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A 4-DAY GEOLOGICAL FIELD TRIP IN THE WESTERN DOLOMITES

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With 28 Figures

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Introduction and geological setting of the Dolomites

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-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. 1). All these faults are inherited structures which were remobilized 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.

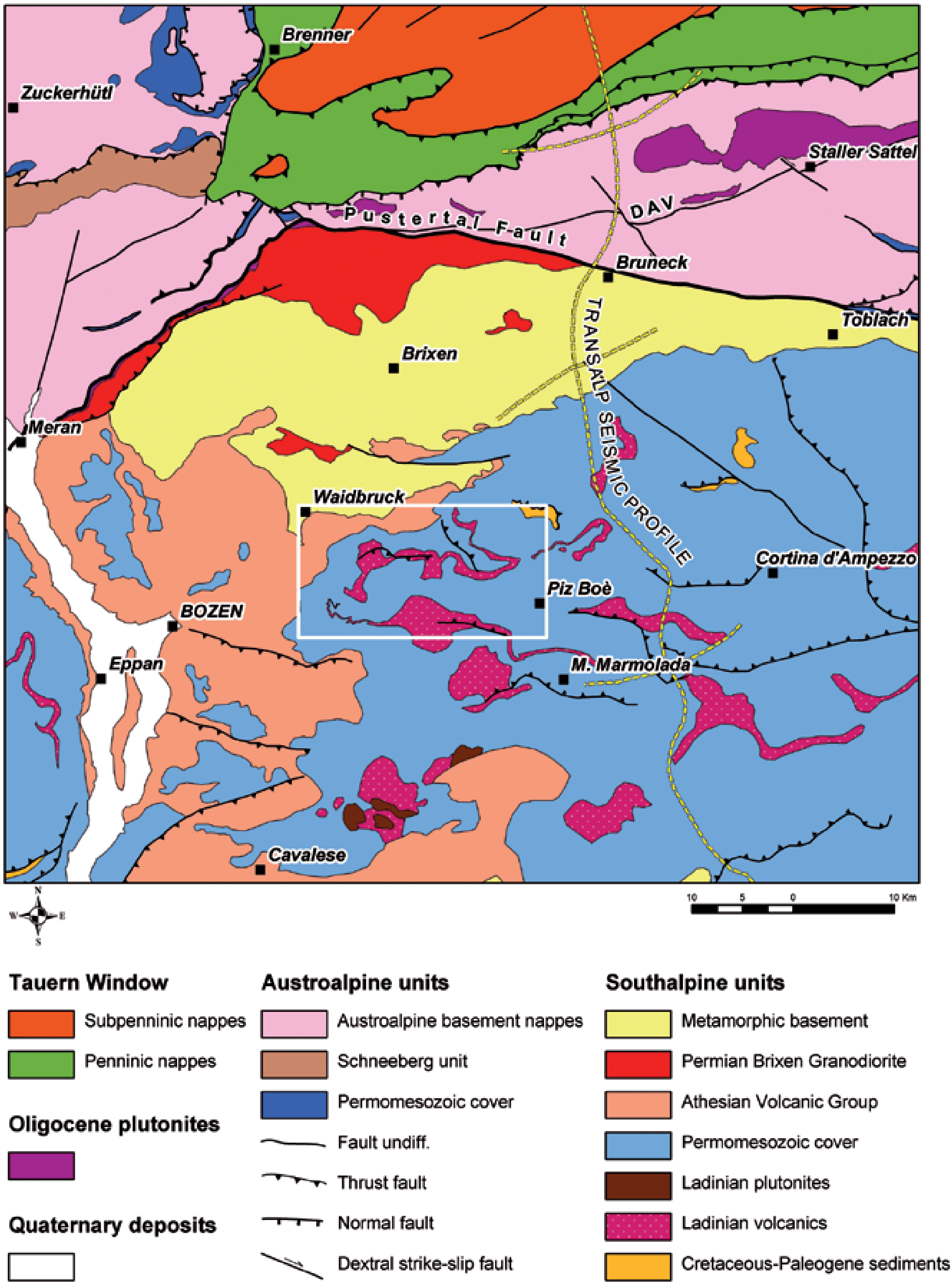

Fig. 1: Regional geologic overview with location of the excursion area in the Dolomites (rectangular).

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 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 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 intracontinental 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 Sarldolomite.

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 in-

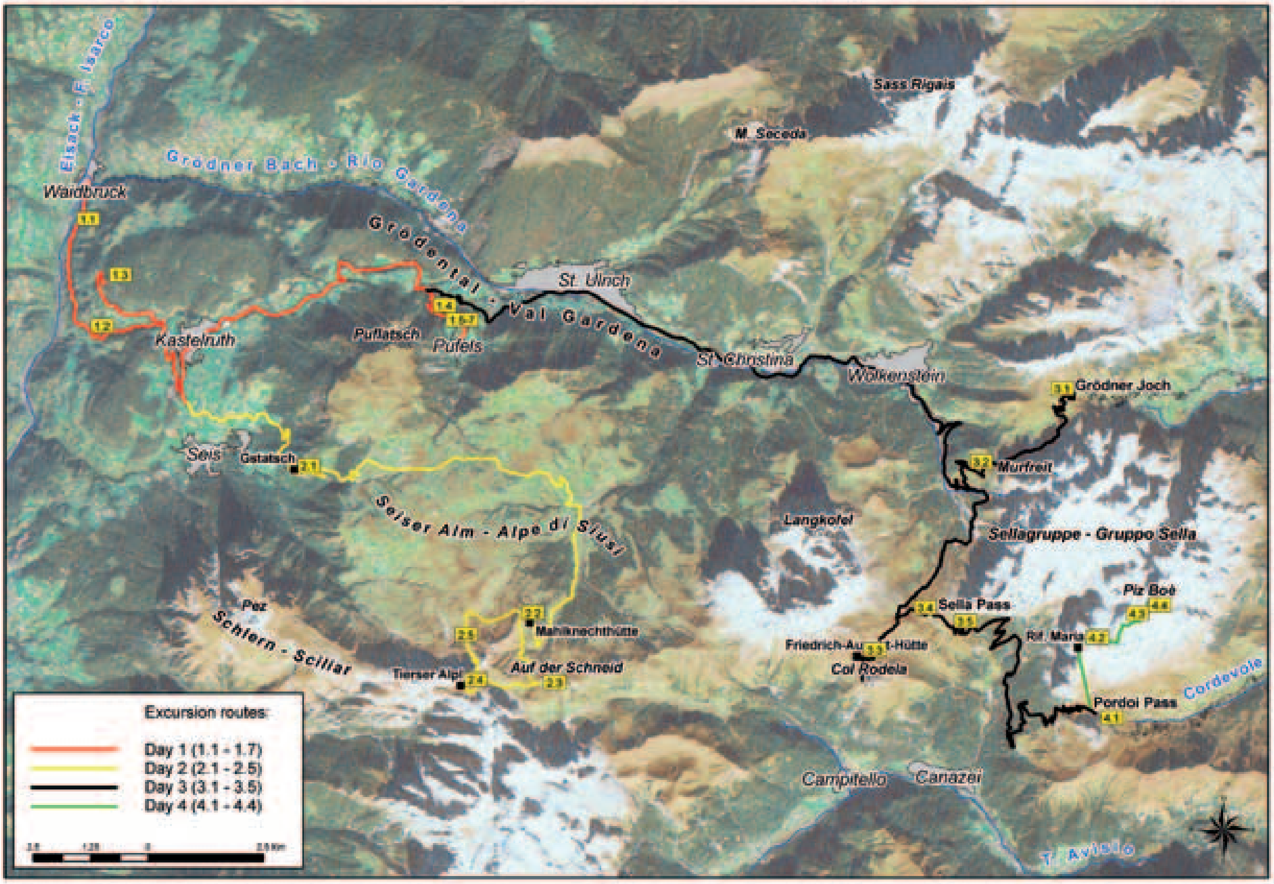

Fig. 2: Satellite image of the Dolomites with location of the four-day excursion routes.

volved 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, boardering 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).

The four-day excursion focuses on the geodynamic and stratigraphic evolution of the Permian– Triassic and presents with its spectacular outcrops the most representative key sections of the Western Dolomites (Fig. 2). Triassic extensional vs. alpine compressional tectonics of the Col Rodela imbricate zone as well as the "Gipfelüberschiebungen" (= summit thrusts), i. e. Dinaric thrusts on top of the Triassic Sella atoll-reef, Raibl Group, Hauptdolomit and Lower Jurassic drowning of the shallow-water platform, are further impressive targets of the excursion.

DAY 1

The Permian volcanic event and the upper Permian to lower Triassic stratigraphic succession

The Bozen/Bolzano basin, filled by a succession of up to 3 km thick volcanics and intercalated sediments, documents the development of a new tensional regime in the interior of Pangea after the end of Variscan orogeny. The fundamental plate boundary reorganisation is seen in the context of the above mentioned intra-Pangea dextral megashear system at the transition of an Early Permian Pangea "B" to a Late Permian Pangea "A" configuration (see Muttoni et al., 2003), contemporary to the opening of the Neotethys Ocean.

The thick volcanic sequence, in the older literature known as "Bozner Quarzporphyr", ranges from basaltic andesites to rhyolithes and spans a period lasting from ca. 285 Ma to 275 Ma. The sequence is now defined as Athesian Volcanic Group (AVG) (see Carta Geologica d'Italia, 2007, Marocchi et al., 2008). High-precision extrusion ages combined with detailed field mapping over extended areas of the AVG were provided by Morelli et al. (2007) and Marocchi et al. (2008). Mapping of several newly established and well-dated volcanic stratigraphic units enables for the first time the reconstruction of the three-dimensional emplacement history within the strongly tectonically influenced basin development.

The Bozen/Bolzano basin is confined by a system of NNE and ESE striking, normal or transtensive faults. The most prominent faults are the Giudicarie fault in the west, the Pustertal fault in the north, the Calisio line in the southwest and the Valsugana line in the southeast (Fig. 3). All these Permian paleo-lines were reactivated several times later on, but at different deformation regimes. The Lower Permian age of similar striking faults of other volcanic basins is shown by the fact that these faults are sealed with intercalated sediments or volcanic formations (Brandner et al., 2007, Marocchi et al., 2008). Detailed field mapping indicates half-graben geometries, for instance, in the area of Waidbruck-Villnöß and Meran 2000 with block-tilting toward NW. With the new geochronological data of the volcanic sequence it is now possible to recognize a temporal polarity within the Permian fault pattern (Marocchi et al., 2008), i.e. a younging trend of the volcanic formations from the northwestern margin of the basin to the central part in the southwest. These data imply, together with the half graben geometries, an opening trend of the basin in a NW–SE direction. Because of the geometries of the Lower Permian fault pattern, a transtensional opening of the basin would only be possible in a sinistral shearing system, which is in contrast with the timing of plate tectonic models of Muttoni et al. (2003) and Cassinis et al. (2011). At this point it is essential to mention, that the Bozen/Bolzano volcanic basin formation does not correspond to the first transtensional event in the Southern Alps. In the Carnic Alps, the up to 2000 m thick filling of the transtensional Naßfeld/Pramollo basin, with the mixed siliciclastic-carbonate sediments of the Auernig, Rattendorf and Trogkofel Groups, spanning a time period from the Upper Carboniferous to the Artinskian in the Early Permian (Venturini, 1991, Krainer et al., 2009), occurs i.e. circa 20 Ma earlier than the Bozen/Bolzano megacycle. Thus, we speculate, that the basic change in plate kinematics took place within the period of Lower Permian magmatism that largely affected Paleo-Europe.

The AVG is subdivided into a lower part with mainly andesitic and rhyodacitic volcanic products and an rhyolithic upper part. The change of the geochemical composition is closely related to a volcano-tectonic collapse. Cogenetic subvolcanic rhyodacitic intrusions along fractures are described by Morelli et al. (2007) near Terlan/Terlano. Five kilometres to the south, a second important collapse fracture is mentioned by the authors, producing a considerable depression. Ac-

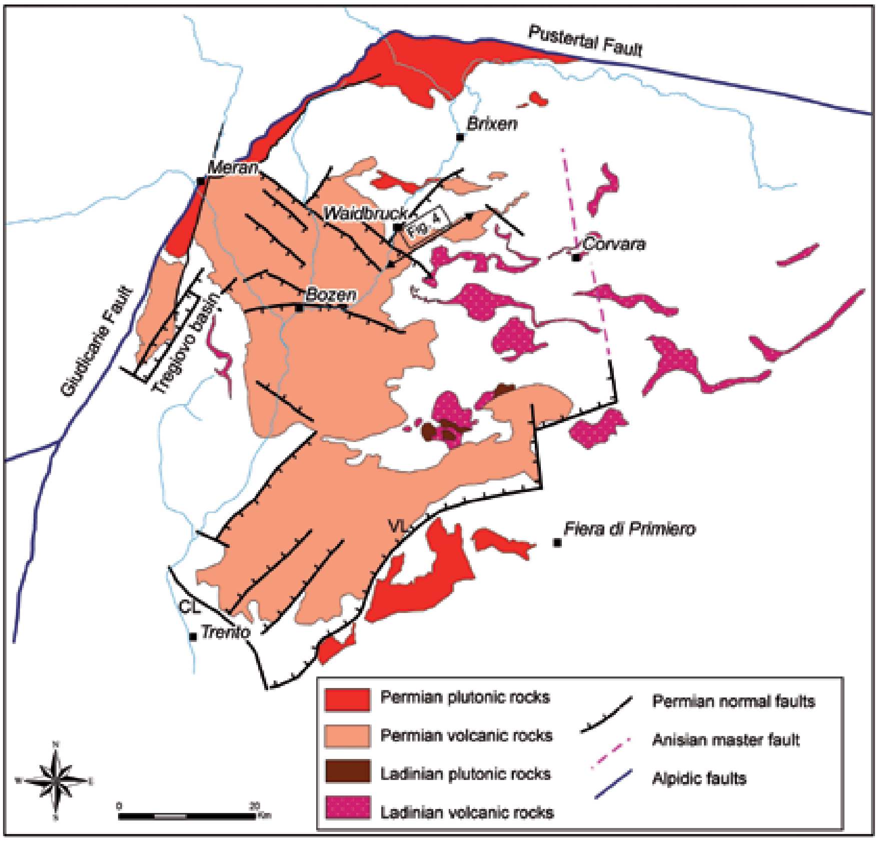

Fig. 3: (a) Distribution of present-day Permian and Ladinian plutonic and volcanic rocks. The formation of Permian volcanics seems to be connected to synvolcanic extensional tectonics with NW-SE and NE-SW trending faults with half graben geometries. Configuration of the Permian faults could be related to an overall sinistral megashear associated with the beginning of the opening of the Neo-Tethyan Ocean in the Far East. Data on Permian faults based on own field mapping, Carta Geologica d'Italia (2007, sheet "Appiano-Eppan"), Carta Geologica d'Italia (2010, sheet "Merano-Meran"), Selli (1998) and Morelli, C. (pers. comm., 2011). The Ladinian magmatites in the Dolomites are located close to the Permian ones – thus a genetic connection, i.e. a similar uplifted position of the mantle as in the Permian, could be proposed. The Anisian master fault serves as an example and shows the inheritance of the Permian fault pattern in the Triassic and Jurassic. CL = Calisio paleo-line, VL = Val Sugana paleo-line (modified after Selli, 1998).

cording to Morelli et al. (2007) more than 1000 m of pyroclastic flow deposits accumulated, i.e. ignimbrites of the Auer/Ora Formation. A similar scenario can be observed along the road from Waidbruck/Ponte Gardena to Kastelruth/Castelrotto at stop 1.2 with the collapse escarpment of the WNW–ESE striking Bundschuh normal fault (Figs. 4, 5). We recognize here the sealing of the fault with ignimbrites of the Auer/Ora Formation (Brandner et al., 2007). The volcanic activity is interrupted at different stratigraphic levels marked by alluvial conglomerates, sandstones and lacustrine deposits with plant remains (Hartkopf-Fröder et al., 2001).

The volcano-sedimentary Lower Permian megasequence is unconformably overlain by the spacious cover of continental clastic deposits of the Gröden/Val Gardena Fm., which forms the basis of the 2nd megacycle and is devoid of volcanics. Thermal subsidence dominated the sedimentary development of this cycle, which is evident by widespread interfingering of continental and shallow-marine facies. The general marine transgression of the Neotethys to the west took place in several third-order sequences ranging from coastal plain environments with sabkha evaporates to shallow-shelf carbonates of the Bellerophon Fm. After the end Permian mass extinction mixed shallow-marine carbonates and terrigenous sediments of the Werfen Fm. are characterised by the long lasting biogenic recovery, lacking carbonate producing organisms. The first carbonate bank produced by calcareous algae is of Lower Anisian age (Lower Sarl/Serla Fm) and forms the top of the 2 megacycle.

Excursion route

Stops 1.1–1.3 are located along the classic geological section at Waidbruck/Ponte Gardena on the road to Kastelruth/Castelrotto crossing the whole sequence from the basal conglomerate, volcanoclastic sediments, andesitic and dacitic block lavas to rhyodacitic and rhyolithic ignimbrites.

Stops 1.4 to 1.7 are dedicated to the Permian-Triassic sequence of the Pufels/Bulla key-section along the abandoned road to Pufels/Bulla (Fig. 2).

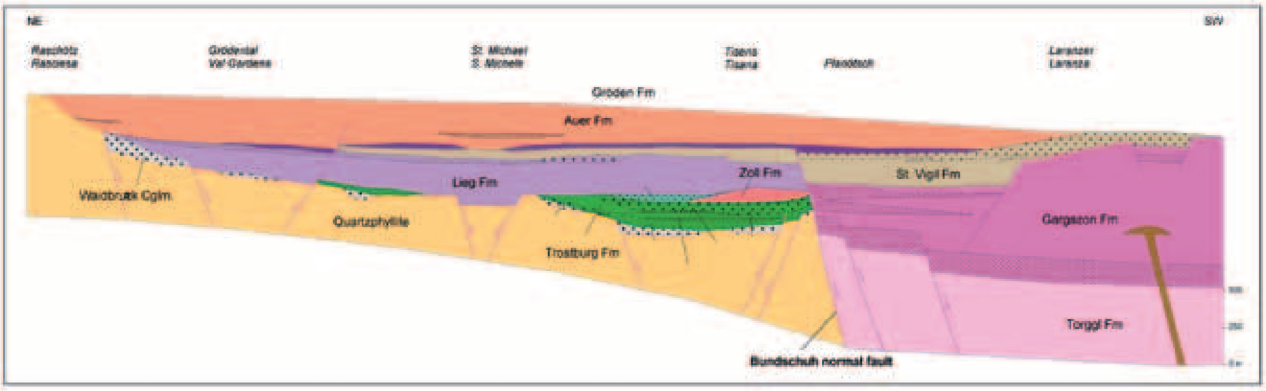

Fig. 4: Schematic lithostratigraphic model of the Permian Athesian Volcanic Group east of the Eisack valley, based on Geologische Karte der Westlichen Dolomiten 1:25.000 (2007) and Brandner et al. (2007). The location of the schematic section is shown in Fig. 3.

Stop 1.1 – Waidbruck/Ponte Gardena Conglomerate

The classic geological section along the road to Kastelruth/Castelrotto starts with the well-known outcrop of the Waidbruck/Ponte Gardena Conglomerate at the basis of the volcanics of the AVG (Fig. 4). The unconformable contact with the underlying crystalline basement is covered by Quaternary debris. The thickness of the basal conglomerate differs strongly, in some places it reaches 50 m, while at others the conglomerate is lacking. Geological field mapping showed an abrupt pinching out of the conglomerates along NW-SE and NE-SW striking Permian normal faults.

Krainer (1989) studied the section in detail (Fig. 6) and recognized three lithofacies types: (1) massive, poorly sorted and matrix-rich conglomerates with a matrix-supported grain fabric, (2) crudely bedded, clast-supported conglomerates filling up to 1 m deep erosive channels and (3) fine-grained, cross bedded conglomerates, filling smaller channels. The conglomerates consist of poorly rounded clasts of rocks of the crystalline basement, predominantly quartz phyllite and better rounded quartz pebbles. The quartz pebbles and grains are covered by a reddish thin film of hematite indicating semiarid to arid climatic conditions. Mature quartz pebbles with a long transportation history and angular, immature phyllite pebbles are mixed in the poorly sorted debris flow sediments. They testify, in combination with the poorly sorted channel fills, an ephemeral stream environment with wadi channels. Higher up in the section, the amount of volcanic pebbles and sandstones increases to turn into a ca. 70 m thick pyroclastic/volcanic sequence with block lavas, tuffs, explosion breccias, irregularly intercalated in the lava flows (Di Battistini et al., 1989). Fluvial conglomerates with quartz pebbles and sporadic metamorphic clasts from the basement are locally interbedded. The mixed volcaniclastic/volcanic-terrigenous sequence is overlain by 60–80 m thick, finely crystalline andesitic lavas (Trostburg Fm., Brandner et al., 2007). Visonà et al. (2007) determined from this lava flow a SHRIMP U-Pb zircon age of 290.7+/-3 Ma indicating that the andesitic lavas of the northern region preceded the general onset of the volcanism of the AVG with 284.9+/-1.9 Ma (Marocchi et al., 2008) in the Etsch/Adige valley.

Stop 1.2 – First turn of the road, near the locality Zoll: the Bundschuh fault, a Permian normal fault

The Bundschuh normal fault is situated in a small valley in between the farmsteads Planötsch and Bundschuh (Figs. 4, 5). The Permian age of the fault is expressed by its sealing with rhyolithic ignimbrites of the Auer/Ora Fm at the top of the AVG. The fault has been reactivated insignificantly several times later on. The Bundschuh fault crosses the Eisack/Isarco valley in WNW-ESE direction and delimits in the lower section the crystalline basement toward thick sequences of ignimbrites of the Gargazon and Torggl Fms in the hanging wall located in the south. The remarkable difference in the thickness of the fluvial sediments of the St. Vigil Fm of about 70 m on both sides of the fault is interpreted by levelling of the strong relief created by faulting.

The Bundschuh fault and the Villnöß/Funes paleofault mark together with the Meran 2000 fault system the northern margin of the Lower Permian Bozen/Bolzano basin.

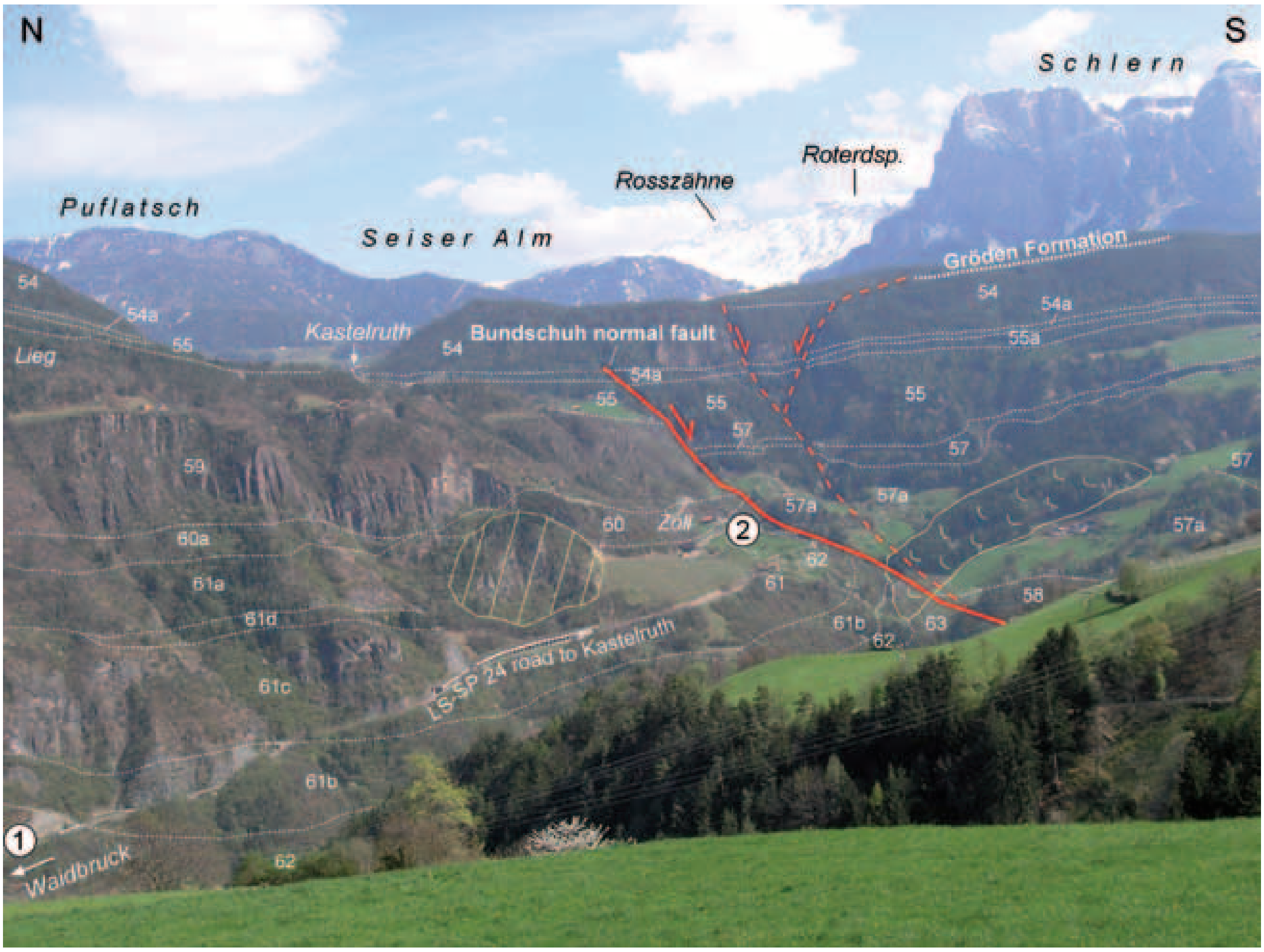

Fig. 5: Panoramic view of the Permian volcanics between Waidbruck/Ponte Gardena and Kastelruth/Castelrotto. A major upper Permian syn-volcanic, WNW-ESE running, steep normal fault between Bundschuh-Planötsch is present. This fault also causes the abrupt thickness change of the epiclastic sediments of the St. Vigil Fm. Numbers correspond to the facies model of Fig. 4. (after Brandner et al., 2007). Numbers 1 and 2 = excursion stops.

Stop 1.3 – Tisens, little quarry near Lieg Inn: typical succession at the base of the Auer/Ora ignimbrite formation.

The section starts along the access road with a sedimentary sequence of the St. Vigil Fm with sandstones and conglomerates of reworked volcanic rocks, randomly also quartz grains and phyllites occur of the crystalline basin. The sandstones are cross bedded and are arranged in small channels with graded channel fillings typical for point bar sequences. A 2 m thick sandstone bank marks the top of the sequence. After a non exposed part in the outcrop a black vitrophyric rhyolithic tuff of 8–12 m thickness follows at the base of red coloured ignimbrites of the Auer/Ora Fm. The whole volcanic succession is exposed in a quarry. The vitrophyre is known in the older literature as "Pechsteinporphyr von Tisens" and is still used as building and décor stone. The vitrophyre is characterized by nearly unaltered glass (a petrographic peculiarity for an age of 275 Ma) in the groundmass, which is responsible for the black colour. Eutaxitic microstructures and perlithic fracturation can be observed under the microscope, as well as scattered crystals of quartz, sanidine, plagioclase and biotite (Mostler, 1982, Bargossi et al., 1998).

The vitrophyre is overlain with a sharp boundary by red rhyolithic ignimbrites of the Auer/Ora Fm. The petrographic composition and structure are similar to the vitrophyre, the difference is only the altered, red coloured groundmass. Intercalated are aphyric, red and black lithoclasts. Typical are juvenile aphanitic inclusions with flame structures ("fiamme"). The sharp boundary with the yellowish horizon on top of the vitrophyre is interpreted by Mostler (1982) and Bargossi et al. (1998) as a weathering horizon (spherical weathering).

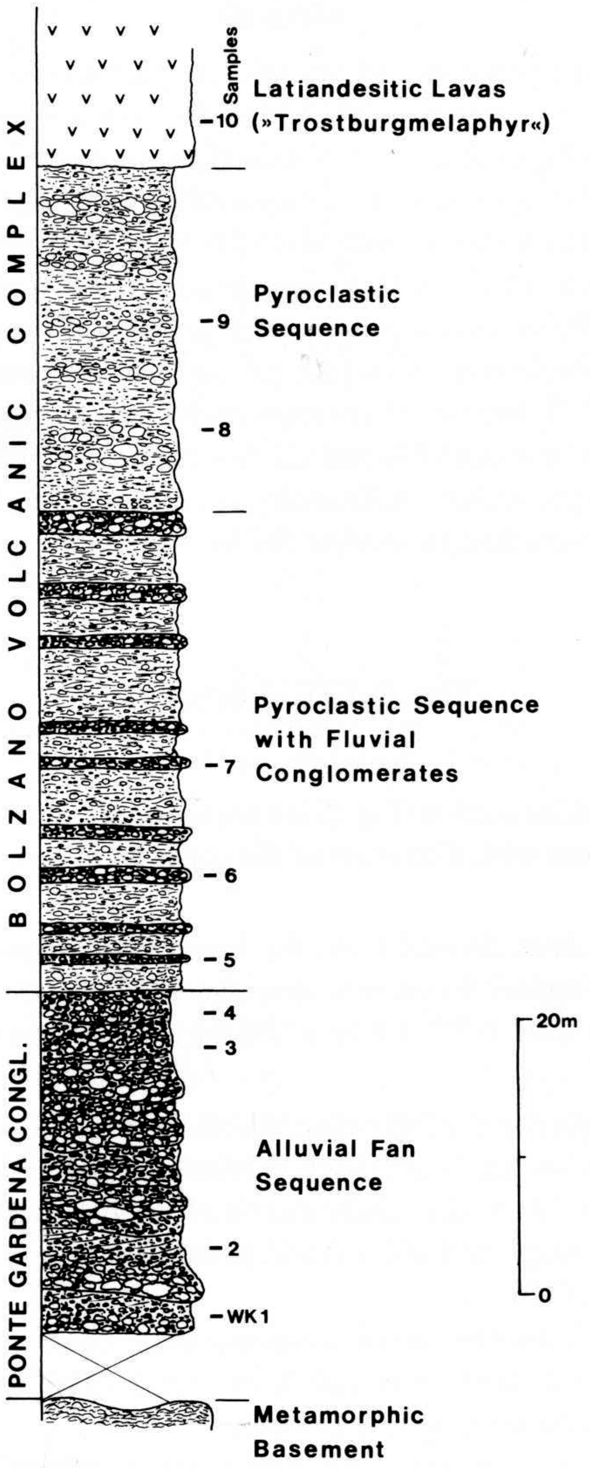

Fig. 6: Measured section of the Ponte Gardena (Waidbruck) Conglomerate and the lower part of the volcanic sequence along the road from Waidbruck to Kastelruth, after Krainer (1989). Reworked clasts of the Ponte Gardena (Waidbruck) Conglomerate consist essentially of quartz phyllite of the underlying metamorphic basement. Upsection, these conglomerates are gradually replaced by conglomerates and sandstones with abundant and well rounded volcanic clasts.

The Pufels/Bulla road section: from the Permian-Triassic Boundary (PTB) to the Induan-Olenekian Boundary (IOB)[1]

[1] The following chapter is basically a reproduction of the published field guide by Brandner et al. (2009).

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 continuous section that reaches from the PTB to the Induan/Olenekian boundary (IOB) located within the Campill Member (Fig. 7). 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 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

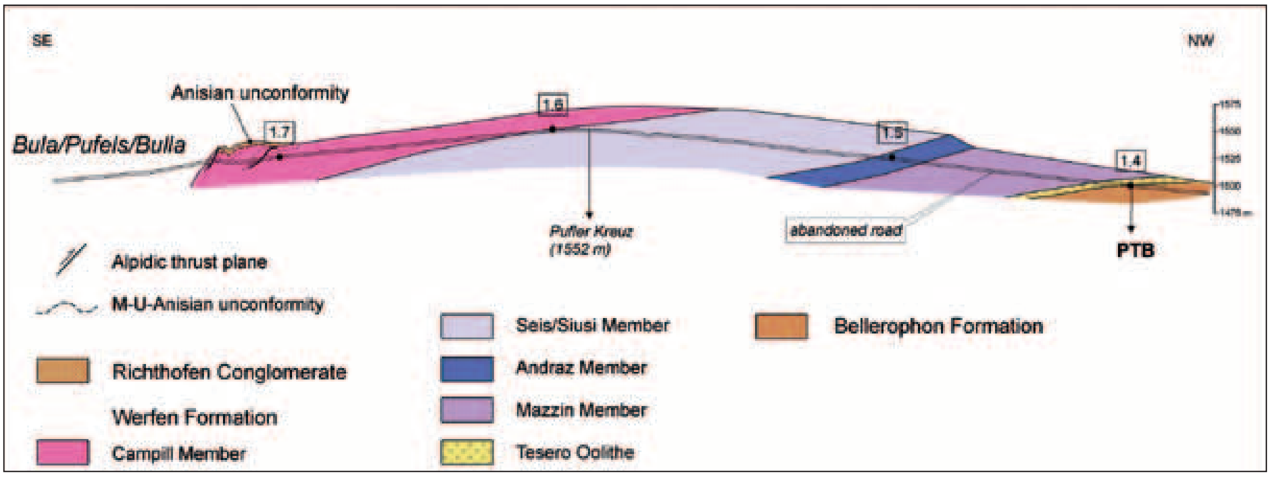

Fig. 7: Geological cross section along the abandoned road to Pufels/Bulla with location of the single excursion stops (1.4–1.7). PTB = Permian-Triassic Boundary (after Brandner et al., 2009).

facies developments, such as 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. 7).

Stop 1.4 – 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. 8a). 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).

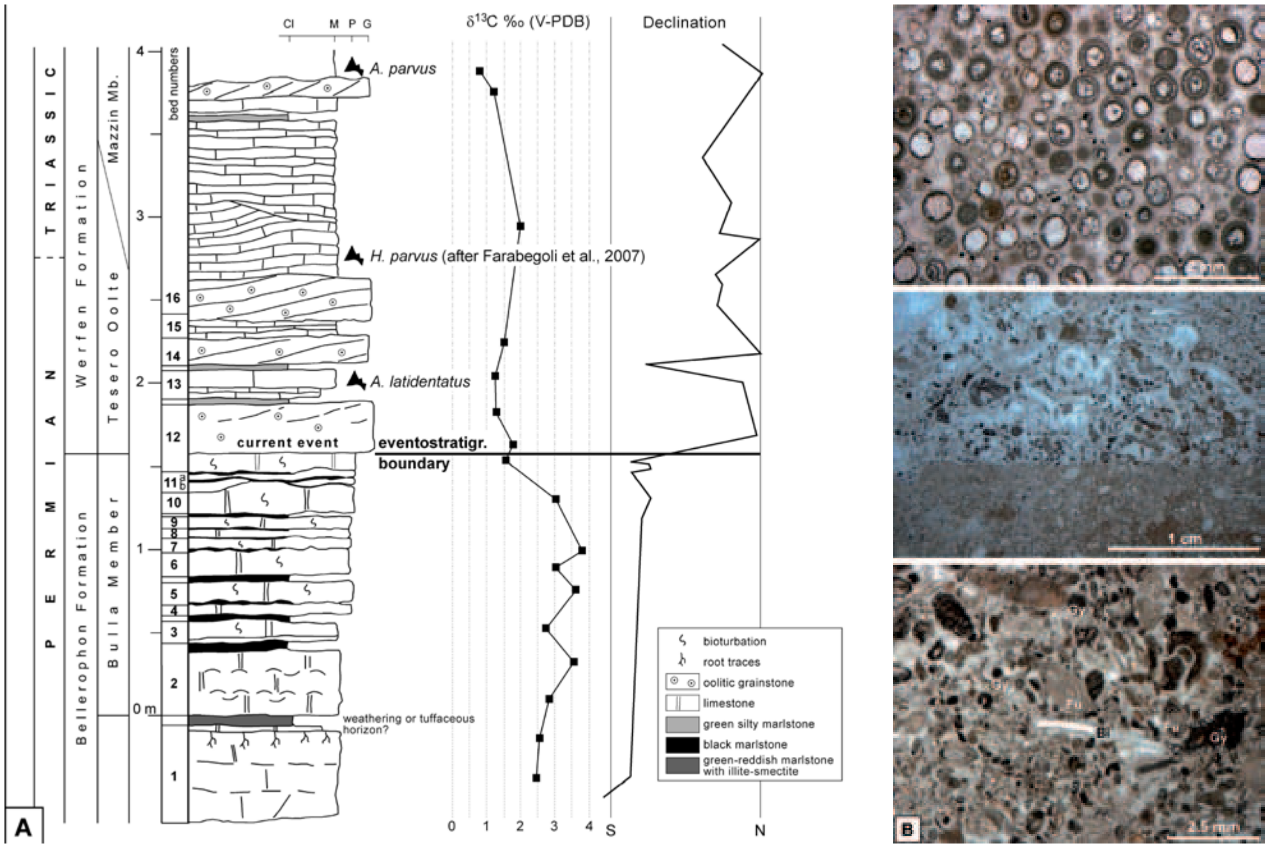

Fig. 8: The Perm-Triassic Boundary: (a) detailed measured section of the PTB with litho-, bio-, chemo- and magnetostratigraphy. Conodonts and position of the PTB after Mostler (1982) and Farabegoli et al. (2007), magnetic declination after Scholger et al. (2000); (b) Three thin-section photomicrographs 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 (after Brandner et al., 2009).

Werfen Fm: The Werfen Fm starts with the *Tesero Oolite Mb* within bed number 12 of the detailed section (Fig. 8a). Fossiliferous packstones are overlain with a sharp contact by well washed, fossiliferous grainstones, 4 to 5 cm thick (Fig. 8b), 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. 8a). 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. 8a 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. 8b). 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).

On the contrary, 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 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 (Shaffer et al., 2009). 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 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^- 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. 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 (Figs. 8a, 9); 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 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, about 40 km SW of Pufels (Brandner et al., 2009). 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. 9). 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).

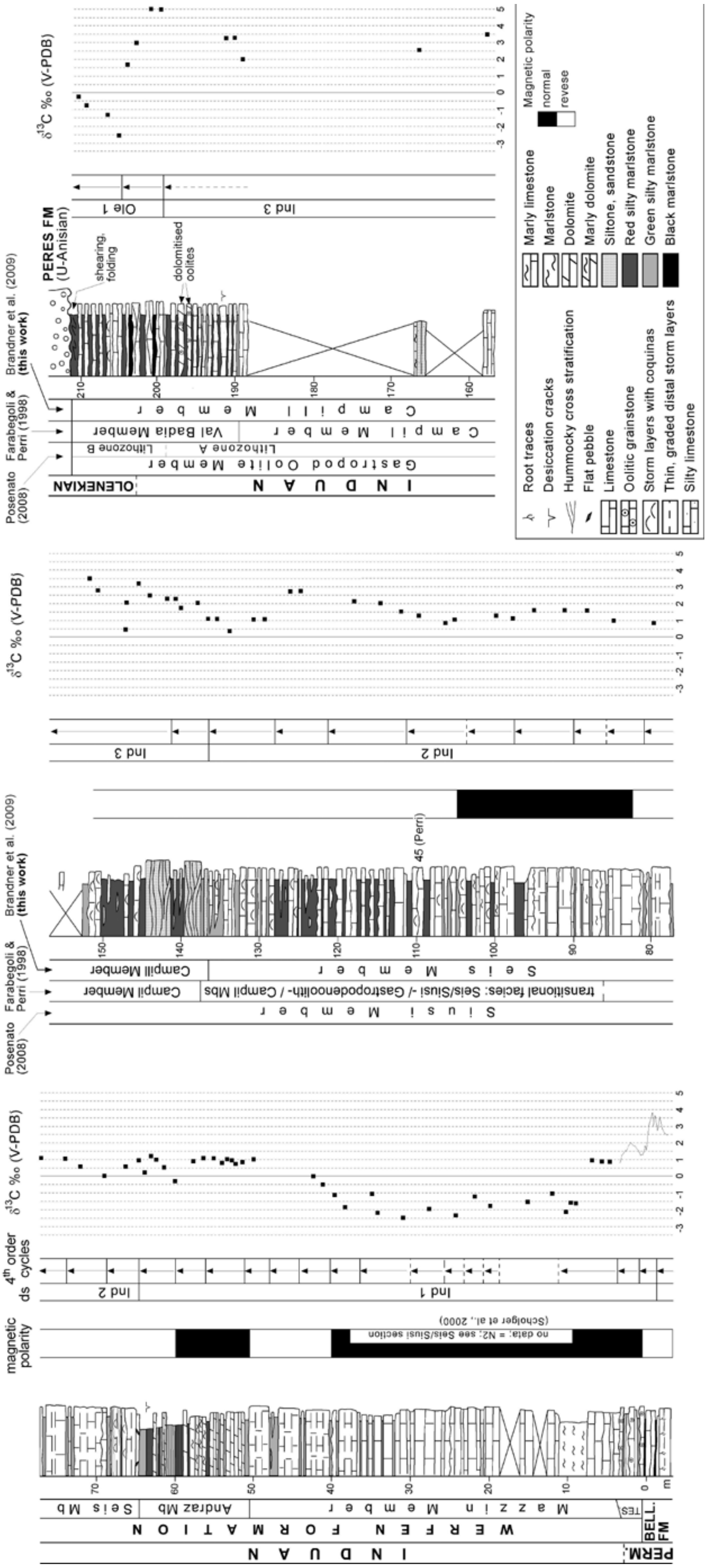

Fig. 9: Measured section through the Werfen Formation along the abandoned road to Pufels/Bulla. The top of the section shows alpine ramp folds which can be restored bed by bed. Upper Anisian conglomerates unconformably overlie the lower part of the Campill Member recording upper Anisian uplift and erosion (after Brandner et al., 2009).

Stop 1.5 – 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 analyses (Fig. 9).

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).

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. 9). 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. 10).

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. 9). 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 signalizes 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. 11). 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).

Stop 1.6 – 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

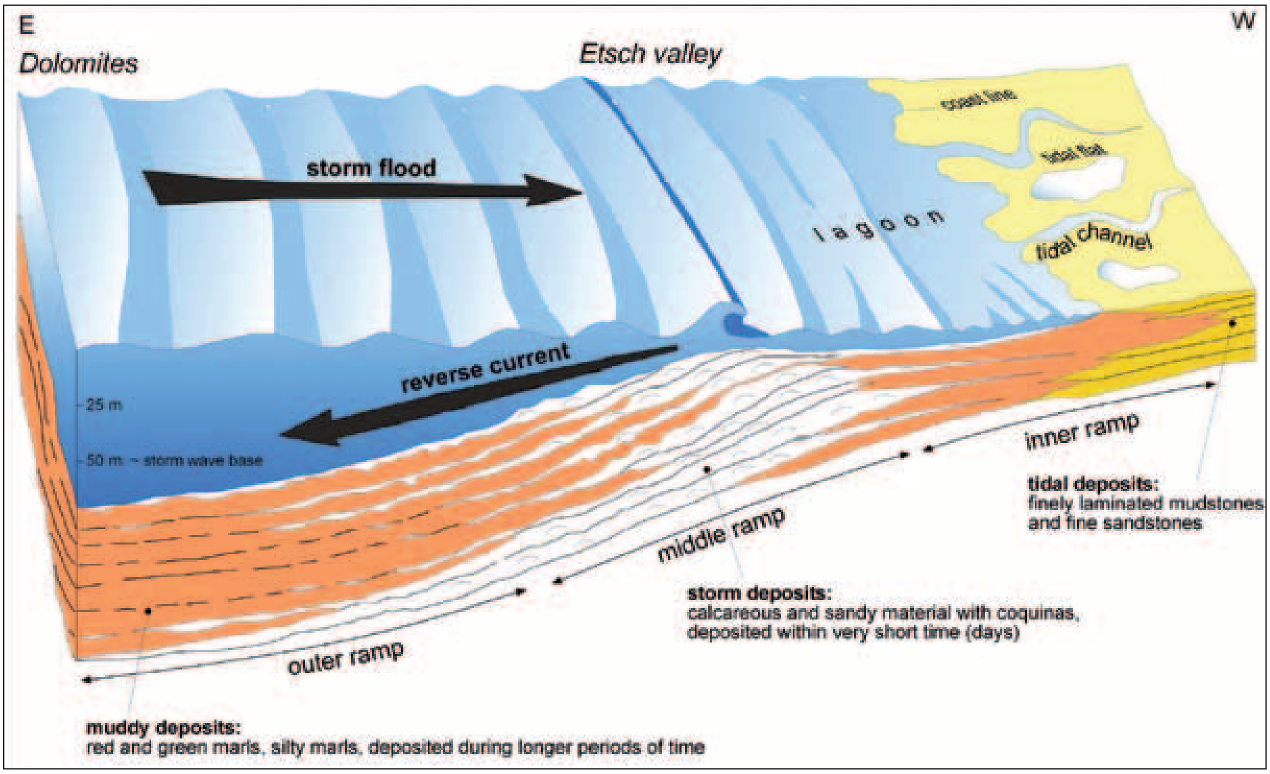

Fig. 10: Schematic model for the deposition of the Werfen Formation on an east-dipping ramp. Sedimentation is essentially controlled by storms; the coast line is supposed to be far to the west near the Como Lake. Mud deposits, now red and green marls, alternate with layers of sand with bivalve and gastropod 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 sepa¬rately forming coquina beds (see Fig. 11) (after Brandner & Keim, 2011).

grade to thinner bedded storm layers (bioclastic shell tempestites) forming thinning upward cycles on the scale of several meters (Fig. 9). 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 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 in Mud (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.

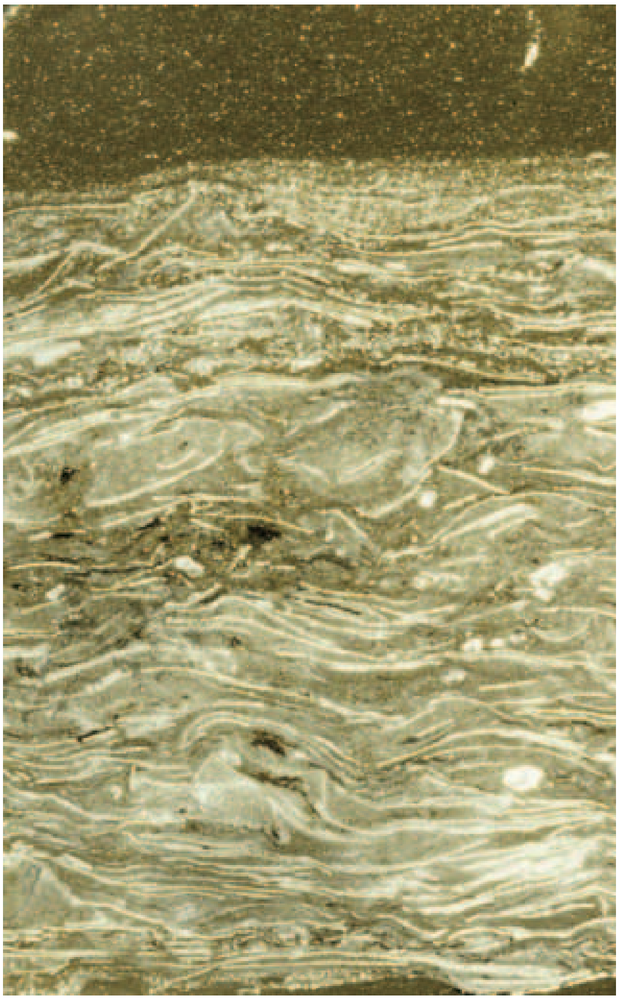

Fig. 11: Thin section photomicrographs of typical tempestite beds with grading and coquinas with *Claraia clarai* (after Brandner & Keim, 2011).

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. (2007) 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.

Stop 1.7 – The Pufels/Bulla overthrust

This point offers a unique panorama of the Pufels overthrust – an alpidic structure due to N-S compression (Fig. 12). The whole pile of rocks, comprising the sequence between Außerraschötz and Piz Culac, is tilted towards the south. However, from Piz Culac to Col dala Dodesc the whole succession between the Bellerophon Fm and the Ladinian lavas is tectonically repeated.

The Pufels (Bulla) overthrust originated from a sheared, overturned syncline: the Contrin Dolomite southwest of Piz Culac shows this folding structure very clearly. Due to gradual compression the S-shaped folding was finally cut through. The whole upper rock package moved further to the north leading to the above cited repetition of the succession.

The basal shear plane of the Pufels thrust probably runs at the border between the Gröden and Bellerophon Fms and subsequently ascends the Werfen Fm presumably to the Schlern Dolomite, which is not preserved in the area.

The Pufels thrust is temporarily connected to the so-called "Val Sugana phase"; this deformation phase was active in the Southern Alps from 13 to 7 million years ago and caused the strongest uplift of the Dolomite Mountains (Castellarin & Cantelli, 2000).

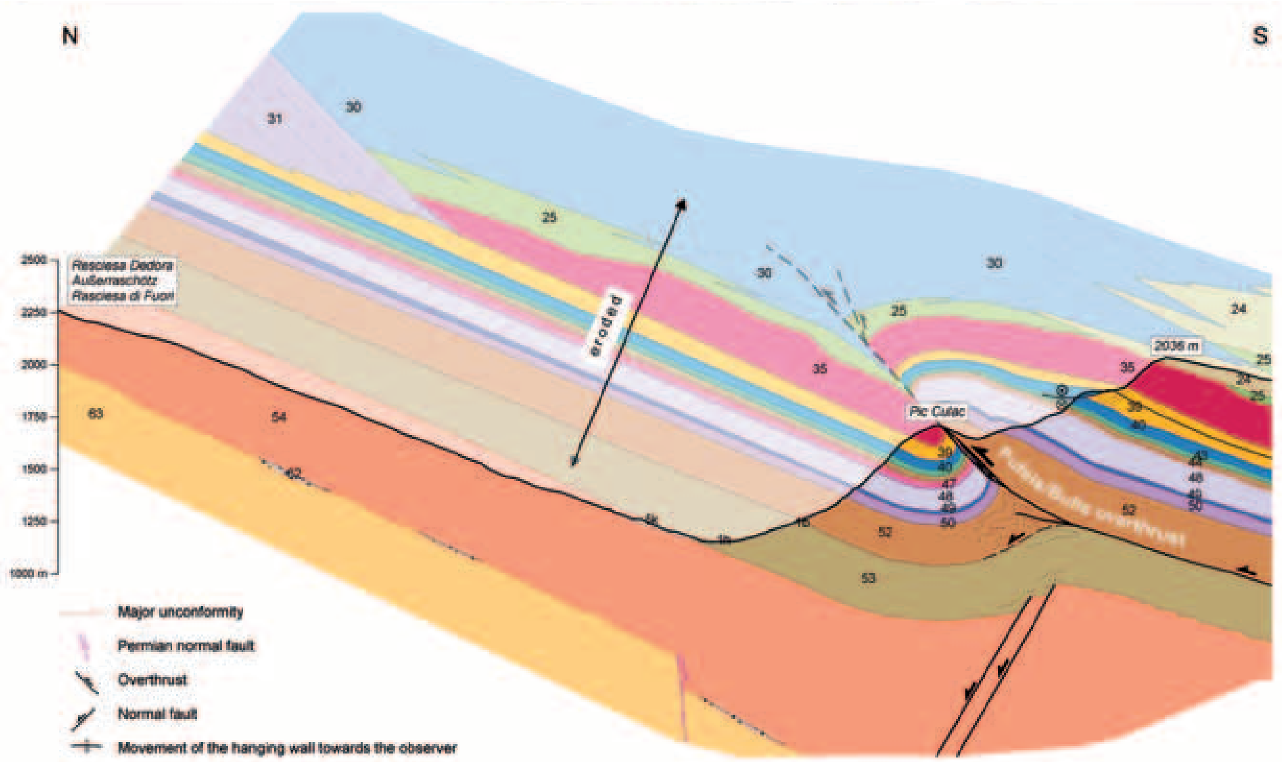

Fig. 12: Geological cross section of the N-vergent Pufels/Bulla overthrust, which developed from the sheared syncline at Piz Culac. The virtual extension of the cross section in the air shows the south dipping clinoforms of the Geisler/Odles on the upper left side. 63 = Southalpine metamorphic Basement, 62 = Waidbruck Conglomerate., 54 = ignimbrites undifferentiated of the Athesian Volcanic Group, 53 = Gröden Fm, 52 = Bellerophon Fm, 50 = Mazzin Mb, 49 = Andraz Mb, 48 = Seis/Siusi Mb, 47 = Campill Mb, 44 = Peres Fm (Voltago/Richthofen Conglomerate), 43 = Morbiac Fm, 40 = Contrin Fm, 39 = Buchenstein Fm, 35 = lavas, 25 = Wengen Fm, 24 = St. Cassian Fm, 5k = till, 1h = alluvial deposits, 1b = talus deposits (after Brandner & Keim, 2011, based on Geologische Karte der Westlichen Dolomiten 1:25.000 (2007)). Foto: H. Rier.

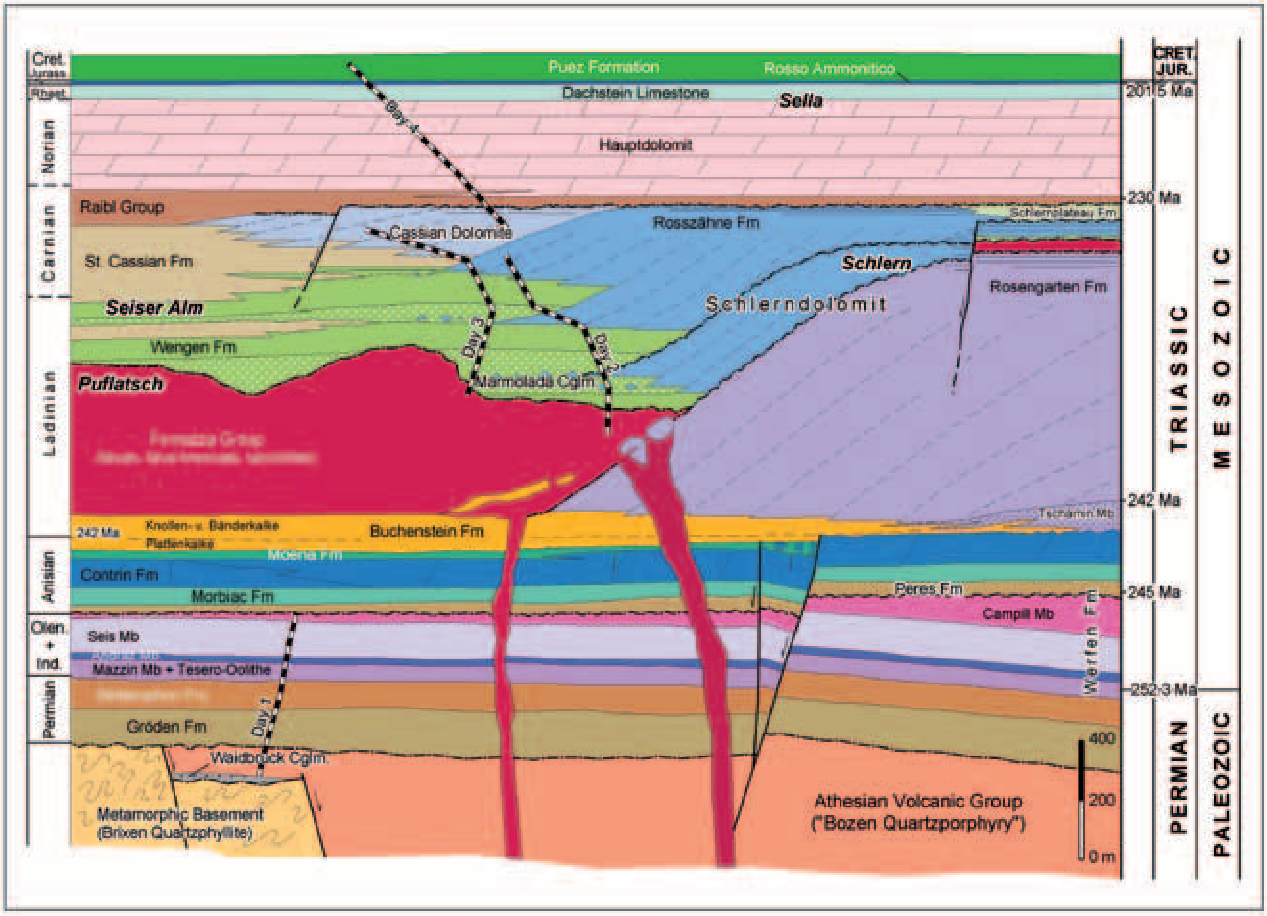

Fig. 13: Lithostratigraphic model for the Permo-Mesozoic succession of the Western Dolomites (modified after Brandner et al., 2007).

DAY 2

Middle and Upper Triassic successions at the NE margin of the Schlern/Sciliar platform and in the Seiser Alm/Alpe di Siusi basin

General remarks on the Middle and Upper Triassic stratigraphy

In the Ladinian the Schlern/Rosengarten carbonate platform forms the primary sedimentary margin of an extended carbonate platform spreading further towards the west on the Trento swell. The platform margins are typically characterized by 30–35° steep clinoforms (= "Überguss-Schichtung" *sensu* Mojsisovics, 1879) with progradation directions towards the NE and the SE. Large parts of this platform are eroded away – some remnants are preserved on the Mendel/Mendola situated to the SW of Bozen/Bolzano. In the adjacent basin, located in the east, pelagic sediments of the Buchenstein Fm were deposited. The platform slope as well as the basinal deposits became buried under a thick sequence of volcanic rocks during the late Ladinian (Longobardian, *Archelaus* zone, see Brandner et al., 1991, Brack et al., 2005) and thus unmistakably confirm the primary lateral change of the different facies. Basinal deposits, ca. 50 m in thickness, are time-equivalent to a ca. 800 m thick series of platform deposits. Based on this difference in relief, the water depth of the Buchenstein basin at the end of the pre-volcanic platform growth could be estimated to be ca. 800 m – such a reliable estimate would not be possible with common bathymetric criteria. Figure 13 shows a lithostratigraphic model for the Permo-Cretaceous succession of the Western Dolomites; Figure 14 shows a chronostratigraphic framework for the Triassic formations.

The focus of the actual field excursion mainly lies on the stratigraphic evolution at the slope-to-basin transition, the geometries of the sedimentary successions with their onlap and downlap structures as well as the resulting sequence stratigraphic implications of a mixed carbonate/volcanic and volcanicla-

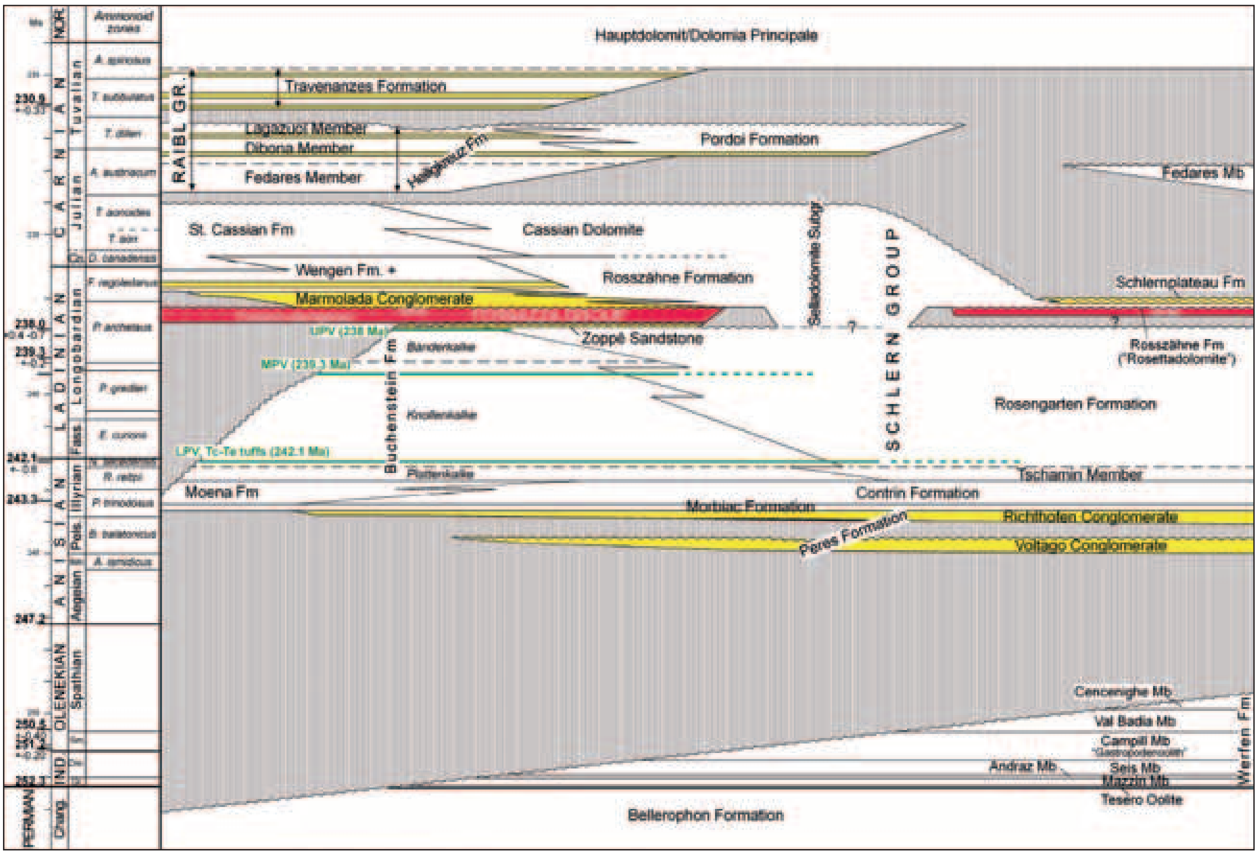

Fig. 14: Chronostratigraphic framework for the Triassic succession of the western Dolomites. LPV, MPV, UPV = Lower, middle and upper Pietra Verde (see Brack et al., 2005). Radiometric ages taken from Mundil et al. (2010). The main siliciclastic intervals are shown in yellow color.

stic depositional realm. The tectonically undeformed large-scale outcrops of the slope-to-basin transition zone can be easily compared with seismic sections and thus may help in the interpretation of seismic lines. So straightforward the outcrop situations are, however, so different are the geological interpretations of the patterns seen (see Bosellini, 1984, Sarg, 1988, Brandner 1991, Yose, 1991).

The underground of the platform-to-basin ensemble is well exposed in the well-known section in the Frötschbach/Rio Freddo situated at the northern flank of the Schlern. Here, the sedimentary succession starts with the Lower Triassic Seis/Siusi and Campill Mb. of the Werfen Fm, which is unconformably overlain by Anisian conglomerates of the Peres Fm, comparable with the Pufels/Bulla road section. This Anisian unconformity is widespread in the entire Western Dolomites and the succeeding conglomerates overlie the Upper Permian Bellerophon in the east (ca. Badia valley) and the Lower Anisian Lower Sarldolomit in the west (Etsch/Adige valley). Based on this erosional cut from young to old a block tilting of a ca. 75 km wide crustal segment with an uplift of ca. 350 m in the east was postulated (Brandner, 1984). This block rotation occurred in three individual phases during the Late Anisian and is interpreted as a new extensional rift tectonics after the Lower Permian.

The 3rd order depositional sequences after this major unconformity in the Western Dolomites are controlled by tectonics, independently form possible eustatic sea-level fluctuations. The genetically connected transgressive-regressive succession above the Anisian unconformity include the continental-marginal marine Peres Fm and the shallow marine Morbiac and Contrin Fms. The three units form a classical depositional sequence ("An 4") with LST, TST and HST. The top of this sequence is again bordered by an unconformity related to extensional tectonics. The carbonate banks of the Contrin Fm break up locally and form megabreccias along extensional faults. The resulting depressions and cavities were filled by anoxic, finely laminated sediments (Moena Fm).

The created submarine relief by this Late Anisian extensional tectonics has as determining influence on the following carbonate platform development of the

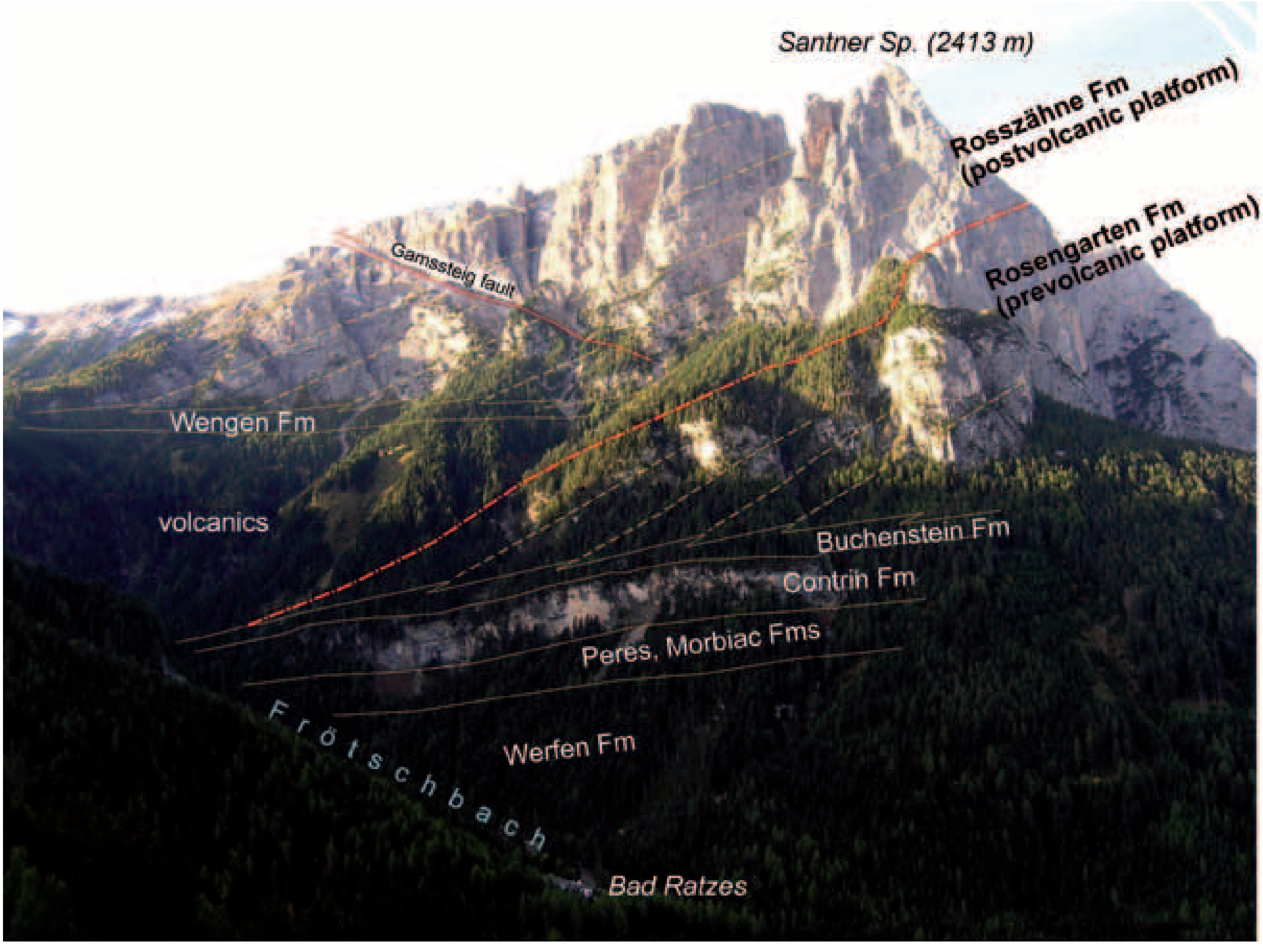

Fig. 15: Panoramic view on the north-eastern flank of the Schlern showing the excellently preserved, seismic-scale platform-to-basin transition of the Anisian to Ladinain carbonate platform. Depositional sequences are bordered by 3rd order unconformities (stippled lines).

Schlern/Sciliar-Rosengarten/Catinaccio. The nucleus of this carbonate platform is situated in the area of the Vajolettürme – a pre-existing high zone of this area that goes back to Permian rift tectonics ("Tiers/Tires Paleo-fault"). After an initial aggradation stage the platform prograded towards the NE, the Seiser Alm/Alpe di Siusi, as well as towards the SE forming the spectacular clinoform geometries exposed at the Rosengarten Group. Maurer (1999) succeeded in calculating the vertical and lateral growth rates of the Anisian-Ladinian platform. Biostratigraphic and radiometric ages of the sediments of the basinal Buchenstein Fm, which interfingers with the clinoforms, indicate an initial vertical platform growth of 600–700 m within the *Reitzi* and *Secedensis* zones (Late Anisian, see Brack et al., 2005). In a later stage, the *Curionii* zone (Early Ladinian), the platform switched to strong progradation, which lasted until the *Archelaus* zone (Late Ladinian), after which the Buchenstein basin and the clinoforms became buried under a thick volcanic sequence. The total thickness of the platform edifice is in the order of 850 m – the stratigraphic top is eroded –, the distance over which progradation took place ca. 5,5 km. Similar values can be assumed for the Schlern/Sciliar platform.

The lowermost deposits of the Buchenstein Fm, the so-called *Plattenkalke*, consist of finely laminated, bituminous limestones with radiolarian micrites that interfinger with the gently dipping slope deposits of the Tschamin-Member. This unit consists of dolomitized, reefal grainstones with stromatactoid cavities. The postulated interfingering zone is located near the drowning structural high zone at the Vajolettürme. The gently dipping slope of the Tschamin Mb is overlain by steep clinoforms of the Rosengarten Fm marking the start of the progradational phase at the transition from the TST to the HTS. In the basinal succession this change of sedimentation style is shown by the transition from the *Plattenkalke* to the *Knollenkalke* of the Buchenstein Fm. The succeeding *Bänderkalke* show a coarsening-upward trend with overlying toe-of-slope breccias beds, and corresponds to a rapid progradational phase during the late HST. The volcanics of the Fernazza Group above show different thicknesses and are characterized by a distinct relief at the top. The volcanics devide the carbonate platforms of the Schlern Group into the pre-volcanic Rosengarten Fm and the post-volcanic Rosszähne Fm and Cassian Dolomite. For a diverse stratigraphic terminology, however, see Carta Geologica d'Italia (1972, 1977), Brondi et al. (1976), Bosellini (1984), and De Zanche et al. (1993). At the north face of the Schlern/Sciliar the volcanics wedge out on the lower/middle platform slope (Figs. 13, 15); upslope the clinoforms of the post-volcanic Rosszähne Fm directly overly those of the pre-volcanic Rosengarten Fm without any recognizable interruption. The post-volcanic basinal deposits of the Wengen Fm are locally characterized by strong gravity sheddings of volcaniclastic and epiclastic sediments (Marmolada Conglomerate), which probably derived from a volcanic island near the Marmolada (Bosellini, 1996).

In the interfingering zone of the Wengen Fm with the Rosszähne Fm at the north-eastern flank of the Schlern/Sciliar and at the Mahlknechtwand three distinct progradational cycles of reef tongues with intercalated volcanoclastic sandstones and conglomerates are present. Within the single cyclothems the amount of volcanic detritus decreases gradually upsection and becomes almost absent at the transition to the St. Cassian Fm. At this time the relief of the debris delivering volcanic hinterland is almost levelled out and re-flooded of this area occurs again as a consequence of the general subsidence after the Mid-Triassic rifting period. The rather complex, but intriguing interactions between subsidence, sea-level fluctuations and sediment input from two contrasting sources (carbonate platform vs. volcanic island) into the marine basin are discussed on the second day at the Mahlknechtwand (Stop 2.2).

At the platform top itself (Schlern/Sciliar plateau) there was hardly any accommodation space available and several subaerial exposures with karst and soil formation (iron ore) were formed. After a further depositional gap in the Lower Carnian sedimentation proceeded in some shallow-marine depressions with the deposition of thin black marls and shales of the Raibl Group (Fedares Mb) and finally the Norian Hauptdolomit/Dolomia Principale.

Excursion route

From Bula/Pufels to Seiser Alm/Alpe di Siusi to the Mahlknechthütte/Rif. Molignon by bus, then hiking to the Mahlknecht cliff, walk to Auf der Schneid/Cresta Alpe di Siusi, walk to Tierser Alpl Hütte, Rosszahnscharte/Forc. di Denti di Terra Rossa, walk down to the Wiedner Woadn and back to Mahlknechthütte.

Stop 2.1 – Gasthof Gstatsch

General Explanation of the panorama at the NE-flank of the Schlern (Fig. 15). The interruption of the carbonate platform development by the intercalation of Upper Ladinian volcanics is clearly visible. The volcanic rocks form an onlap onto the paleoslope of the Rosengarten Fm (Schlern Group) and wedge out towards the SW. Contemporaneous, thinner layers of volcanics are present on the platform top as well (not visible from here). The growth of the post-volcanic platform started directly on top of the pre-volcanic one without any distinct unconformity in between. Therefore we assume that the interruption of the platform growth was only of minor duration. The post-volcanic platform (Rosszähne Fm) is characterized by a stronger progradational geometry compared to the pre-volcanic Rosengarten Fm. At the platform top there is hardly any accommodation space available for aggradation. The major part of the Schlern massif consists of the pre-volcanic Rosengarten Formation. Due to the rapid fill of the ca. 800 m deep Buchenstein basin by a ca. 450 m thick volcanic sequence – towards the SE the thickness of the volcanics increases with the formation of islands (eroded) in the area of the Marmolada – the former submarine topography was completely remodeled. This topographic change led also to profound changes of the sedimentation pattern.

Stop 2.2 – Mahlknechthütte/Rif. Molignon

This spectacular outcrop of the Mahlknecht wall shows the sedimentation on the slope and toe-of-slope of the Rosszähne reef. A varicoloured succession of megabreccias, calcarenites, volcaniclastic sandstones and conglomerates (Marmolada Conglomerate) directly overlie well-preserved pillow lavas that occur on top of the thick volcanic sequence,

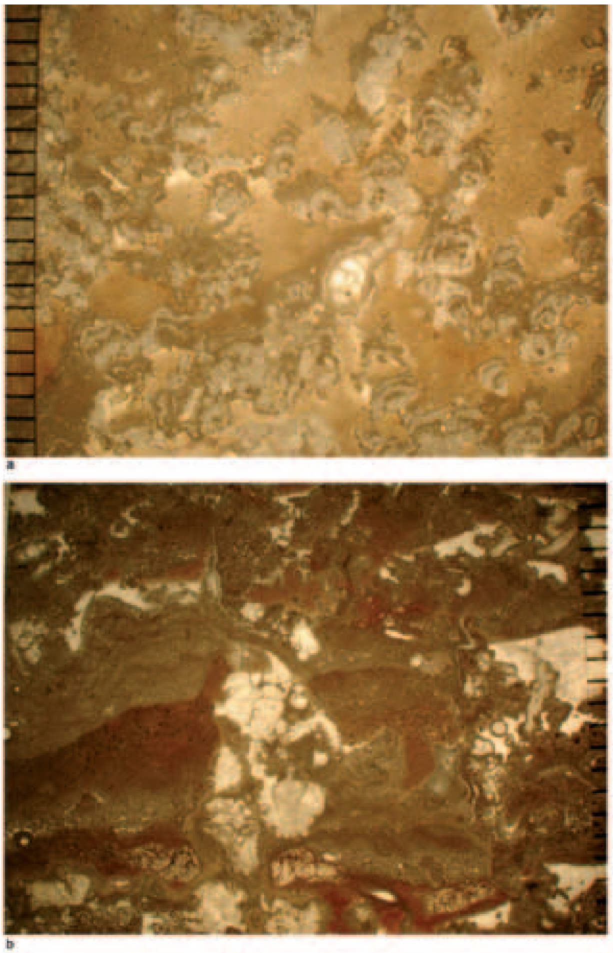

Fig. 16: Thin section photomicrographs of Cipit boulders from the Mahlknechtwand: (a) Thrombolitic boundstone with Tubiphytes and microbial encrustations and large cavities filled with internal sediment; (b) Boundstone with clotted peloidal micrite, festooned crusts, *Tubiphytes*, botryoidal cements and various generations of tilted geopetal sediment infills. Scale in mm.

which itself succeeds the Buchenstein Fm and the Rosengarten Fms.

In the interstitial pores and cooling cracks of the pillows locally radiolarian micrites with sponge spiculae occur. These remnants of pelagic deposits correspond to a ca. 20 m thick succession of the lowermost Wengen Fm in a similar facies in the Tschapid creek, located ca. 2.5 km to the west, with conodonts and *Daonellae* of the Longobardian substage (*Archelaus* zone, Brandner, 1991). The thickness variation results from an onlap geometry onto the very irregular, ca. NW-dipping surface of the volcanics. The sedimentary succession is dominated by megabreccias with the so-called "Cipit boulders". They result from high-density, clast-supported gravitative debris flows, and formed the distinct relief of the outer surface of the debris stream. The Cipit boulders exhibit very well-preserved depositional fabrics and shells, partially still with their original aragonite composition. Thus the growth fabrics and reef building organisms can be studied in detail in these rocks. The dominating constituents are bindstones and bafflestones with peloidal micite crusts, various festooned crusts as well as masses of *Tubiphytes* and other microproblematica (Brandner et al., 1991). Corals, calcareous sponge bafflestones or oncolites, which could have derived from the platform margin, are rare. Most of the limestone boulders originate from the middle and upper slope (Brandner et al., 1991, Flügel, 1991). Growth cavities of centimetre - to decimetre-size that are filled with internal sediments in various phases (tilted geopetals), and fibrous and botryoidal cements are common (Fig. 16). These microbial boundstones were indurated upon formation and combined with syndepositional cementation these processes resulted in the formation of semi-stabilized clinoforms. The formation of breccias and megabreccias tongues calls for multiphase gravitational mass movements with repeated encrustation and cementation. The single clasts or boulders may consist of other, smaller breccia clasts, i.e. the overall fabric is that of breccias within other breccias with a trend of enlargement of the clasts. These data point to multiple interactions of platform shedding, *in situ* carbonate precipitation and microbial encrustation on the clinoforms, geopetal infill, early cementation, breccia formation due to oversteepening or seismic shocks, microbial encrustation and stabilization, cementation, geopetal infill, renewed brecciation, and so on (Fig. 17). Moving down slope, the thickness of the breccia beds increases significantly. Isolated megabreccias at the toe-of-slope and the proximal basin, known as Cipit boulders, are therefore not the product of erosion of the platform margin commonly related to sea-level lowstands. None of the Cipit boulders shows dissolution pores or vadose cements, indicative of subaerial exposition. We postulate that the main reasons for the gravitative mass movements of the prograding reef tongues are the different rheological characteristics and thus the instability of the slope succession: the rapidly cemented carbonate breccia beds overlie water-saturated volcaniclastic sediments which were not yet cemented. This alternation reduces distinctly the shear strength and any earthquake may lead to the downslope sliding of the rigid carbonate layers ("hard" on "soft") along a discrete shear surface (= clinostratification). At the frontal side of the mass movement body the carbo-

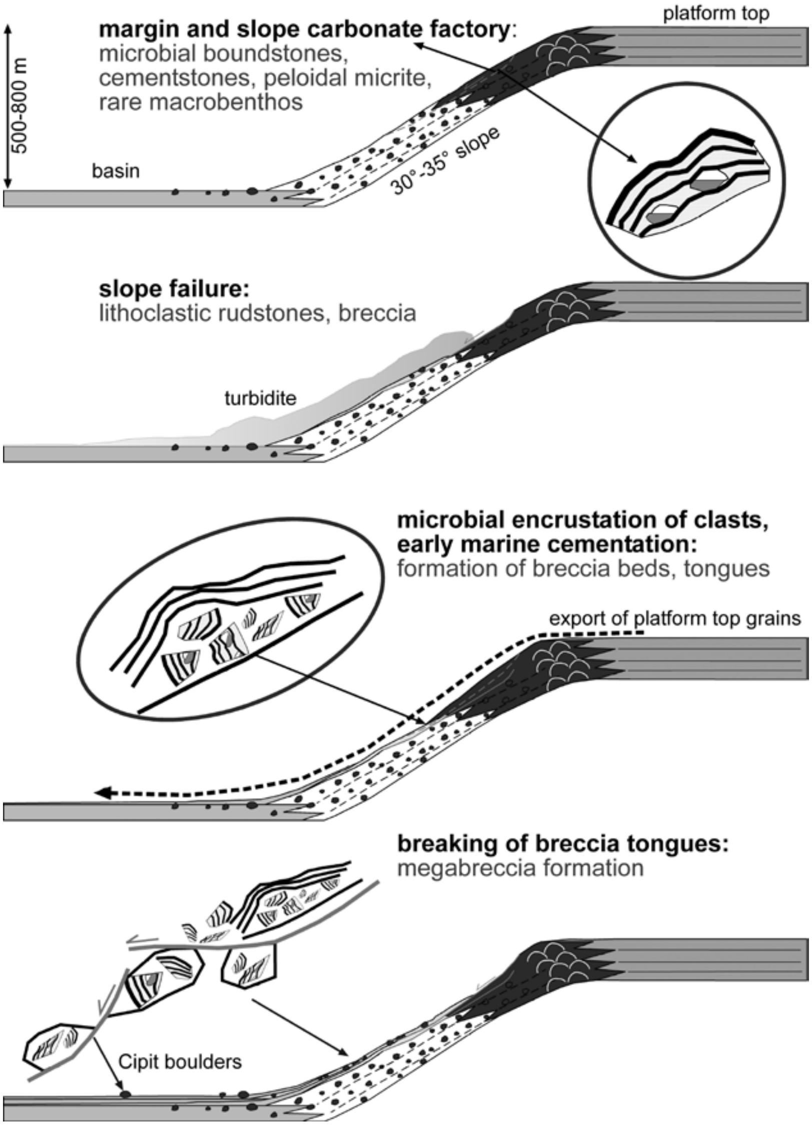

Fig. 17: Schematic model for steeply dipping, prograding carbonate slopes. The formation of breccias and megabreccias on the slope requires multiple interactions of platform shedding, *in situ* carbonate precipitation and microbial encrustation, geopetal infill, early cementation, break up of already hardened sediments by gravitational mass-movements that were triggered by oversteepening or seismic shocks, followed by renewed encrustation and cementation, etc. The clinostratification corresponds partially to discrete submarine shear planes.

nate banks turn into single boulders (Fig. 17). In the distal part the megabreccias turn into dm bedded calciturbidites with shallow-water derived grains. Ooids and coated grains testify their provenance from the flooded platform top.

Well-bedded sedimentary intervals with volcaniclastic detritus overlie the platform tongues and form an onlap geometry onto the paleo-slope (see also Stop 2.3). The succession is made up of sandstones and conglomerates as channel fills (Marmolada Conglomerate). They are epiclastic sediments with well-rounded pebbles originating from fluvial transport. Their actual position on the lower reef slope and in the deep basin resulted from gravitative redeposition. The volcaniclastic intervals are repeatedly interbedded with the reef tongues, but not by chance. The carbonate/volcaniclastic succession shows a certain rhythmicity, whose control mechanisms are still a matter of debate. The peculiarity of the depositional environment is the different provenance of the sediments: the carbonates were formed on the Rosszähne platform itself, whereas the volcaniclastic sediments were transported from a far away situated volcanic island (surroundings of Marmolada?). The regularity in the sedimentary successions suggests that sea-level fluctuations were the controlling parameter. There is, however, no consensus whether the megabreccias together with the Cipit boulders were formed during a sea-level lowstand (LST) or highstand (HST) (see Yose, 1991). We postulate that more arguments are in favor of the transport of the volcaniclastics during a sea-level lowstand, whereas the progradation of the reef tongues with shallow water grains (oolites) occurred during sea-level highstands.

Fig. 18: Panoramic view from "Auf der Schneid" (Cresta di Siusi) to the Rosszähne and Mahlknechtwall showing the interfingering between prograding reef slope deposits of the Rosszähne Fm (Rz1, 2) and volcaniclastic sandstones and conglomerates (V1). Wedging-out of volcaniclastics onto the upper carbonate slope (= onlap) as well as the succeeding downlap surface (DLS) of reef tongue 2 are clearly visible. The natural cut of the Mahlknechtwand runs obliquely to the depositional dip of the clinoforms, therefore the true dip-angle is steeper. V = volcanics (Fernazza Group) which cover the paleo-slope of the pre-volcanic Rosengarten Fm (Ro) to the south of the Tierser Alpl (after Brandner et al., 2007).

Stop 2.3 – Auf der Schneid/Cresta di Siusi

Panorama of the seismic-scale outcrops of the entire slope domain of the post-volcanic Rosszähne platform (Fig. 18). The wedging out of the volcaniclastic sequence onto the post-volcanic carbonate slope at the transition to red beds at the Roterd Sp./Cima di Terra Rossa, which may reflect intermittent subaerial exposure of the platform top, is clearly visible. Above it follows the downlap surface of the prograding Rosszähne reef tongues of the early highstand. South of the Tieser Alpl the onlap of the volcanics is well exposed within the Rosengarten massif. The steeply dipping Tierser Alpl fault does not significantly disturb the platform geometry and the stratigraphic successions.

Stop 2.4 – Tierser Alpl Hütte and Rosszahn Scharte

General explanation of the spectacular panorama and of the isolated Langkofel/Plattkofel carbonate platform with its W dipping paleoslope. Between the Rosengarten/Schlern and the Langkofel/Plattkofel reef a narrow seaway can be assumed, but its actual extension does not correspond exactly to the original, Triassic, one: during the Alpine deformation the Langkofel/Plattkofel platform was sheared off its underground and thrusted towards the north.

At the Rosszahn Scharte the ca. 30° steep N dipping paleoslope with the above described phenomena of gravitative submarine sliding of carbonate banks and megabreccia formation can be observed (Fig. 19). The later dolomitization of the entire carbonate platform and slope – the exact timing is not known, but a first stage of dolomitization during the Ladinian during subaerial exposure and a second one during burial seem plausible – affected only the still connected carbonate tongues, which were permeable for dolomitization fluids. The further transported boulders in the basin were isolated by the fine grained sedimentary matrix and thus escaped the dolomitization.

Stop 2.5 – above Wiedner Woadn

Exemplary outcrop in a little gully: Marmolada Conglomerate and volcaniclastic sandstones form an onlap onto the steeply dipping paleoslope of the Rosszähne carbonate platform.

Fig. 19: Outcrop photo of steeply N-dipping clinoforms west of the Rosszahn Scharte with typical slope breccia tongues.

DAY 3

Geology of the Sella platform and Col Rodela

Introduction

The third day is dedicated to the Sella massif as well as to the Col Rodela. The Sella Group, one of the most prominent mountains of the Dolomites, is located in the central Dolomites and is orographically bordered by the four, well-known passes: the Gröden/ Gardena Pass (2121 m) in the north, the Campolongo Pass (1875 m) in the east, the Pordoi Pass (2239 m) in the south and the Sella Pass (2244 m) in the west (Fig. 2). From a geological point of view, the Sella massif can be subdivided into two parts: (1) a lower one that consists of the Late Ladinian to Early Carnian carbonate platform in the strict sense; (2) an upper one that essentially comprises the Norian Hauptdolomite and a thin cover of Rhaetian to Cretaceous sediments. These two major carbonate bodies are separated by the Carnian "Raibl beds", forming the typical recessively weathering ledge at the outer rim of the massif. The lower carbonate edifice consists of post-volcanic, platform and flank deposits (Selladolomite Subgroup: Rosszähne Fm and Cassian Dolomite) and exhibits excellently-preserved, steep clinoforms (ca. 35°) on all sides. It exhibits a sub-round shape in plan view, measures 7–8 km in diameter and interfingers on all sides with basinal sediments of the Wengen and St. Cassian Formations, respectively. This atoll-like geometry of the Sella platform thus has become one of the classical examples in the study of large-scale depositional geometries of isolated carbonate platforms (Leonardi & Rossi, 1957, Bosellini, 1984, Kenter, 1990, Bosellini & Neri, 1991, Keim & Schlager, 1999, 2001).

The growth of the Sella platform came to a standstill in the Early Carnian and was subsequently covered by a sequence of mixed carbonate-siliciclastic deposits, the "Raibl beds" *Auct.*, hereafter termed Pordoi Formation. It consists of volcanoclastic sandstones at the base, followed by peritidal dolomites interbedded with marlstones. The sedimentation pattern of the Pordoi Fm was strongly influenced by synsedimentary tectonics (Doglioni, 1992, Keim & Brandner, 2001). Extensional tectonics led to local fissures, block-tilting, graben structures and breccia deposits. Towards the centre of the mountain, the thickness of the Pordoi Fm decreases distinctly and is locally reduced to zero.

The upper part of the Sella is formed by the well-bedded Hauptdolomit/Dolomia Principale, an approx. 250 m thick succession of peritidal deposits, which are overlain by some tens of meters of Rhaethian Dachstein limestone. At the summit of the Sella, the Piz Boè (3152 m), the stratigraphic succession terminates with red nodular limestones (Ammonitico Rosso, Jurassic) and hemipelagic marlstones (Puez Marls, Cretaceous, see Fig. 13).

Lithostratigraphy of the Sella platform

The lithostratigraphic units used in this guidebook follow the "Geologische Karte der Westlichen Dolomiten – Carta geologica delle Dolomiti Occidentali 1:25.000". The lithostratigraphic terms of the Ladinian-Carnian deposits differ in some way from the names used so far in this region (e.g. Carta geologica d'Italia, F. "Marmolada", 1977, Bosellini, 1991):

Basinal sediments: Wengen Fm, St. Cassian Fm: lithologic interfingering of each other.

Carbonate platform: Selladolomite Subgroup: postvolcanic Schlerndolomite undifferentiated; locally the Selladolomite can be subdivided into an older platform, termed Rosszähne Fm (like at the Schlern massif, see day 2), which interfingers with the Wengen Fm, and a younger platform, the Cassian Dolomite, which interfingers with the St. Cassian Formation. The "Gardena Megabreccia" *sensu* Bosellini & Neri (1991) belongs to the Rosszähne Formation.

Post-carbonate platform sediments: Pordoi Formation (the former "Raibl beds").

Biostratigraphy

The biostratigraphic data are derived from various basinal sections (Wengen and St. Cassian Fms.) around the Sella and from the Pordoi Fm. overlying the platform top. Ammonoid faunas (Reithofer, 1928, Mietto & Manfrin, 1995, Mietto et al., 2008) obtained from the basinal successions indicate an Upper Ladinian (*Regoledanus* Zone) to Lower Carnian age. The topmost part of the section above the so-called "Gardena Megabreccia" to the south of the Gardena Pass (Col de Frea) was assigned by Mietto & Manfrin (1995) to the *Daxatina* cf. *canadensis* subzone, nowadays termed *Canadensis* zone = base of the Carnian stage (Broglio Loriga et al., 1999, Mietto et al., 2008). Conodonts of the Wengen and St. Cassian Fms (Mastandrea et al., 1997) around the Sella (*Budurovignathus* group) belong to the *diebeli* assemblage zone *sensu* Krystyn (1983), which corresponds to the standard *Regoledanus* zone (Upper Ladinian).

The youngest basinal deposits, time-equivalent to the final platform growth, are exposed at the eastern side of the Sella, at the foot of Crep de Munt. A preliminary pollen study from dark marls of the St. Cassian Fm, showed a rich fauna containing among others the taxa *Concentricisporites* cf. *bianulatus* and *Gordonispora fossulata* (Keim & Roghi, 2006). These findings confirm a Lower Carnian age (Julian 1/II = *aonoides* zone). Pollen from the uppermost Pordoi Fm at Piccolo Pordoi, just a few metres below the Hauptdolomit (Dolomia Principale) contained the taxa *Vallasporites ignacii, Duplicisporites verrucatus, Pseudoenzonalasporites summus, Patinasporites densus, P.* cf. *densus, Ovalipollis pseudoalatus, Camarozonosporites* cf. *rudis* and *Hevizipollenites* sp.. This association indicates a late Julian age (*Austriacum* zone) and thus correlates with the basal Heiligkreuz Fm. in the eastern Dolomites. Thus a major stratigraphic gap, which probably occupies most of the Tuvalian, has to be assumed to exist between the topmost Pordoi Fm and the overlying Hauptdolomit.

Alpine tectonic deformation

Alpine deformation of the Sella Group is rather weak and thus the Triassic submarine paleo-topography is still well preserved. The oldest, pre-alpine deformation patterns are Carnian extensional structures with numerous, nearly N-S trending fissures, grabens and halfgrabens, which became sealed by the Norian Hauptdolomite (Doglioni, 1992, Keim & Brandner, 2001). These structures are present all around the Sella massif, but especially at the E-side. The most conspicuous alpine deformation structures are also exposed at the eastern side with overthrusts in a ramp-flat system (Doglioni, 1985, 1992) leading to the so-called "Gipfelüberschiebung" (summit thrusts) at Piz Boè; here the Rhaetian Dachstein limestone, the Jurassic Ammonnitico Rosso and the Cretaceous Puezmarls are strongly folded and overthrusted by several slices of Hauptdolomit. This deformation is of Paleogene age and was correlated with the Dinaric, W-vergent compression (Doglioni, 1992). The succession at the northern part of the Sella was folded along the E-W trending Plan-Grödnerjoch/Passo Gardena anticline and was tilted towards the south by 15°–20°. The Sella S-side is involved into the E-W running Padon anticline and thus the succession is tilted towards the north.

Additionally, the entire Sella massif is dissected by numerous NE-SW and NW-SE running transcurrent faults, the most prominent one is the sinistral strike slip fault along the Val de Mesdì to the Pordoi Pass.

Platform-basin transition: geometry and sedimentology

The entire platform shows pervasive dolomitization. In contrast to the hundreds of meters thick clinoforms, the topset beds at the outer rim of the Sella reach only some tens of meters. Towards the centre of the Sella the thickness of the topsets increases considerably. Based on the height of the clinoforms, the thickness of the Selladolomite Subgroup ranges between 400 to 700 m. The transition between topsets and steep slope occurs within tens of meters. The clinoforms show a primary depositional angle of 30–35° and interfinger on all sides with basinal deposits (Bosellini, 1984). Intensive downslope transport is indicated by debris aprons at the toe of the clinoforms; they consist of turbidites, debris-flow breccias and swarms of meter-size boulders (Bosellini & Neri, 1991, Mastandrea et al., 1997). In addition, the basins were fed with volcanoclastics (conglomerates, sandstones, siltstones) and terrigenous mud.

The topsets show horizontal, planar bedding with bed-thicknesses between 0.1 and 1 m. Occasionally, patches of cross-bedded are¬ni¬tes as well as meter-size tepees occur (e.g. in Val de Mesdì). At Pisciadù, within the topsets coral colonies of the type *Thecosmilia* have been found in growth position. The content of skeletal grains from the measured section at Pisciadù is generally less than 5% and consists predominately of echinoderm debris, bivalves, foraminifera, dasycladacean and solenoporacean fragments, *Tubiphytes*?, cyanophyta, such as *Rivularia*, *Cayeuxia* or *Hedstroemia* and uncertain sphinctozoan sponges (Keim & Schlager, 2001). The skeletal grains in most cases are totally recrystallized and often show micritic encrustations. The most striking observation is the presence of automicrite facies in all different platform domains, although the amount varies considerably (Keim & Schlager, 1999, 2001). Most of the samples from the margin-upper slope consist of automicritic boundstones with large cement-filled cavities in-between ("evinosponges"-like structures).

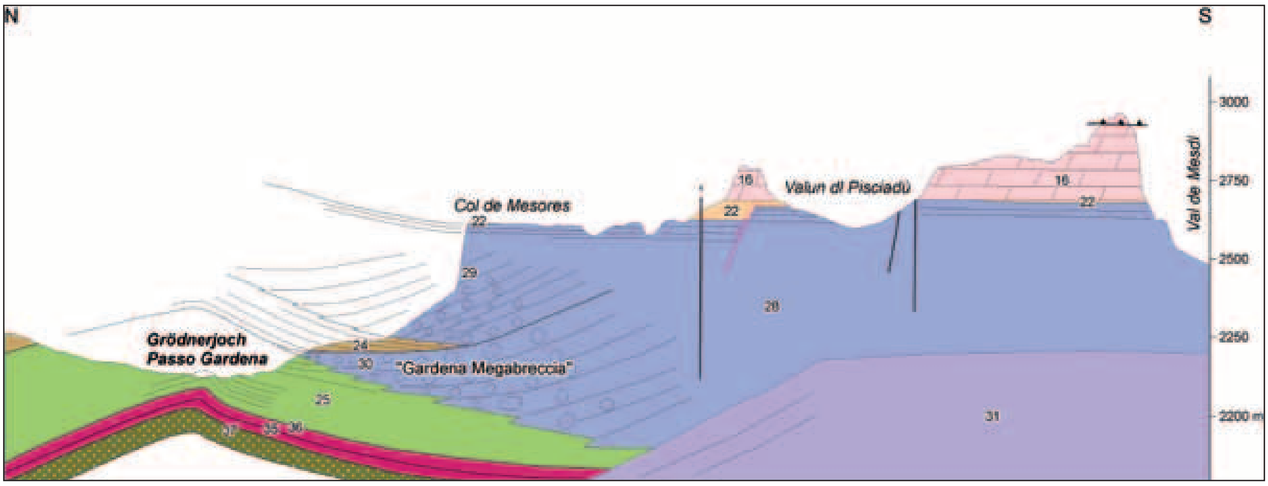

Fig. 20: The geological situation at Grödner Joch/Passo Gardena: (a) The geological cross section illustrates the antiformal deformed lower slope megabreccias ("Gardena megabreccia") and basinal deposits during alpine tectonics along the E-W trending Plan-Grödner Joch/Passo Gardena anticline; (b) close up view of the "Gardena megabreccia" (= Rosszähne Fm) wedging out in the basinal sediments of the Wengen Formation. See text for explanation. 37 = "Caotico eterogeneo", 35 = lava, 37 = Hyaloclastites, 31 = pre-volcanic Schlerndolomite (Rosengarten Fm), 30 = post-volcanic Schlerndolomite (Rosszähne Fm), 29 = Cassian Dolomite, 28 = Selladolomite Subgroup (post-volcanic platform carbonates undiff.), 25 = Wengen Fm, 24 = St. Cassian Fm, 22 = Pordoi Fm ("Raibl beds"), 16 = Hauptdolomit/Dolomia Principale.

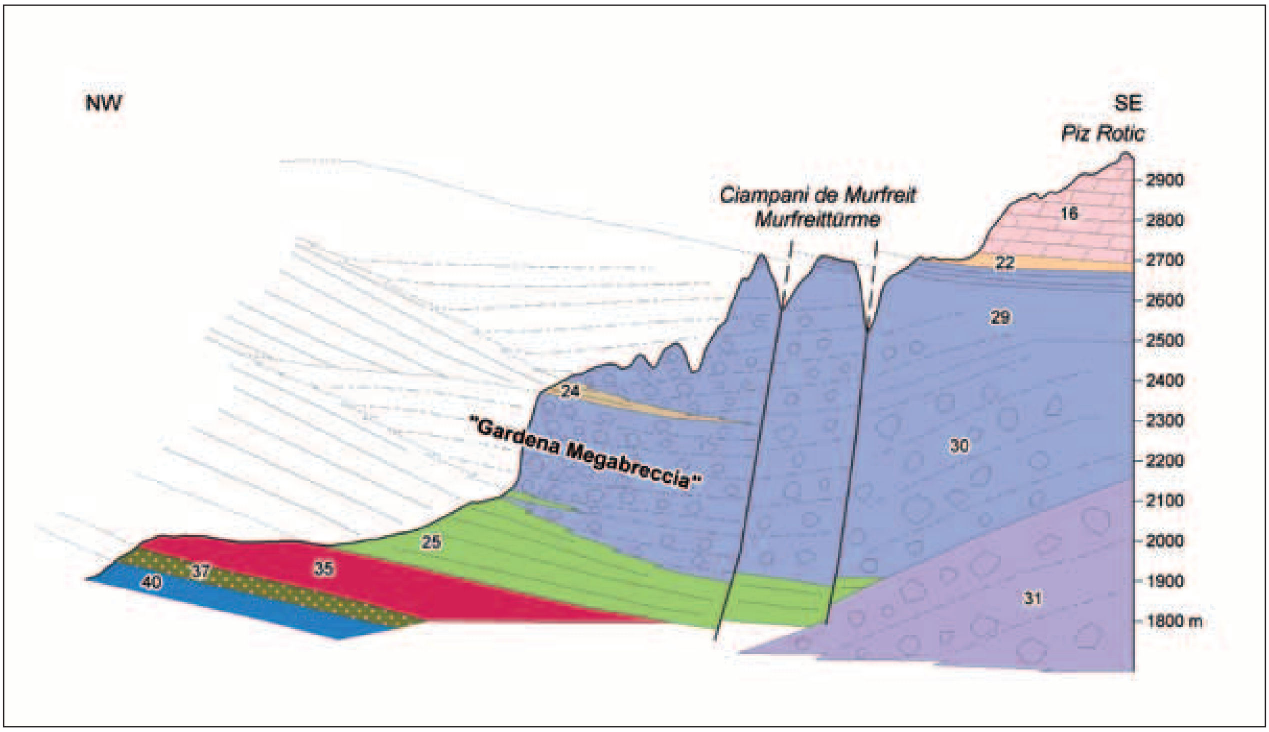

Fig. 21: Geologic cross section at Campani de Murfreit. Alpine antiformal deformation of the entire stratigraphic succession up to the Norian Hauptdolomite clearly shown. 40 = Contrin Fm; for a detailed legend see Fig. 20.

Skeletal grains from the margin-upper slope may include *Tubiphytes*, *Macrotubus*, *Girvanella*, serpulids?, and occasionally some bivalve filaments, ostracods and gastropods. The high cement content of the samples comprises mainly fibrous cements in the form of botryoids or even druses. All cements are altered to dolomite. Fibrous cements are inclusion-rich and may form cm-thick isopachous layers. The volumetrically most important cement type are isopachous layers of former radiaxial fibrous calcites. The breccia tongues of the lower slope contain abundant boulders up to several m in diameter. The planar shape and steep angle of the clinoforms, however, indicate that the large-scale geometry of the slope was controlled by non-cohesive layers of sand and rubble piled up to the angle of repose (Kenter, 1990, Keim & Schlager, 1999, 2001, Schlager & Reijmer, 2009).

Excursion route

During the excursion, we will approach the Sella from the Gardena Valley and continue in a counterclockwise direction. From the Gardena Pass we will pass the Sella Pass, walk to Col Rodela, turn back to the Sella Pass, and then proceed to the Pordoi Pass.

Stop 3.1 – Grödnerjoch/Passo Gardena

The N-front of the Sella platform, including the outcrops at Meisules dala Biesces/Murfreit, is one of the most controversial examples in terms of depositional geometries (e.g. Leondari & Rossi, 1957, Bosellini, 1982, Bosellini & Neri, 1991). The platform shows a subdivision which is twofold (Fig. 20): (1) a lower unit, the so-called "Gardena Megabreccia" (Bosellini, 1982, Bosellini & Neri, 1991), which is covered by basinal sediments (Wengen and St. Cassian Fms.) and (2) an upper unit, composed of steeply inclined slope deposits and thin flat-lying top-set beds of the Sella platform proper (Cassian Dolomite). The megabreccia body is distinctly stratified: at Gardena Pass the beds are nearly horizontal, at Meisules/Murfreit, however, the boulder beds dip with ca. 20° to SE. The same dip angle is present in the underlying Wengen Fm and also in the platform-top sediments at the Meislues/ Murfreit Towers (Fig. 21). Locally, the basinal St. Cassian Fm between the "Gardena Megabreccia" and the above lying Cassian Dolomite wedge out, causing the two units to be weld together. The thickness of the "Gardena Megabreccia" varies between about 200 m at Meisules/Murfreit and zero at the Gardena Pass. At Gardena Pass, the megabreccia tongues pinch out by interfingering with the basinal Wengen Formation and outrunner blocks ("Cipit boulders") which are clearly visible in the basin sediments. The "Gardena Megabreccia" mainly consists of tongues of boulders with diameters of up to several meters and intercalations of some dm-thick beds of calciturbidites. The boulders are largely composed of automicritic boundstones, with microproblematica like *Tubiphytes*, scarce metazoans (sponges, corals), peloidal to skeletal packstones and cement-filled cavities (Russo, in Bosellini & Neri, 1991). The "Gardena Megabreccia" was interpreted by Bosellini (1982) and Bosellini & Neri (1991) as channelized megabreccia as the result of multiple collapses of a "pre-existing carbonate platform, rather than a buildup". De Zanche & Gianolla (1995) regarded it as the lowstand prograding complex of their Car1 depositional sequence.

We do not share these interpretations and regard the "Gardena Megabreccia" as folded lower slope breccia tongues of the Rosszähne Fm (Keim & Neri, 2004, Brandner et al., 2007). The strong thickness variation (0–200 m) of the megabreccia body is related to the oblique erosive cut of the proximal-distal parts of these lower slope deposits. The variation of the dip-angle of the megabreccia (flat-lying, SE-dip) is the result of alpine tectonic deformation along the ca. E-W trending Plan-Grödnerjoch anticline: the former N-dipping, lower slope deposits, which interfinger with the basinal sediments of the Wengen Fm were tilted by 15–30° and are actually part of the southern limb of the above mentioned Plan-Grödnerjoch/Passo Gardena anticline.

In the surroundings of the Grödnerjoch/Passo Gardena, the Cassian Dolomite situated above the "Gardena Megabreccia" does not show this tilting and is characterized by the classical 30–35° steep clinoforms and horizontal lying topsets. At this location the folded part of the platform and slope has simply been eroded away (Fig. 20). Further to the SW, however, at the Murfreit Towers, the topset beds of the Cassian Dolomite, the overlying Carnian Pordoi Fm ("Raibl beds") as well as the Norian Hauptdolomite are tilted 15–20° towards the S-SE (Fig. 21). These data clearly point to folding at the N-NW side of the Sella Group during alpine deformation.

Stop 3.2 – Hotel Gerhard, at the foot of Meisules dala Biesces

This short stop on the road again impressively shows the tilted Rosszähne Fm ("Gardena Megabreccia") with distinctly SE dipping breccia beds (Fig. 21); this alpine folding with formation of the Plan-Grödnerjoch/Passo Gardena anticline affected also the younger stratigraphic units including the Hauptdolomite. Furthermore, the facies interfingering of the lower slope breccias and the basinal sediments of the Wengen Fm is clearly expressed by the alternation of calciturbidites, marls, sandstones and a ca. 20 m thick dolomitized limestone breccia tongue.

From Sella Pass to Col Rodela: geological introduction

The area of Col Rodela is one of the most interesting examples in the Dolomites that allows for a controversial interpretation of stratigraphy and tectonics. At the southern flank of Col Rodela a highly complex, repeated series of successions of the upper Permian Bellerophon Fm and the upper Ladinian "Caotico eterogeneo" are present. It is one of the areas, where ca. 30 years ago the idea of Middle Triassic compressional or transpressional tectonics with folding and overthrusting was born (e.g. Pisa et al., 1980, Castellarin et al., 1982, 1988, Doglioni, 1987). According to these authors this tectonic model is essentially based on two field observations: (1) at Col Rodela the tectonic sheet stacks are sealed by the undisturbed upper Ladinian Marmolada Conglomerate, and (2) in the Valle di San Nicolò south of Col Rodela the evaporitic Bellerophon Fm is strongly folded and cross-cut by volcanic dikes. Therefore, the folds, which were believed to result from compressional tectonics, predate the volcanic event.

But ca. 20 years later, Castellarin et al. (1998, 2004) abandoned the model of Ladinian compressional tectonics at Col Rodela and re-interpreted the entire sheet stack as a diapiric mélange in connection with the formation of breccias and megabreccias

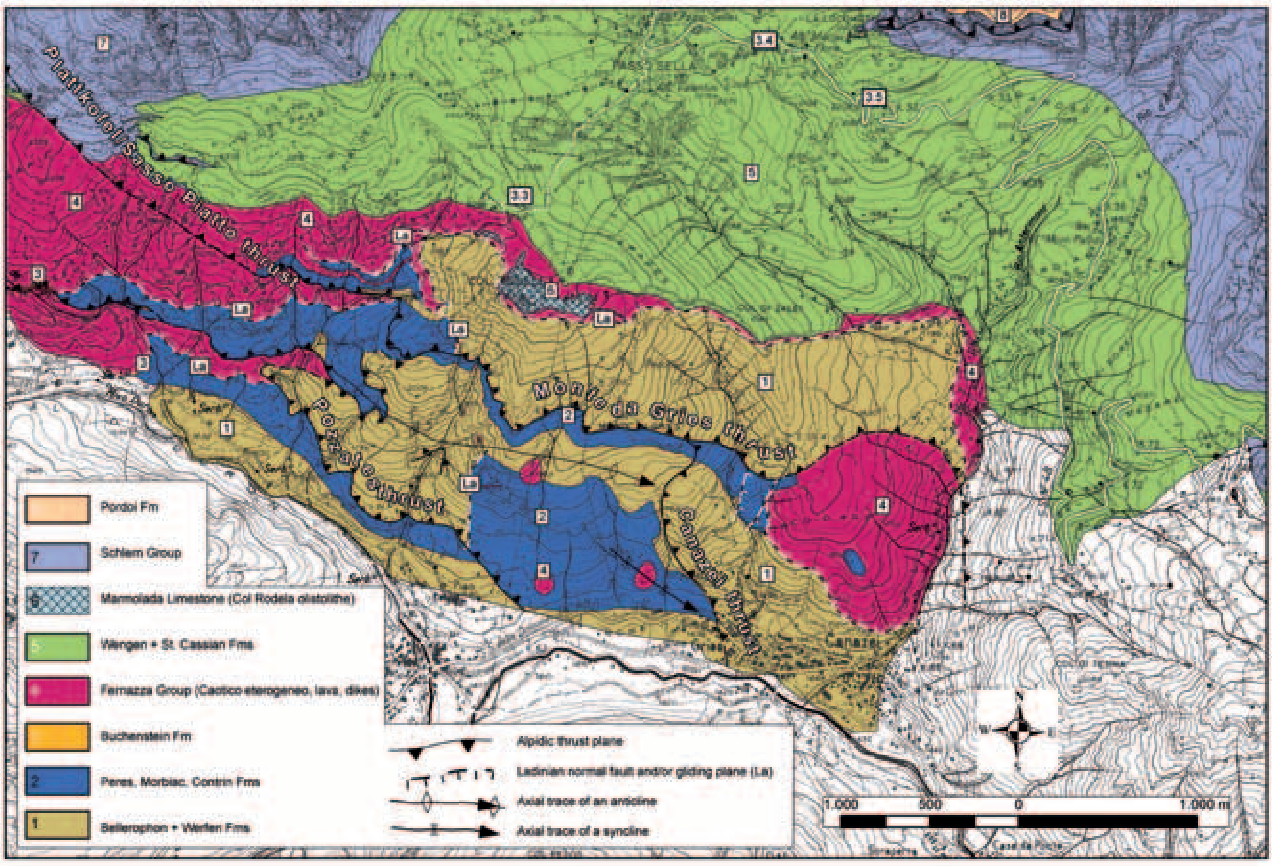

Fig. 22: Simplified tectonic map of the area between Canazei (Val di Fassa) and Col Rodela, based on the Geologische Karte der Westlichen Dolomiten 1:25.000 (2007). Tectonic repetition of the stratigraphic succession is caused by a two-phased alpine, an early and a late Dinaric deformation phase.

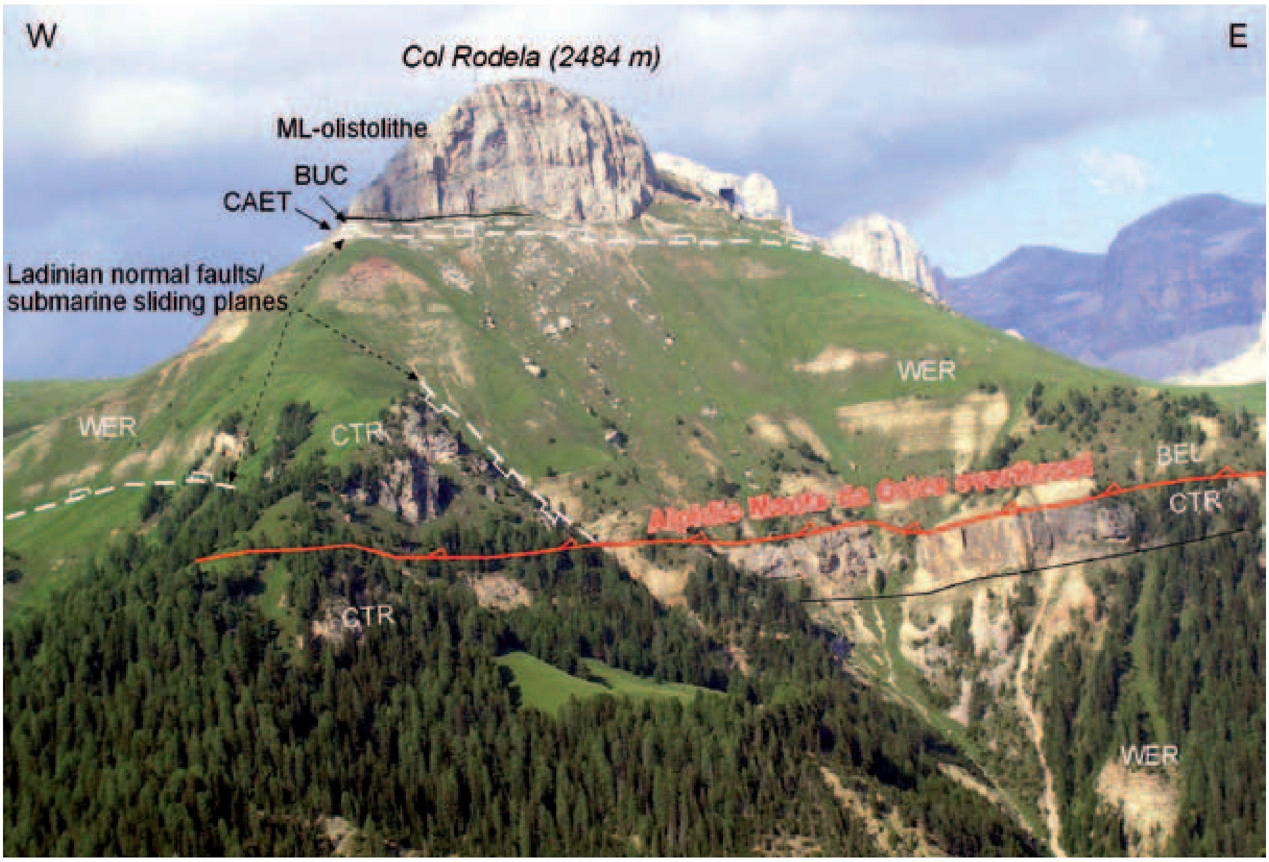

Fig. 23: Panoramic view of the southern flank of Col Rodela with outline of the most important tectonic structures. BEL = Bellerophon Fm, WER = Werfen Fm, CTR = Contrin Fm, CAET = "Caotico eterogeneo", BUC = Buchenstein Fm, ML = Marmolada Limestone (olistolithe).

of the "Caotico eterogeneo". Only extensional faults were regarded to represent Ladinian faults.

In the course of our geologic mapping project of the Western Dolomites also the area between Campitello and Col Rodela has been mapped again (Geologische Karte der Westlichen Dolomiten, 2007). Based on these new field data we reached the following conclusions: (1) confirmation of various Ladinian, synsedimentary normal faults with formation of the "Caotico eterogeneo" and (2) two-phase alpidic compressional tectonics with folding and thrust structures (Fig. 22).

Stop 3.3 – August-Friedrich-Hütte

This stop offers a good view to the N- and W-side of Col Rodela and invites the visitor to discuss its tectono-stratigraphic setting. The Col Rodela (2484 m) itself consists of a ca. 100 m thick remnant of Anisian-Ladinian reef slope limestone (Marmolada limestone) with some meter thick coeval basinal sediments (Buchenstein Fm) at its base (Figs. 23, 24). This reef-slope-basin pair is underlain by some meter thick polymict breccias of the "Caotico eterogeno", which themselves rest on the Lower Triassic Campill Member (Werfen Formation). The "Caotico eterogeneo" essentially consists of submarine scarp megabreccias and mass flow deposits. The Marmolada limestone of Col Rodela is a giant block inside the "Caotico eterogeneo" (Mutschlechner, 1935, Pisa et al., 1980, Bosellini et al., 1982, Castellarin et al., 1988, 1998, 2004). The entire succession is overlain by upper Ladinain lavas breccias, lavas and by the Marmolada Conglomerate (Wengen Formation) and dips with ca. 15–30° towards the NE. The boundary surface between the Campill Mb. and the breccias of the "Caotico eterogeneo" is interpreted herein as a Ladinian extensional fault or as a submarine sliding plane, respectively (Fig. 23). The stratigraphic loss at this boundary includes the Anisian conglomerates (Peres Fm) and the above following transgressive deposits of the Morbiac and Contrin Formations with a total thickness of about 100 m. Since the bounda-

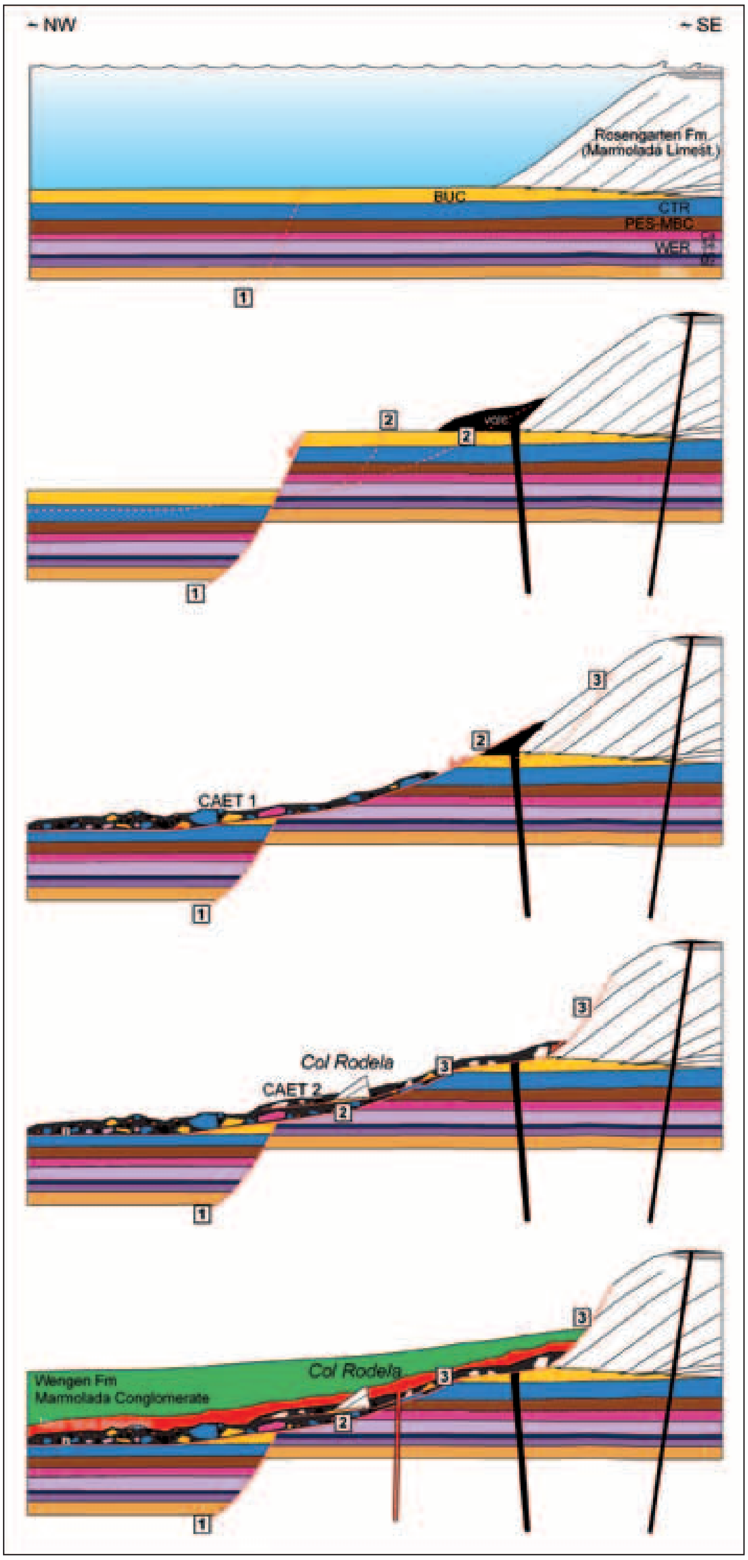

Fig. 24: Schematic model for the development of the "Caotico eterogeneo" for the area of Col Rodela during the Late Ladinian. The formation of breccias and megabreccias with reworking of sediments down to the Werfen Fm requires multiple extensional tectonic processes with steep and flat lying normal faults and/or gliding planes in connection with the volcanic activity. The breccias and megabreccias resulted essentially from submarine mass flow deposits. The presence of Ladinian normal faults combined with a complex stratigraphic succession of the "Caotico eterogeneo" with local olistoliths complicates the interpretation of the succession at the southern flank of Col Rodela. Alpidic thrust planes cut through various stratigraphic levels and younger rocks, which were downfaulted during the late Ladinian, may have been thrusted over older rocks during the alpine (Dinaric) deformation.

ry surface between the Campill Mb and the "Caotico eterogeneo" is a rather stratiform surface over considerable distances, the dip angle of the inferred Ladinian extensional fault or submarine sliding planes, must have been very gentle or nearly horizontal, at least in the surroundings of Col Rodela (Fig. 24). However, further to the N/NW, another steep normal fault must have existed in order to create the necessary space for the submarine gliding mass. This extensional tectonic process was multiphased and obviously related to the contemporaneous basic volcanism/magmatism in the central western Dolomites (Val di Fassa, Gröden/Val Gardena). The breccias and megabreccias of the "Caotico eterogeneo" with reworked clasts and blocks of Lower Triassic to Ladinian successions including reworked volcanic clasts are the response to this volcano-tectonics.

Alpine tectonic deformation

The repetitions of the sedimentary successions at the southern flank of Col Rodela are interpreted herein as a two phased Dinaric (Paleogene) WSW and SW directed thrust tectonics and folding. The new mapping (Fig. 22) shows three slices, the Campitello slice in the footwall, the Elbetina slice in the middle and the Rodela slice in the hanging wall. All three slices comprise incomplete sequences spanning from Bellerophon Fm, operating as lower detachment, to the Contrin Fm and the heterogenous Fernazza Group ("Caotico eterogeneo"). The thicknesses are variable due to Upper Anisian and Ladinian normal faulting and erosion. The Pozzates thrust with the Canazei branch thrust are interpreted as early Dinaric top to the WSW thrust planes which were folded subsequently by the late Dinaric SW–NE compression. In the roof of the antiformal deformed slice stack the Monte da Gries thrust brings up the Rodela slice. Due to Ladinian normal faulting, volcanic rocks of the footwall slice are overthrusted by similar volcanoclastic sequences in the hangingwall Rodela slice above Canazei. Therefore it is difficult to recognize the trace of the thrust plane toward the SE. The whole duplex structure is gently dipping to the E and disappears therefore below the thick sequence of the Fernazza Group, Wengen and St. Cassian Fms to the east of Canazei.

Stop 3.4 – Sella Pass

At this stop the facies interfingering in the basinal deposits (Wengen and St. Cassian Fms) as well as the W-dipping clinoforms of the Sella platform can be observed. The basinal deposits are characterized by a alternation of volcaniclastic and carbonate dominated successions (Fig. 25). The entire succession has been described by Bosellini & Neri (1991) and Mastandrea et al. (1997). The typical dark coloured marls, shales, sandstones and fine conglomerates with typical intercalated Cipit boulders of the Wengen Fm are replaced upsection by beige marls and light coloured calcarenites of the St. Cassian Fm. direct at the Hotel Maria Flora. This carbonate rich interval is about 40 m thick and is again covered by volcaniclastic sandstones and conglomerates of the Wengen Fm, ca. 50 m thick; this clastic interval is overlain essentially by calcarenites, rudstones and breccia beds of the prograding platform. This upper part of the St. Cassian Fm contains one more volcaniclastic layer, ca. 2 m thickness, which occurs just below the "Locomotiva" (Fig. 25). This lithofacies variation in the basin is the response to a different amount of clastic input derived from a volcanic hinterland and carbonate grains that were exported by the producing carbonate platform. This variation in sediment input to the basins may be governed by sea-level fluctuations, climatic or tectonic processes that resulted in the interfingering between Wengen and St. Cassian Fm. The final dominance of light coloured marls and calcarenites of the St. Cassian Fm goes hand in hand with the complete flooding of the debris delivering volcanic island, supposed to be located in the area west of Marmolada.

The W-dipping clinoforms of the Cassian Dolomite (Selladolomite Subgroup) are distinctly flattening out towards the basin and their dip angle decreases in the progradational direction from about 30° in the Val Lasties to 20° at the Sella towers (Kenter, 1990). The topsets are only 10–20 m thick; the transition zone to the steeply dipping clinoforms is rather massive to structureless.

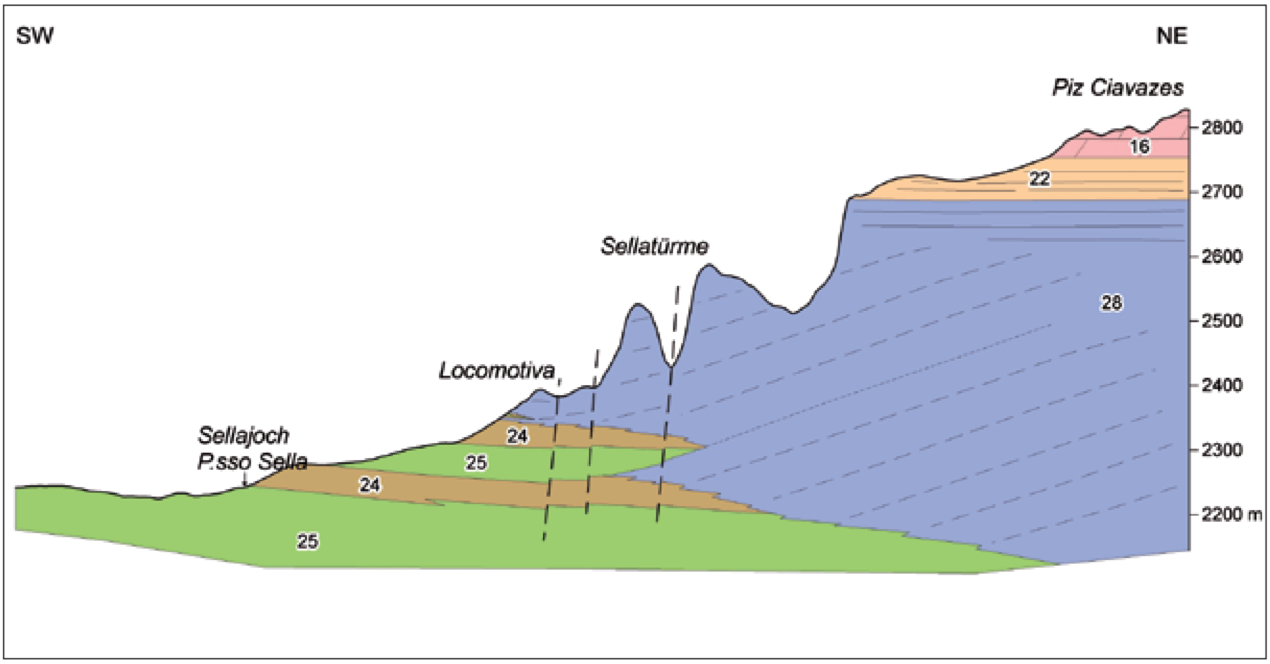

Fig. 25: Interpretative cross section between Piz Ciavaces and Passo Sella. The subdivision of the platform and slope deposits into the Rosszähne Fm and Cassian Dolomite, such as at the Grödner Joch/Passo Gardena, is not possible here. Therefore the term Selladolomite-Subgroup is used. The two-fold repetition of the Wengen and St. Cassian Fms originates from the different input of carbonate vs. volcaniclastic material into the basin. 25 = Wengen Fm (incl. Marmolada Conglomerate), 24 = St. Cassian Fm, 28 = Selladolomite Subgroup, 22 = Pordoi Fm, 16 = Hauptdolomit/Dolomia Principale.

Stop 3.5 – road curve just below the Sella Pass

This stop offers an excellent panoramic view of the WNW-exposed wall of Sass Pordoi, shows topsets and clinoforms of the Selladolomite Subgroup, and gives some insights into the nucleus of the Sella platform in the Val Lasties. In addition, the thinning out of the Pordoi Fm towards the centre of the platform, the overlying stratified Hauptdolomite as well as the youngest sediments at Piz Boè can be observed.

DAY 4

Stratigraphy and tectonics at the southern side of the Sella Group

Excursion route

This day is dedicated to the general geology at the Pordoi Pass itself and to the tectonic deformation at the summit Piz Boè (3152 m). From the Pordoi Pass we ascent to Sas Pordoi by cable car, walk to the Piz Boè (3152 m), and turn back to Sas Pordoi und descend by cable car. The Sass Pordoi and Piz Boè offer one of the most spectacular panoramic views over the entire Dolomites.

Stop 4.1 – Pordoi Pass

The area of the Pordoi Pass represents a Carnian seaway between the S-prograding Sella platform flanks in the north and the N-prograding Sas Becè platform located in the south. Actually, the lowermost clinoforms of both platforms are separated by a narrow basin zone of ca. 330 m width only. This distance, however, probably was shortened by alpine, N-S-directed compressional tectonics (Fig. 26). Additionally, the NE-SW running sinistral strike slip fault of the Val de Mesdì passes just west of the Pordoi Pass and has caused the formation of intense fracture zones within the Cassian Dolomite. The basinal sediments of the St. Cassian Fm are rather badly exposed and consist of beige-brown marls and calcarenites and occasionally some Cipit boulders. Beds of the St. Cassian Fm dip ca. 20–30° towards the north as a result of the above mentioned alpine deformation. Therefore also the actual dip angle of clinoforms of Sas Becè is too steep with respect to their original

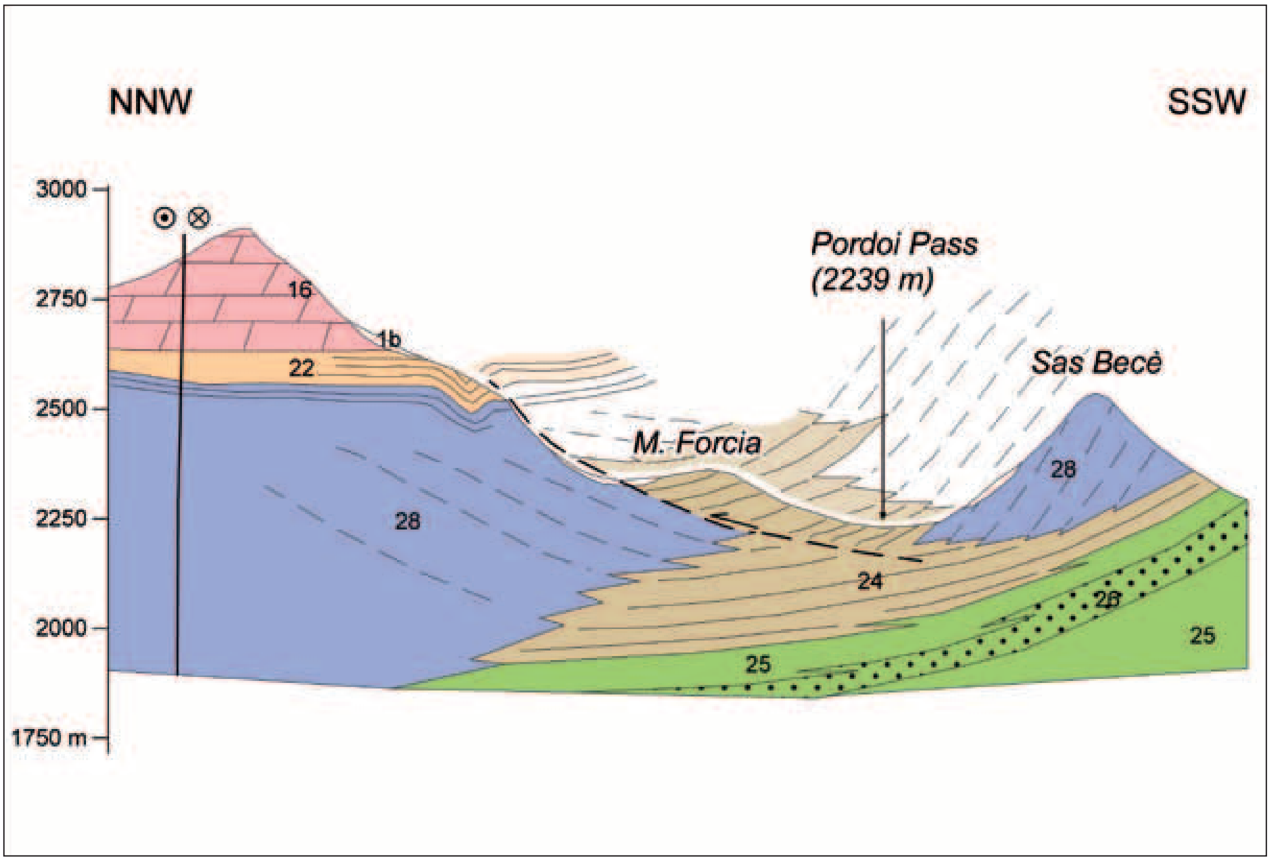

Fig. 26: Interpretative N-S cross section across Passo Pordoi. See text for explanation. 28 = Selladolomite Subgroup, 26 = Marmolada Conglomerate, 25 = Wengen Fm,, 24 = St. Cassian Fm, 22 = Pordoi Fm, 16 = Hauptdolomit/Dolomia Principale, 1b = talus deposits.

depositional angle. North of the Pordoi Pass, the basinal sediments of the St. Cassian Fm cover the entire area to the M. Forcia (2356 m). This is the highest point with basinal sediments at the S-side of the Sella platform, but unfortunately, the contact with the above lying platform dolomites is not exposed. The outcrop at M. Forcia is located about 140 m higher than the interfingering zone between clinoforms and basinal sediments exposed NW and ENE of the Pordoi Pass. This difference in height can been explained in two ways: (1) an onlap geometry of the St. Cassian Fm onto the clinoforms during standstill of platform growth and thus basin filling or (2) N-vergent overthrusting of the St. Cassian Fm, possibly over the S-dipping clinoforms. Based on the actual state of knowledge, we prefer a combination of both mechanisms (Fig. 26).

The ascent to Sas Pordoi by cable car offers unique views on the platform geometry with steep clinoforms and topsets as well as the sharply overlying Pordoi Fm and the Hauptdolomit/Dolomia Principale.

Stop 4.2 – Sas Pordoi and walk to Piz Boè

The spectacular panoramic view at Sas Pordoi (2950 m) enables to see most of the prominent Triassic carbonate platforms in the Dolomites. Along the trail to Piz Boè, the Norian Hauptdolomite with its typical peritidal cyclothemes can be observed. The basic cycles include a subtidal unit of dolomicrites with gastropods and megalodontid bivalves, an intertidal unit with laminated, stromatholitic layers with fenestral fabrics and bird's eyes, and, occasionally, a thin supratidal unit composed of teepee structures, intraclastic breccias, desiccation cracks and greenish dolomitized mudstones. In the upper part of the Hauptdolomit the frequency of intraclast breccias and subaerial exposure surfaces increases. At the base of the overlying Dachstein Limestone a distinct level, ca. 80 cm thick, of intraclast breccias with black pebbles is present. The Dachstein Limestone is about 40 m thick and consists of some decimeter thick calcareous beds interbedded with green marls.

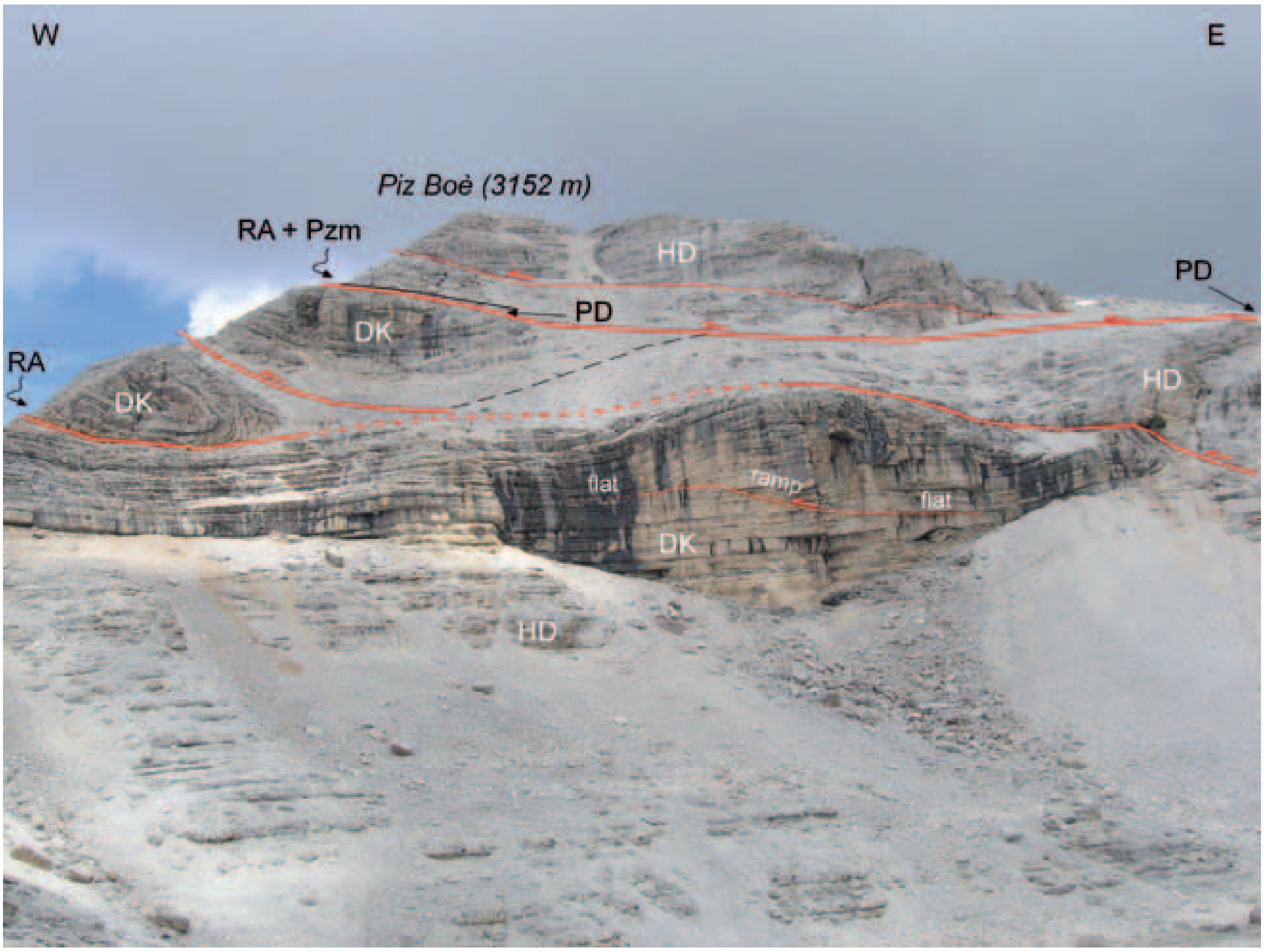

Fig. 27: Foto and line drawings of the southern flank at Piz Boè showing a stack of W vergent thrust slices. PD = Pordoi Fm, HD = Hauptdolomite, DK = Dachstein Limestone, RA = Rosso Ammonitico, Pzm = Puez Marls.

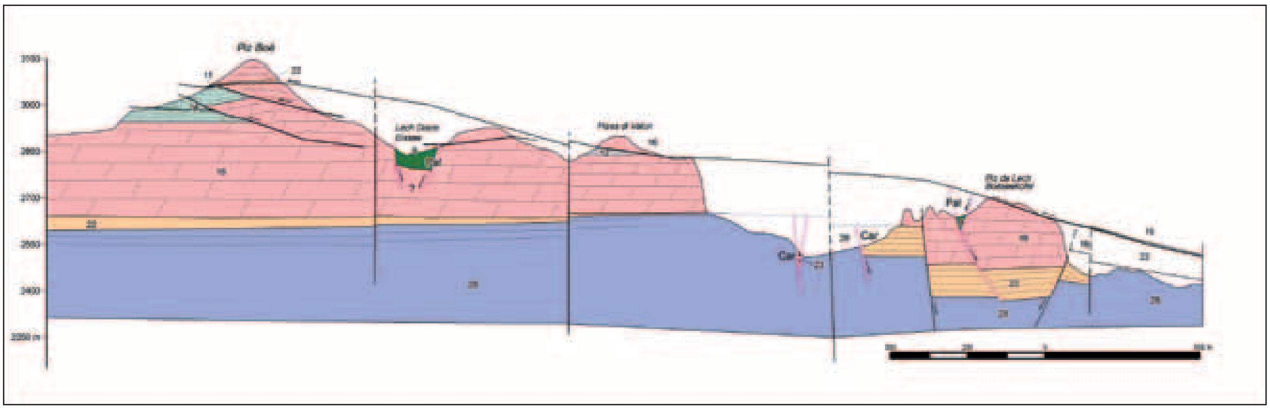

Fig. 28: Geologic cross section of the Piz Boè-Piz da Lech overthrust sub-parallel to the Dinaric NE-SW directed compression. The footwall is dissected by numerous steeply dipping normal faults of Carnian (Car) and late Cretaceous?-Paleogene (Pal) age associated with the formation of graben structures. Note the strong thickness variation of the Carnian Pordoi Fm ("Raibl beds"). At Pizes dl Valun the thickness of the Hauptdolomit/Dolomia Principale is distinctly reduced due to an erosional surface of probably Jurassic age. Based on this cross section the transport width of the uppermost slice of Hauptdolomit from the eastern side of Piz da Lech to Piz Boè can estimated to be at least 3 km.
28 = Selladolomite Subgroup (= Cassian Dolomite in the present case), 22 = Pordoi Fm, 23 = breccias (Pordoi Fm), 16 = Hauptdolomit/ Dolomia Principale, 14 = Dachstein Limestone, 12 = Gardenacia Fm (breccias, dolosparites), 11 = Rosso Ammonitico, 9 = Puez Marls.

The succession was described in detail by Bosellini & Broglio Loriga (1965), and contains locally abundant foraminifera, among others the age diagnostic *Triasina hantkeni* (Maizon) for the late Triassic (Rhaetian).

Piz Boè summit thrust – some general remarks

The thrust structures at the summit of the Sella Group, the so-called "Gipfelüberschiebungen" (= summit thrust) at Piz Boè, were described already 100 years ago by Ogilvie Gordon (1910). Generally spoken, several slices of Hauptdolomit/Dolomia Principale are thrusted over the Rhaetian Dachstein Limestone, the Jurassic Rosso Ammonitico and the Cretaceous Puez Marls. A first detailed geological map and description of these structures was presented by Reithofer (1928). Doglioni (1985, 1990) re-interpreted the thrust structures by applying modern structural analyses as "Klippen" of an eroded, WSW-directed Dinaric overthrust in a ramp-flat system. Most of the hanging wall of the ramp at the eastern slope of the Sella is now eroded. Doglioni (1990) presented a detailed geological map of the Piz Boè area and calculated a total shortening by the overthrusts of ca. 0.7 km based on balanced cross sections. According to the author the thrust plane is irregular along the strike and shows lateral and oblique ramps. Along these ramps fold-bend folding is common with ENE to E-W trending axes. As such, these fold-bend fold axes trend in the direction of the maximum, Dinaric compression (ENE-WSW) and should not be confused with another perpendicular tectonic phase (Doglioni, 1990).

Based on our geological mapping we agree mostly with the observations and interpretations made by Doglioni (1985, 1990), but question some of his cross sections, since he did not recognize or neglected the presence of slices of the Pordoi Fm ("Raibl beds") at the base of the ENE dipping, main thrust plane.

Stop 4.3 – Southern flank of Piz Boè

From this viewpoint some of the main tectonic structures can be observed: the Piz Boè overthrust consist of several (3–4) thrust planes, which are clearly related to the WSW to SW directed, Dinaric compression. A classical ramp-flat geometry of the thrust plane as well as an overturned, NW-SE trending syncline in the Dachstein Limestone is well visible (Fig. 27, see also Doglioni, 1985, 1990). The presence of slices of the Pordoi Fm at the base of the overthrusted Hauptdolomit/Dolomia Principale wedge suggests that the basal shear plane of the main thrust plane is located within the Pordoi Formation further to the east – an area, which today is completely eroded away (Fig. 28). Interestingly, none of such slices of the Pordoi Fm are present along this Dinaric thrust plane at Piz da Lec, which is the prolongation of the Piz Boè overthrust to the NE (Doglioni, 1985, 1990; see Fig. 28). Thus we assume that the shortening along of the Piz Boè summit thrust is by far greater than the calculated 0.7 km of Doglioni (1990). At Piz da Lac, the Dinaric thrust plane shows a distinct ramp-flat geometry within the Hauptdolomit/Dolomia Principale and cuts an older, ca. N-S trending graben structure in the Hauptdolomit/Dolomia Principale with down faulted Cretacous Puez Marls (Doglioni, 1992). A similar graben structure with down faulted Puez Marls crops out at the Eissee/Lago Gelato at the E-side of Piz Boè. At the eastern flank of Piz Boè, Dinaric thrust planes and intense folding of the Jurassic-Cretaceous sediments are well developed between Cresta Strenta and Piz Lech Dlace/Eisseespitze.

Stop 4.4 – Piz Boè (3152 m)

The summit of the Sella Group offers a unique panoramic view over the entire Dolomites and some more insights on the complex tectonic structures on the eastern side of Piz Boè.

Acknowledgements

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