Geo.Alp, Vol. 8, S. 56–75, 2011

FACIES ANALYSIS, GEOMETRY AND ARCHITECTURE OF A CARNIAN CARBONATE PLATFORM: THE SETTSASS/RICHTHOFEN REEF SYSTEM (DOLOMITES, SOUTHERN ALPS, NORTHERN ITALY)

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with 22 Figures

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ABSTRACT

The Settsass/Richthofen Reef carbonate platform system, together with the other central-western Dolomites post-volcanic carbonate complexes, forms the palaeogeographic scenario of the Lower Carnian. These Lower Carnian platforms were dwelled by coral patch-reefs and sponge mounds separated by small lagoons characterized by muddy sedimentation. The Settsass/Richthofen Reef is a small platform system (3-4 km^2 in plain view and about 150 m thick) and is characterized by two superimposed carbonate complexes (DC 1 and DC 2) showing different geometric features:

a) the lower complex, known as the Richthofen Reef (DC 1), shows a plane-convex geometry where the core is constituted by coral patch-reefs and sponge bodies, while the lateral portion is represented by the slope sediments interfingering with the basinal deposits (San Cassiano Formation);

b) the upper complex, the proper Settsass relief (DC 2), shows a tabular geometry and/or some thickening basinward. This upper complex covers a variety of depositional settings, from inner platform deposits (back-reef) at the southwestern side, to slope deposits at the southeastern side. Its slope deposits are formed by clinostratified breccias with slope angles ranging from 20° - 25° in the proximal area, to 10° - 15° more distally. The Settsass platform complex shows a basinward progradation (NE direction) which can be traced in outcrops for almost 2 km.

Keywords: Carbonate platforms, Cassian Dolomite, Sponges and Coral-reefs, clinoforms, progradation, Triassic, Dolomites Region, Southern Alps,

Introduction

The Dolomites are physiographically located in the eastern part of the Southern Alps and form a fold and thrust belt (one of the major structural units of the Alpine Chain). They are constituted by a large (several tens of km) pop-up synclinorium of Neogene age which is well confined within the Southern Alps domain (Castellarin, 1979; Doglioni & Castellarin, 1985; Doglioni & Bosellini, 1987; Schönborn, 1999). They are characterized by a slightly deformed sequence of sedimentary and volcanic rocks, offset southwards during the Alpine collision as a very coherent upper crust slab.

As a region which was only weakly deformed during the Alpine orogenic phases the Dolomites represent unique geologic outcrops and display many well preserved types of carbonate platform-slope-basin systems which have been objects of detailed geological studies in the last decades.

In particular, the Dolomites are well known for their spectacularly exposed Middle-Late Triassic progradational carbonate platforms, which have been studied in great detail in terms of geometries (Leonardi, 1968; Bosellini & Rossi, 1974; Bosellini, 1984; Kenter, 1990; Keim & Schlager, 2001; Keim et al.,

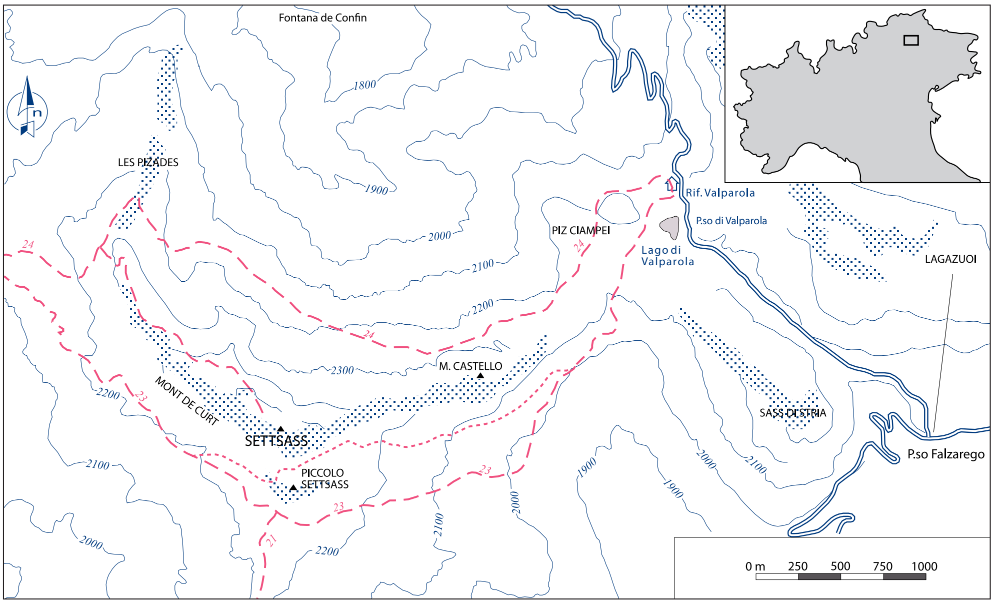

Fig. 1: Topographic map showing the study area and the main outcrop areas (stop points). The Settsass outcrops between the Valparola Pass and the Badia Valley.

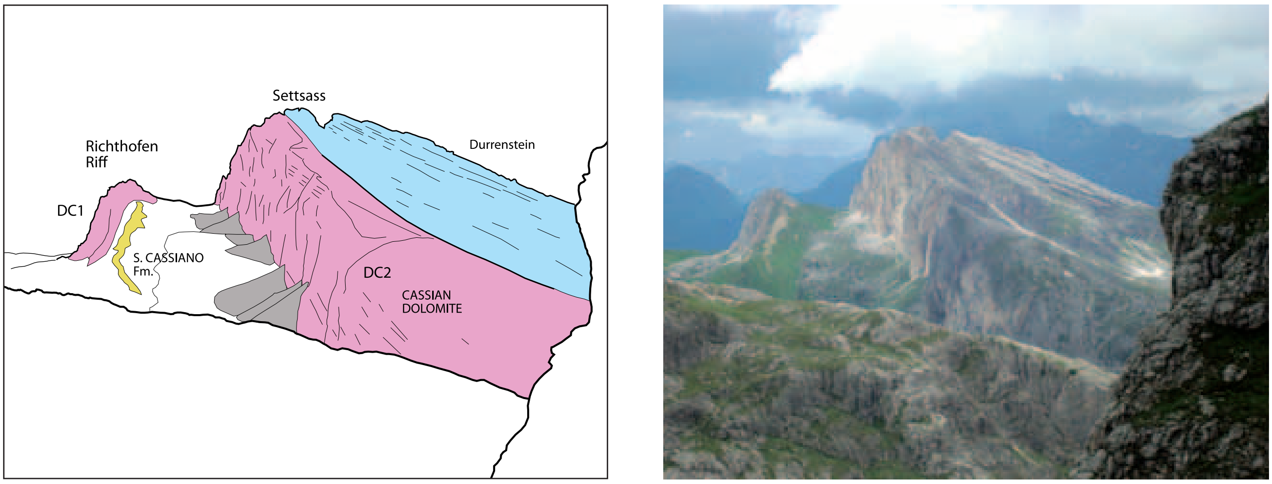

Fig. 2: Panoramic view of the Settsass from the Lagazuoi cableway. Note, from left to right, the Richthofen Reef relief, the San Cassiano Formation, the Settsass platform and the onlap relationships of the Heiligkreuz Formation. In the foreground, the slope scarp of the Cassian Dolomite of Sass di Stria is visible.

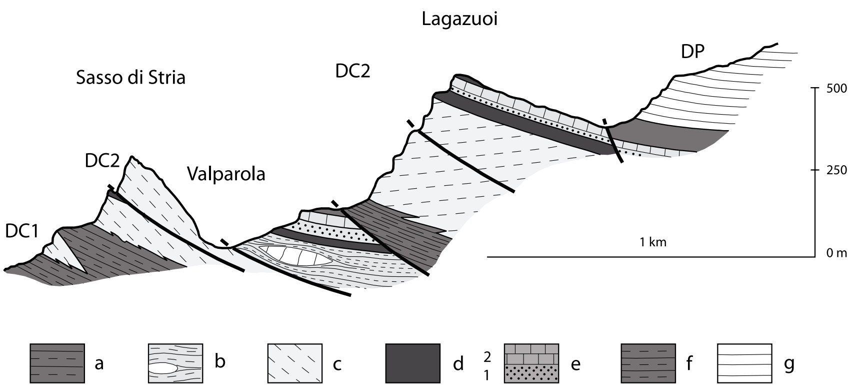

Fig. 3: Cross-section through the Sass di Stria and the Lagazuoi. Note the opposite progradation direction of the Cassian Dolomite of Lagazuoi and the Sass di Stria – Settsass carbonate platform. a) San Cassiano Formation; b) shallow-water deposits of the San Cassiano Fm; c) Cassian Dolomite; d) Heiligkreuz Formation ; e) Dibona sandstone, (1) lower member of marls, calcarenites and sandstones; (2) upper carbonate beds; f) Travenanzes Fm; g) Dolomia Principale (redrawn after Bosellini et al., 1982).

2001) and facies (Gaetani et al., 1981; Brandner et al., 1991a, b; Harris, 1993; Russo et al., 1997).

The growth and the development of the various carbonate edificies in the Dolomites region was mainly controlled by carbonate bioconstructors forming coral patch-reefs and sponge mounds, whose framework was stabilized by diverse types of binding communities, such as blue-green algae, spongiostromata, *Tubiphytes* and biogenic crusts related to different encrusting organisms (Biddle, 1980; Gaetani et al., 1981; Brandner et al., 1991). Subsequently other authors have described the occurrence of various biotic micritic crusts, microproblematica and syndepositional cements to support the stabilization of the bioconstructed framework (Harris, 1993); in other cases, the slope sediments have been regarded as in situ boundstones primarily composed of micritic crusts, early cements and various microproblematic organisms (Blendinger, 1994). Recently, the importance of automicrite (i.e. autochthonous micrite, as originally described by Wolf, 1965) has been used to explain the stabilization of the platform margin and the upper slope (Keim & Schlager, 2001).

The various carbonate edifices of the Dolomites have been divided into three groups according to their age:

a) The pre-volcanic carbonate edifices (Sciliar Dolomite of Lower Ladinian age) developed from the previous topographic highs of the sedimentary substrate (Masetti & Trombetta, 1998) during a relative rise of the sea-level. These edifices show progradational and aggradational geometrical features with limited amount of deposits transported into the basins, which were then evolving under deepening-upward conditions. The final geometry of this platform type displays an almost tabular architecture (often over 1000 meter thick) like the Catinaccio/Rosengarten platform (Bosellini, 1984; Bosellini & Stefani, 1991; Maurer, 1999, 2000).

b) The post-volcanic carbonate edifices (Cassian Dolomite of Lower Carnian age) developed during a relative sea-level still-stand. The carbonate platforms show marked progradation features; this platform-type was characterized by abundant resedimented deposits infilling the adjacent basins. In this respect, the basins display a shallowing-upward trend marked by a thinning outward geometry of the platforms (such as the climbing clinoforms of the Carnian Sella Platform, e.g. in Bosellini, 1984).

c) The pre-Cassian Dolomite carbonate platforms (= SD II, or "Rosszähne Fm." - Fm. di Denti di Terrarossa; Brandner, 1991; Brandner et al., 2007; Geologische Karte der Westlichen Dolomiten 1:25.000, 2007; Gianolla et al., 2010) whose slope deposits interfinger with volcaniclastic deposits (Wengen Fm and/or Marmolada Conglomerates); these edifices were characterized by huge volumes of megabreccia with typical blocks derived from the platform margin (like the Cipit boulders).

This paper summarizes the preliminary results of a study addressing the geometry and architecture of the carbonate platforms in the Richthofen/Settsass system, and is part of a larger and detailed research focusing on the petrography, sedimentology and stratigraphy of this peculiar post-volcanic carbonate platform system.

Geological setting of the Settsass

The Mt. Settsass is located in the surrondings of the Falzarego Pass, SW of the Valparola Pass at the head of the Badia Valley, one of the geologically most famous sectors in the Dolomites (Fig. 1). This area is crossed by an important tectonic structure known as the Passo Falzarego Line (Bosellini & Semenza, in Leonardi, 1968), a wide overthrust of E-W direction and northward dip (Fig. 2) which overimposed the northern Lagazuoi–Tofane system on top of the southern block (Cinque Torri, Nuvolau, Averau, Col Gallina, Stria Sass and the Settsass). Due to the structural setting of the footwall, the Settsass is actually a homoclinal dipping block of N-N10°E direction, with dip angles of about 35° - 40°. The subject of this study is the Settsass/"Richthofen Riff" (Fig. 1), an isolated carbonate platform of Carnian age (3 - 4 km^2 in plain view and about 150 m thick), located between the Falzarego Pass and the Badia Valley (Fig. 3). The formation is here called "Cassian Dolomite" (Bosellini, 1984; Bosellini and Neri, 1991). In the entire region of the Dolomites the Carnian paleogeography was characterized by carbonate platforms prograding across the relatively shallow basins (Bosellini & Neri, 1991). In the selected study area, the clinoform heights and the dip slope angles represent important geometric proxies which allow to estimate the maximum Cassian basin paleodepth in this area to be about 80 - 100 meters. At the Settsass/"Richthofen Reef" the clinostratification shows NE progradation and interfingering with basinal sediments of the Cassian Formation. The entire platform shows pervasive dolomitization and this has discouraged detailed facies studies up till now. Intensive downslope transport is indicated by debris aprons at the toe of the clinoforms formed by debris-flow breccias, swarms of metre-size boulders and turbidites. In contrast to the huge breccia volumes of the clinoforms, the inner-platform and back-reef deposits, located at the southwest side of the Settsass, are poorly preserved because they were largely eroded. Therefore the history of the platform interior cannot be conclusively addressed.

Post-volcanic palaeogeography

At the Ladianian-Carnian boundary, about 236 Ma (Mundil et al., 2010), a regional sea level fall of several tens of meters triggered subaerial exposure leading to erosion and dismantling of huge amounts of volcanic and volcaniclastic deposits and of karstified flanks of the pre-volcanic platforms (Biddle, 1984; Haq et al., 1987).

From these topographic highs, which included relict volcanic reliefs, two new generations of carbonate platforms developed: the first edifices were pre-Cassian platforms (Upper Ladinian age) because their slope deposits interfingered with the Marmolada Conglomerate (see Schlern/Seiser Alm system; Brandner, 1991; Brandner et al., 1991; Punta Grohmann/Sasso Piatto; Russo et al., 1997; Col Rossi and Crepe Rosse/Mt. Padon; Bosellini et al., 1977) the so-called Cassian platforms. The subsequent generation of carbonate platforms (Cassian Dolomite of Lower Carnian age) developed under conditions of sea-level still-stand and, as a result, they are characterized by relatively thin, even-bedded platform-top facies and consist mainly of clinostratified coarse slope debris.

The palaeogeographic scenario of the Lower Carnian platforms is similar to the previous Lower Ladinian and is characterized by the following carbonate main edifices (illustrated in details in Fig. 4, redrawn after Bosellini, 1996):

- Pale di S. Martino/Civetta, a northward prograding carbonate platform;
- Sass Beccè, a small clinostratified megabreccia body prograding northward, connected with a wider Carnian platform that probably covered the whole Marmolada area (now completely dismantled);
- Sassolungo and Sassopiatto reliefs: the first one formed by the southward and westward clinostratified megabreccia slope; the second one corresponding to a spectacular submarine escarpment;
- Gardenaccia, a subrounded carbonate platform which outgrew from the Ladinian flank of the Odle Group and prograded outward;
- Sella, an almost subcircular atoll, radially prograding outward;
- Settsass/Nuvolau, examples of small northestward prograding platforms;
- Lagazuoi, a Carnian platform whose northern and eastern terminations are probably respectively overlain by the La Varella and the Tofana di Rozes mountain group;
- Picco di Vallandro/Monte Piana/Cadini di Misurina group, forming a wide southward and westward prograding platform which started from the Ladinian platform of the Dolomiti di Sesto.

Several Cassian Platforms consist of two or more superimposed carbonate edifices, showing the same direction of progradation and being nucleated on the same pre-existing topographic high. This has suggested that subsequent pulses of platform growth and demise took place during the development of the Cassian platforms. The various episodes of progradation and retreat of the overimposed platforms may be recognizable only basinward, where two or three platform progradational tongues are separated by wedges of basinal deposits (S. Cassiano Formation), thinning out until vanishing towards the central area of the carbonate buildup.

Post-volcanic stratigraphy

The post-volcanic basins of the Dolomites are characterized by an overall shallowing-upward trend, due to the combined effect of low subsidence rate, relative sea-level still-stand and high sediment supply from the adjacent carbonate platforms. Moreover, the lateral progradation of the carbonate platforms progressively reduced their extension. The result was the almost complete infilling of these intervening basins, an event that, most probably, was not synchronous over the whole area of the Dolomites (Bizzarrini et al., 1989, Mastandrea et al., 1997; Mietto & Manfrin, 1995; Neri et al., 1994; Russo et al., 1997).

The stratigraphic interval which is exposed at the Mt. Settsass and has been the subject of this study is mainly characterized by the Cassian Dolomite

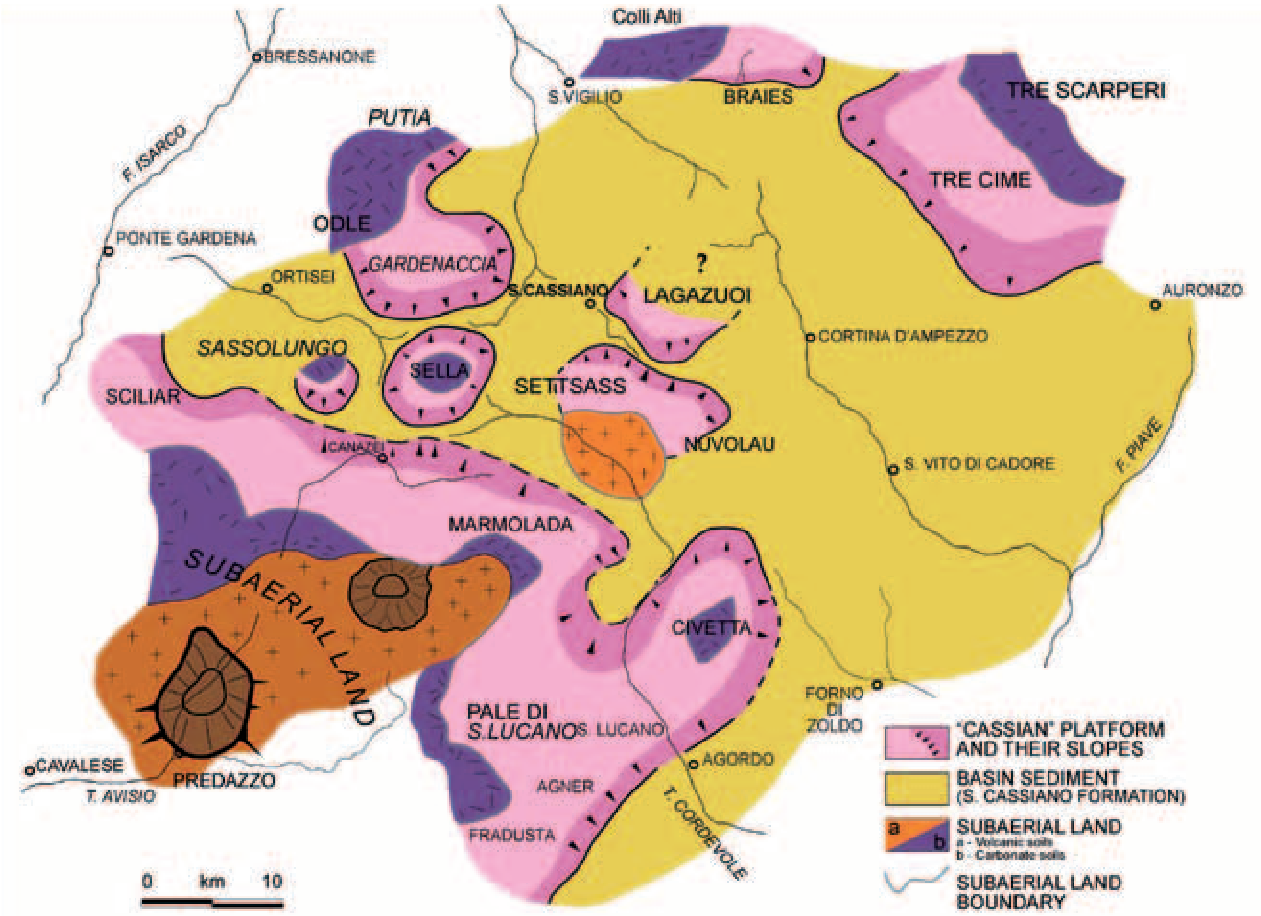

Fig. 4: Palaeogeographic map representing schematically the distribution of post-volcanic Triassic carbonate platforms of the Dolomites region and the spatial relationships with the Predazzo and the Monzoni volcanic edificies (redrawn after Bosellini, 1996).

and, marginally, by the San Cassiano Formation. At the base of Mt. Settsass the volcanoclastic deposits of the Wengen Formation and Marmolada Conglomerate are exposed, while the upper part is marked by the terrigenous-carbonate deposits of the Heiligkreuz and Travenanzes Formations (Fig. 5).

From the base to the top, the stratigraphic units which have been described at the Mt. Settsass are: a) Wengen Formation; b) San Cassian Formation; c) Cassian Dolomite; d) Heiligkreuz Formation; e) Travenanzes Formation. In the ensuing section an overview of their characteristics and interpretations is presented.

a) Wengen Formation. This unit is characterized by volcanoclastic turbidites with a composition analogous to the heterotopic underlying Marmolada Conglomerate (i.e. trachy-andesitic and andesitic) (Rossi et al., 1977; Sacerdoti & Sommavilla, 1962; Viel, 1979). The Marmolada Conglomerate is interpreted as a sedimentary sequence formed by the dismantling the volcanic edifices within the Predazzo - Monzoni district, and by the subsequent discharge of large amounts of volcanoclastic sediments through high density turbidite flows (Bottoli & Trombetta, 1998).

The Wengen Formation is formed by a sequence of thin, black, normally graded sandstone layers, ranging from cm to dm in thickness, alternating with finely laminated black pelitic beds. This formation represents the most distal parts of the Marmolada Conglomerate widely outcropping south of Mt. Settsass in the surroundings of Mt. Padon. The transition between the Wengen Formation and the Marmolada Conglomerate is markedly heterotopic, and mostly controlled by proximal-to-distal factors in relation to the sediment source areas.

b) San Cassiano Formation. This unit is a cyclic succession of shales and marls alternating with micritic limestone and oolitic-bioclastic calcarenites (Fig. 6). The San Cassiano Fm shows a coarsening and thickening-upward arrangement which results from

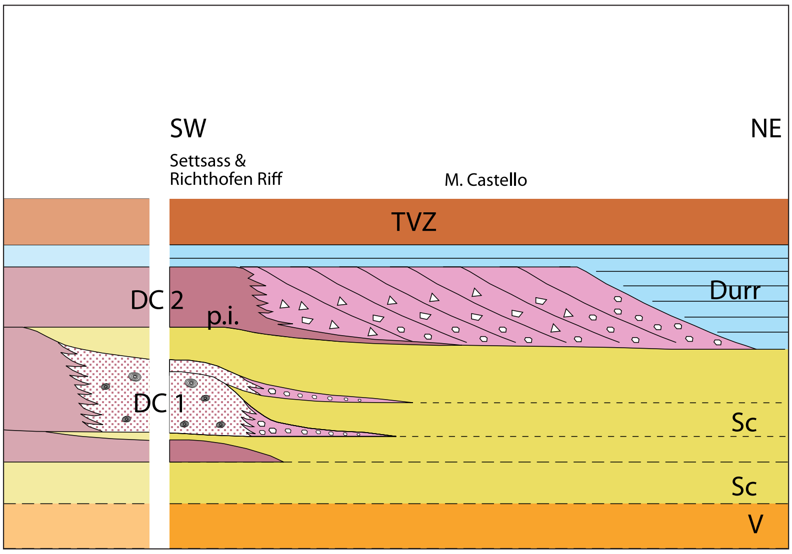

Fig. 5. Lithostratigraphic model showing various phases of carbonate platform growths and the lateral shifts of platform margin and slope facies: a) the first step is marked by a breccia platform base wedge (DC 1a), probably connected to the clinoform breccias derived from an older carbonate platform. These breccia deposits represent a first nucleus of a carbonate platform; b) the following step is characterized by the development of the second bioconstructed body (DC 1b) from the previous nucleus; c) the Richthofen Reef represents a topographic high surrounded by basinal deposits (San Cassiano Formation) and provides the development of the Settsass platform (DC 2) development. (V: Marmolada Conglomerate; Sc: San Cassiano Fm.; DC1: Cassian Dolomite 1; DC 2: Cassian Dolomite 2; HKS: Heiligkreuz Fm.; TVZ: Travenanzes Fm).

Fig. 6: Graded calcarenites derived from the platform areas from the lower portion of the San Cassiano Fm (outcrop at the base of the Richthofen Riff).

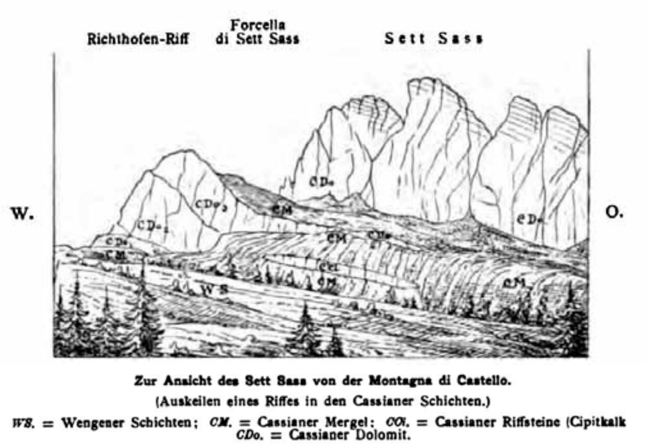

Fig. 7: Original sketch of the Richthofen Riff and Settsass relief drawn by Mojsisovics (1879).

Fig. 8: a) Shallow water carbonate platform deposits: subtidal cycles of Packstones and skeletal Grainstones. Note large gastropods, oncolites, oolites and algae.

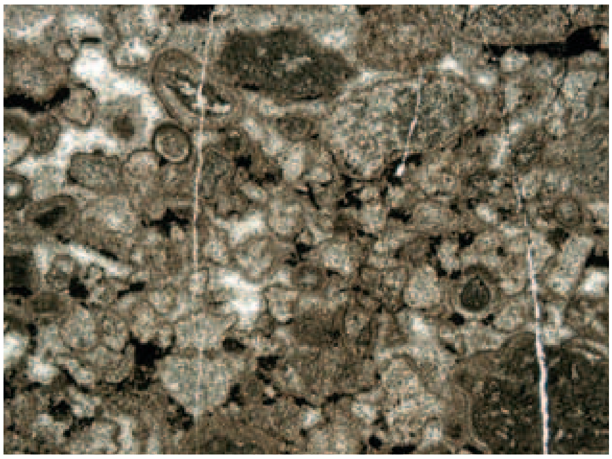

Fig. 8: b) Grainstone-Packstone with oolites and coated grains of the Dürrenstein Fm.

multi-meter thick cycles linked to the sediment supply derived from the platforms basinward, and driven by periodic sea-level change (Masetti et al., 1991).

This unit can be subdivided in two vertically stacked members. The lower member is dominated by volcanoclastic turbidites while the upper member is formed by a cyclic alternation of marls and micritic limestones, with less carbonate turbidites, and is characterized by a very rich and diverse fossil content (e.g. Fürsich & Wendt, 1977, Urlichs, 1994, Broglio Loriga et al., 1999,). The entire succession records a shallowing-upward evolution due to the basin infilling and the progradation of the Cassian platforms.

c) Cassian Dolomite. In the past decades the Falzarego Pass area has been the object of several studies which focused on the geometry and architecture of the Cassian Dolomite. This area shows evidence of two platforms convergently prograding over a basinal sequence recorded in the "Tra i Sass" stratigraphic section (Bosellini et al., 1982): the Lagazuoi platform in the north and the Nuvolau platform in the south with progradation directions respectively towards SSE and NE (Fig. 2).

In this palaeogeographic scenario the Settsass ridge is here interpreted as a platform isolated from the nearby Sasso di Stria platform (also located south of the Falzarego Line), but bearing the same progradation direction towards NE. These two platforms appear not tectonically displaced by faults and the Settsass clinoforms seem to prograde toward the inner platform deposits of the Sass di Stria platform. Based on these evidences, therefore, it seems difficult to consider the Settsass and the Sass di Stria as one single platform system. Both of these relatively small scale depositional systems are composed of two stacked platform carbonate sequences, subdivided by the San Cassiano Fm, which is here characterized by relatively shallow marine deposits, as testified by the occurrence of coral patch-reefs in growth position (Fig. 14)

At the Mt. Settsass two separate platforms can be distinguished: the Settsass strictu sensu (which constitutes the bulk of the ridge) and the Piccolo Settsass, also known in the literature as the Richthofen Riff (Fig. 7).

The Cassian Dolomite is here mainly composed of dolomitized slope breccias, often organized in clinostratified deposits, while the inner platform and platform margin deposits are outcropping only in limited parts of the studied field area. This recent geological field mapping campaign and the associated sedimentological studies have in fact allowed to describe the inner platform facies along the southwestern side of the Richtofen Reef, and distinguish them from the bioconstructional marginal facies of the already known Richthofen Reef.

d) Heiligkreuz Formation and Dürrenstein Dolomite.

This unit was introduced by Wissmann & Münster in 1841 and then described in detail by Koken (1913) and ascribed to the Upper Carnian. Later it was named "Strati di Santa Croce" (Bosellini et al., 1965a,b) and "Dürrenstein Formation ("sensu" De Zanche et al., 1993). In the last decades, the Heiligkreuz Formation was redefined (Keim et al., 2001; Stefani et al., 2004; Neri et al., 2007).

The Heiligkreuz Fm. is divided into three members (Neri et al., 2007) which testify the filling phases of the remaining Cassian basins and the crisis of the rimmed carbonate platforms.

The lower member (HKS 1) is made up of dolomitic limestone, arenaceous dolomite and well-stratified hybrid arenite with abundant pelitic intervals.

The overlying member (HKS 2) is composed of the Dibona Sandstone (Bosellini et al., 1982) formed by polymict conglomerate, cross-bedded sandstone, brown, gray or blackish pelites, with frequent oolitic-bioclastic packstone-grainstone beds.

These two members are not exposed at the Mt. Settsass; in fact only the upper member was deposited here: this is defined as HKS 3 (Lagazuoi member; Neri et al., 2007) and represents the levelling of the paleotopography in this area with the subsequent re-establishment of the carbonate platform growth conditions.

This upper member (HKS 3) consists of a cyclic succession of dolomitized shallow water platform carbonates which conformably overlie the Cassian Dolomite. This inner platform succession is arranged in meter-thick peritidal cycles (Fig. 8), formed by the repeated vertical stacking of subtidal deposits and tepee lithofacies ultimately capped by subaerial exposure surfaces (Hardie et al., 1986; Claps, 1996 in Bosellini, Neri & Stefani, 1996).

The Dürrenstein Dolomite crops out in the uppermost part of the Settsass ridge but yields only a limited thickness due to the dip of the homocline.

The subtidal lithofacies is constituted of replacive microcrystalline dolomite forming massive layers, ranging from a few tens of cm to about one meter in

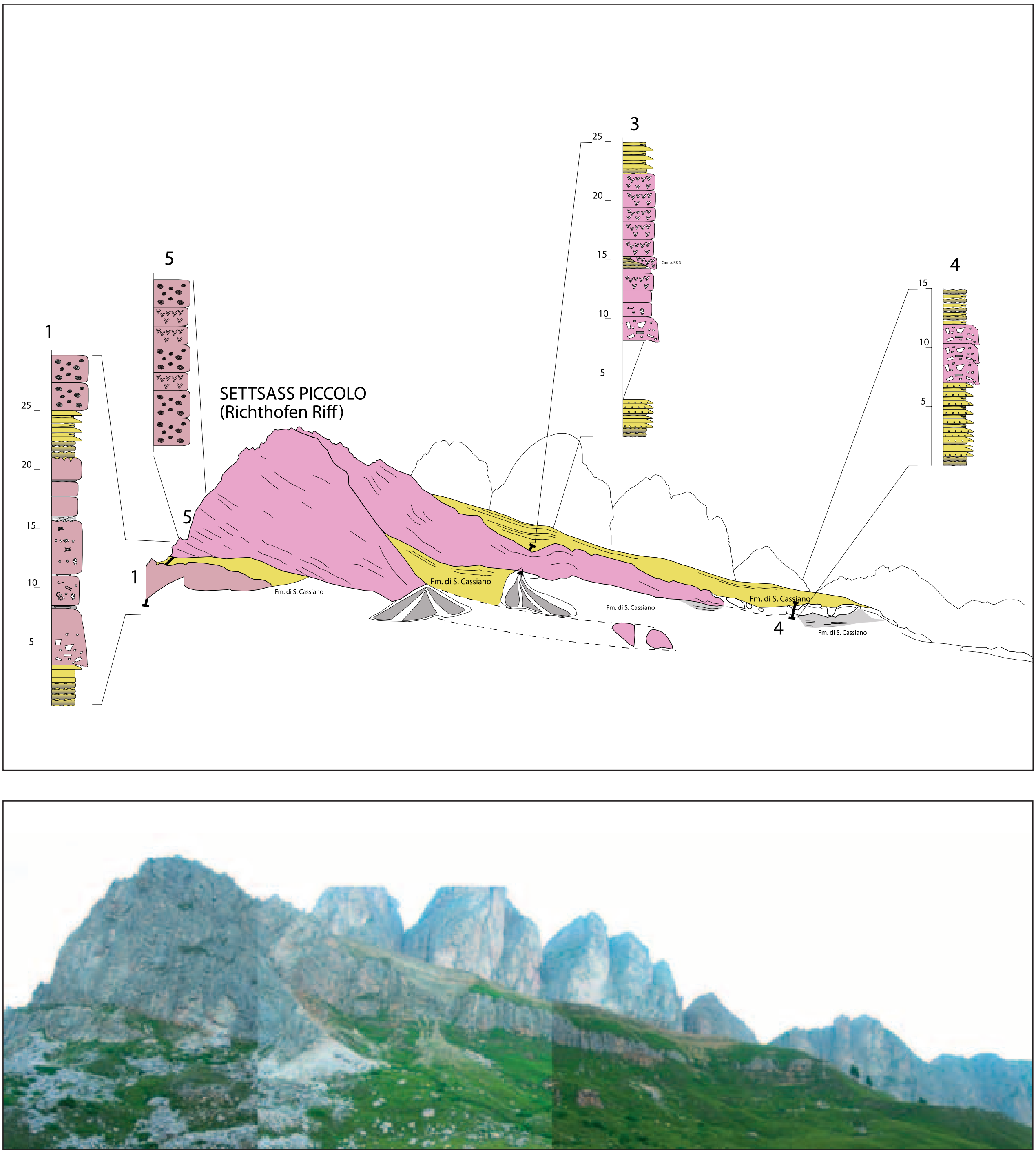

Fig. 9: The "Richthofen Reef" (Cassian Dolomite 1) is subdivided into three carbonate units. The lower unit starts with reworked breccias deposits. The second unit represents a reefal complex with sponges, corals and microbialitic mats, laterally interfingering with the basinal deposits of the San Cassiano Fm. The upper unit is a thrust wedge and represents the margin/slope deposits of the underlying unit, which is dominated by coral and sponge bioherms.

RICHTHOFEN RIFF

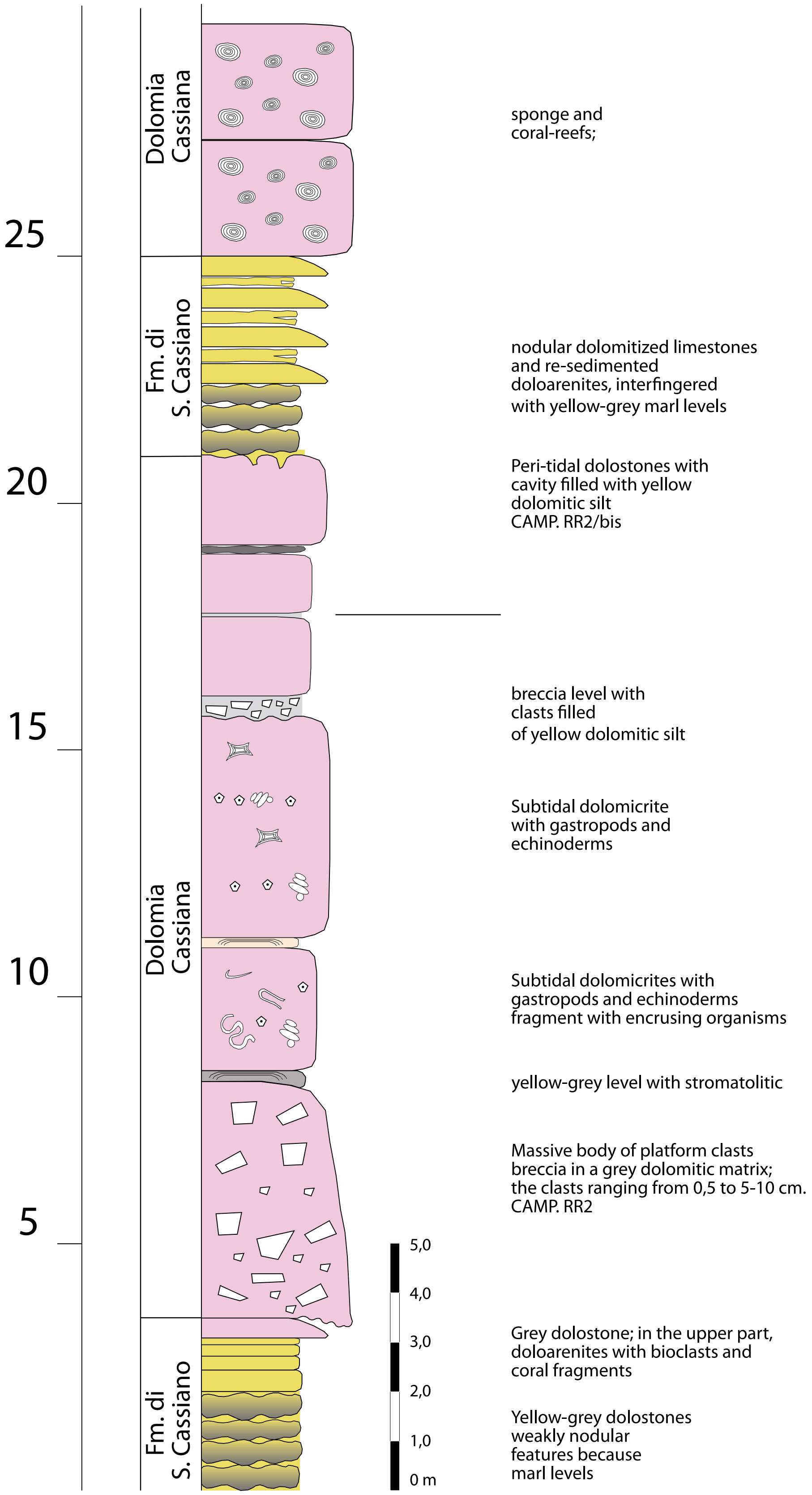

Fig. 10: The base of the Richthofen Reef (DC 1a) represents a carbonate wedge overlying the basin deposits with an erosional base (San Cassiano Fm). Note the details of the stratigraphic section.

thickness, and bearing megalodonts, gastropods and small bivalves. Isolated coral patch-reefs also occur. The tepee litofacies with subaerial exposure surfaces commonly mark the top of the depositional cycles (tepee caps, Hardie et al., 1986), showing early diagenetic alteration, and are often associated with breccia horizons. The tepees can be locally polyphase and, in association with mudcracks and sheet-cracks (Demicco and Hardie, 1994), are the most significant structures characterizing this formation. Interbedded within the deformed tepee structures are lenses of pisolitic grainstones and reworked mud intraclasts derived by the erosion of dessicated substrates. From a depositional standpoint the Heiligkreuz Formation has been interpreted as a Bahama-type carbonate platform developed within a mostly tropical climate. This environmental and climatic setting appears to dominate the shallowest part of the Cassian platform-rim-slope systems, developed during the Carnian (Hardie et al., 1986; Claps, 1996).

e) Travenanzes Formation. This stratigraphic unit has been recently formalized (Neri et al., 2007) for the Western and central Dolomites areas and it replaces the previous Raibl group (Assereto et al., 1968), which is now limited to the Eastern Dolomites area.

In the Falzarego Pass area, the Travenanzes Formation consists of terrestrial to shallow-marine, mixed siliciclastic-carbonate sediments (Bosellini at al., 1996; Neri et al., 2007). This unit is mainly composed of green, red, violet and gray pelites and marls alternating with clear aphanitic dolomites; other deposits which occur near the base of the succession are thin beds of green and gray sandstone and reddish conglomerates.

The boundary with the underlying Heiligkreuz Formation is marked by a sharp erosive surface with associated breccia levels; the boundary with the overlying Dolomia Principale is gradual, with a transition from dolomitic limestone and green-whitish dolostone to gray subtidal dolostones alternated with black dolomitic stromatolites organized in metric peritidal cycles.

The Travenanzes Formation marks the beginning of a new megasequence which also includes the overlying Dolomia Principale. The depositional environment of this carbonate unit is referred to as coastal shallow marine, and includes fluvial-deltaic settings, marsh-lagoons, tidal flats, tide-controlled shoals, beaches and wave-dominated shelves (Bosellini et al., 1982).

Settsass and Richthofen Reef

The results presented in this paper are based on an integrated approach combining detailed geological mapping, facies analysis of key outcrops and analysis of several stratigraphic sections of the Settsass ridge; as a result this integrated study has lead to reconstruct the main characteristics of the complex Settsass platform system as well as its vertical and lateral evolution.

The Richthofen Reef

The term "Richthofen Reef" was introduced by Mojsisovics (1879) in honor of Baron F. v. Richthofen (1860) for his geological pioneer work in the Dolomites.

The Richthofen Reef can be subdivided in two main carbonate bodies (as displayed in Fig. 9).

The sedimentary succession begins with a carbonate breccia at the base, unconformably overlying the basinal deposits with an erosional base (Fig. 10). The breccia is composed of clasts ranging in size from

Fig. 11: Polished slab of clast-supported carbonate breccia constituted of light clasts ranging in size froma few mm to 3-4 cm. Scale is in cm

granules to pebbles within a calcarenitic matrix (Fig. 11); this breccia represents probably a remnant of clinoforms of a previous carbonate platform (DC 1a of Fig. 5). These chaotic deposits of the lower platform body are 5 - 6 m thick; they can be laterally traced over a distance of about 60 - 80 m, and represent the first paleotopographic reliefs which were colonized by carbonate producers in a relatively shallow basinal setting. In fact the first carbonate deposits overlying these braccia layers were formed by subtidal dolomicrites rich in diverse shallow marine fossils (such as echinoderm fragments, gastropods, bivalves and a variety of encrusting organisms). These deposits are capped by thin layers characterized by reddish shales and dolomitic crystal silt filling subvertical cavities, which are interpreted as deposited during a subaerial exposure event.

The overall vertical evolution of this first phase of deposition of the Piccolo Settsass in the post-volcanic complex records a general shallowing-upward trend.

This lower platform unit is overlain by thin basinal deposits of the San Cassiano Fm, with nodular grey limestone and yellowish-grey marls. At the Piccolo Settsass the San Cassiano Fm reaches a maximum thickness of 3 - 3.5 m (Fig. 10, Fig. 12).

The overlying carbonate body has been duplicated by a southward overthrust (Doglioni, 1992 Geologische Karte der Westlichen Dolomiten 1:25.000, 2007; DC 1b of Fig. 5, 9): the thrust portion is represented by the lateral deposits of the lower carbonate body, which formed the core of the Piccolo Settsass.

The sedimentation of this second carbonate body started on these thin layers of the San Cassiano shallow deposits. The succession is composed of massive dolomitized beds (ranging in thickness from 1 m to about 3 m) intercalated with dark dolomicritic thin beds (a few cm thick).

These massive beds are characterized by the occurrence of coral and sponge patch-reefs, interpreted as bioconstructed mounds, whereas the thin dolomicritic layers represent muddier intermound deposits (Fig. 12).

The core of the coral and sponge bioconstructed bodies of the Piccolo Settsass reaches up to about 80 - 100 m of thickness and extends laterally over at least 300 m (Fig. 9).

This massive carbonate body grades laterally into a sedimentary breccia tongue that interfingers with the basinal deposits of the San Cassiano Fm. These deposits, which form the thrust body (Fig. 9), are composed of breccia units about 1 - 2 m in thickness bearing mainly platform-derived clasts. These breccias are overlain by meter-scale coral-dominated patch-reefs, which indicate a shallow marine environment with the establishment of platform margin-type depositional conditions.

The vertical evolution of the bioconstructed nucleus of the Richthofen Riff shows a northeastward progradation over the basin with a slope dip angle of about 20° - 25°, in the proximal area, flattening out over the basinal deposits in the more distal parts (downslope dip, Fig. 13).

The boundary between the two carbonate systems of the Cassian Dolomite, as mentioned before, (Fig. 9, DC 1b and DC 2 of fig. 5) is marked by a few meters thick succession of yellow/light grey bioturbated marls and calcilutites of the San Cassiano Formation. These basinal deposits testify the final drowning of the Piccolo Settsass platform. Nevertheless, in this portion of the San Cassiano Formation the occurrence of several coral patch-reefs, with typical growth position assemblages (about 0.5 m thick, as illustrated in Fig. 14), have been documented, and this proves the shallow-water conditions reached by the San Cassiano Fm at this location.

The duplicated part of the carbonate unit DC 1b (the southward overthrust) of the Piccolo Settsass shows a shallowing-upward trend too: the basinal deposits of the San Cassiano Formation are overlain by breccia units which are about 1 - 2 meter thick and contain mainly platform-derived clasts. These are overlain by meter-scale, coral-dominated patch-reefs, which represent again a shallow marine, platform-margin type depositional environment.

The intervening basin was filled by a substantial amount of volcanoclastic sediment derived from the dismantlement of the volcanic edifices located therein (Marmolada Conglomerate and Wengen Formation), and then followed by mixed carbonate-clastic basinal sediments typical of the San Cassiano Fm. (locally characterized by large platform-derived olistolites).

The Settsass

The Settsass represents the second generation of the Cassian Dolomite platforms (indicated as CD 2) and is well exposed along the southeastern and southwestern flanks of the Settsass Mt. (Fig. 15 and Fig. 16).

At the southwestern side, the inner platform deposits of the Cassian Dolomite show a monotonous cyclic succession (Fig 17) with dominantly subtidal, fine

Fig. 12: a) Platform margin of the Richthofen Riff: massive coral reefs intercalated with thin layers of a muddy intermound lithofacies

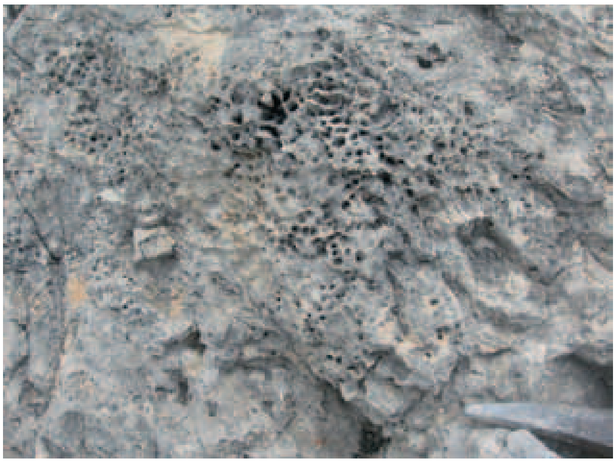

Fig. 12: b) Detail of coral patch-reef.

Fig. 13: The core of the Richthofen Riff: down-lap between the clinostratified breccia slope and overlying basin deposits. The down-lap angle is about 20°-25°. On the left, the first body of the Cassian Dolomite (DC 1/a), which dips conformably on the basin deposits below (not shown in the photograph).

Fig. 14: Coral patch-reef in growth position occurs within the San Cassiano Formation located between the Richthofen Riff and Settsass. The coral are well preserved because the interbedded marls and shales inhibited the penetration of dolomitization fluids.

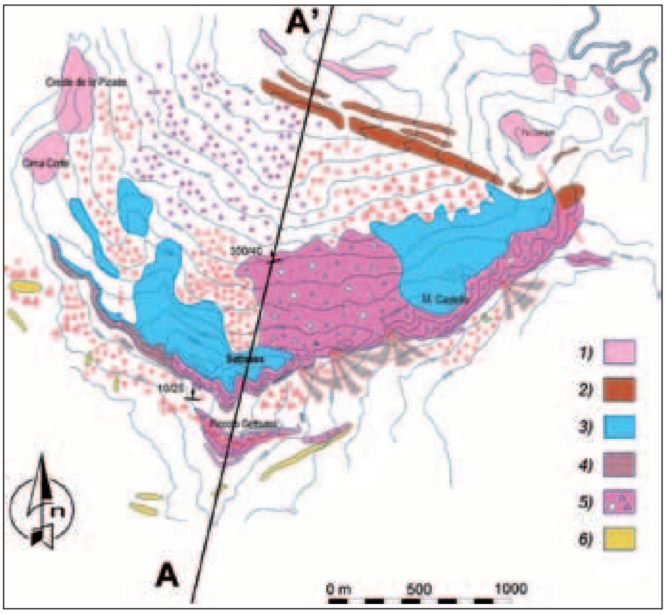

Fig. 15: Geologic map of the Settsass/Richthofen Reef interpretated as an homoclinal block dipping N-N10°, with dip angles of about 35°-40°. Note that the southwestern side is formed by the inner platform facies of the Cassian Dolomite while the southeastern side is constituted by the breccia slope of the Cassian Dolomite. 1) Dolomia Principale; 2) Travenanzes Formation; 3) Heiligkreuz Formation; 4) Cassian Dolomite (slope facies); 5) Cassian Dolomite (inner platform facies); 6) San Cassiano Formation.

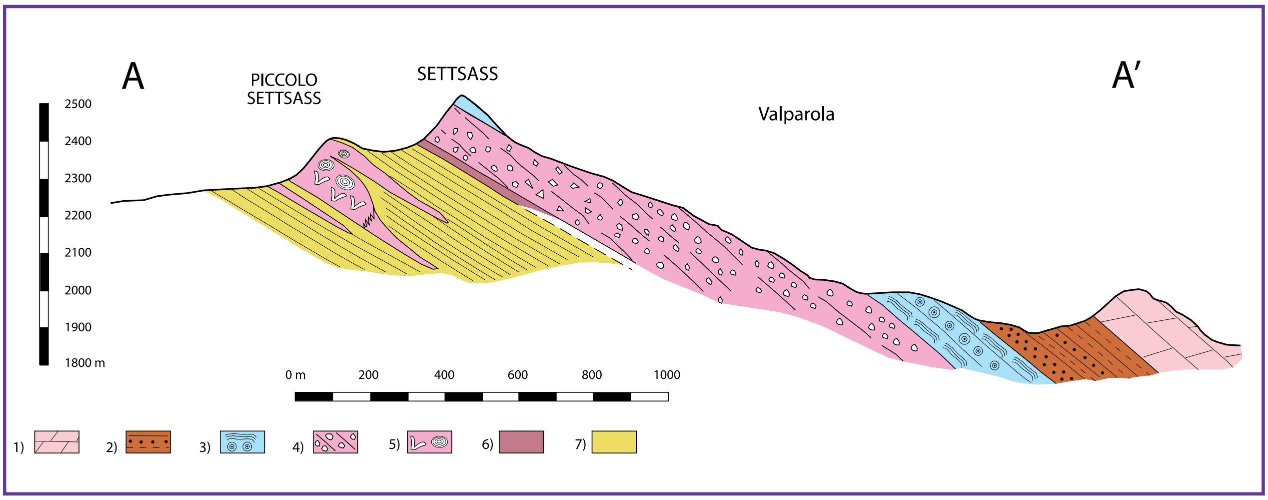

Fig. 16: Cross-section across the Piccolo Settsass (Richthofen Riff) and the Grande Settsass (approximately in N-S direction) showing two Cassian Dolomite platforms. Note the Settsass clinostratification over the basin deposits (San Cassiano Formation). 1) Dolomia Principale; 2) Heiligkreuz and Travenanzes Fms; 3) Dürrenstein Formation; 4) Cassian Dolomite (slope facies); 5) Cassian Dolomite (margin platform facies); 6) Cassian Dolomite (inner platform facies); 7) San Cassiano Formation.

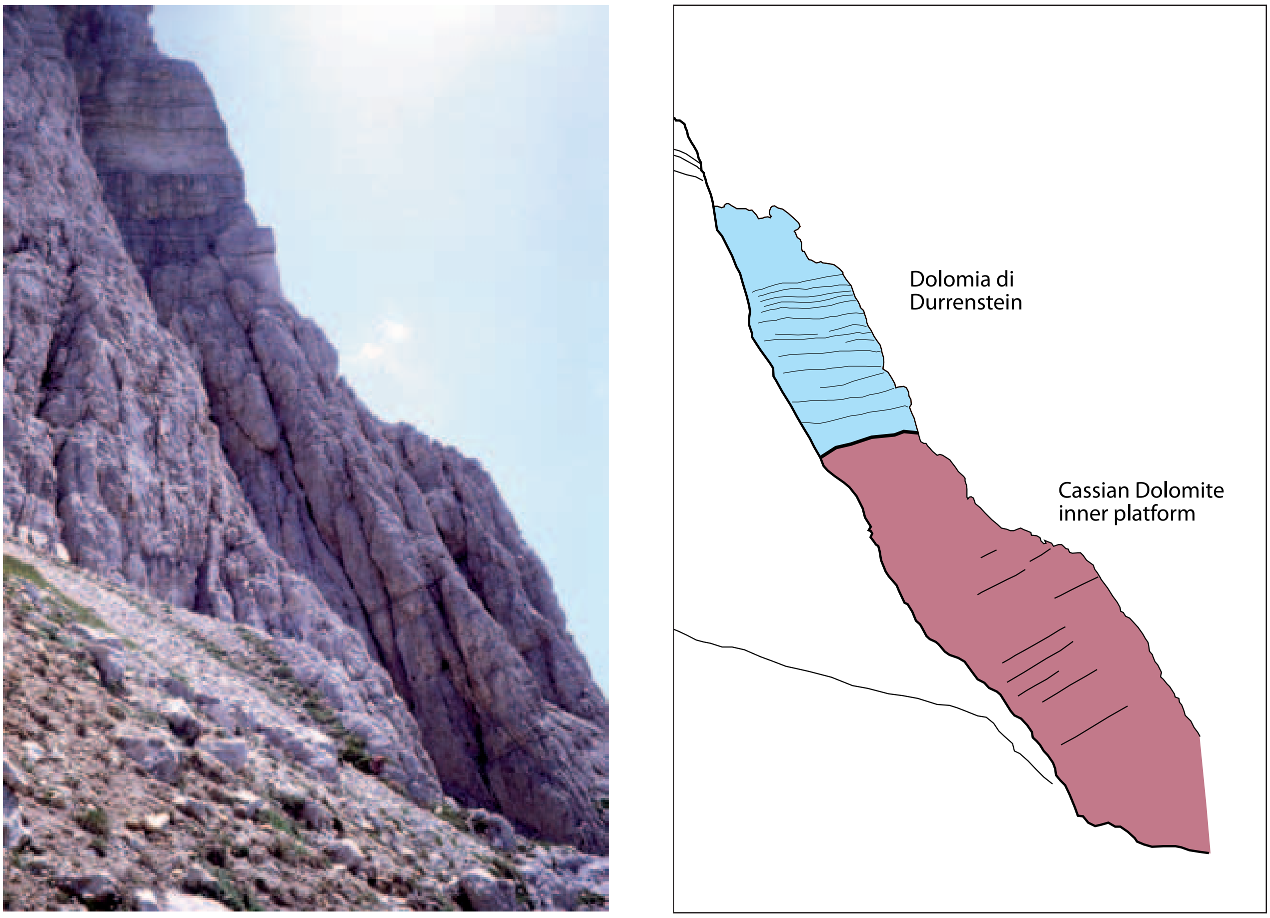

Fig. 17: Southwestern side of the Settsass showing the stratigraphic boundary between the inner platform facies of the Cassian Dolomite and the Dürrenstein Formation.

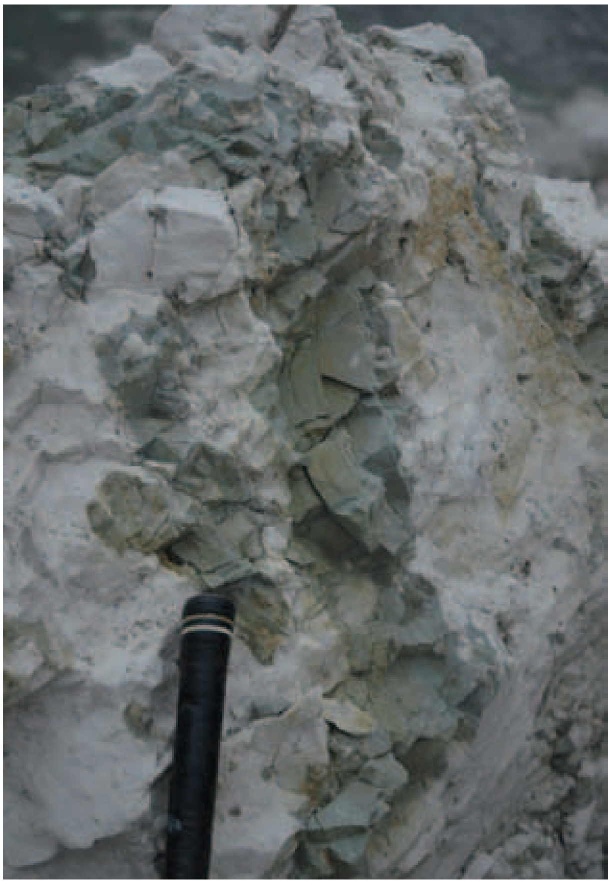

Fig. 18: Sedimentary dikes originated at exposure surfaces and are filled with light-green silt, cross-cutting well cemented microbial limestone, which are interpreted as microkarstic features.

grained facies (skeletal-peloidal packstones) capped by thin subaerial exposure surfaces with deeply incised internal pockets filled with greenish-grey shales (microkarst cavities, Fig. 18). In the vicinity of the clinostratifications microbial and algal-clotted peloidal limestone patches occur. These bodies are locally incised by subaerial exposure surfaces and are characterized by the presence of dissolution vugs filled by subsequent cement phases (Fig. 19). Some of these cavities are filled with reddish shale and dolomitic silt. This platform sequence is overlain by the Heiligkreuz Formation (Fig. 16).

The southeastern side of the Settsass shows clinostratified breccias downlapping over the basinal deposits of the San Cassiano Fm. The downlap angle between the clinoforms and the basinal deposits ranges from 20° - 25° in the proximal area, decreasing to to 10° - 15° in its distal part.

The clinostratified breccia is mostly composed of platform-derived debris with grain size from a few mm up to 5 - 10 cm, Fig. 20). At the toe of the slope the breccia tongues interfinger with the basinal deposits, associated to the carbonate turbidites and grey-yellow dolomitized nodular fine grained limestones of the San Cassiano Formation. The progradation of the Settsass platform over the basin reaches a horizontal offset of about of 2 km (Fig. 21).

The downlap surface between the clinoforms and the basinal beds is in most places covered by quaternary deposits at the toe of the rock walls, but appears to be well exposed at a few key locations (as displayed in Fig. 22).

The Settsass platform geometry is constrained by its upper and lower stratigraphic boundaries: at the top, the boundary with the overlying Heiligkreuz Formation is flat (toplap), while the lower boundary with the underlying San Cassiano Formation corresponds to an unconformity surface (Fig. 16 and 21). The resulting Settsass platform geometry is therefore tabular and/or slightly thickening outward, with an overall slightly descending progradation pattern.

Summary of the platform margin architecture and main depositional features

The Settsass-Richthofen Reef platform system consists of two superimposed carbonate edifices, nucleated on a stable topographic high, which is the remnant of a clinoform body originated from a predecessor carbonate platform (DC 1a of Fig. 5). These two systems were then aggrading vertically and prograding in the same direction towards northeast. The various progradation phases are recognized by the interfingering of the slope breccia deposits and the basinal deposits of the San Cassiano Fm above the shallow carbonate facies (Fig. 5). The carbonate platform productivity in these two systems came to a temporary stop probably due to subsequent eustatic sea-level falls which caused subaerial exposure and some degree of karstification of the platform interior and platform margin system.

The main features of the Settsass platform system can be summarized as follows:

- its overall platform geometry is tabular, with an outcropping thickness of about 150m, and is slightly thickening basinward;
- its evolution is conformable to the preexisting basin morphology (Richthofen Reef platform-basin system);
- its upper boundary displays a toplap geometric relationship;

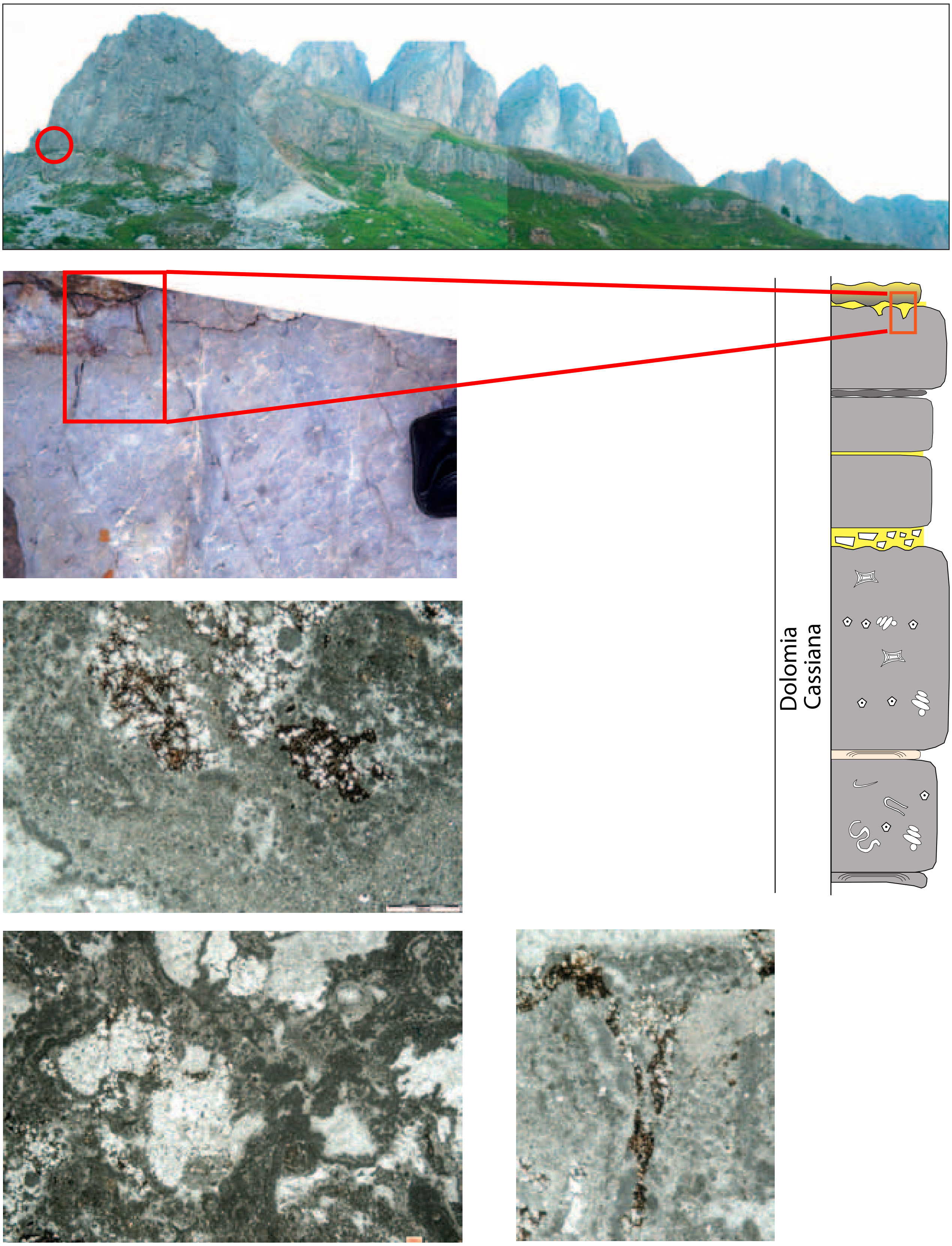

Fig. 19: Subaerial unconformity cutting through microbial and clotted peloidal limestone. The subaerial exposure is testified by the occurrence of microkarstic cavities. Dissolution vugs now appear mostly cemented and are filled with reddish shale and siltstone composed of dolomite crystals.

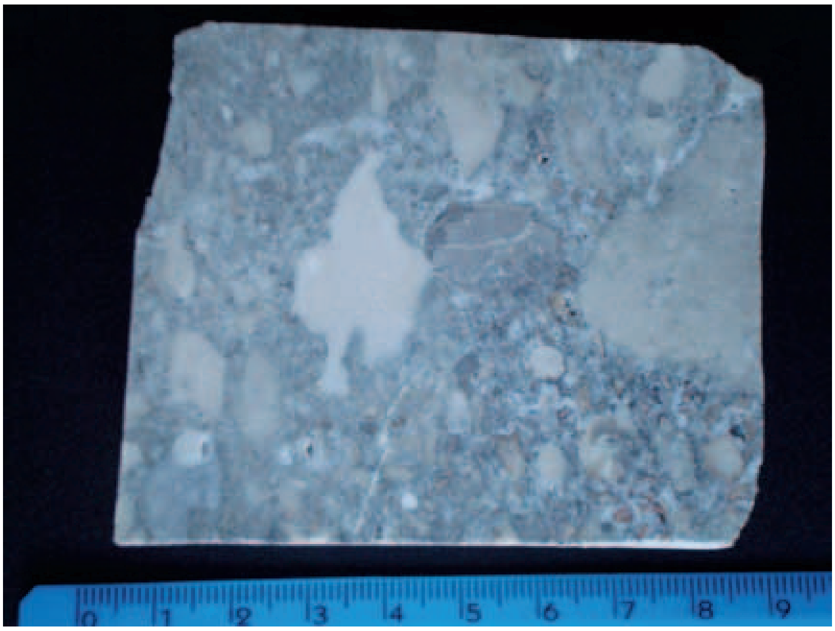

Fig. 20: Polished slab of a clinostratified breccias deposit. The light-colored clasts are derived from the platform areas. Outcrop at the lower portion of the slope, under the M. Castello rock wall.

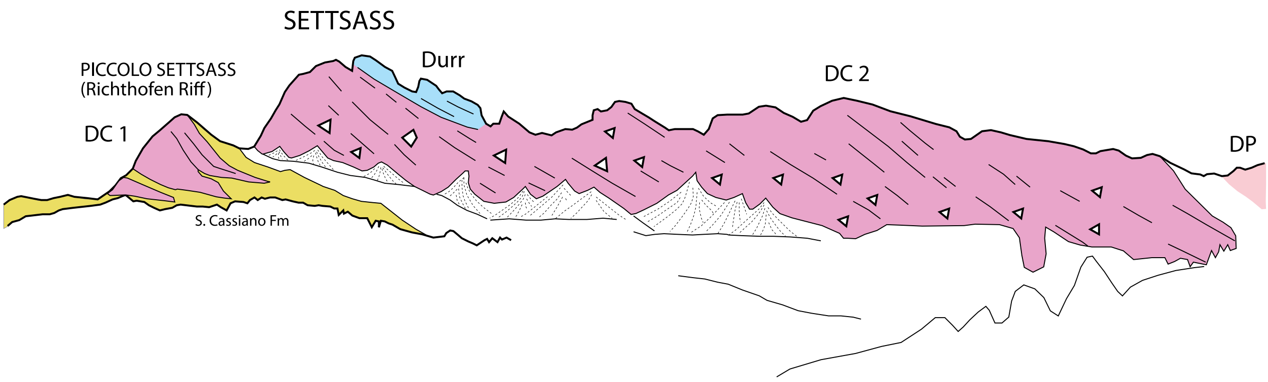

Fig. 21: Geological interpretation of the Settsass group. In the foreground the Richthofen Reef (Cassian Dolomite 1, CD 1) is constituted by a Carnian reef system and two platform progradational lenses intercalated with the adjacent basinal deposits, which then in turn onlap the platform margin body (S. Cassian Fm). The Settsass (in the background, Cassian Dolomite 2, CD 2) clearly shows the clinostratification geometry of the youngest platform, laterally prograding on the basin. The extent of the progradation measures at least about 2 km. DC 1a & DC 1b: Cassian Dolomite (Richthofen Reef); DC 2: Cassian Dolomite (Settsass); SC: S. Cassiano Formation; HKS: Heiligkreuz Formation; DP: Dolomia Principale.

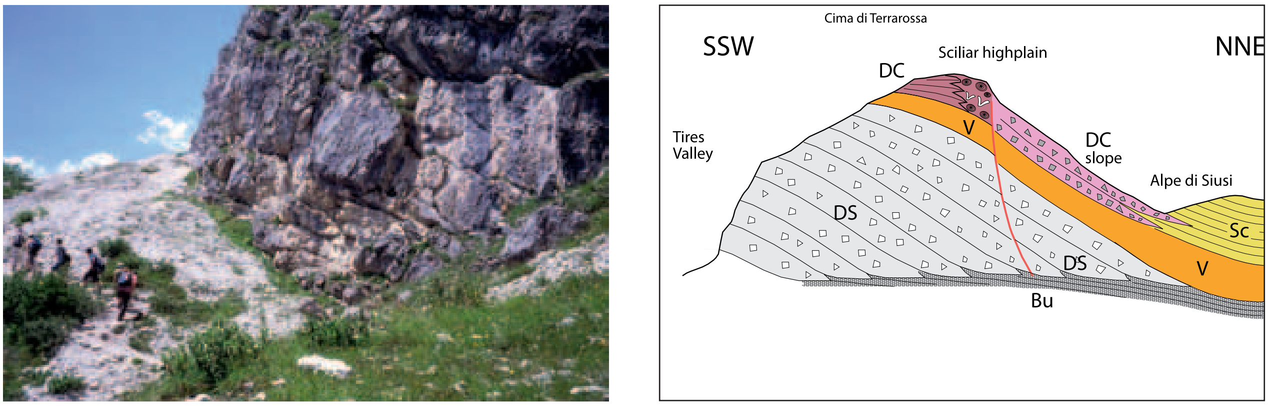

Fig. 22: The lower portion of the clinostratification in the rock cliff beneath Castello Mountain. Note the load structures linked to the large boulder deforming the underlying thin strata of calcilutites and calcarenites. Sc = San Cassiano Fm.; Dc slope = Cassian Dolomite (slope facies); DC = Cassian Dolomite

- its lower boundary is represented by an unconformity and bears a slightly descending geometry;
- the adjacent basin shows shallow water conditions, probably controlled by a relative sea-level stillstand and low subsidence rate
- the slope angle of the clinoforms range from 20° - 25° in the proximal area to 10° - 15° in the distal part;
- the extent of the platform progradation can be traced in outcrop over a distance of about 2 km.

Conclusions

The Settsass/Richthofen Reef shows common features with the other Lower Carnian edifices, like the occurrence of huge volumes of carbonate megabreccias (including the olistolithic blocks known as "Cipit" blocks) which interfinger with the basinal deposits of the San Cassiano Formation. The megabreccia slopes are often organized in clinostratified deposits with dip angle slopes ranging from 20° - 25° to 40° - 45°. These steep slope cannot be explained only with the grain-size of the reworked sediments (Kenter, 1990); in fact the carbonate platform slope flanks were also stabilized by microbialites, early cementation and activity of encrusting microorganisms (as discussed in Keim & Schlager, 2001).

The presented case study of the Settsass/Richthofen Reef provides new insights about the Lower Carnian platform evolution that can be summarized as follows:

a) At the Settsass/Richthofen Reef two carbonate platform systems are clearly identified by the occurrence of platform margin bioconstructors (i.e. coral patch-reefs in growth position) and the two platform growth phases (DC 1 and DC 2) are subdivided by the intervening relatively shallow basinal deposits.

b) The Richthofen Reef shows a plane-convex geometry reaching up to about 80 - 100 m in thickness and extending at least 300 m laterally. This reef is formed by two main bodies (DC 1a and DC 1b):

1) DC 1a is constituted by white carbonate breccias, overlying the basinal deposits (San Cassiano Formation) with an erosional base. This first body presents a tabular geometry;

2) DC 1b represents the reef core, and corresponds to a bioconstructed body formed by coral patch-reefs and sponge mounds as well as by margin/slope deposits which interfinger with basinal deposits. This second body yields an overall plane-convex geometry.

c) The Settsass platform (DC 2) displays a tabular geometry and records a complete depositional environment spectrum from its inner platform succession (back-reef) down to the slope deposits composed of clinostratified breccias. The inner platform succession, which has not been documented before, is arranged in shallowing-upward cycles overlain by the Heiligkreuz Formation. The slope deposits are formed by clinoforms with a slope dip angle ranging from 20° - 25° in the proximal area to 10° - 15° more distally.

The Settsass platform shows a basinward (NE direction) progradation over a distance of almost 2 km comparable to other examples from the Dolomites (Bosellini, 1984; Bosellini & Stefani, 1991; Maurer, 1999; Keim & Schlager, 2001).

ACKNOWLEDGMENTS

The author is indebted to M. Claps (Petroleum Development Oman, R. Longoni (ENI), A. Boz (ENI) and M. Cella (ENI) for fruitful discussions during the field work. The review by L. Keim and K. Krainer considerably improved the first version of this manuscript. The early English version was kindly revised by M. Claps.

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Manuscript submitted: 20.6.2011
Revised manuscript accepted: 18.10.2011