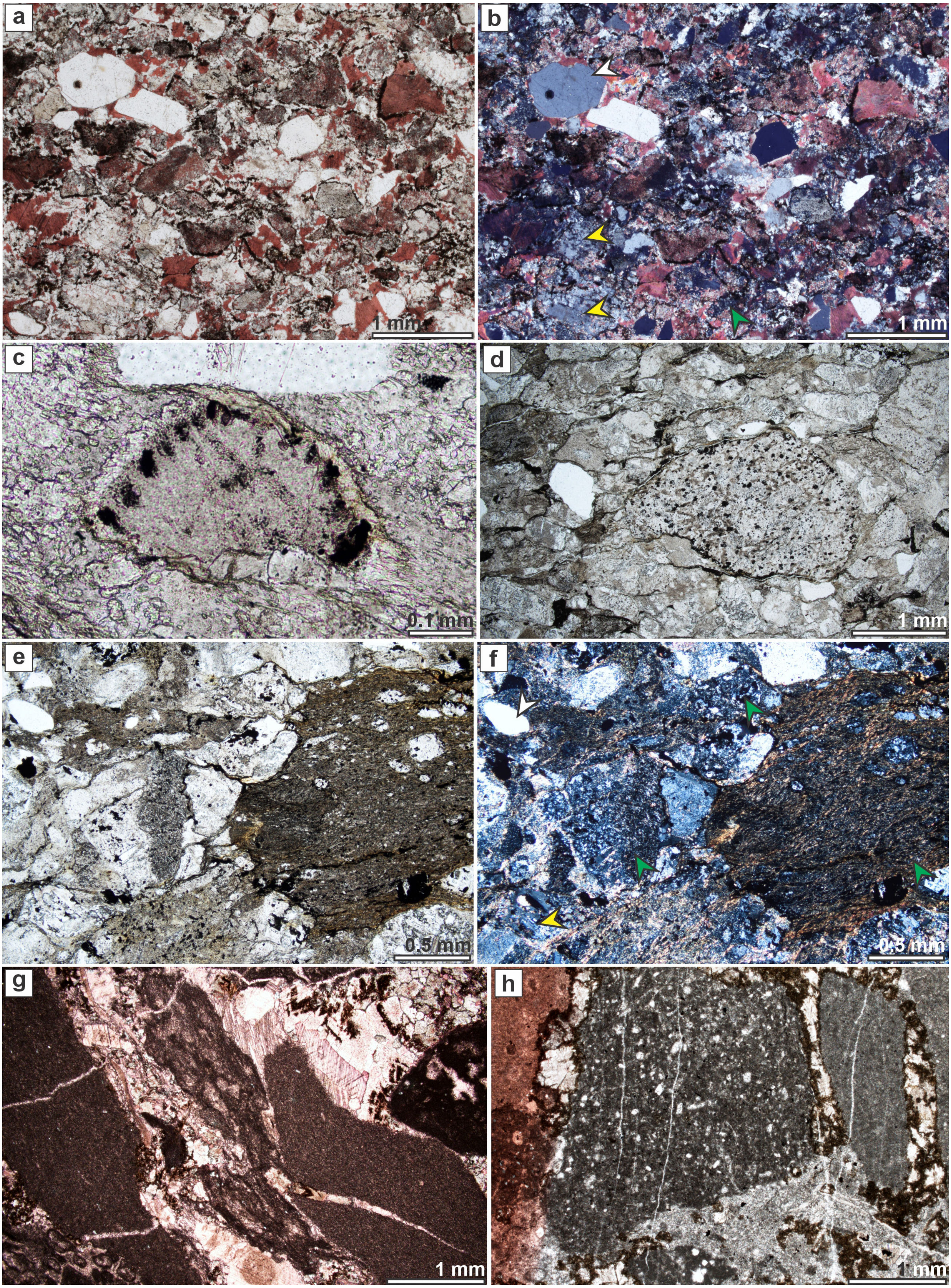

Fig. 18. Microfacies of the Ladinian – Carnian sedimentary succession of the Slovenian Basin (Pseudozilja and Amphiclina formations). **a:** Medium-grained sandstone. Calcitization is revealed by staining. Sample Hudajužna H:64.8. **b:** Same sample, crossed Nichols. White arrowheads point at quartz, green arrowheads point at grains of felsic volcanic rocks, yellow arrowheads point at feldspar. **c:** *Lamelliconus* ex gr. *ventroplanus* (Oberhauser). Sample Novaki N1:18.0. **d:** Coarse-grained sandstone. The large grain in the middle belongs to volcanic rock. Sample Novaki N5:18.2. **e:** Coarse-grained pebbly sandstone. Sample Novaki N4:1.0. **f:** Same sample, crossed Nichols. White arrowheads point at quartz, green arrowheads point at grains of felsic volcanic rocks, yellow arrowheads point at feldspar. **g:** Pebbly breccia (lithoclastic rudstone). Sample Poče Po1:4. **h:** Cobble breccia. Sample Hudajužna H6.8.

Discussion

One or two formations

For over 150 years, the volcano-sedimentary succession underlying the Bača dolomite formation has presented a considerable stratigraphic challenge. Based on the presence or absence of volcanics and tuff, respectively, some distinguished between the Ladinian Pseudozilja formation and the Carnian Amphiclina formation (Rakovec, 1950; Turnšek et al., 1982; Buser, 1986; Buser & Ogorelec, 1987), even though the early descriptions of both formations, based on observations from different geographic areas, do not mention volcanics or tuffs (Stur, 1858; Teller, 1885, 1889; Kossmat, 1901, 1907, 1910, 1913). Other authors suggest that the two represent the same formation (Kossmat, 1910, 1913; Čar et al., 1981; Ogorelec, 2011). The main volcanism in the eastern Southern Alps and the northern External Dinarides took place from the late Anisian to the early Ladinian (Gianolla et al., 1998; Kralj & Celarc, 2002; Dozet & Buser, 2009; Celarc et al., 2013; Smirčić et al., 2018; Gianolla et al., 2019; Kukoč et al., 2023; Oselj et al., 2023; Kukoč et al., 2024). However, reliably dated successions from the region show renewed volcanism in the late Ladinian and at the transition to the early Carnian (e.g. Jurkovšek, 1984; Kolar-Jurkovšek, 1991; Jelaska et al., 2003; Celarc, 2004, 2007; Kolar-Jurkovšek & Jurkovšek, 2019). Thus, the products of volcanism may indeed be limited to the upper Anisian – uppermost Ladinian/lowermost Carnian successions.

From the described sections, we summarize that the lithological compositions of the upper Pseudozilja and the Amphiclina formations (sensu Demšar, 2016) are virtually the same, comprising shale, siltstone, sandstone, bedded hemipelagic limestone, conglomerate, and breccia (including olistostromes) in varying proportions. Unfortunately, precise correlation between the sections is not possible due to the lack of biostratigraphic data. Although it would be expected from their position on the geological map that tuffs and/or volcanics would be present in the Črni Vrh (and maybe also in the Jesenica) sections this is not the case, even though the Črni Vrh section reaches 44 m in thickness. Volcanics and tuffs were recorded instead only in the Malenski Vrh section that belongs to the lower Pseudozilja formation. It must be emphasized, however, that the Malenski Vrh section is located in a different tectonic unit, in the Trnovo Nappe, which belongs to the External Dinarides. Thus, a question appears whether the tuffs and/or volcanics are common enough after the lower Ladinian to be useful as a distinct feature for the entire Pseudozilja formation. Instead, it could be said that volcanics and tuffs may indicate that the observed succession is of the late Anisian – latest Ladinian age, but their absence is not enough to recognize the observed unit as the Amphiclina formation. More sections from the upper Pseudozilja formation should be logged in order to further substantiate this proposition.

Sedimentary environment

The depositional environment of the described volcano-sedimentary succession has mostly only been hinted at (e.g. Rakovec, 1950; Turnšek et al., 1982; Flügel & Ramovš, 1970; Ramovš, 2004). Flügel and Ramovš (1970) interpreted the sedimentation of muddy sediments in the aphotic zone of the sedimentary basin within low energetic water conditions, with interruptions of carbonate sedimentation. The sections from Zgornja Davča were already investigated by Babić and Zupanič (1978), who interpreted the limestone beds as autochthonous marine sediments, and the sandstone as sediment of turbidity currents in a relatively shallow basin. Ramovš (2004) suggested deposition of fine-grained conglomerate, sandstone, and shale from turbidite flows. Rakovec (1950), Čar et al. (1981), and Skaberne and Čar (1986) all envisioned deposition in the transitional zone between the shoreline and the shelf (Čar et al. 1981). An interpretation of the sedimentary environment will be given based largely on the logged sections, and later on, drawing from more regional aspects.

The only section enclosing the lowermost succession of the Pseudozilja formation (sensu Demšar, 2016) is the Malenski Vrh section, which is, as mentioned before, located in an entirely different tectonic position, in the Trnovo Nappe, which belongs to the External Dinarides. The succession of volcanic rocks followed by lithoclastic-crystalloclastic tuff with intercalations of diabase uncomformably overlies the Lower Triassic oolitic limestone. The overlying, shale dominated succession with some larger sandstone lenses, interpreted as sand bars, indicates a relatively quiet shelf environment.

The other sections, representing the upper Pseudozilja formation (Črni Vrh 3–4), the upper Pseudozilja/the lower Amphiclina formation (Jesenica 1–2), and the lower Amphiclina formation (Novaki 1–4) have similar lithological compositions. Clastic sedimentary rocks prevail in all of these sections. The composition of conglomerate and sandstone is dominated by siliciclastic components, by fragments of volcanic rocks and their tuffs, followed by quartz and feldspar grains. In the muddy conglomerates that are present only in sections Jesenica 1 and 2, pebbles of sandstone predominate, although some limestone pebbles were also found in the Jesenica 2 section. Sediments were partly transported by turbidity currents and debris flows, as indicated by sedimentary textures (normal grading for turbidites, matrix support for debris flow deposits), and partly as hemipelagic deposits. Small scour channels indicate a N–S direction of transport. The coarsening-upward sequence of the Jesenice 1 section corresponds to the progradation of submarine fan deposits, with lower fan, dominated by turbidite deposits passing upwards into middle and perhaps upper fan, dominated by debris-flow deposits (Walker & Mutti, 1973).

The somewhat larger number of sections (Davča 1–2, Poče, Zakojca 1–2, Orehek, Hudajužna, Koritnica) logging the upper Amphiclina formation (sensu Demšar, 2016) allows us to observe vertical and lateral differences in sediment composition and in sedimentation within roughly the same stratigraphic interval. The Davča sections are the most eastward lying of these sections. The lowermost sedimentary succession of the Divača 1 section indicates predominantly calcareous and subordinate muddy hemipelagic sedimentation, interrupted by turbidity currents transporting sandy siliciclastic material. The rest of the section is characterised by predominately siliciclastic, fining-upward, retrograding succession. It begins with slump/debris flow deposits followed by sandy deposits of proximal turbidites, passing into muddy hemipelagic deposits and distal turbidites. Limestone hemipelagic sediments prevail in the upper part of the section. The Davča 2 section is dominated by hemipelagic limestone. In the upper part of the section, the non-terrigenous siliceous component within the sediment increased and was later concentrated in chert nodules.

The Hudajužna section and the lower part of the Poče section are characterized by the longest lasting relatively quiet sedimentary conditions. The lower part of the Hudajužna section comprises mostly hemipelagic limestone, interrupted by higher energy currents, and depositing conglomerate with limestone clasts. The upper part of the Hudajužna section and lower part of the Poče section indicate prevailing muddy sedimentation, interchanging with hemipelagic limestone sedimentation with intercalations of siliciclastic sandy sediments deposited by (mostly distal) turbidity currents.

The Zakojca sections show quick lateral changes of sedimentary conditions. The Zakojca 1 section indicates relatively quiet, muddy and hemipelagic limestone sedimentation that was locally interrupted by distal turbidity currents. In contrast, the sedimentary successions in the Zakojca 2 section indicate energetic, highly variable, predominately high energy sedimentary conditions with debris flows and high- and low-density turbidity currents, interchanging with hemipelagic sedimentation. In the lower two-thirds of the section, hemipelagic limestone prevails, with some admixture of siliciclastic components in the upper part. The uppermost muddy breccia deposited from debris flow, has only noncarbonate clasts, mostly of sandstone and shale. Debris flow was followed by hemipelagic muddy sedimentation. The orientation of the erosional channels indicates transport in a N–S direction; the sediments were deposited on or near the continental slope.

The Orehek section includes the thickest part of the upper Amphiclina formation and is characterized by the most intensive slumping – debris flows. Syndepositional folds indicate transport from the NE. Massive blocks of limestone from this section are currently interpreted as in-situ mud mounds.

The Koritnica section is the westernmost section of the upper Amphiclina formation. Its heterogeneous composition indicates particularly versatile sedimentary conditions. The lower part of the succession is dominated by hemipelagic carbonate sedimentation, interrupted by slumps/debris flows, turbidity, and higher energy currents transporting calcareous and siliciclastic sediments. The middle part of the section shows the most dynamic sedimentary conditions and is dominated by slide, slump, debris flow, and turbidity current deposits. The slumps indicate N to S transport of the sediment. Subordinate to the mass-flow deposits are hemipelagic sediments. Sedimentation largely took place on a slope generally inclined towards the south.

To summarize, the upper Pseudozilja formation and the Amphiclina formation consist of hemipelagic deposits intercalated with sediment that was transported via slides, slumps, debris flows, and turbidity currents. Sedimentation mostly took place on or near the continental slope, generally inclined towards the south, and the transport was largely from north to south. Only olistostromes in the Orehek section indicate a more easterly direction of sedimentary transport.

It appears that sedimentary conditions became more uniform towards the end of the Carnian, when carbonate sedimentation completely prevails over siliciclastics in all the sections. This could be due to the relative rise of the sea level, the shift of the coastline and/or change in the fluvial network, and the subsequent spreading of carbonate platforms (see Gianolla et al., 1998; Haas & Budai, 1999; Gawlick & Böhm, 2000; Gianolla et al., 2003; Berra et al., 2010).

Regional comparisons

The described volcano-sedimentary succession from the Slovenian Basin differs from contemporaneous volcano-sedimentary formations in the region in its pronounced thickness and in its higher shale content. Depending on the palaeogeographic position, the Pseudozilja/Amphiclina formations are succeeded either by the Bača dolomite formation in the late Carnian in the central part of the Slovenian Basin, or earlier (late Ladinian/early Carnian) by platform carbonates in the marginal parts of the basin (Šmuc & Čar, 2002).

According to Placer and Kolar-Jurkovšek (1990), the southernmost exposure of the Pseudozilja formation is the Zagorje area in the Posavje Hills. Considerable differences can be observed among individual sections further south, which structurally belong to the External Dinarides (see Dozet & Buser, 2009; Kolar-Jurkovšek & Jurkovšek, 2019; Oselj et al., 2023). Tuffs and volcanogenic sandstone usually occur in association with bedded limestone, dolostone, and marlstone (Buser, 1974; Jurkovšek, 1984; Dozet, 2006). A thick succession some hundreds of metres thick of Ladinian volcano-sedimentary succession from the Rute plateau in central-southern Slovenia was recently described by Kocjančič et al. (2022) and Rožič et al. (2024). This laterally highly variable succession consists of packages of tuff, volcanogenic sandstone, shale, marlstone, laminated limestone (calcimudstone), hemipelagic limestone, and resedimented limestones (calcarenite and limestone breccia).

In the Julian Alps and the Kamnik-Savinja Alps (Julian Nappes of the eastern Southern Alps), the volcano-sedimentary series occurs between Anisian platform limestone/dolostone (Contrin Formation) and Ladinian massive carbonates of the Schlern Formation (Jurkovšek, 1987; Celarc et al., 2013; Goričan et al., 2022; Gale et al., 2023). The most widespread unit, which can be considered the equivalent of the Buchenstein Formation from the western Julian Alps and the Dolomites (Celarc et al., 2013; Gale et al., 2023), consists of tuff, sandy claystone, marlstone, sandstone (some beds with plant fragments), and bedded limestone, with intercalations of volcanics and rarely volcaniclastic breccia (Ramovš, 1990). Limestone locally contains numerous involutinid foraminifers, small coral colonies, and bivalves (Ramovš, 1990; Gale et al., 2023). In the smaller half-grabens developed on top of the Contrin platform the Buchenstein Formation locally overlies pinkish nodular pelagic limestone of the Loibl (Ljubelj) Formation, and tuff and rhyolites and/or pinkish nodular limestone of the Vernar member, and the Uggowitz Breccia (Celarc et al., 2013; Gale et al., 2023). The cumulative thickness of the upper Anisian – lower Ladinian succession between the two platform units reaches up to a few tens of meters. Volcaniclastics also occur near the top of the Schlern Formation in the form of "pietra verde" tuffs associated with thin-bedded limestone with chert nodules and calcarenites, described as the Korošica Formation (Jurkovšek, 1984; Celarc, 2004, 2007).

Buchenstein-type facies is further present in many successions in Croatia and Bosnia and Herzegovina (Smirčić et al., 2018). Much thinner siliciclastic-dominant facies than in the Tolmin Nappe was documented in the Donje Pazarište section on the Velebit Mts. The series consists of 18 m of volcaniclastic (lithic) sandstone and shale, and 28 m of carbonate shale. Akin to sandstone from the herein described sections, sandstone from Donje Pazarište shows planar and cross lamination, and grading. The siliciclastic facies deposited via turbidity currents in a deepened basin, probably on a distal part of a submarine fan (Smirčić et al., 2020). The following lithologies consist of pyroclastic density-current facies, platy limestone with pyroclastics, limestone breccia, and slumped limestone with pyroclastics and chert (Smirčić et al., 2020).

Basinal deposits continue into the Carnian in the Southern Alps and the Internal Dinarides, whereas shallow water and terrestrial conditions prevail in the External Dinarides (Buser, 1989; Dozet, 2009; Gerčar et al., 2017). In the western Julian Alps, the Eastern and the Northern Dolomites, the Buchenstein Formation is followed by the Ladinian Zoppè Sandstone (arkosic turbiditic sandstone; slope fan), Aquatona Formation (pelagic limestone, tuff), Fernazza Formation (volcanics and volcaniclastics, chaotic breccia), the uppermost Ladinian Wengen Formation (volcanic-detritic sediments, gravity flow deposits), and the uppermost Ladinian - Carnian San Cassiano Formation (Gianolla et al., 1998; Neri et al., 2007; Mietto et al., 2020). The latter consists of alternating shale, marlstones, marly to pure micritic limestone, oolitic calcarenite, bioclastic and oncolytic calcarenite, and calcirudite. Volcaniclastic sandstone is present in various proportions, depending on the paleotopography. Mixing of carbonate and siliciclastic grains is frequent. Sandstone layers show erosional bases, normal grading, and planar and cross lamination, indicating turbiditic transport with episodes of debris flow and slumping (Neri et al., 2007). In the proximity of the Cassian platform, the lower boundary of the San Cassiano Formation can be defined based on the lowest occurrence of oolitic calcarenites, whereas elsewhere the boundary with the Wengen Formation may be difficult to decide (Neri et al., 2007). The lateral variability within the San Cassiano Formation, depending on the paleotopography, is consistent with the lateral variability observed among the sections studied herein. The San Cassiano Formation differs from the Carnian successions from the Slovenian Basin in greater proportion of calcarenites. In the Internal Dinarides, the upper Anisian shallow marine carbonates are locally overlain by breccia, tuffite and basalt, and/or the hemipelagic cherty limestone and distal turbiditic cherty limestone of the Kopaonik Formation (Schefer et al., 2010). Drowning of the platform took place in the late Anisian and onward up until the end of the early Ladinian. Sedimentation of the Kopaonik Formation lasted at least into the Norian (Schefer et al., 2010).

Finally, a notable terrigenous input characterises the upper Julian (Carnian) Tor Formation in the Julian Alps. The Tor Formation overlies peritidal carbonates and consists of siltstone, marly limestone and dolostone, micritic limestone, bivalve lumachellas, marlstone, and claystone (De Zanche et al., 2000; Gianolla et al., 2003; Gale et al., 2015). The siliciclastic input is thus notably younger and less pronounced than in the Tolmin Basin.

Conclusions

The Ladinian – Carnian volcano-sedimentary succession from the Slovenian Basin consists largely of shale, sandstone, and limestone (hemipelagic and gravity-flow deposits), with subordinate breccia/conglomerate. According to the present data, only the lower part of the Pseudozilja formation comprises lithologically distinct facies assemblage, with a substantial proportion of diabase and tuff. Despite previous suggestions by some authors, the lithological similarities between the upper part of the Pseudozilja formation and the Amphiclina formation documented herein seem to preclude a distinction between the two formations. Based on the continuous presence of thin-shelled bivalves and radiolarians, the entire succession deposited in an open marine setting. The common occurrence of carbonate gravity-flow deposits, debris breccias, slump and channel structures, suggests the succession deposited on or near continental slope. Channel directions and slump fold-axes suggest slope inclination towards the south and the prevailing transport direction from north to south. As the Ladinian – Carnian succession of the Slovenian Basin is dominated by shale, sandstone, and hemipelagic limestone, it is distinguished from deeper-marine successions of the same age in the Dinarides and in the Julian Nappes of the Southern Alps.

Acknowledgements

Fieldwork and laboratory work for this research were carried out in the scope of the research project "Sedimentological and geochemical research of the "Pseudozilja" and equivalent formations". Finalization of the paper was made possible thanks to research core fundings No. P1-0011 and P1-0195 is co-funded by the Slovenian Research and Innovation Agency. We are thankful to the anonymous reviewers who carefully read the manuscript and provided constructive remarks.

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