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Upper Carnian Clastites from the Lesno Brdo Area (Dinarides, Central Slovenia)

Zgornjekarnijski klastiti z območja Lesnega Brda (Dinaridi, osrednja Slovenija)

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Ključne besede: Zunanji Dinaridi, Lesno Brdo, karnij, tuval, klastični sedimenti, karbonatna konkrecija

Abstract

This paper presents a detailed study of the Tuvalian clastic member in the Lesno Brdo Area in Central Slovenia (External Dinarides). The member represents the uppermost part of the mixed siliciclastic – carbonate Carnian succesion that overlays the carstified emersion surface on top of the "Cordevolian" limestone and dolomite. The Tuvalian member is composed of red and violet sandy mudstone and marlstone that are interbedded with sandstone and gravelly sandstone. Calcite concretions are common, particularly in mudstone and marlstone. The succession was deposited on the flood plain, where fine-grained flood sediments are interrupted by medium- to coarse-grained crevasse splay sandstone and cross-stratified gravely sandstone of the small river channels. Alternatively, this succession could have been deposited in the distal zone – terminal splay/fan sediments. According to paleogeographic subdivison we suggest that the provenance area was located to the south, where carbonates, volcanoclastites/vulcanites as well as clastites were eroded.

Izvleček

V pričujočem članku je opisana litološka sestava t.i. tuvalskega klastičnega člena iz okolice Lesnega Brda v osrednji Sloveniji. Člen predstavlja zgornji del paketa karnijskih karbonatnih in klastičnih kamnin, ki prekrivajo kraško-erozijsko diskordanco na vrhu »cordevolskega« apnenca in dolomita. Tuvalski klastični člen sestavljajo rdeči do vijoličasti rahlo peščeni muljevci, oziroma laporovci, z vmesnimi plastmi apnenčevih polilitičnih peščenjakov in prodnatih peščenjakov. Predvsem drobnozrnati različki kamnin vsebujejo kalcitne konkrecije. Zaporedje je bilo odloženo na poplavni ravnici, kjer prevladujoče drobnozrnate poplavne sedimente prekinjajo vmesne plasti srednje do debelozrnatih peščenjakov prebojnih pahljač in navzkrižno laminiranih prodnatih peščenjakov manjših rečnih korit. Alternativno bi se to zaporedje lahko odložilo na območju zaključnih vršajev. Glede na takratno paleogeografijo sklepamo, da je bilo izvorno območje sedimenta na jugu, kjer so bile razgaljene in erodirane predvsem karbonatne, vulkanoklastične in tudi klastične kamnine.

Introduction

The Middle and Upper Triassic in the External Dinarides is dominated by thick dolomite and subordinate limestone successions that are, following the Carnian regional emersion and the formation of bauxite, interrupted by mixed clastic-carbonate series (Dozet, 1979; Jelen, 1990; Dozet, 2004; Celarc, 2004, 2008; Dozet, 2009; Čar, 2010). In the Lesno Brdo Area, located 15 km southwest of Ljubljana, the succession is composed of the lower clastic member, a middle limestone member and an upper clastic member Julian in age, overlain by carbonate and siliciclastic members that are Tuvalian in age. So far, only the Julian beds with rich bivalve macrofauna and microfossils have been investigated in this part of the succession (Jelen, 1990). Oblak (2001) also analysed the foraminiferal assemblage in the Julian limestone member. Up above, the Carnian succession passes into the Norian-Rhaetian Main Dolomite (Grad & Ferjančič, 1974; Jelen, 1990).

With the exception of the paleontological work in the Julian carbonate rocks, the thick succession of younger clastics was poorly studied. In this paper, we present a sedimentological analysis of the Tuvalian clastic member, the succession of which is well exposed along the road that connects the villages of Lesno Brdo and Drenov Grič with the village of Zaklanec.

Geological Setting

Structurally, the Lesno brdo area belongs to the External Dinarides (Fig. 1), more precisely to the Hrušica Nappe, which are characterized by a post-Eocene Dinaric thrusting phase with compression running in the northeast-southwest direction (Placer, 1999, 2008). In central and western Slovenia, the External Dinarides are composed predominantly of thick carbonate successions interbedded by Ladinian volcanoclastics and Carnian siliciclastics (Buser, 2010). The Carnian succession in the Lesno Brdo – Drenov grič area was investigated by Jelen (1990) (Figs. 2 and 3). According to his stratigraphic subdivision, the Carnian succession of the area starts with "Cordevolian" grey coarse-sparry dolomite and micritic limestone with an erosional unconformity on top. Above follow the Julian lower clastic member, Julian middle limestone member, and Julian upper clastic member (Jelen, 1990). The lowermost member is deposited on the macro-paleorelief; bauxite is locally present on its base (Dozet, 1979; Celarc, 2008; Ogorelec, 2011). The Tuvalian succession starts with the carbonate member composed of various limestones and terminates with the Tuvalian clastic member, which was investigated and presented herein. Jelen (1990) described this member as massive and shaley mudstone, violet-red multi-coloured sandstone and conglomerate with quartz pebbles. Upwards, it passes through transitional beds into the Norian-Rhaetian Main Dolomite.

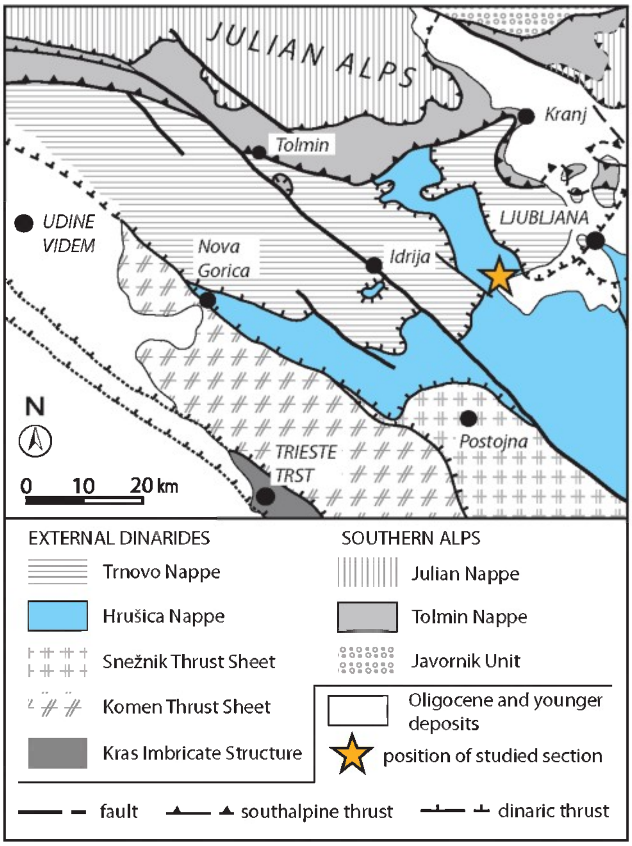

Fig. 1. Macrotectonic emplacement of the investigated area (modified from: Placer, 2008).

Methods

The sedimentological section at 1:50 scale was logged along the road that connects the villages of Lesno Brdo and Drenov grič with the village of Zaklanec (E 14°19'25", N 46°0'15"). During the logging, samples of coarse-grained clastites were taken with the aim of making thin sections and samples of fine-grained clastites for the XRD and geochemical analysis. Apart from host-rock samples, several samples of carbonate concretions were taken, from which two thin sections were made. On one such sample XRD and geochemical analysis was performed.

The nomenclature of clastics is based on their structure (for example: gravelly sandstone) and the naming of their composition-based classification (for example: quartz-polilithic gravelly sandstone).

The mineral compositions of three samples of fine-grained clastites and one sample of carbonate concretions were determined using a Panalytical PW 3830/40 XRD device, which uses a PW 1820 goniometer and a PW3830 X-ray generator, with copper tube PW 2273/20 under an electric current of 30 mA and a voltage of 40 kV. Difractograms were analysed with use of X'pert HighScore Plus software, together with the PAN - ICSD database for mineral determinations. For the geochemical analysis we used a Thermo Niton XL3t 900S-He Series Analyzer XRF device. For the elemental analysis a "mining" filter was used.

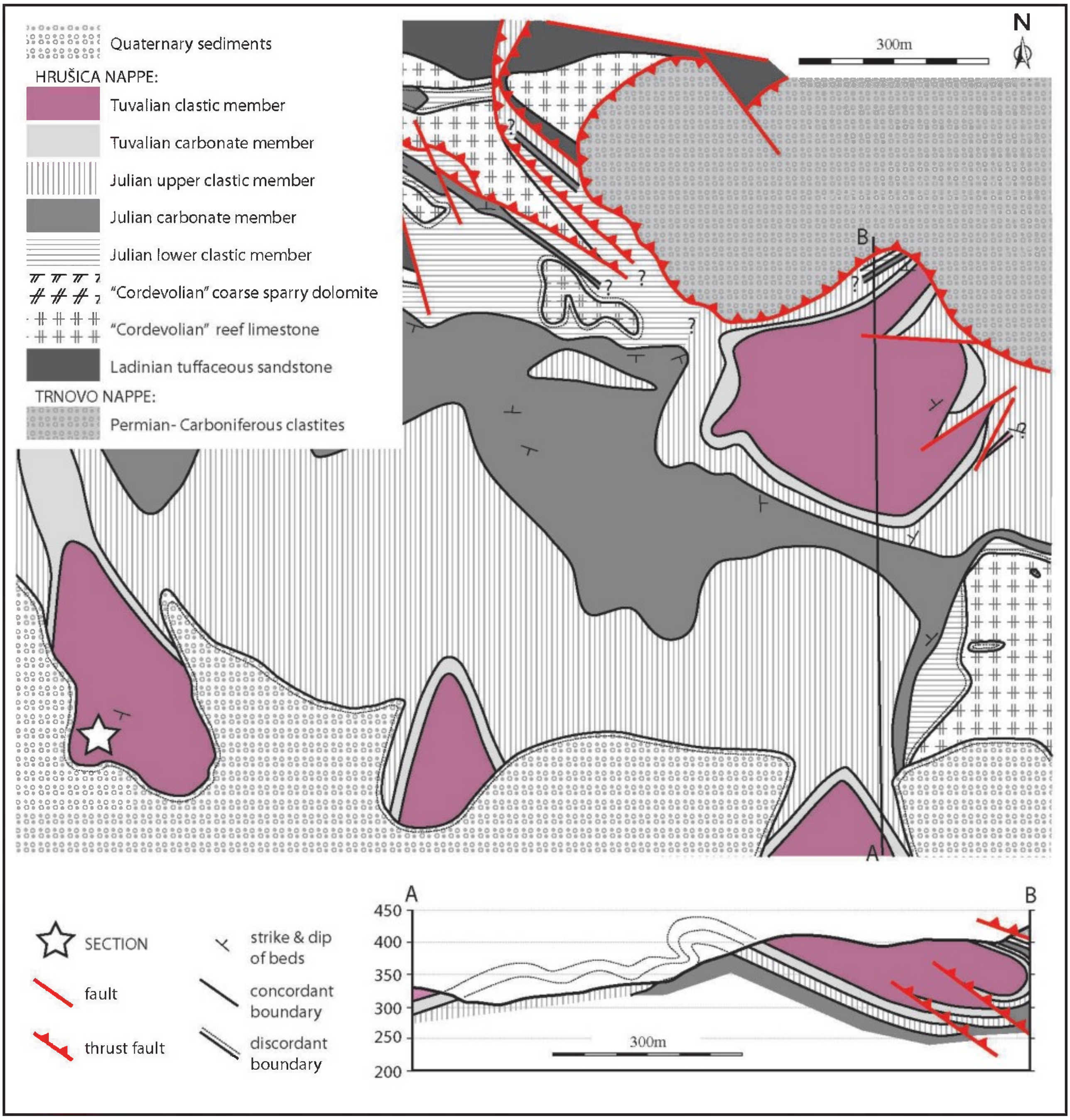

Fig. 2. Geological map and cross-section of the surrounding area and the location of the investigated section marked by a star (modified from: Jelen, 1990).

Description of Lesno Brdo section

The overall thickness of the section is 39 meters, with minor covered intervals between the 12th and 14th meter of the section (Fig. 3). The beds dip 20 degrees south–southwest. Through the entire section slightly sandy mudstone and marlstone prevail, which are coloured red and violet, but sporadic grey to greyish-green intervals also occur. The lower 15 meters of the section contain interbedded sandstone and gravelly sandstone, up to 60 cm thick (Fig. 4a). These beds are also coloured, mostly red and violet. Sandstone is deposited mostly in channels several meters wide and often exhibits cross lamination. An interbed between the 10th and 11th meter of the section shows clear normal grading. The number of gravelly-sandy interbeds decreases upwards along the section. Similarly, a lower sand content in the marlstone/mudstone is observed. Carbonate concretions are common largely in the lower 8 meters of the section. They appear in fine-grained as well as coarser- grained rocks. Upwards they occur only sporadically – locally between the 15th and 22nd meter, and at the 26th and 38th meter of the section.

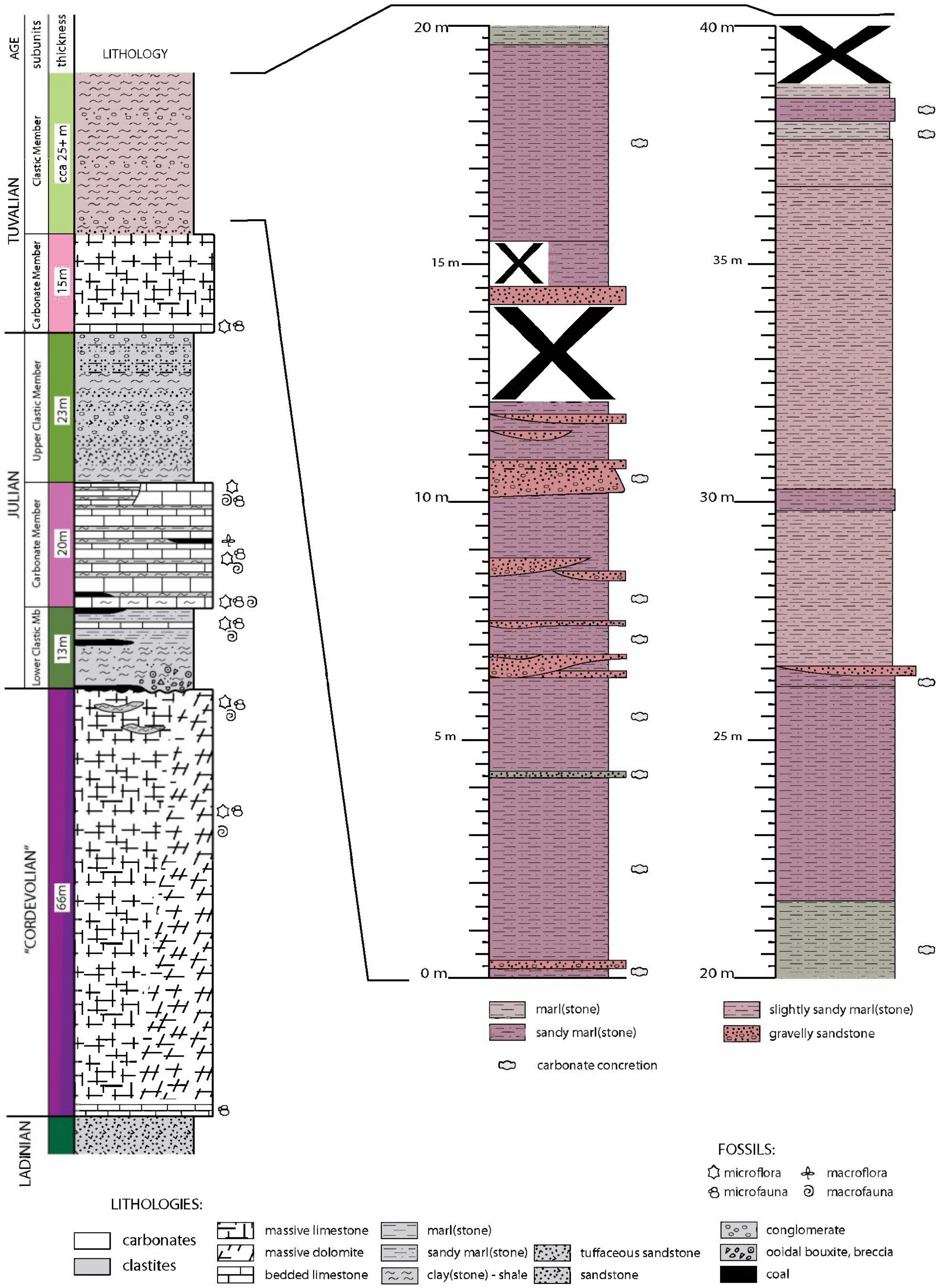

Fig. 3. Carnian succession of the Dinaric Carbonate Platform at Lesno Brdo (modified from: JELEN, 1990) with an investigated section of the Tuvalian clastic member.

Microfacies of the clastites

From the coarse-grained clastites we provide description of gravelly sandstones and fine- to medium-grained sandstones (Figs. 4b-e), and sandy mudstones/marlstones are described separately. Herein, we emphasise that the transitions between the described varieties are gradual.

(Quartz) carbonate lithic and poly-lithic gravelly to slightly gravelly sandstone

Most samples contain up to 60 % of grains, which are bounded by a fine-grained matrix (Fig. 4b) and in some rare cases, also by drusy mosaic and bladed calcite cements. The grain-size varies between 0.1 and 6 mm, with up to 30 % of grains larger than 2 mm. Two grain-size classes prevail – the first between 0.2 and 0.5 mm, and the second approximately 1.5 mm. Rocks are medium- to well-sorted, in some cases also poorly sorted. Grains are predominantly subrounded to subangular, and are in point, concavo-convex and occasionally sutured contacts and immature to semi-mature in texture. Beds are often normally graded.

The composition remains almost unchanged along the entire studied section, but we do find some minor variations, predominantly in the quantitative relationship between particular grain-types. The most common are carbonate lithoclasts, among which recrystallized micritic to microsparitic limestones with common partial replacement by opaque minerals, probably iron oxides, prevail. Some grains are entirely composed of opaque minerals. The surroundings of such grains (crystals) often show a red zoning coloring. Rarer but still present are darker micritic lithoclasts, which often appear in irregular shapes. Locally, the margins of these lithoclasts show silification, and some also show micritic coverings. Next in terms of abundance are quartz grains, grains of opaque mineral, feldspars and micas. Above the 10^{th} meter of the section lithoclasts of granitoid volcanic rocks are also common. Quartz grains can be subdivided into the following groups: A) monocrystal quartz grains, B) simple polycrystal quartz grains, and C) microcrystal quartz grains with or without mica. In most cases, such grains are likely recrystallized matrixes of granitoid volcanic rocks, whereas some grains could also be chert lithoclasts.

Among the cements, the most common are intergranular drusy mosaic and bladed calcitic cements. Corrosive carbonate cements, which substitute and obliterate the primary structure of quartz grains, are also present.

Quartz poly-lithic and carbonate lithic fine-to medium-grained sandstone

Samples contain some 60 % of grains, with intergranular spaces filled largely by a fine-grained matrix and in rare cases, also by drusy mosaic and bladed calcite cements. Grain-size varies between 0.05 mm and 2 mm, where most grains fall into size-classes of around 0.1 mm and 0.5 mm. Rocks are medium- to well-sorted, whereas grains are mostly subangular to subrounded. Grains are predominantly in concavo-convex and point contacts, while some grains are also floating. Rock texture is immature to semi-mature.

The composition is similar to the previously described gravelly sandstones, with a quantity of the carbonate lithoclasts. Owing to their smaller grain size the grains that can be definitely described as granitoid volcanics are also less common.

Quartz poly-lithic sandy mudstone or marlstone

The sample is composed of 35 % of grains in a fine-grained matrix. Most grains fall within the size-class of mud, and only some 30 % grains are between 0.06 and 0.4 mm in size. Grains are predominantly subrounded and floating, but rare point and concavo-convex contacts also appear. The studied sample is poorly sorted and immature in texture.

Among the grains the monocrystal quartz grains and carbonate lithoclasts prevail. Other, less frequent grains belong to polycrystal quartz, opaque mineral, feldspars micas and very rare lithoclasts of granitoid volcanic rock.

Microfacies of calcitic concretions

Concretions are composed of calcite (see also next chapter) and occur predominantly in fine-grained clastites (Figs. 5a-5b) in the lower part of the section, and rarely also present higher up. The outer margins of the concretions form irregular/nodular surfaces. Concretions consist mostly of fine-crystaline microsparite, whereas the size of crystals increases gradually and irregularly towards their interiors. These include rare, unreplaced quartz grains. Concretions are dissected by variously oriented fractures that

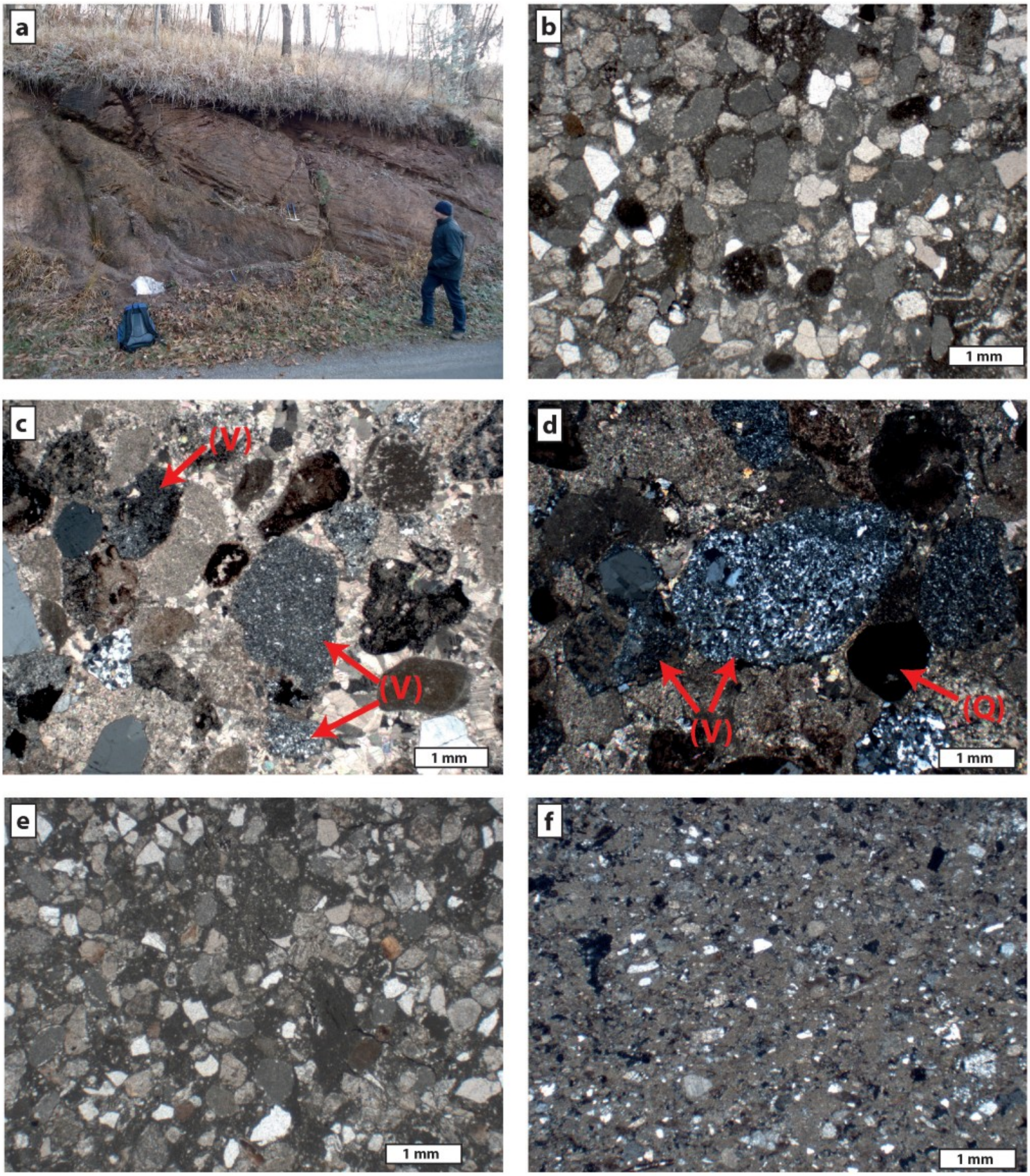

Fig. 4. Facies of the Tuvalian clastic member at Lesno Brdo. **a**) Lower part of the section in which sandy marlstone is interbedded with channels of gravelly sandstone. **b**) Medium- grained sandstone with quartz grains and carbonate lithoclasts. **c**) medium- to coarse-grained sandstone with various carbonate lithoclasts, quartz grains and lithoclasts of vulcanics (V); some carbonate grains contain opaque mineral (cross-polarized light). **d**) Pebbly sandstone with lithoclasts of vulcanics (V) with microcrystalline matrix and quartz and feldspar phenocrysts; various carbonate lithoclasts are also present; in the lower--right corner of the micrograph a monocrystal quartz grain is marked (Q) (cross-polarized light). **e**) Fine- to medium-grained sandstone composed predominantly of carbonate lithoclasts and monocrystal quartz grains; at margins of particular carbonate grains thin monocrystal quartz occurs. **f**) Sandy siltstone in which some grains up to 0.2 mm are visible – mostly quartz, carbonate lithoclasts and some lithoclasts of vulcanics (cross-polarized light).

form a complex network. They are filled predominantly by mosaic sparite, and in the marginal parts the surrounding sediment can be infiltrated in them. Sparite-filled fractures can occur also on the contact surface between concretion and sediment. Cement in this enveloping fracture is prismatic, with individual crystals oriented perpendicular to the concretion margin. This structure appears younger with respect to other fractures, as it also cuts parts where sed-

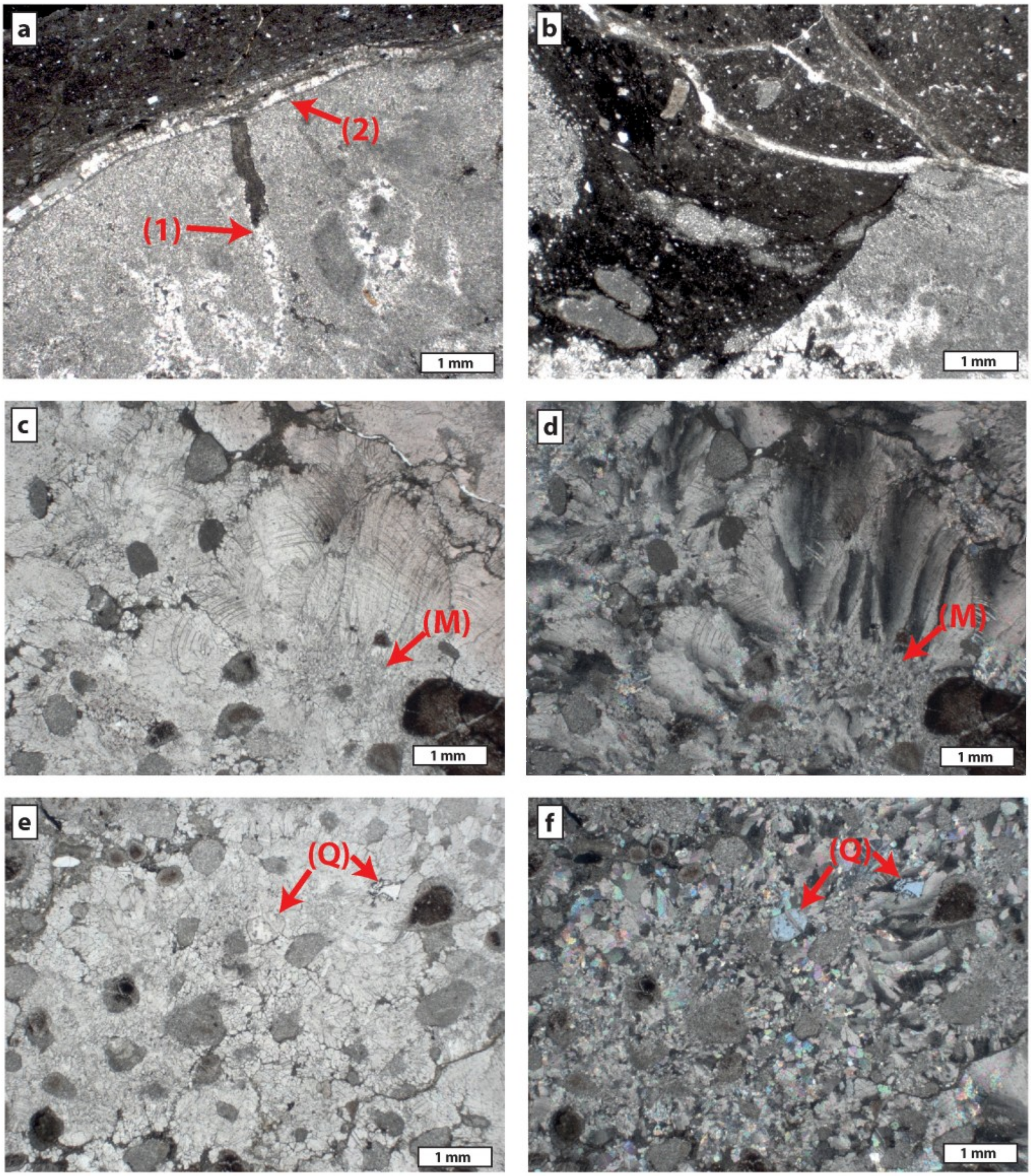

Fig. 5. Facies of the Tuvalian clastic member at Lesno Brdo. **a**) Concretion from mudstone/marlstone composed of microsparite, but irregular enlargement of crystals towards the center is also visible; in the center is a fracture filled mostly with mosaic cement (1), whereas in the marginal part it is infiltrated by sorrounding sediment; a younger generation of fractures (2) runs parallel to the margin of the concretion and is filled with prismatic cement. **b**) Concretion from mudstone/marlstone: signs of compaction – bending of laminae in the surrounding sediment and the younger generation of fractures in the part where the sediment is embedded deeper into the concretion **c**) Concretion from sandstone: larger carbonate lithoclasts are still visible, whereas the fine-grained fraction is replaced by radiaxial bladed cement; mosaic cement (M) is also present **d**) Figure 5c under cross-polarized light. **e**) Concretion from sandstone with recognisable carbonate lithoclasts as well as quartz grains; (Q) grains are bounded mostly by mosaic cement. **f**) Figure 5e under cross-polarized light.

iment infiltrates the fractures. The surrounding sediment is sandy mudstone, which on irregular contact with concretion shows signs of intense compaction, such as bended laminas and dissolution seams in the vicinity of the contact.

Calcite concretions occur rarely also in the more coarse-grained clastites (Figs. 5c-5f) and show more complex internal composition. In such concretions the primary texture and their composition only partially are still visible. Most recognizable are quartz grains and carbonate grains impregnated with opaque mineral. Some other carbonate grains are also visible, but they are mostly recrystallized into microsparite. In parts of the thin-section where the primary packing was denser, the intergranular space is filled with mosaic cement. In parts with looser primary packing the intergranular spaces are made of very coarse-crystalline radiaxial bladed calcite cement. The transition between the described textural types of concretion is gradual.

Mineral and geochemical composition

Mineralogical analysis was elaborated on three samples of fine-grained clastites and one sample of carbonate concretion. Clastites were sampled at approximately the 4th, 24th and 37th meter of the sections (samples: LB3,8; LB24,0 in LB37,2). The composition of samples taken from the fine-grained clastites is uniform. Samples contain five main minerals: quartz, calcite, hematite, alkaline plagioclase, and muscovite/illite (Fig. 6). Carbonate concretion, taken at approximately the 16th meter of the section (sample: LB15,7), is predominantly composed of calcite, whereas some quartz reflections/peaks were also detected.

Geochemical analysis was made on the same samples as were used for mineralogical analysis. Table 1 one presents concentrations of the main elements (in percentages), whereas Table 2 presents the concentrations of oxides of main elements.

The samples of fine-grained clastites (LB3,8; LB24,0 in LB37,2) show a higher volume of silicium bound to SiO_2 (quartz varieties and silicates). This is followed by calcium as a part of calcite and dolomite. The particularly lower magnesium content indicates the greater presence of calcite with respect to dolomite. Samples also contain iron as part of Fe_2O_3 (hematite). It is visible on the macro level as well as microscopically as a typically red colour of rocks/grains. Samples also contain some aluminium, which is bound in alumosilicates and potassium that is connected to the presence of the muskovite/illite. All three samples contain similar amount-values of their main constitutive elements.

Like fine-grained clastites, the results of mineralogical and geochemical content profiles also correspond to the carbonate concretion sample (Table 1 and Table 2), where the most common elements are calcium and silicon or, written in oxide-form, CaO and SiO_2.

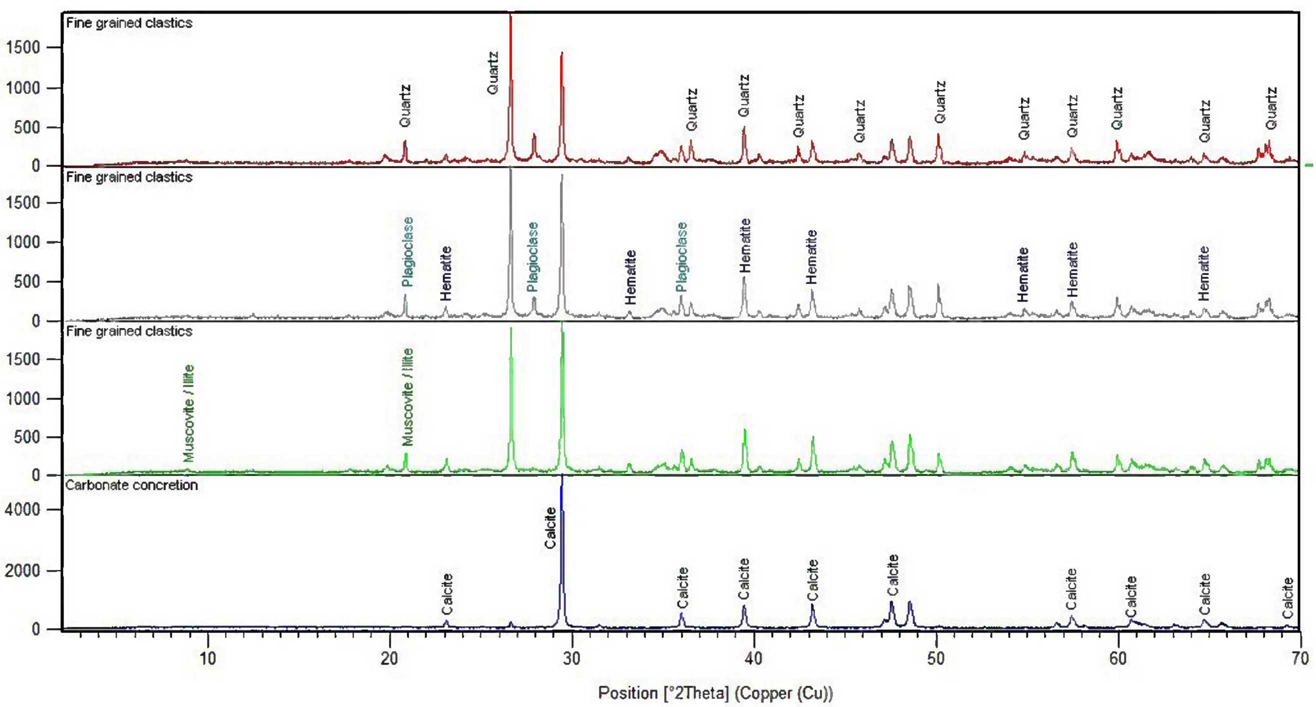

Fig. 6. Diffractograms of fine-grained clastics (upper three) and carbonate concretion (below).

Table 1. Concentration (as percentages) of main-group elements of fine-grained clastics (three upper) and carbonate concretion (below).

Element	Ca	K	Ti	Al	Mg	Si	Fe
LB 3.8	8.56	3.08	0.26	8.44	0.92	22.93	2.83
LB 24.0	14.18	2.24	0.20	6.84	1.14	18.21	2.81
LB 37.2	12.26	2.14	0.23	6.79	0.97	19.74	2.77
LB 15.7	35.86	0.14	0,03	0.89	0.95	2.99	0.63

Table 2. Percentages of main-group element oxides of fine-grained clastics (three upper) and carbonate concretion (below).

Oxide	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	TiO_2
LB 3.8	49.06	15.94	4.05	1.53	11.97	3.71	0.43
LB 24.0	38.95	12.93	4.01	1.90	19.84	2.70	0.34
LB 37.2	42.24	12.84	3.96	1.61	17.16	2.57	0.38
LB 15.7	6.39	1.68	0.91	1.57	50.17	0.17	0.05

Sedimentary analysis of Lesno Brdo section

The studied succession is composed exclusively of clastic rocks, where fine-grained clastics (sandy mudstones/marlstones) prevail and are interbedded with (quartz) poly-lithic sandstones and gravelly sandstones. The composition of clastics is indicative of continental sedimentation, whereas facies, structure and texture emplace the studied section in an alluvial environment, most probably a floodplain. Fine-grained clastics are suspension sediments of flood events; thin-bedded and structureless sandstones can be described as crevasse-splay deposits, whereas channelized and sometimes cross-laminated gravelly sandstones can be interpreted as deposits of either crevasse-channels or small meandering river channels (Skaberne, 1995; Bridge, 2003; Miall, 2006; Aslan, 2013).

An arid climate, which is typical for the Upper Carnian (Breda et al., 2009; Kiessling, 2010), is indicated in the studied section by a characteristic red to violet rock colour, which is a consequence of the presence of iron in oxide form (hematite), and by the presence of carbonate concretions (Alonso-Zarza, 2003; Khalaf, 2007; Moussavi-Harami, 2009; Breda & Preto, 2011). Given the pronounced arid conditions, the studied section could alternatively be interpreted as terminal fan deposits of a dryland river system with a diminishing discharge down-flow, causing a transition from a channelized to an unconfined flow (Nichols & Fisher, 2003).

Like the sedimentation on terminal fans, was interpreted a comparable Travenanzes Formation of the Dolomites was interpreted (Breda et al., 2009; Breda & Preto, 2011; Preto et al., 2015), where based on the overall analysis of far-better exposed Tuvalian rocks the authors presented a comprehensive sedimentological/facies model (Fig. 7). The southernmost facies zone A, in which also the Lesno Brdo studied section could be emplaced, is characterized by meandering dry-land rivers concluding in terminal fans. This zone passes through sabkhas and tidal flats of facies zone B to facies zone C with restrictive lagoons and sub-tidal marine environments. The Travenanzes Formatian is also characterized by the presence of carbonate concretions, mostly dolocretes. Preto and colleagues (2015) consider a dolomite as a primary diagenetic mineral. In contrast to carbonate concretions of the Travenanzes Formation, at Lesno brdo these are composed of calcite. In the future, it would be worthwhile making additional geochemical and mineralogical analyses with the aim of defining their formation more precisely.

The direction of transport cannot be distinguished from the data on the Lesno Brdo section, but taking into consideration the paleogeographic reconstruction of the Upper Triassic, where the deep marine Slovenian Basin was located to the north (Buser, 1989; Gale, 2010; Gale at al., 2012; 2016), we conclude that the sediment source-area was generally located to the south (present-day orientation). The composition of sediments indicates that in the hinterland, i.e. the provenance area of clastites, outcropping rocks were carbonates, volcanoclastites/vulcanites and possibly also clastites. Some grains, like those composed of coarse sparite or opaque mineral, could be of pedogenic origin. An intense pedogenesis and formation of carbonate and iron concretions occurred on the dried flood plain, which was followed by deflation, fragmentation of these into smaller grains, and redeposition by wind within a series of diverse sub-environments (Breda & Preto, 2011).

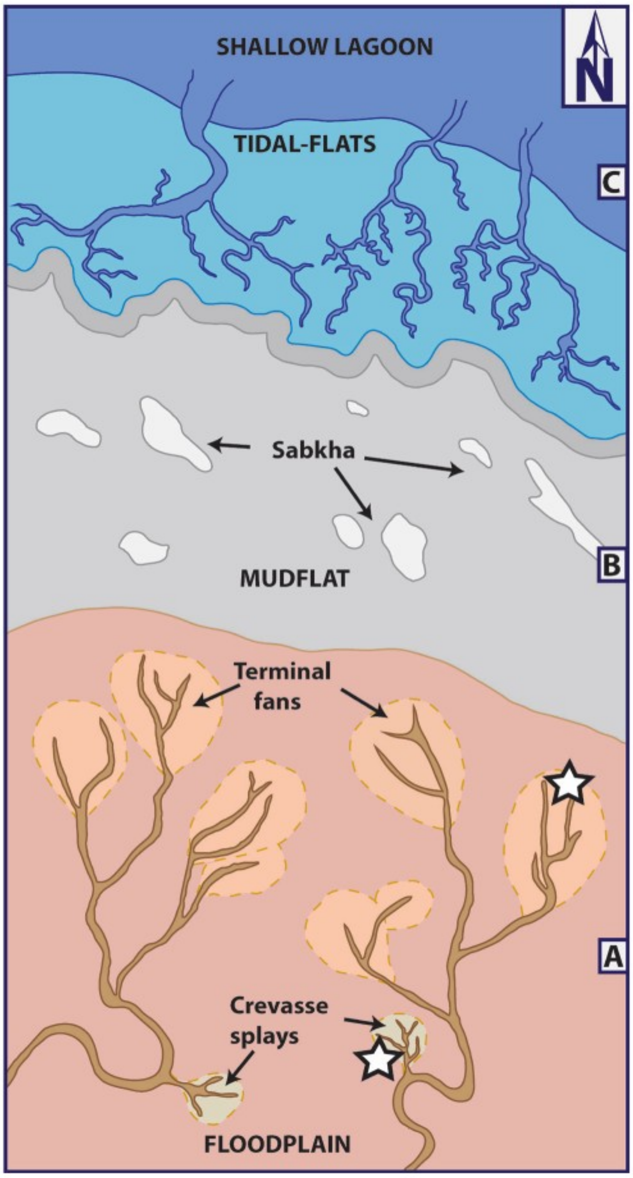

Fig. 7. Schematic paleoenvironmental reconstruction of the Travenanzes Formation (modified from Breda & Preto, 2011) A = aluvial plain with river channels, terminal fans, crevasse splays and a flood plain; B = Mudflat and coastal sabkha; C = Carbonate tidal flats and shallow lagoons. The stars mark the two most likely locations of the Lesno Brdo area.

Conclusions

The studied upper Carnian (Tuvalian) succession from the Lesno Brdo area consists of red and violet slightly sandy mudstone and marlstone, which are interbedded with sandstone and gravelly sandstone. Facies association is typical for sedimentation of flood plain deposits interrupted by medium- to coarse-grained sediments of crevasse splay or terminal fans, and less commonly of small-scale river channels. The composition indicates that in the (south-located) source area carbonate, volcanoclastic and siliciclastic rocks were eroded, while some grains could be of pedogenic origin.

Correlation with the sedimentological model of Tuvalian strata from the Dolomites in Italy (Travenanzes Formation) puts our section within facies zone A, which is characterized by sediments from flood plains, meandering river beds, crevasse splays and terminal fans. The presence of hematite and carbonate (calcite) concretions indicates an arid continental climate during the process of deposition.

Acknowledgments

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Zgornjekarnijski klastiti z območja Lesnega Brda (Dinaridi, osrednja Slovenija)

Uvod

Srednje in zgornjetriasno zaporedje na območju Zunanjih Dinaridov predstavljajo predvsem debeli horizonti dolomitov in podrejeno apnencev, katere v karniju po regionalni emerziji in tvorbi boksitov prekinja mešana serija klastičnih in karbonatnih kamnin (Dozet, 1979; Jelen, 1990; Dozet, 2004; Celarc, 2004, 2008; Dozet, 2009; Čar, 2010). Na območju Lesnega Brda, 15 km jugozahodno od Ljubljane, zaporedje predstavljajo julski spodnji klastični člen, julski srednji apnenčevo – lapornati člen, julski zgornji klastični člen, tuvalski karbonatni člen in tuvalski klastični člen. Do sedaj je bila podrobno raziskana le školjčna združba julskih plasti (Jelen, 1990). Oblak (2001) je pozneje v julskem apnenčevo – lapornatem členu določila še foraminiferno združbo. Karnijske kamnine navzgor postopno prehajajo v Glavni dolomit (Grad & Ferjančič, 1974; Jelen, 1990).

Z izjemo omenjenih paleontoloških analiz, predvsem julskih karbonatov, debelo zaporedje klastičnih plasti nad njimi ni bilo deležno podrobnih geoloških raziskav. V članku predstavljamo sedimentološko analizo tuvalskega klastičnega člena, katerega zaporedje je lepo razgaljeno v useku ob cesti, ki povezuje Drenov Grič in Zaklanec.

Geološka umestitev

Raziskovano ozemlje pripada geotektonski enoti Zunanjih Dinaridov (sl. 1), natančneje Hrušiškemu pokrovu, za katero je značilna posteocenska dinarska narivna tektonska faza s kompresijo v smeri severovzhod – jugozahod (Placer, 1999, 2008). Zunanje Dinaride v zahodni in osrednji Sloveniji sestavljajo predvsem debelo zaporedje mezozojskih karbonatnih kamnin, katero v ladiniju in karniju prekinjajo intervali vulkanoklastične in klastične sedimentacije (Buser, 1989, 1996). Karnijsko zaporedje je na območju Lesnega Brda in Drenovega Griča proučeval Jelen (1990) (sl. 2-3). Po njegovi razdelitvi se karnijsko zaporedje ožjega območja začne s »cordevolskimi« sivimi zrnatimi dolomiti in mikritni apnenci. Nad erozijsko diskordanco ležijo julski spodnji klastični člen, srednji apnenčevo – lapornati člen in zgornji klastični člen (Jelen, 1990). Prvi člen je odložen na makropaleoreliefu. Na sami bazi so lokalno prisotni boksiti (Dozet, 1979; Celarc, 2008; Ogorelec, 2011). Tuvalsko zaporedje se začne s karbonatnim členom, katerega sestavljajo raznoliki apnenci, zaključi pa se s tuvalskim klastičnim členom, v katerem se nahaja naš raziskani profil. Jelen (1990) je ta člen opredelil kot masivne in skrilave muljevce, vijolično-rdeče pisane apnenčeve peščenjake in konglomerate s prodniki kremena. Navzgor klastično karnijsko zaporedje preko prehodnih plasti preide v norijsko – retijski glavni dolomit.

Sl. 1. Geotektonska umestitev območja raziskav (prirejeno po Placer, 2008). Glej angleški del prispevka.

Sl. 2. Geološka karta in prerez ožjega območja z lokacijo raziskanega profila označeno z zvezdo (prirejeno po Jelen, 1990). Glej angleški del prispevka.

Metode

Detajlni sedimentološki profil je bil posnet v merilu 1:50 v useku ob cesti, ki povezuje Lesno Brdo, oziroma Drenov grič in Zaklanec (E 14°19’25”, N 46°0’15”). Ob snemanju profila so bili nabrani vzorci debelozrnatih kamin, iz katerih so bili narejeni petrografski zbruski, in vzorci drobnozrnatih kamnin, na katerih je bila izvedena rengtenska in kemijska analiza. Poleg tega smo nabrali tudi nekaj vzorcev karbonatnih konkrecij, iz katerih sta bila narejena dva petrografska zbruska. Na enem vzorcu konkrecije je bila prav tako izvedena rentgenska in kemijska analiza. Poimenovanje kamnin temelji na strukturi (npr. prodnati peščenjak) in imenovanju glede na klasifikacijo po sestavi (npr. kremenov polilitični prodnati peščenjak), kot predlaga Skaberne (1980a, b). Mineralna sestava treh vzorcev drobnozrnatih kamnin in enega vzorca konkrecije je bila določena z rentgensko praškovno difrakcijsko metodo (XRD) na napravi Panalytical PW 3830/40. Naprava deluje z goniometrom PW 1820 in generatorjem PW3830, z bakreno cevjo PW 2273/20 pri jakosti toka 30 mA in napetosti 40 kV. Difraktograme smo rešili s pomočjo programa X’pert HighScore Plus, z nameščeno PAN - ICSD podatkovno bazo za določevanje mineralov. Kemijska analiza je bila narejena z rentgensko fluorescenčno spektroskopijo (XRF) na napravi Thermo Niton XL3t 900S-He Series Analyzer. Za merjenje elementne sestave sedimenta je bil uporabljen način »mining«.

Opis profila Lesno Brdo

Skupna debelina raziskanega zaporedja znaša 39 m, z vmesnim pokritim delom med 12. in 14. m (sl. 3). Plasti vpadajo približno proti jugu z vpadom 200/20°. V zaporedju prevladujejo rdeči do vijoličasti peščeni muljevci in laporovci s posameznimi plastmi bolj sivkaste do sivo-zelene barve. Predvsem v prvih 15 m so pogoste do 60 cm debele plasti rdečih do vijoličnih peščenjakov in prodnatih peščenjakov, prav tako prevladujoče rdeče do vijoličaste barve (sl. 4a). Ti peščenjaki so večinoma odloženi v kanalih, širokih do nekaj metrov in imajo pogosto izraženo navzkrižno laminacijo. Plast med 10. in 11. m ima zelo dobro izraženo postopno zrnavost. Številčnost prodnato – peščenih plasti se navzgor po profilu zmanjša, prav tako se niža vsebnost peščene komponente znotraj muljevcev, oziroma laporovcev. Predvsem v prvih 8 m so zelo pogoste kalcitne konkrecije velikosti med 0,5 in 4 cm. Pojavljajo se tako v drobno, kot tudi debelejše zrnatih različkih kamnin. Višje nastopajo le še poredko – lokalno med 15. in 22. m, ter v plasteh nad 26. in nad 38. m profila.

Sl. 3. Shematski stratigrafski stolpec karnijske stratigrafije pri Lesnem Brdu (prirejeno po Jelen, 1990) z umeščenim detajlnejšim sedimentološkim profilom tuvalskega klastičnega člena. Glej angleški del prispevka.

Mikrofacies klastičnih kamnin

Iz bolj debelozrnatih klastičnih različkov podajamo opis prodnatih peščenjakov in drobno do srednjezrnatih peščenjakov (sl. 4b-4e), posebej pa opis peščenih muljevcev oziroma laporovcev. Pri tem poudarjamo, da so prehodi med opisanimi različki postopni.

(Kremenovi) karbonatno litični in polilitični prodnati do malo prodnati peščenjaki

Večina vzorcev vsebuje do 60 % zrn, ki so vezana z drobnozrnato osnovo (sl. 4b), redkeje tudi z medzrnskim druzimozaičnim in stebričastim kalcitnim cementom. Velikost zrn se giblje med 0,1 in 6 mm, do 30 % zrn je večjih od 2 mm. Prevladujoča sta dva velikostna razreda zrn, velikosti med 0,2 in 0,5 mm in približno 1,5 mm. Sortiranost kamnine je srednja do dobra, v posameznih primerih tudi slaba. Prevladujoča oblika zrn je polzaobljena do pologlata, kontakti so točkovni, konkavno konveksni in lahko tudi stilolitski. Struktura je nezrela do polzrela. Plasti so pogosto normalno postopno zrnate.

Sestava zrn in razmerje med njimi se skozi celoten profil skorajda ne spreminjata, a vseeno so prisotna manjša odstopanja predvsem v količinskih odnosih posameznih vrst zrn. Najpogostejši so karbonatni litoklasti, med katerimi prevladujejo rekristalizirani mikritni do mikrosparitni klasti, v katerih je pogosto prisoten nepresevni mineral – najverjetneje železov oksid. Posamezna zrna so v celoti sestavljena iz nepresevnega minerala. Okolica takih zrn (kristalov) je pogosto conarno rdeče obarvana. Manj pogosti so temnejši mikritni litoklasti, pogosto nepravilnih oblik. Lokalno so ti klasti okremenjeni po robovih. Posamezni karbonatni litoklasti imajo tudi mikritne obloge. Naslednja po pogostosti so zrna kremena, sledijo zrna nepresevnih mineralov, glinencev, sljud in od 10. m zaporedja višje tudi pogosti klasti granitoidnih predornin. Kremenova zrna bi lahko uvrstili v naslednje skupine: A) monokristalna kremenova zrna, B) preprosta polikristalna kremenova zrna in C) mikrokristalni kremen z ali brez lističev sljude; najverjetneje gre za rekristalizirano steklasto osnovo granitoidnih predornin, del teh zrn bi lahko bil tudi roženec.

Med cementi so najpogostejši medzrnski druzimozaični in stebričasti kalcitni cement. Pojavlja se tudi kalcitni korozivni cement, ki nadomešča kremen in s tem zabriše primarno strukturo kremenovih zrn ter otežuje njihovo natančno opredelitev.

Kremenovo polilitični in karbonatno litični drobno do srednje zrnati peščenjaki

Vzorci vsebujejo okoli 60 % zrn, katera povezuje drobnozrnata osnova, redkeje tudi medzrnski druzimozaični in stebričasti kalcitni cement. Velikost zrn se giblje med 0,05 in 2 mm, s tem da večina zrn sodi v velikostni razred od 0,1 do 0,5 mm. Sortiranost kamnine je srednja do dobra, oblika zrn predvsem pologlata do polzaobljena. Kontakti so večinoma konkavno-konveksni in točkovni, najdemo pa tudi lebdeča zrna. Struktura kamnine je nezrela do polzrela.

Sestava je podobna kot v predhodno opisanih prodnatih peščenjakih, s tem da se zniža vsebnost karbonatnih litoklastov. Zaradi manjše zrnavosti je manjša tudi vsebnost zrn, ki jih lahko nedvoumno opredelimo kot litoklaste granitoidnih predornin.

Kremenov polilitični peščeni muljevec, oziroma laporovec

Kamnino sestavlja do 35 % zrn v drobnozrnati osnovi. Večino zrn sodi v velikostni razred mulja, le okoli 30 % zrn je velikih od 0,06 do 0,4 mm. Zrna so večinoma polzaobljena in lebdeča, prisotni so le posamezni točkovni in konkavno – konveksni kontakti. Sortiranost kamnine je slaba, struktura nezrela.

Med zrni prevladujejo zrna monokristalnega kremena in drobni karbonatni litoklasti. Prisotna so tudi posamezna polikristalna zrna kremena, nepresevni minerali, glinenci, sljude in zelo redki litoklasti granitoidne predornine.

Sl. 4. Faciesi tuvalskega klastičnega člena pri Lesnem Brdu. **a**) Spodnji del profila, kjer peščeni laporovec prekinjajo kanali prodnatih peščenjakov. **b**) Srednje zrnati peščenjak z zrni kremena in karbonatnimi litoklasti. **c**) Srednje do debelo zrnati peščenjak z raznovrstnimi karbonatnimi litoklasti, zrni kremena in litoklasti predornin (V); posamezna karbonatna zrna vsebujejo nepreseven mineral. (X-Nikoli). **d**) Prodnati peščenjak z litoklasti predornin (V) z mikrokristalno osnovo, ter vtrošniki kremena in glinencev; prisotni so tudi raznovrstni karbonatni litoklasti. V spodnjem desnem delu je vidno zrno monokristalnega kremena (Q) (X-Nikoli). **e**) Drobno do srednje zrnati peščenjak, katerega sestavljajo predvsem karbonatni litoklasti in zrna monokristalnega kremena. Ob robovih posameznih karbonatnih litoklastov se pojavlja droben mikrokristalen kremen. **f**) Rahlo peščen muljevec, kjer so vidna posamezna do 0,2 mm velika zrna – večinoma kremen, karbonatni litoklasti in posamezni klasti predornin (X-Nikoli). Glej angleški del prispevka.

Mikrofacies kalcitnih konkrecij

Konkrecije so kalcitne sestave (glej tudi naslednje poglavje) in se pojavljajo predvsem v drobnozrnatih klastitih (sl. 5a-5b) v spodnjemu delu profila, redke pa tudi višje. Zunanji robovi konkrecij tvorijo nepravilno/gomoljasto površino. Konkrecije sestavlja predvsem drobnokristalni mikrosparit. Velikost kristalov se proti notranjosti konkrecij postopoma in nepravilno veča. V konkrecijah so vidna tudi redka zrna nenadomeščenega kremena. Konkrecije so razpokane z mrežo različno usmerjenih razpok, ki so večinoma zapolnjene s sparitnim mozaičnim cementom, na zunanji delih konkrecij pa je lahko v njih infiltriran obdajajoči sediment. Sparitne žilice se lahko pojavljajo tudi na stiku med konkrecijo in sedimentom. Cement v tej obdajajoči žilici je prizmatski, s posameznimi kristali orientiranimi pravokotno na rob konkrecije. Ta tekstura je očitno mlajša od preostalih razpok, saj poteka tudi preko dela kjer sediment infiltrira v razpoke. Obdajajoči sediment je peščeni muljevec, ki na stiku z nepravilno površino konkrecije kaže močne znake kompakcije, kot so povijanje lamin ali pojavljanje disolucijskih šivov v bližini stika.

Kalcitne konkrecije se redko pojavljajo tudi v debeleje zrnatih klastitih (sl. 5c-5f). Te kažejo bolj kompleksno notranjo zgradbo. V njih je še vedno vidna prvotna struktura in deloma sestava sedimenta. Najlepše so vidna zrna kremena in karbonatna zrna impregnirana z nepresevnim mineralom. Vidna so tudi nekatera preostala karbonatna zrna, ki so praviloma prekristaljena v mikrosparit. V delih preparata, kjer je prvoten zlog kamnine bolj gost, se med zrni pojavlja mozaični cement. V delih z bolj redkim primarnim zlogom pa prostore med zrni tvori zelo debelo kristalen radialno – žarkovit stebričast kalcitni cement. Prehod med obema opisanima strukturnima tipoma konkrecij je postopen.

Sl. 5. Faciesi tuvalskega klastičnega člena pri Lesnem Brdu. **a**) Konkrecija iz plasti muljevca/laporova, sestavljena iz mikrosparita. Vidno je tudi nepravilno večanje velikosti kristalov proti notranjosti konkrecije. V sredini je razpoka (1), ki je v večji meri zapolnjena z mozaičnim cementom. V obrobnem delu konkrecije je vanjo infiltriran obdajajoči sediment. Mlajša generacija razpok (2) je vzporedna z robom konkrecije in zapolnjena s prizmatskim cementom. **b**) Konkrecija iz plasti muljevca/laporova z znaki kompakcije – povijanje lamin v obdajajočem muljevcu in mlajših generacij razpok na mestu, kjer se sediment zajeda v konkrecijo. **c**) Konkrecija iz peščenjaka: ohranjena so večja karbonatna litoklastična zrna, bolj drobnozrnato frakcijo prvotnega sedimenta pa zamenjuje radialno – žarkovit stebričast cement. Prisoten je tudi mozaični cement (M). **d**) Slika 5c pod navzkrižnimi Nikoli. **e**) Konkrecija iz peščenjaka: prepoznavna so karbonatna litoklastična zrna in tudi zrna kremena(Q). Zrna povezuje predvsem mozaični cement. **f**) Slika 5e pod navzkrižnimi Nikoli. Glej angleški del prispevka.

Mineraloška in geokemična analiza

Naredili smo minerološko analizo treh vzorcev drobno zrnatih klastičnih kamnin in enega vzorca karbonatne konkrecije. Vzorci klastitov so bili vzeti na približno 4., 24. in 37. m profila (LB 3,8; LB24,0 in LB37,2). Mineralna sestava drobnozrnatih klastitov je podobna. Vsebujejo pet glavnih mineralov: kremen, kalcit, hematit, kisli plagioklazi in muskovit/ilit (sl. 6). Vzorec konkrecije, ki je bil vzet približno na 16. m profila (LB15,7), sestavlja predvsem kalcit in v manjši meri kremen. Na istih vzorcih kot mineraloška analiza je bila opravljena tudi geokemična analiza. Tabela 1 prikazuje koncentracijo glavnih prvin (v odstotkih), Tabela 2 pa deleže oksidnih oblik glavnih prvin.

V vzorcih drobnozrnatih klastitov (LB 3,8; LB24,0 in LB37,2) je največji delež silicija, ki se veže v SiO_2 (kremenovi različki in ostali silikati). Količinsko mu sledi kalcij, ki gradi minerala kalcit in dolomit. Manjša vsebnost magnezija, nam kaže večinsko pojavljanje kalcita in ne dolomita. V vzorcih je tudi železo, ki se veže v Fe_2O_3 (hematit). V vzorcih je tudi nekaj aluminija, ki se veže v alumosilikate, in kalija, ki je vezan na prisotnost muskovita/ilita. Vsi trije vzorci imajo zelo podobne količinske vrednosti glavnih prvin.

Podobno kot pri drobnozrnatih klastitih se ujemajo rezultati rentgenske in kemijske analize tudi pri vzorcih karbonatne konkrecije (Tabela 1 in Tabela 2), kjer sta najbolj pogosta elementa kalcij in silicij, oziroma CaO in SiO_2 zapisano v oksidnih oblikah.

Sl. 6. Difraktogrami drobnozrnatih klastiov (trije zgornji) in karbonatne konkrecije (spodaj). Glej angleški del prispevka.

Tabela 1. Koncentracija (v procentih) glavnih prvin drobnozrnatih klastitov (trije zgornji) in karbonatne konkrecije (spodaj).

Element	Ca	K	Ti	Al	Mg	Si	Fe
LB 3,8	8,56	3,08	0,26	8,44	0,92	22,93	2,83
LB 24,0	14,18	2,24	0,20	6,84	1,14	18,21	2,81
LB 37,2	12,26	2,14	0,23	6,79	0,97	19,74	2,77
LB 15,7	35,86	0,14	0,03	0,89	0,95	2,99	0,63

Tabela 2. Deleži (v procentih) oksidnih oblik glavnih prvin drobnozrnatih klastitov (trije zgornji) in karbonatne konkrecije (spodaj).

Oxide	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	TiO_2
LB 3,8	49,06	15,94	4,05	1,53	11,97	3,71	0,43
LB 24,0	38,95	12,93	4,01	1,90	19,84	2,70	0,34
LB 37,2	42,24	12,84	3,96	1,61	17,16	2,57	0,38
LB 15,7	6,39	1,68	0,91	1,57	50,17	0,17	0,05

Sedimentacijska analiza raziskanega profila

Raziskano zaporedje sestavljajo izključno klastične kamnine, kjer prevladujejo zelo drobnozrnati klastiti (peščeni muljevci oziroma laporovci), le te pa prekinjajo posamezne plasti (kremenovo) polilitičnih peščenjakov in prodnatih peščenjakov. Sestava klastitov kaže na kontinentalno sedimentacijsko okolje, medtem ko facielna združba, struktura in teksture umeščajo raziskano zaporedje v aluvijalno okolje, natančneje poplavno ravnico. Drobnozrnate klastite interpretiramo kot sediment, odložen iz suspenzije ob poplavnih dogodkih. Tankoplastnate peščenjake brez opaznih tekstur lahko interpretiramo kot sediment prebojnih pahljač, kanalizirane in občasno navzkrižno laminirane prodnate peščenjake pa kot sedimente rečnih korit manjših meandrirajočih rek (Skaberne, 1995; Miall, 1996; Bridge, 2003; Aslan, 2013).

Aridna klima, ki je značilna za večji del zgornjega karnija (Breda et al., 2009; Kiessling, 2010) se v raziskanem zaporedju odraža po tipično rdeči do vijoličasti barvi kamnin, ki je posledica prisotnosti železa v oksidni obliki (hematit), in po prisotnost karbonatnih konkrecij (Alonso-Zarza, 2003; Khalaf, 2007; Moussavi-Harami, 2009; Breda & Preto, 2011). Upoštevajoč izrazito aridno klimo, bi opazovano zaporedje alternativno lahko umestili tudi v zaključne (terminalne) vršaje (Nichols & Fisher, 2003), katerih nastanek bi bil v tem primeru najverjetneje posledica nizke vodne bilance zaradi česar reke niso dosegle morja. Podobno, s sedimentacijo na zaključnih vršajih interpretirajo tudi primerljivo klastično zaporedje Travenanzes formacije iz Dolomitov (Breda et al., 2009; Breda & Preto, 2011; Preto et al., 2015), kjer so na podlagi analize bolje razgaljenih tuvalskih kamnin izdelali celosten sedimentacijski/faciesni model (sl. 7). Njihova rekonstrukcija paleookolja je razdeljena na tri faciesne cone. Najbolj južno faciesno cono A, v katero bi lahko umestili tudi zaporedje pri Lesnem Brdu, opredeljujejo meandrirajoče reke v puščavskem okolju, ki se končujejo z zaključnimi vršaji. Ta faciesna cona proti severu, preko sabk in plimskih ravnic faciesne cone B, prehaja v faciesno cono C z restriktivnimi lagunami – podplimsko morsko okolje. Tudi za Travenanzes formacijo je značilna prisotnost karbonatnih konkrecij, predvsem v obliki dolokretov. Preto in sodelavci (2015) domnevajo, da je dolomit primaren. Za razliko od karbonatnih konkrecij Travenanzes formacije so le te na Lesnem Brdu kalcitne sestave. V prihodnje bi bilo vredno opraviti dodatne mineraloške in kemijske raziskave, s čimer bi lahko natančneje opredelili njihovo genezo.

Smer transporta na podlagi podatkov iz profila ni mogoče določiti, vendar pa glede na paleogeografsko porazdelitev v zgornjem triasu, kjer proti severu prehajamo v globokomorski Slovenski bazen (Buser, 1989; Gale, 2010; Gale at al., 2012; 2016), lahko zaključimo da je bilo izvorno območje sedimenta zagotovo nekje na jugu (današnja orientacija). Sestava sedimentov kaže, da so bile v zaledju, torej na izvornemu območju klastitov, razgaljene karbonatne, vulkanoklastične in verjetno tudi klastične kamnine. Nekatera zrna imajo lahko tudi pedogen izvor, kjer je na izsušeni poplavni ravnici prišlo do intenzivne pedogeneze in tvorbe karbonatnih in železovih konkrecij. V dolgih sušnih obdobjih je sledila fragmentacija le teh v sparitna zrna in zrna iz neprosojnega minerala, deflacija, ter vetrni transport med različnimi podokolji (Breda & Preto, 2011).

Sl. 7. Shematska rekonstrukcija paleookolj Travenanzes formacije (prirejeno po Breda & Preto, 2011) A = aluvialna ravnica z rečnim koritom, prebojnimi pahljačami, zaključnimi vršaji in poplavno ravnico; B = blatna ravnica in sabke; C = karbonatna plimska ravnica in plitve lagune. Zvezdi označujeta najbolj verjetni lokaciji območja raziskav. Glej angleški del prispevka.

Zaključki

Proučeno zgornjekarnijsko (tuvalsko) zaporedje pri Lesnem Brdu po večini sestavljajo rdeči do vijoličasti rahlo peščeni muljevci oziroma laporovci z vmesnimi plastmi peščenjakov in prodnatih peščenjakov. Faciesna združba je značilna za poplavno ravnico, kjer prevladujoče drobnozrnate poplavne sedimente prekinjajo vmesne plasti srednje do debelozrnatih sedimentov prebojnih ali zaključnih pahljač, redkeje manjših rečnih korit. Po sestavi klastitov sklepamo, da so bile na južno ležečem izvornem območju erodirane predvsem karbonatne, vulkanoklastične in tudi klastične kamnine, obenem pa imajo določena zrna verjetno tudi pedogen izvor.

Pri korelaciji s sedimentacijskim modelom tuvalskega zaporedja (Travenanzes formacija) v italijanskih Dolomitih uvrščamo opisano zaporedje v faciesno cono A, katero opredeljujejo sedimenti poplavne ravnice, rečnih korit, prebojnih pahljač in zaključnih vršajev (Breda et al., 2009). Prisotnost hematita in karbonatnih (kalcitnih) konkrecij, kažeta na aridno klimo v času sedimentacije.

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Literatura

Glej angleški del prispevka.