

PETROLOGY OF CARBONATE BEDS FROM THE STRATOTYPE OF THE CARNIAN (STUORES WIESEN SECTION, DOLOMITES, ITALY): THE CONTRIBUTION OF PLATFORM-DERIVED MICROBIALITES.

Nereo Preto^{1,2}

With 4 Figures, 4 Plates and 2 Tables

¹ Department of Geosciences, University of Padova, Italy; nereo.preto@unipd.it

² Leibniz Center of Marine Tropical Ecology, Bremen, Germany

Abstract

The modal composition of carbonate grains in para-autochthonous carbonate beds from the Ladinian–Carnian stratigraphic succession of Stuores Wiesen in the Dolomites was evaluated by point-counting. The stratigraphic series of Stuores, which includes the GSSP of the Carnian stage, is mostly composed of shales and marls deposited in a rather deep-water setting, at the foot of high-relief carbonate platforms. Numerous cm- to dm-scale calciturbidite beds, ranging from carbonate mudstone-siltstone to rudstone, are intercalated within the fine siliciclastics. In the Ladinian – lowermost Carnian portion of the succession, many of these calciturbidites are mixed carbonate-siliciclastic. Most of the carbonate grains in the granular facies of Stuores are fragments of microbialite with clotted peloidal fabric, *Tubiphytes*, calcimicrobes, peloids, ooids, mollusks, echinoderms and other types of skeletal grains. The major constituents of the carbonate grain associations are microbialitic allochems of various types, accounting for 64% of the volume of carbonate on average, with peaks of ca. 90%. This is in agreement with estimates on in-situ microbial-metazoan boundstones of the Dolomites with approximately the same age, and suggests that not only boundstone facies, but also basinal calciturbidites faithfully register the modal composition of microbial carbonate platforms. It is presently impossible to reconstruct the provenance of these microbialites within the depositional profile of the carbonate platform, because the formation of microbialites is not restricted to the photic zone: microbial carbonates may form at water depths of 0 to 250 m and below. Ooids are commonly associated with coarse terrigenous sand, and often grew on siliciclastic nuclei, demonstrating that siliciclastics were encroaching the submerged shelf on adjacent platforms. Overall, terrigenous supply did not hamper the development of high relief carbonate platforms during the Late Ladinian – Early Carnian at Stuores, but seems to have had an influence on carbonate grain associations. Fine carbonates contain calcareous nannofossils, which however contribute minimally to the sediment budget at Stuores.

1. Introduction and geological settings

Marine carbonate depositional systems are complex, because they do not only respond to changes of physical environmental parameters, as hydrodynamic energy or sea level, but also to the chemistry of seawater and to the biology of the ecosystems involved in the precipitation of calcium carbonate. The complex array of environmental controls that influence carbonate systems are reflected in the modal compositions of sandy carbonate rocks (skeletal associations). It was soon realized, however, how

difficult it is to disentangle the effects of, e.g., latitude, temperature, nutrient and terrigenous supply and light availability from skeletal associations alone (Carannante et al., 1988). Nowadays, the complexity of carbonate systems is widely recognized (e.g., Pomar and Hallock, 2008; Westphal et al., 2010), but the quantitative analysis of allochems in rocks and sediments still remains a fundamental instrument in the interpretation of carbonate environments. In this work, para-autochthonous rudstones, grainstones

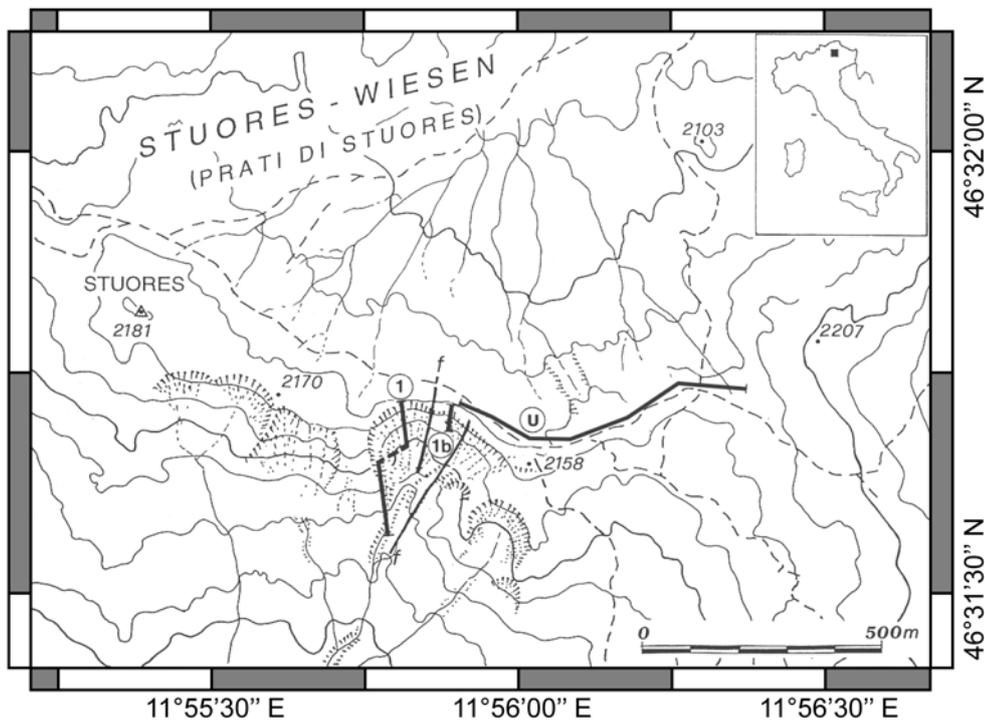


Fig. 1 Location of the Stuores Wiesen section (modified from Mietto et al., 2008). The section is a composite, tracts 1 and 1b are those of the Carnian stratotype (Broglia Loriga et al., 1999; Mietto et al., 2012), while the trace marked U links approximately the outcrops that make up for the composite of Urlichs (1994; 2011). The geographical coordinates of tract 1 are 46°31'37.85"N 11°55'47.71"E

and packstones from the Triassic locality of Stuores Wiesen were point-counted in order to better understand the modes of carbonate precipitation on adjacent carbonate platforms.

The stratigraphic succession of Stuores Wiesen in the Dolomites (Fig. 1) was recently selected for the GSSP of the Carnian stage (Mietto et al., 2007, 2012), mostly because of its excellent fossil documentation (e.g., Urlichs, 1974, 1994, 2011; Broglia Loriga et al., 1999; Mietto et al., 2008). The section encompasses the uppermost Wengen Formation and the Lower San Cassiano Formation, and can be subdivided into two parts. The lower part is exposed in a series of connected gullies on a steep slope, and includes the GSSP horizon. The exposure is excellent and continuous for more than 100 m with substantial lateral continuity. This lower part of the section is described in detail by Broglia Loriga et al. (1999) and Mietto et al. (2012). The upper part is a composite section that crops out in places within the meadows of Stuores, and was logged and described in detail by Urlichs (1994; 2012).

The area of Stuores was in a basinal setting during Late Ladinian to Early Carnian times (Fig. 2), and the sedimentation was dominated by volcanoclastic arenites and clays, derived from the subaerial erosion of Late Ladinian volcanic edifices. Intercalated

with volcanoclastic and shale deposits, carbonates are found in cm- to dm-thick beds that are interpreted to be derived from adjacent high relief carbonate platforms (Cassian Platforms of, e.g., Leonardi, 1967; Bosellini, 1984; De Zanche et al., 1993; Neri et al., 2007).

Numerous paleontological, stratigraphical and sedimentological studies were carried out to establish this GSSP since it was initially proposed (Broglia Loriga et al., 1999), that added up to a long history of early research on the well known Carnian fauna of the San Cassiano Formation, or Cassian beds for some authors (e.g., Münster, 1834; Ogilvie, 1893; Urlichs, 1974; Fürsich and Wendt, 1977). The petrology of carbonate rocks attracted comparably less attention, despite its potential importance for the understanding of the coeval carbonate platforms: the Lower Carnian platforms in particular are deeply dolomitized in the Dolomites, and their facies are mostly known from allochthonous boulders deposited in the basins that are interbedded with clays and volcanic arenites, and escaped dolomitization: the so-called Cipit boulders (Fig. 3) (e.g., Richthofen, 1860; Scudeller Baccelle, 1971; Wendt, 1982; Russo et al., 1991, 1997; Neuweiler and Reitner, 1995). While Cipit boulders were well studied, only little work was done on calciturbidites.

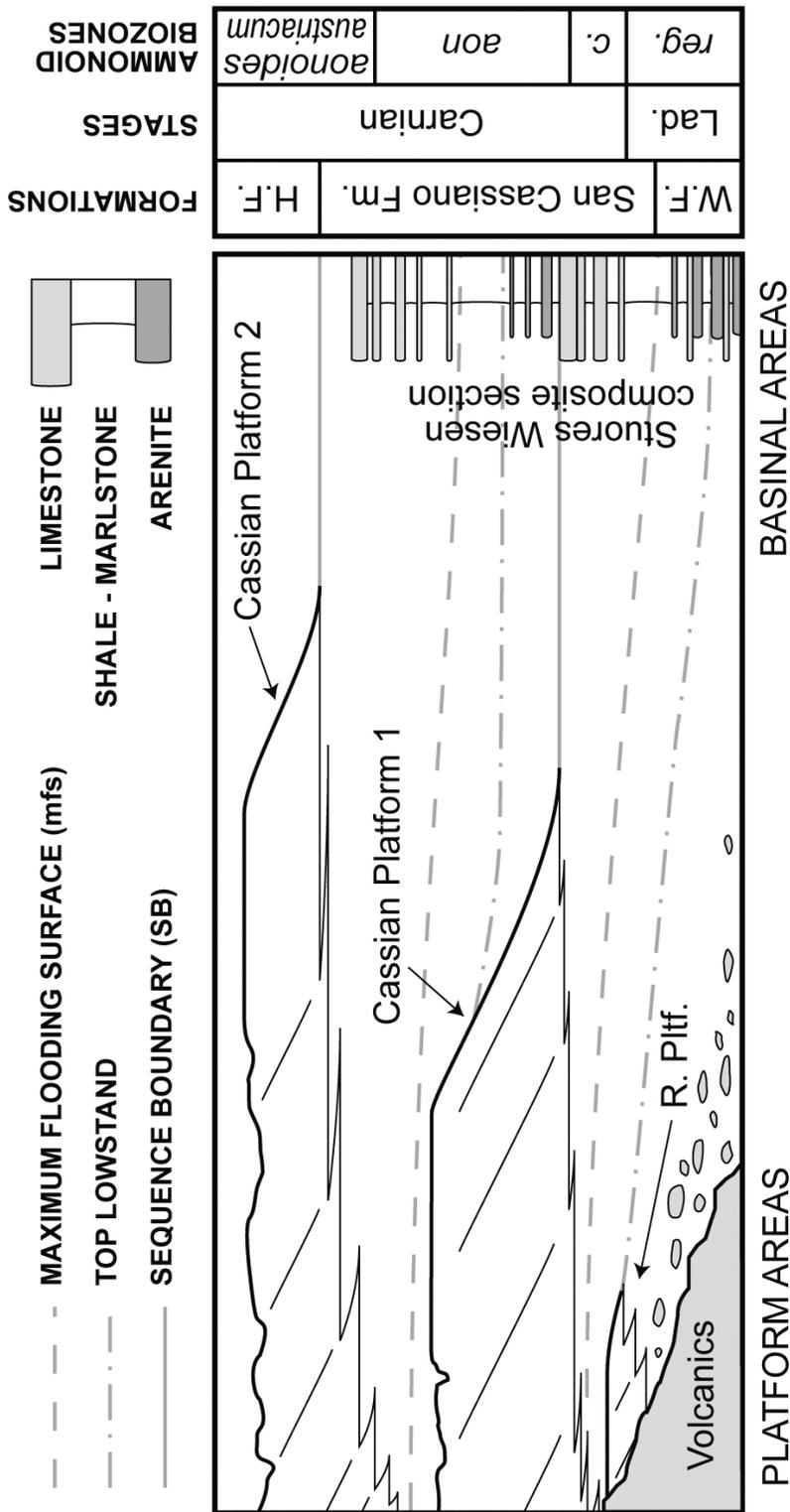


Fig. 2
 Stratigraphic setting of the central Dolomites from the end of the Ladinian to the Early Carnian. The study locality (Stuores composite section) represents a basinal setting. R.Pliff.: Rosszähne Platform; W.F.: Wengen Formation; H.F.: Heiligkreuz Formation; Lad.: Ladinian; *reg.*: *regoledanus* subzone; *c.*: *canadensis* subzone. Modified from De Zanche et al. (1993) and Gianolla et al. (1998; 2011).



Fig. 3
Example of a Cipit boulder within the Wengen Formation (upper Ladinian) near Passo Sella. The large boulder is ca. 2 m high. Cipit boulders are found also at Stuoeres, although they are not often so evident in outcrop.

The petrology of calciturbidites was quantitatively assessed (Reijmer, 1998) in a study that was focused on the younger part of the San Cassiano Formation of Picco di Vallandro / Dürrenstein, some 25 km Northeast of Stuoeres. Reijmer (1998) identified carbonate grains such as ooids, calcisponges, fragments of *Tubiphytes*, peloids and intraclasts with clotted peloidal (grumoleuse) fabric, that are also the major constituents of coarse carbonate beds at Stuoeres. He classified carbonate grains mostly as a function of the facies belt they likely derived from, and was thus able to quantify what proportion of carbonate derived from the platform interior, reef, and basin.

In this work, the point-counting approach of Reijmer (1998) is also applied, and the general idea that the platform composition and evolution can be inferred from carbonate sediment shed into the adjacent basins (Reijmer and Everaars, 1991) is considered valid. However, recent developments in the understanding of the facies distribution within Triassic carbonate platforms of the Dolomites suggest caution when carbonate grains are attributed to specific facies belts, in particular for what microbial carbonates are concerned. Facies analysis of Cipit boulders revealed that the carbonate factory of the late Ladinian and Carnian high-relief carbonate platforms of the Dolomites was dominated by benthic carbonates which precipitation was microbially induced (microbialites). Russo et al. (1997) and Keim and Schlager (2001) pointed out that the contribution of microbial

carbonates to the carbonate budget of reefal facies was nearly one order of magnitude larger than that of skeletal components. Similar results were reported by Marangon et al. (2011) for the Middle Triassic. Such microbial carbonates, and especially microbialites with clotted peloidal fabric, are not exclusive of the platform margin. Instead, since their formation is not limited by the availability of light, they are typical constituents of the upper slope, and were found as deep as 200 m below the margin in the lower Carnian Sella platform (Keim and Schlager, 1999). Similarly, the upper slopes of the middle Triassic Latemar platform were also found to be dominated by microbialites down to a depth of 200–250 m below the margin (Marangon et al., 2011). Blendingner (1994) suggested that the main factory of Triassic carbonate platforms of the Dolomites was indeed on the slope, rather than on the margin and platform interior.

In the light of these recent developments, it is unclear whether the contribution of different portions of late Ladinian to Carnian carbonate platforms could be disentangled in basinal calciturbidites. However, the type and proportion of microbialites can still be assessed. In this work, the modal composition of calciturbidites and other granular carbonate beds sampled in the Stuoeres section has been determined by point counting, with the primary aim to describe and quantify the contribution of platform microbialites to the carbonate sedimentation at Stuoeres, and its possible variations through time.

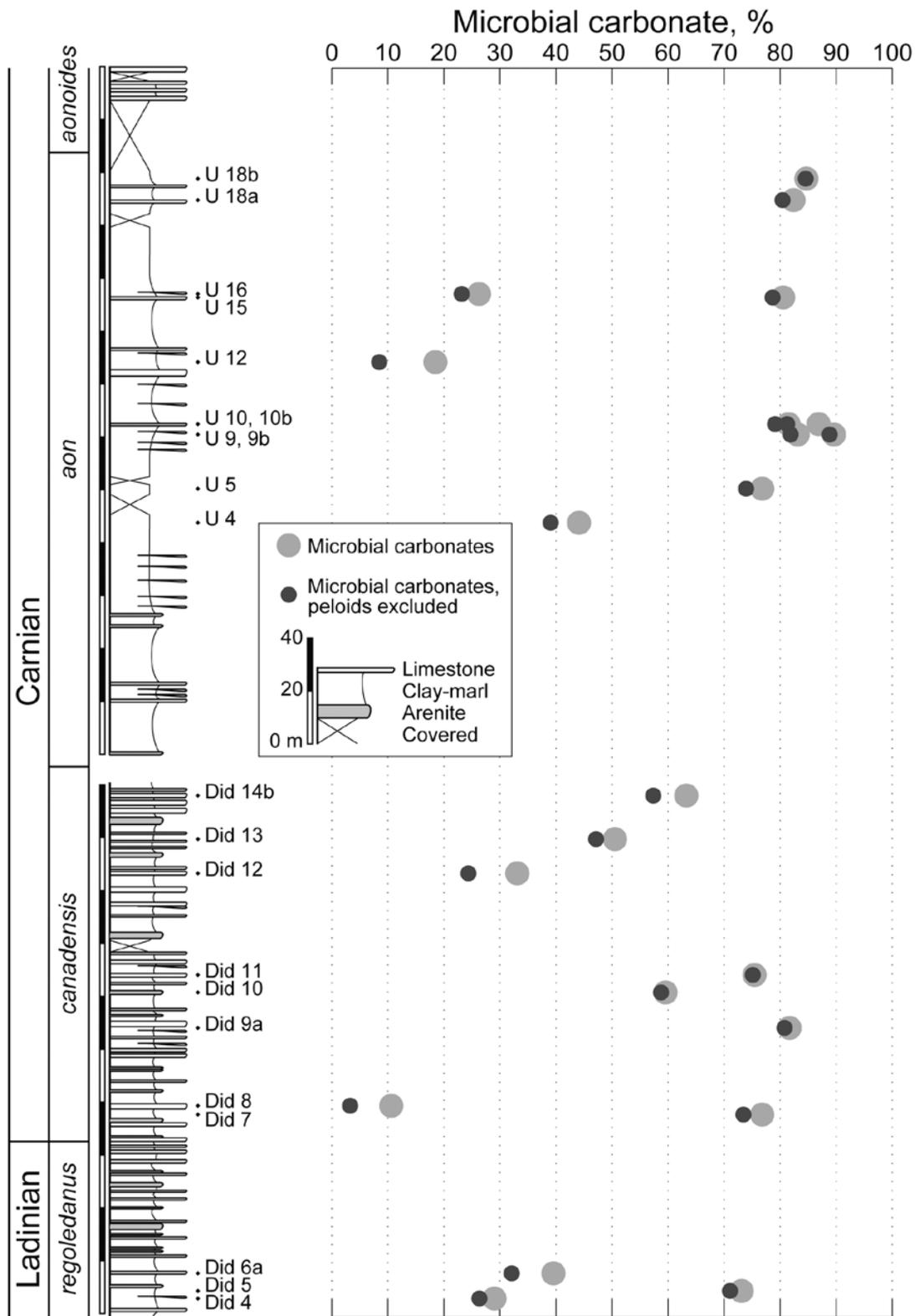


Fig. 4

Logs of the Stuores Wiesen sections, simplified from Broglio Loriga et al. (1999) for the lower part and from Urlichs (1994; 2011) for the upper part. Different clay content might be an artifact due to the different approach on logging the two parts of the section by the different authors. The correlation between the two parts is uncertain, but no significant gap is expected (Neri et al., 1995).

2. Materials and methods

Twenty-two standard (30 µm thick) uncovered thin sections were prepared and studied under a polarized microscope, and were also studied with a fluorescence microscope. Eleven samples were selected in the lower part of the section (Ladinian *regoledanus* and Carnian *canadensis* ammonoid biozones), and eleven in the upper part (Carnian *aon* ammonoid zone). All samples are positioned precisely on the logs of Broglio Loriga et al. (1999) and Urlichs (1994; 2011) (Fig. 4).

Between 400 and 650 (average 546) points were counted for each thin section, which guarantees statistically significant estimation of modal abundances (Van del Plas and Tobi, 1965). All samples were very well preserved and free from pervasive recrystallization, thus, virtually all carbonate grains could be determined with good confidence. Uncertainty is inherited with the determination of smaller grains.

Thin sections were also observed under fluorescent light with a Zeiss Axioscop 40 equipped with a mercury arc 50/ac uv lamp and 450–490 nm (exciter) – 515 nm (barrier) filters at the Geological Department of the University of Bremen, in order to evaluate the occurrence of organic matter and its distribution among different carbonate grains. Carbonate in fact exhibits epifluorescence when it incorporates organic matter, and if the rock maturation was not too intense. Epifluorescence is thought to derive mostly from unsaturated aromatic organic compounds (Dravies and Yurewicz, 1985; Machel et al., 1991).

Twenty-four samples, mostly of fine carbonate, were selected for Scanning Electron Microscopy (SEM) observations. These samples were prepared following the procedure of Munnecke (1997) as detailed by Preto et al. (2013): rock samples were cut into blocks ca. 5X5 mm wide, polished with 500 and 800 borcarbide powder and cleaned in ultrasonic bath. Polished surfaces were then etched with highly diluted (ca. 0.3%) hydrochloric acid for 10–20 seconds and gold coated.

3. Results

3.1. Field observations

The stratigraphic succession of the GSSP interval at Stuores is dominantly fine terrigenous (clays and silt), with cm- to dm-thick beds of arenite and limestone intercalated. Some beds are of mixed composition, i.e., they are hybrid arenites or sandy limestones, especially

in the first 120 meters of the section. This work focuses on carbonates; sandstone beds are composed of dark lithic (volcanic) arenites, with an erosive base, normal grading and often a laminated upper portion. They range in thickness from one cm or less to several tens of cm. They are not present in the upper part of the succession (*aon* and *aonoides* ammonoid biozones).

Carbonate beds rarely exceed few tens of cm of thickness in the lower part. They have typically an erosive base with bottom marks (e.g., flute casts and lineations) and graded bedding. A plane-bed lamination is visible especially in cm-thick beds and in the upper part of dm-thick beds. At the base of the section, and approximately up to the GSSP level, carbonate beds often display a fine (micritic) upper part. Lime mudstones decrease in abundance upward, and from about 90 meters above the base of the section coarse carbonate beds (rudstones) appear. Rudstones with cm-large carbonate grains then become common in the upper part of the section, and normal grading is less commonly observed. Oolites are more common and carbonate beds may constitute up to 50% of the succession in some intervals. Mixed carbonate-clastic beds are commonly observed in the lower part of the section (*regoledanus* and *canadensis* ammonoid biozones). Furthermore, terrestrial plant fragments are often found in carbonate beds, typically at the top of coarse intervals or within fine intervals. Nearly all coarse-grained carbonate beds of the section can readily be interpreted as calciturbidites, derived from a carbonate platform polluted by terrigenous influx or from the mixing of different (carbonate and siliciclastic) sources.

3.2. Components of coarse carbonates of Stuores in thin section

All studied samples are grainstones, rudstones or floatstones, of which the main carbonate components are ooids, peloids and intraclasts. Oncoids, *Tubiphytes*, calcimicrobes, agglutinated tubes, mollusks, foraminifers (mostly agglutinated) and echinoderms are common. Other components are rare. Generally, grains attributed to microbialite are bright fluorescent. On the contrary, most skeletal grains are dull or completely dark under fluorescence light.

The large majority of intraclasts are irregular carbonate grains with rugged outline composed of clotted peloidal micrite (PI 1c, d; PI 2c, f; PI 3c, d), a typical constituent of microbial reefs, commonly identified in

non dolomitized olistoliths (Cipit boulders) embedded in Late Ladinian to Early Carnian basinal successions (e.g., Neuweiler and Reitner, 1995; Russo et al., 1997). Among the many grains contained in the carbonate beds of Stuores that are fluorescent, fragments (intraclasts) of clotted peloidal micrite appear particularly bright. This is in agreement with previous studies on Cipit boulders (e.g., Neuweiler and Reitner, 1995; Russo et al., 1997). Oncoids (Pl. 2c, upper part; Pl. 3e-h) are mostly coated by irregular laminae of clotted peloidal micrite, that exhibit the typical bright green fluorescence. The walls of agglutinated tubes (cf. *Macrotubus* sp.) are also composed of bright fluorescent clotted peloidal micrite.

Tubiphytes is a problematic fossil common in microbial Paleozoic and Mesozoic reef communities, that is characterized by a thick (up to mm scale) laminated or vaguely peloidal micritic envelope around a central thin, hollow tube. Fragments of *Tubiphytes* are commonly found as components of grainstones, rudstones and floatstones at Stuores (Pl. 1e, f; Pl. 3a-d). *Tubiphytes* is usually found as isolated tube segments, but associations of two or more individuals grown together were also observed (Pl. 1e, f). In some cases, clotted peloidal micrite partially envelops the individual tubes (Pl. 3c, d). *Tubiphytes* is always bright fluorescent, and fluorescence often highlights a distinct growth banding (Pl. 1e, f; Pl., 3c, d). Among calcimicrobes, tufts of calcified cyanobacteria (*Cayeuxia*) are common (Pl. 3a, b), and filamentous coatings (cf. *Girvanella*) were also observed (Pl. 3h).

Ooids are tangential, with dimensions typically of 200–500 μm (Pl. 1a, b, g, h; Pl. 2a, c, d; Pl. 4f). Their nuclei are formed by a variety of small carbonate grains (e.g., mollusk fragments, intraclasts, echinoderms and foraminifers) along with quartz and lithic fragments (Pl. 2d). The coating of ooids also shows bright fluorescence, and concentric laminae are well distinguishable under fluorescent light (Pl. 1b, h).

Detrital non-carbonate grains were also observed and are occasionally common (Pl. 2a). Although a modal analysis of siliciclastic grains was not performed, the main siliciclastic grains are lithics of volcanic origin derived from the dismantling of Late Ladinian volcanic edifices of the Dolomites and nearby areas, e.g., toward the South (Brusca et al., 1982; Breda and Preto, 2011). Quartz and rarer feldspar grains were also observed.

The results of point counting are provided in table 1. Although the preservation of all samples was very

good, some small components could not be attributed to a specific group. This applies especially to peloids and unidentified skeletal grains. Peloids can be of various origin (see Flügel, 2004 for a comprehensive review), including the complete micritization of previous skeletal grains or intraclasts. However, peloids could also be small fragments of microbialites with clotted peloidal fabric. While on the one hand it is easy to define and identify peloids as a broad category, it is nearly impossible to decide whether they are to be included or not among microbial carbonates.

Fragments of skeletal grains are often too small to be attributed to specific fossil groups. This is particularly true for fragments of originally aragonitic shells and skeletons, that are recrystallized and thus do not exhibit any recognizable ultrastructure. Fortunately, although specific attribution is not possible, these small fragments are readily distinguished from microbial carbonates. Unrecognized skeletal grains may be common, especially in fine-grained facies.

3.3. SEM petrography of lime mudstones (and wackestones)

Scanning Electron Microscopy (SEM) was used for the study of fine-grained carbonates and to observe the fine structure of ooids (Pl. 4). Fine-grained carbonates are constituted by a mosaic of densely pitted microsparite crystals, with an average diameter of ca. 10–15 μm . Microsparite crystals normally show irregular boundaries (Pl. 4c). These fine carbonates are seen, under the SEM, to incorporate numerous microfossils including calcispheres (Pl. 4a, b), detrital sand grains (Pl. 4d), and crystals of authigenic minerals such as pyrite (Pl. 4g, h).

Calcispheres of the Stuores section are similar to those observed in Upper Carnian and Norian periplatform hemipelagic carbonates of the Southern Apennines and Sicily (Di Nocera and Scandone, 1977; Bellanca et al., 1993; Preto et al., 2012). Such calcispheres were interpreted by Preto et al. (2013) as nanofossils comparable to those of the „*Pithonella*“ group of Bolli (1974). Originally, the calcispheres were less than 10 μm in diameter, but were typically overgrown by epitaxial diagenetic calcite which eventually constitutes most of the visible nanofossil. Pyrite occurs either as framboids (Pl. 4h) or as isolated microscopic crystals, usually where organic matter was present, as, e.g., within mollusk shells (Pl. 4g).

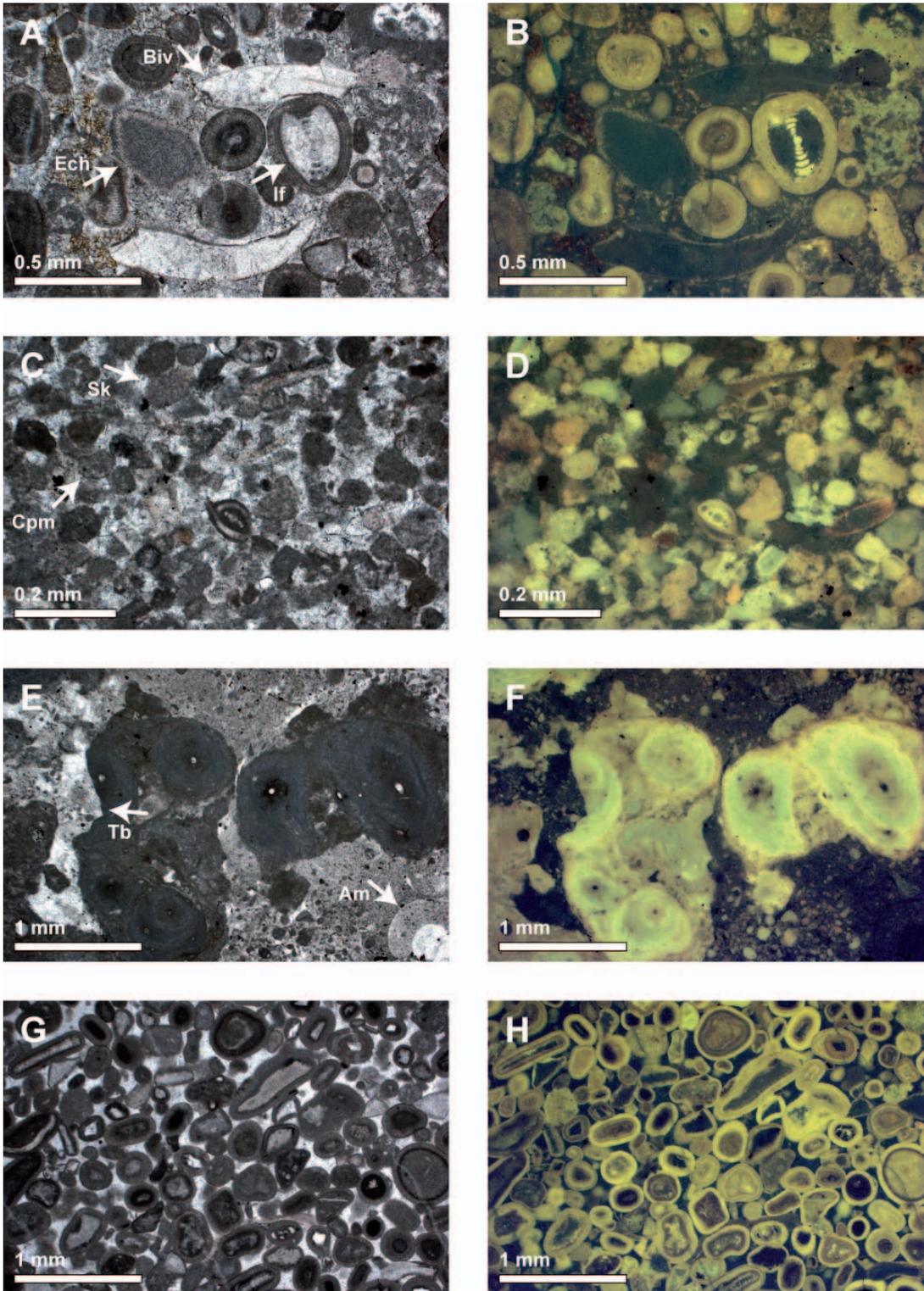


Plate 1:

Microfacies of the Stuores Wiesen section, upper part (see Urlachs, 1994), as seen under visible polarized light (on the left) and fluorescent light (on the right). (A, B) Oolitic-bioclastic grainstone. Ooid coatings are bright fluorescent, while skeletal grains are usually non fluorescent or dull: e.g., the echinoderm fragments (Ech), bivalve shells (Biv) and the aragonitic involutinid foraminifer (If) at the nucleus of an ooid. From horizon 4 of Urlachs (1994). (C, D) Intra-peloidal-bioclastic grainstone. Intraclasts (and peloids) are systematically bright fluorescent. Those exhibiting a clotted peloidal fabric (Cpm) are interpreted as intraclasts derived from microbial boundstones. Skeletal grains (Sk) are, with the exception of porcelaneous foraminifera, dull or non fluorescent. From horizon 5 of Urlachs (1994). (E, F) Rudstone with *Tubiphytes*. *Tubiphytes* are coated by clotted peloidal micrite and are sometimes fractured (Tb). Skeletal grains, e.g., ammonoid shells (Am) are not fluorescent. From horizon 9 of Urlachs (1994). (G, H) Oolitic grainstone. Ooid coatings are bright fluorescent. Horizon 16 of Urlachs (1994).

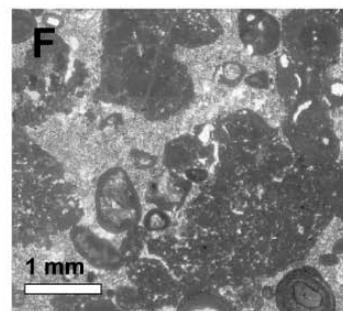
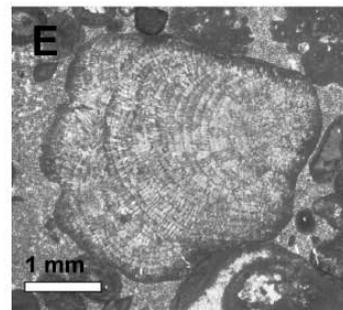
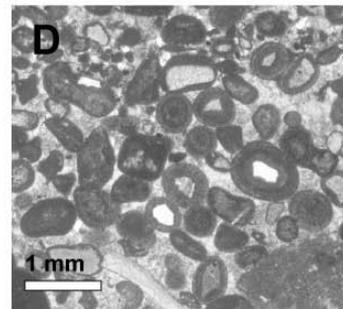
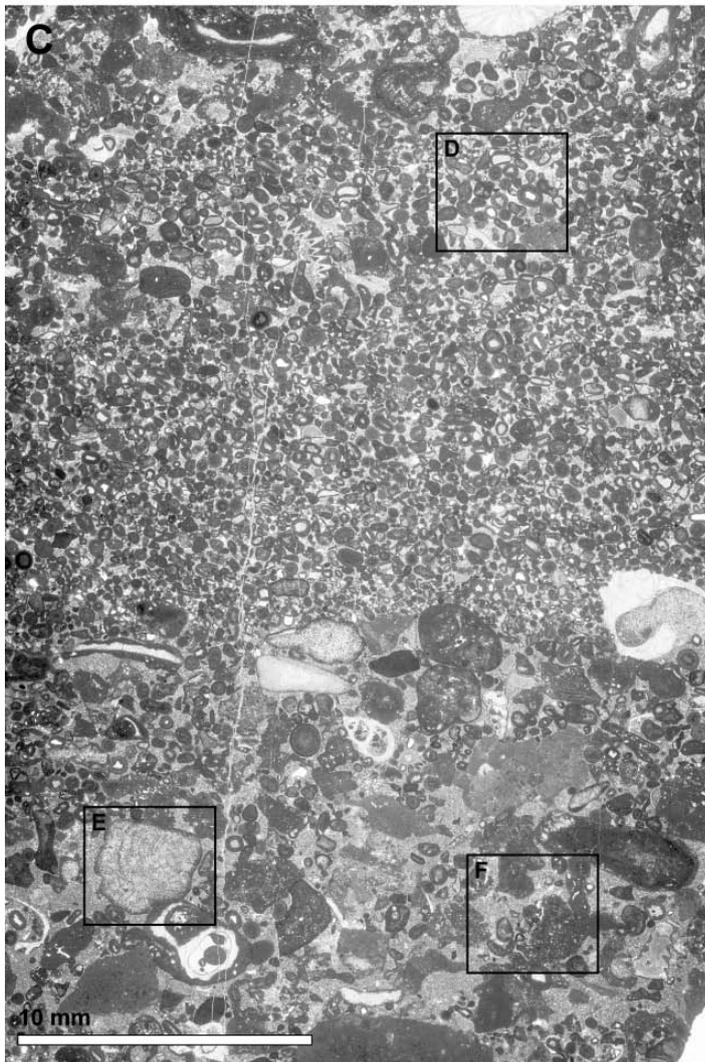
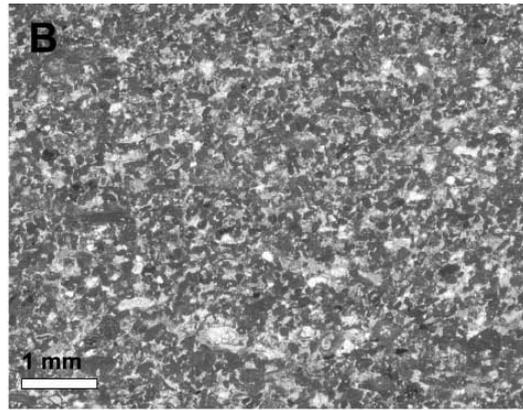
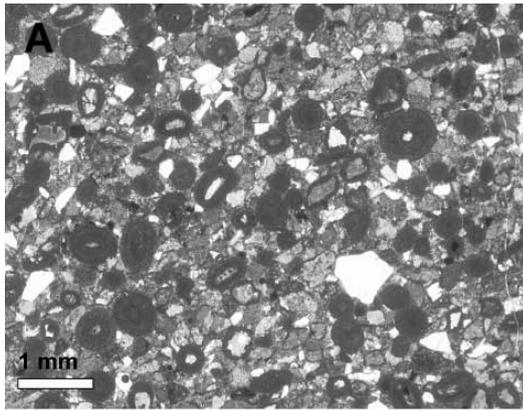


Plate 2:

Microfacies of the Stuoeres Wiesen section, lower part (see Broglio Loriga et al., 1999), as seen under polarized light. **(A)** Hybrid arenite (quartz-lithic arenite with carbonate allochems), containing abundant ooids, often with siliciclastic nuclei. Lower Carnian, m 58 ca. **(B)** Intra-peloidal grainstone. Most intraclasts are small fragments of clotted peloidal micrite. This microfacies typically contains less coarse siliciclastics than oolites. Lower Carnian, m 55 ca. **(C)** Laminae of oolitic grainstone and intraclastic-bioclastic rudstone. Ooids often have siliciclastic grains (e.g., quartz) at their nuclei **(D)**. Oncoids, gastropods, echinoderms and reef-building metazoans as chaetetid sponges **(E)** are common, but the most abundant elements in the rudstones are intraclasts with clotted peloidal fabric **(F)**. Lower Carnian, m 159 ca.

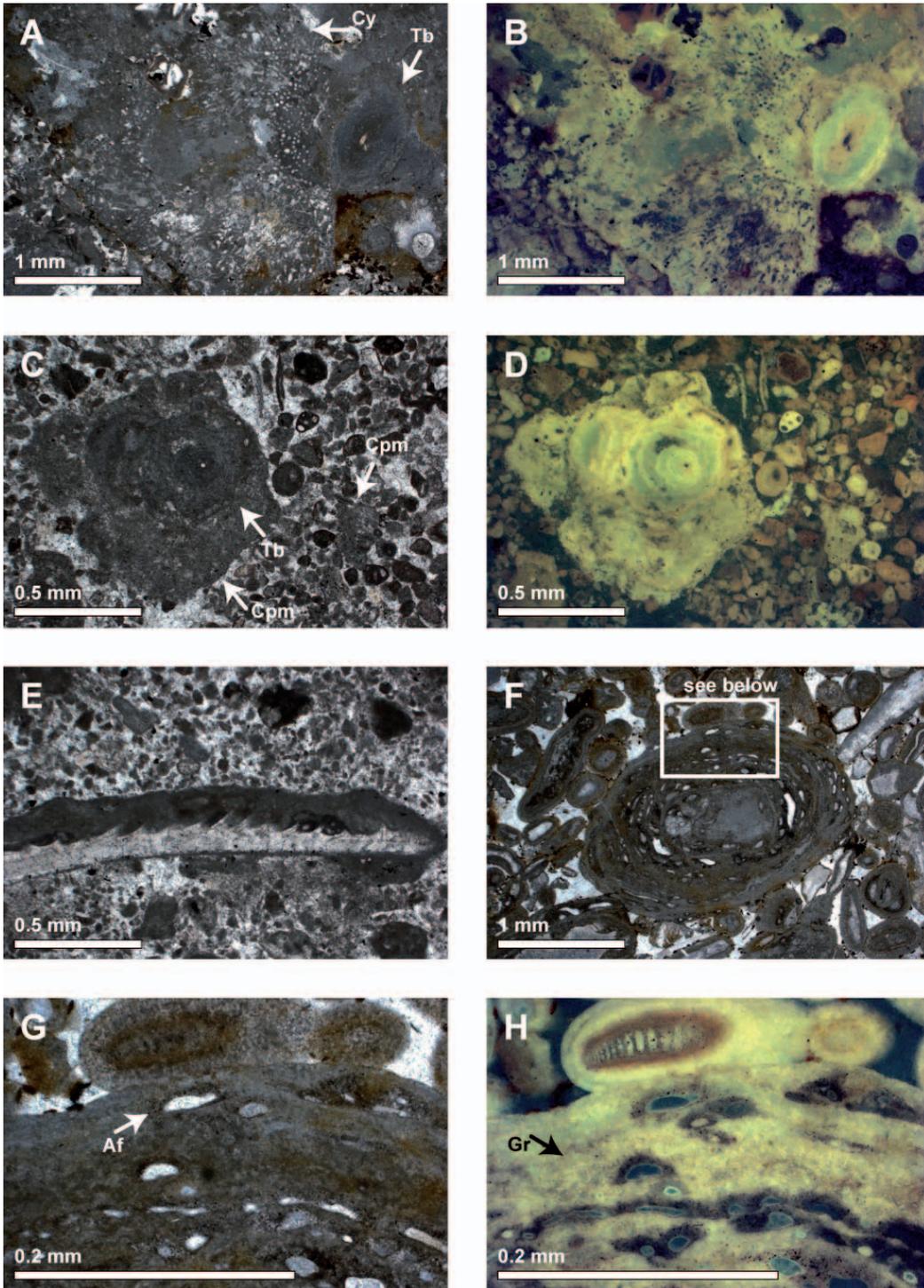


Plate 3:

Examples of microbial carbonate grains, in thin section, under polarized visible light and fluorescence. (A, B) A cyanobacterial calcimicrobe (cf. *Cayeuxia*, indicated as Cy) encrusting a *Tubiphytes* (Tb). From horizon 9 of Urlich's (1994). (C, D) *Tubiphytes* (Tb), encrusted by a microbial boundstone facies made of clotted peloidal micrite (Cpm), reworked within an intra-bioclasic grainstone. Other fragments of clotted peloidal micrite are visible in the sample. Fluorescence highlights clear concentric growth bands of the *Tubiphytes* (see also Plate 1F). Horizon 10 of Urlich's (1994). (E) Oncoidal coating of a mollusk shell of the „thrombolitic“ type (i.e., made of clotted peloidal micrite). The oncolitic coating also includes agglutinated foraminifera. Horizon 9 of Urlich's (1994). (F) Oncoid of the „stromatolitic“ type, i.e., with well laminated microbial coating, in a oolitic-bioclasic grainstone. The oncolitic envelope also includes abundant agglutinated foraminifera. See enlargement below. Horizon 16 of Urlich's (1994). (G, H) Stromatolitic oncolitic envelope, enlargement of (F). The envelope includes abundant tests of agglutinated foraminifera (Af), the stromatolitic laminae locally show a vermicular texture (Gr) similar to *Girvanella* that suggests a cyanobacterial origin. Foraminiferal tests are conspicuously less fluorescent than stromatolitic laminae. Horizon 16 of Urlich's (1994).

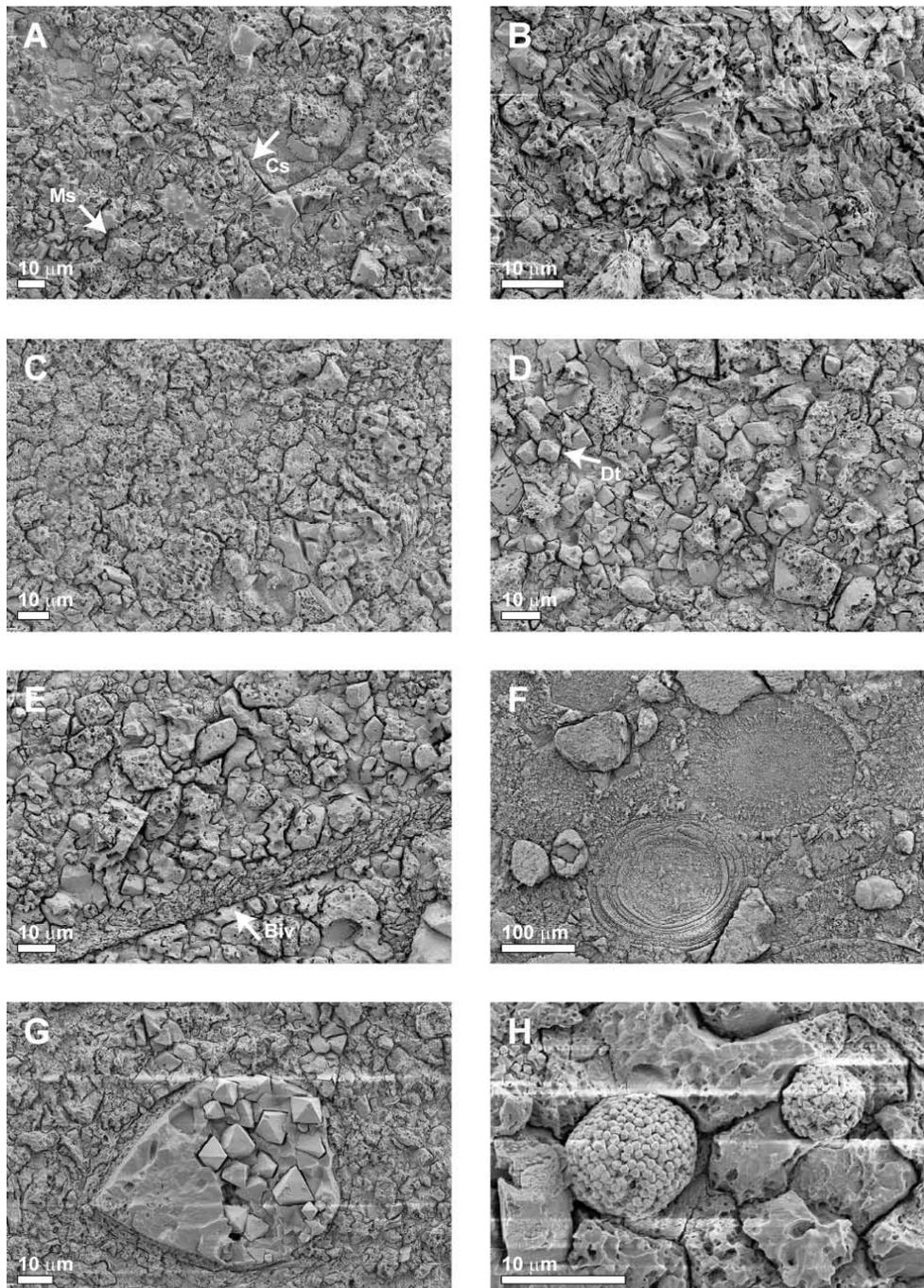


Plate 4:

Carbonates of Stuores under the SEM. (A) Fine carbonate with mainly strongly pitted and irregular microspar crystals (Ms) with average dimensions of $>10\ \mu\text{m}$. Calcispheres (Cs) are also present in the sample. Lower Stuores section. (B) Calcispheres. The irregular elongated calcite crystals that form the calcisphere should be interpreted as mostly epitaxial overgrowth (Preto et al., 2013). Compare with the Upper Carnian – Norian calcispheres of Sicily (Bellanca et al., 1993; Preto et al., 2012). Lower Stuores section. (C) Lime mudstone made of compenetrated, highly pitted microspar with average crystal dimensions of $\geq 10\ \mu\text{m}$. Lower Stuores section. (D) Silty lime mudstone with microspar crystals and detrital siliciclastic grains (Dt). Non-carbonate grains (detrital) are identified because they are not pitted and not etched. Lower Stuores section. (E) Silty lime mudstone with thin-shelled bivalve (Biv). Lower Stuores section. (F) Oolitic grainstone, with detrital siliciclastic grains (Dt). Etching highlights the concentric tangential laminae of ooids. Lower Stuores section. (G) Octahedral pyrite crystals grown within a semi-closed cavity (articulated juvenile bivalve shell). The chemical composition of octahedral crystals was tested with EDX. Precipitation of pyrite where organic matter was probably available is here interpreted as the result of bacterial sulphate reduction (see Mietto et al., 2012). Lower Stuores section. (H) Pyrite framboids also suggest bacterial sulphate reduction within the sediment in a early diagenetic stage. Lower Stuores section.

4. Discussion

4.1. Proportion of microbial carbonate in the calciturbidites of Stuores

Microbial carbonates are those that formed by microbes (mostly bacteria and archaea) that induced carbonate precipitation as a byproduct of their metabolism, or carbonate which precipitation was induced through nucleation on the template of dead organic matter (Burne and Moore, 1987 ; Schlager, 2003). Carbonate of microbial origin is present in different forms in the calciturbidites of Stuores. While some carbonate grains are easily interpreted as microbialites (i.e., cyanobacterial calcimicrobes, intraclasts with clotted peloidal fabric), other may be ambiguous.

Tubiphytes was considered to be a microbial constituent. Similarities are found with the Jurassic form „*Tubiphytes*“ *morroneensis* (now *Crescientella morroneensis*) described by Senowbari-Daryan et al. (2008). According to these authors, the Jurassic „*Tubiphytes*“ represents a consortium between a foraminifer at the nucleus and a microbial community coating its test. The chambers of the foraminifer coincide with the central cavity and the growth of microbial carbonate determines a faint lamination that is seen as concentric in equatorial sections. Triassic *Tubiphytes* exhibit similar features, and most noticeably a laminated microbial coating in some cases with a clotted peloidal fabric (Pl. 1e, f; Pl. 3a-d). A walled internal cavity that might be interpreted as a foraminiferal test is in some cases also observed (Senowbari-Daryan and Flügel, 1993; Senowbari-Daryan et al., 2008; and own observations). In all cases, the micritic coatings, interpreted as microbial, constitute most of the grain volume.

Agglutinated tubes similar to *Macrotubus* were probably coatings of filter feeding „worms“ (e.g., anellids). However, precipitation of carbonate tubes was microbially induced, as suggested by their clotted peloidal fabric and bright luminescence. The fabric of agglutinated tubes in the carbonate rocks of Stuores is virtually indistinguishable from that of microbial boundstones made of clotted peloidal micrite. Tiny isolated tubes, which show the same diameter as those of *Cayeuxia* and *Girvanella* calcimicrobes, were also interpreted to be of cyanobacterial origin.

Ooids are bright fluorescent, which might suggest a microbial contribution to their formation. The microbial formation of ooids is a long-lived hypothesis (e.g., Mitterer, 1972; Folk and Lynch, 2001) which has

been recently addressed by Duguid et al. (2010). Following these authors, aragonitic tangential ooids of the Bahamas are grown abiotically, perhaps through an intermediate stage of formation of a film of an amorphous calcium carbonate phase. However, cyanobacteria thrive on ooid surfaces and drill microbores in which an early diagenetic aragonite cement precipitates. Organic matter of these cyanobacteria is typically incorporated in laminae and microborings, as already noted by Davies et al. (1978). The ooids of Stuores are similar to the Recent examples of the Bahamas, and in thin section exhibit similar microborings. It is thus suggested that their precipitation was also similar, i.e., abiotic though with an early alteration by microbes, most probably cyanobacteria.

Small peloids cannot be attributed with confidence to a microbial origin, nor can this be excluded, except for the cases where the peloid is obviously a fecal pellet or an angular lithoclast derived from a carbonate rock. None of the peloids at Stuores belongs to these easily interpreted categories. Peloids of Stuores are however typically bright fluorescent (Pl. 1d; 3d), while interstitial micrite is not. This is why peloids were tentatively considered microbial, i.e., fragments of clotted peloidal micrite that are too small to identify their fabric. Excluding peloids from point counting does not affect the results significantly (Fig. 3; Table 1, 2).

Given this classification of microbial versus non microbial carbonate grains, the calciturbidites of Stuores contain up to 90% of microbial carbonate, with a weighted average of 64%. This figure compares well with the estimates of Russo et al. (1997) and Keim and Schlager (2001) for the boundstone facies of Carnian cipit boulders and carbonate platforms in the Dolomites. This further suggests that the composition of allochthonous carbonate grains in calciturbidites represent the proportion of carbonate-secreting organisms of the source, not only in terms of skeletal composition (Reijmer and Everaars, 1991; Reijmer, 1998) but also for the presence and proportion of microbial carbonate.

4.2. From where did microbial carbonate come from?

Microbialites of various types are thus the most common carbonate grains at Stuores. Because of their occurrence only in calciturbidites (*in situ* microbialites were not observed), they are inferred to be derived exclusively from carbonate platform environments. It is

not possible at the moment to disentangle which part of the microbial carbonate derived from the margin and platform interior and which was instead formed on the slopes, with a few exceptions.

One exception are cyanobacterial calcimicrobes. These must have been growing in the photic zone, and were thus most probably derived from the platform interior or margin. Also microbial carbonates strictly associated with ooids must have derived from above the fair weather wave base. However, the formation of most abundant microbial carbonates (fragments of microbial boundstones with clotted peloidal fabric) are not limited by light availability or a specific range of hydraulic energy, and could potentially form at any water depth. Clotted peloidal micrite is in fact commonly found on the upper slope of microbial carbonate platforms, including the Carnian Sella Platform in the Dolomites (Keim and Schlager, 1999; 2001). The same is observed for *Tubiphytes*, which is commonly overgrown by clotted peloidal microbialites. Microbial carbonate production on slopes occurs at least down to depths of approximately 250 m in the Dolomites (Keim and Schlager, 1999; Marangon et al., 2011). This implies that carbonate production is virtually unaffected by sea-level changes, which magnitude could hardly exceed a few tens of meters in the ice-free Triassic world: slopes would shed carbonate to basins irrespective of the position within the sea-level cycle, in agreement with the slope shedding model of Kenter et al. (2005).

4.3. Coarse siliciclastic input and the response of carbonate platforms.

Siliciclastic grains are common in the Stuores section, especially in its lower part (Broglia Loriga et al., 1999). Siliciclastic grains are found to form the nuclei of tangential ooids, recrystallized but with originally aragonitic mineralogy. This type of ooids forms in high-energy shallow water carbonate platform environments (e.g., Simone, 1981; Flügel, 2004). Thus, at least part of the coarse siliciclastics that fed the basin at Stuores must have been encroaching the carbonate platforms, which were probably attached to a volcanic interland or to isolated volcanic edifices. This also implies that siliciclastic input is not necessarily related to sea-level falls or low-stands: in order to constitute ooid nuclei, in fact, siliciclastic grains must have been brought to the shallow water platform interior (or margin) when the platform was submerged.

A major contribution of a complex variety of environmental factors is increasingly recognized to strongly influence the skeletal composition of Recent and fossil carbonate systems. These parameters include, among others: temperature, light availability, nutrient supply, and the chemistry of seawater (e.g., Caranante et al., 1988; Mutti and Hallock, 2003; Pomar et al., 2004; Pomar and Hallock, 2008; Westphal et al., 2010). Some correlation is observed in the lower Stuores section (*regoledanus* and *canadensis* ammonoid biozones) between carbonate grain associations and the amount of coarse (sand-size) siliciclastic grains. More specifically, ooids are more abundant when the siliciclastic input is higher, while the amount of microbial carbonates decreases. Also in the upper (*aon* biozone) part of the section, abundant ooids are always associated with some siliciclastic sand (Table 1). These variations of the proportion of ooids and skeletal grains seem thus to be related not only to sea-level change, as suggested by Rejmer (1998), but also to siliciclastic input and possibly associated nutrient supply and/or changing water turbidity.

The intermittent supply of coarse siliciclastics may have modified the type of carbonate production on the lower Carnian platforms of the Dolomites, but did not determine a significant production crisis. The lower Carnian high-relief platforms are known to have grown undisturbed throughout the time of deposition of the Stuores section, up to the top of the *aon* ammonoid subzone at least (e.g., Bosellini, 1984; Cassian Dm. 1 in De Zanche et al., 1993; Gianolla et al., 1998).

5. Conclusions

Platform-derived grains in the calciturbidites of Stuores contain a significant proportion of microbialites, up to 80-90% of total carbonate grains. Part of these carbonates, and specifically those associated with ooids and shallow-water biota, and calcimicrobes of cyanobacterial origin, were derived from the platform top or at least from the photic zone; however, the majority of microbial carbonates (including *Tubiphytes* and intraclasts with clotted peloidal fabric) lack clear evidence of an origin within the photic zone and might be derived from intermediate-deep portions of the platform slopes.

Despite their bright fluorescence, ooid coatings are interpreted as chiefly abiotic precipitates. Ooids are often associated with coarse terrigenous influx, and

Sample	Microbial carbonate	Ooids and skeletal	Microbial carbonate, peloids excluded	Total points (N)	Points, carbonate grains only	Points, peloids excluded
U18B	84.7	15.3	84.6	492	385	382
U18A	82.4	17.6	80.4	562	471	424
U16	26.3	73.7	23.2	688	575	552
U15	80.5	19.5	78.7	575	488	445
U12	18.5	81.5	8.5	520	438	390
U10B	86.9	13.1	81.3	548	411	288
U10	81.5	18.5	79.1	499	373	330
U09B	83.1	16.9	81.9	530	427	397
U09	89.6	10.4	88.8	526	384	358
U05	76.8	23.2	73.9	645	500	445
U04	44.1	55.9	39.0	628	458	420
Did 14b	63.3	36.7	57.4	520	362	312
Did 13	50.5	49.5	47.2	532	394	369
Did 12	33.1	66.9	24.4	603	269	238
Did 11	75.4	24.6	75.1	515	403	398
Did 10	59.6	40.4	58.7	631	356	349
Did 9a	81.7	18.3	80.8	490	322	307
Did 8	10.6	89.4	3.3	437	132	122
Did 7	76.8	23.2	73.4	564	366	320
Did 6a	39.6	60.4	32.1	572	182	162
Did 5	73.1	26.9	71.0	522	361	335
Did 4	29.0	71.0	26.3	408	193	186

Table 2:

Proportion of microbial VS ooid-skeletal carbonate grains. Bold numbers in percent. Cement, matrix and non-carbonate grains are excluded. Note that the proportion of microbial carbonate does not change significantly if peloids are excluded from the estimate.

contain siliciclastic grains as their nuclei. This implies that the carbonate platforms adjacent to Stuores were most probably attached to a hinterland which was eroded, and that coarse siliciclastics were encroaching the carbonate shelves not only during sea level falls and lowstands, but also when the platform was submerged. Terrigenous input does not seem to have negatively influenced carbonate production. Along with sea level changes, the supply of coarse siliciclastics, and perhaps some associated environmental changes as a modified supply of nutrients, contributed to determine the skeletal associations at Stuores.

The fine-grained carbonates of Stuores are composed of microsparite and contain calcispheres, implying a pelagic contribution to the net carbonate budget that is, however, still minimal.

6. Acknowledgements

This paper was written as a follow-up of my last scientific discussion with Lorenz Keim, which took place at Stuores in August 2011 and was a pleasant and stimulating episode. It is very unfortunate there will be no more. John Rejimer was also there in the field and greatly contributed to that discussion. Max Urlichs kindly indicated the stratigraphic position of his fossiliferous beds right on the spot. Evelyn Kustatscher organized the meeting where such discussion took place, and was involved on most of the episodes that made me meet with Lorenz Keim. Petra Witte (Bremen University) helped with the SEM study. Comments by Jörn Peckmann and Karl Krainer significantly improved the manuscript. Research was funded by the Alexander von Humboldt Foundation.

References

- Bellanca, A., Di Stefano, E., Di Stefano, P., Erba, E., Neri, R., Pirini Radrizzani, C. (1993): Ritrovamento di "Calcisfere" e nanofossili calcarei in terreni carnici della Sicilia. – *Paleopelagos*, 3: 91–96
- Blendinger, W. (1994): The carbonate factory of Middle Triassic buildups in the Dolomites, Italy – a quantitative analysis. – *Sedimentology* 41 :1147–1159.
- Bosellini, A. (1984): Progradation geometries of carbonate platforms: examples from the Triassic of the Dolomites, Northern Italy. – *Sedimentology*, 31: 1–24
- Bolli, H.M. (1974): Jurassic and Cretaceous Calcisphaerulidae from DSDP leg 27, Eastern Indian
- Breda, A., Preto, N. (2011): Anatomy of an Upper Triassic continental to marginal-marine system: the mixed siliciclastic-carbonate Travenanzes Formation (Dolomites, Northern Italy). – *Sedimentology*, 58: 1613–1647
- Broglio Loriga, C., Cirilli, S., De Zanche, V., di Bari, D., Gianolla, P., Laghi, M.F., Lowrie, W., Manfrin, S., Mastandrea, A., Mietto, P., Muttoni, C., Neri, C., Posenato, C., Rechichi, M.C., Rettori, R., Roghi, G. (1999): The Prati di Stuares/Stuares Wiesen Section (Dolomites, Italy): a candidate Global Stratotype Section and Point for the base of the Carnian stage. – *Riv. Ital. Paleont. Strat.*, 105: 37–78
- Brusca, C., Gaetani, M., Jadoul, F., Viel, G. (1982): Paleogeografia ladinico-carnica e metallogenese del Sudalpino. – *Soc. Geol. Ital. Mem.*, 22: 65–82
- Burne, R.V., Moore, L.S. (1987): Microbialites; organosedimentary deposits of benthic microbial communities. – *Palaios*, 2: 241–254
- Carannante, G., Esteban, M., Milliman, J.D., Simone, L. (1988): Carbonate lithofacies as paleolatitude indicators: problems and limitations. – *Sed. Geol.*, 60: 333–346
- Davies, P.J., Bubela, B., Ferguson, J., (1978): The formation of ooids. – *Sedimentology*, 25: 703–729
- De Zanche, V., Gianolla, P., Mietto, P., Siorpaes, C., Vail, P.R. (1993): Triassic sequence stratigraphy in the Dolomites (Italy). – *Mem. Sci. Geol.*, 45: 1–27
- Di Nocera, S., Scandone, P. (1977): Triassic nannoplankton limestones of deep basin origin in the central mediterranean region. *Palaeogeogr. Palaeoclimat. Palaeoecol.*, 21: 101–111
- Dravies, J.J., Yurewicz, D.A. (1985): Enhanced carbonate petrography using fluorescence microscopy. – *J. Sediment. Petrol.*, 55: 795–804
- Duguid, S.M.A., Kyser, T.K., James, N.P., Rankey, E.C. (2010): Microbes and ooids. – *J. Sediment. Res.*, 80: 236–251
- Flügel, E., (2004): Microfacies of carbonate rocks. Analysis, interpretation and application. – Springer, Berlin Heidelberg New York, pp. 1–976
- Folk, R.L., Lynch, F.L. (2001): Organic matter, putative nanobacteria and the formation of ooids and hardgrounds. – *Sedimentology*, 48: 215–229
- Fürsich, F.T., Wendt, J. (1977): Biostratigraphy and palaeoecology of the Cassian Formation (Triassic) of the Southern Alps. – *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 22: 257–323
- Gianolla, P., De Zanche, V. and Mietto, P. (1998): Triassic sequence stratigraphy in the Southern Alps (northern Italy): definition of sequences and basin evolution. – In: de Graciansky, P.-C., Hardenbol, J., Jacquin, T. & Vail, P.R. (eds.), *Mesozoic and Cenozoic sequence stratigraphy of European basins*, SEPM Spec. Publ., 60: 719–747
- Gianolla, P., Stefani, M., Caggiati, M., Preto, N. (2011): Triassic platform and basinal bodies of the Dolomites as outcrop analogues for hydrocarbon carbonate systems. – Field trip excursion guidebook, AAPG International Conference and Exhibition, October 19–22, Milan, 84 pp.
- Keim, L., Schlager, W. (1999): Automicrite facies on steep slopes (Triassic, Dolomites, Italy). – *Facies*, 41: 15–25.
- Keim, L., Schlager, W. (2001): Quantitative compositional analysis of a Triassic carbonate platform (Southern Alps, Italy). – *Sediment. Geol.*, 139: 261–283
- Kenter, J.A.M., Harris, P.M., Della Porta, G. (2005): Steep microbial boundstone-dominated platform margins – examples and implications. *Sediment. Geol.*, 178: 5–30
- Leonardi, P. (1967): *Le Dolomiti. Geologia dei monti tra Isarco e Piave. Volume 1. Consiglio Nazionale delle Ricerche, Roma, 552 pp.*
- Machel, H.G., Mason, R.A., Mariano, A.N., Mucci, A. (1991): Causes and emission of luminescence in calcite and dolomite. – In: Barker, C.E., Kopp, O.C. (eds.): *Luminescence microscopy and spectroscopy: qualitative and quantitative applications*. – *Soc. Econ. Paleont. Miner. Short Course*, 25: 9–25, Tulsa
- Marangon, A., Gattolin, G., Della Porta, G., Preto, N. (2011) – The Latemar: a flat topped, steep fronted platform dominated by microbialites and syndimentary cements. *Sediment. Geol.*, 240: 97–114

- Mietto, P., Andretta, R., Broglio Loriga, C., Buratti, N., Cirilli, S., De Zanche, V., Furin, S., Gianolla, P., Manfrin, S., Muttoni, G., Neri, C., Nicora, A., Posenato, R., Preto, N., Rigo, M., Roghi, G., Spötl, C. (2007): A candidate of the Global Boundary Stratotype Section and Point for the base of the Carnian Stage (Upper Triassic): GSSP at the base of the canadensis Subzone (FAD of Daxatina) in the Prati di Stuores/Stuores Wiesen section (Southern Alps, NE Italy). - *Albertiana*, 36: 78-97
- Mietto, P., Manfrin, S., Preto, N., Gianolla, P. (2008): Selected ammonoid fauna from Prati Di Stuores/Stuores Wiesen and related sections across the Ladinian-Carnian boundary (Southern Alps, NE Italy). *Riv. Ital. Paleont. Strat.*, 114: 377-429
- Mietto, P., Manfrin, S., Preto, N., Rigo, M., Roghi, G., Gianolla, P., Posenato, R., Muttoni, G., Nicora, A., Buratti, N., Cirilli, S., Spötl, C. (2012): The Global Boundary Stratotype Section and Point (GSSP) of the Carnian stage (Late Triassic) at Prati di Stuores/Stuores Wiesen section (Southern Alps, NE Italy). - *Episodes*, 35: 414-430
- Mitterer, R.M. (1972): Biogeochemistry of aragonite mud and oolites. - *Geochim Cosmochim Acta*, 36: 1407-1422
- Munnecke, A. (1997): Bildung mikritischer Kalke im Silur auf Gotland. *Cour Forschungsinstitut Senckenberg*, 198: 1-71
- Münster, G., von (1834): Über das Kalkmergel-Lager von St. Cassian in Tyrol und die darin vorkommenden Ceratiten. - *N. Jb. Miner. Geogn. Geol. Petrefactenk.*, 1834: 1-15
- Mutti, M., Hallock, P. (2003): Carbonate systems along nutrient and temperature gradients: some sedimentological and geochemical constraints. - *Int. J. Earth Sci.*, 92: 465-475
- Neri, C., Russo, F., Mastandrea, A., Baracca, A. (1995): Litostratigrafia, ammonoidi e conodonti della Formazione di San Cassiano: la sezione dei Prati di Stuores (Stuores-Wiesen, Dolomiti). *Ann. Univ. Ferrara, Sci. Terra*, 5(suppl.): 59-74
- Neri, C., Gianolla, P., Furlanis, S., Caputo, R., Bosellini, A. (2007): Carta Geologica d'Italia alla scala 1:50000, foglio 029 Cortina d'Ampezzo, e Note illustrative. APAT, Roma, 200 pp.
- Neuweiler, F., Reitner, J. (1995): Epifluorescence-microscopy of selected automicrites from lower Carnian Cipit-boulders of the Cassian formation (Seeland Alpe, Dolomites). - *Facies*, 32: 26-28
- Ogilvie, M.M. (1893): Contributions to the Geology of the Wengen and St. Cassian Strata in Southern Tyrol. *Quart. J. Geol. Soc.*, 49: 1-78
- Pomar, L., Hallock, P. (2008): Carbonate factories, A conundrum in sedimentary geology. - *Earth-Sci. Rev.*, 87: 134-169.
- Pomar, L., Brandano, M., Westphal, H. (2004): Environmental factors influencing skeletal grain sediment associations: a critical review of Miocene examples from the western Mediterranean. *Sedimentology*, 51: 627-651
- Preto, N., Rigo, M., Agnini, C., Bertinelli, A., Guaiumi, C., Borello, S., Westphal, H. (2012): Triassic and Jurassic calcareous nanofossils of the Pizzo Mondello section: a SEM study. - *Riv. Ital. Paleont. Strat.*, 118: 131-141
- Preto, N., Willems, H., Guaiumi, C., Westphal, H. (2013): Onset of significant pelagic carbonate accumulation (calcareous dinocysts?) after the Carnian Pluvial Event (CPE) in Western Tethys. - *Facies*, DOI 10.1007/s10347-012-0338-9
- Reijmer, J.J.G. (1998): Compositional variations during phases of progradation and retrogradation of a Triassic carbonate platform (Picco di Vallandro/Durrenstein, Dolomites, Italy). - *Geol. Rundsch.*, 87: 436-448
- Reijmer, J.J.G., Everaars, J.S.L. (1991): Carbonate platform facies reflected in carbonate basin facies (Triassic, northern Calcareous Alps). - *Facies*, 25: 253-278
- Richtofen, F. von (1860): Geognostische Beschreibung der Umgegend von Predazzo, St. Cassian und der Seiser Alpe in Südtirol. - 327 p., Gotha
- Russo, F., Neri, C., Mastandrea, A., Laghi, G. (1991): Depositional and diagenetic history of the Alpe di Specie (Seelandalpe) fauna (Carnian, Northeastern Dolomites). - *Facies*, 25: 187-210.
- Russo, F., Neri, C., Mastandrea, A., Baracca, A. (1997): The mud mound nature of the Cassian platform margins of the Dolomites. A case history: the Cipit boulders from Punta Grohmann (Sasso Piatto Mas-sif, Northern Italy). - *Facies*, 36: 25-36
- Schlager, W. (2003): Benthic carbonate factories of the Phanerozoic. *Int. J. Earth. Sci.*, 92: 445-464
- Scudeler Baccelle, L. (1971): La serie ladino-carnica alla base della Punta Grohmann (Gruppo del Sasso Lungo, Dolomiti occidentali): strutture sedimentarie e petrologia della facies carbonatica. - *Mem. Geopaleont. Univ. Ferrara*, 3/2: 19-35

- Senowbari-Daryan, B., Flügel, E. (1993): *Tubiphytes* Maslov, an Enigmatic Fossil: Classification, Fossil Record and Significance through Time. Part I: Discussion of Late Paleozoic Material. – In: Barattolo, F., De Castro, P., Parente, M. (eds.): Studies on Fossil Benthic Algae. – Boll. Soc. Paleont. Ital. Special Vol., 1: 253–382
- Senowbari-Daryan, B., Bucur, I.I., Schlagintweit, F., Săsăran, E., Matyszkiewicz, J. (2008): *Crescentiella*, a new name for "*Tubiphytes*" *morronensis* Crescenti, 1969: an enigmatic Jurassic – Cretaceous microfossil. *Geol. Croatica*, 61: 185–214.
- Simone, L. (1981): Ooids: a review. – *Earth-Sci. Rev.*, 16: 319–355
- Urlichs, M. (1974): Zur Stratigraphie und Ammonitenfauna der Cassianer Schichten von Cassian (Dolomiten/Italien). – *Schrift. Erdwiss. Komm. Österr. Ak. Wiss.*, 2: 207–222.
- Urlichs, M. (1994): *Trachyceras* Laube 1869 (ammonoidea) aus dem Unterkarn (Obertrias) der Dolomiten (Italien). *Stuttgarter Beitr. Naturk. B*, 217: 1–55
- Urlichs, M. (2011): Stunting in invertebrates from the type area of the Cassian Formation (Early Carnian) of the Dolomites (Italy). – *GeoAlp*, 8: 164–169
- Van der Plas, L., Tobi, A.C. (1965): A chart for judging the reliability of point counting results. – *Am. J. Sci.*, 263: 87–90
- Wendt, J. (1982): The Cassian patch reefs (lower Carnian, Southern Alps). – *Facies*, 6: 185–202
- Westphal, H., Halfar, J., Freiwald, A. (2010): Heterozoan carbonates in subtropical settings in the present and past. – *Int. J. Earth Sci.*, 99: S153–S169

Manuscript submitted: 10.9.2012

Revised manuscript accepted: 18.1.2013