Jurassic and Cretaceous neptunian dikes in drowning successions of the Julian High (Julian Alps, NW Slovenia)

Neptunski dajki v potopitvenih zaporedjih Julijskega platoja (Julijske Alpe, SZ Slovenija)

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Abstract: In the Julian Alps the Jurassic neptunian dikes are common features of the drowning successions of the Julian High. In the research area, comprising Ravni Laz, Lužnica Lake and Triglav Lakes Valley areas, neptunian dikes are present in the Pliensbachian shallow – water limestone and in the Bajocian to the Tithonian Prehodavci formations. The dikes were formed by two mechanisms: A) the initiation of the voids by mechanical fracturing and later reshaping by dissolution, B) formation solely by mechanical fracturing of the host rock. The time span of dike infillings ranges from the Bajocian to late Cretaceous in age. According to the age of the host rock and neptunian dike infillings, the following phases of neptunian dike formation in the investigated area are recognized: Pliensbachian and/or Bajocian phase, Late Kimmeridgian-Early Tithonian phase and Late Cretaceous (pre-Senonian) phase.

Izvleček: V Julijskih Alpah se v jurskih potopitvenih sekvencah Julijskega praga pogosto pojavljajo neptunski dajki. Na raziskanem območju Ravnega Laza, Jezera v Lužnici ter Doline Triglavskih jezer se dajki pojavljajo v pliensbachijskih plitvovodnih apnencih in znotraj bajocijske do tithonijske Prehodavške formacije. Zapolnitve dajkov so od bajocijske do zgornjekredne starosti. Dajki so nastali na dva načina: A) z mehanskim razpokanjem

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matične kamnine, razpoke pa so bile kasneje preoblikovane z raztapljanjem; B) nastanek izključno z mehanskim razpokanjem matične kamnine. Na podlagi raziskav matične kamnine in zapolnitev smo določili naslednje faze nastajanja dajkov: pliensbachijska in/ali bajocijska faza, kimmeridgijska faza in zgornjekredna faza.

Key words: neptunian dikes, Julian High, Jurassic, Cretaceous, Julian Alps

Ključne besede: neptunski dajki, Julijski prag, jura, kreda, Julijske Alpe

Introduction

Neptunian dikes are defined as bodies of younger sediment filling fissures in rocks exposed on the seafloor. They are of great importance in the paleogeographic interpretation of an area because 1) fracture fillings often preserve unique bits of stratigraphic and paleontological information, which can be missing in normal bed-on-bed successions, 2) understanding the mechanism of opening and infilling is of great help in highlighting the relative importance of extensional tectonics, slope instability and sub-aerial or submarine dissolution.

In Slovenia the most frequent occurrences of neptunian dikes are in the western part of the Julian Alps. The dikes outcrop at Kanin, near Učeja, in the surroundings of Bovec at the Mangart Saddle and in the Krn ridge. The host rocks of the dikes are Triassic, Jurassic and Cretaceous carbonate rocks. The dikes themselves are of Jurassic and Cretaceous ages. The present study investigated in detail the neptunian dikes of Julian Carbonate Platform-Julian High drowning successions in three key areas; the Ravni Laz area under the Kanin massive, the Lužnica Lake area in the eastern part of the Krn ridge and the neptunian dikes of the Triglav Lakes Valley.

The aims of this study were to define the stratigraphical distribution of neptunian dikes in the aforementioned areas, to define their frequency, to decipher all varieties of neptunian dike forms and their infillings and to interpret geological processes that were responsible for their formation.

Geological setting

The Julian Alps are located in the NW part of Slovenia and NE part of Italy. Structurally, they belong to the Julian

Nappe and, together with the underlying Tolmin Nappe, they represent the easternmost continuation of the Southern Alps (Figure 1). In the Julian Alps the Paleogene Dinarides intersect with the Neogene Southern Alps. The area was first deformed by SW-vergent thrusts related to the most external Dinarides during the Oligocene – early Miocene and then by S to SSE-vergent ''Alpine'' thrusting since the late Miocene (Doglioni & Siorpaes, 1990; Bresnan et al., 1998; Placer, 1999; Placer, 2008; Placer & Čar, 1998; Mellere et al., 2000; Vrabec & Fodor, 2006). At the Miocene-Pliocene transition the major strike-slip deformation started in the Julian Alps (Vrabec & Fodor, 2006). From the Neogene to the present NW-SE trending dextral faults cut the area and displaced both the Dinaric and South Alpine fold-and-thrust structures.

Paleogeographically, the area in the Jurassic belonged to the Adriatic-Apulian microcontinent, bordered by the Alpine Tethys and the Vardar Ocean (Stampfli et al., 2001). From the Late Triassic to the earliest Jurassic, the area of the Julian Alps belonged to the Julian Carbonate Platform. During Early Jurassic rifting, the platform was dissected into blocks, forming a horst-and-graben structure. Some of these blocks became part of an isolated pelagic carbonate platform named the Julian High (Figure 2), while other blocks formed deeper basins, for example, the Bovec Trough (Šmuc, 2005; Šmuc & Goričan, 2005).

Neptunian dikes are present only in the drowning successions of the Julian High and they are completely absent in the Bovec Trough.

In general, the drowning succession of the Julian High is represented by Pliensbachian platform limestones of the Julian Carbonate Platform that are unconformably overlain by Bajocian to lower Tithonian highly-condensed limestones of the Prehodavci Formation or by middle Cretaceous Scaglia variegata or Senonian Scaglia rossa. Distinct features of all Julian High successions are numerous polyphase neptunian dikes that occur in Pliensbachian shallow water limestones and in the Prehodavci Formation. In the most extreme cases the dikes represent the only preserved Jurassic sediments that are otherwise missing from bed-on-bed successions.

Previous research

The Jurassic neptunian dikes are well documented in the Carpathians (Aubrecht, 1997; Luczynski, 2001), Sicily (Mallarino, 2002; Martire & Pavia, 2004) and the in Southern Alps (Lehner, 1991; Winterer et al., 1991; Martire, 1992) while in Slovenia detailed studies

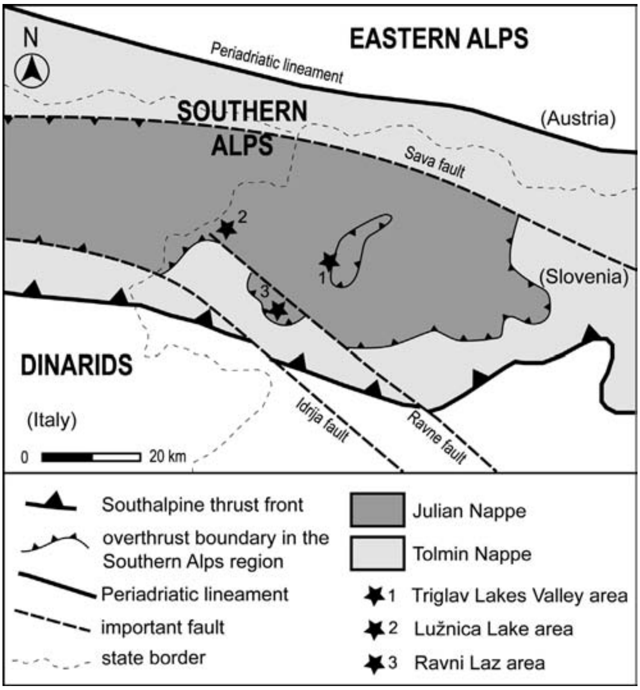

Figure 1. Location of the studied area with marked larger geotectonic units and regional faults

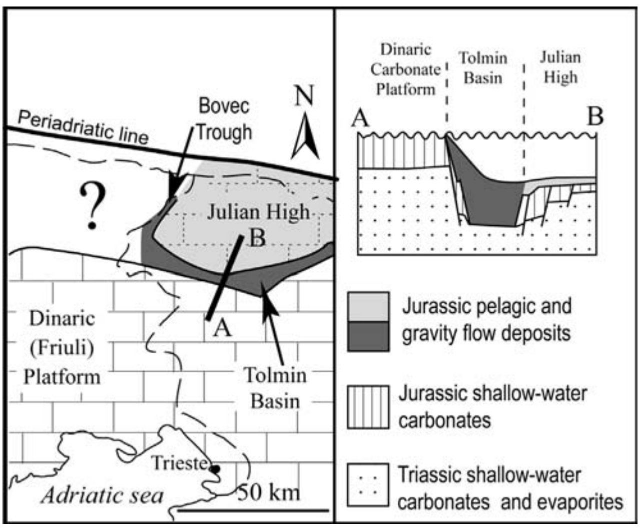

Figure 2. Present-day position of paleogeographic units (compiled from Buser (1989) and Placer (1999, 2008) and schematic cross-section (A-B) at the end of the Jurassic

of the neptunian dikes are scarce (Babić, 1981; Črne et al., 2007, Šmuc, 2005).

The neptunian dikes in the Julian Alps were first reported by Babić (1981). He observed and described fractures in the Upper Triassic Dachstein Limestone that were filled with the angular Upper Triassic and Lower Jurassic limestone clasts embedded in a red Middle-Upper Jurassic matrix. He interpreted them as neptunian dikes that were formed by extensional fracturing and later filled with pelagic sediments in the marine environment. Buser (1986, 1987, 1996) observed heavily karstified Jurassic fractures in the Dachstein limestone that were filled with assumed Bajocian-Bathonian grey-red crinoidal and micritic limestone. He suggested that these fractures were intensively karstified during the Early Jurassic emersion of the platform and later, when the platform drowned, filled with marine sediments.

Šmuc (2005) described in detail the Jurassic and Cretaceous successions of the Julian Alps. Within investigated sections he reported neptunian dikes from the Mangart area, Ravni Laz, Lužnica Lake and Triglav Lakes Valley. Neptunian dikes from the Mangart area were investigated in detail by Črne et al. (2007), whereas a detailed analysis of the neptunian dikes in the Lužnica Lake, Ravni Laz and Triglav Lakes Valley areas is presented in this article.

Research of the Mt. Mangart dikes system by Črne et al. (2007) represents an exemplar study of the complex neptunian dike system. The dikes at Mt. Mangart exhibit several different geometries: dissolution cavities, thin penetrative fractures, larger fractures and laterally confined breccia bodies. They were filled by two main generations of infillings. The first generation is Pliensbachian in age and represented by bioclastic limestone subdivided into five microfacies. The second generation is composed of breccias with a marly matrix. The timing of the second generation is only broadly assigned from the Pliensbachian to the Late Cretaceous.

Description of neptunian dikes and interpretation of their formation

The research areas of Lužnica Lake, Ravni Laz and Triglav Lakes Valley paleogeographically belong to the Upper Triassic – Lower Jurassic Julian Carbonate Platform and Middle to Upper Jurassic Julian High. In all of the investigated sections the drowning succession starts with the Pliensbachian platform limestone that is unconformably overlain by condensed limestone of the Bajocian to lower Tithonian Prehodavci Formation (Šmuc, 2005) (Figure 3).

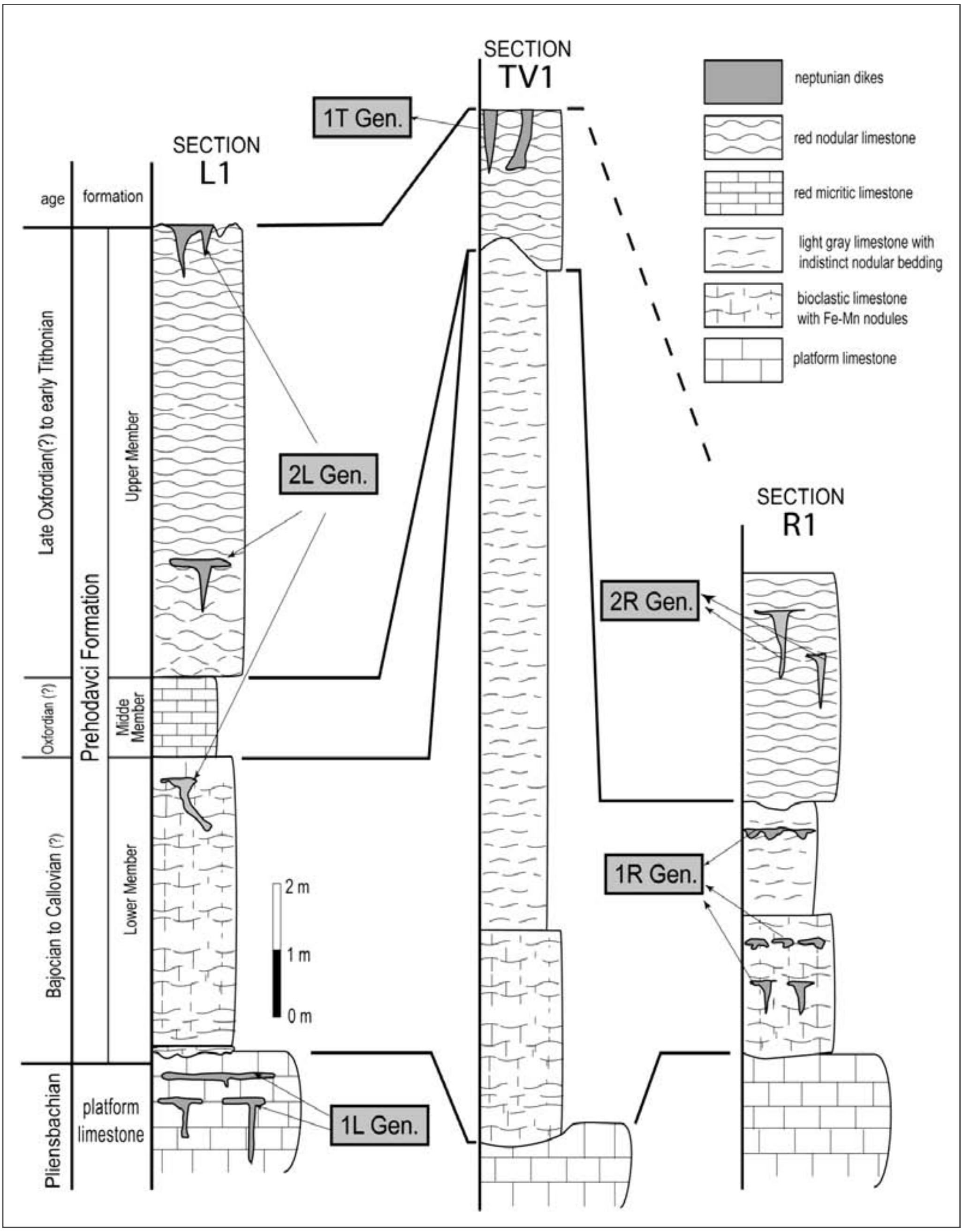

Figure 3. Lithostratigraphic sections of the investigated areas with marked occurrence of the neptunian dikes

The Lower Jurassic platform limestone is primarily a massive and bedded oolitic limestone that in places alternates with beds of micritic limestone, laminated dolomite and dolomitic limestone (Buser, 1986; Jurkovšek, 1986; Jurkovšek et al., 1990; Šmuc, 2005; Šmuc & Goričan, 2005). The limestone was deposited in a variety of different peritidal environments ranging from intertidal to a high-energy subtidal environment.

The Prehodavci Formation unconformably overlies the Lower Jurassic platform limestone (Figure 3). The contact is represented by a highly irregular unconformity surface that marks a stratigraphical gap comprising at least Toarcian to Aalenian. The Prehodavci Formation consists of condensed limestone of Ammonitico Rosso type and is subdivided into three members (Šmuc, 2005). The Lower Member (Bajocian to? Callovian) is composed of condensed, red, bedded bioclastic limestone with Fe-Mn nodules that gradually passes into light grey, indistinctly nodular limestone. The Middle Member (early Oxfordian?) consists of thin-bedded micritic limestone. The Upper Member (late Oxfordian? to early Tithonian) unconformably overlies the Lower or Middle Members. It is represented by red nodular limestone and red marly limestone with abundant *Saccocoma* sp. (Šmuc, 2005).

Neptunian dikes are present in all of the investigated sections (Figure 3). In the Triglav Lakes Valley and in Ravni Laz area the neptunian dikes only occur in the Prehodavci Formation while in the Lužnica Lake area neptunian dikes are also present in the Lower Jurassic shallow-water limestone.

Neptunian dikes at Lužnica Lake section

At Lužnica Lake (section L1 in Figure 3, y = 399234 x = 124072 z = 1865) the neptunian dikes occur in Pliensbachian platform limestone and in the Prehodavci Formation. Two generations of neptunian dikes were recognized.

I. Generation

The dikes located in the Pliensbachian platform limestone represent I generation (1L Gen. in Fig. 3). They are elongated, mostly sub-vertical, bed-crossing and occasionally bed-parallel oval cavities with smooth walls filled with younger limestone. The neptunian dikes are up to 10 cm wide and can cut up to 70 cm deep into the host rock. The neptunian dikes show polyphase laminated infillings. The oldest sediment is microsparitic limestone with rare ostracods, followed by a wackestone-packstone with echinoderm fragments, small sparite grains and Fe-Mn encrusted clasts that grade into wackestone with planktonic foraminifera (Protoglobigerinids), be-

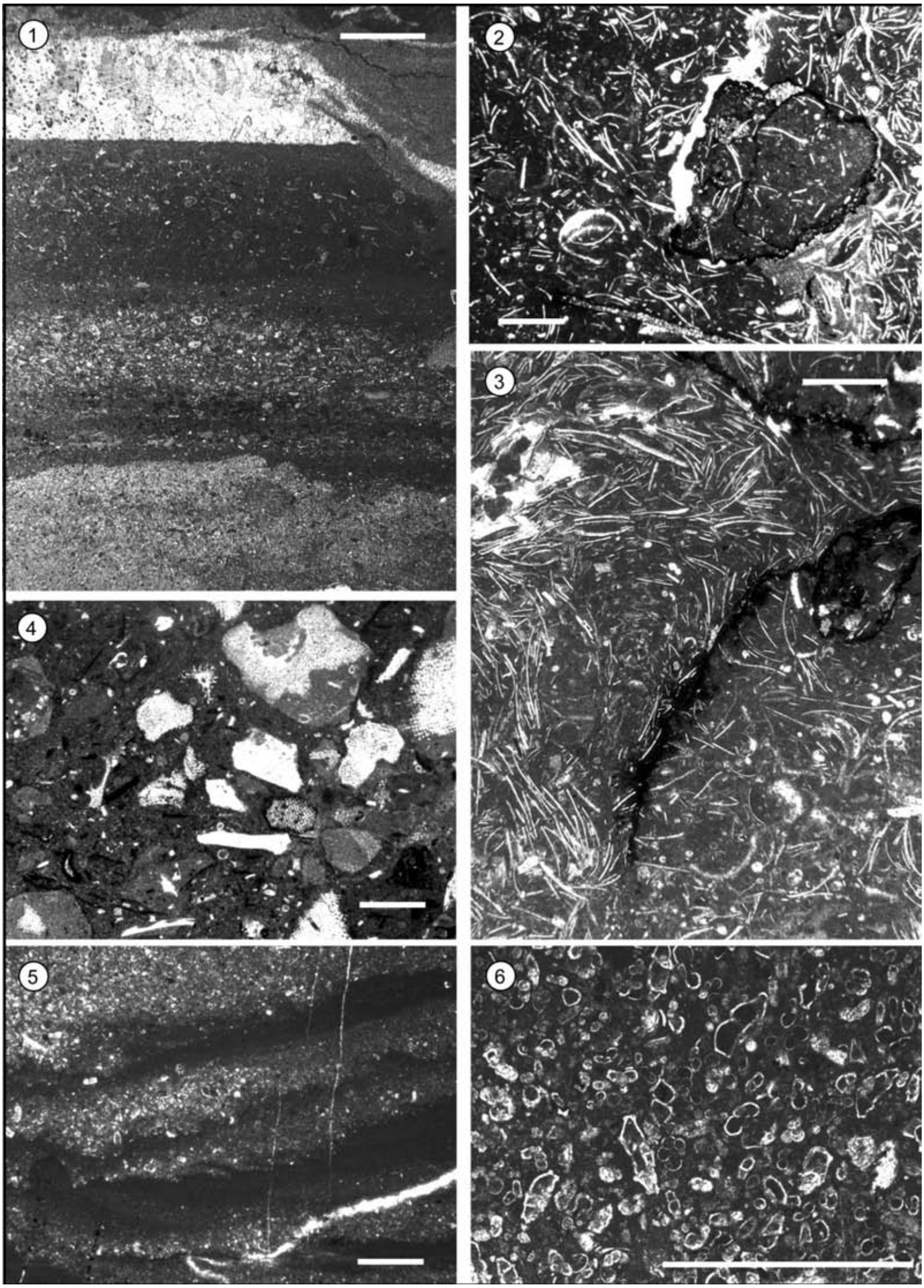
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Plate 1

Pl. 1, Fig. 1: 1L Generation of neptunian dikes filled with wackestone with small sparite grains (lower part of the photograph) overlain by wackestone-packstone with planktonic foraminifera (Protoglobigerinids), belemnites, echinoderm fragments, filaments and occasional benthic foraminifera (middle part of the photograph). In the uppermost part the infill is calcite cement. The scale bar is 1 mm long.

Pl. 1, Fig. 2: 2L Generation of neptunian dikes filled with packstone mainly composed of filaments and encrusted intraclasts of bioclastic limestone. The scale bar is 1 mm long.

Pl. 1, Fig. 3: 2L Generation of neptunian dikes filled with packstone mainly composed of filaments and encrusted intraclasts of host rocks. The scale bar is 1 mm long.

Pl. 1, Fig. 4: 1R Generation of neptunian dikes filled with lower Berriasian fine-grained breccias. The breccia is clast-supported and composed of lithoclasts of wackestone to mudstone with echinoderm fragments, benthic foraminifera and calpionelids Calpionella elliptica (Cadisch). The scale bar is 1 mm long.

Pl. 1, Fig. 5: 2R Generation of neptunian dikes. The laminated infill in the upper part of the neptunian dikes is composed of alternatiing packstone laminae up to 5 mm thick and thinner mudstone. The scale bar is 1 mm long.

Pl. 1, Fig. 6: 2R Generation of neptunian dikes filled with Upper Cretaceous wackestone-packstone with planktonic globular foraminifera, globotruncanids and rare echinoderm fragments. The scale bar is 1 mm long.

lemnites, echinoderm fragments, filaments and rare benthic foraminifera (Pl. 1, Fig. 1). The clasts of the host rock are occasionally observed. The matrix is micrite to microsparite. On the basis of the presence of planktonic foraminifera, (Protoglobigerinids) this neptunian dike infill is Bajocian. The Bajocian infillings are in places additionally cut by younger dikes that are partly filled by a radiaxial fibrous calcite cement and micrite. The uppermost Bajocian sediments are occasionally encrusted with Fe-Mn oxides and the remaining pore space is filled by upper Tithonian mudstones with *Calpionella alpina* (Lorenz).

II. Generation

The II generation of neptunian dikes occurs in the Prehodavci Formation (2L Gen. in Fig. 3). The dikes are represented by sub-vertical and bed-parallel cavities up to few dm in diameter showing smooth and straight walls. In the Lower Member the neptunian dikes are filled with packstone mainly composed of filaments and encrusted intraclasts of bioclastic limestone (Pl. 1, Fig. 2). Other grains include echinoderm fragments and gastropod protoconchs. In the Upper Member of the Prehodavci Formation the infill is characterized by an Upper Kimmeridgian to Lower Tithonian packstone composed of numerous filaments, *Saccocoma* sp. fragments and intraclasts of host rock (Pl. 1, Fig. 3). In places the dikes are also filled with mudstone with calpionellids (*Calpionella alpina* (Lorenz)) of Tithonian age.

The overall geometry, smooth walls and clasts of the host rock of the I. generation of neptunian dikes indicate formation of the cavities by mechanical fracturing. However, subsequent reshaping of the existing voids by dissolution is also indicated (small scale undulation of the walls). Neptunian dikes of the II generation were formed due to mechanical fracturing of the host rock and were later episodically filled with younger sea-bottom sediments. The infilling of the dikes is represented by autochthonous and allochthonous sediments. Autochthonous sediments are clasts of the Prehodavci Formation, derived from the walls of the fracture, while all other sediments are allochthonous and derived from an active sea bottom surface.

Neptunian dikes at Ravni Laz

At Ravni Laz (section R1 in Fig. 3, y = 388997 x = 134741 z = 720), neptunian dikes occur only in the Prehodavci Formation. The neptunian dikes are subparallel to the bedding and occur in a distinct horizon within the Prehodavci Formation. On the basis of the stratigraphic position and age of infillings, two different generations of neptunian dikes were recognized.

I. Generation

I generation (1R.Gen. in Fig. 3) occurs in the Lower Member of the Prehodavci Formation and is filled with Kimmeridgian to lower Berriasian limestone. The geometry of the dikes is bed-crossing fractures down to 0.5 m deep, however, smaller oval cavities with undulating walls that occur in a distinct horizon are also observed. The base of these neptunian dikes is characterized by laminated and graded packstone to mudstone with abundant fragments of *Saccocoma* sp. The remaining space in the dikes is filled with graded microsparitic limestone composed of echinoderm fragments, calpionellids (*Calpionella alpina* (Lorenz)) and intraclasts of packstones with *Saccocoma* sp. In places, the neptunian dikes of the I. generation are filled only by fine-grained clast-supported carbonate breccias (Pl. 1, Fig. 4). The clasts consist of lithoclasts of mudstone to wackestone with echinoderm fragments, benthic foraminifera (*Lenticulina* sp., Textularidae) and *Calpionella elliptica* (Cadisch). Other grains include individual echinoderm fragments and Fe-Mn encrusted bioclasts.

II. Generation

The II generation of neptunian dikes (2R Gen. in Fig. 3) occurs in the Upper Member of the Prehodavci Formation and is filled by late Cretaceous deposits. These dikes are up to 10 cm wide bed-crossing and bed- parallel cavi-

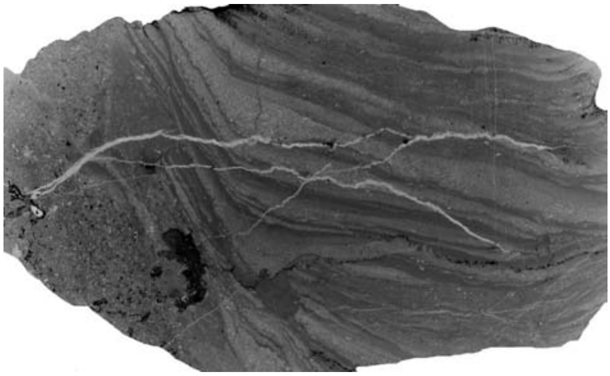

Figure 4. 2R Generation of neptunian dikes. On the left side of the photograph is wackestone with planktic globular foraminifera and globotruncanids. On the right side of the photograph is horizontal and oblique laminated infill represented by thicker packstone and thinner mudstone layers. The photograph is 5.5 cm wide.

ties, with undulating wall geometries in places. The dikes are filled with red-brown wackestone with planktonic globular foraminifera, globotruncanids and rare echinoderm fragments (Pl. 1, Fig. 5). In the upper part of the dike, the infilling is grey in colour, laminated and graded. Laminations are bed-parallel and oblique (Fig. 4). The laminations are represented by alternations of up to a few mm thick packstone and thinner layers of mudstone (Pl. 1, Fig. 6). In places, packstone grades into mudstone. The packstone is exclusively composed of fragmented globotruncanids and extremely rare echinoderm fragments.

The geometry of the neptunian dikes of the Ravni Laz section is characterized by bed-crossing and bed-parallel fractures, smooth walls of the host rock and also by undulating oval cavities. Thus the formation of the cavities was most probably caused by initial mechanical fracturing of the host rock and also subsequent dissolution in places, the latter causing reshaping of the existing voids. All of the different infillings of the neptunian dikes represent allochthonous sediments as is evidenced by the marked age difference of the host rock and infilling. The sedimentary structures, such as grading and lamination, are result of minor turbidity currents which episodically transported the sediment into the open voids (Sarti et al., 2000). The oblique laminations usually occur in the vicinity of the cavity walls (Figure 4) and most are probably formed as a result of the impact of minor turbidity currents with the cavity walls.

Neptunian dikes in Triglav Lakes Valley

Neptunian dikes in the Triglav Lakes Valley (section TV1, Figure 3, y = 40755 x = 134509 z = 2000) are developed only in the uppermost part of the Prehodavci Formation (1T Gen. in Fig. 3) as bed-crossing fractures up to 50 cm deep and a few tens of cm wide (Figure 5), with a preferential SE – NW orientation (Pl. 2, Figs. 1 and 2). In places the neptunian dikes exhibit a jigsaw structure (Pl. 2, Figs. 1 and 2). The walls of the fractures are usually encrusted with Fe-Mn oxides. The fractures are filled with two different breccias. The first breccia consists of fragments of ammonite moulds and centimetre-sized lithoclasts of red wackestone to packstone with disarticulated valves of thin-shelled bivalves and calcified radiolarians of the red nodular facies (Pl. 2, Fig. 3). The matrix of this breccia is packstone with filaments, rare echinoderm fragments, belemnites and foraminifera (*Lenticulina* sp.) The second breccia is composed of euhedral grains of terrigenous quartz, lithoclasts of red nodular limestone, packstone with calcified radiolarian moulds and wackestone with aptychi (Pl. 2, Fig. 4). The matrix of the breccia is wackestone with echinoderm fragments, opaque minerals and Fe-Mn incrusted bioclasts.

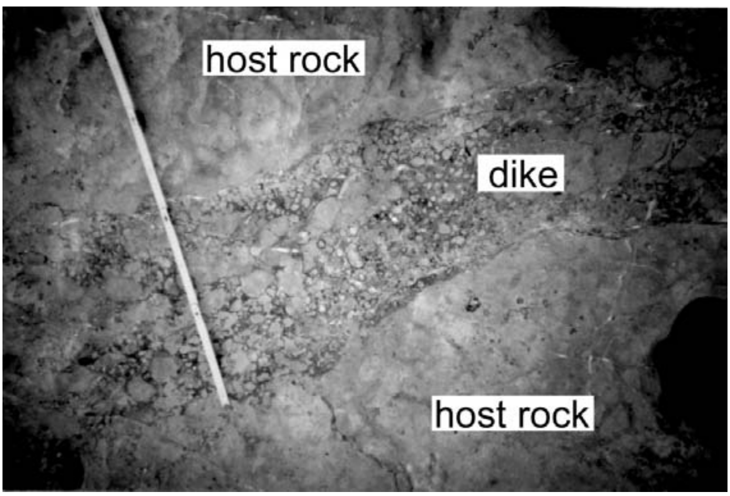

Figure 5. Photograph of the neptunian dike outcropping in the bed surface of the Upper Member of the Prehodavci Formation from the Triglav Lakes Valley. The photograph is approximately 1m wide

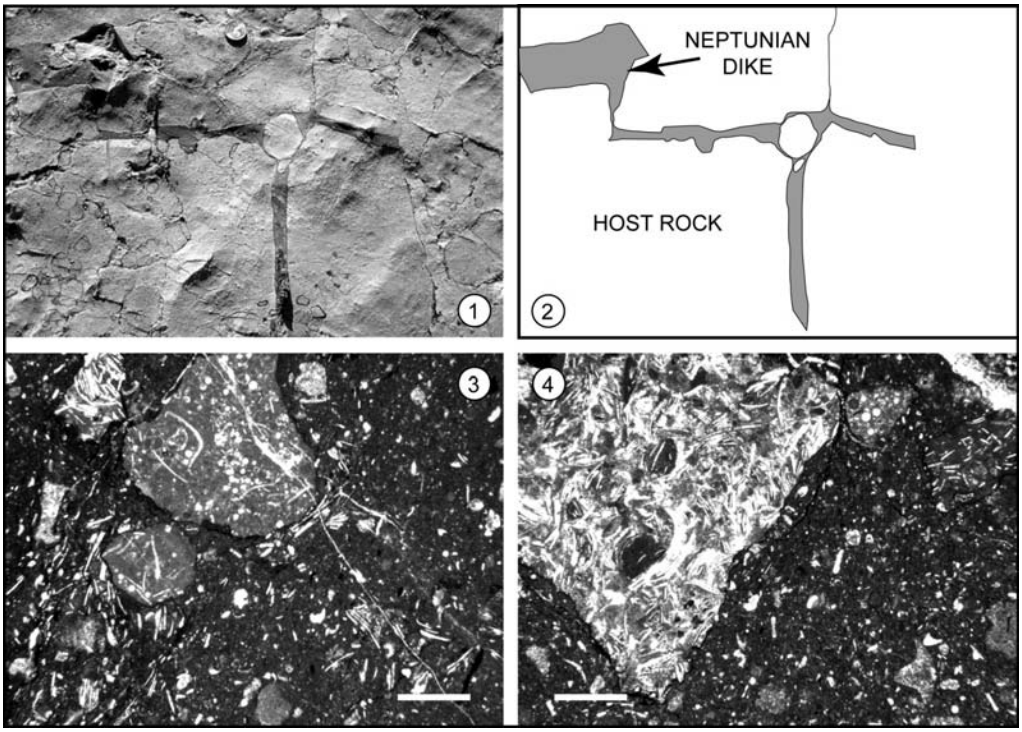

Plate 2
Pl. 2, Fig1: 1T Generation of neptunian dikes. Neptunian dikes with jigsaw structure. Host rock is limestone of the Prehodavci Formation.
Pl. 2, Fig. 2: Sketch of the neptunian dike in Pl. 2, Fig. 1.
Pl. 2, Fig. 3: 1T Generation of neptunian dikes. First breccia with lithoclasts of red wackestone to packstone with calcified radiolarians and filaments. The matrix of breccia is wackestone-packstone with filaments and rare echinoderm fragments.
Pl. 2, Fig. 4: 1T Generation of neptunian dikes. Second breccia composed of lithoclasts packstone with filaments and calcified radiolarian moulds and intraclasts of red nodular limestone. The matrix of the breccia is wackestone with echinoderm fragments.

The dikes are clearly open fractures formed due to a brittle fracturing of a well-lithified host rock. The jigsaw structure additionally indicates a mechanical deformation by penetrative fracturing of the host rock (Cozzi, 2000). Fe-Mn impregnated walls of the fractures indicates phases of non-deposition following fracture formation.

Discussion

Neptunian dike formation

The formation of the neptunian dikes in the investigated areas was the result of two different mechanisms. Neptunian dikes of I. generation of Lužnica Lake and I and II generation in Ravni Laz are bed-crossing or bed-parallel oval cavities with smooth and undulating walls and represent a group of neptunian dikes in which at least reshaping of the voids by dissolution is indicated. This reshaping by dissolution can occur by meteoric waters, indicating an episode of sub-aerial exposure and karstic dissolution or it can occur on the sea-floor. The episode of sub-aerial exposure is a valid hypothesis for the I generation of neptunian dikes in Lužnica Lake. Namely they are located in the Lower Jurassic shallow-water limestone stratigraphically under the unconformity surface separating shallow-water limestone and the Prehodavci Formation. Similar, but more intensively karstified Jurassic fractures in the Dachstein Limestones were reported by Buser (1986, 1987, 1996) and attributed to emersion during the Early Jurassic. The emersion scenario, however, is difficult to apply for the I and II generation of neptunian dikes in Ravni Laz. The dikes are located within the Prehodavci Formation that represents typical deposits of a pelagic plateau with depth of the deposition at least a few ten to hundreds of metres (Martire, 1996). The dissolution and reshaping of the voids most probably occurred on the seafloor in a phreatic marine environment. However, in both cases the initiation of the voids was probably related to mechanical fracturing.

The second group of neptunian dikes includes dikes that were formed only by a mechanical fracturing of the host rock. This group includes the II generation of neptunian dikes in the Lužnica Lake and dikes from the Triglav Lakes Valley. The dikes are bed-crossing straight fractures filled with autochthonous sediments derived from the walls of fracture. The jigsaw structure of the fractures that is present in places indicates a mechanical deformation by penetrative fracturing of the host rock (Cozzi, 2000) which is commonly the result of a seismic shock (Montenat et al., 1991, Cozzi, 2000).

Timing of the neptunian dike formations

The detailed study of the neptunian dikes from Ravni Laz, Lužnica Lake and Triglav Lakes Valley areas revealed the following main phases of neptunian dike formation.

1. Pliensbachian or Bajocian phase

The I generation of neptunian dikes from Lužnica Lake represents the oldest investigated neptunian dikes.

They were formed in the Pliensbachian shallow-water host rock and filled with Bajocian and Tithonian deposits. These neptunian dikes are correlative with I. generation of neptunian dikes from Mt. Mangart (same host rock and mechanism of void formation) (Črne et al., 2007). Črne et al. (2007) determined that void initiation as well as infilling with sediments occurred in the Pliensbachian. The dikes from Lužnica Lake however are filled by younger strata ranging from Bajocian to Tithonian. Thus, two possible explanations exist:

A). I generation of the neptunian dikes from Lužnica Lake formed in the Pliensbachian and started to communicate with the seafloor no earlier than the Bajocian. In this case, dike formation is related to the Julian Carbonate dissection that occurred during that time (Šmuc, 2005; Šmuc & Goričan, 2005). The fragmentation of the platform caused fracturing of the host rock and differential subsidence of blocks. Some blocks were most probably emerged and this caused reshaping of the initial voids by meteoric waters. The Early Jurassic tectonic event is widely recognized across the entire south Tethyan passive margin and a great number of dikes was formed at that age (Winterer & Bosellini, 1981; Winterer et al., 1991; Bertotti, 1993; Sarti et al., 1992, Clari & Masetti, 2002).

B). another possibility is that I generation of neptunian dikes at Lužnica Lake were formed in the Bajocian. If the dikes were formed in the Bajocian, their formation was related to the Bajocian tectonic phase that caused deepening of the Julian High and the beginning of the sedimentation of the Prehodavci Formation (Šmuc, 2005). The accelerated subsidence pulse is well documented in the Southern Alps (Winterer & Bosellini, 1981; Martire, 1992, 1996; Winterer, 1998) and also in the successions of the Slovenian Basin (Rožič & Popit, 2006; Rožič, 2009)

2) Late Kimmeridgian-Early Tithonian phase

Neptunian dikes of this phase (II generation of dikes from Lužnica Lake and I generation of dikes from Ravni Laz and neptunian dikes from Triglav Lakes Valley) are mainly located in the Upper Member of the Prehodavci Formation. The same age – mainly Late Kimmeridian to Early Tithonian – was determined for the host rock and for the oldest dike infillings. This suggests that opening of the voids occurred soon after the deposition of the Upper Member. The dikes are filled with Kimmeridgian to Berriasian deposits. Different infillings of the dikes in different areas represent rather local lateral variations in the sedimentary environments, and most possibly also tectonic styles of deformation. Additionally, some of the voids (Lužnica Lake and Ravni Laz) exhibit relatively continuous infilling ranging from Kimmeridgian to Late Tithonian, while the dikes at Triglav Lakes Valley exhibit phases of deposition and non-deposition as proved by Fe-Mn incrustations of the walls of neptunian dikes and also of clasts of the infillings.

The Late Kimmeridgian – Early Tithonian phase of the neptunian dike formation is tentatively related to the onset of convergent plate movements in the Dinaric Tethys that caused normal faulting and differential subsidence in the external domains (Dozet, 1994; Dozet et al., 1996; Vlahović et al., 2005).

3) Late Cretaceous phase (pre-Senonian)

Neptunian dikes in the Prehodavci Formation that are filled with Late Cretaceous limestone with globotruncanids are present only in the Ravni Laz section. The late Cretaceous phase is most probably related to the tectonic pulse in the Late Cretaceous, more precisely, before the Senonian.

Conclusions

Neptunian dikes in the investigated area of the Julian High are present in the Pliensbachian shallow-water limestone and in the Prehodavci Formation. The following generations of dikes were defined.

Lužnica Lake

I. generation dikes are located in the Pliensbachian shallow-water limestone host rock and filled with Bajocian to Tithonian limestone. II generation is represented by dikes in the Prehodavci Formation that are filled by Upper Kimmeridgian to Lower Tithonian sediments.

Ravni Laz:

I. generation is represented by dikes in the Lower Member of the Prehodavci Formation filled with Kimmeridgian to Berriasian sediments. II generation of dikes is placed in the Upper Member of the Prehodavci Formation and filled with late Cretaceous deposits.

Triglav Lakes Valley

The dikes occur in the Upper Member of the Prehodavci Formation and are filled by Late Kimmeridgian and Early Tithonian breccias.

The dikes were formed by two different mechanisms; A) the initiation of the voids by mechanical fracturing and later reshaping of the voids by dissolution. The reshaping by dissolution occurred by meteoric waters indicating an episode of sub-aerial exposure and karstic dissolution (I generation of Lužnica Lake dikes) or it could have occurred on the seafloor in a phreatic marine environment (I and II generation of dikes from Ravni Laz). B) The dikes were formed only by mechanical fracturing of the host rock and in places by penetrative fracturing of the host rock as a result of seismic shock. This group includes the II generation of neptunian dikes in the Lužnica Lake and dikes from the Triglav Lakes Valley.

According to the age of the host rock and neptunian dike infillings, three main phases of neptunian dike formation in the investigated area are recognized: Pliensbachian and/or Bajocian phase, Late Kimmeridgian-Early Tithonian phase, and Late Cretaceous (pre-Senonian) phase.

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