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ORIGINAL ARTICLE

Jurassic neptunian dikes at Mt Mangart (Julian Alps, NW Slovenia)

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Abstract Jurassic neptunian dikes are common within Upper Triassic to Lower Jurassic platform limestone of the Julian Alps. At Mt Mangart, the following geometries were observed: irregular dissolution cavities, thin penetrative fractures, larger fractures with sharp sidewalls, and laterally confined breccia bodies. Inside a complex neptunian dike system two main generations of infillings were differentiated. The first generation is heterogeneous and consists of bioclastic limestones, representing uniquely preserved sediments subdivided into five different microfacies. The second generation is more common and typically consists of coarse-grained breccias with host-rock clasts and marly limestone matrix containing echinoderms. Fracture formation and void filling of the first generation of neptunian dikes is dated as Pliensbachian and is interpreted to be caused by the Julian carbonate platform dissection due to widely recognized Lower Jurassic Tethyan rifting. The timing of formation for the second generation is only broadly constrained, ranging from the Pliensbachian to the Late Cretaceous.

Keywords Neptunian dikes · Jurassic · Julian carbonate platform · Southern Alps · Julian High · Pliensbachian · Subsidence

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Introduction

Bodies of younger sediment that infilled voids in rocks exposed at the sea floor are defined as neptunian dikes (review in Smart et al. 1988). Fundamental for definition of (1) "neptunian dikes", which are filled with sediment in marine environment, (2) their terrestrial equivalents "fissure fills" and (3) subaqueous brackish and phreatic "cavern fills" are conditions of sediment deposition. Formation and/or development of voids can take place in any one of these environments. Processes such as deformation due to tectonic extension (Lehner 1991), gravity sliding (Winterer et al. 1991; Winterer and Sarti 1994), seismic shocks (Vachard et al. 1987; Montenat et al. 1991) and dissolution (Vera et al. 1988; Molina et al. 1995) enable the formation of voids within the host rock; infill with younger sediments in a marine environment produces features defined as neptunian dikes.

Neptunian dikes are very common in Mesozoic carbonate successions in the Mediterranean Tethys (Winterer and Bosellini 1981). They are commonly formed on rifted carbonate-platform margins, which are often sites of sediment non-deposition; infill of neptunian dikes may thus be the only form of sediment preservation. Furthermore, the processes of void formation inside the host rock (e.g., mechanical fracturing, dissolution) are reflected in the geometry of neptunian dikes. Therefore, detailed studies of both the geometry of neptunian dikes and their sediment infill provide important additional clues to local stratigraphic evolution.

Numerous studies on Jurassic neptunian dikes have been published, including Aubrecht (1997) and Luczynski (2001) who provide exemplary studies in the Carpathians; the most abundant examples are found in Sicily (Martire et al. 2000; Ronchi et al. 2000; Mallarino 2002; Martire and

Pavia 2004). Details about not only Jurassic but Liassic to Paleogene sediments filling fractured Jurassic limestone are given by Bouillin et al. (1992, 1999) and Sarti et al. (2000). In addition to the neptunian dikes researched by Martire (1996), the Southern Alps were the research area of two of the key articles that discuss mechanisms of neptunian dike formation (Lehner 1991; Winterer et al. 1991). In the Julian Alps, which are part of the Southern Alps, neptunian dikes have been observed at several locations (Babić 1981; Buser 1986, 1989, 1996). The most recent investigations in the Julian Alps were done by Šmuc (2005). Several localities were studied, among them Mt Mangart, which is the object of this publication.

At Mt Mangart (Fig. 1a), neptunian dikes are typically up to a few tens of metres of laterally confined breccia bodies in Upper Triassic to Lower Jurassic platform limestone. In the following, the term "host rock" will be used exclusively for Upper Triassic to Lower Jurassic platform limestone. Cousin (1981) interpreted the formation of massive breccia by emersion and karstification at the end of the Triassic, followed by a transgression in the Early Jurassic. Jurkovšek (1987) and Jurkovšek et al. (1990) considered the occurrence of these breccias as an evidence of a short-term emersion and karstification in the Early Jurassic. Recently, Šmuc (2005) mapped the area of Mt Mangart. Based on his stratigraphic studies, he concluded that the breccia bodies owed their origins to neptunian dikes.

The main goal of this paper is a detailed description of the geometry of neptunian dikes and their internal sediments in order to establish a time frame and a model of their formation. Secondly, we also compared microfacies of neptunian dike infill with sediments in normal stratigraphic successions, as well as with other neptunian dikes in the Julian Alps; and thirdly, we correlated the timing of the neptunian dike formation with local and regional tectonic events.

Geological setting

Jurassic stratigraphy of the Julian Alps

Mt Mangart is located in the Julian Alps, which comprise the NW part of Slovenia and extend westwards into eastern Italy (Fig. 1a). The Julian Alps structurally belong to the Julian Nappe, which forms the Southern Alps together with the underlying Tolmin Nappe (Fig. 1a) (Placer 1999). During the Jurassic, the Julian Alps belonged to the southern Tethyan passive continental margin, which was subjected to extensional faulting due to rifting (Winterer and Bosellini 1981; Bertotti et al. 1993). From the Late Triassic to the Early Jurassic, the Julian Alps were a part of the Julian carbonate platform (Buser 1989, 1996; Šmuc 2005). The Julian carbonate platform is characterized by Upper Triassic Dachstein limestone, followed by Lower Jurassic platform limestone. The latter includes various depositional settings: ooidal shoals, lagoons and small patch-reefs. Due to the extensional tectonic phase in the Early Jurassic, the Julian carbonate platform was dissected into blocks with different subsidence rates leading to the platform drowning (Šmuc and Goričan 2005) and the formation of two different paleogeographic domains: (1) a deeper water Bovec Trough and (2) a pelagic plateau named the Julian High (Šmuc 2005). In the Bovec Trough, Pliensbachian distal shelf limestones (Sedlo Formation) and Toarcian black shales (Skrile Formation) deposited, while the main part of the Julian High was probably emergent (Buser 1989, 1996; Šmuc 2005). The only sediments of that age are preserved within neptunian dikes, which formed along the submerged rim of the Julian High. The Bajocian tectonic event caused further subsidence—the Bovec Trough became deeper and started to receive carbonate gravity flow deposits (Travnik Formation). Meanwhile, the Julian High was completely drowned and sedimentation of condensed limestones of Ammonitico Rosso type (Prehodavci Formation) began (Šmuc 2005). At the lower/upper Tithonian boundary, a uniform sedimentation of pelagic Biancone limestone started in the Bovec Trough and on the Julian High, which shows that differences in topography were less pronounced (Šmuc 2005).

Neptunian dikes in the Julian Alps

In the Julian Alps, at Mt Krn, Babić (1981) recognized fractures and larger bodies of breccia as neptunian dikes or sills. Fractures in the Upper Triassic platform limestone are filled with angular Upper Triassic and Lower Jurassic limestone clasts floating in red Middle-Upper Jurassic limestone matrix, which in places contains filaments and planktonic foraminifers (Babić 1981). Open dikes and sills were formed by tectonic extensional fracturing and were later filled with pelagic sediments in a marine environment (Babić 1981). Buser (1986, 1989, 1996) reported on Jurassic fractures in the Dachstein limestone and suggested that tension joints were intensively karstified during emersion in the Early Jurassic. Some of the fractures were filled with red and/or grey crinoidal biomicritic limestone, others with calcarenite or grey calcilutites (micritic limestone) containing filaments; the age of the latter is assumed to be Bajocian-Bathonian (Buser 1996). In some places limestone similar to Ammonitico Rosso is also found as neptunian dike infill (Buser 1986).

Structure and stratigraphy at Mt Mangart

The area of Mt Mangart was thoroughly studied by Šmuc (2005), who mapped the units there (Fig. 1b). Two larger structural units form Mt Mangart: the Travnik and

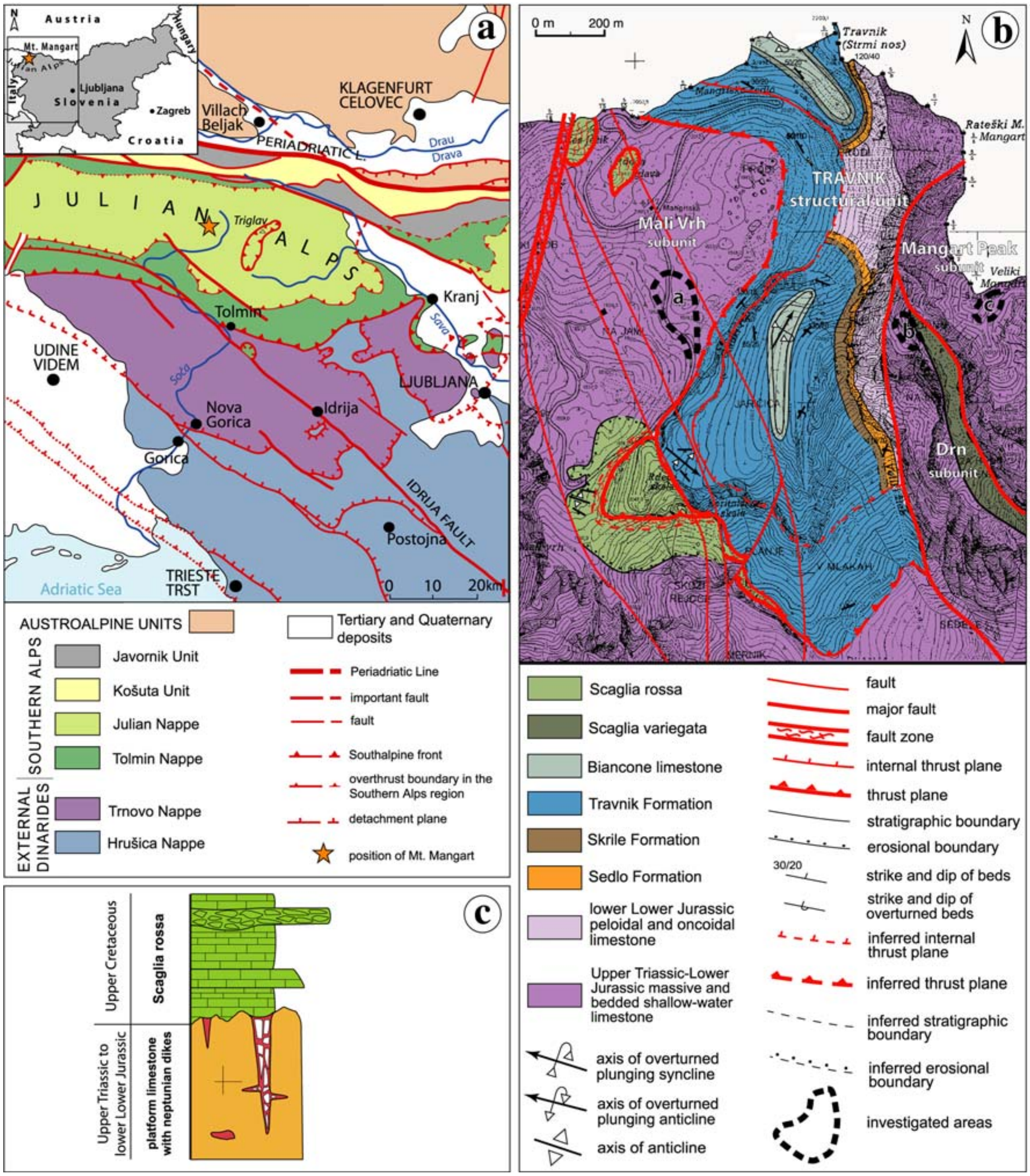


Fig. 1 Location and stratigraphy. **a** Macrotectonic subdivision of W Slovenia (Placer 1999) with geographic location of the investigated area in *top left corner*. **b** Geological map of the Mt Mangart Saddle, where structural units, subunits and location areas are illustrated. Mali Vrh, Drn and Mangart Peak are structural subunits of the Mangart structural unit (Šmuc 2005). **c** Stratigraphic situation in the Mali Vrh structural subunit

the Mangart structural units. From the Early Jurassic, the Travnik structural unit was a part of the Bovec Trough, while the Mangart structural unit belonged to the Julian High margin. The studied area belongs to the Mangart structural unit, which is subdivided into several subunits.

Our primary research interest lies within the lowest structural subunit Mali Vrh (a in Fig. 1b). The best exposed outcrops are situated along the road leading to the Slovenian–Italian border (y=5,396,159 m, x=5,144,676 m, z=1,960 m). Concerning the stratigraphy at the outcrop (Fig. 1c), the Upper Triassic to Lower Jurassic massive platform limestone is cut by Jurassic neptunian dikes. The platform limestone is unconformably overlain by Senonian Scaglia rossa, which was called the Bovec beds by Radoičić and Buser (2004). Apart from the very noticeable example of neptunian dikes in the road-cut, comparable features are also present within the Mangart structural unit: (1) at the Drn subunit (b in Fig. 1b; y=5,396,704 m, x=5,144,749 m,

z=2,526 m) Lower Jurassic platform limestone containing neptunian dikes is directly overlain by Albian Scaglia variegata (Goričan and Šmuc 2004); and (2) at the Mangart Peak subunit (c in Fig. 1b; y=5,397,013 m, x=5,144,790 m, z=2,630 m) pelagic sediments are present inside the Upper Triassic Dachstein limestone, above which there is no sedimentary cover (Šmuc 2005).

Description of neptunian dikes at Mt Mangart and interpretation of their formation

Host-rock lithology

Neptunian dikes can be observed over an area of 20,000 m^2 and are best exposed along a 150-m-long road-cut leading to the Mt Mangart Saddle (locality a in Fig. 1b). Neptunian dikes penetrate the host rock, which consists of light grey massive boundstone with sponges (Fig. 2a), corals, calcareous algae, and fragments of bivalves, gastropods, brachiopods and echinoderms. Peloids, oosparitic intraclasts and foraminifers are also present. Jurkovšek et al. (1990) reported on Rhaetian foraminifers *Galeanella panticae* (Zaninetti and Brönnimann) and *Triasina hantkeni* (Majzon) in the lower part, while the upper part is dominated by *Agerina martana* (Farinacci). A Pliensbachian age of the platform limestone is confirmed by the presence of the coral *Rhabdophyllia phaceloida* (Beauvais) (Fig. 2b, determined by D. Turnšek), which was found in host-rock clasts inside the breccia.

We recognized seven facies inside a complex neptunian dike system and they filled differently shaped voids of various origins. On the basis of crosscutting relationships and compositional differences, two main generations of neptunian dike formation were defined. The second generation is more widespread and crosscuts neptunian dikes of the first generation.

The appearance and structure for each generation of neptunian dikes is described in a few sentences, their beginning is marked with capital letters (A, B, C). A unified key for neptunian dike infill is given: a roman number (I., II.) indicates generation; small letter (a, b) indicates group—establishing a fill sequence between groups was not possible due to lack of contacts between them; facies and microfacies are marked as F, cements as C; the assigned number corresponds to relative order of sedimentation/precipitation:

- I. generation, group a: I.aC_1, I.aF_1, I.aC_2, I.aC_3, I.aF_2
- I. generation, group b: I.bF_1, I.bC_1, I.bF_2, I.bC_2, I.bF_3
- II. generation, facies a and b: II.aF, II.bF

I. Generation of neptunian dikes

Appearance, dimensions and structure

The first generation of neptunian dikes was formed by sediment infill and cement precipitation in three types of voids according to their appearance and structure (Fig. 3): (A) irregular cavities ranging from a few centimetres up to few decimetres with undulate walls; (B) smaller breccia bodies, only a few decimetres in size; (C) thin fractures, a few millimetres wide and several decimetres long, penetrating the host rock and consequently forming mosaic breccias (sharp shapes of side walls and angular clasts which fit together well).

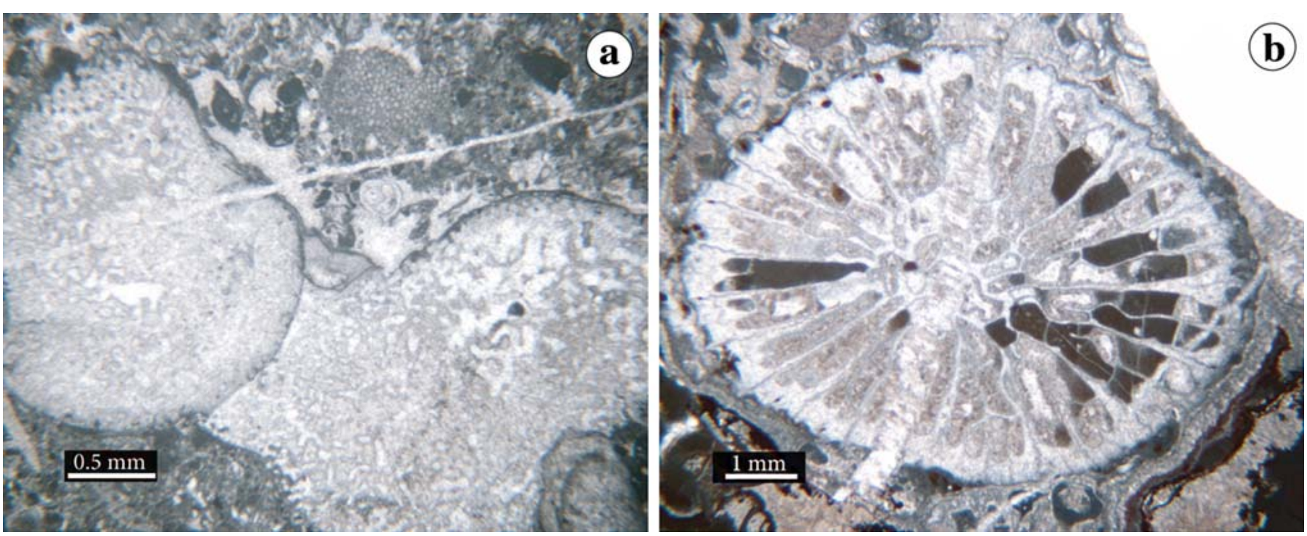


Fig. 2 Thin sections of the host rock. **a** Boundstone with sponges. **b** *R. phaceloida* in a host-rock clast, cut by a calcite vein. Intraskeletal spaces inside the coral were filled with sparite cement and red micrite

Lithology and facies

A relative timing of internal sediment deposition and cement precipitation was determined individually for the two groups: I.a and I.b. Due to the lack of contact between sediments of these two groups, an overall history of deposition and brecciation cannot be reconstructed. Microfacies and precipitates filled the voids in the following order.

Group I.a (Fig. 4)

- I.aF$_1$: Macroscopically pinkish wackestone–packstone appears red in thin sections and contains predominantly fragmented ostracode shells, benthic foraminifers including *A. martana* (Farinacci), and minor proportions of fragments of echinoderms, gastropods and sponge spicules (Fig. 4a). In places Fe–Mn impregnated surfaces are present within the sediment (Fig. 4b). In some of the voids, cements precipitated prior to the sedimentation of I.aF$_1$ as radiaxial fibrous calcite (I.aC$_1$, Fig. 4c). Sometimes irregular cavities with undulate walls were not completely filled by I.aF$_1$ and cementation with two generations of radiaxial fibrous calcite followed (I.aC$_2$, Fig. 4c, d). I.aF$_1$ fills irregular cavities and thin fractures penetrating the host rock, forming mosaic breccias.
- I.aF$_2$: Ostracode coquinas with tightly packed ostracode shells. Most shells are filled with sparite cement and enclosed in micrite matrix (Fig. 4e). Facies I.aF$_2$ is extremely rare. It represents the matrix of the smaller sized breccias with host-rock clasts covered by radiaxial fibrous calcite cement (I.aC$_3$, Fig. 4e, f). Some of the clasts contain facies I.aF$_1$ (Fig. 4f).

Group I.b (Fig. 5)

- I.bF$_1$: Red packstone with mainly small (up to 1 mm) limestone fragments (host rock?) and some bioclasts, among them foraminifer *Involutina liassica* (Jones) (Fig. 5a). I.bF$_1$ fills irregular cavities inside the host rock.

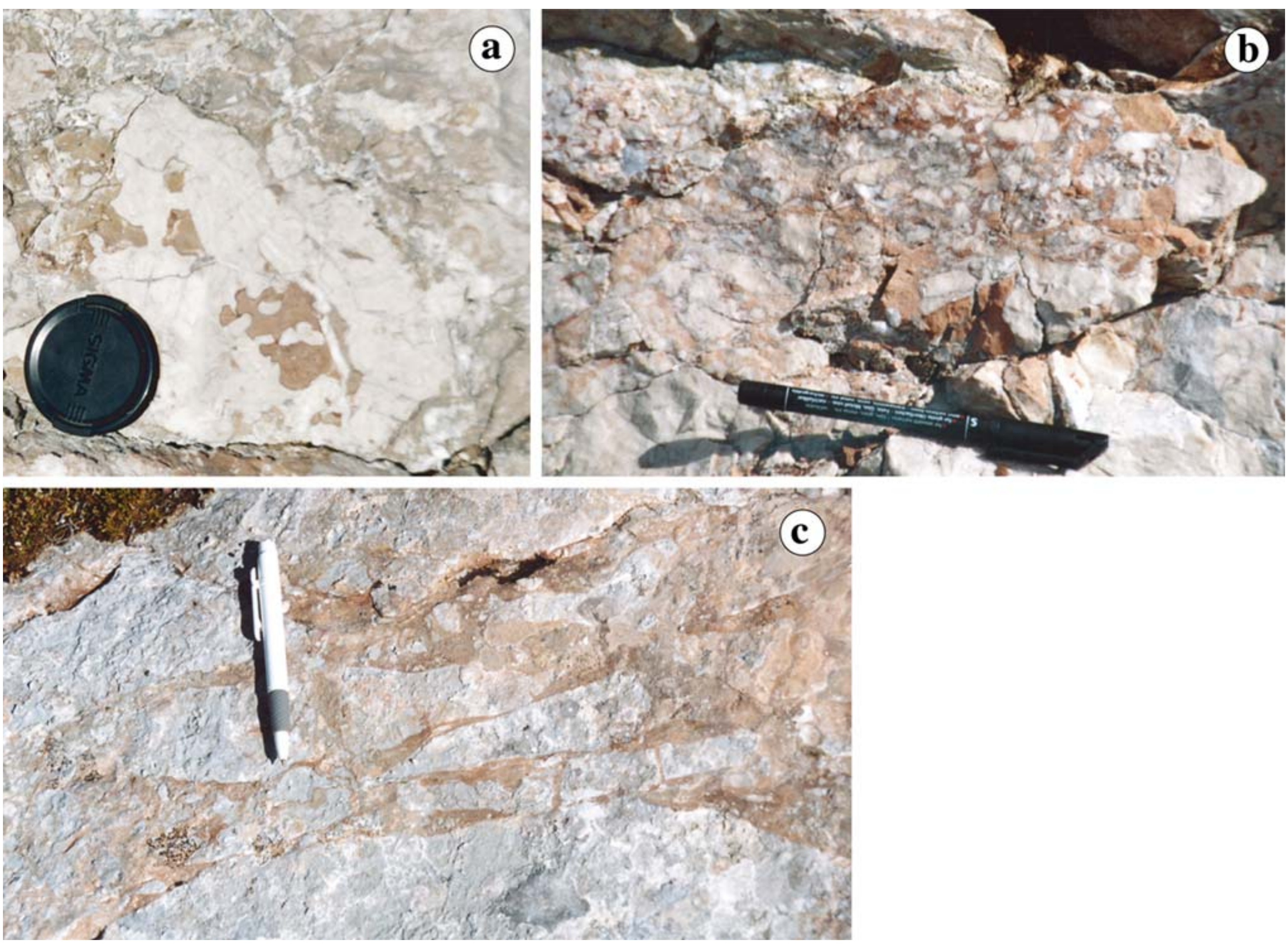
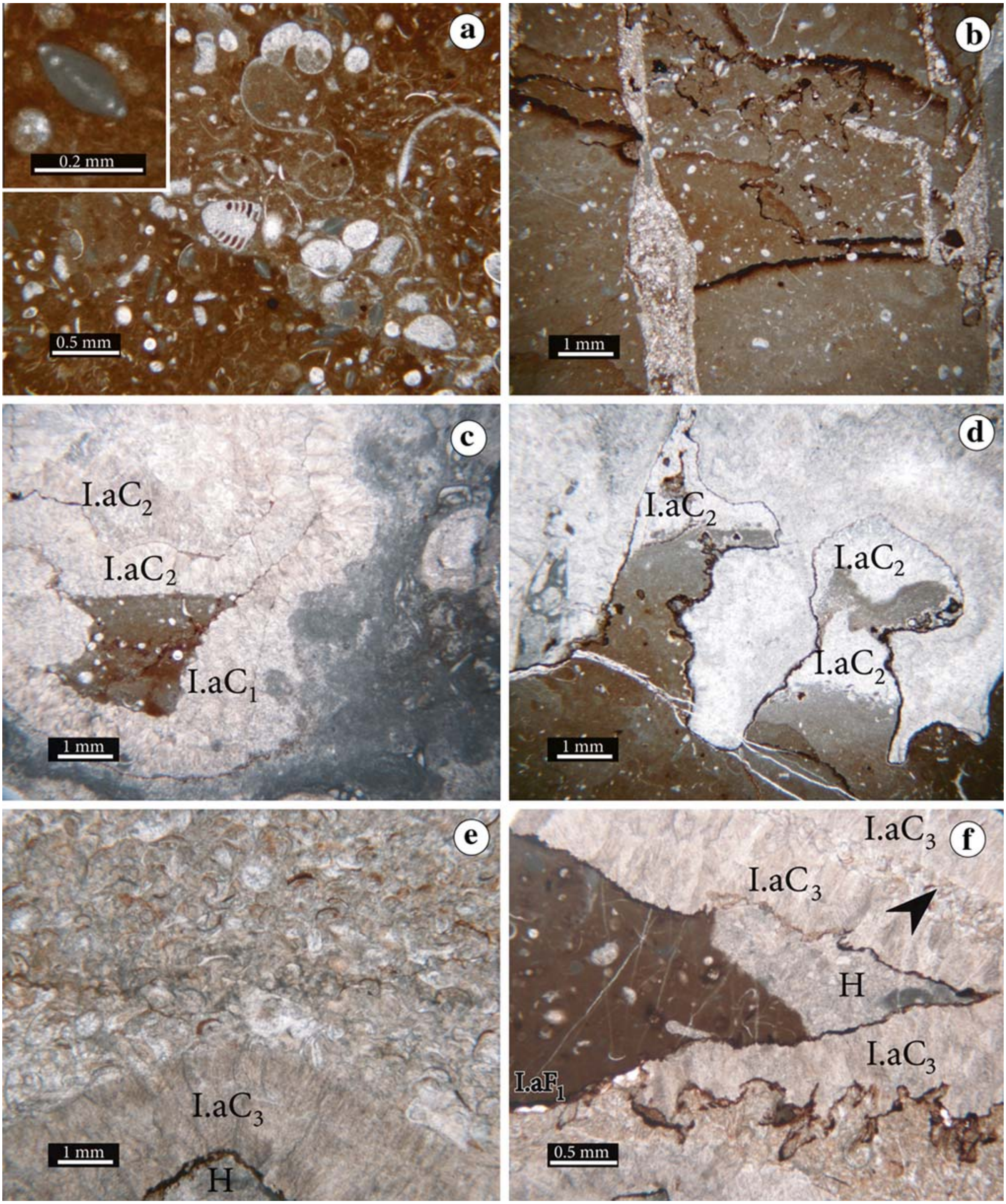


Fig. 3 Geometries of the I. generation of neptunian dikes. **a** Irregular dissolution cavity inside a host rock clast. **b** Smaller-sized breccia body. **c** Thin fractures penetrating the host rock, forming mosaic breccia



– I.bF_2: Grey, in places pinkish, mudstone to wackestone with sponge spicules and radiolarians (Fig. 5a–c). I.bF_2 represents the matrix of the breccia containing host-rock clasts covered by Fe–Mn crusts and bladed sparite cement (I.bC_1, Fig. 5d). Some of the host-rock clasts contain I.bF_1.
– I.bF_3: Red micrite fills small cracks, where sparite cement precipitated beforehand (I.bC_2, Fig. 5d).

◀ **Fig. 4** Thin sections of the I. generation, group a. **a** Pink packstone (*I.aF₁*) with ostracodes and foraminifers. In the *centre* of the figure is *Trocholina* sp., in the *upper left corner* is the magnified *A. martana*. Some of the ostracode shells contain geopetal structures. **b** Pink wackstone with benthic foraminifers and ostracodes (*I.aF₁*) containing several Fe–Mn impregnated surfaces. It is cut by red packstone with echinoderm fragments of the II. generation. **c** Dissolution cavity inside the host rock: first filled by radiaxial fibrous calcite (*I.aC₁*), then with pink wackestone with foraminifers and ostracodes (*I.aF₁*). In the remaining space, two generations of radiaxial fibrous calcite precipitated (*I.aC₂*). **d** Pink wackestone (*I.aF₁*) filling dissolution cavity inside the host rock. Remaining spaces filled with two generations of granular calcite cements (*I.aC₂*). **e** Ostracode coquina (*I.aF₂*); *lower part* of the photo shows a small part of the host rock (*H*) covered with radiaxial fibrous calcite with up to 1.2 mm long crystals (*I.aC₃*). **f** Clast of host rock (*H*) containing wackestone with benthic foraminifers and ostracodes (*I.aF₁*), covered with radiaxial fibrous calcite cement (*I.aC₃*). *Arrow* points to breccia's matrix—ostracode coquina

Interpretation

The formation of irregular cavities could occur either solely by limestone dissolution, or by mechanical fracturing and subsequent limestone dissolution, the latter causing reshaping of existing voids. Radiaxial fibrous calcite cements inside the dissolution voids show that circulation of water providing the carbonate was possible and indicate phreatic-marine diagenetic environment. Several Fe–Mn impregnated surfaces in the internal sediment show filling in phases with intervals of no deposition. On the other hand, the mosaic breccias were formed by the mechanical deformation and penetrative fracturing of the host rock (cf. Cozzi 2000, in situ brecciation produces "shatter breccias"), which is commonly caused by seismic shocks (Vachard et al. 1987; Montenat et al. 1991; Cozzi 2000).

Exclusively, ostracode shells of the ostracode coquina (I.aF$_2$) could have accumulated by mechanical sorting of empty shells through the natural sieve (cf. Winterer et al. 1991). Such a sieve could have been formed by tightly packed host-rock clasts, cemented together by radiaxial fibrous calcite cement. In this case, the remaining larger voids would be filled with smooth ostracodes (cf. Mišik et al. 1995), while finer sediment, micrite, would be transported further (I.bF$_3$?).

The presence of the foraminifer *A. martana* in the facies I.aF$_1$ is indicative of a Pliensbachian age (Chiocchini et al. 1994). The same age is determined for the upper part of the platform limestone. Furthermore, *I. liassica* in facies I.bF$_1$ also suggests that the beginning of infilling occurred prior to the Toarcian. Therefore, both processes of neptunian dike formation (cf. Smart et al. 1988; Winterer et al. 1991) i.e., void initiation (deformation of host rock by mechanical fracturing and/or dissolution) as well as infilling with sediments and/or precipitates, occurred in the Pliensbachian.

II. Generation of neptunian dikes

Appearance, dimensions and structure

The neptunian dikes of the second generation are far greater in dimension and abundance in comparison to those of the first generation. The following geometries have been recognized (Fig. 6): (A) laterally confined breccias and; (B) variously orientated fractures with sharp sidewalls, up to a few dm wide and up to 1 m deep (Fig. 6e, f). The laterally confined breccias, up to 20 m wide and more than a few metres deep (the lower contact with the host rock is not completely exposed), most probably represent vertical fractures filled with chaotic breccias (Fig. 6a); in places a mosaic structure is observed, which is more evident in smaller sized breccias (Fig. 6b–d).

Lithology and facies

The second generation of neptunian dikes is characterized by two lithotypes: II.aF and II.bF. Chaotic polymict breccias (II.aF) are present as both laterally confined large breccia bodies (A) and infill of evident fractures (B). Monomict breccias containing exclusively host-rock clasts (II.bF) are only present as laterally confined breccias of smaller dimension (1).

- II.aF: Breccia with angular host-rock clasts (up to 1.2 m in size); some clasts include sediments of the first generation of neptunian dikes (Fig. 6c). Other clasts are: clasts of micritic and microsparitic limestone, up to 8 cm in length (Fig. 7a); black clasts, from a few mm to 3 cm in size, containing opaque minerals (Fig. 7b); clasts of graded packstone to wackestone, up to 15 cm in size, with pelagic pelecypods, echinoderm fragments, peloids and glauconite (Fig. 7c, close-up of a clast marked by an arrow in Fig. 6f); and clasts of the first generation of neptunian dikes (I.aF$_1$; Fig. 7d). The matrix is mostly red, in places grey, marly limestone (wackestone to packstone) containing echinoderm fragments (Fig. 7e). In thin section, normal grading of breccia into calcarenite or calcilutite can be observed (Fig. 7f). Horizontal, vertical and oblique laminations are present in places (Fig. 8).
- II.bF: Breccia containing exclusively host-rock clasts (Fig. 6b, d) and marly limestone matrix. Clasts are angular and fit to each other. The matrix of the breccia is a red/grey marly limestone containing echinoderm fragments and is equivalent to the matrix of II.aF.

Interpretation

Variously orientated fractures and breccia bodies were formed by the mechanical deformation of the host rock. Smaller-sized breccias of the second generation were formed by mechanical fracturing of the host rock. Larger breccia bodies most probably represent vertical fracture fillings several metres deep, caused by fracturing of the carbonate platform margin. Fractures were filled with autochthonous as well as allochthonous sediments. Autochthonous sediments are clasts of host rock, derived from the walls of the fracture; allochthonous sediments are various rounded clasts (described within II.aF) and red/grey marly limestone with echinoderm fragments (matrix of breccias II.aF and II.bF). The remaining empty spaces were gradually filled by laminated marly limestone. Horizontal laminations

Fig. 6 Geometries of the II. generation of neptunian dikes. **a** Breccia with angular host-rock clasts embedded in red matrix. **b** Mosaic breccia with red matrix and host-rock clasts which fit together well. **c** Mosaic breccia with grey matrix and host-rock clasts, *arrow* pointing at the ones containing sediments of the I. generation of neptunian dikes. **d** Polished section of mosaic breccia where it is evident that host-rock clasts are almost unmoved. **e** Ground view of an evident vertical crack with sharp side walls filled with grey sediment. **f** Sill within the host rock with red matrix; *arrow* pointing at pinkish clast (microfacies of the clast is shown in Fig. 7c) ▶

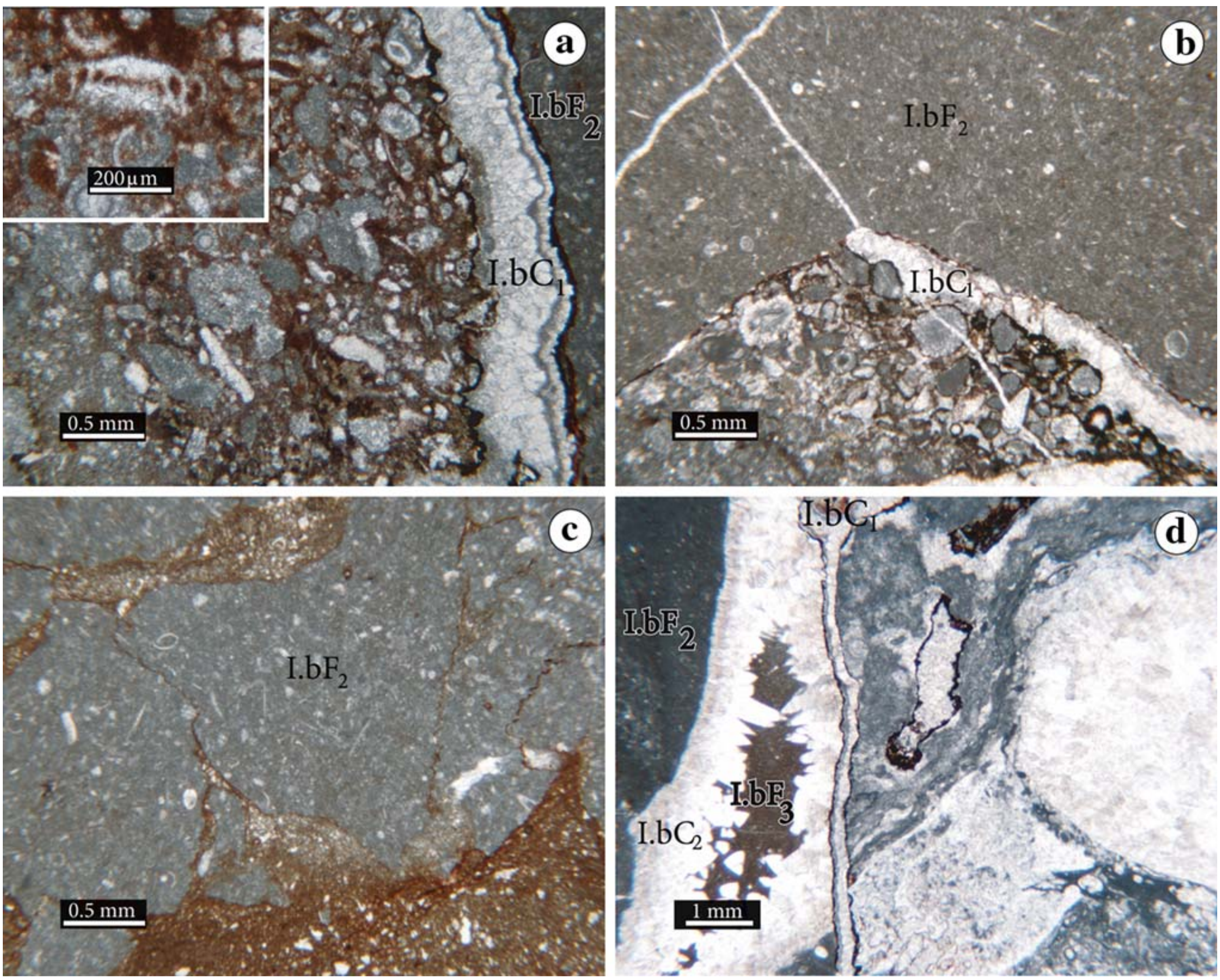


Fig. 5 Thin sections of the I. generation, group b. **a** Clast of red packstone (*I.bF*$_1$), in the upper left corner is the magnified *I. liassica*. Clast is covered by Fe–Mn crust, bladed circumcircular calcite cement with up to 0.5-mm-long crystals (*I.bC*$_1$) and micritized upper part, and another Fe–Mn crust. The very right part of the photo is breccia's matrix—grey mudstone (*I.bF*$_2$). **b** Clast of host rock containing red packstone (*I.bF*$_1$) and radiaxial calcite cement (*I.bC*$_1$) with micritized upper part and Fe–Mn crust on one side. Clast is embedded in grey wackestone matrix (*I.bF*$_2$). **c** Grey wackestone (*I.bF*$_2$) cut by II. generation of neptunian dikes. **d** On the *right side* of the photo, is host rock clast covered with sparite cement and Fe–Mn crusts (*I.bC*$_1$). On the *left side* is grey wackestone matrix (*I.bF*$_2$) with a crack, filled with bladed and dogtooth calcite cement (*I.bC*$_2$) and red micrite (*I.bF*$_3$)


a
b
c
d
e
f

could have been produced by minor turbidity currents, which episodically transported the sediment into the remaining space (cf. Sarti et al. 2000). Smaller-sized breccias exhibiting a mosaic structure are a product of mechanical fracturing, where only certain small areas of the platform limestone, pockets with a diameter of a few decimetres, were fractured and the clasts were not transported. On the other hand, the chaotic breccia filled wider open fractures, where host-rock clasts of greater dimensions were derived from the fracture walls. Host-rock blocks are volumetrically by far the most important constituents in chaotic breccias. Therefore, the prevailing mechanism of infill is rock fall. The presence of the first generation of neptunian dikes in some of the clasts shows that the host rock was fractured prior to brecciation.

The age of the sediments representing the second generation of neptunian dikes is poorly constrained due to the lack of index fossils. Similar facies, i.e., crinoidal limestones, are widespread in the Early Jurassic of the Mediterranean Tethys (encrinite bodies deposited at the bottom of Jurassic escarpment; e.g., Di Stefano et al. 2002). However, clasts of packstone with filaments (Fig. 7c) inside the breccia II.aF that were lithified prior to redeposition (see also Fig. 6f), suggests that the age of brecciation might be younger than the onset of pelagic deposition in the area.

Other facies

In addition to the above-described facies, rare samples of folded laminated microsparite (Fig. 9a) were found filling irregular cavities up to a few centimetres in size. Folded and fractured laminae are not uncommon inside neptunian dikes; e.g., Sano and Orchard (2004) noticed such structures in the Necoslie breccia, which they interpreted as neptunian dike. Due to the geometry of the filled voids and the presence of cements (Fig. 9b), the facies could belong to the first generation of neptunian dikes. However, we did not find any crosscutting relationship with sediments of either first or second generation. Therefore, the relative time of formation cannot be determined.

Other neptunian dikes at Mt Mangart

Apart from the above-described neptunian dikes at Mt Mangart, related features occur in the Mangart peak subunit and in the Drn subunit. In the Drn subunit (b in Fig. 1b), larger blocky breccia bodies occur in the Lower Jurassic platform limestone. The lateral contact with the host rock is sharp, the dimensions of breccia bodies are less than a few tens of metres and up to 1-m-sized boulders of host rock are embedded in red matrix. The breccia is clast supported; some of the host-rock clasts contain dissolution voids filled with red calcilutite. The matrix is red microsparite with aptychi, fragments of echinoderms and of pelagic crinoid *Saccocoma* sp. The occurrence of *Saccocoma* sp. suggests that the matrix is Late Kimmeridgian to Early Tithonian in age (e.g., Sartorio and Venturini 1988).

Near the Mangart peak (c in Fig. 1b), laterally confined breccias crop out within the Upper Triassic Dachstein limestone. The breccias contain mainly clasts of Dachstein limestone. The matrix is marly limestone with echinoderm fragments, the same as matrix of the breccias II.aF and II.bF. Based on matching host rock, equivalence of matrix and similarity in geometry, the breccias are interpreted as neptunian dikes of the second generation.

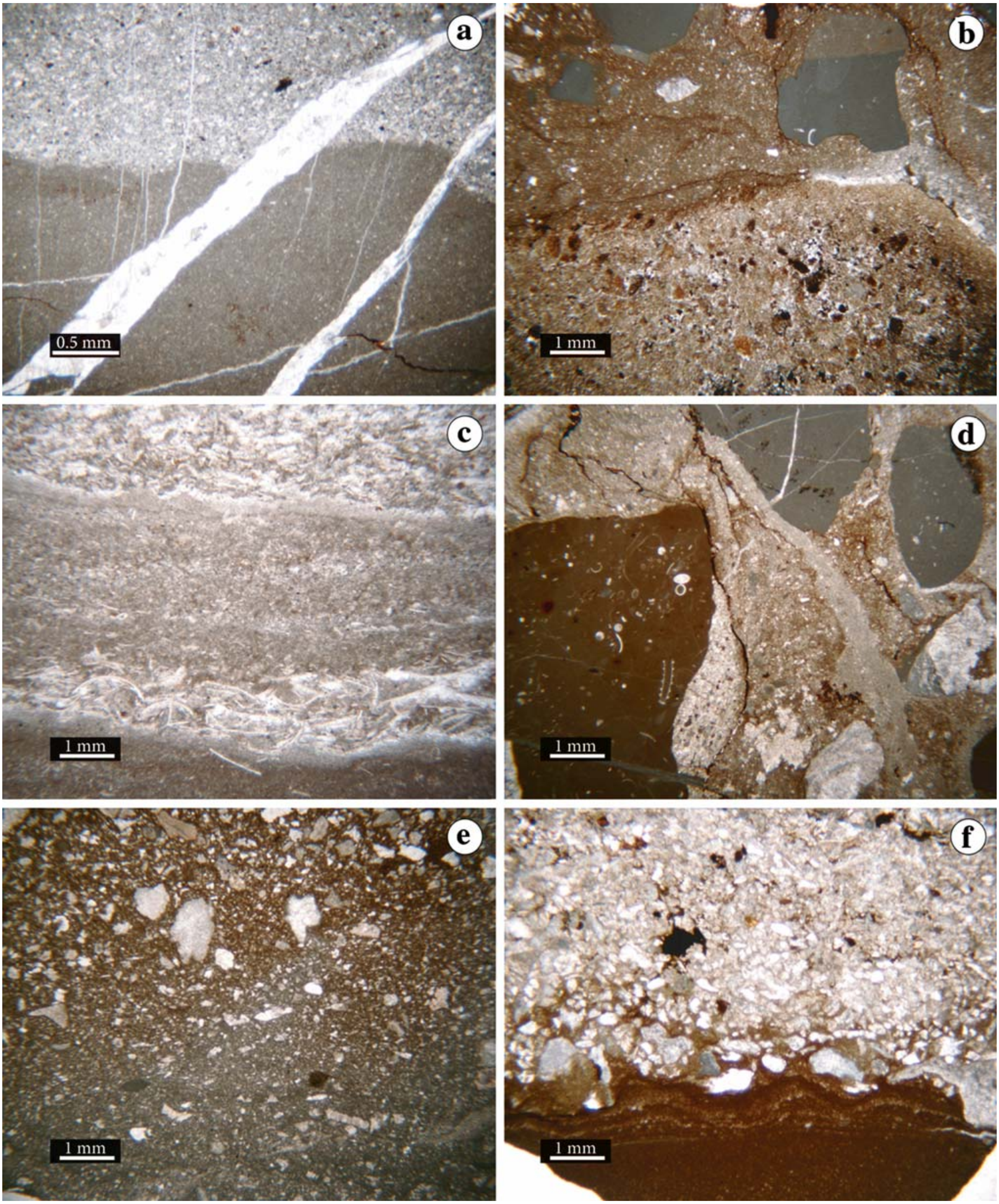
Fig. 7 Thin sections of the II. generation of neptunian dikes. **a** Micrite and microsparite with cracks, filled with sparite cement (clast). **b** In the *lower* part of the photo is macroscopically black clast, brown in thin section, which contains opaque minerals. The *upper* part of the photo shows red matrix with clasts of grey and reddish mudstone. **c** Graded packstone to wackestone with filaments and pellets (clast). **d** Breccia with red packstone with echinoderm fragments as matrix and clasts of grey mudstone and pink wackestone containing ostracodes and benthic foraminifers of the I. generation ($I.aF_I$). **e** Packstone with echinoderm fragments—matrix of the breccias of the second generation. This microfacies is by far the most abundant matrix in breccias of the II. generation. The photo exhibits both colours (*red* and *grey*) of the matrix. **f** In the *lower* part of the photo, red mudstone with load casts (representing the upper part of graded packstone), in the upper part red packstone with echinoderm fragments ▶

Discussion

Neptunian dike formation

The formation of neptunian dikes at Mt Mangart is a product of mechanical deformation of the host rock. Irregular cavities represent the only group of neptunian dikes in which formation by dissolution is indicated. The same age (Pliensbachian) was determined for the host rock and for the first generation of neptunian dikes, suggesting that the initiation of the voids and the subsequent infill with deeper-marine sediments occurred almost simultaneously.

The origin of breccias of the second generation fits well with the existing models of neptunian dike and/or breccia formation. Open fissures, internal breccias and mass flow breccias can form either on a carbonate platform margin (i.e., slope; Füchtbauer and Richter 1983) or on a steep escarpment (Vachard et al. 1987; Montenat et al. 1991). Both models show that breccias can represent either infill of open fractures or escarpment sediments. Breccias of comparable dimensions and appearance as studied breccias at Mt Mangart were formed at different times in analogous environments. Sudden collapses of the carbonate platform produced laterally discordant intraformational breccias during the Late Triassic rifting phase in the Southern Alps



(Cozzi 2000). The same mechanism, disintegration of the platform margin, triggered submarine rock falls and debris-flows in the late Early Jurassic in the Southern Apennines (Iannace et al. 2005). Recently, Aubrecht and Szulc (2005) introduced a model for the deposition and cementation of the Krasin breccia, where various breccias are formed on different parts of the platform escarpment and represent either void infill or escarpment sediments. Breccias at Mt

Mangart are interpreted as fracture fills due to the limited extent of brecciated sediment, which gradually passes into a non-deformed host rock.

The overall development of open voids and their infilling, consequently forming a network of neptunian dikes, is shown on Fig. 10. Due to the lack of crosscutting relationship between the groups I.a and I.b, an overall interpretation is not possible. Two separate sequences (I.a, I.b) of void formation and their infill by sediments and the precipitation of calcite cements are shown. The second generation of neptunian dikes clearly crosscuts the first generation of neptunian dikes.

Timing of neptunian dike formation and local correlation with other Jurassic facies in the Julian Alps

Here, we compare facies of the first and the second generation of neptunian dikes with previously studied neptunian dikes as well as with normal stratigraphic successions of the Bovec Trough and Julian High (see Fig. 11). None of the sediments of the first generation have hitherto been recognized as neptunian dike infill elsewhere in the Julian Alps.

The first generation of neptunian dikes can only be compared to sediments deposited in the Bovec Trough (Fig. 11), because there are no sediments preserved on the Julian High from the Pliensbachian to the Bajocian. There is no facies analogue for ostracode coquinas (I.aF_2) or for red packstones with limestone fragments and *I. liassica* (I.bF_1). Microfacies I.aF_1, and I.bF_2 are comparable to the Pliensbachian Sedlo Formation (red line in Fig. 11). Packstones with ostracodes, echinoderms and foraminifers including *A. martana* (I.aF_1), and grey wackestones with sponge spicules (I.bF_2) are virtually identical to facies of the Sedlo Formation. Because we determined the same age, i.e., Pliensbachian, for both the host rock and neptunian dike infills, we can establish the timing of fracturing. The fracturing of the host rock and the shift from platform facies to deeper marine sediments in open fissures on the Julian High coincides with the pronounced deepening in the area of the newly formed Bovec Trough.

The facies of the second generation match with neptunian dike sediments elsewhere in the Julian Alps, briefly described by Buser (1986). The age of the breccias was presumed to be late Early Jurassic to Middle Jurassic (Buser 1986). The Middle to Upper Jurassic matrix of the breccias at Mt Krn (Babić 1981) and at Lužnica Lake (Šmuc 2005) contains planktonic foraminifers and therefore differs from breccia matrices II.aF and II.bF. The matrix of the breccias of the second generation in the Mali Vrh structural subunit lacks fragments of the *Saccocoma* sp., which are the prevailing grains in neptunian dikes at Ravni Laz (Šmuc 2005). However, fragments of *Saccocoma* sp. are present in the matrix of the breccia in the Drn structural subunit.

Fig. 8 Structures inside the breccia of the II. generation. **a** Horizontal to oblique lamination of the breccia's matrix. **b** Deformed breccia matrix probably caused by sudden movement and deformation of semi-lithified sediment. **c** Horizontal laminae of the breccia matrix in thin section. **d** Oblique laminae of the breccia matrix ▶

Since the Bajocian, the Bovec Trough was a deep basin, characterized by resedimented limestones. An analogue of neptunian dike infill is therefore possible only on the Julian High. The matrix of the breccias of the second generation differs from deposits of the Prehodavci Formation (Fig. 11). However, the clast (Figs. 6f and 7c) in the breccia of the second generation of neptunian dikes corresponds to limestones of the Prehodavci Formation (Fig. 11). Both, the Lower and the Upper Member of the Prehodavci Formation mostly contain filaments. They are, nevertheless, easily differentiated by their colour: the Lower Member is grey and the Upper Member is red. This change in colour is systematic for all sections studied by Šmuc (2005). It is therefore more probable that the clast (Figs. 6f and 7c) corresponds to the Upper Member of the Prehodavci Formation. If this comparison is correct, the infill of the second generation of neptunian dikes is at least partly posterior to the Kimmeridgian. However, a much younger age of sediments of the second generation cannot be excluded.

In the Mali Vrh subunit, the deposit overlying the platform limestone with neptunian dikes is the Upper Cretaceous Scaglia rossa, while in the Drn subunit it is the Albian Scaglia variegata. Therefore, the upper time limit for the formation of the second generation of neptunian dikes is Albian, or at least the infill of open voids may have continued until this time. The timing of the main fracturing for the second generation of neptunian dikes has not been satisfactorily constrained yet. For the time being it seems most likely that the major brecciation occurred during Kimmeridgian-Early Tithonian. This assumption is based on the age of neptunian dikes containing fragments of *Saccocoma* sp. in the Drn structural subunit and the presence of pelagic clast with filaments in the chaotic breccias. Moreover, well-dated neptunian dikes of this age occur in the Triglav Lakes Valley (Fig. 11; Šmuc 2005).

Regional correlation

Neptunian dikes of the first generation are interpreted as being caused by the Julian carbonate platform dissection during the Pliensbachian. The fracturing of the host rock and differential subsidence of various blocks was related to regional extensional faulting due to rifting. The detailed timing of faulting across different segments of the Tethyan margins varies from one locality to another (Winterer and Bosellini 1981). Within the widely recognized latest Triassic


a
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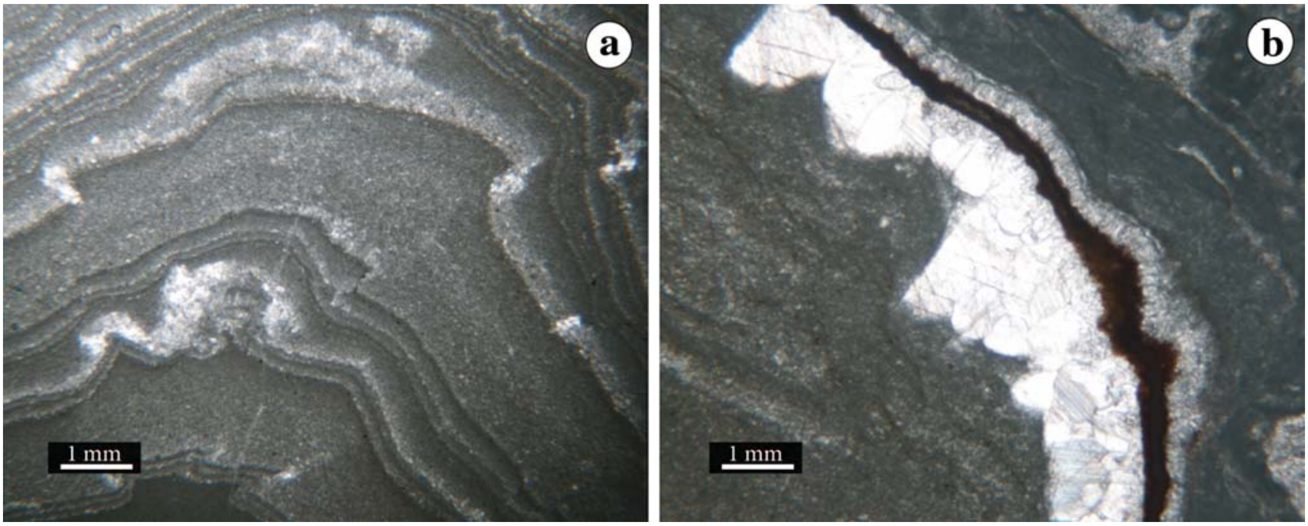

Fig. 9 Thin sections of uncategorized neptunian dike infill. **a** Laminated microsparite with deformed laminae. **b** The *right* part of the photo shows host rock covered with Fe–Mn crust and sparite cement, in the *left* part is the laminated microsparite

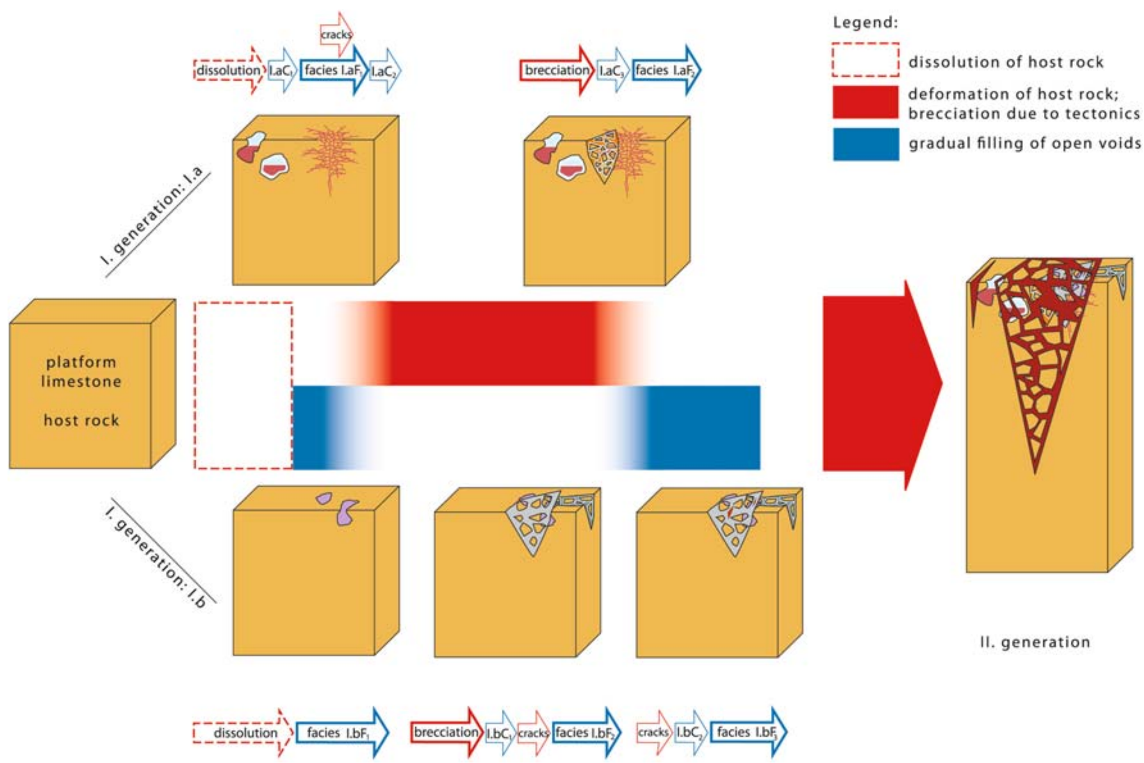

Fig. 10 An overall interpretation of neptunian dike formation—void formation and their infill. Two groups of infill (*I.a* and *I.b*) represent the I. generation of neptunian dikes. Because contacts between sediments of these two groups are lacking, the relative timing of void formation (*red arrows*) and infill (*blue arrows*) is indicated for each group individually. Sediments of the II. generation of neptunian dikes are far more abundant and crosscut most of the sediments of the I. generation

to Early Jurassic episode, the Early Jurassic phase was the most important in the area of the Southern Alps and a great number of the neptunian dikes were emplaced in rocks of that age (Winterer et al. 1991). However, there are few examples of Lower Jurassic neptunian dikes, where the infill of open voids immediately followed their formation. The latter is very well documented at Mt Mangart. Pliensbachian neptunian dikes are known in southern Spain (Winterer and Sarti 1994), Sicily (Boullin et al. 1992; Mallarino 2002), and in the Southern Alps (this study), pointing to contemporaneous faulting across a wider Tethyan region.

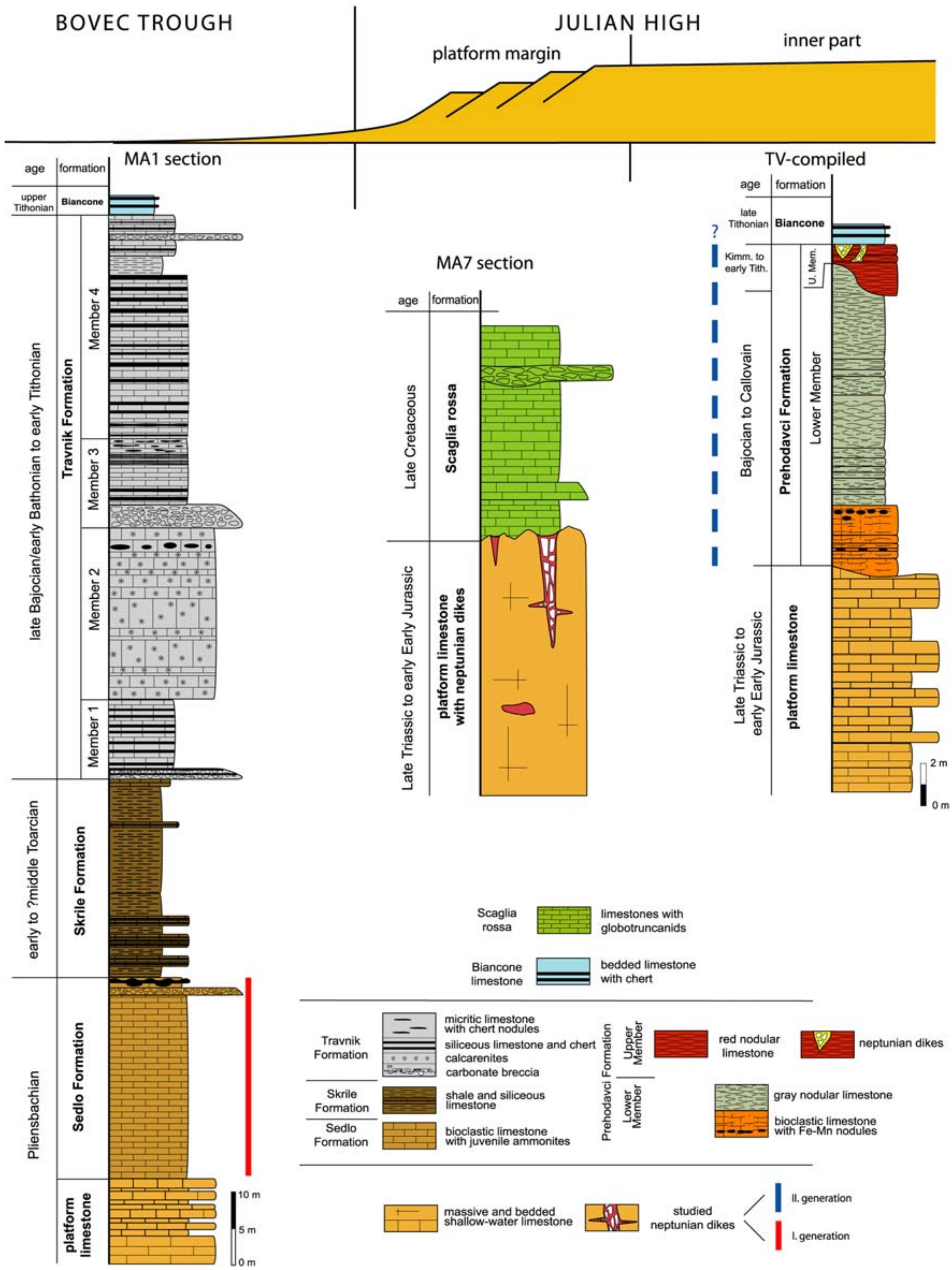

Fig. 11 Jurassic reconstruction across the Bovec Trough and Julian High with typical stratigraphic successions (after Šmuc 2005, modified). The MA1 section illustrates sediments deposited in the Bovec Trough during the Jurassic (location: Mt Mangart, Travnik structural unit); the TV-compiled section illustrates Jurassic stratigraphy of the inner part of the Julian High (location: Triglav Lakes Valley); the MA7 section represents stratigraphic situation at investigated area, which belongs to the marginal part of the Julian High (location: Mt Mangart, Mali Vrh structural subunit). *Red and blue lines* beside the stratigraphic columns show which sediments deposited are possible equivalents to neptunian dike infill. The names of the sections correspond to the names used by Šmuc (2005)

Neptunian dikes of the second generation are more widespread, but the timing of void formation and filling can be only broadly constrained. Therefore, possible analogues include Middle and Upper Jurassic breccias and neptunian dikes. Breccias with Middle Jurassic matrix containing pelagic pelecypods (*Bositra*) and/or crinoids were recognized in the southern Spain (Winterer and Sarti 1994), Sicily (Mallarino 2002; Martire and Pavia 2004) and in the Southern Alps (Winterer et al. 1991; Martire 1996). Matrix of breccias at Mt Mangart in the Drn structural subunit is comparable to infill of small dikes filled with *Saccocoma* fragments in the Southern Alps (Martire 1996) and in Sicily (Martire et al. 2000; Sarti et al. 2000). Even though a Late Jurassic tectonic pulse was recognized in northern Greece (Carras et al. 2004), western Sicily (Martire and Pavia 2004) and locally in the Southern Alps (Martire 1996), we cannot consider it to be the only possible explanation of neptunian dike formation at Mt Mangart. Alternatively, formation of voids occurred any time between Pliensbachian and Late Cretaceous, but their infill continued at least until the Kimmeridgian. A time gap of 10 million years between sedimentation of limestone, hosting neptunian dikes, and the infill is very common (e.g., Winterer et al. 1991). Very long time spans of escarpment sedimentation have been reported, e.g., Pliensbachian to Neocomian (Santantonio 1993). Sarti et al. (2000) recognized even longer periods of repeated fracturing and infilling: late Early Jurassic to Albian-Cenomanian. Repeated fracturing or slope failure is, therefore, common along carbonate platform margin or paleoescarpment settings; as a result, long time periods of neptunian dike formation are not extraordinary.

Platform limestone with neptunian dikes at Mt Mangart is unconformably overlain by Scaglia rossa. Unconformity between Upper Cretaceous and underlying deposits is well recognized also on Trento Plateau in northern Italy. An example, equivalent to the Mt Mangart stratigraphic situation, is at the Pra dei Papi section, where neptunian dikes are hosted by Upper Triassic to Lower Jurassic dolomite, overlain by Campanian to Maastrichtian Scaglia rossa (Lehner 1992, 87).

Conclusions

Neptunian dikes at Mt Mangart are a product of a multiphase void formation and their infill. A complex system was differentiated into two main generations. On the basis of crosscutting relationships and composition, the order of the sediments filling variously shaped voids was established. An overall development of open voids and their filling, consequently forming a network of neptunian dikes, is shown in Fig. 10.

Neptunian dikes of the first generation are interpreted to be caused by the Julian carbonate platform dissection during the Pliensbachian. The fracturing of the host rock and differential subsidence of various blocks was related to rift-related regional extensional faulting. Formation of open voids and their immediate infill is very well documented at Mt Mangart; we were able to determine the same stage age for both the host rock and for the infilling sediments. Presence of the Pliensbachian neptunian dikes in southern Spain, Sicily and in the Southern Alps, exhibits contemporaneous faulting across a wider Tethyan region. Second generation neptunian dikes are more widespread; possible age of their formation encompasses the Pliensbachian to the Late Cretaceous. However, as inferred from the local stratigraphic correlation, a Kimmeridgian-Early Tithonian age seems the most probable.

Overall, not many of the sediments filling the neptunian dikes at Mt Mangart correspond to sediments deposited in "normal" stratigraphic successions in the Julian Alps. This could be due to the fact that sedimentation in small voids or narrow channels differs fundamentally from sedimentation on the sea floor. Nevertheless, due to the fact that a wide time gap exists on the Julian High from the Pliensbachian to the Bajocian, sediments filling neptunian dikes may represent the only preserved sediments of that age on the Julian High.

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