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Biancone transformed into dolosparite: evidence for secondary recrystallisation (Dolomite Mountains, S.Tyrol, N.Italy)

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(With 12 figures)

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Abstract

Information is provided about the dolosparite from the Puez area (Gardenacia Plateau, Southern Alps) near Wolkenstein (S.Tyrol, N.Italy). At the Puez locality on the northern part of the Trento Plateau, the dolosparite appears with a whitish to yellow, granulated structured facies. The term Gardenacia Formation was established for this dolomitised facies on the Gardenacia Plateau. The dolosparites were transformed from Lower Cretaceous limestones of the primary Biancone/Maiolica type facies. The succession of the whitish dolosparite, the overlaying greyish Biancone Formation and the reddish Rosso Ammonitico facies sheds light on the late diagenetic and tectonic history of the Puez area and the Dolomites. The age of the primary limestone is late Valanginian to early Hauterivian. Based on the fabrics and stable isotope data ($\delta^{13}C$, $\delta^{18}O$) of the dolosparites a burial recrystallisation with a late diagenetic (consolidated sediment) dolomitisation cycle is assumed.

Keywords: Dolosparite, Late Diagenesis, Early Cretaceous, Puez, Dolomites, Italy

Zusammenfassung

Informationen zur Dolosparit Fazies aus dem Puez Gebiet (Gardenacia Plateau, Südalpen) nahe Wolkenstein (S. Tirol, N. Italien) werden präsentiert. An der Lokalität Puez am nördlichen Teil des Trento Plateaus tritt der Dolosparit mit weißlich bis gelblicher, körniger Fazies auf. Der Terminus Gardenacia Formation wurde für diese dolomitisierte Fazies auf dem Gardenacia Plateau eingeführt. Die Dolosparite wurden aus unterkretazischen Kalken der primären Biancone/Maiolica Fazies transformiert. Die Abfolge von weißlichem Dolosparit, der überlagernden Biancone Formation und den rötlichen Rosso Ammonitico Puezzese Kalken wirft Licht auf die spät-diagenetische und tektonische Geschichte des Trento Plateaus und der Dolomiten. Das Alter des Ausgangsgesteines ist spätes Valanginium bis frühes Hauterivium. Basierend auf dem Gefüge und

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den Daten der stabilen Isotope (δ^{13}C, δ^{18}O) der Dolosparite wird eine Versenkungs-Rekristallisation mit einem spät-diagentischen (verfestigtes Sediment) Dolomitisations-Zyklus angenommen.

Schlüsselworte: Dolosparit, Späte Diagenese, Unter-Kreide, Puez, Dolomiten, Italien

Introduction

The complex Mediterranean palaeogeography of Jurassic and Cretaceous domain (Fourcade *et al.* 1993; Lukeneder 2010, 2011) is characterised by the presence of microplates situated in the middle of the Tethyan oceanic corridor between the African and European landmasses. The microplates were limited by the Penninic Ocean (= Alpine Tethys) to the North and the Vardar Ocean (= Meliata Ocean) at its South-East border (Dercourt *et al.* 1993; Scotese 2001; Stampfli & Mosar 1999; Stampfli *et al.* 2002).

In the Southern Alps and especially in the Dolomite Mountains, Upper Jurassic to Lower Cretaceous cephalopod-bearing deposits are mainly recorded in three different facies, the red, nodular carbonates of the Rosso Ammonitico Formation (RAP = Rosso Ammonitico Puezzese at Puez; Lukeneder 2011) formed on submarine highs, the calcareous nannofossil limestones of the Biancone Formation (= Maiolica Formation elsewhere in Italy; Lukeneder 2011) and the more marly Puez Formation (marls–marly limestones) formed mainly on slopes and basins.

The formation of these different facies types occur on a mosaic of platforms and submarine rises (*e.g.*, Trento Plateau; Weissert 1981; Lukeneder 2010, 2011) and several depths and basins (*e.g.*, Lombardian Basin, Belluno Basin) to the east, were established due to Jurassic tectonics, caused by the opening of the Atlantic and Penninic Oceans (Bosellini 1998; Fourcade *et al.* 1993). The history of this area reflects the evolution of the Circum-Tethyan area. The evolution of marine biota on the Southern Alpine microplate and the southern European shelf was influenced by continuing disintegration of carbonate platforms during the Early Cretaceous. The central Atlantic, the western adjacent Ligurian Ocean, and the newly formed Penninic Ocean were opening during Early–Middle Jurassic (Cecca *et al.* 1992; Fourcade *et al.* 1993). The Puez area is situated on the northernmost part of the Trento Plateau within the Dolomites, located on one of the so formed submarine plateaus the Puez-Gardenacia Plateau. The history of this elevation lasts back to the Triassic, over the Jurassic and ends with sediments of the Lower to Middle Cretaceous (Weissert 1981; Bosellini 1998).

Cretaceous pelagic to hemipelagic sediments cover relatively small, restricted areas in the Southern Alps. Lower Cretaceous deposits form a major element of the mountainous area of the higher Dolomites (Hoernes 1876; Haug 1887, 1889; Uhlig 1887; Rodighiero 1919; AGIP Mineraria 1959; Baccelle & Lucchi-Garavello 1967a, b; Stöhr 1993, 1994; Costamoling & Costamoling 1994; Lukeneder & Aspmair 2006). The geology of the Dolomites and adjacent areas has been described and summarised in detail by Avanzini & Wachtler (1999), Pozzi (1993), Geyer (1993), Heissel (1982), Bosellini (1998), Bosellini *et al.* (2003), and Lukeneder (2008, 2010, 2011).

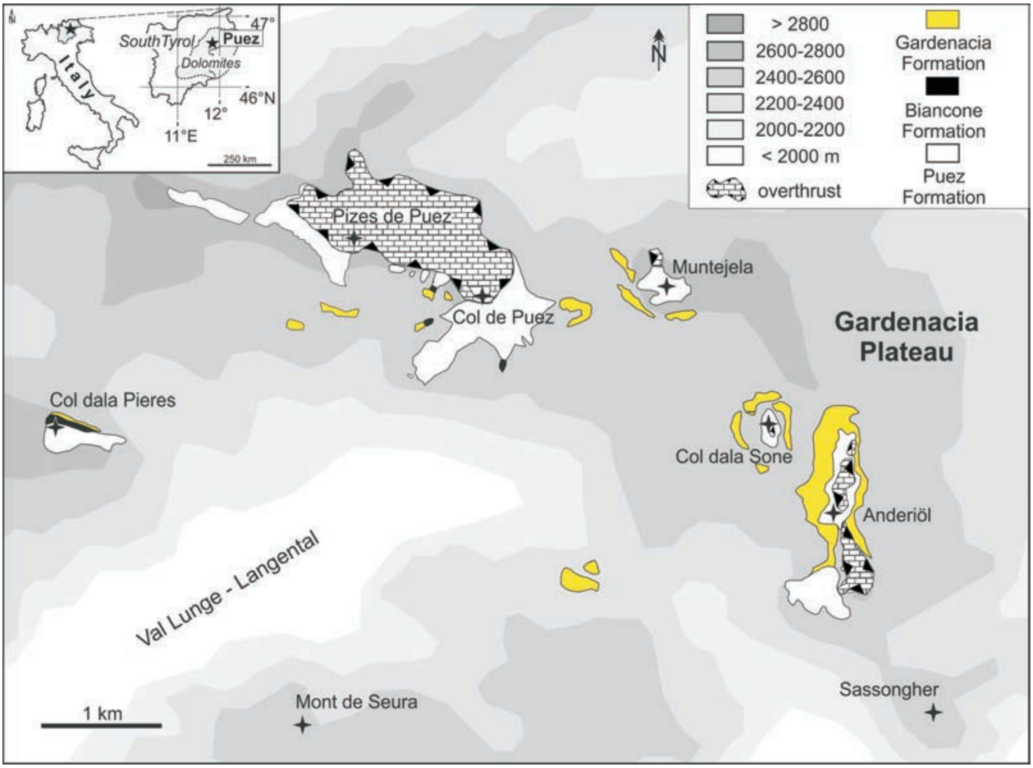

Fig. 1. Geographical overview (Dolomites, S.Tyrol, Italy) showing the study area and the type locality of the Puez Formation, Piz de Puez. Outcrops of Lower Cretaceous rocks and dolosparites (yellow) on the Puez-Odle-Gardenacia Plateau are indicated.

In the Dolomites, Lower Cretaceous cephalopod-bearing deposits are mainly recorded in two different facies, the calcareous limestones of the Biancone Formation (= Maiolica Formation elsewhere in Italy) and the Puez Formation (marls–marly limestones). The Lower Cretaceous relicts are situated on the Triassic limestones of the Dolomites (Hauptdolomit = *Dolomia Principale*, up to 1000 m thick) covered at the Puez area by Dachsteinkalk with megalodontid bivalves (up to 10 m; see KEIM 2007). At most of the localities where Lower Cretaceous sediments were found in the Dolomites, a relatively thin bed of dolosparites (4–8 m), overlain by Biancone type limestones (2–4 m) and followed by red nodular limestone of the Rosso Ammonitico facies type (= Ammonitico Rosso Fm.; 5–20 m) between the Triassic and Lower Cretaceous Puez Formation is observed (LUKENEDER 2010, 2011).

The time of the formation of dolomite crystals (dolomite $CaMg[CO_3]_2$) by the transformation of primary sediments during the diagentic history is crucial, but still under debate, for the entire diagenetic process. The two main genetic dolostones are synsedimentary dolomites and postsedimentary dolomites (= postdepositional dolomites; see BUDD 1997; MACHEL 2003). Such whitish to yellow dolosparites with granulated

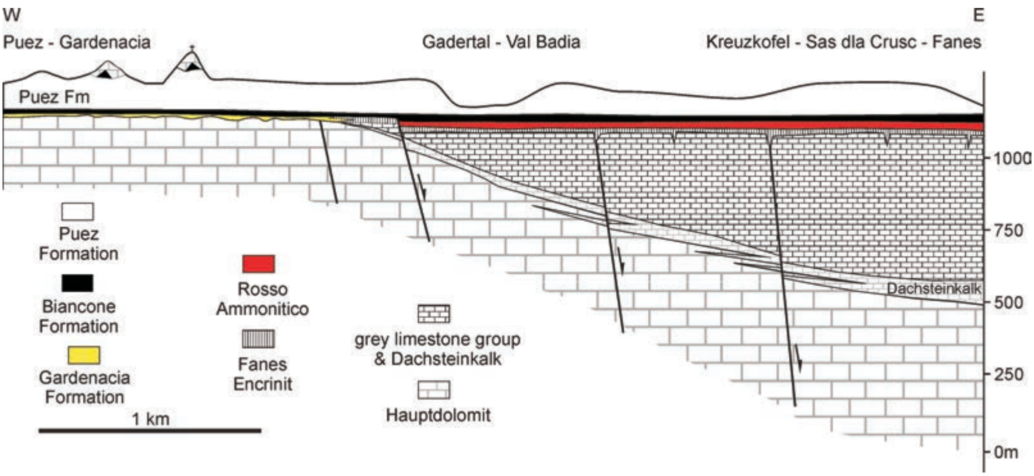

Fig. 2. Composite schematic E/W transect of the relevant Triassic to Cretaceous formations and lithologies around and at the Northern Trento Plateau and the Puez sections. The dolosparites of the Gardenacia Formation are indicated in yellow (modified after Keim 2007; not palinspastically corrected).

structure were recognised by Geyer (1993) and Keim (2007) in the Dolomite Mountains (Southern Alps) and by Cecca *et al.* (1995) from the Umbria-Marche region (Central Apennines) as "*Maiolica with saccharoidal structure*". All of the latter authors noted already the possibility that these dolosparites were transformed from limestones of the primary Biancone and Maiolica formations.

The main goal is to present more details on the dolosparites of the Puez area within the Southern Alps, to have an appropriate instrument for earth scientists dealing with that kind of secondary, transformed sediments.

Geographical and geological setting

Geography

The outcrop is situated on the Puez-Odle-Gardenacia Plateau in the Dolomites (Trentino – Alto Adige; South Tyrol). The exact position is about 30 km northeast of Bozen (Fig. 1). The localities are accessible from the village Selva di Val Gardena (= Wolkenstein, 1,560 m) in the Val Gardena (Grödner Tal) by following the Val Lunga (= Langental) to its eastern end and then hiking on paths 16 and 2 up the steep dolomite wall. An additional possibility is to hike from Colfosco (= Kolfuschg, 1,645 m) with the Rifugio Edelweiss (= Edelweiss Hütte, 1,836 m) on paths 4 and 2 (Lukeneder 2014). The outcrops are located near the Rifugio Puez (= Puez Hütte, 2,475 m). The Lower Cretaceous crops out running between the Col da la Pieres (2,747 m) at the west flank and the Col de Puez (2,725 m) at the eastern border (Figs 1–2). The whitish, yellowish, grey, green to red succession, comprising the dolosparite layers at the lowermost part of the non-Triassic succession, is located on the southern side of the Pizes de Puez (= Puezspitzen, up to 2,918 m, 1:25,000, sheet 05 Val Gardena) and the Col de Puez (= Puezkofel, 2,725 m). The dolosparite occurrence is exposed on the steep southern flanks. Almost 3,000 m high mountains, steep terrain and coverage by rock fall debris after the winter made sampling very difficult.

Geology

The section studied is located in the Southern Alps (Dolomites) of northern Italy (Lukeneder & Aspmair 2006; Lukeneder 2008). The stratigraphy of the Lower Cretaceous sediments here is based on ammonoids, microfossils and nannofossils. During the late 19th and early 20th century, a rich fauna of cephalopods was collected from Lower Cretaceous sediments from this area and determined by Haug (1887, 1889), Hoernes (1876), Uhlig (1887) and Rodighiero (1919). Additionally Faraoni *et al.* (1995, 1996, 1997) reviewed the papers published on Cretaceous ammonoids of the Maiolica Formation (= Biancone Formation in the Southern Alps) from the Venetian Alps, which directly adjoin to the south of the Dolomites, and the real Maiolica Formation of the Central Apennines.

The outcrops described herein are exposed on the Puez-Gardenacia Plateau. They are located within the area of the Puez-Odle-Geisler natural park in the northern part of the Dolomites. The Dolomites (Permian to Cretaceous) are an internal part of the Southern Alps which are a Northern Italian chain that emerged during the deformation of the passive continental margin of the Adriatic (Bosellini *et al.* 2003).

The geological landscape of the Puez region is dominated by the giant Triassic carbonate platforms. The top of these carbonates bears relicts of Lower Cretaceous sediments which were formerly much more widespread but have been eroded through time. The Lower Cretaceous sediments here are overthrusted ("Gipfelüberschiebung") by the older Triassic Hauptdolomit (Fig. 2). This phenomenon can only be observed at the Puez-Gardenacia and Sella areas located directly to the south (Heissel 1982). The thickness of the overthrusting dolomite differs markedly at different localities (0–150 m). Triassic Hauptdolomit (= *Dolomia Principale*) is overlain by strongly dolomitised layers (granulated structure, whitish to yellow) from most probably dolomitised former Biancone facies (see Geyer 1993; Fig. 3). This type of dolomitised sediments was called, in the Umbria-Marche region, "*Maiolica with saccharoidal structure*" (Cecca *et al.* 1995). Such dolomitised limestones characterise the first portion of the Maiolica deposited on the Jurassic pelagic carbonate platforms (PCP). Their thickness varies from 40–80 m on PCP up to 450 m in basin areas Cecca *et al.* (1995). On the geological map by Keim (2007) such dolosparites located on the Puez-Gardenacia Plateau were termed dolosparites of the Gardenacia Formation.

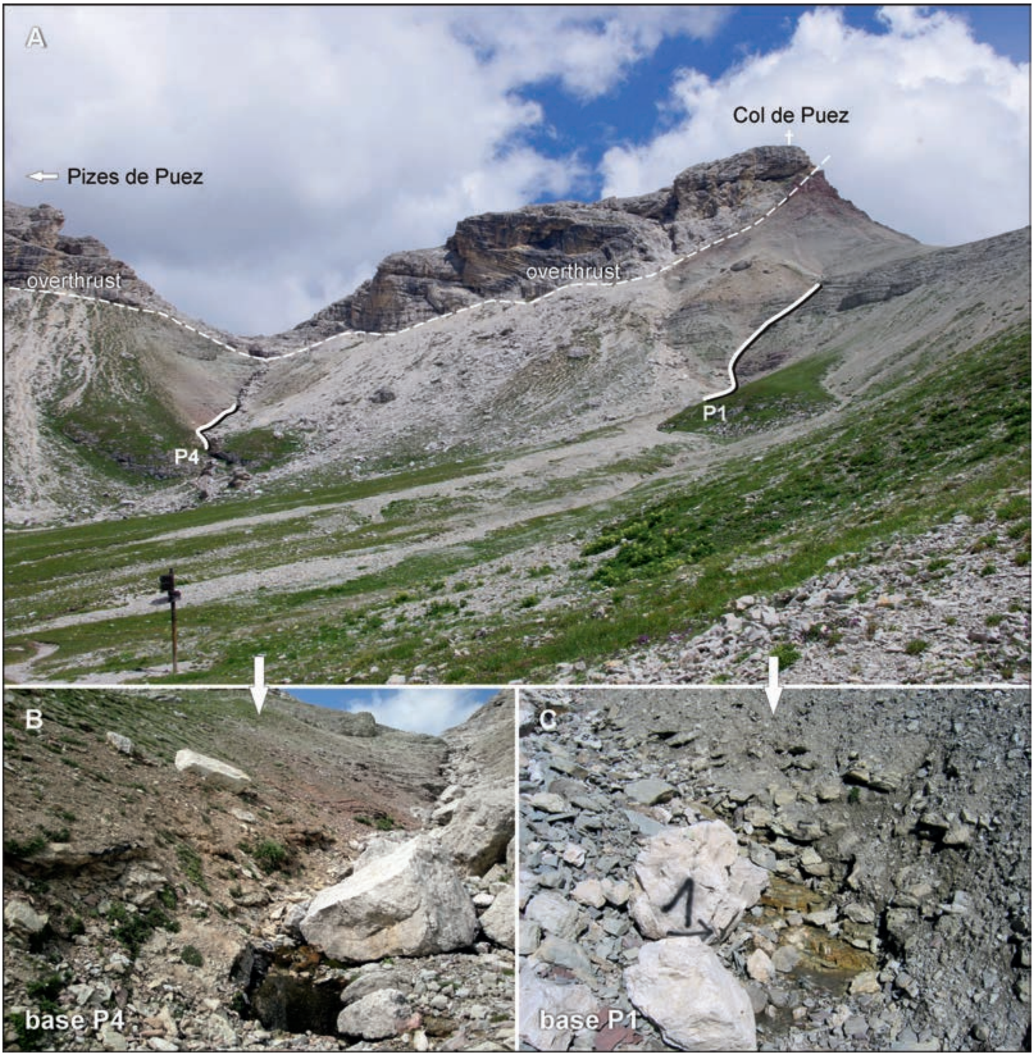

Fig. 3. Locality and stratotype of the Puez Formation with logs P1 and P4 at the Col de Puez (= Puezkofel). A, logs P1 and P4 below the Col de Puez at the transition from Triassic Hauptdolomit, over dolosparites to Biancone limestones. B, dolosparite beds at the base of log P4. C, dolosparite beds at the base of log P1. Overthrust of the Triassic Hauptdolomit over the Lower Cretaceous Puez Formation is marked by the white, dashed line.

The Lower Cretaceous (late Valanginian – early Cenomanian) at Puez starts with pure limestones of the reddish to grey Biancone limestone (late Valanginian – early Hauterivan; Fig. 4). Biancone is the local name for the more broadly known Italian Maiolica Formation (Faraoni *et al.* 1995, 1996, 1997; Wieczorek 1988). The Maiolica limestone appears with variegated colours and microfacies. It shows numerous changes from grey to red beds within approx. 20 m of thickness (Lukeneder 2011). The situation in this lowermost parts is not completely clear due to the bad outcrop conditions (talus debris and snow) in the lower parts of the Lower Cretaceous. The following beds (4–6 m thickness) show similarities to the Rosso Ammonitico (A.R. Superiore), termed as Rosso Ammonitico Puezzese (Fig. 4; LUKENEDER 2011). The Rosso Ammonitico Puezzese facies is followed by the Puez Formation with its distinct members. The succession shows a transition from limestones into the marly upper half of the log. This sequence shows the evolution of the northernmost part of the Trento Plateau at this time (DERCOURT *et al.* 1993). The Trento Plateau (= Piattaforma Atesina) reaches from the south (around Trento) up to the Puez region and was formerly surrounded by two basins: the Lombardian Basin (= Bacino Italiano) to the west and the Belluno Basin (= Fossa di Belluno) to the east (BOSELLINI *et al.* 1981; GEYER 1993; BOSELLINI 1998). The reason for the Upper Jurassic to Lower Cretaceous separation into a basin-plateau-basin succession lies in the rifting history of the Piemont-Ligurian Ocean (South Penninic Ocean; MAYER & APPEL 1999).

Material and methods

This study examines 38 rock samples, 20 polished samples and 16 thin sections. Samples derive from the lowermost part of the sections Puez/P1 (log P1) and to the west from Puez/P4 (log P4; Figs 1–3), where the lithological transition from the dolosparite, the Biancone to Rosso Ammonitico facies crops out (LUKENEDER 2011). Rock samples were sliced and polished. Thin sections were made in vertical directions. Additionally, fossil groups including ammonoids, aptychi, belemnoids, bivalves, brachiopods, corals, echinoids, plant fossils and trace fossils were collected (*e.g.*, LUKENEDER 2012, 2014; LUKENEDER *et al.* 2012a, b ; KUSTATSCHER *et al.* 2013; SCHNEIDER *et al.* 2013; KROH *et al.* 2014).

The sections at the Col de Puez and Pizes de Puez were studied with the focus directed to the lowermost interval of about 20 m (P1/1–P1/15 and P4/0 m–P4/20 m) that was studied in detail (Figs 3–4). Samples were collected at intervals of 0.2 to metres for thin sections. Sample numbers, for example P1/1 or P4/1 m, correspond to the sample interval at P1 and P4 within the log (for all numbers and figures; *e.g.*, P1 = Puez log 1). All samples are stored at the Natural History Museum of Vienna, in the collection of the Department of Geology and Palaeontology with inventory numbers from NHMW 2010/0127/0001–0021, 2010/0260/0001–0065, 2010/0353/0001–0065, and 2014/0397/0001–0007. All the chemical analyses and additional SEM-photographs (10 kV; magnification ×200, ×600, ×2000; working distance WD 12–18 mm) and back-scattered micrographs (15 kV; ×600, ×1200, ×2300; WD 15–16 mm) were carried out in the laboratories of the Department of Mineralogy at the Natural History Museum Vienna. Data on the dolomite composition and its elements were gained by energy-dispersive analysis resulting in energy-dispersive X-ray spectra, performed on the latter institution. Additional results on biostratigraphy (*e.g.*, ammonoids, foraminifera, dinoflagellates, calpionellids, nannofossils), gamma ray (GR), magnetic susceptibility (MS)

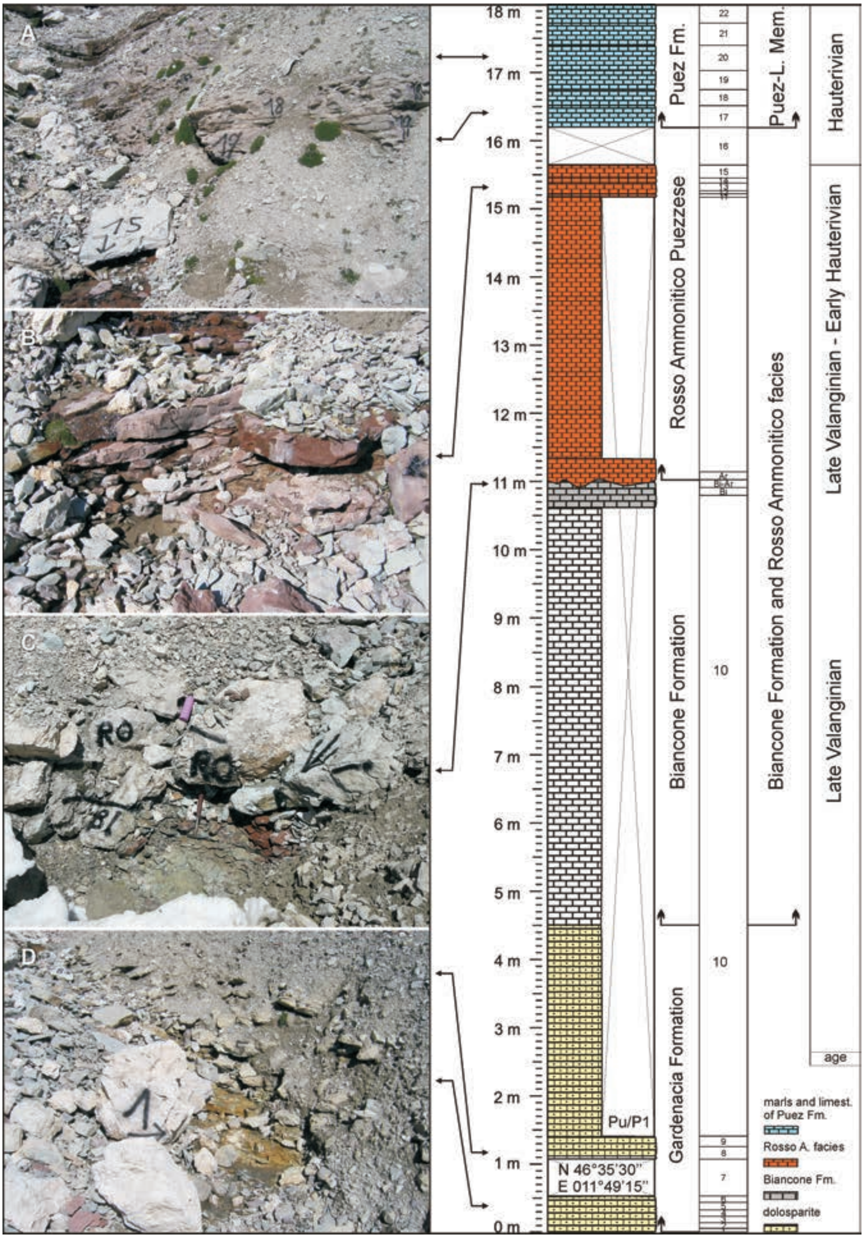

Fig. 4. Right: Lower part of the Puez log P1 with beds P1/1–18 (at 0–16 m). Dolosparite (beds 1–10), grey limestones of the Biancone Formation (beds P1/10 – P1/Bi) and the red, nodular limestones of the overlying Rosso Ammonitico facies with beds P1/Ar – P1/15. Left: A, transition from Ammonitico Rosso facies with its last bed P1/15 into the Puez Formation starting with bed P1/17. B, Red nodular beds of the Rosso Ammonitico facies at beds P1/13–15. C, transition from the Biancone Formation (P1/Bi) into the Rosso Ammonitico Puezzese (P1/Ar), at the transition layer P1/Bi–Ar). D, underlying dolosparite bed with the starting point of log with bed P1/1. Puez L. Member = Puez Limestone member, adapted from Lukeneder (2011).

and magnetostratigraphy, geochemistry (carbonate content $CaCO_3$, total organic carbon TOC, sulphur S), and stable isotopes (bulk rock $\delta^{18}O$, $\delta^{13}C$, $\delta^{87}Sr$) will be published in details elsewhere (LUKENEDER *et al.* in press).

The formalised Gardenacia Formation

Validity: invalid status, "dolosparites of the Gardenacia Formation – Formazione di Gardenacia" by KEIM (2007) on the geological map of the western Dolomites (see Fig. 2). The latter author has used the term Gardenacia Formation somehow but did not formalise (no type-log, no GPS data *etc.*). No logging, detailed stratigraphy or precise description of a type section are known yet.

Type area: IT 1:50,000, map sheet 55 Cortina d'Ampezzo, geological map western Dolomites (Westliche Dolomiten) 1:25,000, sheet east, area north of Wolkenstein in the Department Trentino-Alte Adige (South Tyrol, Italy). The locality is situated on the Gardenacia Plateau in the heart of the natural park Puez-Odle within the UNESCO world heritage, the Dolomites.

The lower boundary: defined at the type locality at the Col de Puez by an abrupt change from typical grey limestones of the Triassic "Hauptdolomit" (= *Dolomia Principale*) units with its up to 2000 m thick dolomites (Figs 2–4). The transition of the latter facies types in the lowermost parts of the section is covered by talus debris most of the year.

The upper boundary: sharp transition (*e.g.*, log P1 bed P1/10) to the overlying whitish to greyish Biancone facies. The dolosparite is approx. 3–5 m thick, extending from beds P1/1 to the lower part of bed 10 (Fig. 4). The transition of the latter facies types in the lower parts of the section is covered by talus debris most of the year. The lowermost transitional parts had to be excavated before investigations were possible.

Synonyms: Gardenacia formation – Formazione di Gardenacia by KEIM (2007).

Lithology: dolosparites, traditionally defined as greenish to whitish, sometimes grey, middle to coarse granulated, saccharoidal dolomite. The outcrops are generally exposed on steep walls on the Puez-Gardenacia Plateau near the Pizes de Puez, Col de Puez, Muntejela, Col dala Sone and and Anderiöl (Figs 1–3). Silicium nodules (cherts), formed by the primary Si-material fom radiolaria skeletons, occur in numerous beds (*e.g.*, P4/4m). Incomplete dolomitisation occurs hence belemnoids and radiolaria are preserved entirely or in parts.

Colour: greenish to whitish, sometimes grey (Figs 5–6).

Geochemistry: $CaCO_3$ P1 – P1/1 84.3 %, P1/6 85.2 % and P1/8 with 90.7 % (mean 86.7 %); grey scale P1 – P1/1 227, P1/6 225 and P1/8 with 188 (mean 213); grey scale P4 – P4/0m 216, P4/1m 230, P4/2m 226, P4/3m 210, P4/4m 204 (mean 208); TOC P1: P1/1 0.81 %, P1/6 0.47 % and P1/8 with 0.36 % (mean 0.55 %); S P1 – P1/1 0.267 %, P1/6 251 % and P1/8 with 0.340 % (mean 0.286 %).

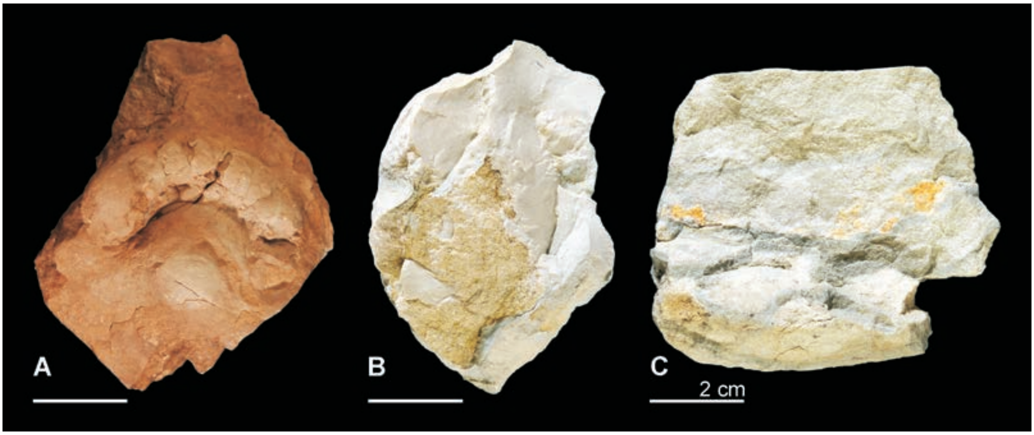

Fig. 5. Rock samples from the significant lithologies at the base of the Puez sections. A, NHMW 2010/0127/0001, a typical rock samples of the Rosso Ammonitico facies at the log P1 at the Puez locality. Note the calcareous ammonoid steinkern, a lotoceratid morphotype. B, NHMW 2010/0127/0004, a whitish rock sample of the Biancone Formation (P1/Bi). C, NHMW 2010/0127/0007, a rock sample of the underlying dolosparite (P1/4).

Energy-dispersive X-ray data (EDX): P1/1 – Ca calcium (43.05 wt%), Mg magnesium (23.69 %), Fe iron (0.27 %), Mn manganese (0.11 %), O oxygen (32.89 %). P1/8 – Ca (43.26 %), Mg (23.44 %), Fe (0.46 %), Mn (0,00 %), O (32.83 %).

The $\delta^{13}C$ values from the dolosparites at logs P1 and P4 show a mean of +2.26 ‰ and no explicit trend. $\delta^{13}C$ values from the basal limestones of the Biancone and Rosso Ammonitico, in contact with the dolosparites, are compared to the dolosparite values decreased with a $\delta^{13}C$ mean of +1.80 ‰.

$\delta^{13}C$ P1 – P1/1 1.94 ‰, P1/6 1.81 ‰ and P1/8 with 0.99 ‰ (mean 1.58 ‰); $\delta^{13}C$ P4 – P4/0m 2.80 ‰, P4/1m 3.19 ‰, P4/2m 2.12 ‰, P4/3m 2.10 ‰, P4/4m 2.38 ‰ and P4/4.3m with 2.70 ‰ (mean 2.55 ‰).

The $\delta^{18}O$ values from the dolosparites at logs P1 oscillates around a mean of −2.13 ‰. The minimum value is −5.67 ‰ at bed P1/8 and the highest is −0.63 ‰ at P4/2m. $\delta^{18}O$ values from the basal limestones of the Biancone and Rosso Ammonitico, in contact with the dolosparites, are compared to the dolosparite values decreased with a $\delta^{18}O$ mean −0.63 ‰. The coefficient of correlation between $\delta^{13}C$ and $\delta^{18}O$ is R^2= 0.0405, as it is very low no significant further diagenetic alteration can be inferred from the isotope record.

$\delta^{18}O$ P1 – P1/1 −4.39 ‰, P1/6 −5.63 ‰ and P1/8 with −5.67 ‰ (mean −5.23 ‰).

$\delta^{18}O$ P4 – P4/0m −2.06 ‰, P4/1m −4.35 ‰, P4/2m −0.63 ‰, P4/3m −4.88 ‰, P4/4m −3.08 ‰ and P4/4.3m with −2.26 ‰ (mean −2.88 ‰).

The Early Cretaceous (late Valanginian) dolosparite $^{87}Sr/^{86}Sr$ isotope data of the logs P1 and P4 show a $\delta^{87}Sr$ value at P1/1 with 0.707850 ‰. This is significantly higher than

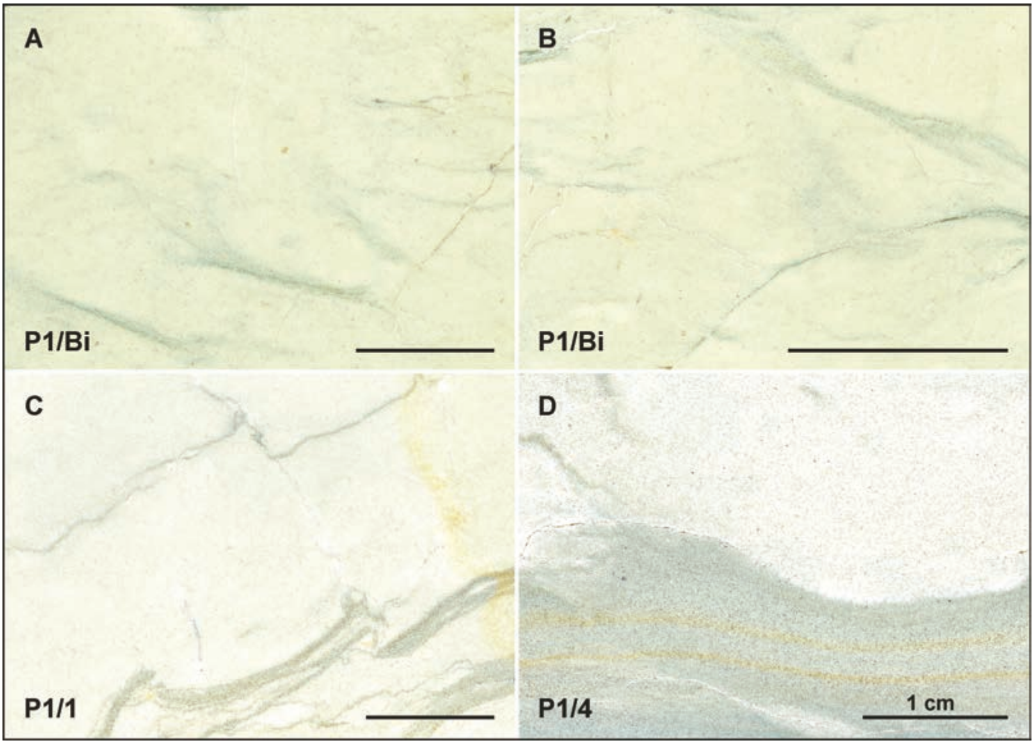

Fig. 6. Polished rock surface images of the Biancone Formation and the dolosparite from the Puez locality with (Puez log 1). Rock samples are positioned in stratigraphical order as found in the outcrop (lowermost dolosparites and Biancone). A and B, whitish limestones of the Biancone Formation with P1/Bi (NHMW 2010/0127/0014–15). C and D, whitish to yellowish dolosparites of the Gardenacia Formation with P1/1 (NHMW 2010/0353/0001) and P1/8 (NHMW 2010/0260/0003). Note the bedding and incorporated flaser-like parts, caused by primary lithology resulting in different dolomite crystal size and shape.

oscillating mean values of δ^{87}Sr 0.707541 ‰ from late Valanginian to early Cenomanian marly limestones and limestones from the Puez Formation. The measured NBS 987 standard value during measurements was 0.710256 +/−0.000003 (7 runs).

Geophysics: gamma ray P1 – P1/1 13cps, P1/6 9cps and P1/8 with 6cps (mean 9cps); P4 – P4/0m 11cps, P4/1m 8cps, P4/2m 8cps, P4/3m 7cps, P4/4m with 12cps (mean 9.2cps).

Susceptibility P1 – P1/1 15×10^{-6}, P1/6 18×10^{-6} and P1/8 with 25.5×10^{-6} (mean 19.5×10^{-6}); susceptibility P4 – P4/0m 6×10^{-6}, P4/1m 13×10^{-6} and P4/2m 13cps, P4/3m 7×10^{-6}, P4/4m with 21×10^{-6} (mean 14.9×10^{-6}).

Bed thickness: 3–10 cm.

Bed surfaces: straight, sharp to wavy (less).

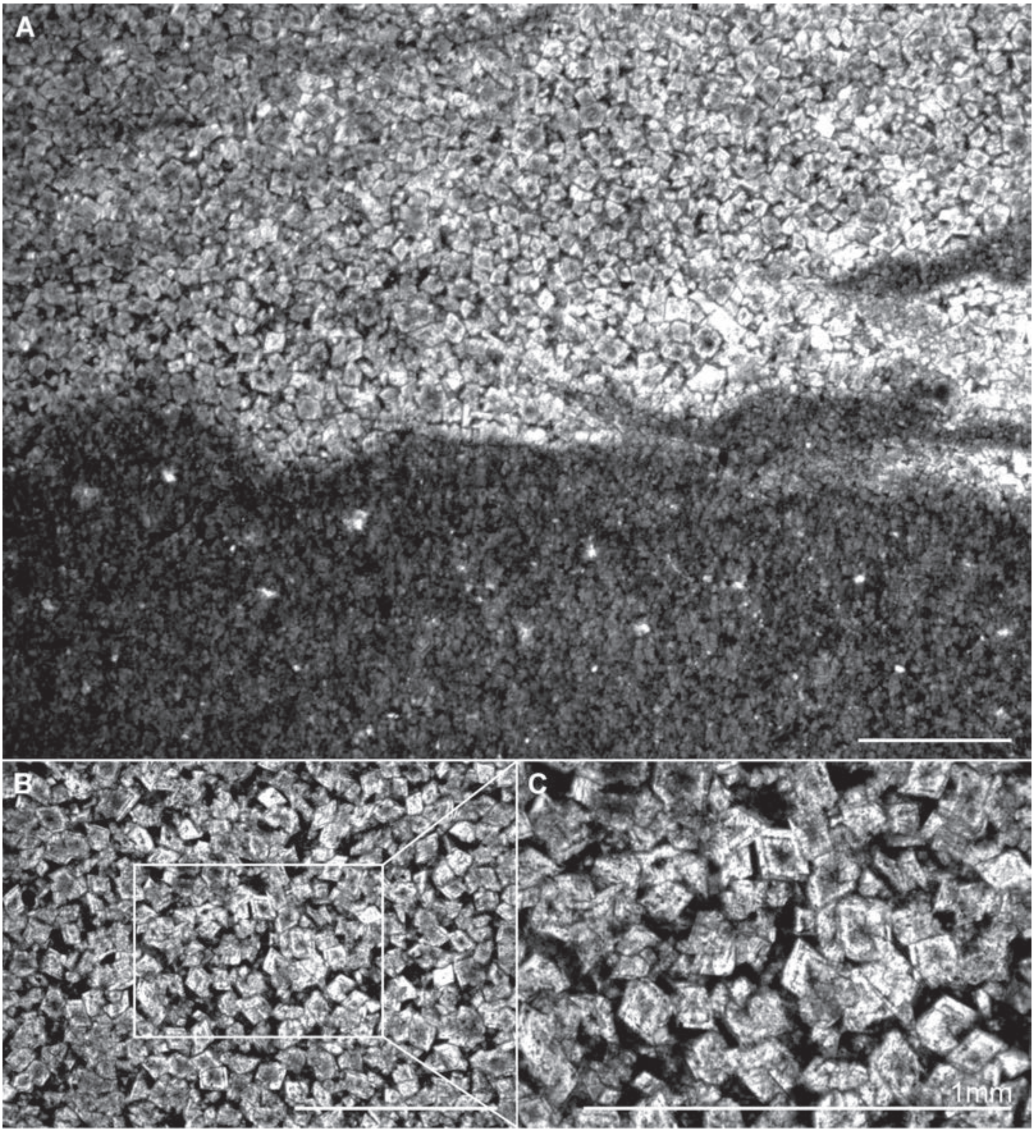

Fig. 7. Thin sections of the dolosparites of the Gardenacia Formation from the Col de Puez localities. A lowermost part of the dolosparite facies from P1/8 (NHMW 2010/0353/0002), note the flaser like bedding caused by fabric and crystal size changes within one layer, coarse top with euhedral crystals and below fine, anhedral mosaic with xenotopic structure. B, detail of the coarse dolosparite (euhedral to subhedral crystals) parts within bed P1/8 (NHMW 2010/0353/0002 a). C, enlarged detail of B, note the characteristic zonation of euhedral to subhedral crystals (mostly rhombs) with dark core and clear rim.

Origin, facies: secondary dolomitisation of the Biancone Formation (Figs 5–6), primary a pelagic-hemipelagic facies of water depths from approx. 100 m down to 500 m (Lukeneder 2011).

Macrofossils preserved: belemnoids, bivalves, crinoids.

Chronostratigraphic age: primary formation of the original sediments during the late Valanginian – early Hauterivian (GRADSTEIN *et al.* 2004; OGG *et al.* 2008).

Biostratigraphy: in accordance with microfacies and microfossils late Valanginian/ early Hauterivian (pers. comm. Daniela REHÁKOVÁ), possible range of late Valanginian *Saynoceras verrucosum* to early Hauterivian *Lyticoceras nodosoplicatum* zones (see REBOULET *et al.* 2009, 2014).

Thickness of formation: approx. 5–10 m at the sections on the Gardenacia Plateau and at the southern flank of the Col de Puez and Pizes de Puez (Fig. 4).

Lithostratigraphically higher rank: Trento Plateau within Dolomites (Southern Alps).

Lateral units: not known.

Geographic distribution: Gardenacia Plateau and area around the Col de Puez and Pizes de Puez (KEIM 2007), but only preserved at relict areas due to erosive processes.

Complementary references: HOERNES (1876), HAUG (1887, 1889), UHLIG (1887) RODIGHIERO (1919) BACCELLE & LUCCHI-GARAVELLO (1967a, b), COSTAMOLING & COSTAMOLING (1994). The geology of the Dolomite Mountains and adjacent areas has been described and summarised in detail by HEISSEL (1982), POZZI (1993), and GEYER (1993).

Remarks: for a discussion on ammonoids, bivalves, corals, echinoids, fossil trees and ecology from the Puez area, see LUKENEDER & ASPMAIR (2006), LUKENEDER (2008, 2010), LUKENEDER *et al.* (2012a, b), KUSTATSCHER *et al.* (2013), LUKENEDER & GRUNERT (2013), SCHNEIDER *et al.* (2013), KROH *et al.* (2014), and LUKENEDER *et al.* (in press).

Discussion

The Dolosparites from Puez

The main aim of the presented study is to formalise and describe in details the little known dolosparite succession at the base of the Lower Cretaceous Puez sections in the Dolomites (South Tyrol, Southern Alps, North Italy).

The formation of the mineral dolomite and the dolostones are often enigmatic and under serious debate since numerous models exist (see ARVIDSON & MACKENZIE 1999; summarised in MACHEL 2003, 2004; AL-AWADI *et al.* 2009; MCKENZIE & VASCONCELOS 2009, MEISTER *et al*. 2013) with the task to clarify the complicated mode of its/their formation. In most cases dolomites (= dolostones) were formed under the influence of multiple and varying geochemical and hydrologic conditions (MACHEL 2003), which influence the morphology of crystals and rocks. In accordance with FLÜGEL (1978) dolomitisation is a constructive diagenetic process with new carbonate formation. During that allochemical process a change in chemical compositon of the sediment takes place. An early diagenetic (soft sediment) and late diagenetic (consolidated sediment) dolomitisation cycle can occur (see Richter 1986).

Three main mechanisms can be observed while dolomites are formed: 1) Replacement of $CaCO_3$ by $CaMg[CO_3]_2$ and/or 2) cementation by dolomite precipitated from Mg^{2+}-rich porewaters (magnesium-enriched hydrothermal solutions in McKenzie & Vasconcelos 2009). 3) Additionally dolomite can be directly precipitated from fluids forming sedimentary deposits. The main amount of dolomites was formed secondarily by transformation of primary limestones into dolostones, evident by the relicts of primary sediment structures (*e.g.*, ripple marks, striae, bedding, lamination) or fossils (*e.g.*, microfossils, macrofossils, trace fossils). In the latter cases the expulsion was not completed or material and matrix dependent (*i.e.*, calcite vs. aragonite, clay vs. marls vs. limestones, carbonate minerals vs. iron minerals *etc.*). Preserved sedimentologic relicts in dolomites can also be formed by periodic precipitation of dolomite from the water column, resulting in such structures (*e.g.*, Meister *et al.* 2011).

Two genetic main groups of dolostones (Machel 2003) can be distinguished with synsedimentary dolomites (= penecontemporaneous dolomites in Budd 1997) and postsedimentary dolomites (= postdepositional dolomites in Budd 1997; see Budd *et al.* 2006). As suggested by Iannace & Frisia (1994) a major transition from penecontemporaneous to burial dolomitisation at the Triassic-Jurassic

Boundary can be observed. The observation of the dolomitised Biancone at the Puez localities fits into this scheme. Almost all known dolostones are formed by postsedimentary and long-lasting, advective porewaters. Sometimes terms as "sekundär" (= secondary) or "spätdiagentisch" (= late diagenetic) have been used (see Deffeyes *et al.* 1965; Zenger *et al.* 1980), what is not completely identical and synonym with postsedimentary (see Machel 2003). Chemical processes and thermodynamic conditions important for the formation of dolomite, in fact a metastabile carbonate (Al-Awadi *et al.* 2009), and dolostones are summarised in Machel (2003, 2004).

As noted by Tucker & Wright (1990) there are numerous unsolved issues in the knowledge concerning the dolomitisation in the geological record (see Frisia & Wenk 1993; Frisia 1994) and various models exist on the formation of primary and/or secondary carbonatic dolomite (= dolostones). A primary precipitation mechanism is opposing a possible secondary replacement process (see Wenk *et al*. 1993; McKenzie & Vasconcelos 2009; Meister *et al*. 2013). The terms "primary/secondary" should not be confused with "early/late" and have to be used with caution. Even a late diagenetic dolomite can be primary if precipitated directly from the porefluid, or a very early (penecontemporaneous) dolomite can be secondary if replacing a precursor phase (pers. comm Patrick Meister 2014).

The dolosparites from the Puez-Gardenacia Plateau (Figs 5, 6–7) are mentioned and classified as Gardenacia Formation (= *Formazione di Gardenacia*) on the geological map of the western Dolomites (Keim 2007), but not correctly formalised. The dolosparites from the plateau were described by KEIM (2007) as *"greenish, grey, middle to coarse granulated dolosparites, overlaying the Triassic Hauptdolomit discordantly and lenticular. Sometimes graded grainstones with glauconitic pellets. At the base often thin breccias formed by sharp-edged dolomite clasts. Locally, e.g. western Gardenacia saddle (= Gardenacia Joch), intercalations of crinoidal limestones of the Fanes Encrinit. The Gardenacia Formation encompasses thicknesses from 0 to 7 meters."* The stratigraphical age given by KEIM (2007) with Early Jurassic (?Pliensbachian) to Late Jurassic (?Malmian = Oxfordian–Tithonian) has to be considered with caution, since there is no clear biostratigraphic evidence. Due to new microfossil findings the age of the primary formation of the original sediments is late Valanginian/early Hauterivian. In accordance with microfacies and microfossils late Valanginian/early Hauterivian (pers. comm. Daniela REHÁKOVÁ), the possible range is late Valanginian *Saynoceras verrucosum* to early Hauterivian *Lyticoceras nodosoplicatum* zones (see REBOULET *et al.* 2009, 2014).

At Puez the Triassic "Hauptdolomit" (= *Dolomia Principale*; see FRISIA & WENK 1993; FRISIA 1994) is overlain by Lower Cretaceous strongly dolomitised (with granulated structure, whitish to yellow), from most probably dolomitised former Biancone or Rosso Ammonitico Puezzese beds (see GEYER 1993; Figs 5–6). Primary lithological structures (*e.g.*, bedding, gradation) and fossils content (*e.g.*, ammonoids, belemnoids, microfossils, nannofossils, trace fossils) are mostly destroyed by the recrystallisation during dolomitisation. In numerous areas of the Southern Alps a uniform dolomitisation from Triassic to Jurassic limestones can be observed (GEYER 1993). A late diagenetic, initial to partial dolomitisation, replaced the primary components but structures and rare fossil remnants are preserved as observable in the Puez dolosparites. This type of dolomitised sediments was termed, in the Umbria-Marche region, as *Maiolica with saccharoidal structure* (CECCA *et al.* 1995). Such dolomitised limestones often characterize the lowermost parts of the Maiolica Formation deposited on the Jurassic pelagic carbonate platforms (PCP). Their thickness varies from 40–80 m on PCPs up to 450 m in basin areas (CECCA *et al.* 1995).

Flaser like (= *flaserig*) structures (Figs 6–7), caused by residual dissolution remnants (*e.g.*, organic material and clays) which are observed in the Biancone and Rosso Ammonitico Puezzese limestones are still observable in the dolomitised dolosparites from Puez. Late diagenetic dolomitisation replaces aragonitic and calcitic components due to the reworking processes caused Mg-rich interstitial fluids in the already consolidated sediments (VINX 2008). During this process carbonates like calcite or aragonite ($Ca[CO_3]$) are replaced by dolomite ($CaMg[CO_3]_2$) (see properties of mineral in CHRISTIE *et al.* 2001), subsequently an increase in crystal size but a decrease in sediment volume of approx. 10 % can be detected causing secondary porosity after late diagenetic dolomitisation (VINX 2008). $CaCO_3$ values of the dolosparites from Puez range from 84.3 % (P1/1) up to 90.7 % (P1/8) (mean 86.7 %), what is in accordance to VINX (2008) classified as marly dolomites. Energy-dispersive X-ray data (EDX) of dolosparite layers appear at P1/1 with Ca 43.05 % and increased values Mg 23.69 %, contrasting typical values of the Biancone limestones at P1/Bi with 69.80 % and Mg 0.47 %.

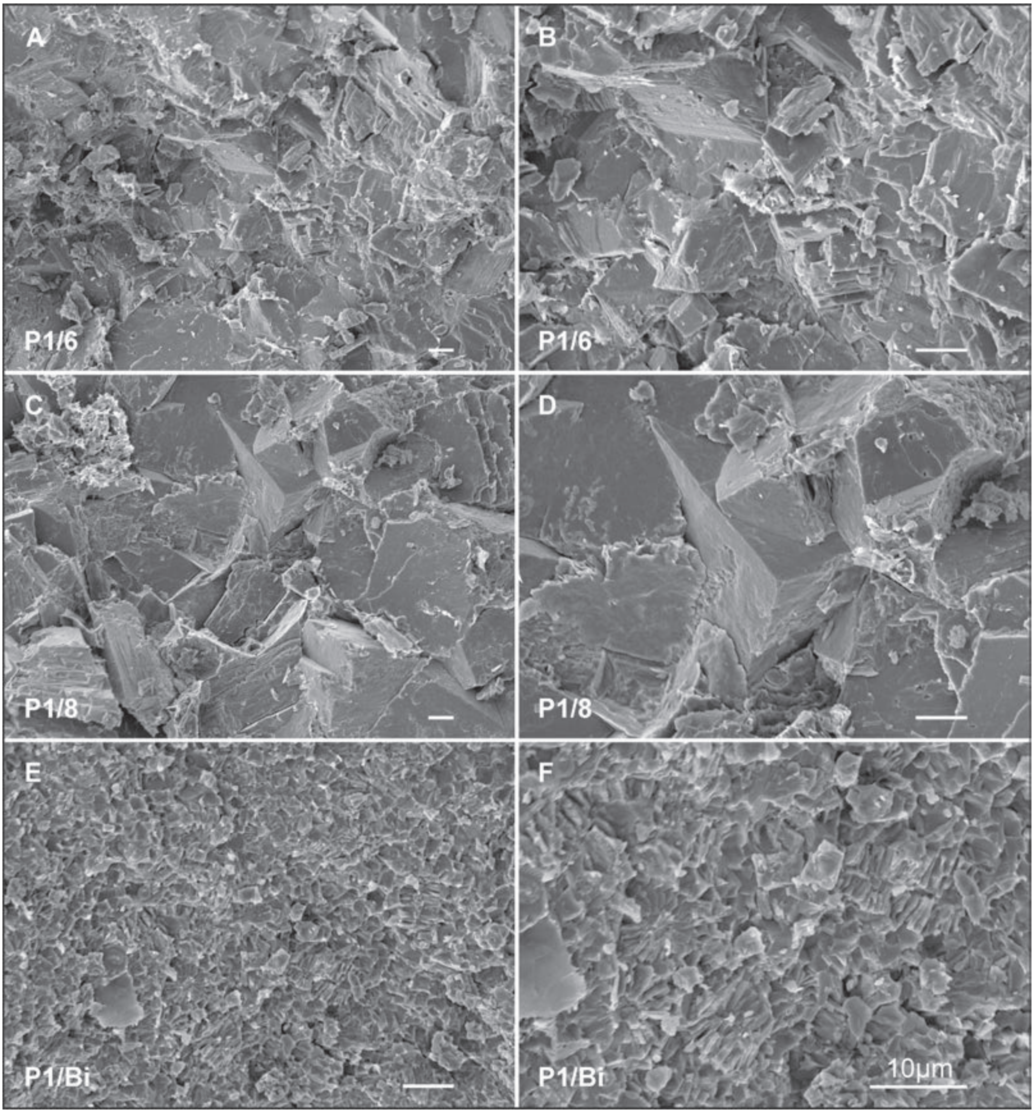

Fig. 8. SEM rock surface images of the Biancone Formation (E, F) and the dolosparites (A–D) from the Puez locality with Puez log 1. A and B, rock surface with densely packed euhedral dolomite crystals from P1/6 (NHMW 2010/0260/0002 a). C and D, rock surface with densely packed euhedral dolomite crystals from P1/8 (NHMW 2010/0353/0002 b). E and F, rock surface with densely packed nannoconid plates and entirely preserved specimens from P1/Bi (note central canal in horizontal- and longitudinal-sections; NHMW 2010/0127/0014 a). All scale bars equal 10 µm.

Within the textural classification in dolomites the crystal size distribution is classified in unimodal and polymodal whereas crystal morphology is grouped in euhedral (planar-e), subhedral (planar-s) and non-planar-a (anhedral). As shown by FLÜGEL (2004) the fabric in dolomite rocks varies from one end-member with limestones with scattered dolomite

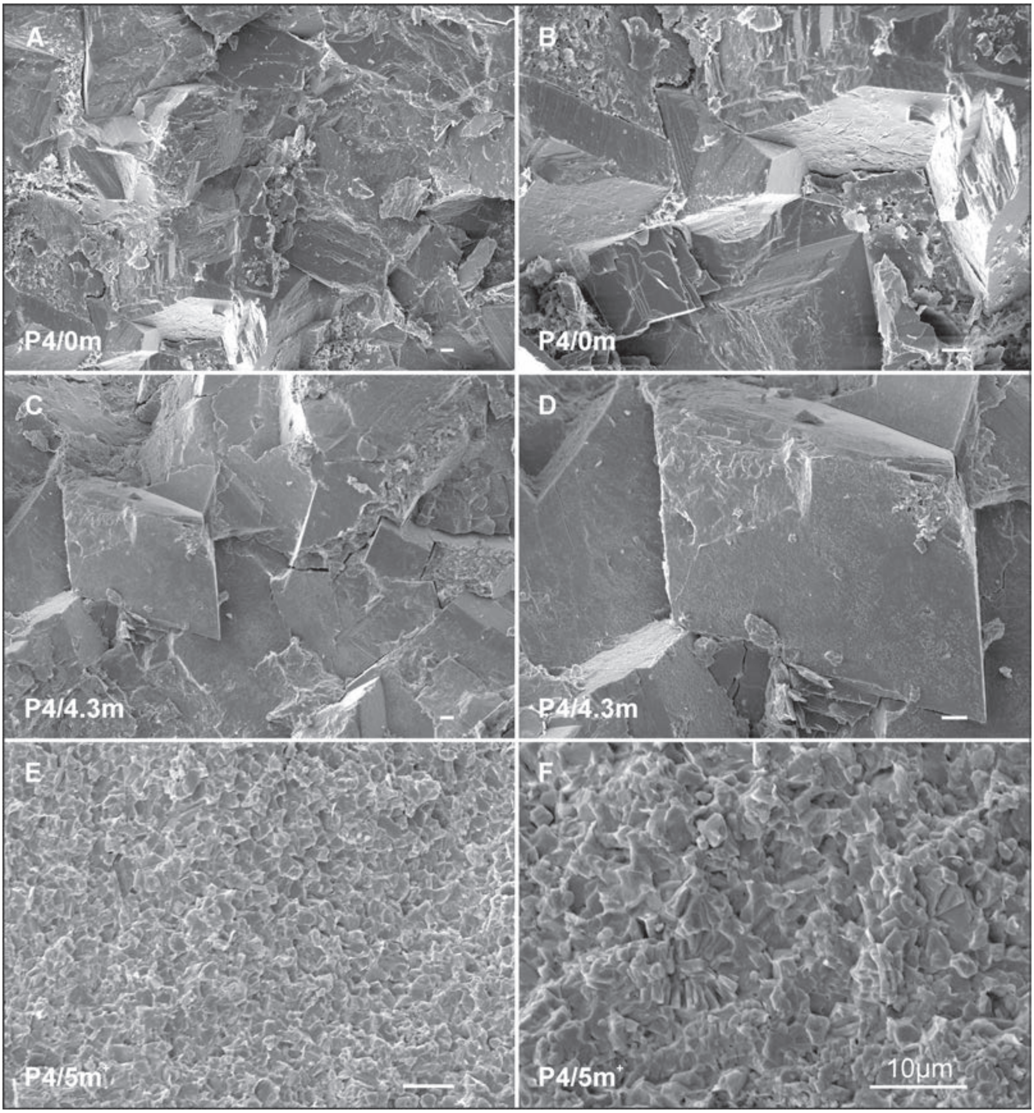

Fig. 9. SEM rock surface images of the Biancone Formation (E, F) and the dolosparites (A–D) from the Puez locality with Puez log 4. A and B, rock surface with densely packed euhedral dolomite crystals from P4/0m (NHMW 2014/0397/0001 a). C and D, rock surface with densely packed and perfect idiomorphic (euhedral) dolomite crystals from P4/4.3m (NHMW 2014/0397/0002 a). E and F, rock surface with densely packed nannoconid plates and entirely preserved *Nannoconus steinmannii steinmannii* specimens from P4/5m^{+} (note central canal in horizontal- and longitudinal-sections; 2014/0397/0003 a). All scale bars equal 10 µm.

rhombs to the other end-member with sucrosic mosaic dolomites (Fig. 6). As noted with caution by MACHEL (2003) planar crystals seem to be formed at temperatures lower than 50°C, the so called critical-roughening-temperature.

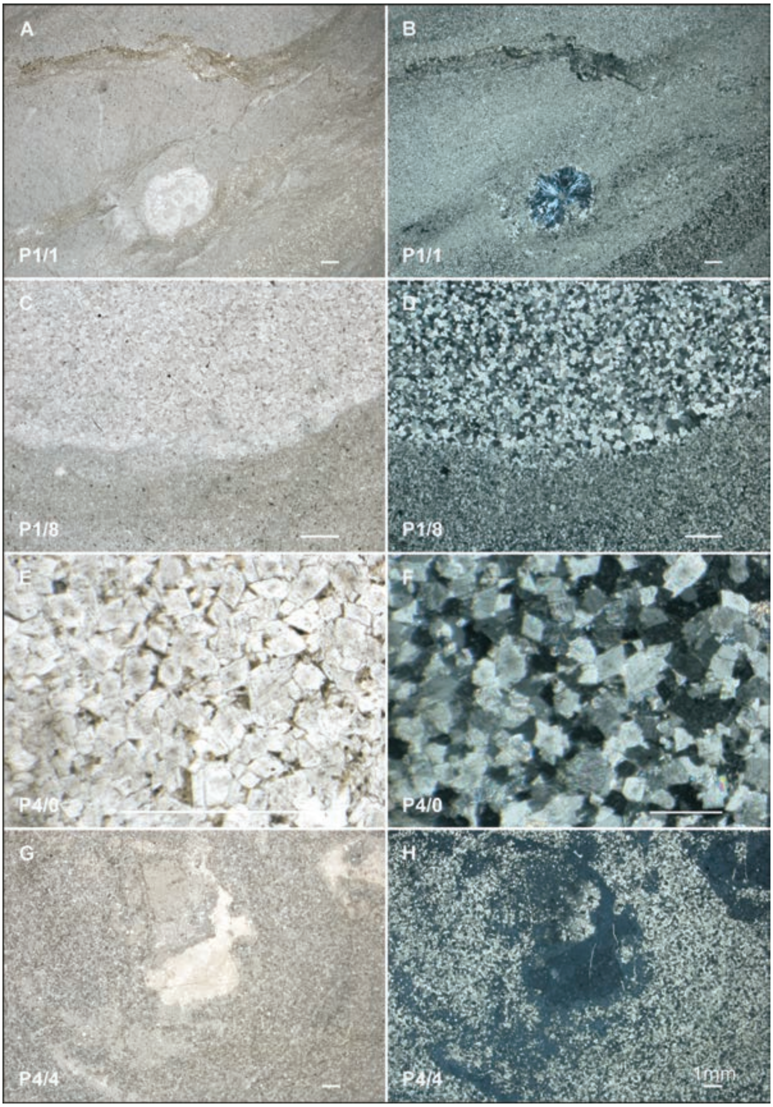

Fig. 10. Thin sections of the dolosparites of the Gardenacia Formation from the Col de Puez localities. Note for all sections of the dolosparites pyrite is dispersed in the matrix (black grains). On the left side (A, C, E, F) under normal light and on the right side (B, D, F, H) the corresponding image under crossed Nichols. A and B, lowermost bed of the dolosparite facies with P1/1 (NHMW 2014/0397/0004 a), note the flaser like bedding caused by the various crystal size and the preserved belemnoid. C and D, detail of a transition from fine (anhedral crystals) to coarse (euhedral to subhedral crystals) dolosparite parts within bed P1/8 (NHMW 2010/0353/0002 a). E and F, lowermost dolosparite bed P4/0m (2014/0397/0001 b), note the characteristic zonation of euhedral to subhedral crystals (mostly rhombs) with dark core and clear rim. G and H, radiolaria dolosparite of P4/4m (NHMW 2014/0397/0005 a), note the white area (black with crossed Nichols) in the middle which is enriched in Si (chert nodule), radiolaria (spheres) are still preserved, the limestone is not fully recrystallised.

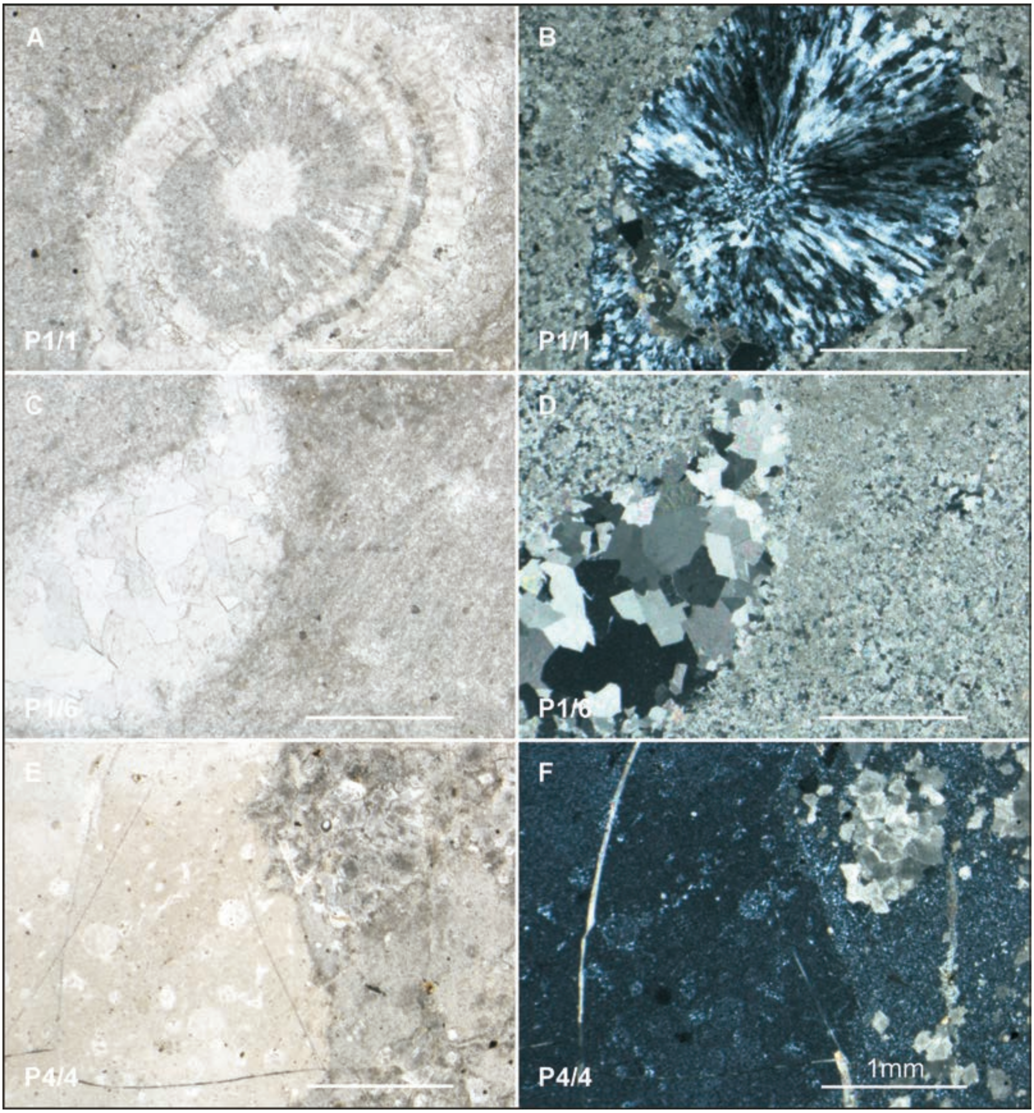

Fig. 11. Thin sections of the dolosparites with its preserved macro- and micro-fossils. Note for all sections of the dolosparites, left (A, C, E normal light) and right (B, D, F) the corresponding image under crossed Nichols. A and B, preserved belemnoid rostrum in the lowermost dolosparite bed P1/1 (NHMW 2014/0397/0004 a), note the radial and fibrous calcite of the rostrum. The rostrum is only recrystallised in its outer parts, partly by dolomite and secondary calcite. C and D, mould of a dissolved bivalve, filled by coarse, sparry calcite in fine dolosparite mass P1/6 (NHMW 2014/0397/0006 a). E and F, detail of the light grey chert nodule (black with crossed Nichols) to dolosparite boundary in bed P4/4m (NHMW 2014/0397/0005 a). Masses of radiolaria skeletons (white spheres), sponge spicules (white cross) and rare bivalve shells (white bow) are visible. Note the nesting of dolomite crystals and single rhombs floating in cherty limestone matrix.

The observed fabrics of the Puez dolosparites vary from bed to bed (see Fig. 7). In accordance to Tucker & Wright (1990) and Flügel (2004) the fabric appears with anhedral (nonplanar), mostly with subhedral (planar-s) to euhedral (planar-e) dolomite crystals with straight edges (see Gregg & Sibley 1984; Sibley & Gregg 1987). Crystals are rhombohedral (Figs 7, 8, 9), compromise boundaries and many crystal-face junctions, and varying from bed to bed and within single beds from idiotopic to hypidiotopic mosaics (Figs 7–12).

The geochemistry with stable isotopes (*i.e.*, bulk rock $\delta^{18}O$, $\delta^{13}C$, $\delta^{87}Sr$) of the dolosparites from Puez was analysed and compared to data given by Machel (2003). Measurements could only be made on bulk rock samples, in contrast to Machel (2003) who discussed isotope analyses performed on single dolomite crystals, which result in different data. The lowered $\delta^{18}O$ values from the dolosparites at logs P1 and P4 with a minimum value of –5.67‰ are typical for coarse crystalline, secondary dolomites (see Type II dolomites in Eren *et al.* 2007; Preto et al. 2014). According to Eren *et al.* (2007) such low $\delta^{18}O$ values hint to burial recrystallisation.

The zonation of the dolomite rhombs is often dull with cloudy cores and lighter and clear rims (Figs 7, 10, 12), lighter zones suggest the presence of elements with higher atomic numbers compared to the dull core (Tucker & Wright 1990).

Burial dolomitisation was described by Tucker & Wright (1990) as a model influenced by dewatering of basinal mudrocks and the expulsion of Mg^{2+}-rich fluids into adjacent shelf-edge and platform carbonates. The magnesium enriched fluids derive from porewater and clay mineral changes caused by burial and increasing temperatures. Interstitial fluids may have moved upwards (see Magara 1978, Machel 2003) from Mg-rich Hauptdolomit into the Biancone and Rosso Ammonitico Puezzese sediments and transformed the lowermost part (*i.e.*, approx. 10 m) into secondary dolosparite.

Most dolomites are formed by a secondary replacement of meta-stable carbonates (*e.g.*, aragonite, high-Mg calcite) positively influenced by the participation of sea water promoted by its high concentration of magnesium ions (Christie *et al.* 2001; McKenzie & Vasconcelos 2009). The calcium in the carbonates is subsequently replaced by magnesium. Especially for the massive, up to 1,000 m thick, Triassic Hauptdolomit in the Dolomite Mountains (S. Alps, N. Italy) possible microbial processes (microbial biomineralisation) mediating the formation of such enormous amounts of primary dolomite was discussed (McKenzie & Vasconcelos 2009).

If dolomitisation, as observed on the Puez-Gardenacia Plateau, occurs only at the top of an extensive dolomite section (*i.e.*, primary, shallow marine deposits; see McKenzie & Vasconcelos 2009) it points to a dolomite occurring after the pelagic sediments capped these deposits (pers. comm. Darryl Green 2014). A pervasive dolomite after deposition of the pelagic sediment and burial dolomite seems likely. Essentially a halo or extension of the large amounts of fluids moving through the area, if the section capping was 200 m thick only the basal few meters would be dolomite as the permeability does not allow it to extend too far (pers. comm. Darryl Green 2014), as observed at the Puez sections. For

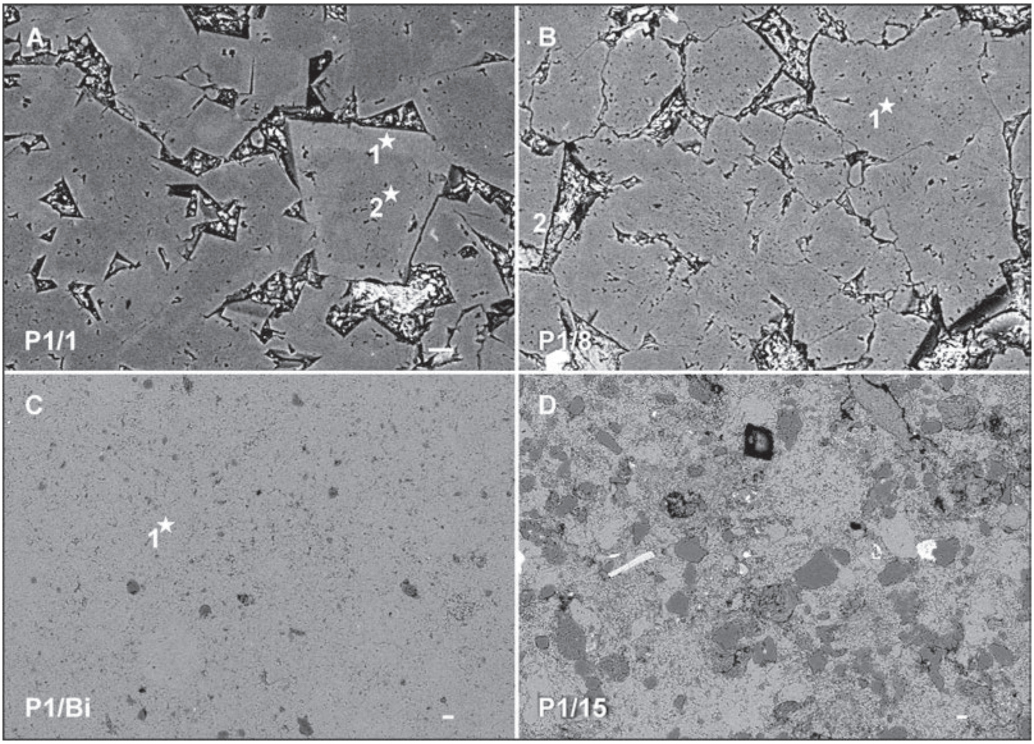

Fig. 12. Back-scattered electron micrographs of the dolosparites, Biancone- and Rosso Ammonitico facies from Puez (polished surfaces; 15 kV; WD 15–16 mm). A, surface with densely packed euhedral dolomite crystals from P1/1 (NHMW 2010/0353/0001 b); note the clear zonation in dolomite rhombs and their porosity. B, polished surface with numerous anhedral multicrystalline dolomite aggregates and few interspaced euhedral to subhedral crystals within bed P1/8 (NHMW 2010/0353/0002 c). Note the porosity between crystals filled with altered clay minerals in A and B. C, almost pure and densely packed nannoconid limestone P1/Bi (biomicritic limestone; NHMW 2010/0127/0014 b). D, spotty, fossiliferous limestone with abundant grains of quartz, feldspar and muscovite in a siliciclastic admixture accompanied by abundant microfossils P1/15 (biomicritic limestone; NHMW 2010/0127/0009 a). Numbers and white stars mark sample points for the energy-dispersive analysis. All scale bars equal 10 µm.

the mechanisms which are ment to cause dolomitisation of the massive Triassic dolomite rocks of which the Dolomite Mountains (S.Tyrol, N.Italy) mainly exists, see MCKENZIE & VASCONCELOS (2009).

$CaCO_3$ allochems (*e.g.*, calcitic fossils) are partly replaced by dolomite crystals, dependent on size of grain. $CaCO_3$ cement is replaced by dolomite rhombs, only pores are filled with altered clay minerals (Figs 11–12). Fabric-selective dolomitisation, distincly zoned euhedral dolomite crystals occur within the fine grained matrix and at the periphery of the belemnoid rostrum with its radial structures (bed P1/1; Figs 10–11). Matrix dolomitisation by unimodal and euhedral planar crystals, termed as medium-crystalline bioclastic dolomite (*cf*. Flügel 2004, p. 334, pl. 40; see Adams *et al.* 1986). Numerous and different forms of radiolaria are preserved in the partly dolomitised samples of bed P4/4 (Figs 10–11), once more documenting the secondary transformation from Biancone sediments into dolosparite from the Puez sections. A late diagentic transformation into dolosparites is indicated by the fabric, fossil and microfacial data, in contrast to former interpretations suggesting primary dolomites formed in shallow water environments.

Matrix- or fabric-selective dolomitisation was reported from deep-burial dolomites (= "Versenkungsdolomit"; Machel 2003.) As noted by Machel (2003) all models concerning burial dolomitisation are in fact hydrogelogic models (Morrow 1998). The fluidal activities are though triggered by compaction, topography, thermic or tectonic mechanisms. Incomplete dolomititsation occurs and subsequently larger and geochemical more stable elements (*e.g.*, belemnoids, radiolaria) are preserved entirely or in parts. Silicium nodules (*e.g.*, P4/4m), formed by the primary Si-material fom radiolaria skeletons, are not affected or recrystallised and protect the incorporated biogene components (*e.g.*, masses of radiolaria) from dolomitisation (Figs 10–11). If dolomitisation proceeds radiolaria were also dolomitised, but molds and vugs show different colours and crystal site compared to the recrystallised matrix.

This succession is very similar to the La Stua (= Ra Stua; 1,739 m; E 011°49′15″, N 46°35′30″) section, 20 km to the east of the Puez section, near Cortina d'Ampezzo, which also shows Rosso Ammonitico, Biancone, and Puez Formation, grey marls and Aptian marls (Cita & Rossi 1959; Baccelle & Lucchi-Garavello 1967b; Zeiss *et al.* 1990; Stöhr 1993, 1994; Lukeneder 2010). Interestingly, no dolomitisation can be observed at the transition from dolomites to Biancone and Rosso Ammonitico formations at La Stua.

Conclusions

A new formation, the Gardenacia Formation (approx. 10 m) is established. At the lower part of the sections at Col de Puez and the Pizes de Puez located on the Puez-Gardenacia Plateau (Dolomites, S.Tyrol, N.Italy), a transition from white to yellow, granulated dolosparites into white limestones and red, nodular limestones occurs. The final deposition of the original Lower Cretaceous sediments from the Puez section took place on the northernmost area of a submarine plateau, the approximately north-south directed Trento Plateau.

Micropalaeontological analyses show a possible late Valanginian to early Hauterivian age for the primary sediments of this transitional interval on the Puez-Gardenacia Plateau. The greenish to whitish, sometimes grey dolosparites with its middle to coarse granulated, saccharoidal fabric (= sugar-like, crystalline structure in McKenzie & Vasconcelos 2009) are overlain by the grey to whitish limestones of the Biancone Formation and subsequently overlain by a more energetic red, nodular limestone facies of the Rosso Ammonitico Puezzese. The successions reflect a early to late diagenetic transformation from primary fine, calcareous sediments into recrystallised, secondary dolosparites of the herein formalised Gardenacia Formation. Numerous and different forms of fossils as macrofossils (*e.g.*, belemnoids, bivalves) and microfossils (*e.g.*, radiolaria) are still preserved in partly dolomitised layers intercalated in entirely dolomitised beds. Such significant fossil relicts are documenting the secondary transformation from fine, calcareous Biancone type sediments accumulated in the deep water (hemipelagic to pelagic), into secondary dolosparites from the Puez sections. A late diagentic transformation into dolosparites is clearly confirmed by the fabric, fossil and microfacial data, contrasting former interpretations as dolomites being primary formed, indicating shallow water environments.

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References

ADAMS, A.E., MACKENZIE, W.S. & GUILFORD, C. (1986): Atlas der Sedimentgesteine in Dünnschliffen. Ferdinand Enke Verlag, Stuttgart, 103 pp.

AGIP MINERARIA (1959): Microfacies Italiane (del Carbonifero al Miocene medio). – San Donato Milanese, Milan, 35 pp., 140 pls.

AL-AWADI, M., CLARK W.J., MOORE, W.R., HERRON, M., ZHANG, T., ZHAO, W., HURLEY, N., KHO, D., MONTARON, B. & SADOONI, F. (2009): Dolomite: Perspectives on a Perplexing Mineral. – Oilfield Review, **21**/3: 32–45.

ARVIDSON, R.S. & MACKENZIE, F.T. (1999): The dolomite problem: control of precipitation kinetics by temperature and saturation state. – American Journal of Science, **299**: 257–288.

AVANZINI, M. & WACHTLER, M. (1999): Dolomiten. Reisen in die Urzeit. Verlagsanstalt Athesia Ges.m.b.H., Bozen, 150 pp.

BACCELLE, L. & LUCCHI GARAVELLO, A. (1967a): Prima segnalazione di Ammoniti Aptiane e Albiane nelle Dolomiti. – Annali dell' Università di Ferrara, **4**/7: 91–101.

BACCELLE, L. & LUCCHI GARAVELLO, A. (1967b): Ammonite dei livelli cretacici di La Stua (Cortina d' Ampezzo). – Annali dell' Università di Ferrara, **4**/9: 117–166.

Bosellini, A. (1998): Die Geologie der Dolomiten. Verlagsanstalt Athesia, Bozen/Bolzano, 192 pp.

Bosellini, A., Masetti, D. & Sarti, M. (1981): A Jurassic "Tongue of the Ocean" infilled witth oolitic sands: The Belluno Trough, Venetian, Alps, Italy. – Marine Geology, **44**: 59–95.

Bosellini, A., Gianolla, P. & Stefani, M. (2003): Geology of the Dolomites. – Episodes, **26**/3: 181–185.

Budd D.A. (1997): Cenozoic dolomites of carbonate islands: their attributes and origin. – Earth-Science Reviews, **42**: 1–47.

Budd, D.A., Pranter, M.J. & Reza, Z.A. (2006): Lateral periodic variations in the petrophysical and geochemical properties of dolomite. – Geology, **34**/5: 373–376.

Cecca, F., Fourcade, E. & Azema, J. (1992): The disappearance of the "Ammonitico-Rosso". – Palaeogeography, Palaeoclimatology, Palaeoecology, **99**: 55–70.

Cecca, F., Faraoni, P., Marini, A., Pallini, G. (1995): Field-trip across the representative sections for the Upper Hauterivian – Barremian ammonite biostratigraphy in the Maiolica exposed at Monte Nerone, Monte Petrano and Monte Catria (Umbria-Marche Apennines). – Memorie descrizione della Carta Geologiche d'Italia, **51**: 187–211.

Christie, T., Thompson, B. & Brathwaite, B. (2001): Mineral Commodity Report 21 – Limestone, marble and dolomite. – New Zealand Mining, **29**: 6–25.

Cita, M.B. & Rossi, D. (1959): Prima segnalazione di Aptiano-Albiano nelle Dolomiti. – Atti Accademia Nazionale dei Lincei, Rendiconti Serie 8, **27**/6: 405–411.

Costamoling, H. & Costamoling, W. (1994): Fossilien des Gardertales. Verlagsanstalt Athesia Ges. m.b.H., Bozen/Bolzano, 111 pp.

Deffeyes, K.S., Lucia, F.J. & Weyl, P.K. (1965): Dolomitization of recent and Plio-Pleistocene sediments by marine evaporite waters on Bonaire, Netherlands Antilles. – In: Pray, L.C. & Murray, R.C. (eds): Dolomitization and limestone diagenesis, SEPM Special Publication, **13**: 71–88.

Dercourt, J., Ricou, L.E. & Vrielynck, B. (1993): Atlas Tethys Palaeoenvironmental Maps. Gauthier-Villars, Paris, 307 p. (with 14 maps).

Eren, M., Kaplan, M.Y. & Kadir S. (2007): Petrography, geochemistry and origin of Lowr Liassic Dolomites in the Aydincik Area, Mersin, Southern Turkey. – Turkish Journal of Earth Sciences, **16**: 339–362.

Faraoni, P., Marini, A. & Pallini, G. (1995): The Hauterivian ammonite succession in the central Apennines, Maiolica formation (Petrano Mt., Cagli -PS) Preliminary results. – Palaeopelagos, **5**: 227–236.

Faraoni, P., Marini, A., Pallini, G. & Pezzoni, N. (1996): The Maiolica Fm. of the Lessini Mts and central Apennines (North-eastern and Central Italy): a correlation based on new bio-lithostratigraphical data from the uppermost Hauterivian. – Palaeopelagos, **6**: 249–259.

Faraoni, P., Flore, D., Marini, A., Pallini, G. & Pezzoni, N. (1997): Valanginian and early Hauterivian ammonite successions in the Mt Catria group (Central Apennines) and in the Lessini Mts (Southern Alsp), Italy. – Palaeopelagos, **7**: 59–100.

Flügel, E. (1978): Mikrofazielle Untersuchungsmethoden von Kalken. Springer-Verlag, Berlin-Heidelberg-New York, 454 pp.

Flügel, E. (2004): Microfacies of carbonate rocks. Analysis, interpretation and application. Springer-Verlag, Berlin-Heidelberg, 976 pp.

Fourcade, E., Azema, J., Cecca, F., dercourt, J., Guiraud, R., Sandulescu, M., Ricou, L.-E., Vrielynck, B., Cottereau, N. & Petzold, M. (1993): Late Tithonian (138 to 135 Ma). In: Dercourt, J., Ricou, L.E. & Vrielynck, B (eds), Atlas Tethys Palaeoenvironmental Maps. BEICIP-FRANLAB, Rueil-Malmaison.

Frisia, S. (1994) Mechanisms of complete dolomitization in a carbonate shelf: comparison between the Norian Dolomia Principale (Italy) and the Holocene of Abu Dhabi Sabkha. – In: Purser, B.H., Tucker, M.E. & Zenger, D.H. (eds), A Volume in Honour of Dolomieu. International Association of Sedimentologists Special Publications, **21**: 55–74.

Frisia, S. & Wenk, H.-R. (1993): TEM and AEM study of pervasive, multi-step dolomitization of the upper Triassic Dolomia Principale (Northern Italy). Journal of Sedimentology and Petrology, **63**: 1049–1058.

Geyer, O.F. (1993): Die Südalpen zwischen Gardasee und Friaul. Trentino, Veronese, Vicentino, Bellunese. Sammlung Geologischer Führer, 86: Bornträger, Berlin-Stuttgart, 576 pp.

Gradstein, F.M., Ogg, J. & Smith, A. (2004): A Geologic Time Scale 2004. University Press, Cambridge, New York, Melbourne, Cambridge, 589 pp.

Gregg, J.M. & Sibley, D.F. (1984): Epigenetic dolomitization and the origin of xenotopic dolomite structure. – Journal of Sedimentary Research, **54**/3: 908–931.

Haug, E. (1887): Die geologischen Verhältnisse der Neocomablagerungen der Puezalpe bei Corvara in Südtirol. – Jahrbuch der Kaiserlich-Königlichen. Geologischen Reichs-Anstalt, **37**/2: 245–280.

Haug, E. (1889): Beitrag zur Kenntniss der oberneocomen Ammonitenfauna der Puezalpe bei Corvara (Südtirol). – Beiträge zur Paläontologie und Geologie Österreich-Ungarns und des Orients, **7**/3: 193–229.

Heissel, W. (1982): Südtiroler Dolomiten. – Sammlung Geologischer Führer, 71, Gebrüder Borntraeger, Berlin-Stuttgart, 172 pp.

Hoernes, R. (1876): Neocomfundorte in der Gegend von Ampezzo und Enneberg in Südtirol. – Verhandlungen der Kaiserlich-Königlichen Geologischen Reichs-Anstalt, **7**: 140–141.

Iannace, A. & Frisia, S. (1994): Changing dolomitization styles from Norian to Rhaetian in southern Tethys realm. – In: Purser, B.H., Tucker, M.E. & Zenger, D.H. (eds): A Volume in Honour of Dolomieu, International Association of Sedimentologists Special Publication, **21**:75–89.

Keim, L. (Editor) (2007): Geologische Karte/Carta Geologica, Westliche Dolomiten/Dolomiti Occidentali, Ost-Blatt/Tavola Est. 1:25.000. Hochbau und technischer Dienst, Amt für Geologie und Baustoffprüfung, Autonome Provinz Bozen-Südtirol, Litografia artistica Cartografica, Firenze.

Kroh, A., Lukeneder, A. & Gallemí, J. (2014): *Absurdaster*, a new genus of basal atelostomate from the Early Cretaceous of Europe and its phylogenetic position. – Cretaceous Research, **48**: 235–249.

Kustatscher, E., Falcon-Lang, H., & Lukeneder, A. (2013): Early Cretaceous araucarian driftwood from hemipelagic sediments of the Puez area, South Tyrol, Italy. – Cretaceous Research, **41**: 270–276.

Lukeneder, A. (2008): The ecological significance of solitary coral and bivalve epibionts on Lower Cretaceous (Valanginian-Aptian) ammonoids from the Italian Dolomites. – Acta Geologica Polonica, **58**/4: 425–436.

LUKENEDER, A. (2010): Lithostratigraphic definition and stratotype for the Puez Formation: formalisation of the Lower Cretaceous in the Dolomites (S. Tyrol, Italy). – Austrian Journal of Earth Sciences, **103**/1: 138–158.

LUKENEDER, A. (2011): The Biancone and Rosso Ammonitico facies of the northern Trento Plateau (Dolomites, Southern Alps, Italy). – Annalen des Naturhistorischen Museums Wien, Serie A, **113**: 9–33.

LUKENEDER, A. (2012): New biostratigraphic data of an Upper Hauterivian–Upper Barremian ammonite assemblage from the Dolomites (Southern Alps, Italy). – Cretaceous Research, **35**: 1–21.

LUKENEDER A. (2014): Abenteuer Dolomiten – Spannende Forschung 3000 Meter über dem Meer. – Seifert Verlag, Wien, 216 pp.

LUKENEDER, A. & ASPMAIR, C. (2006): Startigraphic implication of a new Lower Cretaceous ammonoid fauna from the Puez area (Valanginaian – Aptian, Dolomites, Southern Alps, Italy). – Geo.Alp, **3**: 55–91.

LUKENEDER, A. & GRUNERT, P. (2013): Palaeoenvironmental evolution of the Southern Alps across the Faraoni Level equivalent: new data from the Trento Plateau (Upper Hauterivian, Dolomites, N. Italy). – Acta Geologica Polonica, **63**: 89–104.

LUKENEDER, A., BECHTEL, A. & GRATZLER, R. (2012a): New geochemical data on fossil wood from the Albian of the Dolomites (Southern Alps, Italy). – Geologica Carpathica, **63**/5: 399–405.

LUKENEDER, A., UCHMAN, A., GAILLARD, C. & OLIVERO, D. (2012b): The late Barremian *Halimedides* horizon of the Dolomites (Southern Alps, Italy). – Cretaceous Research, **35**: 199–207.

LUKENEDER, A, HALÁSOVÁ, E., REHÁKOVA, D., JÓZSA, Š., SOTÁK, J., KROH, A., JOVANE, L., SAVIAN, J., FLORINDO, F., SPROVIERI, M. & GIORGIONI, M. (2015 in press): Multistratigraphic records of the Puez key area in N-Italy: Evidences for an Early Cretaceous (Valanginian-Cenomanian) reference section. – Palaeogeography Palaeoclimatology Palaeoecology.

MACHEL, H.G. (2003): Das Dolomitproblem – quo vadis? – Mitteilungen der Gesellschaft der Geologie und Bergbaustudenten Österreichs, **46**: 111–136.

MACHEL, H.G. (2004): Concepts and models of dolomitization; a critical reappraisal. – In: BRAITHWAITE, C.J.R., RIZZI G. & DARKE G. (eds), The geometry and petrogenesis of dolomite hydrocarbon reservoirs: Geological Society Special Publications, Geological Society of London, **235**: 7–63.

MAGARA, K. (1978): Compaction and Fluid Migration – Practical Petroleum Geology. Elsevier, Amsterdam, 319 pp.

MAYER, H. & APPEL, E. (1999): Milankovitch cyclicity and rock-magnetic signatures of palaeoclimatic change in the Early Cretaceous Biancone Formation of the Southern Alps, Italy. – Cretaceous Research, **20**: 189–214.

MCKENZIE, J.A. & VASCONCELOS, C. (2009): Dolomite Mountains and the origin of the dolomite rock of which it mainly consists: historical developments and new perspectives. – Sedimentology, **56**: 205–219.

MEISTER, P., REYES, C., BEAUMONT, W., RINCON, M., COLLINS, L., BERELSON, W., STOTT, L., CORSETTI, F. & NEALSON, K.H. (2011): Calcium- and magnesium-limited dolomite precipitation at Deep Springs Lake, California. – Sedimentology, **58**: 1810–1830.

MEISTER, P., MCKENZIE, J.A., BERNASCONI, S.M. & BRACK, P. (2013): Dolomite formation in the shallow seas of the Alpine Triassic. – Sedimentology, **60**: 270–291.

Morrow, D.W. (1998): Regional subsurface dolomitization: Models and constraints. – Geoscience Canada, **25**/2: 57–70.

Ogg, J.G., Ogg, G. & Gradstein, F.M (2008): The Concise Geologic Time Scale. Cambridge University Press, Cambridge, 177 pp.

Pozzi, E. (1993): Die Fossilien der Dolomiten. Tappeiner Verlag, Lana. 176 pp.

Preto, N., Breda, A, Dal Corso, J., Spötl, C, Zorzi, F. & Frisia, S. (2014): Primary dolomite in the Late Triassic Travenanzes Formation, Dolomites, Northern Italy: Facies control and possible bacterial influence. – Sedimentology (2014). doi: 10.1111/sed.12157

Reboulet S., Klein J., Barragan R., Company M., Gonzalez-Arreola C., Lukeneder A., Raissossadat S.N., Sandoval J., Szives O., Tavera J.M., Vašíček Z. & Vermeulen J. (2009): Report on the 3rd international Meeting on the IUGS Lower Cretaceous Ammonite Working Group, the "Kilian Group" (Vienna, Austria, 15th April 2008). – Cretaceous Research **30**/2: 496–592.

Reboulet S., Szives O., Aguirre-Urreta B., Barragán R., Company M., Idakieva V., Ivanov M., Mikheil V. Kakabadze, Moreno-Bedmar J.A., Sandoval J., Baraboshkin E., Çaglar M.K., Fözy I., González-Arreola C., Kenjo S., Lukeneder A., Raisossadat S.N., Rawson P.F., Tavera J.M. (2014): Report on the 5th International Meeting of the IUGS Lower Cretaceous Ammonite Working Group, the Kilian Group (Ankara, Turkey, 31st August 2013). – Cretaceous Research, **50**: 126–137.

Richter, D. (1986): Allgemeine Geologie. Walter de Gruyter, Berlin-New York, 412 pp.

Rodighiero, A. (1919): Il sistema Cretaceo del Veneto Occidentale compreso fra l'Adige e il Piave con speziale reguardo al Neocomiano die Sette Comuni. – Palaeontographica Italica, **25**: 39–125.

Schneider, S., Crampton, J.S. & Lukeneder, A. (2013): Propeamussiidae, Inoceramidae, and other Bivalvia from the Lower Cretaceous Puez Formation (Valanginian–Cenomanian; Dolomites, South Tyrol, Italy). – Cretaceous Research, **46**: 216–231.

Scotese, C.R. (2001): Atlas of Earth History. Paleomap project. Arlington, 52 pp.

Sibley, D.F. & Gregg, J.M. (1987): Classification of dolomite rock textures. – Journal of Sedimentary Petrology, **57**: 967–975.

Stampfli, G. & Mosar, J. (1999): The making and becoming of Apulia. – Mémoires Science Géologie (University of Padova). Special volume, 3rd Workshop on Alpine Geology, **51**/1:141–154.

Stampfli, G.M., Borel, G.D., Marchant, R & Mosar J. (2002): Western Alps geological constraints on western Tethyan reconstructions. – In: Rosenbaum, G. & Lister, G.S. (eds): Reconstruction of the evolution of the Alpine-Himalayan Orogen. – Journal of the Virtual Explorer, **8**: 77–106.

Stöhr, D. (1993): Die Ammoniten der Kreide von La Stua (Dolomiten, Norditalien). Unpublished PhD thesis, University of Giessen, 173 pp.

Stöhr, D. (1994): Ammonoidea aus Schwarzschiefern von La Stua (Norditalien, Provinz Belluno). – Giessener Geolgische Schriften, **51**: 291–311.

Tucker, M.E. & Wright, V.P. (1990): Carbonate Sedimentology. Blackwell Scientific Publications, Oxford, London, Edinburgh, 482 pp.

Uhlig, V. (1887): Ueber neocome Fossilien von Gardenazza in Südtirol nebst einem Anhang über das Neocom von Ischl. – Jahrbuch der Geologischen Reichsanstalt, **37**/1: 69–108.

VINX, R. (2008): Gesteinsbestimmung im Gelände. 2 Auflage. Springer-Verlag, Berlin-Heidelberg, 469 pp.

WEISSERT, H.J. (1981): Depositional processes in an ancient palagic environment: the Lower Cretaceious maiolica of the Southern alps. – Eclogae Geologicae Helvetiae, **74**: 339–352.

WENK, H.-R., MEISHENG, H. & FRISIA, S. (1993): Partially disordered dolomite: microstructural characterization of Abu Dhabi sabkha carbonates. – American Mineralogist, **78**: 769–774.

WIECZOREK, J. (1988): Maiolica – a unique facies of the western Tethys. – Annales Societatis Geologorum Poloniae, **58**: 255–276.

ZEISS, A., HORRELT, R. PFEFFER, R. & SIEREK, H. (1990): The Jurassic and Cretaceous Sediments in the area NW of Cortina d'Ampezzo (Northern Italy). – Atti Convegno "Fossili, Evoluzione, Ambiente", Pergola II, **1987**: 491–505.

ZENGER, D.H., DUNHAM, J.B. & ETHINGTON, R.L. (Eds) (1980): Concepts and Models of Dolomitization. – SEPM Special Publication, **28**: 320 pp.