Permian-Triassic-Boundary and Lower Triassic in the Dolomites, Southern Alps (Italy)

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With 21 figures

Field Trip Guide

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Lorenz Keim died during a cross country ski tour in a snow avalanche at the Stallersattel (South Tirol, Italy) on February 4, 2012. He just turned 43, was married and had three little boys. In the last years he worked at the Geological Survey as field geologist, as coordinator of geological maps and was involved in reconnaissance studies for the Brenner Base Tunnel on the South Tyrolean side. As excellent geologist he leaves a big hole in the Tyrolean geology. He is painfully missed.

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Abstract

The field trip focuses on the sedimentary response of the end Permian mass extinction and the time of recovery in the whole Lower Triassic. Along some type sections, i.e. the parastratotype section of Bulla/Pufels in the Gröden valley, the Seis/Siusi section further to the southwest and the Tramin/Termeno section south of Bolzano/Bozen, we will have a good opportunity to study facies developments in the inner and outer ramp position. Detailed magneto- and chemostratigraphy enable correlations of cycles and sequences along the wide ramp. This should provoke a discussion on eustatic sea-level changes and climatic changes. The sections are located in the beautiful, world famous landscape of the Dolomites (UNESCO World Heritage).
The shallow marine sediments of the topmost Bellerophon Fm. and Werfen Fm. were deposited on a very gentle, NW - SE extending ramp with a coastal plain environment of the upper Gröden Fm. in the west and a shallow marine, mid and outer ramp environment of the Bellerophon Fm. in the east. The PTB mass extinction of carbonate producing organisms prevented the evolution of a rimmed shelf area for the whole Lower Triassic. After the exceptionally long lasting recovery period for reefal buildups in the whole Tethys area, the first appearance of reef building organisms was found in the lower Middle Triassic nearby in the Olang/Valdaora Dolomites (Bechstädt & Brandner 1970).
The lack of reefal buildups and binding organisms may have caused the extreme mobility of loose carbonate and siliciclastic sediment piles, which have been removed repeatedly by storm-dominated high energy events. This generated a storm-dominated stratification pattern that characterises the specific Werfen facies. Applying the concept of proximality of storm effects (Aigner 1985), i.e. the basinward decrease of storm-waves and storm-induced currents, we tried to interpret relative sea-level changes from the stratigraphic record. Proximal and distal tempestite layers are arranged in shallowing-upward cycles (parasequences) but also in deepening-upward cycles depending on their position within the depositional sequences. However, numbers of cycles and cycle stacking patterns vary from section to section according to the different ramp morphology. Thus the main control seems to be the ratio between accommodation space and sediment supply, which follows the variable position of the base level (see base level concept from Wheeler 1964). Variations of

the base level determine the geometry of progradational, aggradational and retrogradational stacking patterns of the cycles. The base level, however, does not automatically correspond to sea level. Therefore until now it was not possible to proof true eustatic sea level changes within the Lower Triassic.

1. Topics and area of the Field Trip

The field trip focuses on the sedimentary response of the end Permian mass extinction and the time of recovery in the whole Lower Triassic. Along three type sections, i.e. the parastratotype section of Bulla/Pufels in the Gröden valley, the Seis/Siusi section at the foot of the Schlern/Sciliar mountain and the Tramin/Termeno section south of Bolzano/Bozen (Fig. 1), we will have a good opportunity to study facies developments in the inner and outer ramp position. Detailed magneto- and chemostratigraphy enable correlations of cycles and sequences along the wide ramp. This should provoke a discussion on eustatic sea level changes and climatic changes. Both sections are located in the beautiful, world famous landscape of the Dolomites (UNESCO World Heritage).

The shallow marine sediments of the topmost Bellerophon Fm. and Werfen Fm. were deposited on a very gentle, NW - SE extending ramp with a coastal plain environment of the upper Gröden Fm. in the west and a shallow marine, mid and outer ramp environment of the Bellerophon Fm. in the east. The PTB mass extinction of carbonate producing organisms prevented the evolution of a rimmed shelf area for the whole Lower Triassic.

The lack of reefal buildups and binding organisms may have caused the extreme mobility of loose carbonate and siliciclastic sediment piles, which have been removed repeatedly by storm-dominated high energy events. This generated a storm-dominated stratification pattern that characterises the specific Werfen facies. Applying the concept of proximality of storm effects (Aigner 1985), i.e. the basinward decrease of storm-waves and storm-induced currents, we tried to interpret relative sea level changes from the stratigraphic record. Proximal and distal tempestite layers are arranged in shallowing-upward cycles (parasequences) but also in deepening-upward cycles depending on their position within the depositional sequences. However, numbers of cycles and cycle stacking patterns vary from section to section according to the different ramp morphology. Thus the main control seems to be the ratio between accommodation space and sediment supply, which follows the variable position of the base level (see base level concept from Wheeler 1964). Variations of the base level determine the geometry of progradational, aggradational and retrogradational stacking patterns of the cycles. The base level, however, does not automatically correspond to sea level. Therefore until now it was not possible to proof true eustatic sea-level changes within the Lower Triassic.

End Permian and Early Triassic high-resolution stratigraphy allow now detailed correlations of lithostratigraphic units along the gentle ramp, indicating the different timing of the onset of sedimentation of several

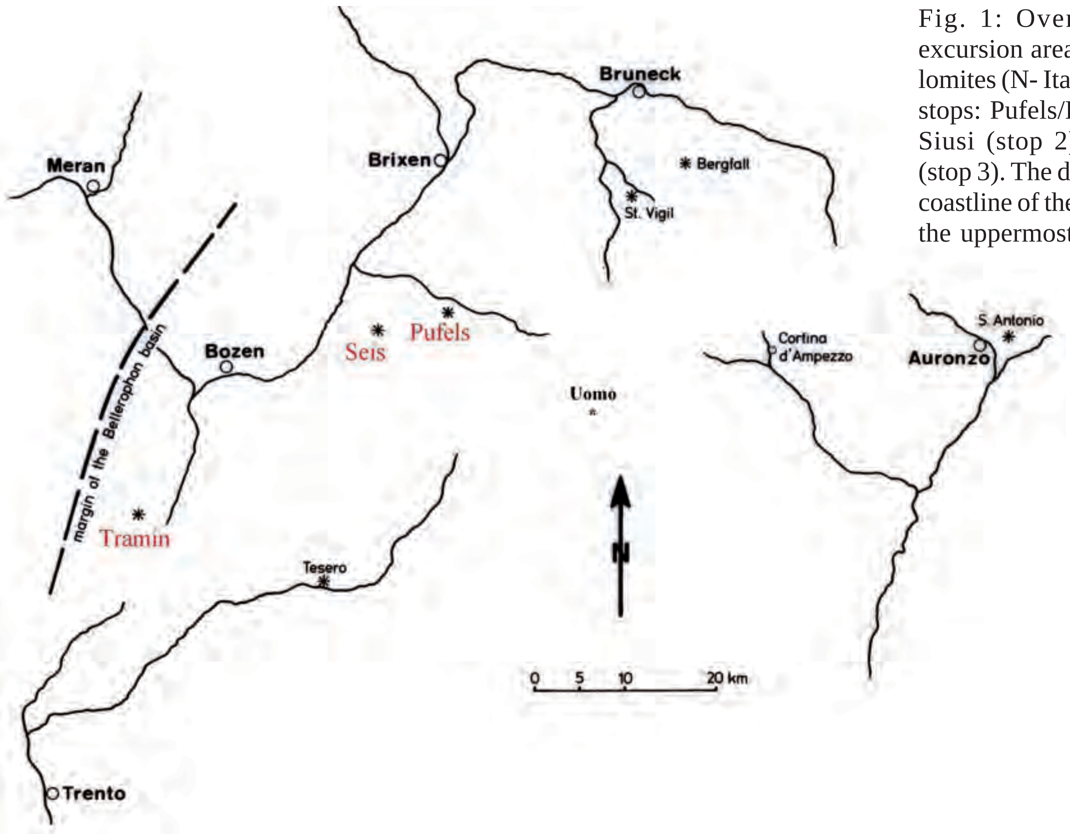


Fig. 1: Overview map of the excursion area in the western Dolomites (N- Italy) with the field trip stops: Pufels/Bulla (stop 1), Seis/Siusi (stop 2), Tramin/Termeno (stop 3). The dashed line marks the coastline of the Bellerophon-Sea in the uppermost Permian.

Werfen members on the gentle ramp.
According to Lower Triassic U-Pb ages and biochronozones (Galfetti et al. 2007) the depositional sequences of the Werfen Fm. span time intervals of about 400-500 ka. 4^{th} order cycles superimposing the 3^{rd} order sequences can be identified especially in the shallow ramp environment quite easily and the number of cycles (16) supports the assumption of orbital forcing of the sea-level changes.

2. Introduction and geological setting of the Dolomites

The following chapters are basically a reproduction of the published field guides by Brandner et al. (2009) and Brandner & Keim (2011).

The Dolomite Mountains are known for their spectacular seismic scale outcrops showing Triassic carbonate platforms and build-ups preserved with their clinoforms and slope facies in primary transition to adjacent basinal areas. The juxtaposition of Middle and Upper Triassic reefs and basins are preserved due to the lack of strong tectonic deformation and is strengthened by erosion to form the extraordinary landscape as seen today. Since the outstanding studies of Richthofen (1860) and Mojsisovics (1879), who correctly recognized the primary geometries of the build-ups ("Überguss-Schichtung") in transition to the basins, the Dolomites are the type area for heteropic facies developments. Bosellini (1984) presented the first modern synthesis of depositional geometries of the build-

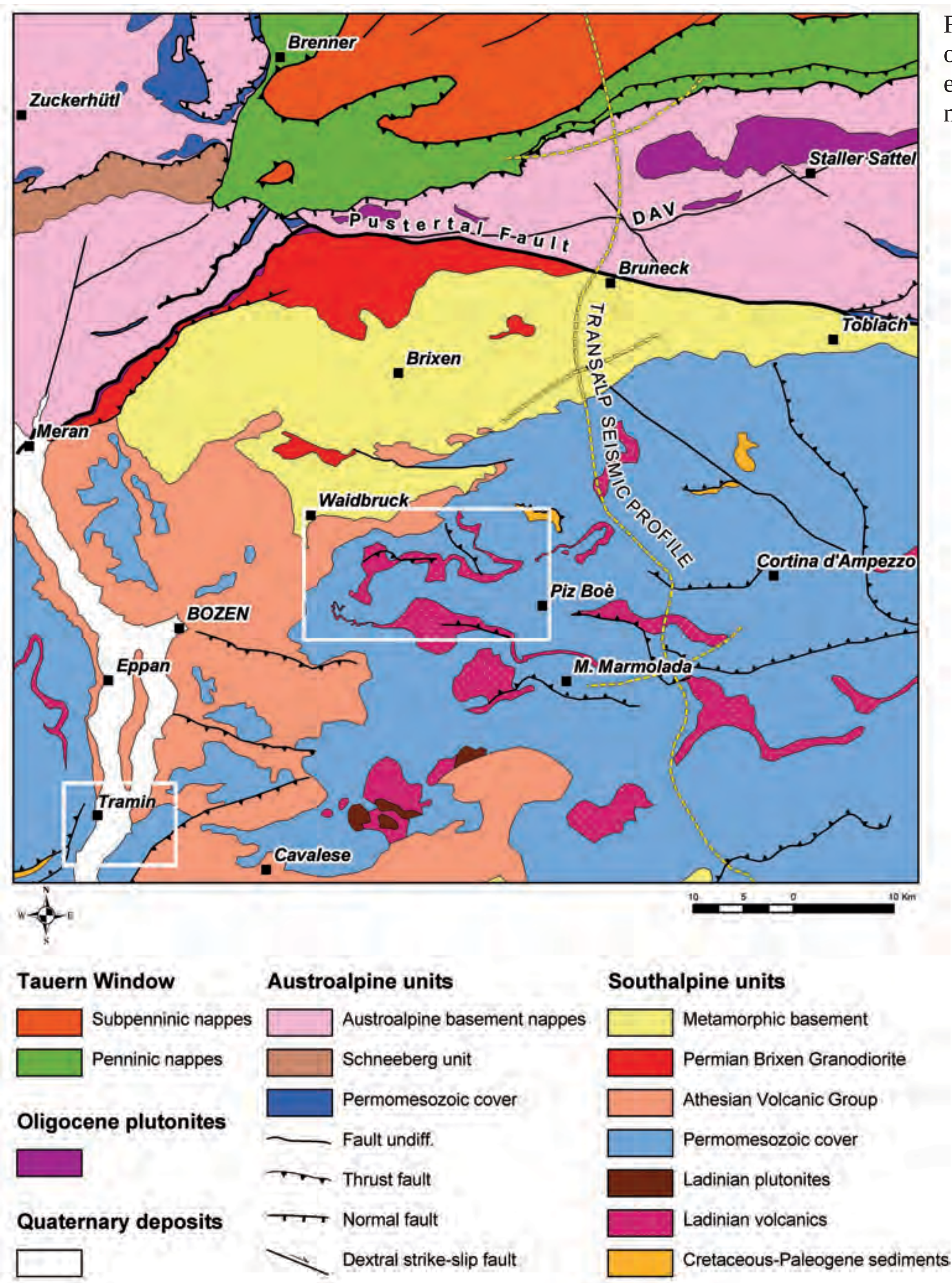


Fig. 2: Regional geologic overview with location of the excursion area in the Dolomites (rectangulars).

ups. Regional sequence stratigraphy was firmly established with the revision of the chronostratigraphic framework by Brack & Rieber (1993), De Zanche et al. (1993) and Mietto & Manfrin (1995). In addition, a better understanding was developed of progradation and retrogradation geometries of carbonate platform development in context with sea-level changes (Gianolla et al. 1998, with further references). A new 1:25.000 scale geological map (Geologische Karte der Westlichen Dolomiten) was provided in 2007 for the whole area of the Western Dolomites on the basis of extensive field work and detailed stratigraphic investigations and structural analyses.

The Dolomites are part of the south alpine retro wedge of the Alpine chain. The Neogene S-vergent thrust- and fold belt is located south of the Periadriatic Lineament (Pustertal Fault), east of the Giudicaria fault system and north of the Valsugana thrust (Fig. 2). All these faults are inherited structures which were remobilised at different times since their installation in the Early Permian (see below). Within this framework of major faults, the Dolomites form a Neogene pop-up structure with only weak tectonic deformation (Doglioni 1987). North of the Pustertal Line, more exactly north of the hinge of the Tauern Window antiform, Austroalpine and Penninic nappes are thrusted toward the north in the Paleogene.

Both, Austroalpine and Southalpine units are part of the passive continental margin of the Apulia microplate with a comparable geodynamic development since the Lower Permian. Early continental rifting processes associated with the break-up of Pangea during the Lower and Middle Permian gave way to the stepwise propagation of the Neo-Tethys from SE. Pulses of distinct rifting tectonics in the Dolomites in the Early Permian and Middle Triassic are closely associated with voluminous plutonic and volcanic rocks deposited largely in the same place. Both, Permian and Triassic magmatic rocks display typical calc-alkaline trends and the geochemical and isotopic composition indicate that the melts originated from the interaction of upper mantle and lower crust (Barth et al. 1993, Visonà et al. 2007). The marked orogenic signature is not compatible with the conventional rifting model. But also for the subduction related model, proposed by Castellarin et al. (1988), unequivocal geological field evidences in the Southern Alps and surroundings are still missing. Nevertheless, in many plate reconstructions we still find a Triassic active margin in prolongation of the closing Paleotethys south of the Southern Alps (e.g., Stampfli & Borel 2002). New paleomagnetic data advocate an intra-Pangea dextral megashear system of >2.000 km to avoid the crustal misfit between Gondwana and Laurasia in the Early Permian (Muttoni et al. 2003). Within this scenario, lithosphere-scale extension enables mantle melt injections in the lower crust to generate hybridisation of magmas (Schaltegger & Brack 2007). This model represents a good

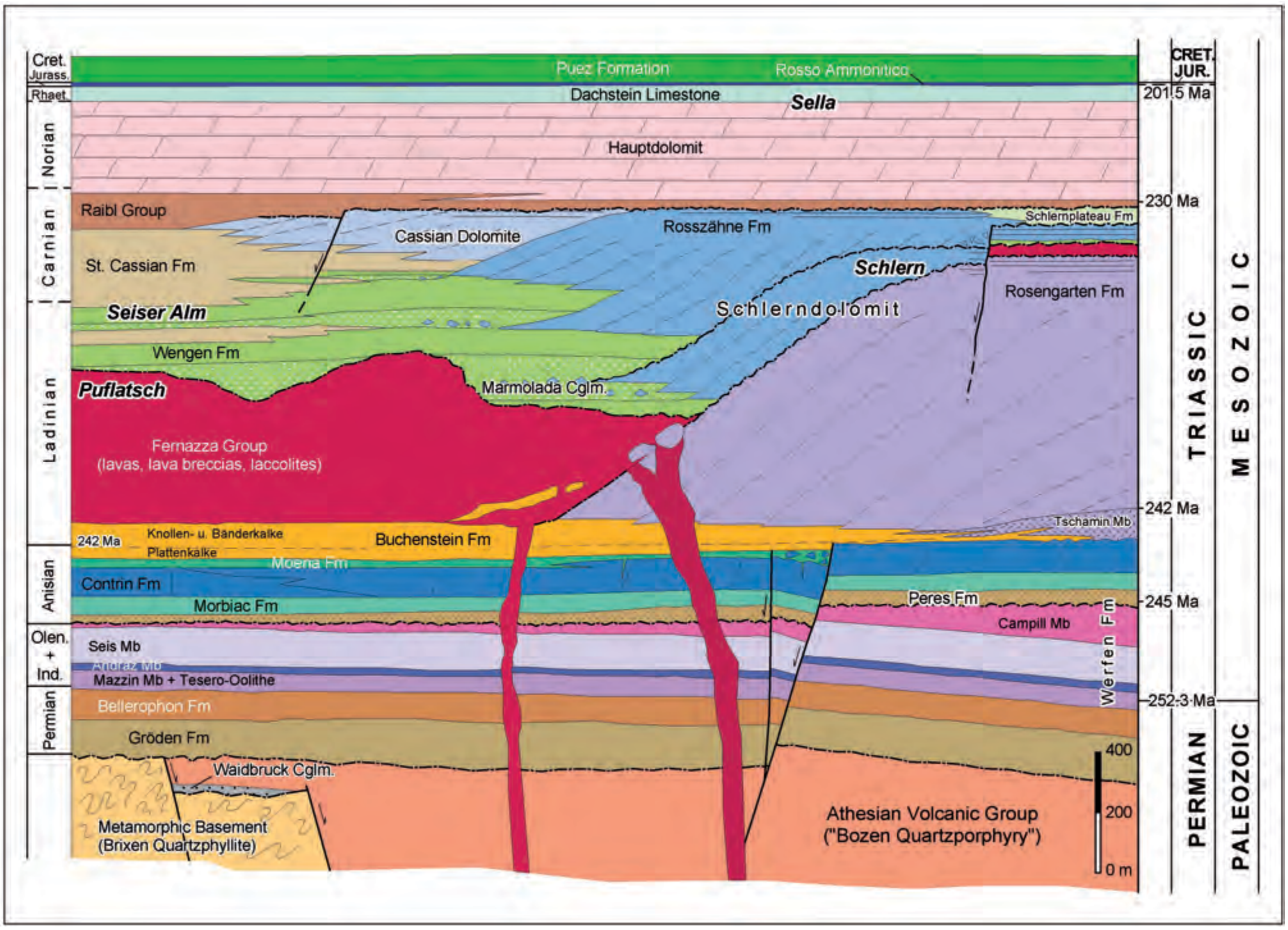


Fig. 3: Lithostratigraphic model for the Permo-Mesozoic succession of the western Dolomites (modified after Brandner et al. (2007).

possibility to unravel the large-scale geodynamic context of Permian and Triassic particularities of the Southern Alps.

Permian and Triassic rifting tectonics are more intensive in the Southalpine realm than in the Austroalpine, where during this time period magmatism and volcanism are nearly absent. This different evolution requires a transcurrent shearing system in between the two realms to facilitate different stretching of the lithosphere. Therefore, we assume already for the Permo-Triassic time span a forerunner of the differentiation of Apulia N and Apulia S, separated by a Paleo-Insubric Line, which proposed Schmid et al. (2004) for the Jurassic.

The Permo-Triassic succession of the Dolomites (Fig. 3) can be subdivided into three tectonically controlled 2nd order megacycles, which are superposed by 3rd order cycles (sequences) and cycles of higher order (e.g., Werfen Fm.):

1. Early Permian volcanic deposits with intercalated fluvio-lacustrine sediments of the Athesian Volcanic Group enclose ca. 10 Ma from 285 to 275 Ma (Marocchi et al. 2008). The up to 3 km thick sequence rests on a basal conglomerate, covering the Variscan crystalline basement by a main unconformity and was deposited in the Bozen/Bolzano intra-continental basin.
2. After a marked stratigraphic gap of ca. 10 Ma, the Gröden/Val Gardena alluvial red beds were deposited on top of the volcanic group as well as on top of the Variscan basement. With the cooling of the crust, sedimentation of Gröden sandstone was very spacious and shallow marine deposits of the Bellerophon Fm. and Werfen Fm. prograded stepwise westward on a very gentle ramp. This second megacycle ends with Lower Anisian shallow-water carbonates of the Lower Sarl dolomite.
3. A second period of rifting starts in the Middle/Upper Anisian with strong block tilting in several phases followed by the "Middle Triassic thermal event" in the Ladinian. Strong subsidence created space for the upward growth of buildups and carbonate platforms adjacent to up to 800 m deep marine basinal areas. Ladinian volcanics infilled basinal depressions and onlapped carbonate platform slopes. With the waning of rifting activity and volcanism thermal subsidence controlled once more the sedimentary development with spacious progradation of carbonate platforms. Minor pulses of rifting still occurred in the Upper Carnian, but in the Norian the accentuate relief was levelled out by the spacious carbonate platform of the Dolomia Principale/Hauptdolomit.

During the Upper Triassic and Jurassic the Southalpine and Austroalpine domains were involved in a new system of rifting processes (Bertotti et al. 1993). Starting from the Atlantic with the Central Atlantic Magmatic Province (CAMP) at the end of the Triassic, the Atlantic propagated north-eastward to form the Alpine Tethys, i.e. the Ligurian/Penninic Ocean (Frizon de Lamotte et al. 2011). Apulia was now surrounded by two different domains, the "Neo-Tethys" in the east and the "Alpine Tethys" in the west, thus forming a terrane or a microcontinent. The Southern Alps with the Dolomites in their heart have been involved in various processes related to these two rifting systems for a long period of time lasting from the Early Permian to the Upper Cretaceous.

The above mentioned three megacycles are superposed by the global mass extinction events at the Permian-Triassic boundary (PTB), in the Carnian and at the Triassic-Jurassic boundary (TJB). All three events strongly affected the reef growth and the carbonate factory, especially the PTB and the Carnian event effectively controlled the sedimentary development in the Dolomites.

The convergent tectonics of the Southalpine is, however, quite different from that of the Austroalpine: W- to NW-vergent thrusting and folding started in the Austroalpine just in the Late Jurassic with the closing of the Meliata Ocean in the SE (Gawlick et al. 1999) heralding the eoalpine orogenesis during the Late Cretaceous (for an comprehensive overview see Schmid et al. 2004). These eoalpine compressive events with metamorphism, do not have any record in the Southalpine, and thus require a kind of kinematic decoupling from the Austroalpine. Froitzheim et al. (2011) propose a sinistral strike-slip zone as a Paleo-Insubric Line, bordering the Austroalpine nappe stack with Late Cretaceous extensional Gosau basins toward the south. The only indication of eoalpine orogenesis nearby the Southalpine is documented by a drastic change in the Upper Cretaceous marine sedimentation in the still existing extensional basins with the input of siliciclastics, Flysch-like deposits with rare chrome spinell (Castellarin et al. 2006).

During the Paleogene compressional deformation occurred and the Dolomites became a foreland basin, a process related to the Dinaric post-collisional orogeny. Predominantly the eastern Dolomites have been affected by a WSW- to SW-vergent thin-skinned thrust belt (Doglioni 1987). Toward NE (Comelico, Carnia) also the crystalline basement was involved in the frontal ramp tectonics (Castellarin et al. 2004, 2006).

With the Neogene Valsugana structural system, i.e. the alpine retrowedge, the Venetian basin became the foreland of the Dolomites. Strong overthrusts in a SSE direction are indicated by uplifting of the hanging wall of the Valsugana thrust of approximately 4 km in the upper Miocene (Castellarin et al. 2004, with references). Remnants of the Oligocene/Miocene coastline are preserved at ca. 2.600 m altitude at the southern flank of Monte Parei in the Eastern Dolomites (Keim & Stingl 2000).

3. The Field Trip

3.1. The Pufels/Bulla road section: from the Permian-Triassic Boundary (PTB) to the Induan-Olenekian Boundary (IOB)

General remarks

The Pufels/Bulla section offers an excellent opportunity to study the Permian-Triassic boundary (PTB) and the Lower Triassic Werfen facies and stratigraphy in a nearly

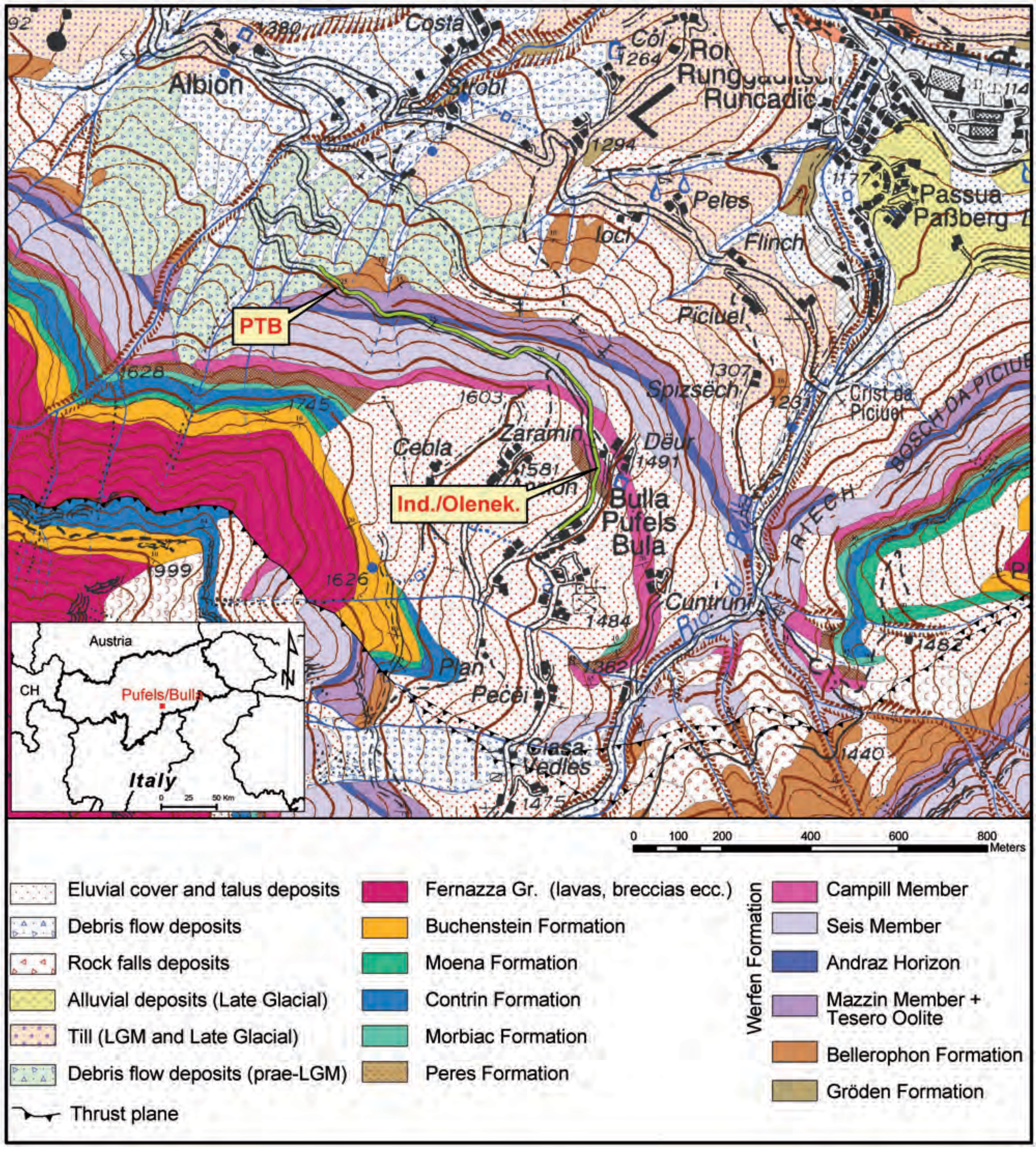


Fig. 4: Geologic map with excursion route (red-green) along the old road to Pufels/Bulla. PTB = Permian-Triassic Boundary. Geologic map after „Geologische Karte der Westlichen Dolomiten 1:25.000“, Autonome Provinz Bozen-Südtirol, Amt für Geologie und Baustoffprüfung, Bozen/Kardaun, 2007.

continuous section that reaches from the PTB to the Induan/Olenekian boundary (IOB) located within the Campill Member (Fig. 4). Based on this key-section at Pufels/Bulla we want to stimulate the discussion on questions of the "system earth", i.e. genetically related correlations of lithofacies, sea-level changes, anoxia and stable carbon and sulphur isotope curves. Magnetostratigraphy enables a direct comparison with continental sedimentary sequences of the German Zechstein and Buntsandstein to understand sequence stratigraphy, cycles and regional climatic influences.

The Pufels/Bulla section is well known for its excellent outcrop quality as well as findings of conodonts constraining the Upper Permian, PTB and Lower Triassic succession. Investigations on lithostratigraphy and biostratigraphy have been carried out by Mostler (1982), Perri (1991) and Farabegoli & Perri (1998). Integrated studies of lithostratigraphy, magnetostratigraphy and chemostratigraphy have been carried out by SCHOLGER et al. (2000), KORTE & KOZUR (2005), KORTE et al. (2005), FARABEGOLI et al. (2007) and HORACEK et al. (2007a). A comprehensive review is given by POSENATO (2008).

Lithostratigraphy and depositional environments

The shallow marine sediments of the topmost Bellerophon Fm. and Werfen Fm. were deposited on a very gentle, NW-SE extending ramp. The coastal plain environment of the upper Gröden Fm. was present in the west while a shallow marine, mid and outer ramp environment of the Bellerophon Fm. could be found in the east. The Bellerophon Fm. shows several cycles representing 3rd order sequences within a general westward prograding sedimentary wedge. The overlying Werfen Formation consists of a strongly varying sequence of mixed terrigenous siliciclastic and carbonatic lithofacies, organized in T/R-cycles of different order and frequency. These 3rd order depositional sequences (see DE ZANCHE et al. 1993, GIANOLLA et al. 1998) are composed of 4th order cycles of storm layers (thickening or thinning upward) and may have been orbitally forced. For detailed descriptions of lithology and biostratigraphy see BROGLIO LORIGA et al. (1983). The PTB mass extinction of carbonate producing organisms prevented the evolution of a rimmed shelf area during the entire Lower Triassic. After this exceptionally long lasting recovery period of reefal buildups in the whole Tethys area, the first appearance of reef building organisms occurred in the lower Middle Triassic, the nearby situated Olang/Valdaora Dolomites (BECHSTÄDT & BRANDNER 1970). The lack of reefal buildups and binding organisms may have caused the extreme mobility of vast amounts of loose carbonate and siliciclastic sediments that have been removed repeatedly by storm-dominated, high-energy events. These processes generated a storm-dominated stratification pattern that characterises the specific Werfen facies. Applying the concept of proximality of storm effects (AIGNER 1985), i.e. the basinward decrease of storm-waves and storm-induced currents, we tried to interpret relative sea-level changes from the stratigraphic record. Proximal and distal tempestite layers are arranged in shallowing-upward cycles (parasequences) but also in deepening-upward cycles depending on their position within the depositional sequences. However, numbers of cycles and cycle stacking patterns vary from section to section according to the position on ramp. The main control for these sedimentary variations seems to be the ratio between accommodation space and sediment supply, which follows the variable position of the base level (see base level concept from WHEELER 1964). Variations in base level determine the geometry of progradational, aggradational and retrogradational stacking patterns of the individual sedimentary cycles. Base level, however, does not automatically correspond to sea-level.

Reviewing the published data of magnetostratigraphy and chemostratigraphy, calibrated with bio-chronostratigraphy, POSENATO (2008) assigned radiometric ages to the Lower Triassic sequence of the western Dolomites. Assuming that the duration from PTB to IOB is roughly 1.3 Ma, the total sediment thickness of 200 m in the Pufels section results in a sedimentation rate of 1 m/6.5 ka, uncorrected for compaction. This rather high sedimentation rate not only suggests a high frequency of storm events (hurricanes), but also stresses the exceptional environmental conditions during this period and may indicate a lack of dense vegetation in the hinterland.

Since the 19th century several attempts have been made to subdivide the Werfen beds into mapable lithostratigraphic units: (1) in a first step, WISSMANNN 1841 (lit. cit. in POSENATO 2008) made a simple subdivision according to the grey and red colours of the interbedded marls in Seisser Schichten and Campiler Schichten; (2) Recent research

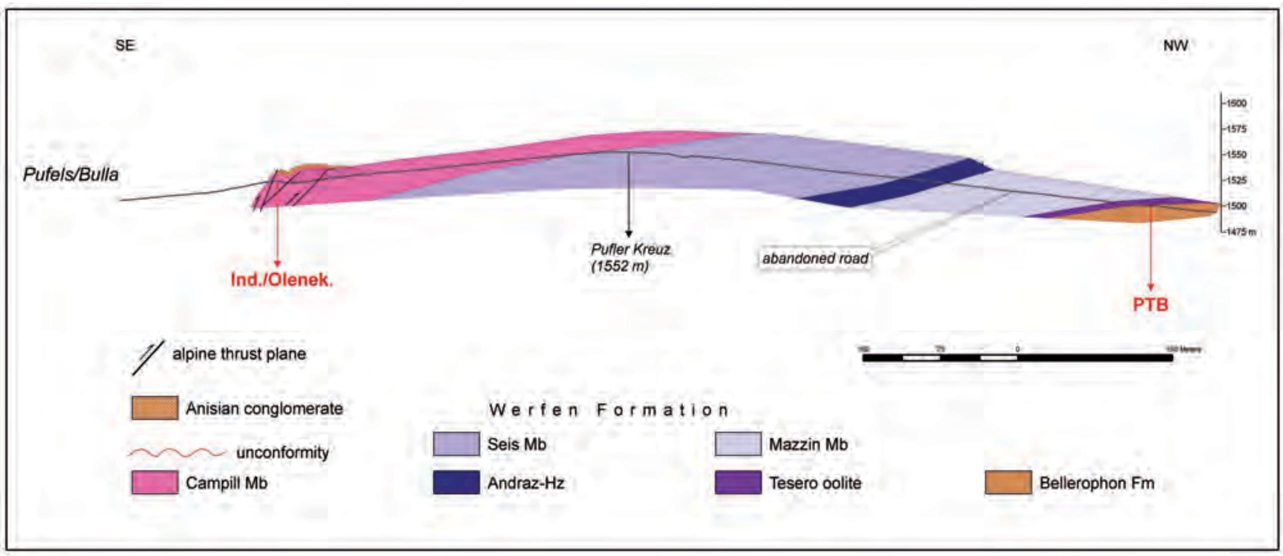


Fig. 5: Section through the Werfen Formation along the abandoned road to Pufels/Bulla. The top of the section is deformed by ramp folds, which can be restored bed by bed. Upper Anisian conglomerates ("Richthofen Konglomerat"/ Peres Formation), which record upper Anisian tectonic uplift by block tilting and strong erosion, overlie unconformably the lower part of the Campill Member.

in sedimentology and biostratigraphy by Bosellini (1968), Broglio Loriga et al. (1983, 1990) and others enabled a division of the Werfen Formation - still an informal unit - into 9 members (Tesero, Mazzin, Andraz, Siusi/Seis, Gastropodenoolith, Campill, Val Badia, Cencenighe, San Lucano) which correspond pro parte to depositional sequences (De Zanche et al. 1993). In general, the Werfen Formation is characterized by subtidal sediments, but intra- to supratidal levels with evaporitic intercalations are present within the Andraz, Gastropodenoolith, the base of Val Badia, Cencenighe and San Lucano members.

Stratigraphic terminology

The historical lithostratigraphic units "Seiser Schichten" and „Campiler Schichten" are now considered members (Siusi/Seis Mb. ("Siusi" is the Italian translation of the German name of the village Seis) and Campill Mb.) but with different usage of the lower and upper boundaries depending on the individual research groups. This mismatch of lithostratigraphic definitions has been ignored by some authors especially from outside of Italy, which resulted in wrong and confusing correlations of biostratigraphy, magneto- and chemostratigraphy (for further information see the review of Posenato 2008).
Due to relative sea-level changes, facies belts shift on the gentle ramp in time and space, with the consequence that lithologies are arranged in cycles and therefore are repetitive. In such a situation it is rather obvious, that members as lithostratigraphic units also shift in time. Hence the defined boundaries of the members are not always isochronous. More stratigraphic studies, which are independent of local facies developments, such as

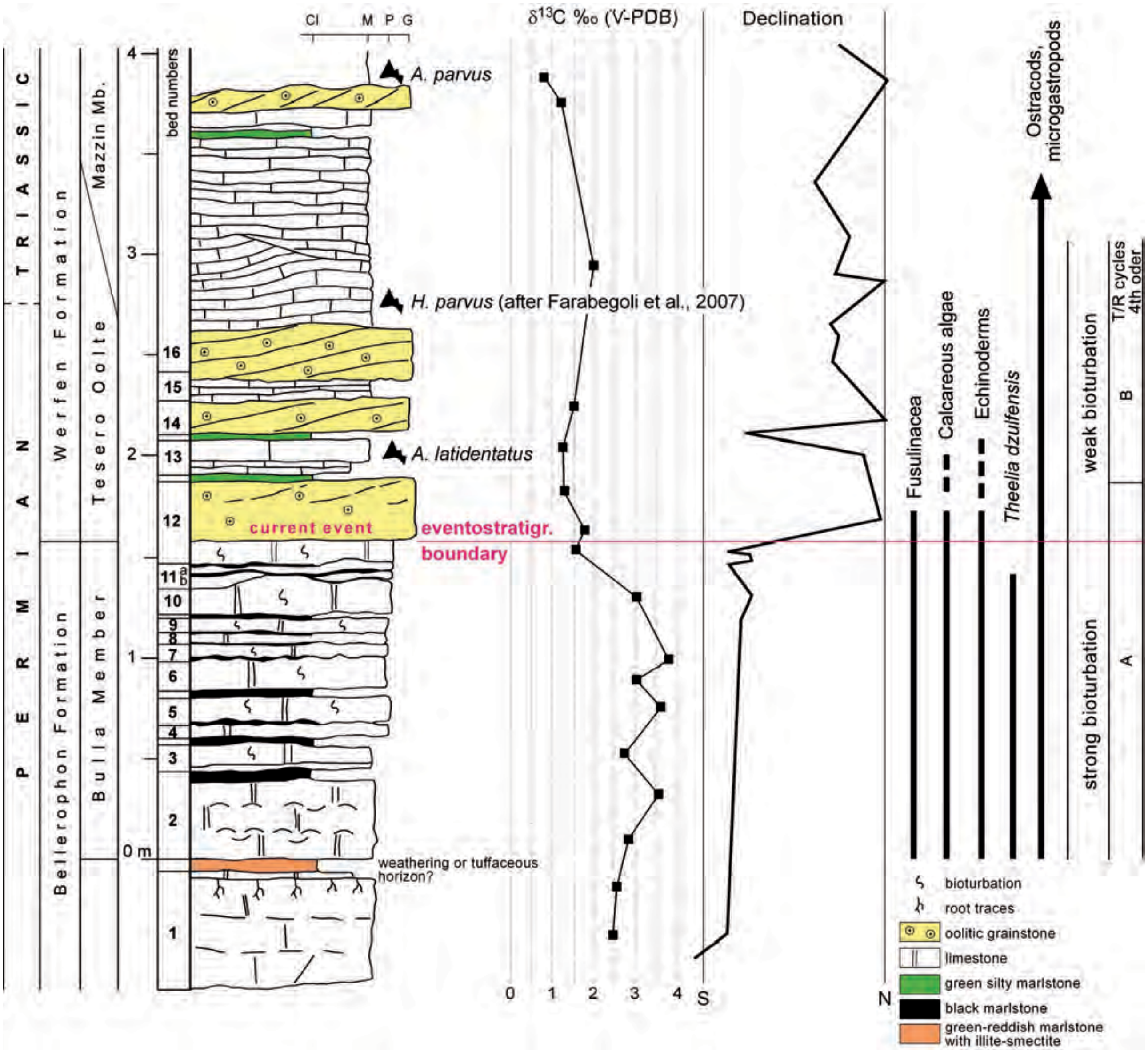


Fig. 6: Detailed measured section of the Permian-Triassic Boundary with litho-, bio-, chemo- and magnetostratigraphy. Conodonts and position of the PTB after Mostler (1982) and Farabegoli et al. (2007), magnetic declination after Scholger et al. (2000), determination of selected microfossils by W. Resch and H. Mostler, Univ. Innsbruck, 1988, unpubl. (after Brandner et al. 2009).

magnetostratigraphy and chemostratigraphy, are needed for a better understanding of the sedimentary evolution and correlation of the successions.

Practicality for field mapping: detailed lithostratigraphic divisions are important for 3-D understanding of palaeogeography, but also for the resolution of tectonic structures. By mapping large areas in the eastern and western Dolomites we always encountered the problem of the correct determination of the “Gastropodenoolith Member“, particularly in areas with isolated outcrops or tectonic disturbances. This member is characterised by a high lateral variability in facies and thickness (Broglio Loriga et al. 1990) with storm layers of oolithic grainstones with microgastropods, and occasionally intraformational conglomerates (“Kokensches Konglomerat“). As these lithotypes occur in different positions in the Seis/Siusi and Campill Mbs, the boundaries of the “Gastropodenoolith Member“ have been defined differently depending on the authors. For geologic mapping in the field we used a practicable solution by defining the lower boundary of the Campill Mb. at the appearance of the first observable sandstone- or calcareous sandstone layers (unit D on top of the Siusi Mb. defined by Broglio Loriga et al. 1990). This terrigenous input marks a distinct break in the sedimentary development of the Werfen Formation and has a very wide palaeogeographical distribution. The stronger clastic input in the overall marine Werfen Fm. is genetically correlatable with the boundaries between Unterer/Oberer Alpiner Buntsandstein in the Austroalpine (Krainer 1987) and Lower/Middle Buntsandstein of Central Germany (Szurlies et al. 2003). The term “Gastropodenoolith“ will be used only as remarkable facies type but not as an individual lithostratigraphic unit (see Geologische Karte der Westlichen Dolomiten, 2007).

The Pufels/Bulla road section exposes the whole sequence from the PTB to the supposed IOB, i. e. uppermost Bellerophon Fm. and Werfen Fm. with Tesero Mb., Mazzin Mb., Andraz Mb., Seis Mb. and lower Campill Mb. Younger members of the Werfen Fm. are lacking in this area due to block tilting and erosion during the Upper Anisian (Fig. 5).

3.1.1 Outcrop 1 - Permian/Triassic Boundary

Bellerophon Fm.: the outcrop at the starting point of the section only shows the top of the formation with gray calcareous dolomite mudstones, and with vertical open tubes, interpreted as root traces (Fig. 6). The dolomites belong to the top of the “Ostracod and peritidal dolomite unit“ described by Farabogoli et al. (2007). They are covered by 4-cm thick, orange to green coloured marls, which probably represent a hiatus that represents a sequence boundary. The sequence “Ind 1“ starts with a sequence consisting of dm bedded, grey to dark grey fossiliferous packstones that are intercalated with irregular cm-thick layers of black carbonaceous marlstones. Bedding planes are wavy due to strong bioturbation. This 155 cm thick sequence is termed Bulla Mb. (Farabegoli et al. 2007).

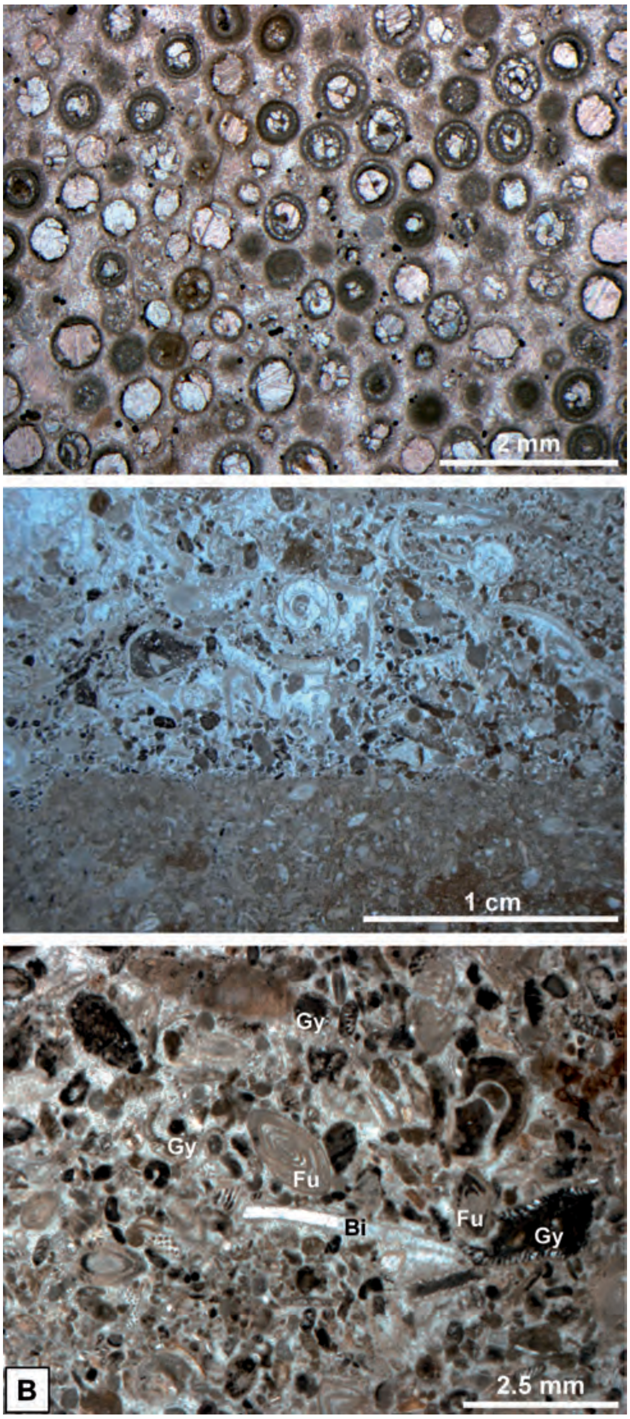


Fig. 7: Three thin-section photomicrographs from the uppermost Bellerophon Formation and the lowermost Werfen Formation. The lower thin section shows a fossil rich, skeletal packstone with typical fusulinids (Fu), red algae (gymnocods, Gy) and bivalves (Bi). The middle thin section shows a variably sharp contact between the fossiliferous packstone to a grainstone along a firm ground. An increase of hydrodynamic energy is documented by outwash of mud and reworking of intraclastic grains. Only a part of the grains is reworked (e.g., fusulinids). Contrary to Farabegoli et al. (2007) we do not see evidence for subaerial exposure. The uppermost image shows a typical oolitic grainstone from the Tesero Oolite.

Werfen Fm.*:* The Werfen Fm. starts with the Tesero Oolite Mb. within bed number 12 of the detailed section (Fig. 6). Fossiliferous packstones are overlain with a sharp contact by well washed, fossiliferous grainstones, 4 to 5 cm thick (Fig. 7), grading to grainstones with superficial ooids (5 cm thick bed) and cross bedded oolites (20 cm thick bed) on the top of the beds. The detailed description of this important environmental change was made possible by sampling the entire 40 cm thick bed in order to prepare a polished slab comprising the entire bed and 5 large thin sections. In contrast to the black carbonaceous marlstone layers of the Bulla Member, centimetre intercalations in the Tesero Oolite Member are composed of greenish terrigenous silty marlstones.

With the Tesero Oolite, at the base of the Lower Triassic Werfen Formation, we observe a fast, several tens of kilometres, westward shift of the shoreline that shows a typical onlap configuration, i.e. transgression and not regression as described from other areas in the world. The topmost Bellerophon Formation (cycle A in Brandner 1988; Bulla Member sensu Farabegoli et al. 2007) and the Tesero Oolite record severe environmental changes at the event stratigraphic boundary of the PTB and includes profound biotic extinctions, which coincide more or less with the well known negative carbon isotope excursion (Fig. 6). The event-stratigraphic boundary of PTB is situated ca. 1.3 m below the FAD of the conodont *Hindeodus parvus*, defining the base of the Triassic (see Mostler 1982 and Fig. 3 in Farabegoli et al. 2007).

The transition from fossiliferous packstones of the Bellerophon Fm. to the barren grainstones of the Tesero Oolite is characterized by a stepwise increase in the hydrodynamic energy (see bed 12, Fig. 6 and „current event" of Brandner 1988). These steps are recorded in three 4-5 cm thick storm layers without a significant unconformity or signs of subaerial exposure. Petrographic evidence suggests friable-cemented firm grounds on the sea floor. Borings show only poorly defined walls (Fig. 7). The uneven surface of the firmground only shows little erosion by storm waves. There is no evidence for vadose diagenesis. For a different interpretation see Farabegoli et al. (2007). The "current event" is to be found as well defined marker bed in the inner and outer ramp position as well, in western and eastern Dolomites (Figs. 8, 9).

On the contrary of Farabegoli et al. (2007), ooids are not leached (such as the oomoldic porosity of the Miami Oolite) but have nuclei of calcite crystals and sparry calcite cortices encrusted by micritic laminae. Calcite crystals show borings of endolithic algal filaments (Fig. 10) underlining their primary precipitation on the sea floor. Further investigations are needed to verify the possible primary low-magnesium calcite precipitation on the Permian-Triassic sea floor. The factors known to control the precipitation of calcium, i. e. low Mg/Ca ratios and faster growth rates (Chuodens-Sánchez & González 2009), would shed an interesting light on the assumed unusual seawater chemistry at the PTB.

Some ooids contain coatings of finely dispersed pyrite, but pyrite is also common in intergranular positions (in agreement with Wignall & Hallam 1992, Bond & Wignall 2010). Enhanced oxygen depletion in the surface water may have been caused by global warming and ocean heating (Horacek & Krystyn 2008, Shaffer et al. 2009, Joachimski et al. 2012). These processes would lead to an increase in alkalinity within a reducing, subtidal environment. The drop of the carbon isotope curve correlating with the Tesero Oolite may indicate an increase of isotopically depleted bicarbonate ions in seawater caused

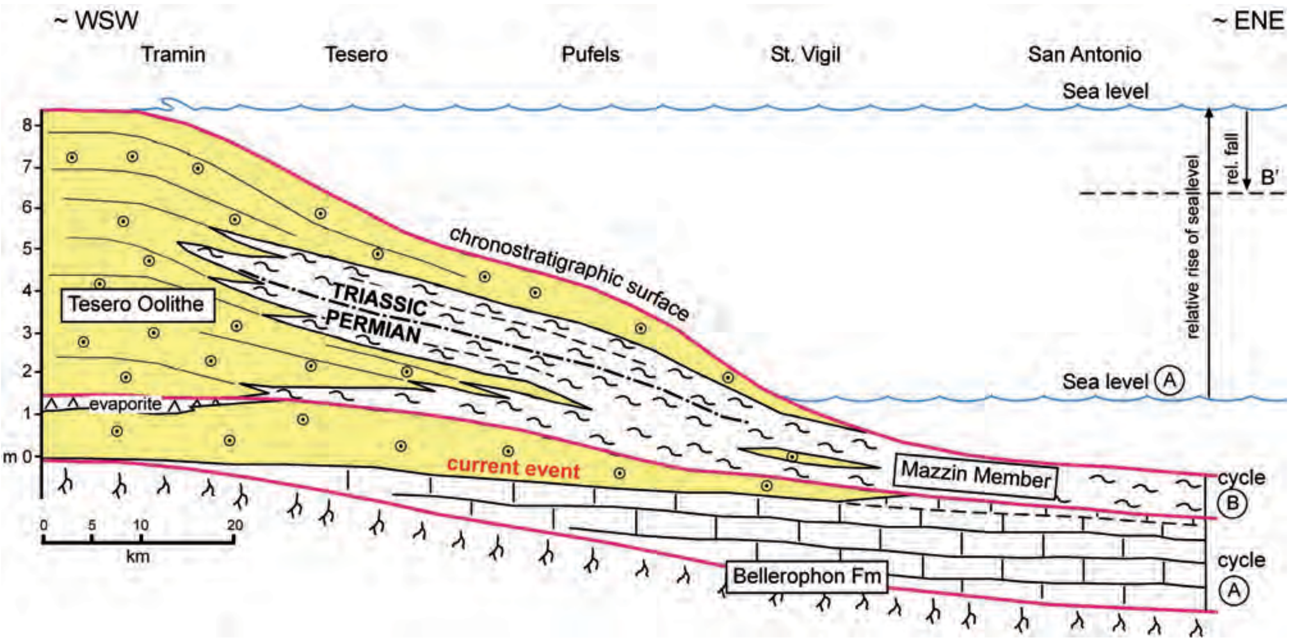


Fig. 8: Palaeogeographic cross section at the end of cycle B, based on correlation of parasequences by the marker bed „Current Event" and isotope stratigraphy of several detailed sections in inner and outer ramp position. Note the fast sea-level rise, which may be in accordance to the end Permian/ Lower Triassic global warming (Joachismki et al. 2012, Brandner et al, 2012). The alignment of the cross section is in WSW - ENE direction from western to eastern Dolomites (redrawn after Brandner 1988).

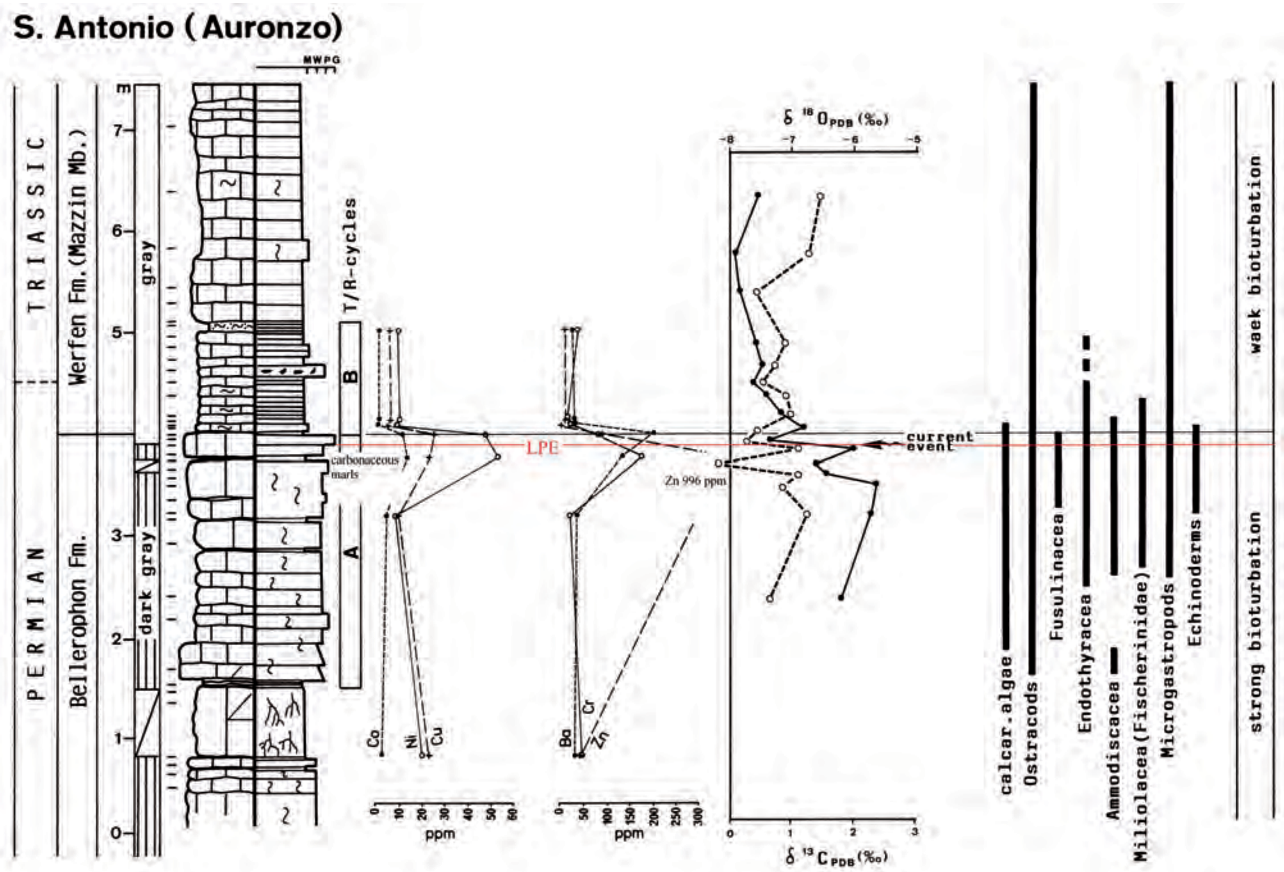


Fig. 9: PTB-section without Tesero Oolite in the outer ramp position for comparison (from BRANDNER 1988 with minor changes). LPE: position of the Latest Permian Extinction event. The San Antonio section was measured along a road-cut near the village Auronzo, east of Cortina d'Ampezzo, eastern Dolomites.

by the activity of sulphate reducing bacteria in a stratified ocean (Tethys as a "giant Black Sea", see KORTE et al. 2004, HORACEK et al. 2007b). An increase in the amount of HCO_3 and temperature elevation forces precipitation of calcite on the sea bottom. The synchronous rise of ^{34}S in correlative sections nearby (Seis/Siusi, NEWTON et al. 2004 and Tramin/Termeno, BRANDNER 1988, HORACEK et al. 2010) supports this model, although there remains a problem of timing (see discussion below at Tramin/Termeno section). Carbonate seafloor crusts and fans and special types of oolites and oncolites are widespread in different levels of the Lower Triassic and are often connected to perturbations of the carbon isotope curve (PRUSS et al. 2006, HORACEK et al. 2007a, b).

Synchronously to the pronounced increase in hydrodynamic energy in the shallow water environment at the event-stratigraphic boundary of the PTB, an increase in humidity and freshwater discharge is documented at the beginning of the continental Buntsandstein facies. This interpretation is based on the magnetostratigraphic correlation of the Pufels/Bulla section and sections of the continental facies realm of the Germanic Trias (SZURLIES et al. 2003, HUG & GAUPP 2006).

Mazzin Member

The contact of the Tesero Oolite to the Mazzin Member is transitional (Fig. 11); some beds of Tesero Oolite occur intercalated within dm-bedded, nearly unfossiliferous grey limestones (structurless mudstones, sometimes microbial structures). The oolite intercalations are interpreted as sand

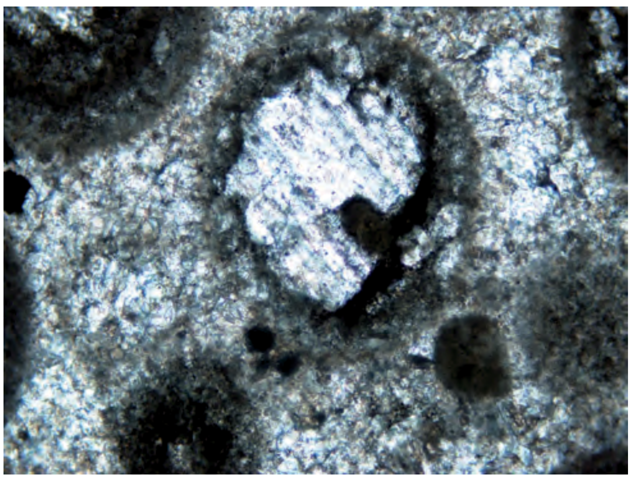


Fig. 10: Thin-section photomicrograph of a single ooid grain (diameter 0.6 mm) of the Tesero Oolite (type "crystalline oolite"). Borings of endolithic algae on the surface of the calcite crystal in the nucleus prove the primary precipitation of calcite on the sea floor. Note also early diagenetic pyrite crystals (black squares) in the pore space.

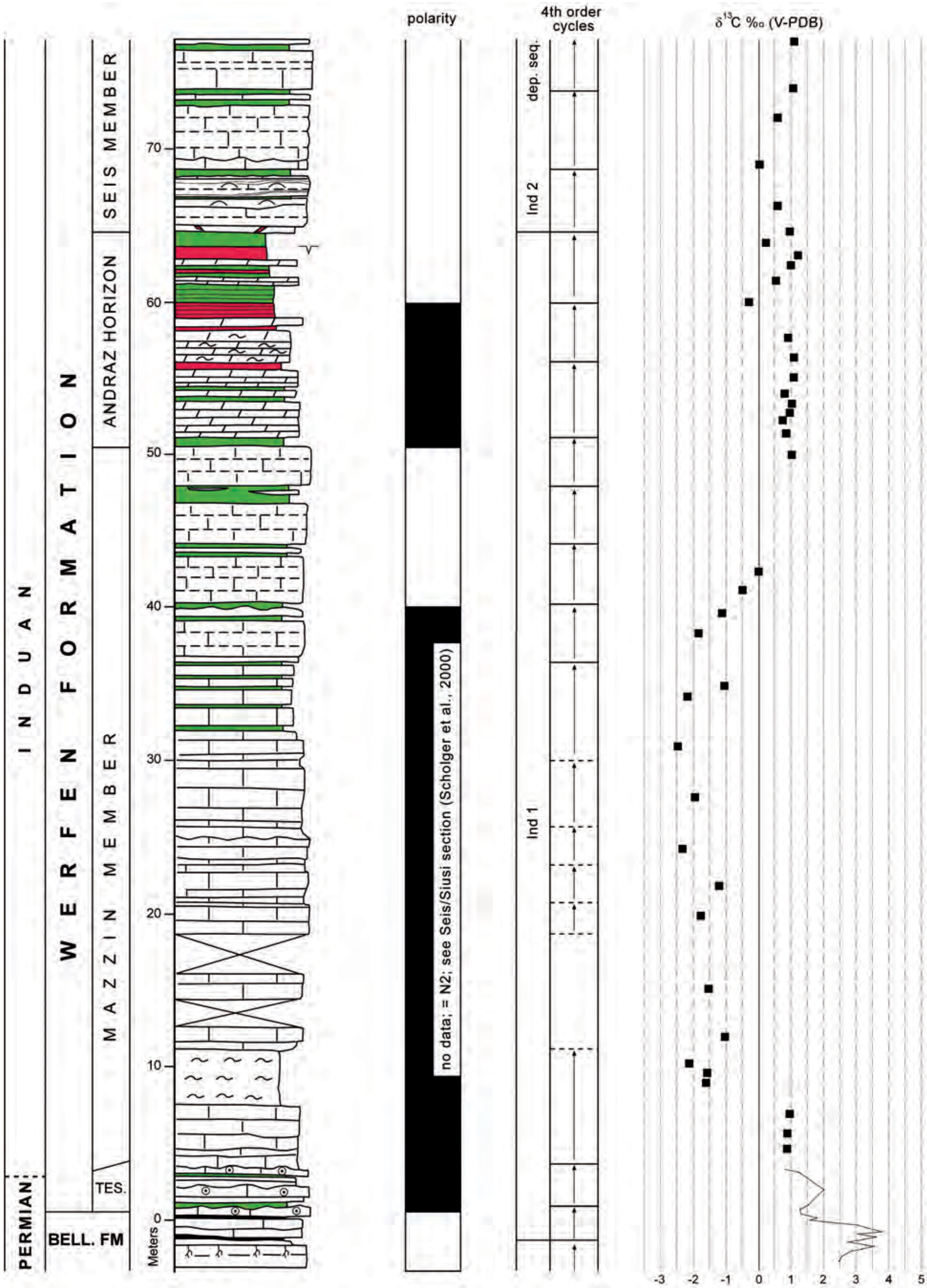


Fig. 11: Pufels/Bulla road section with correlations based on lithostratigraphy, magnetic polarity (Scholger et al. 2000 and new data for the Andraz Member in Brandner et al. (2009), sequence stratigraphy and 13C curve (Horacek et al. 2007a). We revised the definition of the sequences and renamed them according to the new terms of the stages to avoid confusion with the terms of the sequences interpreted by De Zanche et al. (1993). For legend see Fig. 12.

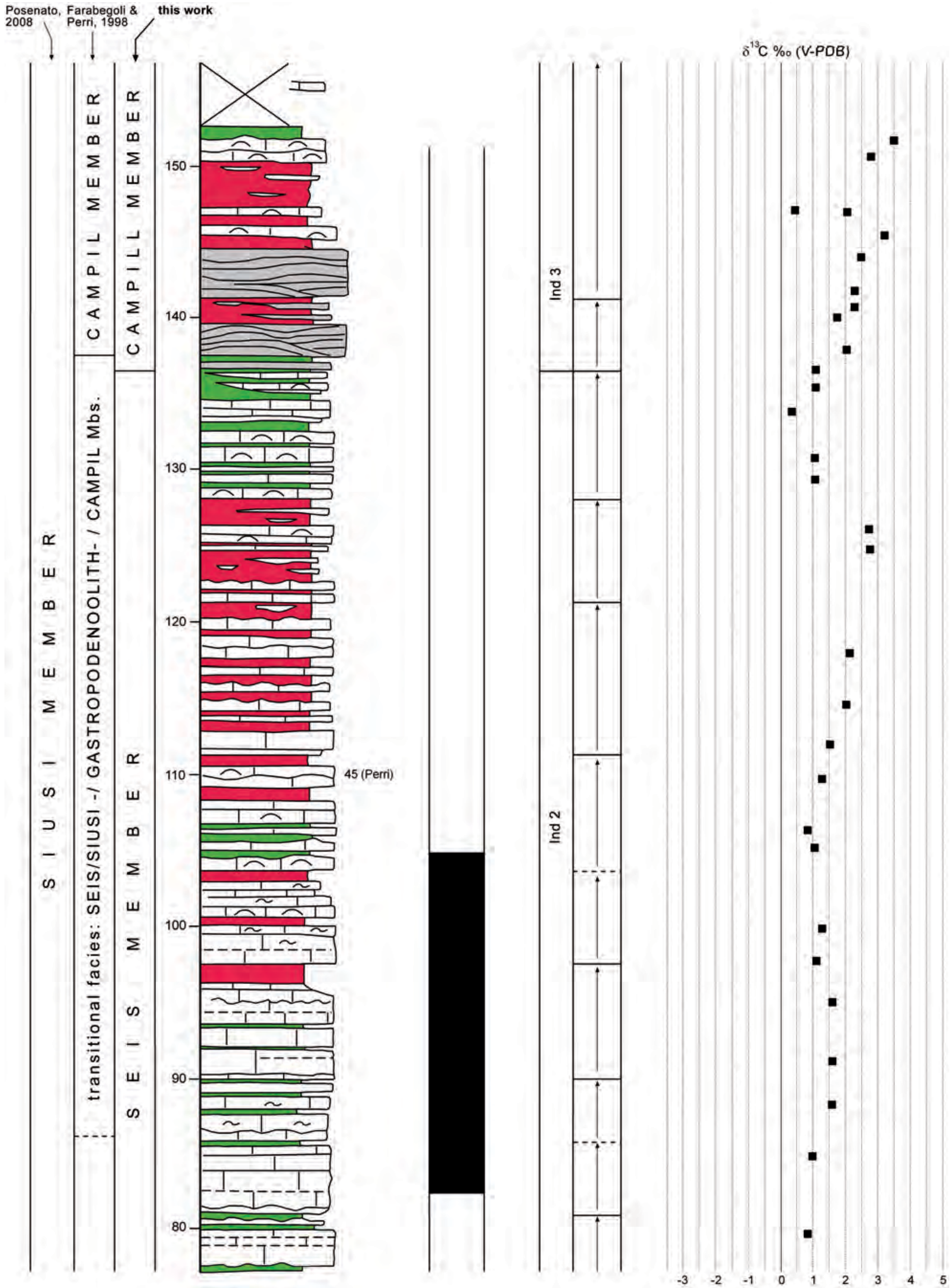


Fig. 12: Upper part of the Pufels/Bulla road section with correlation of lithostratigraphy, magnetostratigraphy and chemostratigraphy (adopted from SCHOLGER et al. 2000 and HORACEK et al. 2007a). Induan/Olenekian boundary after HORACEK et al. (2007a), following the proposal for a GSSP-section (MO4), see KRYSTYN et al. (2007). Note that the arrows of the meter-scaled cycles do not indicate automatically shallowing upward.

waves or sheets of ooid sand accumulating in a mid to outer ramp position. They are fed by about 10 meter thick sand bars which are preserved in the depositional environment as a barrier island and outcrop in the Tramin/ Termeno section (see Chapter 3.3) about 40 km SW of Pufels. The repeated migration of oolitic sand to the shelf area may have been controlled by cyclic sea-level lowstands and storm-dominated transport. Oolitic grainstone layers disappear upward in the section, emphasizing the transgressive trend of the depositional sequence.
A very characteristic lithotype that occurs in the middle part of the section are "streaked" mudstones: beds of grey limestones or marly limestones with low content of silty quartz and micas with mm- to cm thick planar laminae of graded bioclastic packstones (mostly ostracods). They are interpreted as distal storm layers. Streaked mudstones alternate with structureless, bioturbated mudstones generating meter-scaled symmetrical cycles. Mudstones with strong bioturbation correspond to the time-equivalent vermicular limestones in Iranian sections (e.g., Horacek et al. 2007), or the Lower Anisian "Wurstelkalke" in the Austroalpine realm.
The upper part of the section shows an increase in terrigenous input. Meter-scale cycles with thickening storm layers of bioclastic packstones are capped by greenish marlstones suggesting a shallowing-up trend (Fig. 11). This trend results in the predominance of multicoloured laminated siltstone with wave ripples and mud crack structures at the top of the depositional sequence (Ind 1).

3.1.2 Outcrop 2: Supratidal/subtidal facies

Andraz Member

The peritidal unit consists of a cyclic alternation of marly-silty dolomites, locally cellular, laminated silty marls and siltstones with a typical mud-flat facies. As there is no clear interruption in the sequence, we propose that progradation of the coastal tidal flat facies rather than a distinct drop of the sea level formed this sequence.
New artificial outcrops of the Andraz Member (this unit is usually completely covered) that were excavated along the abandoned road and those that were made during the construction of the gallery of the new road to Pufels enabled the measurement of a detailed section and high-resolution sampling for magnetostratigraphy and carbon isotope

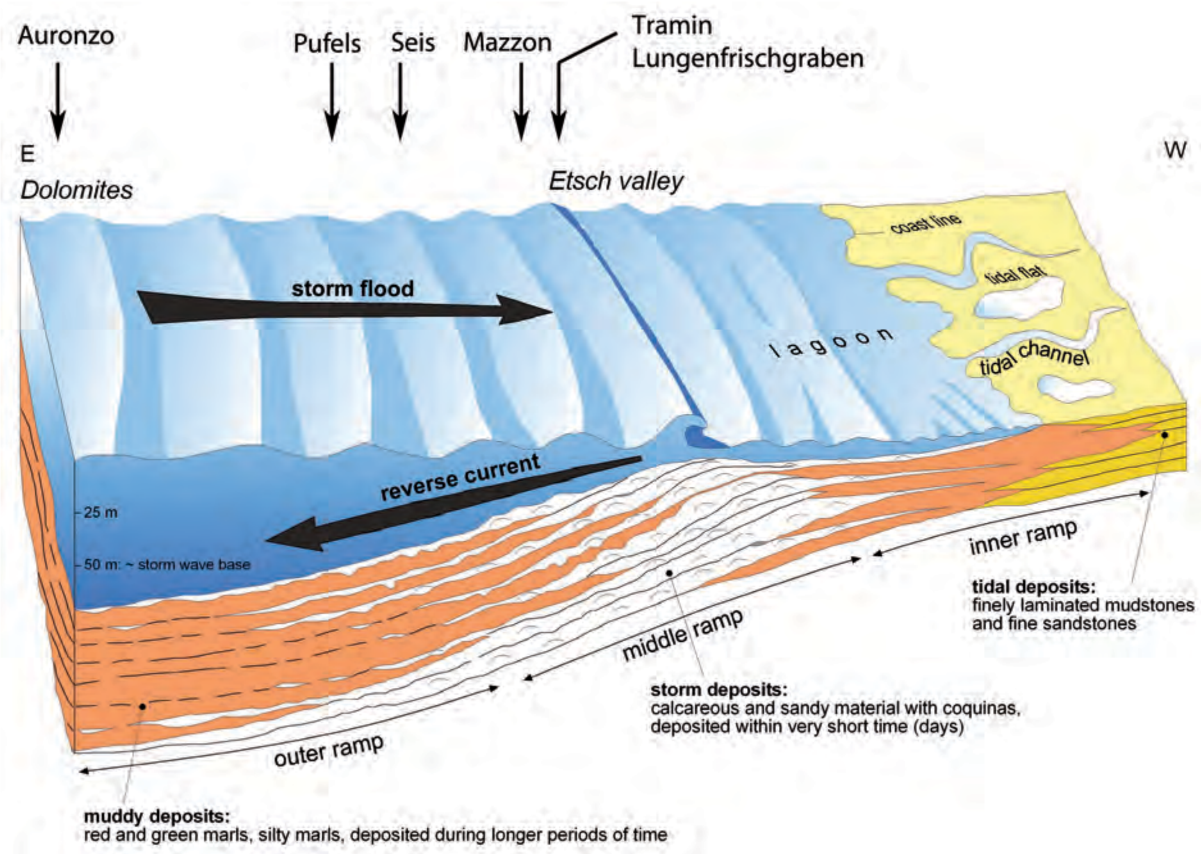


Fig. 13**:** Schematic model for the deposition of the Werfen Formation on an east-dipping ramp (superelevated). Sedimentation is essentially controlled by storms; the coast line is supposed to be far to the west near the Como Lake. Mud deposits, now red and green marls, alternate with layers of sand with bivalve and gastropod shells. Each limestone bed is the product of a storm event and is deposited within some days. Storms generate energy-rich, seafloor-touching waves, which, especially in the coastal zone, are eroding and swirling up the mud and sand on the seafloor. Consequently, bivalve and gastropod shells are washed out and enriched separately forming coquina beds (see Fig. 14) (after Brandner & Keim 2011). Note the positions of index sections Pufels/Bulla, Seis/Siusi and Tramin/Termeno which will be vistited in our excursion.

analyses (Fig. 11).

Seis/Siusi Member

The Seis Member is a sequence of interbedded limestones and silty marlstones with a greenish colour in the lower and reddish one in the upper part. The ubiquitous content of terrigenous quartz and micas, always in the same silt grain size, reveal an air blown silt transport from the hinterland in the west. Limestone beds show textures typical for tempestites. In general they consist of graded litho- and bioclastic packstones and wackestones (often shell tempestites) with bed thicknesses ranging between centimetres and a few decimetres. The base of the beds mostly is sharp and erosional, scours and gutter casts are present. Wave-ripples with wavelengths up to 100 cm are common often causing a lenticular shape of the beds. Hummocky cross stratification occurs at the base of the rippled beds.

A special lithotype is the "Gastropodenoolith". Individual tempestite beds consist of reddish grainstones and packstones with oolites and microgastropodes (often with internal sediments or ferroan dolomite spar fillings and glauconite which do not correspond to the matrix of the packstones). Another one is the "Kokensches Konglomerat", an old term used by German authors, which consists of a conglomerate with flat pebbles. Both lithologies are handled as "leading facies types" for the Gastropod Oolite Member. Unfortunately both types are to be found in the lower and upper part of the Seis Member as well as in the Campill Member, complicating the definition of the Gastropod Oolite Member (see above).

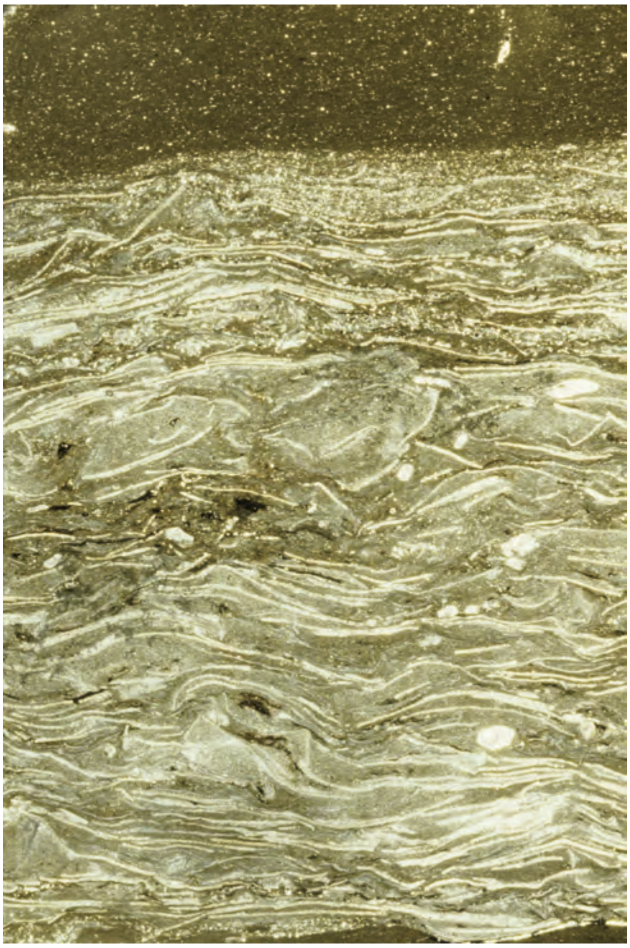


Fig. 14: Thin section photomicrograph of a typical coquina tempestite with *Claraia clarai* and grading (Seis/Siusi Member).

Tempestite proximality (thick-bedded tempestites are more proximal (= shallower) than thinner bedded tempestites (= deeper)) enables the grouping of beds in thickening- or thinning upward cycles on the scale of few meters (Fig. 12). The lithofacies comprise both the upper shoreface and the offshore environment. Hummocky cross stratification and gutter casts indicate the lower shoreface facies and offshore facies of a high-energy type of coast (Fig. 13).

The Seis Member overlies the Andraz Member with a well-preserved erosional unconformity which is interpreted as SB at the base of the depositional sequence Ind 2 (Fig. 11). The sequence starts with a transgressional package of well-bedded tempestites characterized by rip up clasts (flat pebbles), microgastropodes and glauconite.

The onset of reddish marlstone in the upper part of the member signalises a better oxidation of the sea bottom, which may be a consequence of a lower sedimentation rate or better circulation of bottom water. Reddish marlstones in the upper part of the Seis Member are distributed in the western and eastern Dolomites, but their isochronous onset is not demonstrated. Toward the boundary with the Campill Member the predominance of offshore facies in the cycles shifts once more to a shoreface facies with thickening of shell tempestites and scour fillings.

Biostratigraphic remarks: The Seis/Siusi Member in the Dolomites is known for the abundance of *Claraia* specimens defining the *Claraia* Zone (Fig. 14). The subzones with *Cl. wangi-griesbachi*, *C. clarai* and *C. aurita* occur in the upper Mazzin, lower and upper Seis members (Broglio Loriga et al. 1990, Posenato 2008). In the Pufels/Bulla sections several findings of *Claraia* specimens have been documented by Mostler (1982).

3.1.3 Outcrop 3: Siliciclastic input, climate signal

Campill Member

The start of the Campill Member is defined here with the first distinct occurrence of quartz/mica sandstones. Half meter- to meter-thick calcareous sandstone beds with hummocky cross stratification and a remarkable glauconite accumulation represent the transgressive phase of sequence Ind 3. The beds grade to thinner bedded storm layers (bioclastic shell tempestites) forming thinning upward cycles on the scale of several meters (Fig. 15). U-shaped burrows interpreted as *Diplocraterium* burrows, microripples and wrinkle structures are remarkable sedimentary structures in this part of the section. Most typical are "Kinneyia" structures, mm-scale winding ridges resembling small-scale interference ripples. After Porada & Bouougri (2007) these structures formed underneath microbial mats and are usually preserved on flat upper surfaces of siltstone or sandstone beds.

From ca. 152 m to 186 m section along the road is mostly covered. The next outcrops at the top of the section show

Fig. 15: Lower part of the Campill Member with thinning upward cycles of tepestite beds. Road cut of the abandoned road to Pufels/Bulla. Scale: 2 meters. Photo courtesy of Lois Lammerhuber, Vienna.

some folding and ramp folds, but exact balancing of the stratigraphy by retrodeformation is possible.

The last 20 meters of the section are important for two reasons: (1) a prominent change is present in facies development from peritidal to subtidal offshore environment, and (2) this change is accompanied by a strong negative shift in the carbon isotope curve which is correlatable to the proposed GSSP section of the Induan-Olenekian Boundary M0 4 in Spiti, Himalaya (Krystyn et al. 2007). Peritidal cycles are made up of greenish to reddish silty and sandy marls with wave ripples and mud cracks alternating with dm-bedded silty bioclastic limestones and a few yellowish oolitic dolomites and marly dolomites. Posenato (2008) termed this unit "lithozone A" of the Gastropod Oolite Mb. in the definition of Broglio Loriga et al. (1990). Two thinning upward cycles with some dm-thick amalgamated hummocky cross-stratified silty limestone beds at their base represent the transgressive phase of sequence "Ole 1" (accepting the strong negative carbon isotope excursion as a proxy for the IOB). The background sedimentation is still composed of red silty and sandy marlstones. Rare dark gray to black laminated marlstones may indicate short intervals of decreasing oxygen at the sea bottom.

The road section ends with the upper Anisian erosional unconformity on top of the lower part of the Campill Member. Upper Anisian Conglomerates (Voltago-/Richthofen Conglomerate) directly overlie red siltstones, sandstones and silty marls.

Summary

The lithostratigraphic and sedimentologic study has enabled the identification of meter-scale transgressive-regressive cycles (parasequences) in peritidal to subtidal depositional environments. Associations of the parasequences constitute, with varying stacking patterns, four depositional sequences that may have regional significance as shown by Horacek et al. (2007a, b) who carefully correlated the stratigraphy of several sections in the Dolomites and Iran. The main excursions of the carbon isotope curve can be correlated to sequence stratigraphic boundaries: (1) transgressive systems tract (TST) of sequence Ind 1; (2) TST of Ole 1 (see also Krystyn et al. 2007); and (3) the TST at the base of the Val Badia Member (not preserved in the Pufels section). This would imply that the profound changes in the global carbon cycle in the Lower Triassic are forced by eustatic sea-level changes. The TSTs of the sequences Ind 2 and Ind 3 are not clearly mirrored by the carbon isotope curve at Pufels.

Only in the transition towards more terrigenous input, i.e. at the base of the Campill Member, irregularities in the trend of the carbon isotope curve are present. More conspicuous is a negative shift in the Iranian sections (Horacek et al. 2007). On the other hand, the regional importance of the terrigenous input signal is evidenced by the magnetostratigraphic correlation with the continental facies of the German Triassic. Equivalent to the terrigenous Campill event in the Southalpine and the Upper Buntsandstein in the Austroalpine, the Volpriehausen Formation at the base of the Middle Buntsandstein starts with the first basin-wide influx of coarse grained sands (Szurlies 2004). These distinct breaks in sedimentation style indicate a climate change to a more humid environment with increased rainfall and continental runoff.

3.2. Seis/Siusi section and the attempt of PTB high-resolution global correlation by carbon isotope investigation

The following chapter is based on an article by Horacek et al. (2010).

The Seis section is located in the Seiser Klamm/Gola di Siusi along the Weissenbach/Rio Bianco a bit more to the southwest with respect to Pufels (Fig. 1). For the ^{13}C isotope investigation (Horacek et al. 2010) sampling has been started in the Bellerophon Formation 16 m below the overlaying Tesero Oolite, then follows the Mazzin Member which has been sampled for 18 m. The magnetostratigraphic data has been published in Scholger et al. (2000). In Scholger et al. (2000) the eventostratigraphic boundary ("Current Event" in Scholger et al. 2000, Fig. 16) has been defined by the first occurrence of the oolites, however, re-examination of the thin sections revealed that the eventostratigraphic boundary (sediment change from wackestone to packstone with far less organic matter) only occurs 30 cm above the beginning of the oolite sedimentation ("Current Event" in Fig. 17). The findings by Scholger et al. (2000) have been adjusted to this datum. *Hindeodus parvus* first appears about 1.45m above the eventstratigraphic boundary (H. Mostler, Innsbruck University, oral communication 1988).

Comparison of the Seis and Pufels data shows exceptionally good agreement not only in the $\delta^{13}C$ pattern, but also in sedimentation rate and facies development in the Lower Triassic (Fig. 18), evidencing very similar environmental conditions at both localities. Note that the uppermost Permian Bulla Member has a different thickness in the two investigated sections.

In the Seis section there might be a small gap at 0 m, as there is a small step in the $\delta^{13}C$ curve from more than 2.5‰ to less than 1.5‰. Further upwards, at approximately 5 m above the Current Event, there is a step in the Pufels isotope curve from +1 to -1.5‰. This also might be an indicator of a small hiatus; however, as the sampling is less detailed at this interval in the Pufels section and the Seis section curve also shows a very steep drop, the step can be better explained by simply a lack of samples at this interval. The magnetostratigraphic data correlated to the $\delta^{13}C$ isotope curves shows the reversal at the Event Boundary nicely correlating with a small positive peak that marks the beginning of the decrease in $\delta^{13}C$ across the PTB. Exact comparison of the PTB interval of both investigated sections reveals small differences in the sedimentation rate. Whereas in the Pufels section the eventostratigraphic boundary occurs directly above a steep decline in $\delta^{13}C$, in the Seis section there seems to be a

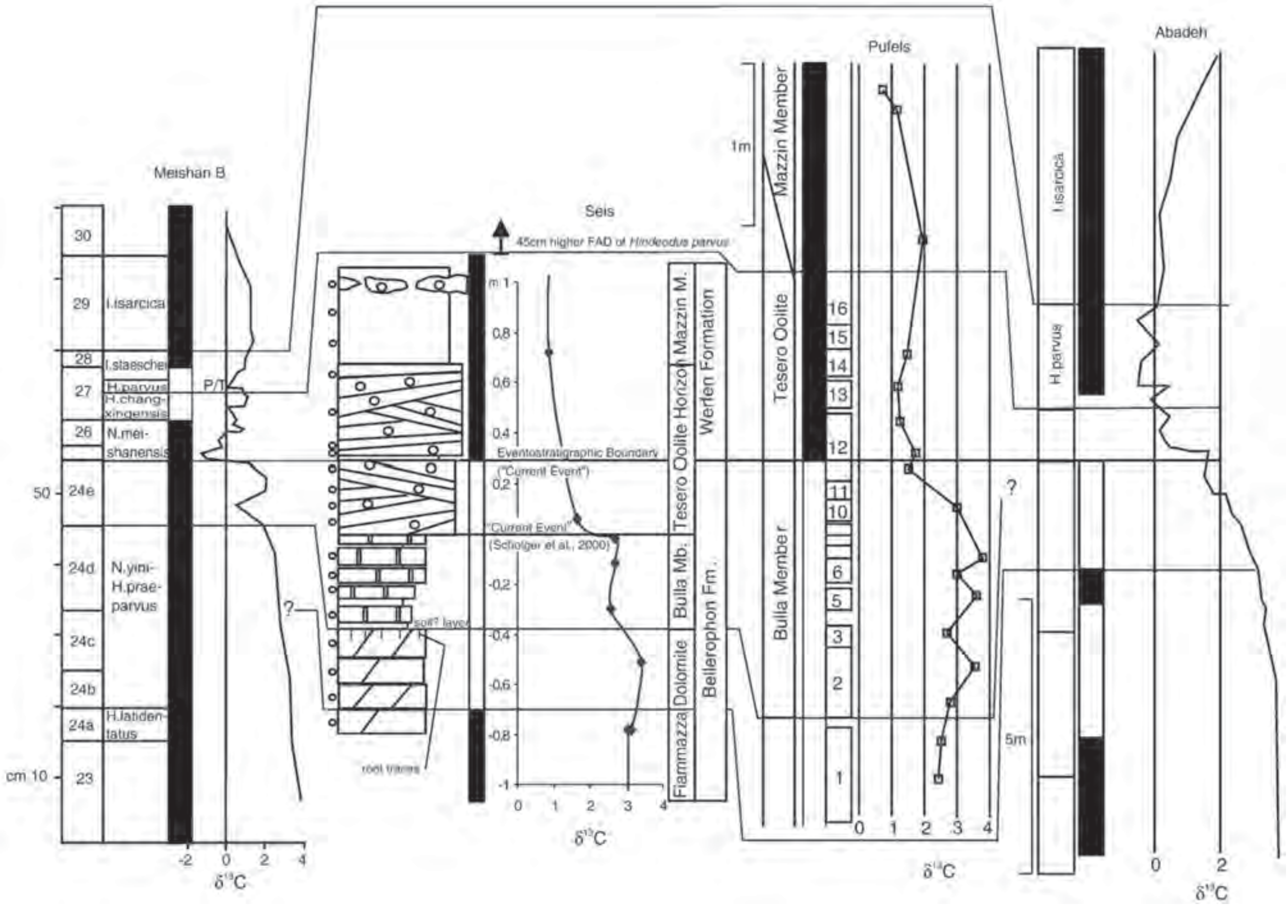


Fig. 16: Boundary detail of the $\delta^{13}C$ curve biostratigraphic data and magnetostratigraphic column of the Seis, Pufels (after Brandner et al. 2008), Abadeh (after Richoz et al. 2010) and Meishan (after Yin et al. 2001) sections. There is a good agreement between the Seis, Pufels and Abadeh sections; the magnetostratigraphy in Meishan (Yin et al. 2001) does not fit with the patterns in Pufels/Seis (Scholger et al. 2000) and Abadeh (Gallet et al. 2000). Numbered boxes in the Pufels section show bed numbering after Brandner et al. (2008, 2009), circles adjacent to Seis section show magnetostratigraphic samples of Scholger et al. (2000). In the Seis section 0 m denotes the lithologic boundary between the Bulla Member and the Tesero Oolite Horizon that was named "Current Event" in Scholger et al. (2000). The revised "Current Event" (Brandner et al. 2008, 2009) is 30 cm further upwards within the Tesero Oolite Horizon. After Horacek et al. (2010a).

larger part of the uppermost bed of the Bulla Member deposited just after the decline in $\delta^{13}C$ but before the eventostratigraphic boundary. This can be explained by subtle differences in the sedimentation rates of the sediment type. In the Pufels section there is bioclastic packstone, whereas in the shallower-marine Seis section there is an oolitic grainstone, which can have been deposited at higher sedimentation rate.

We find a good agreement between $\delta^{13}C$ curves and biostratigraphy in the sections Pufels/Seis and Meishan, when correlating the eventostratigraphic boundary in the Dolomites with the top of bed 24e in Meishan (Fig. 16). This assigns a *yini/praeparvus* age to the Bulla Member and a *meishanensis/praeparvus* and *changxingensis* age for the beds above the eventostratigraphic boundary and below the FAD of *Hindeodus parvus* (Jiang et al. 2007). This is also indicated by the occurrence of *N. changxingensis* found in the well correlatable Tesero section just below the FAD of *H. parvus* (Farabegoli et al. 2007).

H. praeparvus, the oldest conodont found in the Pufels section by Farabegoli et al. (2007), already occurs significantly below the PTB (see Jiang et al. 2007), and is therefore not indicative for the Meishan beds 25-26 of the latest Changhsingian. On the other hand, the palyno-floral overturn at the eventostratigraphic boundary in the Dolomites (Cirilli et al. 1998) seems to correlate nicely with the palynological change at the bas e of Meishan D bed 25 (Ouyang & Utting 1990, Utting et al. 2004). We therefore correlate the Bulla Member with Meishan D bed 24e.

Brandner et al. (2009) demonstrated that there is no gap in sedimentation at the eventostratigraphic boundary, thus the stratigraphic boundary between Meishan D bed 24d and 24e (e.g., Yin et al. 2007) has to be correlated with the clay layer below the Bulla Member (= sequence boundary). The Bulla Member starts with transgressive sediments (bed 2 in the Pufels section, Fig. 16), followed by packstone rich in fossils and intercalated with black marlstone representing deposits of the maximum flooding interval (beds 3-11 with the marlstone between the beds; Fig. 16), succeeded by oolitic sediment representing the shoaling

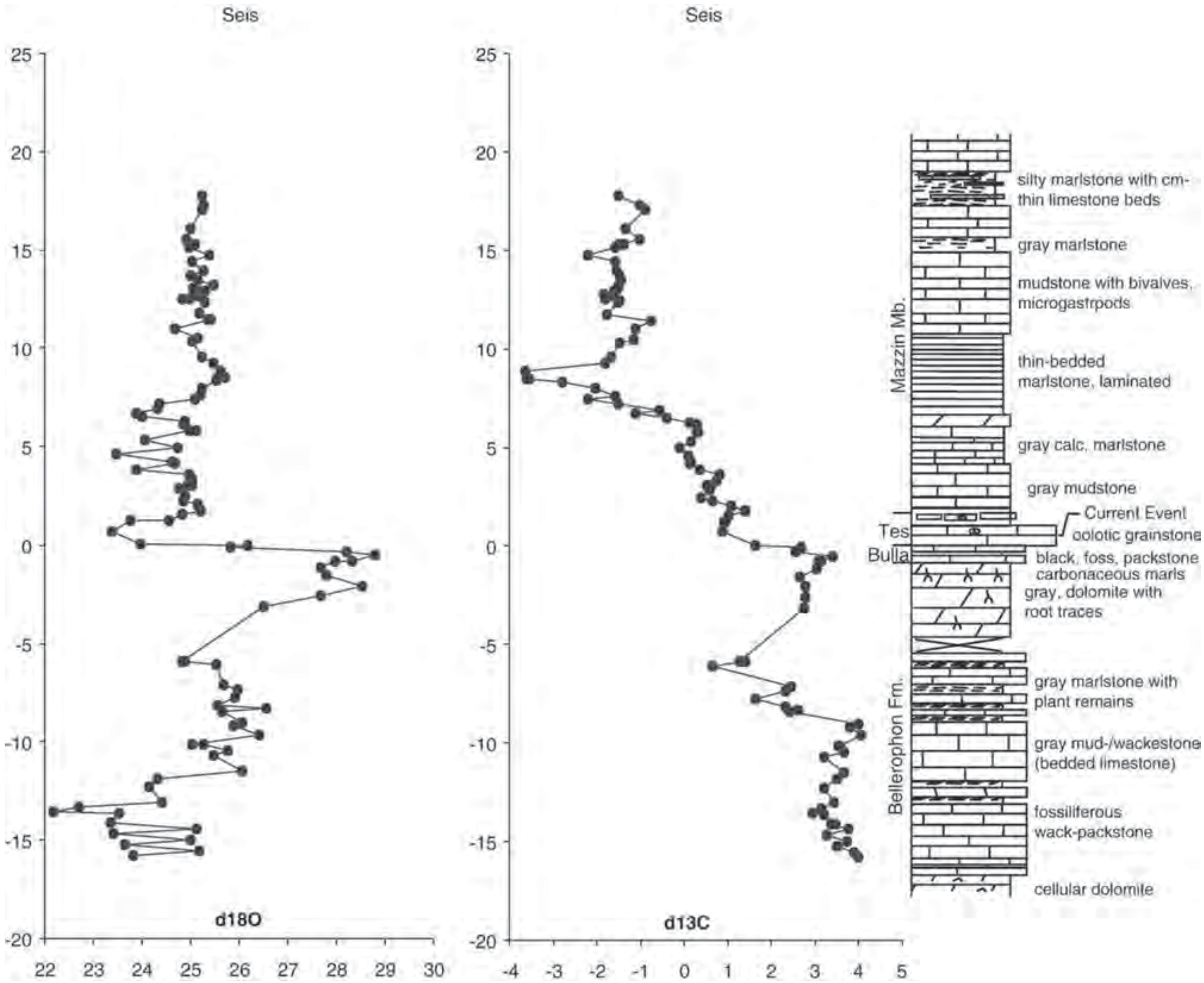


Fig. 17: $\delta^{13}C$ and $\delta^{18}O$ curves of the Seis section with lithologic profile. 0 m is base of Tesero Oolite Horizon (equivalent of "Current Event" Scholger et al. 2000). Current Event in figure marks eventostratigraphic boundary within the Tesero Oolite. Tes = Tesero Oolite Horizon, Bulla = Bulla Member, Mb. = Member, Fm. = Formation, calc. = calcareous, foss. = fossiliferous. Section height in metres. After Horacek et al. (2010a).

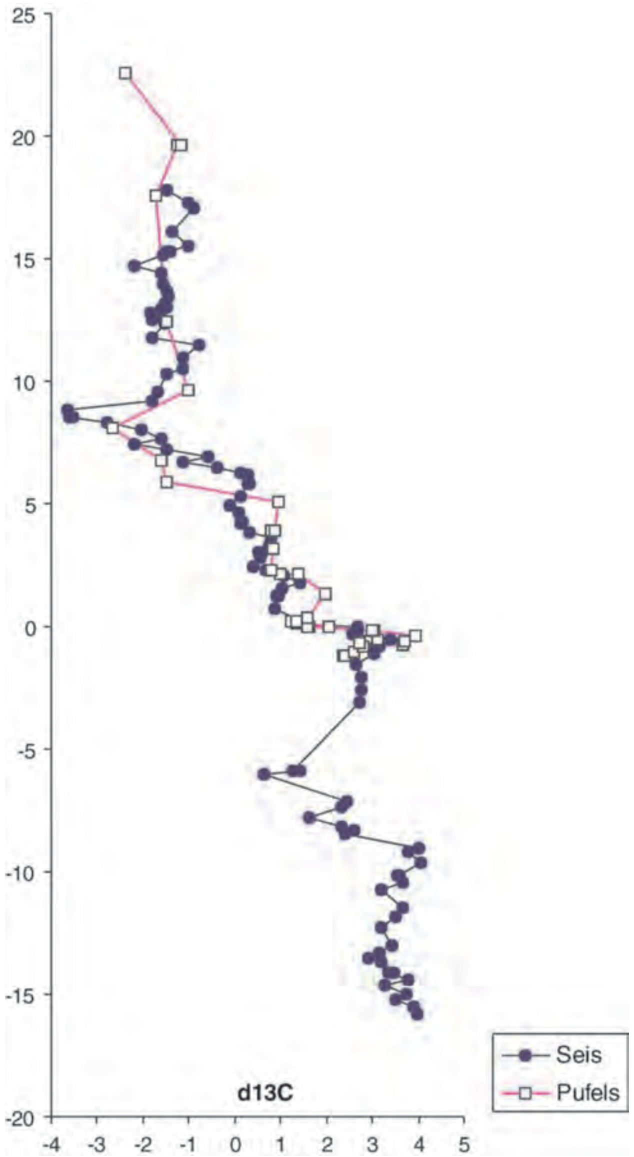


Fig. 18: $\delta^{13}C$ curves of the Seis and Pufels (Horacek et al. 2007a) sections. The sections show very similar isotope patterns evidencing comparable sedimentation rates. After Horacek et al. (2010a).

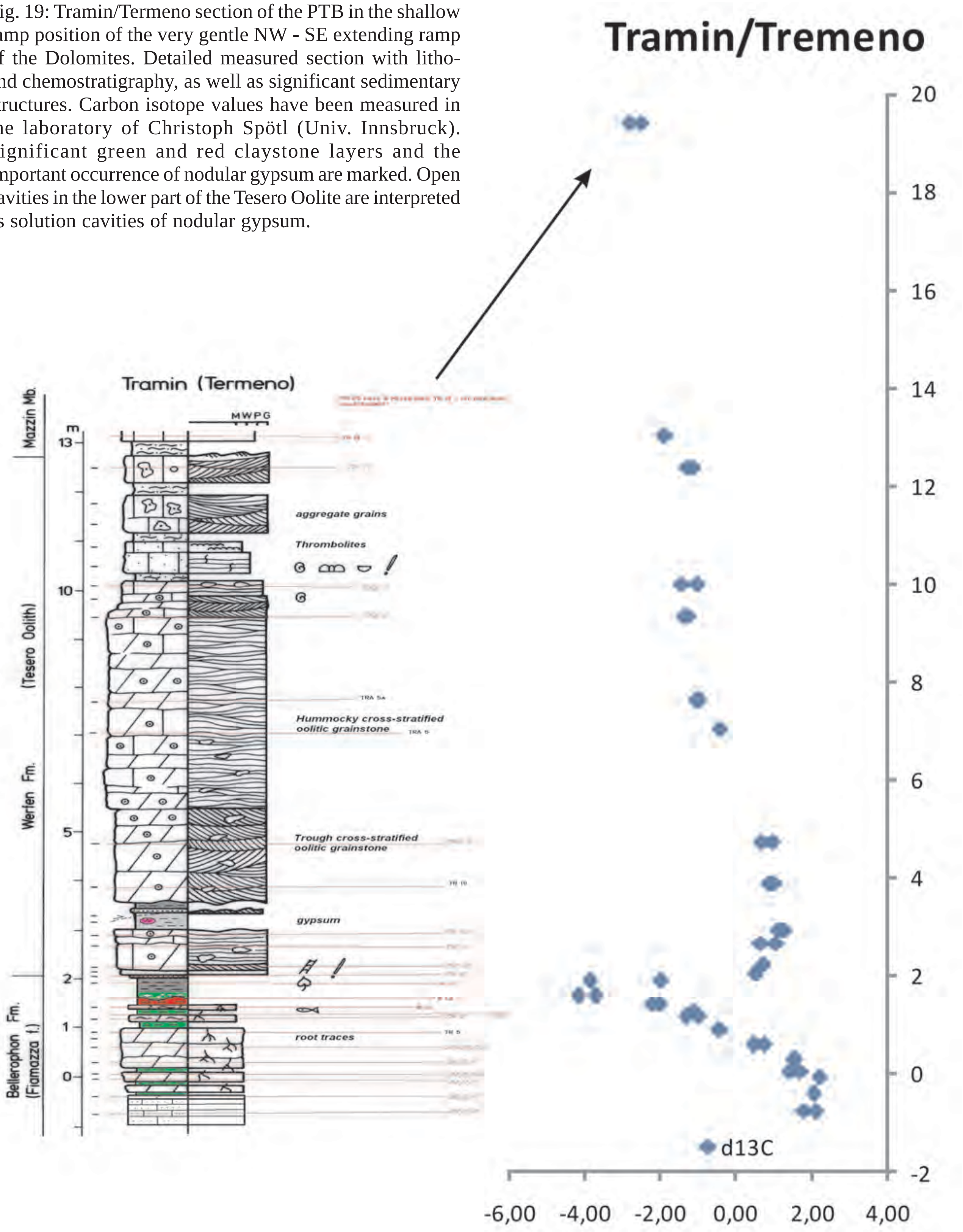
part of the cycle (bed 12). Therefore the Bulla Member and the lower part of the Tesero oolite in the Seis section are interpreted as a 4th order T/R-cycle at the base of a 3rd order depositional sequence (see also Brandner et al. 2009). In the $\delta^{13}C$ curve, the inflection below the PTB close to the base of Meishan D bed 24e can also be identified in the Seis carbon isotope curve supporting the veracity of the correlation. Thus a good fit for bio-, sequence- and isotope-stratigraphy can be achieved by slightly changing the correlation in Jiang et al. (2007) and Yin et al. (2007) (in both articles the top of the Bulla Member has been correlated to Meishan Bed 24e due to an unconformity reported by Farabegoli et al. 2007), but without solving the magnetostratigraphic dispute, as the reversal found in Meishan bed 27 cannot be correlated with the reversal below the eventostratigraphic boundary. However, as the magnetostratigraphic data from Meishan has been questioned by a Chinese working group (Yin et al. 2005), this problem might be related to the magnetostratigraphic data from Meishan. As the old Current Event datum in Scholger et al. (2000) was too low (at the base of the Tesero Oolite), putting the uppermost part of the reversed polarity above the event boundary, Hounslow et al. (2008), consequently correlated the reverse polarity, now just below the revised Current Event, with the first reversed magnetozone (LT1n.1r, Hounslow et al. 2008) within the Lower Triassic. Instead, due to the absence of evidence of a significant gap at the revised Current Event the reversed polarity has to be correlated with the reverse magnetozone of chron P5, as now also the carbon isotope minimum (in the lowermost Lower Triassic N-chron) and the extinction event (close to the polarity transition boundary from reverse to normal polarity) fit with the global pattern (Hounslow et al. 2008, Glen et al. 2009). In the Abadeh section the eventostratigraphic boundary approximately corresponds to the onset of the "boundary clay" and a small positive peak in $\delta^{13}C$ (Richoz et al. 2010), and this correlation also fits with a reversed zone located in the PTB interval below the boundary clay (Gallet et al. 2000). The upper boundary of the reversal has not been identified in the Abadeh section, as it seems to lie within the clay interval (Gallet et al. 2000; Fig. 16), thus the correlation with the Seis/Pufels data leads to a refinement of the duration of the reversal in the Abadeh section.

Summary
A detailed $\delta^{13}C$ curve has been obtained for the Seis section to obtain exact information about the position of the reversed paleomagnetic zone at the PTB. It is demonstrated, that the reversal correlates with a distinct small positive $\delta^{13}C$ peak during the major negative excursion, and can be correlated with the bio-, isotope- and magnetostratigraphic data of Abadeh and the composite magnetostratigraphy by Hounslow et al. (2008). Correlation with the bio- and isotope-stratigraphy of the Meishan D section is also possible, but the Meishan magneto-stratigraphy that has been questioned before, does not fit to the data from the Dolomites.

3.3. Tramin/Termeno section - end Permian coastline and transgression

The Tramin/Termeno section (Fig. 19) is located on the southern wall (Fig 20) of a little gorge immediately west of the village Tramin/Termeno south of Bozen/Bolzano (Fig. 1). The excellent outcrop quality of the section offers a good opportunity to study the PTB and lower Werfen Fm. in a distinct facies development of the mid to inner ramp palaeogeographic postion.
Fluvial sandstones of the Gröden Fm. are overlain by only few meters of light gray dolomitic mudstones with abundant root traces and intercalated green claystones of the Bellerophon Fm. The uppermost part of the sequence is represented by a meter-thick package of nearly unbedded green, red and black claystones. On top of the red claystones occurs dm-scale channel-like erosional features filled with

Fig. 19: Tramin/Termeno section of the PTB in the shallow ramp position of the very gentle NW - SE extending ramp of the Dolomites. Detailed measured section with litho- and chemostratigraphy, as well as significant sedimentary structures. Carbon isotope values have been measured in the laboratory of Christoph Spötl (Univ. Innsbruck). Significant green and red claystone layers and the important occurrence of nodular gypsum are marked. Open cavities in the lower part of the Tesero Oolite are interpreted as solution cavities of nodular gypsum.



debris flows with mudstone pebbles. The red claystones probably represent longer exposed mudflats, whereas the greenish and black claystones suggest generally a reducing environment caused by higher sedimentation rates and/or higher content of organic material (rests of land plants are preserved). No gypsum and no mud cracks have been observed.

Interpretation*:* the dolomitic mudstones are interpreted as short-termed marine ingressions with rooted paleosols on the surface of the banks. The following m-thick claystone sequence may represent a playa lake environment as the very negative $\delta^{13}C$ values of -4‰ could point to

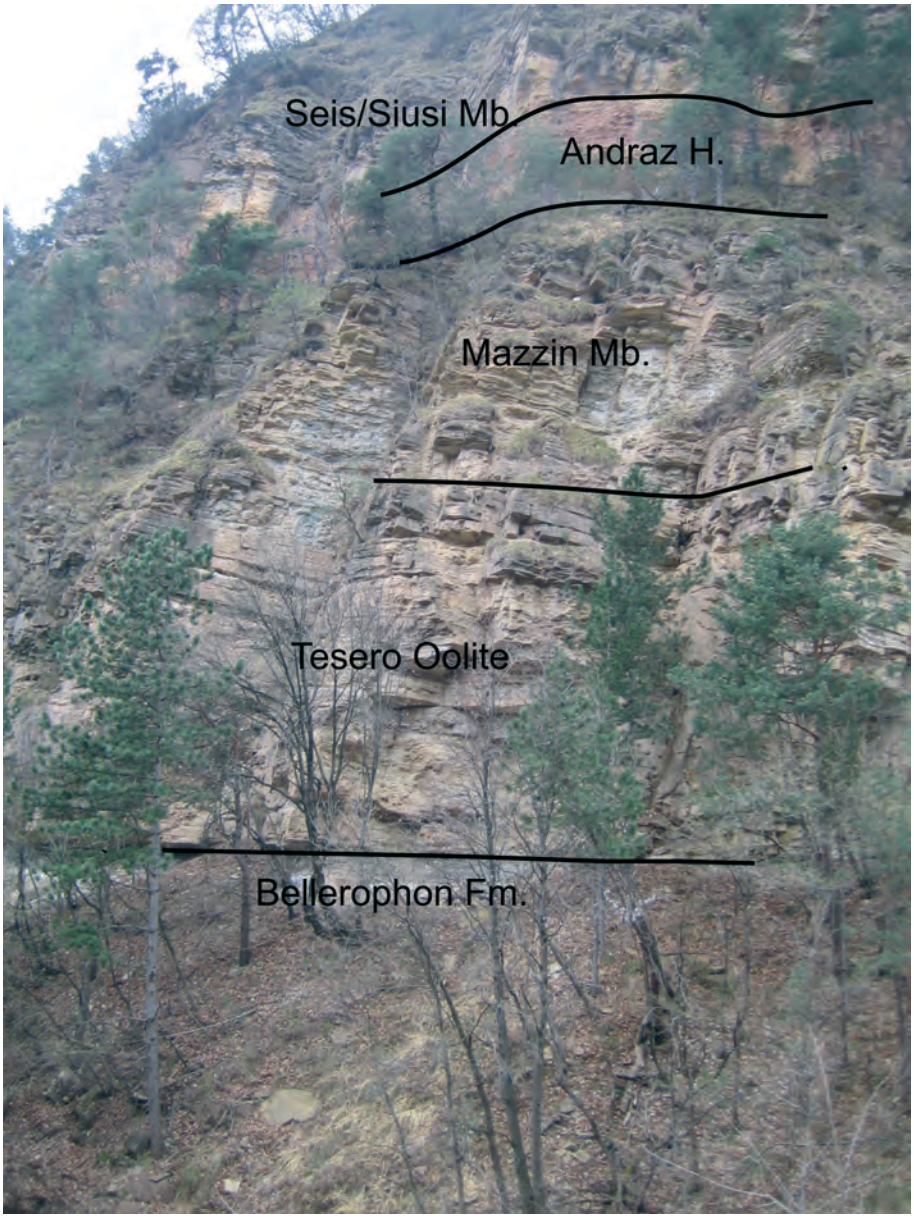


Fig. 20: Overview of the Tramin/ Termeno section on the southern wall of the gorge west of Tramin with outcrops of the uppermost Bellerophon Fm. and Members of the Werfen Fm.

enhanced fresh water influx at this time.

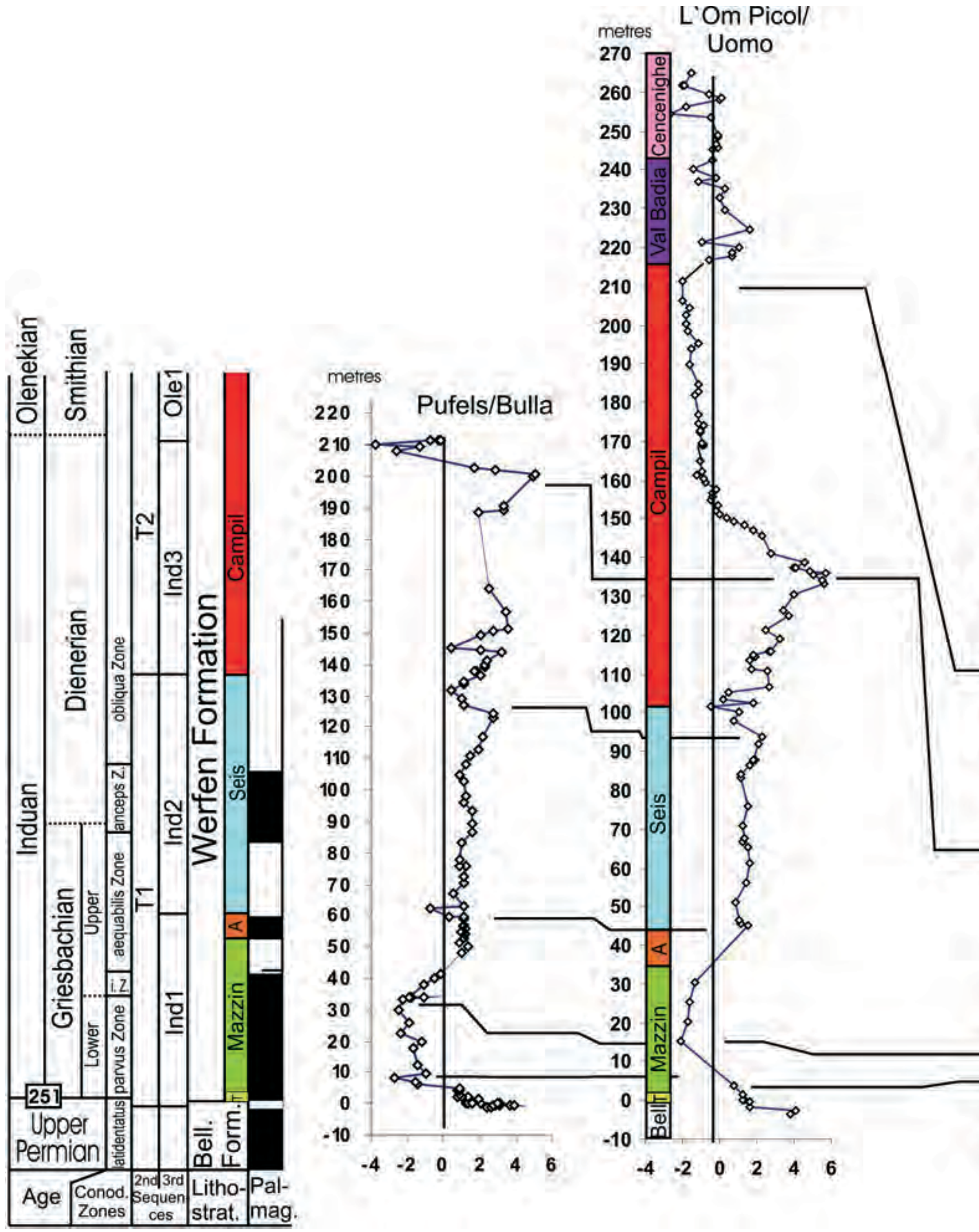
According to the sequencestratigraphic interpretation and the trend of the carbon isotope curve a correlation to the Bulla Member in the open marine environment is obvious. The Werfen Fm. starts with an 8 meter thick sequence of Tesero Oolite. The black claystones are sharply overlain by 1 m bank of dolomitized cross bedded oolithic grainstones with few bioclastic grains of Permian algae and echinoid spines. This first T/R-cycle ends with gray marls with nodular gypsum layers. This part of the section is slightly overprinted by tectonic shearing parallel to the bedding.

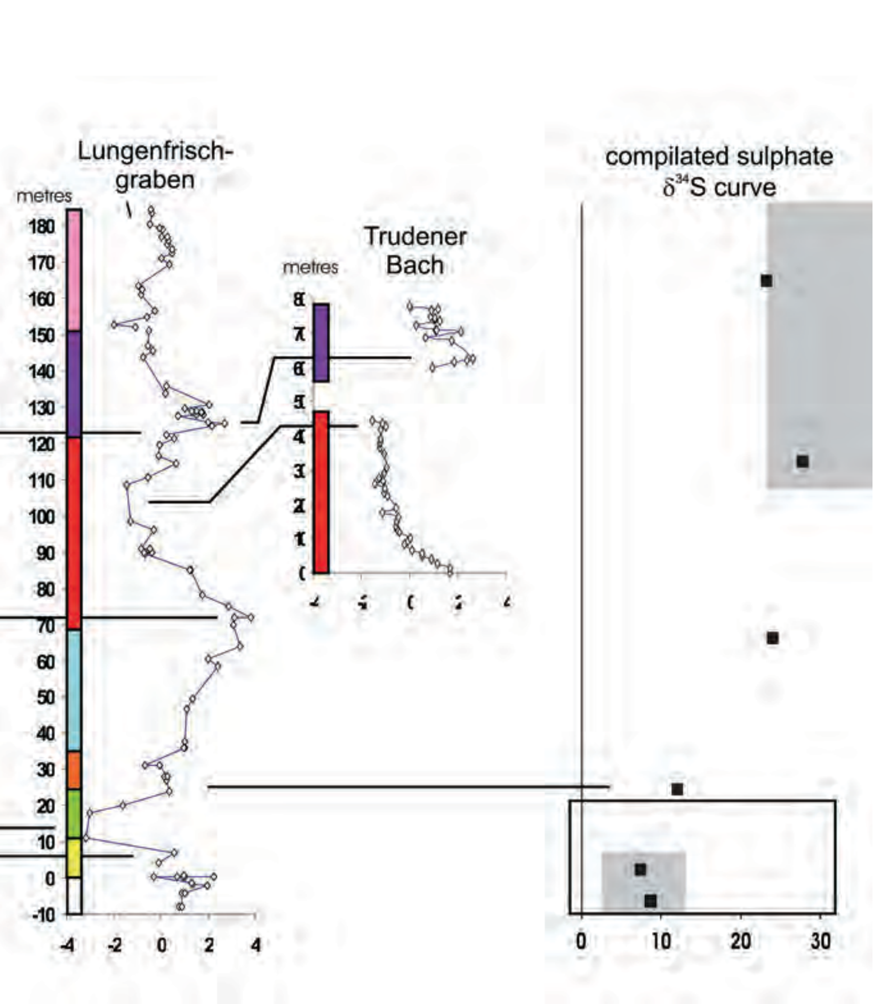
A second T/R-cycle of Tesero Oolite with a thickness of over 6 m starts with trough cross-bedded oolithic grainstones which are overlain by hummocky cross-bedded grainstones in the transgressive part. The regressive top shows again trough cross-bedding of the fore shore environment. Layers with thrombolithes, crossbedded grainstones with aggregate grains and silty marls form the meter-thick transgressive packages at the base of the next cycle which leads to the Mazzin Member.

Solution cavities in dm-scale, possibly originally gypsum nodules, prevail in the lower part of the Tesero Oolite. They probably represent levels of highly saline groundwater fed by temporary run off of the hinterland lagoon. In the palaeogeographic reconstruction the 8 meter thick sand bars represent a barrier island, isolating the western lagoonal facies of the inner ramp from the outer ramp in the east.

Sequencestratigraphic correlation of the parasequences (T/R-cycles) at the base of the Werfen Fm. provide a detailed reconstruction of the facies development along the very gentle, NW-SE extending ramp (see Fig. 8). The sandbars of the Tesero Oolite interfinger toward east with mudstones of the Mazzin Mb. of the deeper ramp. Parasequences (cycles of 4^{th} order) A and B.are correlated well by the trends of the carbon isotope curve in inner and outer ramp sections. This provides the direct measurement of the sea-

Fig. 21: $\delta^{13}C$ curves of the investigated sections and the $\delta^{34}S$ “curve“ from the latest Permian and Lower Triassic evaporites. For comparison the $\delta^{13}C$ curves of the Pufels and L`Om Picol sections are shown, too (modified after Horacek et al. 2007a, 2010a, Brandner et al. 2008, 2009) Shaded boxes show the $\delta^{34}S$ range of evaporites (Pak 1978, Claypool et al. 1980, Cortecci et al. 1981). White box denotes range of CAS $\delta^{34}S$ values (Newton et al. 2004, Riccardi et al. 2006, Gorjan et al. 2007). Y-axis of $\delta^{34}S$ diagram is identical with Y-axis of the Lungenfrischgraben diagram. The Lungenfrischgraben section is close to the Tramin section.





level elevation along the Latest Permian Extinction event of about 6-8 meters (uncorrected). Compared to the global warming of up to 8° C, documented in south China in latest Permian and earliest Triassic surface waters (Joachimski et al. 2012), this value of sea-level rise is in the range of a steric sea-level elevation (Brandner et al. 2012).

Evaporite samples from the Tramin section, the nearby Lungenfrischgraben section and from the Trudener Bach and Bletterbach sections on the opposite eastern slope of the Adige valley have been investigated for their sulphur isotope signals (Horacek et al. 2010b). Although only a small number of samples has been analyzed a steady rise in the basal Lower Triassic from very low to very high ^{34}S values has been documented (Fig. 21), indicating a stratified ocean with bacterial sulphate reduction. However, in contrast to the previous study on bulk rock trace sulphates by Newton et al. (2004), the results show that this rise distinctively post-dates the PTB event, thus this rise does not coincide with the boundary perturbations and cannot be used as evidence for anoxia at that period. Additional research on this topic is necessary.

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