Field trip 1

Pulses of Neotethys-Rifting in the Permomesozoic of the Dolomites

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1 Introduction and geological setting of the Dolomites[1]

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 is 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 the 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 published in 2007 (new edition 2016, in prep.) for the entire area of the Western Dolomites on the basis of extensive field work, detailed stratigraphic investigations and structural analyses.

The Dolomites are part of the Southalpine retro wedge of the Alpine orogen. The Neogene S-vergent thrust- and fold belt is located south of the Periadriatic lineament (Pustertal fault), east of the Giudicarie fault system and north of the Valsugana thrust (Fig. 1). All these faults are inherited structures which were remobilized at different times since their formation 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 fault, more exactly north of the hinge of the Tauern Window antiform, Austroalpine and Penninic nappes were thrusted toward the north in the Paleogene.

Both, Austroalpine and Southalpine units are part of the passive continental margin of the Apulia microplate and show similar 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 (Fig. 2). Both, Permian and Triassic magmatic rocks display typical calc-alkaline

[1] The following chapter is mainly based on the field guide of Brandner & Keim (2011b).

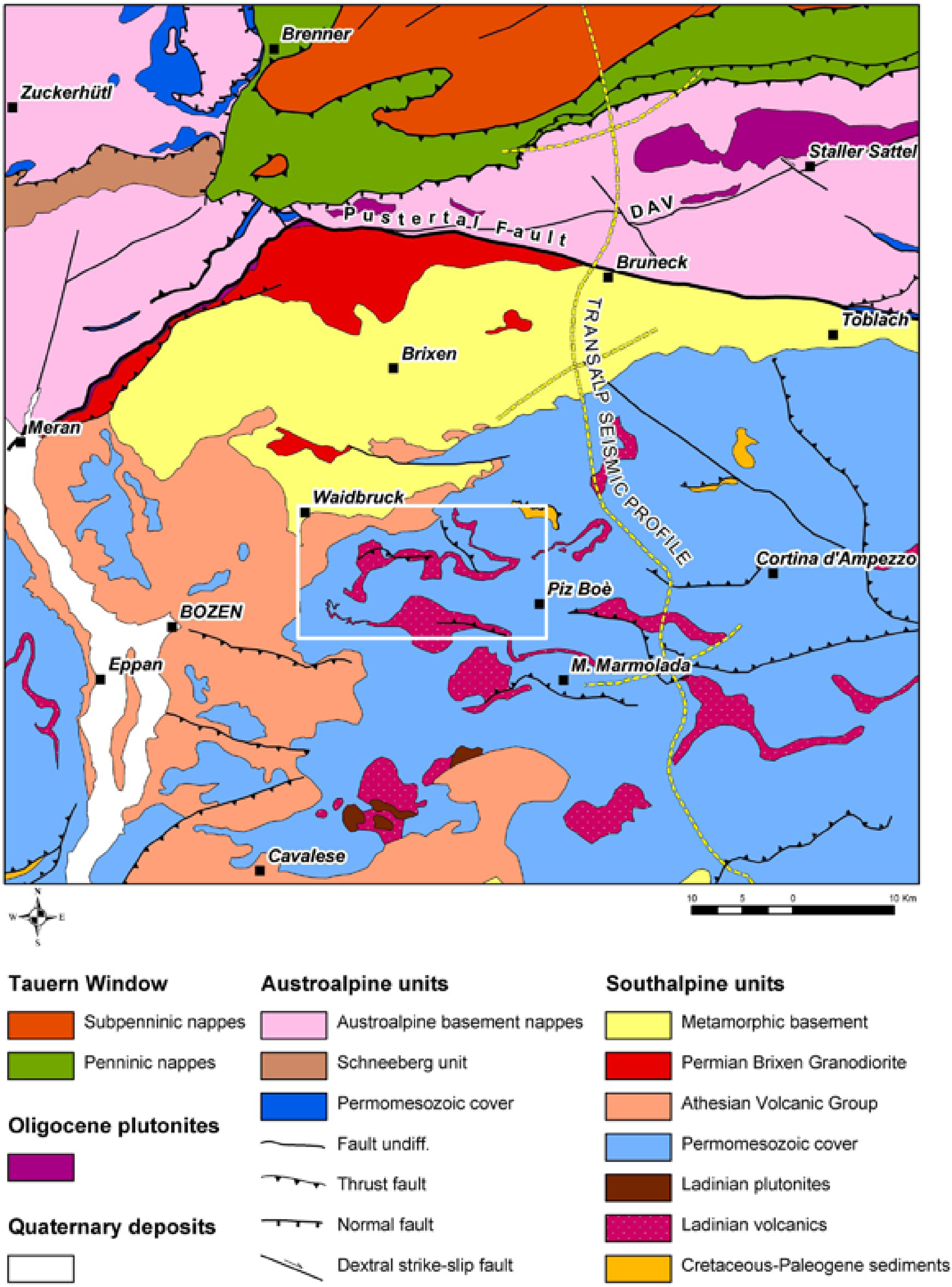


Fig. 1**:** Regional geological overview with location of the excursion area. Day 1 between Bozen/Bolzano and Meran/Merano, day 2 and 3 in the Dolomites (rectangle).

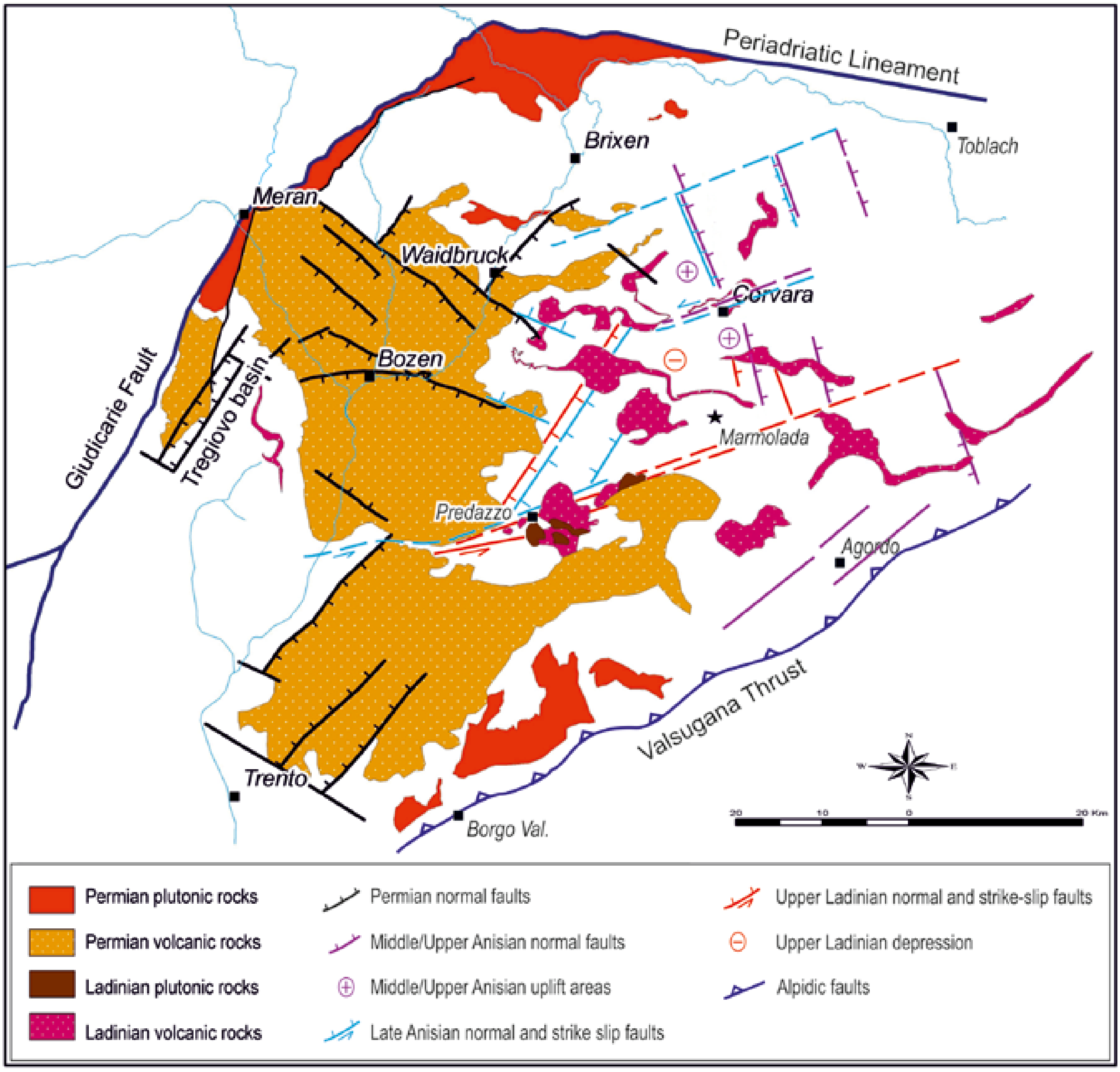


Fig. 2**:** Distribution of present-day Permian and Ladinian plutonic and volcanic rocks. The formation of Permian volcanites is connected to synvolcanic extensional tectonics with NW-SE and NE-SW trending faults with half graben geometries. Configuration of the Permian faults could be related to an overall sinistral megashear associated with the beginning of the opening of the Neotethys Ocean in the Far East. Data on Permian faults based on own field mapping, Carta Geologica d'Italia (2007, sheet " 026 Appiano-Eppan"), Carta Geologica d'Italia (2010, sheet " 013 Merano-Meran"), Selli (1998) and Morelli, C. (pers. comm., 2011). CL = Calisio paleo-line, VL = Val Sugana paleo-line (modified after Selli, 1998).

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, is proposed. Anisian to Upper Ladinian faults are compiled from Bosellini, (1968), Bechstädt & Brandner, (1970), Doglioni, (1984), Masetti & Neri, (1980), Pisa et al., (1979). A general inheritance of the Permian fault pattern is evident.

Note the Anisian uplift areas (uplift of more than 500 m) caused by large scale block tilting with listric faults in the depth in contrast to the local and small transtensional basin in the upper Fassa valley in the Upper Ladinian (Upper Ladinian depression). At the end of the Anisian the Badia normal fault system (near Corvara) stepped back about 25 km to the SW, to form the up to 1 km deep Buchenstein basin.

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 evidence in the Southern Alps and surroundings is 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 compensate 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 opportunity 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 realm, where magmatism and vulcanism are nearly absent during this time period. This evolution requires a transcurrent shearing system in between the two realms to facilitate various rates of stretching of the lithosphere. Therefore, we assume already for the Permo-Triassic the differentiation of Apulia N and Apulia S, separated by a Paleo-Insubric lineament, which Schmid et al., (2004) proposed for the Jurassic.

The Permian-Triassic succession of the Dolomites can be subdivided into four 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 formed over a time span of ca. 10 Ma (from 285 to 275 Ma before present) (Marocchi et al., 2008). The sequence is up to 3 km thick and rests on a basal conglomerate, covering the Variscan crystalline basement by a main unconformity and deposited in the Bozen/Bolzano intra-continental basin.
2. After a marked stratigraphic gap of ca. 10 Ma, the Gröden Fm/Val Gardena Sandstone alluvial red beds were deposited on top of the volcanic group as well as on top of the Variscan basement. While the crust was still cooling, sedimentation of the Gröden sandstone was widespread and shallow marine deposits of the Bellerophon Fm and the Werfen Fm prograded westward in a stepwise fashion 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 several phases of strong block tilting and left-lateral transtension occurring after the Late Anisian and the "Middle Triassic thermal event" following 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. A peculiarity of the central part of the Dolomites is a relatively small depression area with a depth of more than 1 km in the upper Fassa valley (Bosellini, 1984). The transtensional basin formed along a NE-trending strike-slip fault zone shortly before the main magmatic-volcanic event took place in the Upper Ladinian (see Fig. 2). The depression was filled by stacks of thrusted sheets, slabs and olistolithes of Upper Permian to Ladinian strata forming very complex structural units. Detailed mapping has recently shown that thrusting and folding was caused by giant gravitational mass movements (Brandner et al., 2016, Geologische Karte der Westlichen Dolomiten, in prep.; for other interpretations see Doglioni, 1984 and Castellarin et al., 1998 and 2004). Ladinian volcanics, volcanic conglomerates and sandstones sealed these structures and infilled basinal depressions and onlapped carbonate platform slopes. With the waning of rifting activity and volcanism, thermal subsidence once more controlled 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.
4. 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 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 microcontinent.

The Southern Alps, and the Dolomites in central position, have been involved in various processes related to these three rifting systems for a long period of time lasting from the Early Permian to the Upper Cretaceous.

During the above mentioned four megacycles global mass extinction events occurred at the Permian-Triassic boundary (PTB), in the Middle Carnian ("Carnian Pluvial Event") and at the Triassic-Jurassic boundary (TJB). All three events strongly affected reef growth and the carbonate production. Especially the PTB and the Carnian event effectively controlled the sedimentary development in the Dolomites.

The Early Permian Bozen/Bolzano basin is filled by a succession of up to 3 km thick volcanics and intercalated sediments, and thus documents the development of a new tensional regime in the interior of Pangea after the end of Variscan orogeny. The fundamental reorganisation of plate boundaries can be seen in the context of the above mentioned intra-Pangea dextral mega-shear 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 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. 2). All these Permian paleo-lines were subsequently reactivated several times, in the context of different deformation regimes. The Lower Permian age of other, similarly striking faults in other volcanic basins is shown by the fact that these faults are sealed by intercalated sediments or volcanic formations (Brandner et al., 2007, Marocchi et al., 2008 and Morelli & Mair, first day field trip, see below). Detailed field mapping indicates half-graben geometries, for instance, in the area of Waidbruck/Ponte Gardena, Villnöß/Funes and Meran/Merano 2000 with block-tilting toward NW. New geochronological data of the volcanic sequence now show a temporal polarity within the Permian fault pattern (Marocchi et al., 2008), i.e. the volcanic formations becoming younger from the northwestern margin of the basin to the central part in the southwest. Together with the half graben geometries, these data imply 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 is only possible in a sinistral shearing system, which is in contrast to the timing of plate tectonic models of Muttoni et al. (2003) and Cassinis et al., (2011). 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 occurs approximately 20 Ma earlier than the Bozen/Bolzano megacycle, with 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). Thus, we speculate that the basic change in plate kinematics took place within the period of Lower Permian magmatism which largely affected Paleo-Europe.

The magmatic event is associated with a widespread metamorphic thermal imprint ("Permian thermal event") in the European Alps which may be a reflection of lithospheric thinning accompanied by magmatic underplating (Schuster & Stüwe, 2008). The geodynamic setting of the

Permian intracontinental extension may be compared to that of the modern Basin-and-Range province of the western United States, and shows a widespread extensional kinematics similar to the Rotliegend province in central Europe (Eisbacher, 1996).
The extensional tectonic cycles are related to the northwestward progradation of the opening of the Neotethys Ocean. The separation of the Cimmerian terranes from the northeastern margin of Gondwana started in mid Permian (Baud et al., 2012) and may have been governed by slab-pull forces related to subduction of the Palaeotethys Ocean beneath the southern margin of Eurasia (Nikishin et al., 2002). The Palaeotethys suture seems to end at the Tornquist zone in the Dobrogea area (Golonka, 2004).

The timing of the opening of the Neotethys and the geodynamic development in the Dolomites is strikingly well constrained by the $^{87}Sr/^{86}Sr$ curve of the Upper Permian and Triassic seawater isotopic composition (Korte et al., 2003). The remarkable decline of the curve in the Anisian correlates well with the strong block tilting in the Middle Triassic of the Dolomites. The rise of $^{87}Sr/^{86}Sr$ values in the Carnian coincides with the closure of the Palaeotethys, causing uplift and erosion of the Cimmeride orogene, accompanied by an increase in humidity ("Carnian Pluvial Event", Hornung et al., 2007). Finally, the subsequent Upper Triassic-Jurassic decline coincides with the opening of the Ligurian/Penninic Ocean.

The convergent tectonic regime of the Southalpine is, however, quite different from that of the Austroalpine. W- to NW-vergent thrusting and folding started in the Austroalpine only 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 a comprehensive overview see Schmid et al., 2004). These eoalpine compressive events and accompanying metamorphism, have not been recorded in the Southalpine, which requires the assumption of kinematic decoupling from the Austroalpine. Froitzheim et al., (2011) propose a sinistral strike-slip zone as a Paleo-Insubric lineament, bordering the Austroalpine nappe stack with Late Cretaceous extensional Gosau basins toward the south. The only indication of Eoalpine orogenesis near to the Southalpine is documented by a drastic change in Upper Cretaceous marine sedimentation in the extensional basins with the input of siliciclastics and 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) 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 by approximately 4 km in the Upper Miocene (Castellarin et al., 2004, with references). Remnants of the Oligocene/Miocene coastline are preserved at an altitude of ca. 2.600 m at the southern flank of Monte Parei in the Eastern Dolomites (Keim & Stingl, 2000).

The three-day excursion focuses on the geodynamic and stratigraphic evolution of the Permian–Triassic and presents spectacular outcrops of the most representative key sections of the Western Dolomites.

2 Field trip day 1, The Permian Athesian Volcanic Group

(Corrado Morelli, Volkmar Mair)

2.1 Goals and highlights of the excursion

The first day fieldtrip crosses the Etsch/Adige Valley between Meran/Merano and Bozen/Bolzano, where volcanic rocks of the Athesian Volcanic Group (AG) are well exposed (Fig. 3). The widespread uplift and incision of Permian rocks in the Athesian area, together with the modest internal tectonic deformation, allow to observe exceptional outcrop exposure of volcanic bodies' geometry and in particular of caldera fillings and their relationship with the extra-caldera areas.

The excursion gives inside of a complex volcano-tectonic system, which developed in an extensive geodynamic context with multiple calderas formation. In the area between Meran/Merano and Bozen/Bolzano, a progressive collapse of the southeastern parts forces the deposition of the more recent volcanics in the southern depressions. Going from Meran/Merano to Bozen/Bolzano we have the opportunity to observe a complete stratigraphic transect of the Athesian Volcanic Group.

The highlight of the first day is the observation on the Ora Ignimbrite, the youngest eruptive unit of the Athesian Volcanic Group. It is a voluminous caldera-forming ignimbrite. It means that the eruption of the ignimbrite happens together with the collapse of a wide sector of the earth surface. The just formed depression (caldera) will be filled with the most part of the erupted pyroclastic flow. The Ora Ignimbrite currently crops out over an area of approximately 1500 km^2. It has a minimum preserved volume of more than 1300 km^3 and belongs to the world largest ignimbrite eruptions. The geometry of the caldera is still well preserved and there are good exposures of its margin, where the Ora Ignimbrite is abruptly onlapping older dissected stratigraphic units.

2.2 Geological setting

The South-Alpine domain is characterised in the Permian by a widespread and intense continental volcanic activity, which produced a thick succession of volcanic rocks belonging to the Athesian Volcanic Group (AG). With its current outcrop extension over 2000 km^2, mainly between the Trento and Bozen/Bolzano provinces, the AG represents the largest and best-exposed Permian volcanic area in Europe.

The Permian volcanic sequence is bounded by two first order unconformities. The lower one rests on the Variscan South-Alpine metamorphic basement, whereas Upper Permian continental red beds (Val Gardena Sandstone) mark the upper one, which represents the onset of the Alpine depositional cycle. The AG volcanic activity lasted about 10-15 Ma during the Cisuralian (early Permian, from 289 to 274 Ma) with a deposition rate that increased throughout the eruptive cycle and took place in a extensional to transtensional geodynamic context (Schaltegger & Brack, 2007; Visonà et al., 2007; Marocchi et al., 2008; Morelli et al., 2012).

The volcanic rocks of the AG are characterised by a serial sub-alkaline character with calcalkaline geochemical affinity. The magmatic activity in the early phases was characterised mainly by andesites to rhyodacites, followed by dominant rhyolites in the intermediate to late stages. The volcanic products are mostly pyroclastic flows (ignimbrites). Lavas are more abundant during the first phase. Epiclastic products are interlayered at different levels of the sequence and mark periods of inactivity. Facies distribution and thickness of the different stratigraphic units have been strongly influenced by an extensive synvolcanic tectonic. In particular, the nature and distribution of single volcanic units are strictly related to the formation of multiple calderas, formed during a time span of a few million years. Generally, the collapses are getting younger towards the centre of the volcanic system (Fig. 4 and 5). The resulting units' arrangement is characterised by exposure of the more recent volcanic deposits in the central collapsed part (i.e. between Bozen/Bolzano and the Cembra Valley) with older units exposed towards the outer areas. The recent (i.e. 1999-2015) geological survey of the CARG Sheets Merano, Appiano, Mezzolombardo, Trento and Bolzano has shown a quite homogeneous magmatic-stratigraphic evolution for the whole area with important correlations.

In spite of the stratigraphic differences between distinct sectors of the AG, it is possible to recognize a unique evolution shown by large-scale correlation of two important ignimbrite units: the Ora/Auer and the Gargazzone/Gargazon Formation. Both of these units are related to the main caldera collapses (Morelli et al., 2012; Willcock et al., 2013).

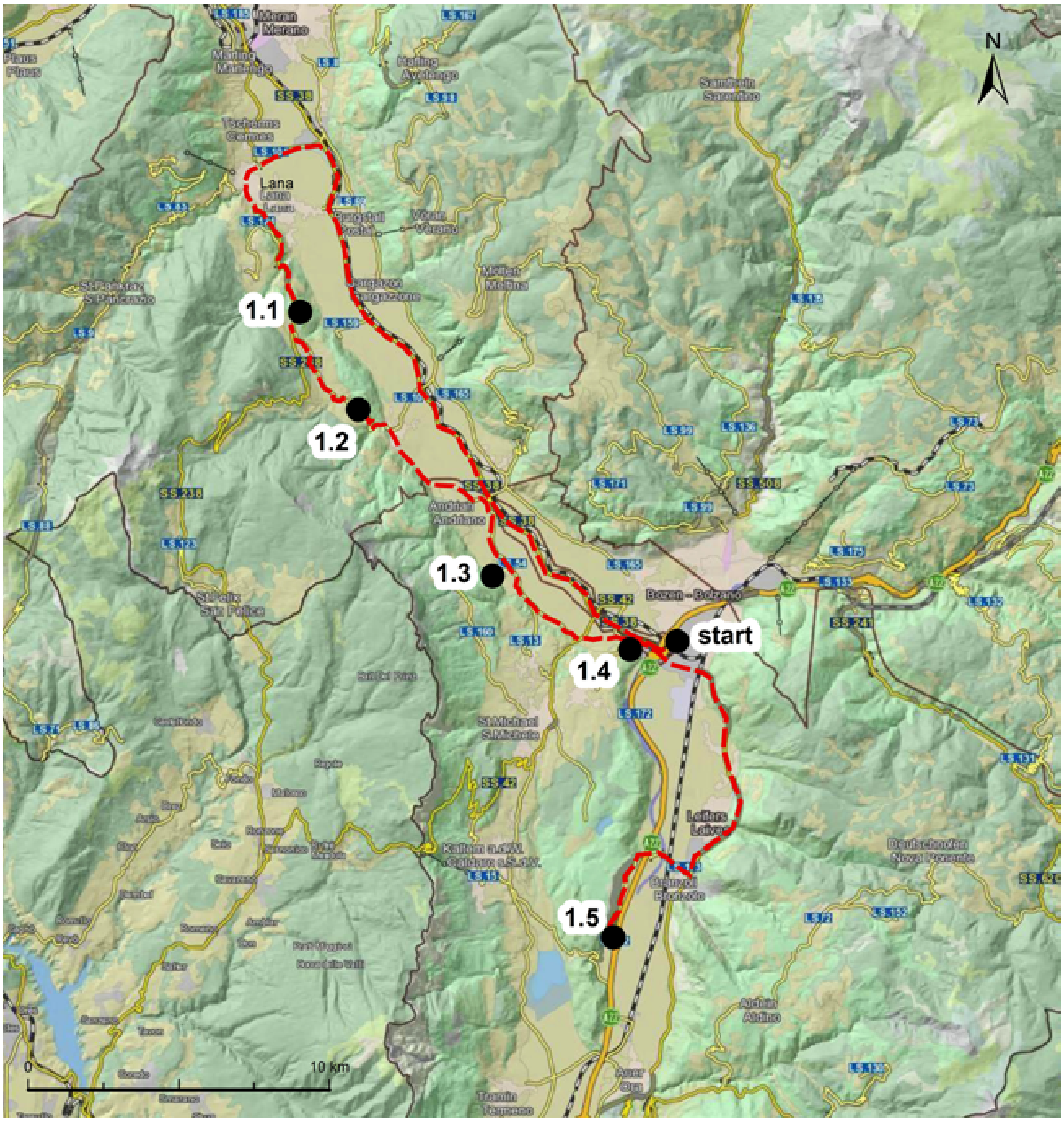


Fig. 3: Map with the excursion itinerary and location of the stops.

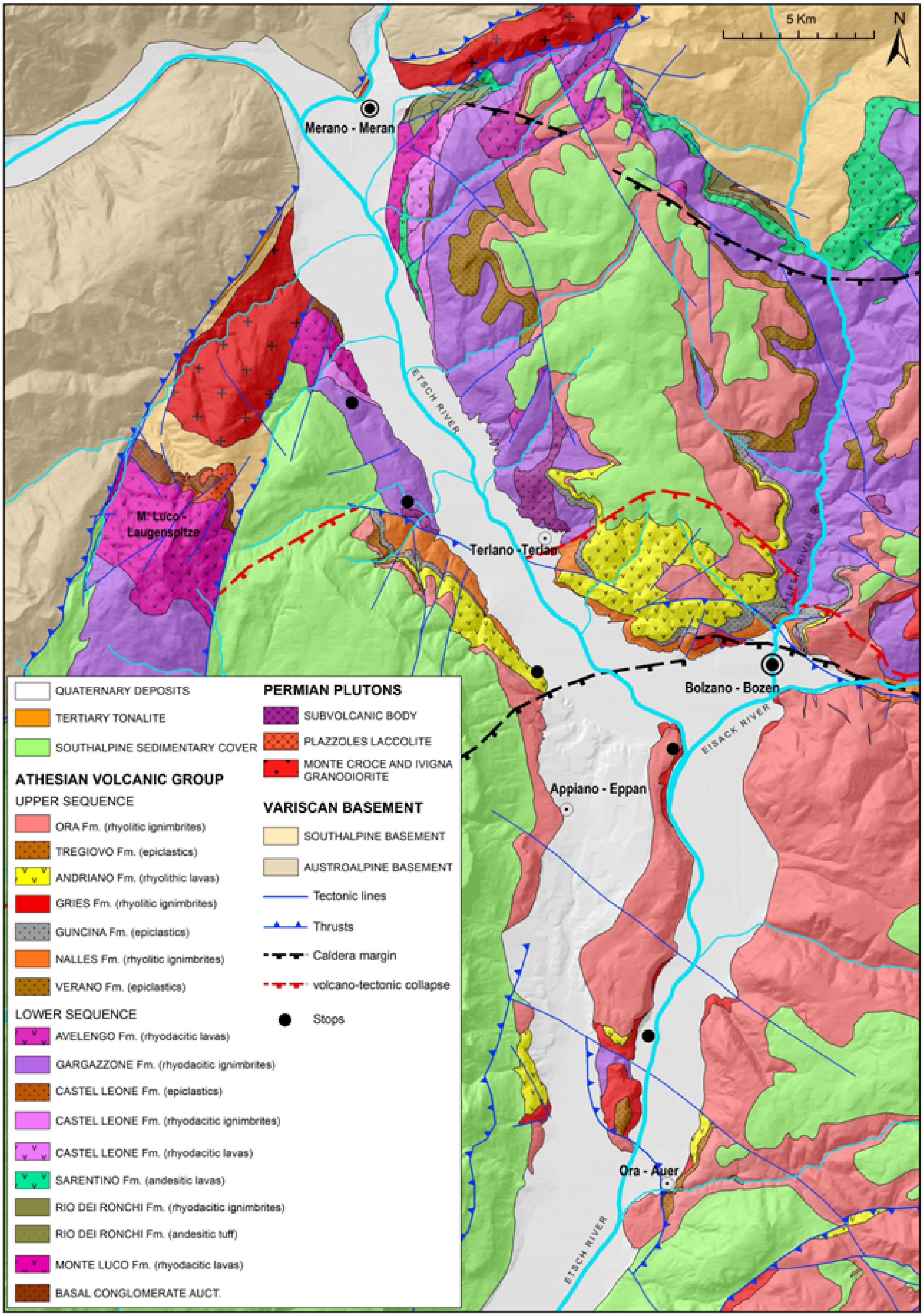


Fig. 4: Schematic geological map of the NW sector of AG (Modified from Morelli et. al 2007).

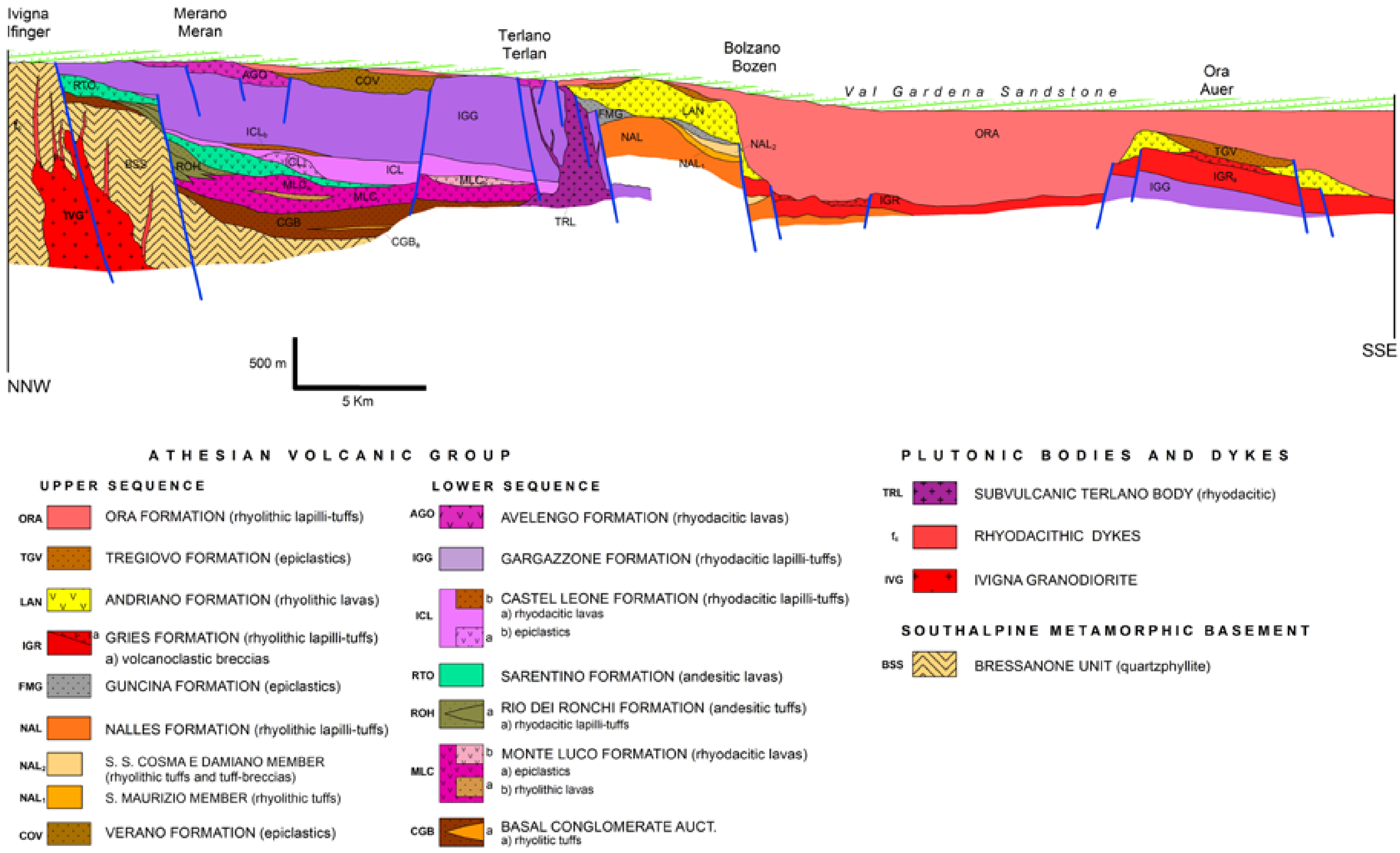


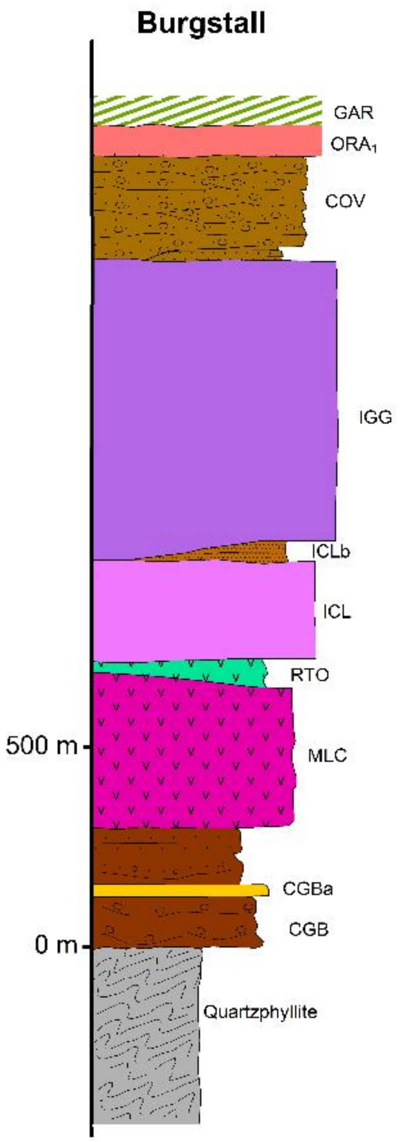
Fig. 5: Schematic stratigraphic cross section of the northern AG from NNW to SSE.

2.3 Excursion route and field trip stops (Fig. 3)

Stop 1.1 – The lower sequence of the AG

From the top of the hill called "St. Hippolyt/San Ippolito" we have a great view on north flank of the Etsch/Adige Valley where the boundaries among the main volcanic units of the lower sequence of the Athesian Volcanic Group (AG) are well exposed and can be traced for some kilometres. The base of the Permian succession on the metamorphic basement is not exposed but it is known from well data (geothermic well of Burgstall/Postal).

The volcanic rocks cropping out all around the hill show typical scratches or gouges of glacial



- **GAR** - Val Gardena Sandstone: continental sandstones
- **ORA_1** - Predonico Member of the Ora Formation: rhyolitic ignimbrites (thickness up to 50 m)
- **COV** - Verano Formation: continental sandstones and conglomerates (thickness up to 250 m)
- **IGG** - Gargazzone Formation: rhyodacitic ignimbrites (thickness up to 800 m)
- **ICL_b** - Castel Leone Formation: continental sandstones and conglomerates (thickness up to 50 m)
- **ICL** - Castel Leone Formation: rhyodacitic ignimbrites (thickness up to 250 m)
- **RTO** - Sarentino Formation: andesitic lava flows (thickness up to 120 m)
- **MLC** - Monte Luco Formation: rhyodacitic domes and lava flows (up to 400 m)
- **CGB_a** - Rhyolitic ignimbrite
- **CGB** - Basal Conglomerate (up to 350 m)
- **Quarzphyllite**: Variscan metamorphic basement

Fig. 6: Volcanic succession of the AG cropping out on the slope above Burgstall/Postal with integration of well data.

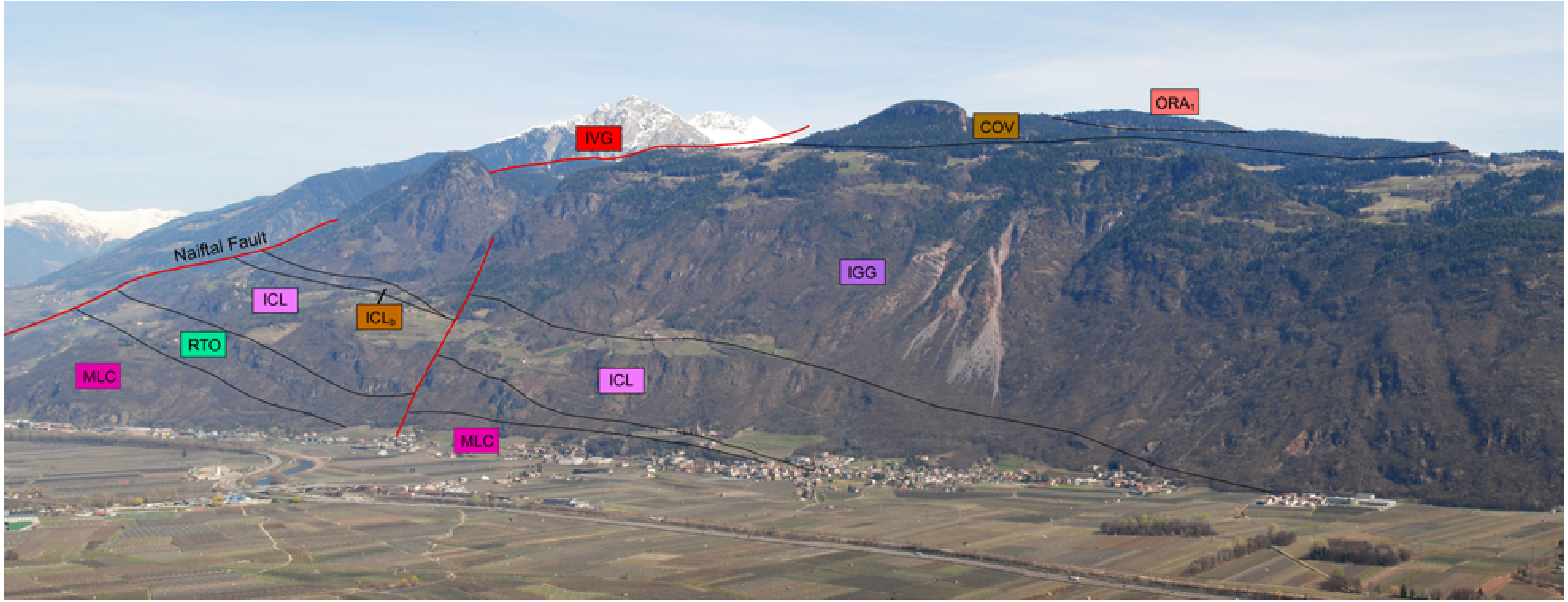


Fig. 7: Panoramic view of the volcanic succession exposed on the left side of the Etsch/Adige Valley between Meran/Merano and Gargazon/Gargazzone. The most part of the slope is built by the Gargazzone Formation (IGG) that reach thickness up to 800 meters and shows a table-like geometry. IVG: Ifinger/ Ivigna Granodiorite. Other abbreviations as in stratigraphic column reported in Fig. 6.

abrasion and belong to the Gargazzone Formation. The rock is a welded rhyodacitic lapilli-tuff, very homogeneous and extremely hard. The rock is generally sharply divided into very regular slabs (1-30 cm) by sub-vertical fractures (Fig. 8). Juvenile inclusions are abundant with dimensions ranging from cm to dm and show a porphyritic microstructure with abundant crystals (Fig. 9). They are more or less flattened and oriented (fiamme), representing magma residual portions, partially crystallized at the time of magma fragmentation during the eruption. The petrographic analysis shows a clastic-like oriented structure, without any granulometric sorting, with abundant broken crystal (40-60%) of plagioclase, quartz and altered biotite or pyroxene inside a groundmass made of a felsitic pseudo-fluidal, cryptocrystalline aggregate.

The Gargazzone Formation records a widespread explosive volcanic activity with emission of huge volumes of crystal-rich ignimbrites. It shows the typical characters of caldera-forming eruptions, i.e. large areal extension (i.e. 4000 to 6000 km^2), strong compositional homogeneity and great thickness reaching up to 900 m.

Fig. 8: Gargazzone Ignimbrite with typical vertical joint.

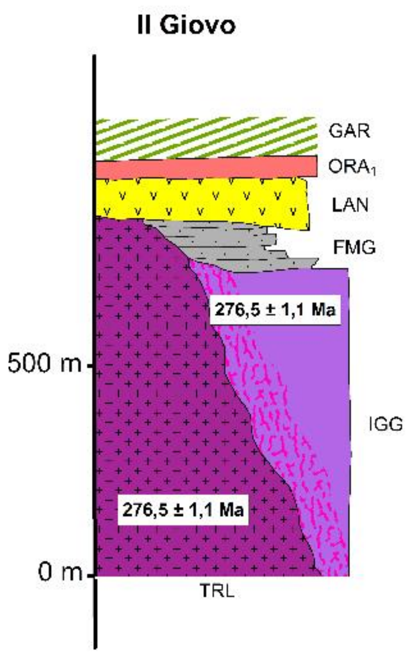
Fig. 9: Gargazzone Ignimbrite with abundant crystal-rich pumice.

Stop 1.2 – The volcano-tectonic collapse of Terlan/Terlano

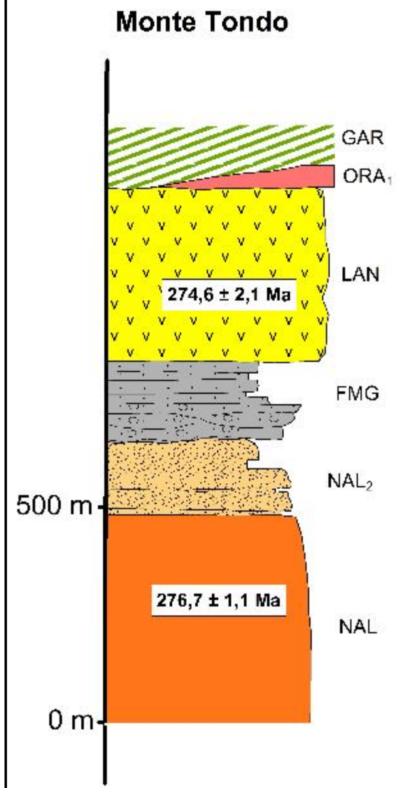
A synvolcanic fault, along which, during the Permian time, an important collapse of the south-western sector took place, is still magnificently exposed on the north site of the Etsch/Adige Valley nearby Terlan/Terlano. Such collapse happened just after the emplacement of the Gargazzone Ignimbrite: the area to the NW remained substantially in erosion, while the SE sector was filled up by a thick volcanic and volcanoclastic sequence. A dike-like subvolcanic body, with maximum lateral thickness of 2 km, crops out inside the Gargazzone Formation close to the border of the collapse. Good outcrops of this rock will be observed just on the road near stop 1.2 (Fig. 12). From outcrop data and from radiometric ages (Fig. 11) we can affirm that the emplacement of this body is related temporally and structurally to the synvolcanic tectonic activity.

The infill of the southern sector (upper sequence of the AG) can actually be observed on the flank of the Etsch/Adige Valley between Terlan/Terlano and Bozen/Bolzano. It is also worth mentioning that the migration of volcanic activity was contemporaneous to a clear change in the chemical composition of the emitted products: from rhyodacitic to rhyolitic. Our interpretation model of this volcano-tectonic collapse points out the concurrent rising of a huge resurgent dome, which uplifted the central portion of the just-filled Gargazzone-caldera, with simultaneous collapse of some sectors, a mechanism well documented in other caldera systems.

Fig. 10: Panoramic view of the slope above Terlan/Terlano. It is possible to observe the sharp juxtaposition between younger volcanic sequences to the east (right) and older ones to the west (left). Abbreviations as in the stratigraphic columns reported in Fig. 11. The blue lines represent synvolcanic faults, the red one is an alpine strike-slip fault.



- **GAR** - Val Gardena Sandstone: continental sandstones
- **ORA_1** - Predonico Member of the Ora Formation: rhyolitic ignimbrites (thickness up to 30 m)
- **LAN** - Andriano Formation: rhyolitic lava flows rapidly thinning toward the NW
- **FMG** - Guncina Formation: continental clastic deposits, erosional on IGG and TRL
- **TRL** - Terlano body: subvolcanic rhyodacite intruding the IGG
- **IGG** - Gargazzone Formation: rhyodacitic ignimbrite



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- **LAN** - Andriano Formation: rhyolitic lava flows with up to 500 m thickness.
- **FMG** - Guncina Formation: continental clastic deposits: maximum thickness (250 m) and more coarse-grained facies close to the tectonic contact
- **NAL_2** - S.S. Cosma e Damiano Member of the Nalles Formation: pyroclastic breccias and surge horizons.
- **NAL** - Nalles Formation: rhyolitic ignimbrites

Fig. 11: On the left (Il Giovo/Tschaufer Nock): Stratigraphic succession of the sector located just NW of the Terlan/Terlano tectonic collapse. On the right (Monte Tondo/Grummenberg): Stratigraphic succession of the sector located just SE of the Terlan/Terlano tectonic collapse. Zircon U/Pb radiometric ages are from Marocchi et al. (2008).

Fig. 12: The Terlano body: massive sub-volcanic rhyodacite with porphyritic structure, characterised by the presence of cm-sized light pink K-feldspar phenocrysts (orthoclase), usually idiomorphic, zoned and geminated. They are set in a groundmass formed of smaller phenocrysts of idiomorphic pink and/or white feldspar (plagioclase), sub-rounded and embayed quartz, biotite, pyroxene and pyrite. The sub-volcanic body is almost totally intruded inside the IGG ignimbrites; at the boundary the ignimbrites typically show sulphide mineralisation zones, assuming a yellowish colour and loosing coherence.

Stop 1.3 – The Andriano Formation and the Ora caldera border

Between Stop 1.2 and Stop 1.3, the typical succession of the upper sequence of the AG is exposed on both sides of the Etsch/Adige Valley. By Stop 1.3, we are close to northern caldera margin of the Ora Formation. In this stop, we observe the pre-Ora successions outside the caldera and in particular, the Andriano/Andrian Formation made up of massive rhyolitic lavas. This is a characteristic unit cropping out in the sector between Terlan/Terlano and Bozen/Bolzano on both sides of the Etsch/Adige Valley, with extremely variable thickness up to 450 m. The maximum thickness of the lava is located near the border of the Ora caldera and gradually thinned out toward north and west. More to the south, in the caldera setting, no outcrop of this rock are normally present. These indicate that the lava might have flown out from eruptive fractures located close to the forthcoming caldera border and accumulated mostly in the outer region.

The Andriano Formation is a massive, rhyolitic lava of red-orange to brick red or red-purple colour, with diffuse flow bands of variable thickness (5 to 20 cm); these have been pointed out by the selective erosion. The shape of the bands ranges from flat-parallel or slightly wavy to strongly wavy and it is possible to observe also band sets intersecting each other with variable angles (Fig 14 and 15). The rock shows a porphyric structure with idiomorphic phenocrysts (1-4 mm) of feldspar and quartz inside a fine-grained homogeneous groundmass that appears completely recrystallized under the microscope (Fig. 16). The percentage of phenocrysts is normally high (35-45%) but levels poor of them or even aphanitic are present.

Fig. 13: The northern caldera margin of the Ora Formation near Unterrain/Riva di sotto. The thickness of the Ora Ignimbrite drops from more than 1000 m in the caldera setting (on the left) to less than 200 m outside the caldera (on the right).

Fig. 14: Rhyolitic lavas of the Andriano Formation with typical wavy flow bands.

Fig. 15: Close up of the flow bands.

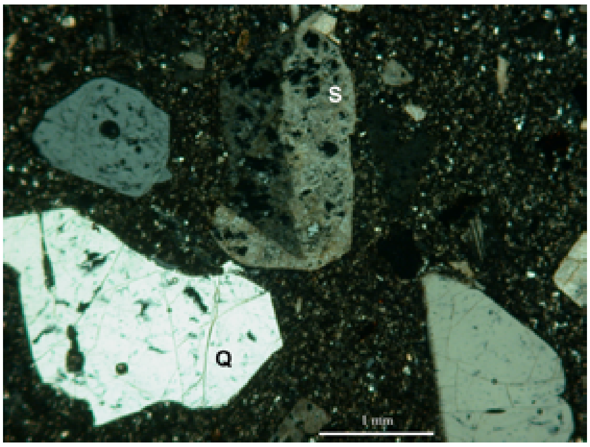


Fig. 16: Microphotograph of the rhyolitic lavas, characterised by a typical porphyric microstructure. The phenocrysts are represented by rounded and embayed quartz (Q), sanidine (S), plagioclase, biotite and pyroxene. Crossed-polarised light.

Stop 1.4 – **The Ora Ignimbrite**

The Ora Formation is the youngest eruptive unit of the Athesian Volcanic Group (274 ± 2,9 Ma). It is a voluminous caldera-forming ignimbrite (minimum preserved volume of about 1300 km^3). The Ora ignimbrite currently crops out over an area of approximately 1500 km^2. The Ora caldera is located between Bozen/Bolzano and the Cembra Valley with a diameter of about 40 km. Most of the preserved ignimbrite is confined in the intra-caldera setting where the thickness is up to 1350 m (Fig. 17). Outside the caldera, the thickness of the ignimbrite varies from less than 10 m to 230 m (Fig. 13).

Fig. 17: In the Monte Pozza/ Titschen section south of Bozen/Bolzano the Ora Ignimbrite shows maximal thickness of about 1350 m.

Fig. 18: Cooling columnar jointing in the Ora Ignimbrite near the Sigmundskron/Firmiano Castle.

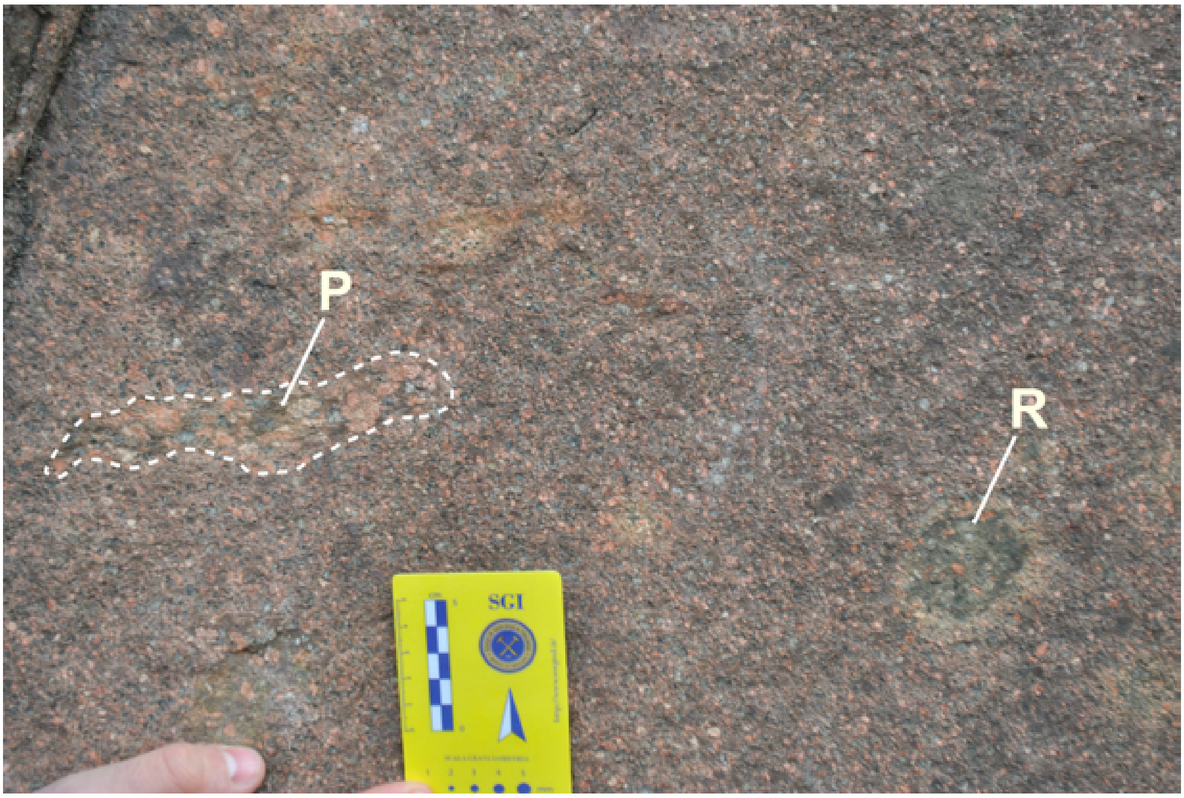


Fig. 19: Detail of the crystal-rich lapilli–tuff with flattened juvenile clast (P) and rock fragment (R) with thermal reaction rim.

The Ora Ignimbrite is a welded rhyolitic lapilli-tuff, which is very coherent and homogeneous, with a colour ranging from pink-red to orange-red. By stop 1.4 we can observe the most important features of this rock. It is crystal-rich, poorly sorted, generally lithic poor, and has common juvenile mesoscopic fiamme and pumice. Phenocryst sizes of juvenile clasts range from 0.5 mm to 30 mm, and are typically euhedral to subhedral. In contrast, the free crystal population in the matrix is usually smaller than 2 mm (Fig.19). The rock shows usually sharp and regular sub-vertical joints along two orthogonal sets; a third less evident set is roughly horizontal and more spaced. In the outcrops of Stop 1.4 the original cooling, columnar jointing is also preserved (Fig.18).

Stop 1.5 - The Ora Caldera

In the inner caldera the Ora Formation lies on the Gries Formation, a previous rhyolithic ignimbrite. The lower boundary shows strong irregularity due to a pre-existing topography, which reflects the erosional surface on top of the underlying units.

The Ora caldera is separated in a north and a south depression by an intra-caldera high located in the central region nearby the Ora/Auer village, where the ignimbrite's thickness drops to ~400 m. The northern margin of the intra-caldera ridge is still well preserved on the right flank of the Etsch/Adige Valley between Pfatten/Vadena and Laimburg/Castel Varco, where the ignimbrite of the Ora Formation is lapping on older stratigraphic units (Figg. 20 und 21). Gently dipping separation lines are clear visible inside the Ora Ignimbrite, indicating progressive flow units which overlap the slope (Fig. 22). The detailed shape of the basal contact and its geometric relationship with the different flow units may suggest that the collapse was time equivalent with the ongoing eruption.

Fig. 20: The lower boundary of the Ora Ignimbrite between Pfatten/Vadena and Laimburg/Castel Varco.

Fig. 21: View of the northern margin of the intracaldera ridge. The shape of the basal contact (white line) suggest contemporaneity of collapse with the Ora eruption.

Fig. 22: Close up of the contact with well-defined onlap geometry of different flow-units (arrows) of the Ora Ignimbrite.

3 Field trip day 2, Lower to Middle Triassic stratigraphy at the Seiser Alm/ Alpe di Siusi basin and NE margin of the Schlern/Sciliar platform; Frötschbach/ Rio Freddo section, SE Seis/Siusi

(Rainer Brandner, Alfred Gruber)

Following 10 million years of non-deposition and erosion in the mid-Permian, the Lower Permian volcano-sedimentary megasequence was unconformably overlain by a spacious cover of continental clastic deposits of the Gröden Fm/ Val Gardena Sandstone, which forms the basis of the 2nd megacycle. 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 constitutes several third-order sequences ranging from coastal plain environments with sabkha evaporates to shallow-shelf carbonates of the Bellerophon Fm. After the Permian mass extinction, mixed shallow-marine carbonates and terrigenous sediments of the Werfen Fm are characterised by a long lasting biogenic recovery, however lacking mass production of carbonates, i. e. reefal buildups. The first carbonate bank produced by calcareous algae is of Lower Anisian age (Lower Sarl/Serla Fm) and forms the top of the 2nd megacycle.

The second day is dedicated to the famous Frötschbach/Rio Freddo-section with a typical

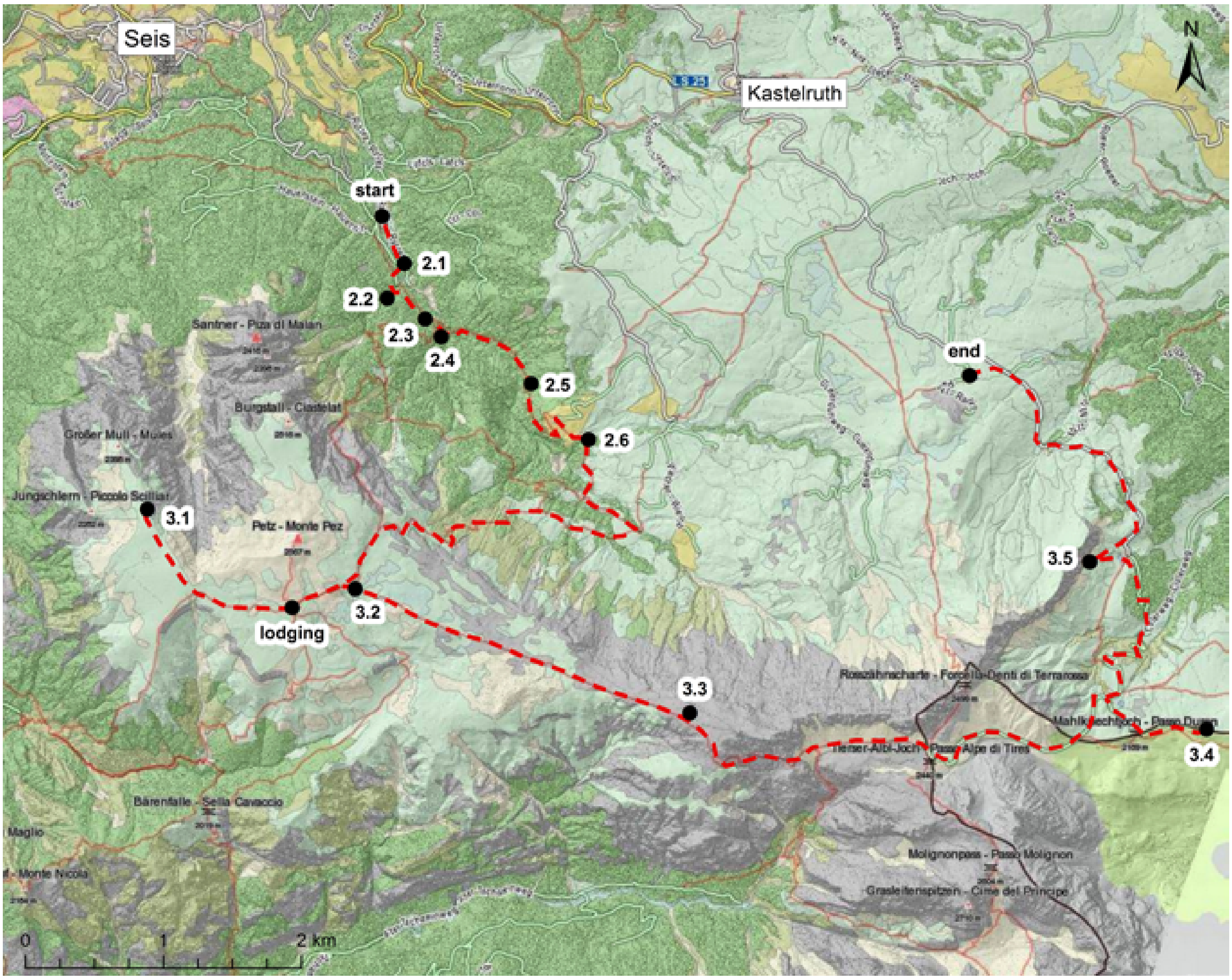


Fig. 23: Map of the excursion itinerary of day 2 and day 3.

Southalpine Triassic development. Discussion will focus on the long lasting aberrant environment after the Permian mass extinction, on the reorganisation of plate tectonics in the Anisian and on controversal interpretations of the violent tectono-magmatic event during the Upper Ladinian. The Seiser Alm/Alpe di Siusi and Schlern/Sciliar impressively show a well preserved palaeoslope. On a tourist path we will walk along the palaeoslope from the basin to the top of the platform (= Schlernhäuser/Rif. Bolzano; Figs. 23 and 24).

3.1 General remarks on the Lower to Upper Triassic stratigraphy (see Figs. 26 and 27)

The area of Seiser Alm/Alpe di Siusi and Schlern/Sciliar is one of the few places in the world where the platform-slope-to-basin transitional zone is preserved in its primary setting. The region is particularly scenic, easily accessible and touristically well developed.
During the Ladinian the Schlern/Sciliar-Rosengarten/Catinaccio carbonate platform formed

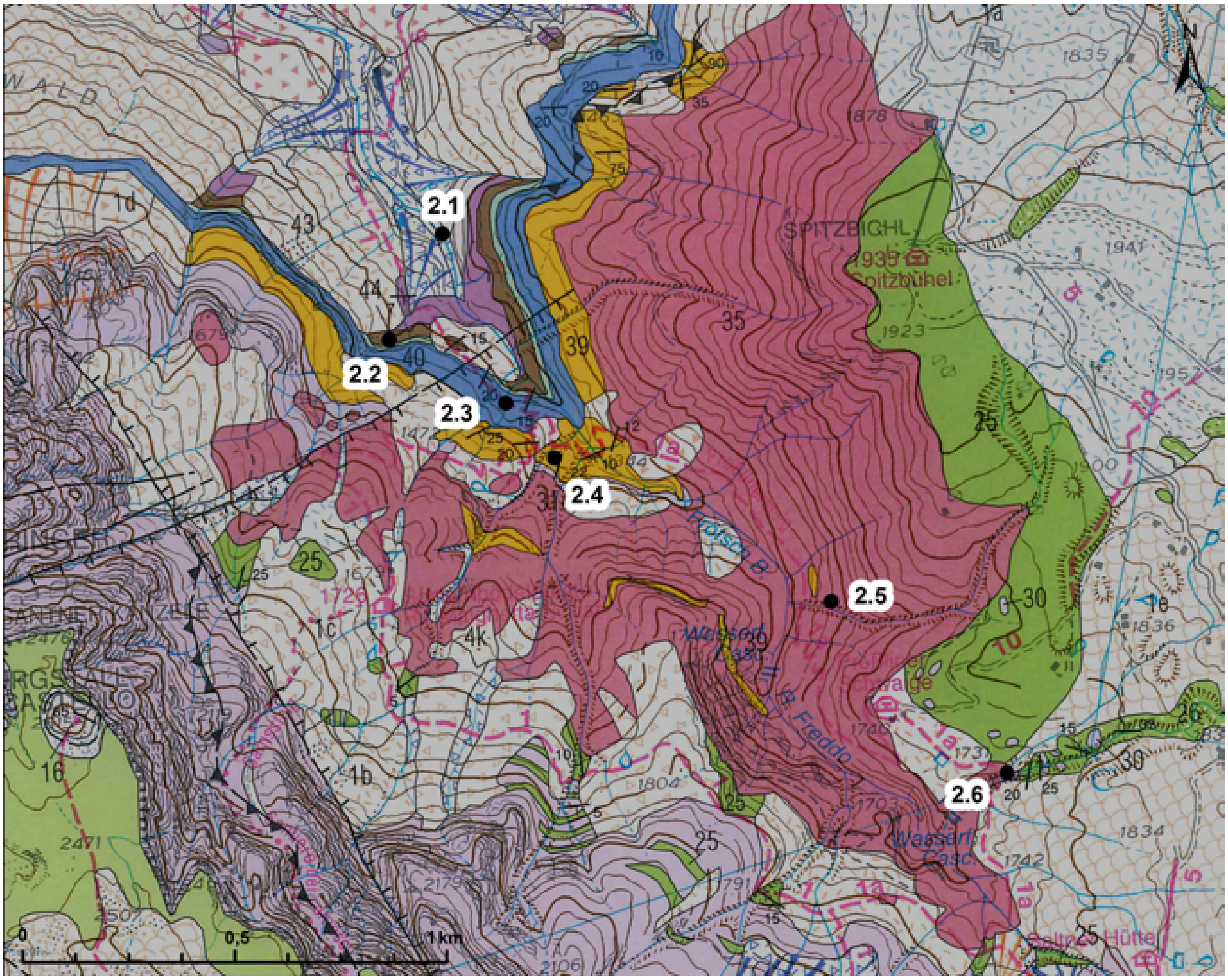


Fig. 24: Geological map (enlarged view of the Geologische Karte der Westlichen Dolomiten 1:25.000) of the Frötschbach/Rio Freddo valley with location of the stops. Signatures: 44, Peres Fm; 43, Morbiac Fm; 40, Contrin Fm; 39, Buchenstein Fm; 35, Fernazza volcanics; 30, Rosszähne Fm; 26, Marmolada Conglomerate; 25, Wengen Fm.

the primary sedimentary margin of an extended carbonate platform extending towards the west to 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 – 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 (Langobardian, *Archelaus* zone, see Brandner et al., 1991a, Brack et al., 2005) and thus unmistakably confirm the primary lateral change of 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 were estimated to be ca. 800 m –a reliable estimate which would not have been possible with common bathymetric criteria.

The focus of the field excursion mainly lies on the stratigraphic evolution at the slope-to-basin transition, on the geometries of the sedimentary successions with their onlap and downlap structures as well as on the resulting sequence stratigraphic implications of a mixed carbonate/volcanic and volcaniclastic depositional realm. The tectonically undeformed slope-to-basin transition zone seen in large-scale outcrops can also be seen in seismic sections and thus may help in the interpretation of seismic lines. Even though the outcrop situation is straightforward, different geological interpretations of the patterns exist (see Bosellini, 1994, Sarg, 1988, Brandner 1991, Yose, 1991).

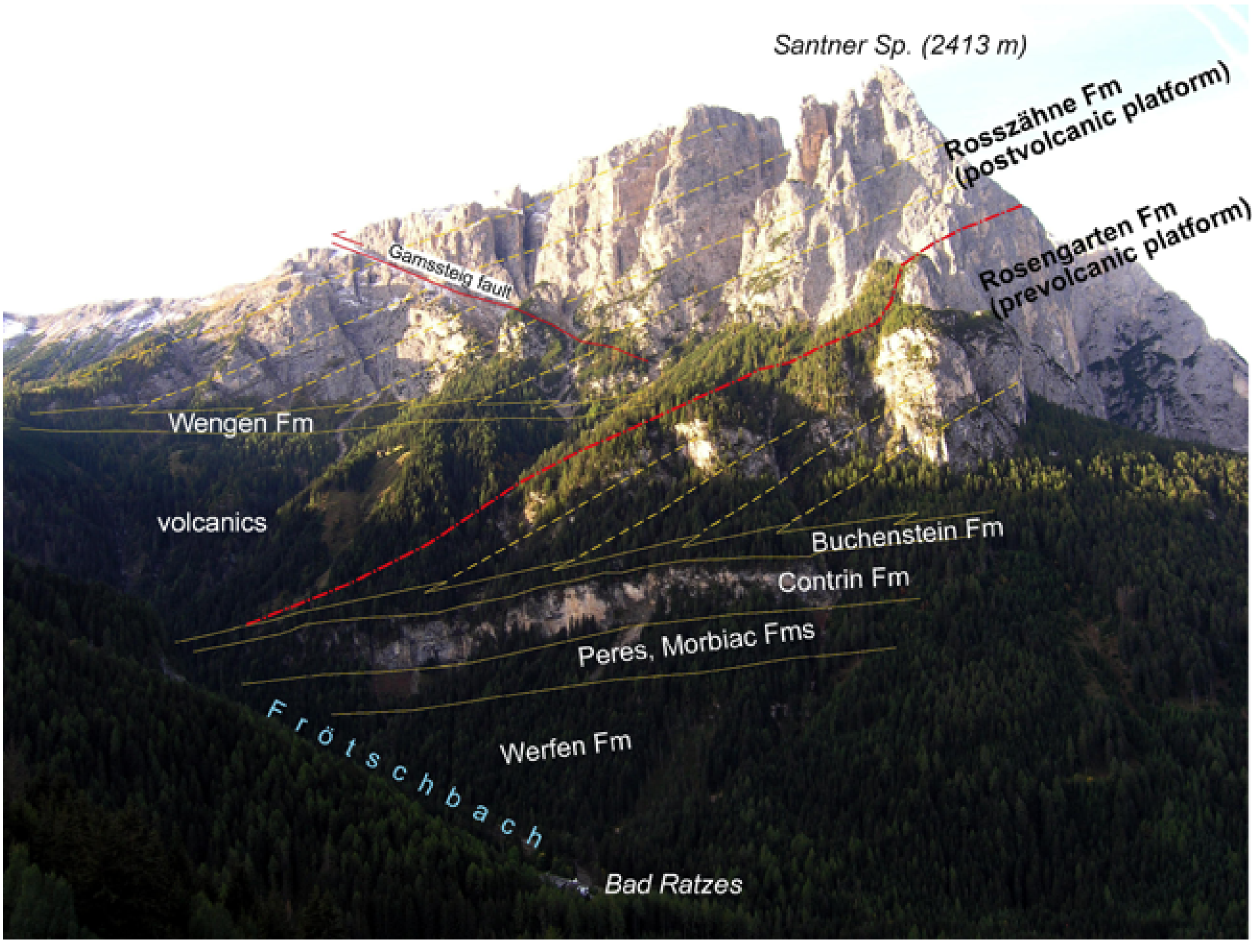


Fig. 25: Panoramic view on the north-eastern flank of the Schlern/Sciliar showing the excellently preserved, seismic-scale platform-to-basin transition of the Anisian to Ladinian carbonate platform. Depositional sequences are bordered by 3rd order unconformities (stippled lines).

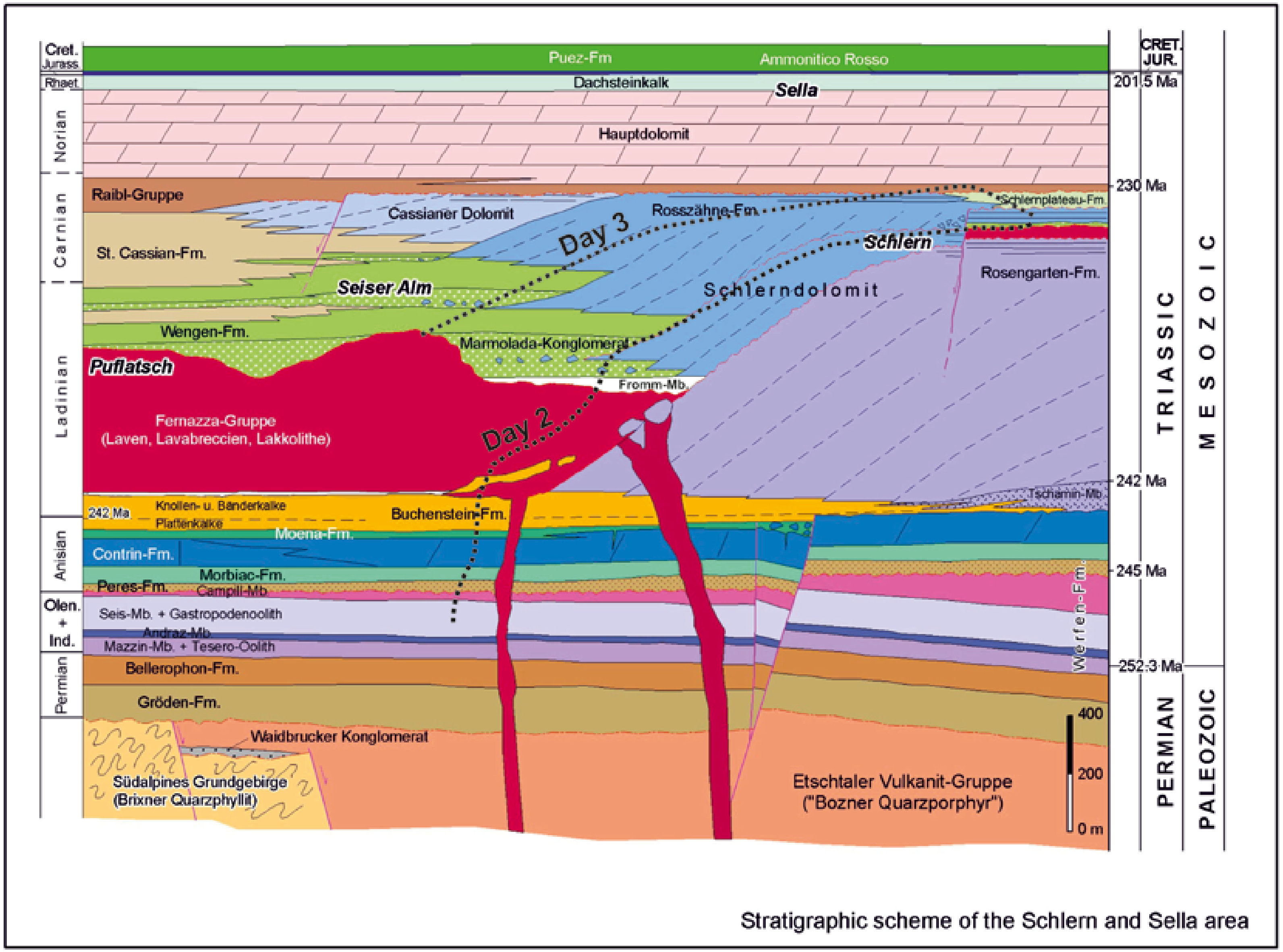


Fig. 26: Lithostratigraphic model for the Permo-Mesozoic succession of the Western Dolomites (modified after Brandner et al., 2007).

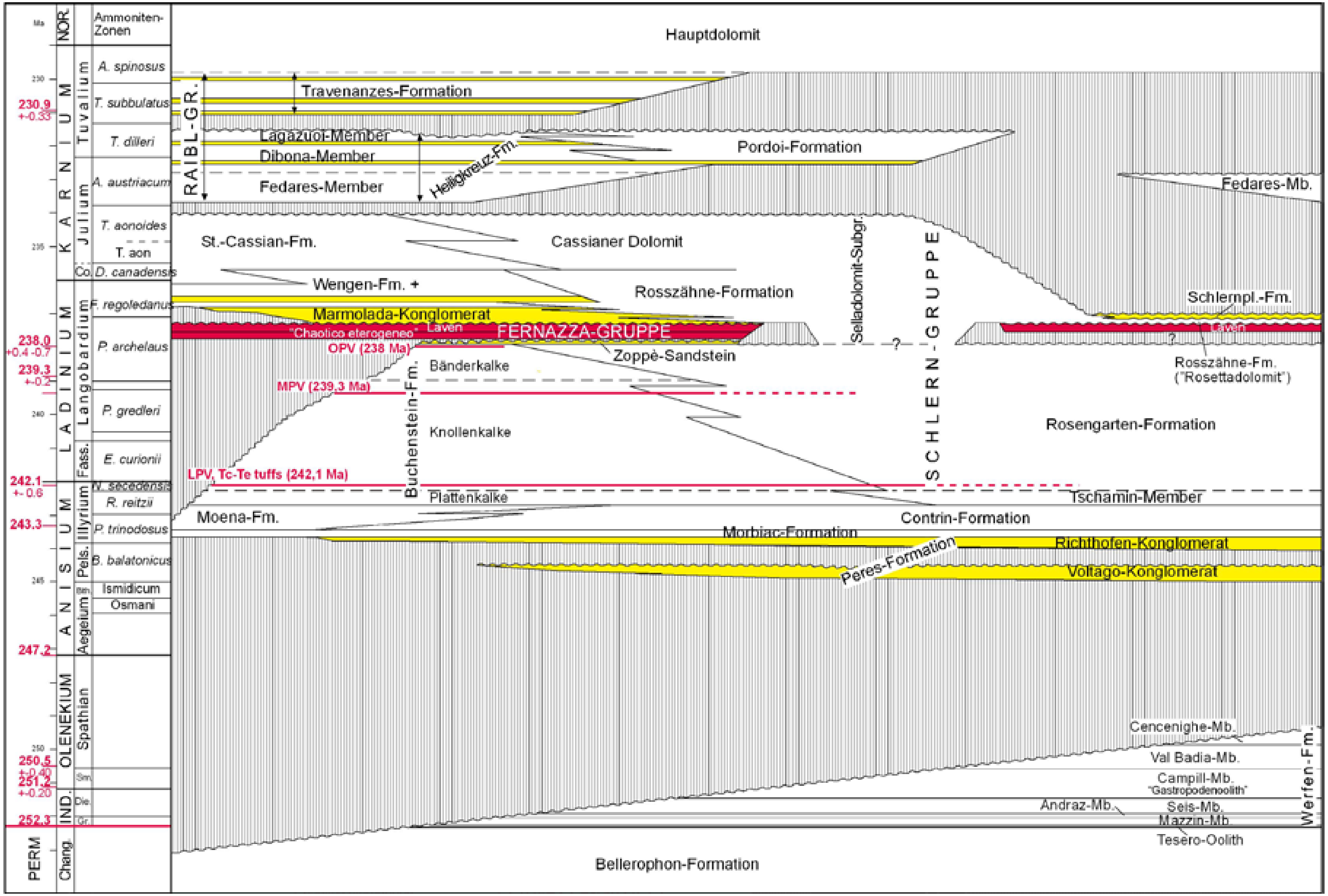


Fig. 27: Chronostratigraphic framework for the Triassic succession of the Western Dolomites. LPV, MPV, UPV = Lower, middle and upper Pietra Verde (see Brack et al., 2005). Radiometric ages taken from Mundil et al. (2010).

The structure below the platform-to-basin ensemble is well exposed in the well-known section of Frötschbach/Rio Freddo situated at the northern flank of the Schlern (Fig. 25). Here, the sedimentary succession starts with the Lower Triassic Seis/Siusi and Campill Mb of the Werfen Fm, which is unconformably overlain by Upper Anisian conglomerates (*Richthofen Konglomerat*) of the Peres Fm. This Anisian unconformity is widespread in the entire Western Dolomites and the succeeding conglomerates overlie the Upper Permian Bellerophon Fm in the east (area of Gader/Badia valley) as well as the Lower Anisian Lower Sarldolomit in the west (Etsch/Adige valley). Based on this erosional cut a block tilting of a ca. 75 km wide crustal segment was postulated with an uplift of more than 500 m in the east (Brandner, 1984; Fig. 30). This block rotation occurred in three individual phases during the Anisian and is interpreted as evidence of new extensional rift tectonics after the Lower Permian. The significance of this tectonic event for the development in the whole Tethys area is underlined by a sustained change in the ecosystem, for example by the start of carbonate platform growth after a long time of recovery following the end Permian mass extinction. This goes hand in hand with a better oceanic circulation, evidenced in the shape of the $d^{13}C$-curve (Korte et al., 2003). It should be pointed out that the large scale block tilting changed to pronounced transtensional tectonics in the uppermost Anisian along ENE-striking faults, cutting previous large tilted blocks (see Fig. 2).

The 3rd order depositional sequences following this major unconformity in the Western Dolomites are controlled by tectonics, independently from possible eustatic sea-level fluctuations. The genetically connected transgressive-regressive succession above the Anisian unconformity includes the terrigenous marine Peres Fm, 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 delimited by an unconformity related to extensional tectonics. The carbonate banks of the Contrin Fm break up locally and form megabreccias along extensional faults (see also Preto et al., 2011). The resulting depressions and cavities were filled by anoxic, finely laminated sediments (Moena Fm).

The submarine relief created by this Late Anisian extensional tectonics (see Fig. 2) has a determining influence on the following carbonate platform development of the Schlern/Sciliar-Rosengarten/Catinaccio. The nucleus of this carbonate platform is situated in the area of the Vajolettürme/Torri del Vaiolet – a pre-existing high zone in this area which goes back to Permian rift tectonics ("Tiers/Tires paleo-fault"). After an initial aggradation stage the platform prograded towards the Seiser Alm/Alpe di Siusi in the NE, as well as towards the SE, forming spectacular clinoform geometries exposed at the Rosengarten/Catinaccio group. Maurer (1999) calculated vertical and lateral growth rates of the Anisian-Ladinian platform. Biostratigraphic and radiometric ages of the sediments of the basinal Buchenstein Fm, which interfinger 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). At a later stage, during 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 – a minimum estimate as the stratigraphic top is eroded. The distance over which progradation took place amounts to approximately 5,5 km. Similar values should be assumed for the Schlern/Sciliar platform. However, at the northern platform margin we observe a shorter progradation distance than in the south. The reason for this is the gently dipping slope of the tilted Contrin substrat toward the south. In contrast the palaeofault zone in the north shows steeper slopes.
The lowermost deposits of the Buchenstein Fm, the so-called *Plattenkalke (Plattenkalk Mb)*, consist of finely laminated, bituminous limestones with radiolarian micrites which interfinger with the gently dipping slope deposits of the *Tschamin/Ciamin Member*. This unit consists of dolomitized, reefal grainstones with stromatactoid cavities. The interfingering zone is postulated to be located near the structural high zone at

the Vajolettürme/Torri del Vaiolet. The gently dipping slope of the Tschamin Mb is overlain by steep clinoforms of the Rosengarten Fm marking the start of extremely high subsidence rates (up to 700 m in less than 1 million years, see Fig. 27) and back-stepping platform margins. Within the basinal succession this change in sedimentation style is evidenced by the transition from the *Plattenkalke* to the *Knollenkalke (Knollenkalk Mb)* of the Buchenstein Fm., i. e. a change from an anoxic to an oxic environment. The succeeding *Bänderkalke (Bänderkalk Mb)* show a coarsening-upward trend with overlying toe-of-slope breccias beds, corresponding to a rapid progradational phase during the late HST.
The volcanics of the overlying Fernazza Group show different thicknesses and are characterized by a distinct relief at the top. The volcanics devide the carbonate platforms of the Schlern/Sciliar Group into the pre-volcanic Rosengarten/Catinaccio Fm, the post-volcanic Rosszähne/Denti di Terrarossa Fm and the Cassian Dolomite. (For a different stratigraphic terminology see Carta Geologica d'Italia (1972, 1977), Brondi et al. (1976), Bosellini (1984), De Zanche et al., 1993). At the north face of the Schlern/Sciliar the volcanics pinch out on the lower/middle platform slope (Fig. 25); 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).

At the interfingering zone between the Wengen Fm and the Rosszähne Fm at the north-eastern flank of the Schlern/Sciliar and at the Mahlknechtwand, three distinct progradational cycles of reef tongues are present with intercalated volcaniclastic sandstones and conglomerates. Within the single cyclothems the amount of volcanic detritus gradually decreases upwards and becomes almost absent at the transition to the St. Cassian/San Cassiano Fm. At this time the relief of the debris delivering volcanic hinterland is almost levelled out and re-flooding of this area occurs as a consequence of the general subsidence after the Middle 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 during the third day at the Mahlknechtwand (Stop 3.5).
At the platform top (Schlern/Sciliar plateau) hardly any accommodation space was available and several subaerial exposures led to karst and soil formation (iron ore). 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 of the Norian Hauptdolomit/Dolomia Principale.

3.2 Excursion route and field trip stops (Fig. 24)

Stop 2.1 – Werfen Formation, Campill Member; start of the Frötschbach/Rio Freddo-section at the beginning of the gorge.

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. A coastal plain environment of the upper Gröden Fm/Val Gardena Sandstone was present in the west while a shallow marine, mid and outer ramp environment (Bellerophon Fm) existed in the east. The Bellerophon Fm shows several cycles representing 3rd order sequences within a general westward prograding sedimentary wedge. The coastal line of the end Permian Bellerophon sea is well preserved west of Tramin/Termeno, south of Bozen/Bolzano (sea insert in Fig. 28) The overlying Werfen Fm 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

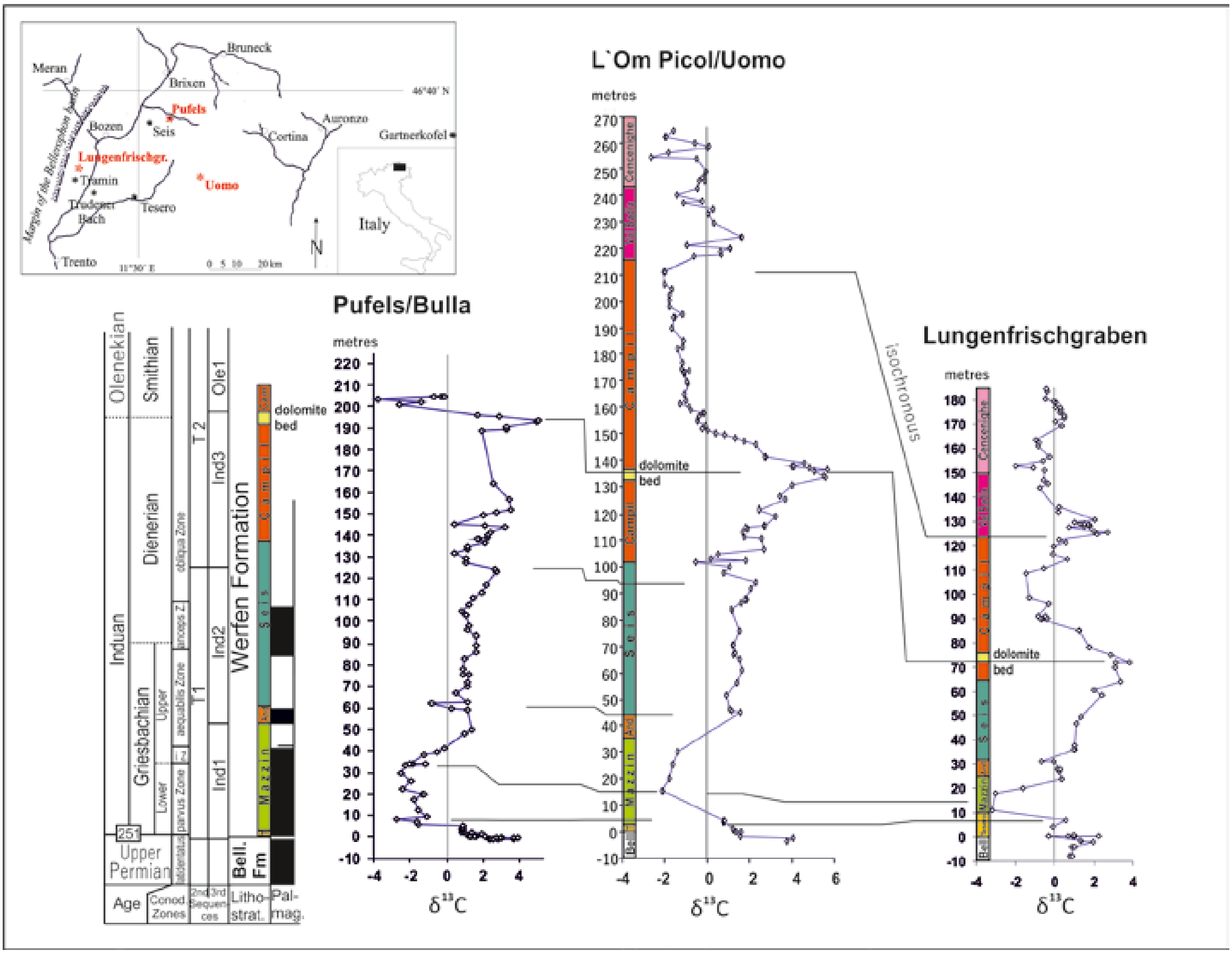


Fig. 28: Chronostratigraphic correlation of sections of the Werfen Formation located along the interpreted inner to outer ramp situation. See insert for location of the sections and the uppermost Permian coastline south of Bozen/Bolzano. Note the different scale of the sections! After Horacek et al., 2010 b, modified.

(For detailed descriptions of lithology and biostratigraphy see Broglio Loriga et al. (1983). The end Permian 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 during the lower Middle Triassic, in the Olang/Valdaora Dolomites situated nearby (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 which were removed repeatedly by storm-dominated, high-energy events. These processes generated a storm-dominated stratification pattern which 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 the stratigraphic record in terms of relative sea-level changes. 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, the numbers of cycles and cycle stacking patterns vary from section to section according to the position on the 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 the duration from the PTB to the IOB (Induan-Olenekian boundary) is roughly 1.3 Ma, the total sediment thickness of 200 m e. g. in the Pufels/Bulla section (Brandner et al., 2009) 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 the *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, Seis/Siusi, Gastropodenoolith, Campill, Val Badia, Cencenighe, San Lucano). The type locality of the "Werfener Schichten" is the area around Werfen, a village south of Salzburg in Austria. However, at the type locality the Werfen beds have quite a different, more terrigenous facies resembling the "Servino" in Lombardy. Therefore, a redefinition of the "Werfener Schichten" as "Werfen Group" is necessary.

The above-mentioned members 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, and at the base of the Val Badia, Cencenighe and San Lucano members.
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 four depositional sequences with varying stacking patterns, that may have regional significance as shown by Horacek et al. (2007, 2010 a) who carefully correlated the stratigraphy of several sections in the Dolomites and in Iran. The main excursions of the carbon isotope curve can be correlated to sequence stratigraphic boundaries: (1) the transgressive systems tract (TST) of sequence Ind 1; (2) the TST of Ole 1 (see also Krystyn et al., 2007); and (3) the TST at the base of the Val Badia Member. This would imply that the profound changes in the global carbon cycle in the Lower Triassic were forced by eustatic sea-level changes.

The regional importance of the terrigenous input signal at the base of the Campill Member 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.

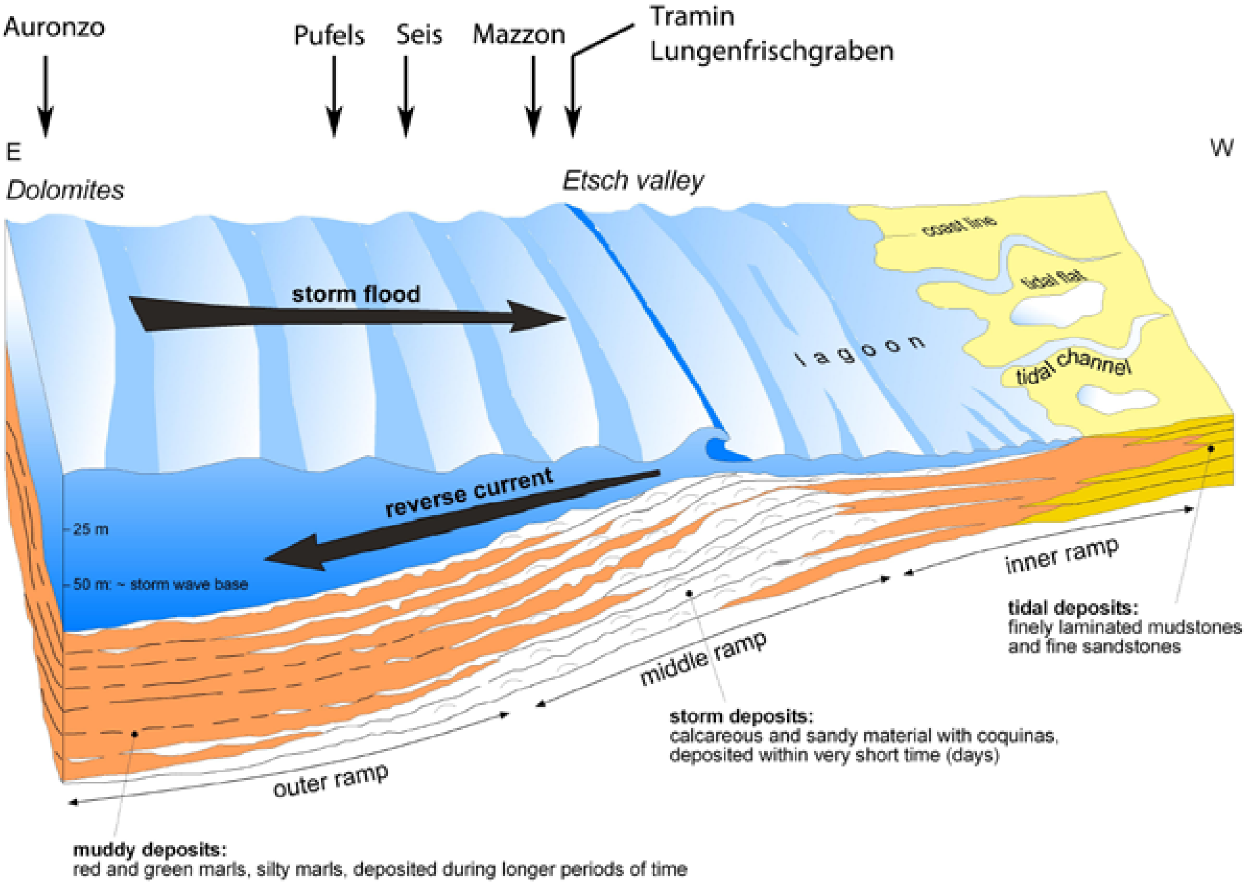


Fig. 29: Schematic model for the deposition of the Werfen Formation on an east-dipping ramp. Sedimentation is essentially controlled by storms; the Lower Triassic coast line is supposed to be far to the west near the Como Lake. Mud deposits, now red and green marls, alternate with layers of sand with bivalve and gastropod shells. Each limestone bed is the product of a storm event and is deposited within some days. Storms generate energy-rich, seafloor-touching waves, which, especially in the coastal zone, are eroding and swirling up the mud and sand on the seafloor. Consequently, bivalve and gastropod shells are washed out and enriched separately forming coquina beds (see Fig. 30) (after Brandner & Keim, 2011a).

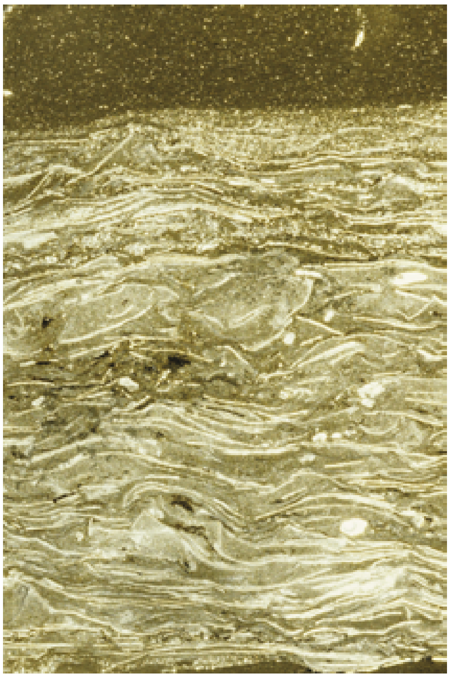
In Fig. 28 we plotted the chronostratigraphic correlation of three sections from different locations using the above mentioned remarkable excursions of the d^{13}C-curves. The middle ramp Lungenfrisch-section (position see Fig. 29) shows a synchronous sequence stratigraphic development with a significant decrease of the thicknesses of the cycles. This applies in particular to the Gastropodenoolith at the base of the Campill Member. A short sequence of yellowish dolomite beds, intercalated in thin bedded silty and sandy marls, marks a sea level lowstand, which is strikingly well correlated with the remarkable positive excursion of the d^{13}C-curve in all sections in the Dolomites.

This part of the section is also to be seen in the Frötschbach/Rio Freddo-outcrop of stop 2.1.
Fig. 30 shows a typical m-scale cycle of thinning up tempestite limestones beds (Fig. 31, 32) intercalated in silty marls. The transgressive cycles are part of the TST of the Campill Member some tens of meters above the Gastropodenoolith dolomites.

Fig. 30: Outcrop near stop 2.1. Thinning upward cycles of the Campill Member. Proximal to distal dm/cm-bedded limestone tempestites with channel filling structures and megaripples. Sandy to silty marls are intercalated.

Fig. 31: Slumped ball-and-pillow structures (seismite) in cm-bedded silty to sandy marls of the Campill Member.

Fig. 32: Thin section photomicrograph of a typical tempestite bed with grading and coquinas with *Claraia clarai* (after Brandner & Keim, 2011a).



Stop 2.2 – Richthofen Konglomerat, Peres Formation. Outcrop in a little creek above the path.

The Richthofen Konglomerat and Peres Formation unconformably cover an erosional surface on which more than 400 m of the Werfen Formation and Lower Sarl/Serla Dolomite have been removed locally. The fluviatile clastics of the late Middle to Upper Anisian are a typical feature of the Dolomites and the Carnian Alps (Muschelkalk Konglomerat, Ugovizza Breccia) covering the eastern part of up to 100 km wide, westward dipping tilted blocks (Fig. 2). The NNW striking master fault zone in the Gadertal/Val Badia area seperates the two blocks (Fig. 33), each including a Middle to Upper Anisian drowning area with synrift sedimentation, e. g. the Prags/Braies Group in the Eastern Dolomites, an elevated area with strong erosion (1st order unconformity) and the abovementioned fluviatile sedimentation.

The Richthofen Konglomerat is characterized by well rounded pebbles, up to dm in diameter, of bimodally distributed clast sizes. The matrix consists of smaller clasts filling the gaps between the grain supported framework (Fig. 34). The grains are sometimes aligned with the currents, also imbrication occurs (Fig. 35). The conglomerates are part of the transgressive fining upward Peres Formation. Reddish, muddy to sandy sediments with a sheet flood facies of distal fans with isolated fine-conglomerate channel fills form the lower part of the formation. At the transition to the shallow marine Morbiac Formation, finely laminated reddish to grayish marls show mud cracks and also some Rynchosauroid tracks from lizard-like reptiles (Fig. 36, see also Brandner (1973) and Avanzini & Renesto (2002).

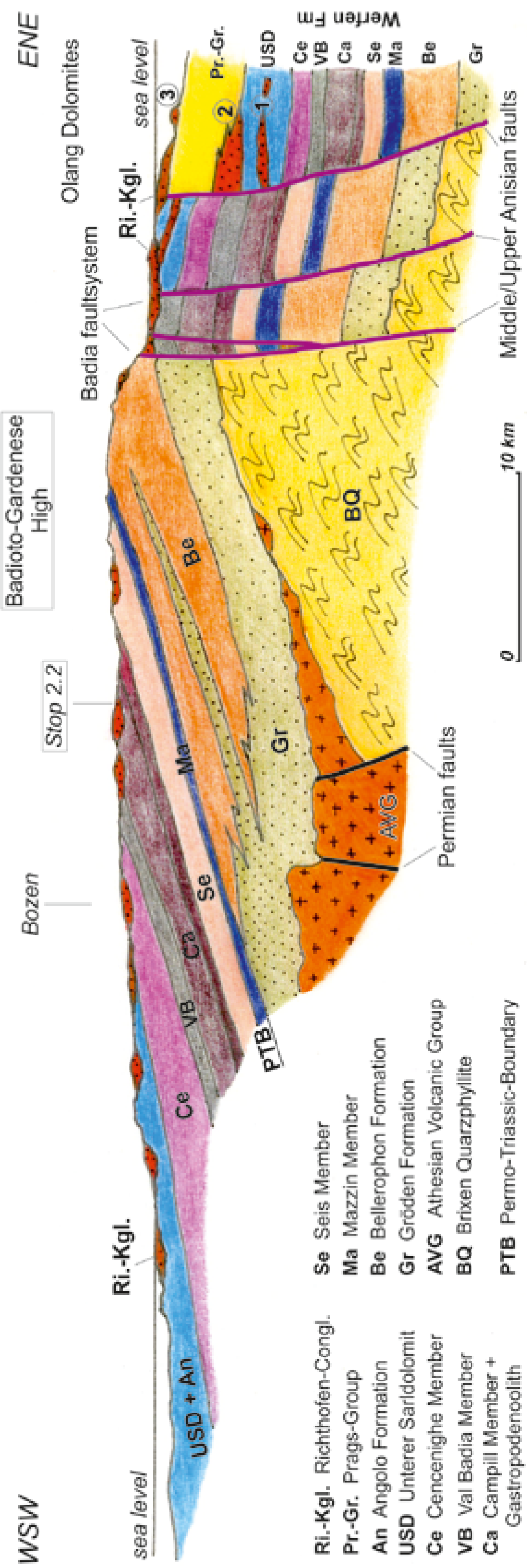


Fig. 33: Reconstruction of the Upper Anisian tilted block of the Dolomites in a WSW striking section (note the strong vertical exaggeration!). The reconstruction is based on subcrop-mapping of the Peres Formation ("Richthofen Konglomerat") according to Bosellini (1968) and Brandner (1984). East of the Gadertal/Val Badia master fault zone we find the age constraining sheddings of conglomerates and sandstones (see numbers 1, 2, 3) intercalated in well dated marine sediments of the Middle/Upper Anisian Prags/Braies Group (Bechstädt & Brandner, 1970). The three intercalations may be interpreted as pulses of rifting in the Middle and Upper Anisian.

Fig. 34: Richthofen Konglomerat, Upper Anisian. Well rounded pebbles of rock fragments of lithologies of Bellerophon limestones, Werfen beds and Lower Sarl/Serla Dolomite (whitish grains).

Fig. 35: Surface of a conglomerate bed with alignment of the pebbles according to the westward current direction.

Fig. 36: Vertebrate track of *Rhynchosauroides tirolicus* Abel on reddish beds of a finely laminated tidal flat facies of the Peres Formation.

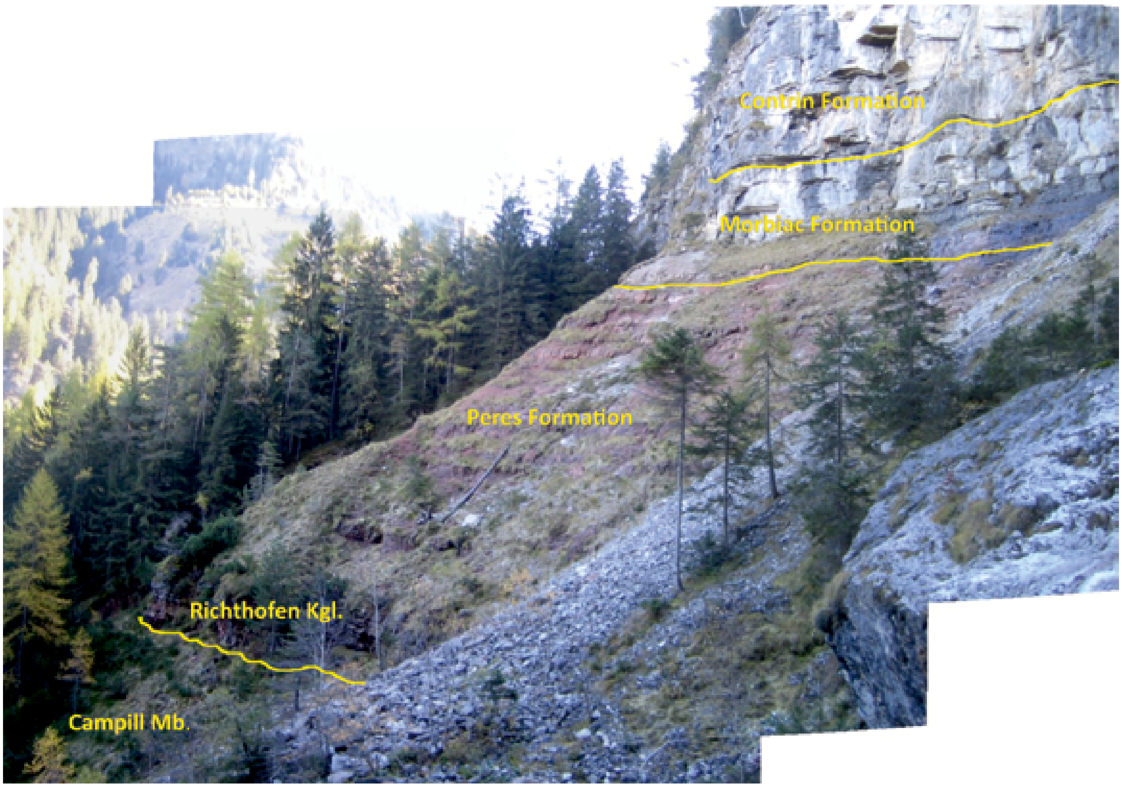


Fig. 37: View of the Upper Anisian section in the cliff above stop 2.2. The Richthofen Konglomerat of our outcrop is seen at the base of the Peres Formation. Most of the intercalated thicker bancs are channel fillings of finer conglomerates. The transgressive 3rd order sequence is topped in the HST by the Contrin Formation.

Stop 2.3 – Top of Contrin Formation

We follow the path to the Prossliner Schwaige and cross the ca. 70 m thick Contrin Formation. The middle to coarse crystalline dolomite with dm to 0.5 m thick bedding is very monotonous, showing rare microbial structures. In the Frötschbach/Rio Freddo section the top of the Contrin Formation is marked by monomict breccias of different clast sizes. This is part of a widespread and important unconformity caused by extensional tectonics (Fig. 2). Depressions and larger cavities on top of the breccia and megabreccia (on the northern side of the Frötschbach/Rio Freddo valley) are filled by anoxic, finely laminated dolomites and limestones (Moena Fm). Interstitial cavities of the breccia in the outcrop are filled with dolomite cement and grayish to black kerogen material with finely dispersed pyrit (Fig. 38). Surficial oxidation of pyrit produced sulfate which is the source of the mineralisation of the mineral water of Bad Ratzes/Bagni di Razzes.

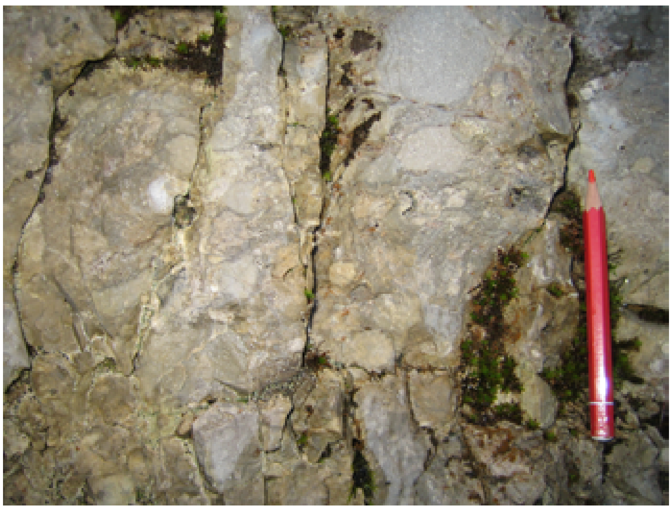


Fig. 38: Breccia of the Contrin Fm with a clast supported framework. Interstitial cavities are filled by isopachous dolomite cement and p. p. with blackish bituminous material (kerogen).

Stop 2.4 – **Buchenstein Formation**

The Frötschbach/Rio Freddo section is a classical section of the "Buchensteiner Schichten" and was defined as one of the type sections by Richthofen (1860) and Mojsisovics (1879). In recent times, important efforts were made to produce an accurate chronological framework by integrated stratigraphic analysis for the exact definition of the Anisian/Ladinian boundary (for further information sea Brack et al, 2005). The integrated high-resolution stratigraphy is based on bio- , chemo- and magnetostratigraphy as well as U-Pb radiometric ages of zircons from three volcanoclastic niveaus (lower, middle and upper *"Pietra Verde"*). Distinct intervals of the volcaniclastic layers can be traced as exact marker horizons throughout the basins of the Southern Alps, and can also be found in the Reifling basins of the Northern Calcareous Alps of the Austroalpine. Tephra stratigraphy proved to be very suitable for exact correlation of sections located in- and outside the Southern Alps.

According to radiometric ages, deposition of the 60-70 m thick Buchenstein Fm took place in a time interval of less than 5 M.y., spanning 5 ammonoid zones. The time aquivalent carbonate platform of the Schlern reaches a thickness of ca. 800 m, other surrounding buildups such as Rosengarten/Catinaccio, Latemar, Geisler/Le Odle, Monte Agnello have similar thicknesses. The short phase of intensive basaltic volcanism in the Upper Ladinian did not always interrupt platform growth. Due to the exceptional outcrop conditions at the northern slope of the Schlern/Sciliar (Fig. 25), the onlap geometry and pinching out of the volcanics can be seen very clearly. The prevolcanic carbonate platform (Rosengarten Fm) is overlain directly by the postvolcanic platform (Rosszähne Fm) without any visible interruption.

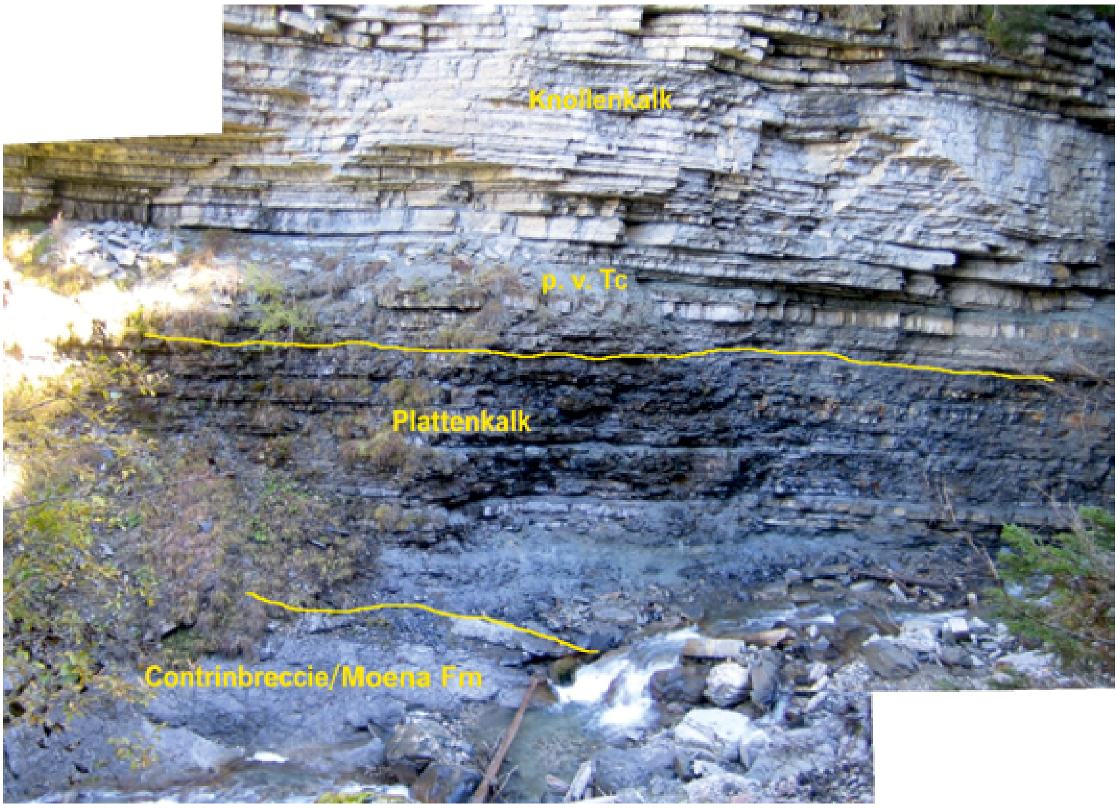


Fig. 39: View of the Buchenstein Fm section on the northeastern side of the Frötschbach/Rio Freddo valley. The top of Contrin breccia and Moena Fm (drowning unconformitiy) is overlain by a sharp contact with the evenly bedded and finely laminated cherty limestones of the Plattenkalk Member. After 8 m the nodular cherty limestones of the Knollenkalk Member follow with the important Pietra Verde correlation horizon tuff layer "Tc".

Basinal sediments of the Buchenstein Fm and the platform slope of the Rosengarten Fm were overlain by masses of volcanics. In areas of high subsidence rate in the surroundings of the Upper Ladinian magmatic center in the Fassa valley, the Latemar and Monte Agnello platforms were completely covered by the volcanics and thereby protected from the elsewhere widespread and intense late diagenetic dolomitisation.

The well preserved platform interior of the Latemar buildup with a 600 m thick succession of up to 1 m thick peritidal shallowing upward cycles has been the object of detailed sedimentological and stratigraphic studies (Goldhammer et al., 1987, Egenhoff et al., 1999, Zühlke et al., 2003). Most of the cycles are capped by subaerial exposure surfaces, indicating periodic sea level lowering. The cycles show a 5:1 bundling. Therefore a Milankovitch-frequence-forcing is the most obvious interpretation for most of the 600 cycles. However, the cyclostratigraphic timing contradicts the duration of Triassic standard ammonoid zones and the radiometric ages mentioned above. Further findings of ammonoids within the platform (Manfrin et al., 2005) as well as radiometric ages of zircons from tuff layers (Mundil et al., 2003) within the platform permit a direct correlation with the Buchenstein basinal fillings and point to a time span of less than 5 M. y. This may indicate the existence of sub-Milankovitch cycles (?sunspot-cycles) with a period of only a few thousand years (Zühlke et al., 2003).

To solve the dispute, bedding rhythms of the time aquivalent basinal Buchenstein beds have been analysed statistically (Maurer et al., 2004) assuming that the basinal sedimentary record should be more continuous than the frequently exposed platform succession. Near the Seceda, a core was drilled through the complete Buchenstein section including the three Members *Plattenkalk, Knollenkalk* and *Bänderkalk.* Unfortunately, the straightforward analysis of orbital forced bedding rhythms has been severly hampered by the frequent interruption of background sedimentation by calciturbidites and episodic fall out of ash layers. No clear evidence could be presented for pro or contra Milankovitch cycles.

The Seceda succession is aquivalent to the Frötschbach/Rio Freddo section, as the correlation of ash beds and distinct packages of limestone beds are possible (see Fig. 40). In contrast to earlier times (Brandner, 1982) the basal contact of the *Plattenkalk Mb* is now fully exposed in the Frötschbach/Rio Freddo valley (Fig. 39). Deep marine facies of evenly bedded, finely laminated black siliceous limestones overlay the drowning unconformity on top of the shallow marine Contrin dolomites and the dolomite breccias of the Moena Fm. The succession is 8-9 m thick and interrupted by "Pietra Verde" ash beds. The mm-lamination is composed of wackestones with filaments (Daonella) and radiolarians, rich in organic matter. Bioturbation is absent indicating an anoxic environment. This is in contrast to the overlying *Knollenkalk Mb* which consists of calcareous mudstones with chert nodules, filaments and radiolarians and intercalated marls. The nodular features in dm-thick beds are caused by bioturbation of firmground-mud, destroying fine lamination. Late diagenetic pressure solution and partly strong stylolithisation resulted in a significant modification of primary limestone/marl couplets. The mud is composed of peloidal material and may have a shallow water source from surrounding platforms. Besides the export of mud from carbonate platforms, carbonate precipitating microbial plankton ("whitings") may be another important source. However, this has not been proven so far. Toward the *Bänderkalk Mb* event sedimentation of calciturbidites and breccias is increasing. The thickening upward sequence ends at the toe-of-slope with the onlap of Upper Ladinian volcanics.

The Bänderkalk Mb pinches out NE of the Frötschbach/Rio Freddo river where *Knollenkalk* and some metre thick dark gray to black, finely laminated, dm-bedded limestones and dolostones are directly overlain by the volcanics along the path to Prossliner Schwaige (Fig. 41). Few calciturbidites and a Pietra Verde ash layer are intercalated in the dm-bedded succession. The change from the proximal CU-succession of the Bänderkalk Mb to the finely laminated, platy limestones of a more distal basinal facies is interpreted as part of the transgressive system tract of the third Ladinian sequence (La 3 sensu De Zanche et al., 1993.

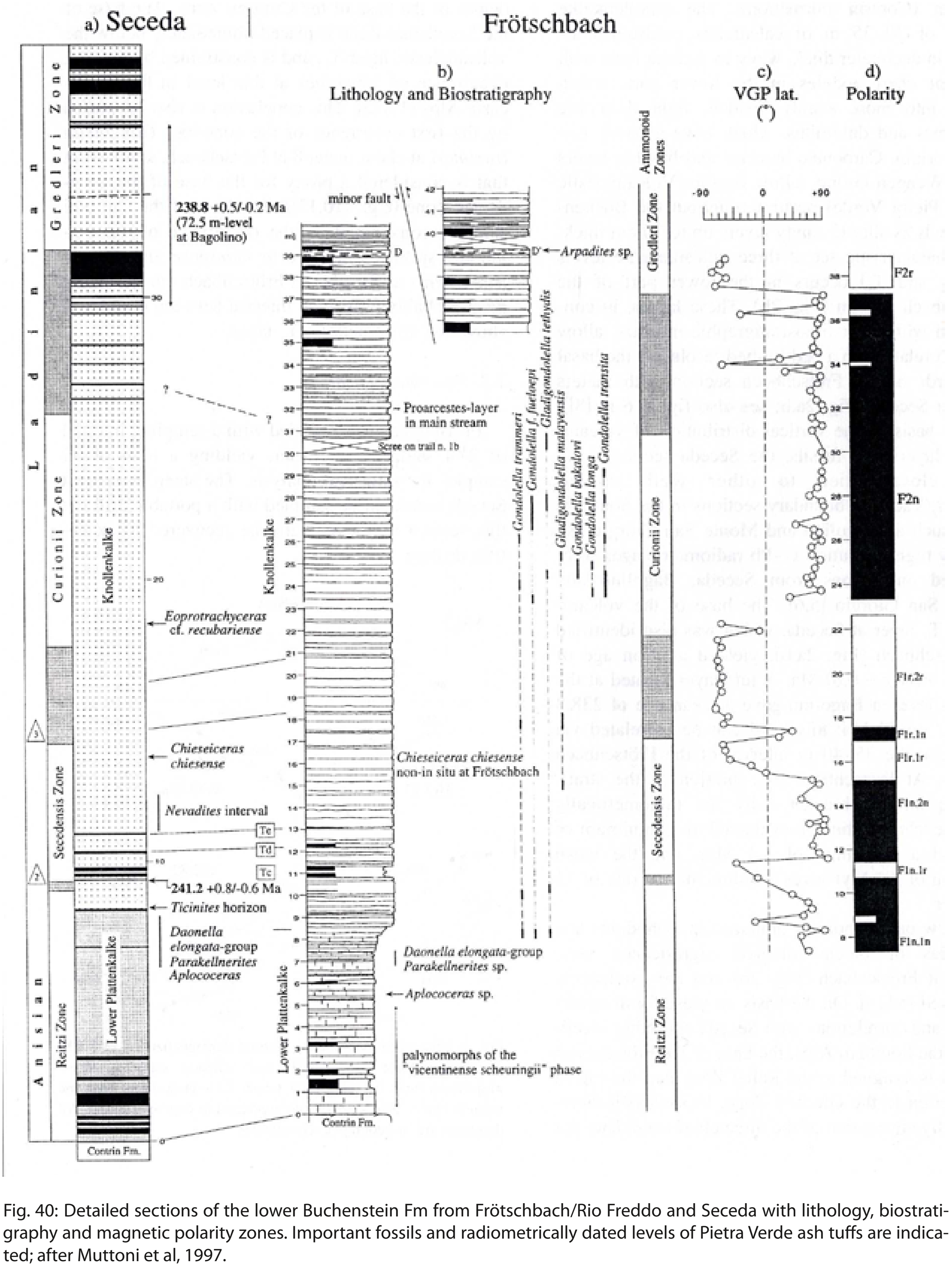


Fig. 40: Detailed sections of the lower Buchenstein Fm from Frötschbach/Rio Freddo and Seceda with lithology, biostratigraphy and magnetic polarity zones. Important fossils and radiometrically dated levels of Pietra Verde ash tuffs are indicated; after Muttoni et al, 1997.
The Anisian/Ladinian boundary is now fixed in position "3" according Brack et al., 2005. The Frötschbach/Rio Freddo section is located at the northern margin of the Rosengarten/Catinaccio-Schlern/Sciliar platform at the southwestern margin of an embayment of the Buchenstein basin. The Seceda section is placed at the northeastern margin of the basin in a distance of ca. 15 km.

Fig. 41: View of the top of the Buchenstein Fm in the Frötschbach/ Rio Freddo section with slump folds in the Bänderkalk Mb at the toe-of-slope of the Schlern/Sciliar carbonate platform (Rosengarten Fm).

Stop 2.5 – Volcanic succession along the path to Prossliner Schwaige

After the "Pietra Verde" rhyodacitic ash layer deposition in the Buchenstein basin and adjacent carbonate buildups, a second, more violent volcanic event took place in the Upper Ladinian in the central part of the Dolomites. The volcanic succession of the Fernazza Group has a thickness of ca. 250 m in the Frötschbach/Rio Freddo section, increasing to more than 400 m toward the east in the Molignon-Val Duron section.
The duration of volcanic activity of less than one ammonoide zone (*Protrachyceras archelaus*) is well constrained by the top of the Buchenstein Fm with the 3rd Pietra Verde layer and the first post-volcanic sedimentation including a rich ammonoid fauna in the Tschapitbach section (Stop 2.6) of Longobardian 2 (Fig. 27). Mietto et al. (2012) reported a new U-Pb date of 237.773±0,052 Ma for an ash bed 24 metres above the top of the Fernazza volcanics west of the Tschapitbach section. Together with the Pietra Verde date of 238.0 Ma (Mundil et al., 2010) from the top of the Buchenstein Fm of the Seceda section it is possible to specify the duration of the volcanic activity with less than 227 Ka.

The Rosengarten/Catinaccio carbonate platform is cut by basaltic dikes, and the toe-of-slope of the Schlern platform is locally carved (path to Schlernbödele/Rif. Malghetta Sciliar and TierserAlpl/Alpe di Tires). The extrusives generally fill the basins with chiefly submarin volcanic material onlapping the slopes of the carbonate platforms. On the Schlern plateau/Altipiano dello Sciliar we find a band of up to 40 m thick volcanics (?subaerial lavas) overlying the topsets of the platform. The volcanics of the basin and those of the Schlern plateau/Altipiano dello Sciliar are of the same age, but are interrupted in the upper slope section.

In a limited area of the eastern part of the Schlern plateau/Altipiano dello Sciliar, a few metres of red fossiliferous nodular limestones cover the Schlerndolomit/Dolomia dello Sciliar indicating a drowning of this part of the platform. Drowning as well as transgression at the toe-of-slope on top of the Buchenstein Fm are part of the above mentioned TST of the La 3-sequence which took place at the same time as the pulses of transtensive tectonics in the nearby Fassa valley. This makes clear that the La 3 depositional sequence was also forced by synsedimentary tectonics.

During the initial phase of the magmatic event, a relatively small transtensive pull-apart basin formed in the area of the upper Fassa valley (Bosellini, 1984) with a pronounced subsidence of more than 2 km (see Fig. 2). The basin was filled by huge slabs of slumped stratified bodys (similar to tectonic sheets) of the Bellerophon, Werfen, Contrin and Rosengarten Fms as well as by debris flows of megabreccias ("agglomerates" of older authors or "Caotico Eterogeneo Fm" of Italian authors) and olistoliths. Shear movements along the evaporitic detachment horizon of the Bellerophon Fm produced folded structures of different size which were cut by volcanic dikes, confirming their Ladinian age. This stack of folds, as for example in the Val San Nicolò and Col Rodella area, has been interpreted by Doglioni (1987) and Castellarin et al., (1998) as diapiric structures related to transpressional Ladinian tectonics. However, it should be noted that the Bellerophon evaporites consist only of anhydrite and gypsum. Rock salt (halite) has not been found to date, calling diapirism into question. The complexity of the structures is also due to later deformation by alpine tectonics in Paleogene and Neogene times. The unique structures and the deviating chemism of intrusives, provoked various geodynamic models and still ongoing discussions (see chapter introduction and below).

The Upper Ladinian igneous rocks filled the interplatform basins as well as the collapsed areas with a various succession of pillow basalts, highly vesiculated basalts and lava breccias, hyaloclastites and pyroxene tuffsandstones – all types can be seen along the path to Prossliner Schwaige. Vesiculae and interstitial cavities in the breccias are filled by zeolite minerals (analcime, etc.) Further upward in the section, increasingly greenish seladonite can be found in joints of lava breccia. Remarkable shallow intrusive bodies with typical contractional joints (columnar basalt) and laccolith-shaped intrusions with elevated scales of Buchenstein limestones can also be found. The rugged steep slope at the opposite side of the valley shows a nearly continuous outcrop of the volcanic succession.

Basalts, basaltic andesites and intrusive rocks (monzonites of Predazzo/Monzoni) are comagmatic and strontium isotope ratios indicate a deep magmatic source with low crustal contamination (Castellarin et al., 1988 and references therein). Further intensive geochemical studies underline the calcalkaline and shoshonitic trends of the basalts and confirm their "orogenic" character. This "orogenic" character is in conflict with the aforementioned "anorogenic" rift model for the development of a passive continental margin of the opening Neotethys. This provoked different geodynamic models which are still in discussion, including:

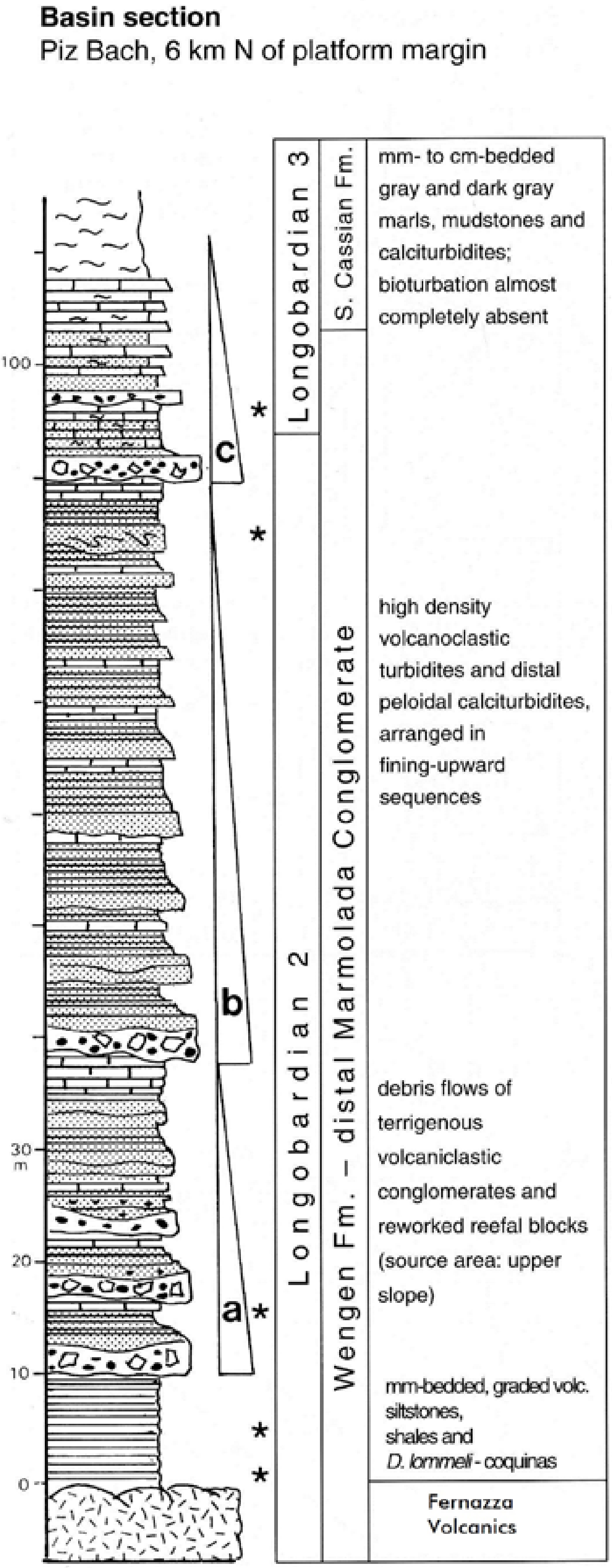
1. Aborted rifting to explain the strong subsidence in the Middle Triassic and its decline in the Carnian, recorded in the geometries of carbonate platforms in the Northern and Southern Alps (Bechstädt et al., 1978).
2. A Middle Triassic subduction zone based on calc-alkaline and shoshonitic magmatism and Triassic compressional structures (Castellarin et al., 1988). A similar orogenic character was also observed by Bèbien et al. (1978) in the "porphyrite – radiolarite" formation (="Diabas-Hornstein Schichten", Ampferer & Hammer, 1921) of the Dinarides, implicating a west-dipping subduction of the Palaeotethys. So far there is however no clear evidence for Middle Triassic subduction zones in the western Tethys realm.
3. A left-lateral strike-slip fault system based on the magma emplacement along relatively small transtensional basins with considerable subsidence (Brandner, 1984; Doglioni, 1987). The orogenic trend of the intrusives could be related to the inheritance of older Variscan or Lower Permian mantle melt injections in the lower crust (Sloman, 1989; Bonadiman et al., 1994).

Stop 2.6 – Tschapit creek (south of Prossliner Schwaige); post-volcanic slope facies development.

Post-volcanic Upper Ladinian sedimentation shows a general inversion of the distribution of sediment thicknesses: the Seiser Alm/Alpe di Siusi basin is filled by over 500 meters thick successions of volcaniclastics and carbonates (Wengen Fm and St. Cassian/San Cassiano Fm) whereas on the Schlern/Sciliar platform only 80 meters of platform sediments were accumulated (Rosetta Dolomite and Schlernplateau beds). Karstification, paleosols and non-deposition are proven in Upper Ladinian and above all in Lower Carnian platform sediments of the Schlern plateau/Altipiano dello Sciliar. The situation on the Mendel/Mendola platform (SW Bolzano/Bozen) is very similar indicating the merging of the platforms to form the spacious Trento platform. Higher rates of basinal sedimentation and a decrease of subsidence rates with a relative stillstand of the sea-level triggered a drastic change in the geometry of the platforms: post-volcanic platforms are characterized by climbing progradation and toplap sedimentation (Bosellini, 1984). It is important to note, that the same holds for geometries of Upper Ladinian-Carnian platforms in the Northern Calcareous Alps – though without Ladinian volcanism (Brandner, 1984). Strong Carnian platform progradation nearly closed the St. Cassian basinal areas. Residual basins are only known in the Eastern Dolomites where St. Cassian beds are directly overlain by shallow marine sediments of the Raibl Group (Keim & Brandner, 2001).

The Tschapit creek represents the type localitiy of the *"Cipit boulders"* ("Kalkstein von Cipit" of Richthofen, 1860). These boulders constitute gravity displaced blocks of up to several meters in diameter and embedded in marly to sandy deposits at the toe-of-slope of the postvolcanic platform. The Cipit boulders are outrunner blocks of megabreccia tongues pinching out by interfingering with basinal sediments (here the basinal Wengen Fm). Isolated blocks were protected against the pervasive dolomitisation by embedding in low permeability basinal sediments. Primary aragonitic cements and fossils are frequently preserved. The Cipit boulders are mainly made up by microbial boundstones with encrusting foraminiferas, *Tubiphytes*, etc. with only few calcisponges, corals, crinoids and echinoid spines. Several centimetre-large growth cavities are filled by radiaxial fibrous cement and volcaniclastic internal sediment. Few cavities are filled by early diagenetic celestine crystals. At Mahlknecht cliff (see Stop 3.5) slope boulders have been studied in detail (Brandner et al., 1991).

The Cipit boulders are part of a coarsening/thickening upward sequence at the base-of-slope in the little creek of Tschapit Bach (Figs. 42, 43). The section starts on top of the volcanics featuring a greenish band of seladonite, formed by submarin weathering during a longer phase of non sedimentation. Findings of well preserved index fossils, as *Daonella lomelli*, *Trachyceras archelaus*, etc. from the base of the section have been known since Zittel (1899). Further findings were published by Brandner (1982, 1991) and Mietto et al. (2012), fixing the Late Ladinian *regoledanus* Sbz. in this part of the section.
Different from the common postvolcanic sedimentation of the Wengen Fm with characteristic turbiditic volcaniclastics, sedimentation started with an alternation of dm-bedded grayish limestones and marls lacking volcaniclastic sandstones and conglomerates. Some beds are rich in *Daonella lomelli*, which is the reason for the old name *"Halobien Schichten"* of Richthofen (1870). The limestones are bioturbated wackestones with filaments (thin shelled bivalves), radiolarians and pyrite. Thin layers of calciturbidites with peloids, coated grains, ooids and skeletal grains of shallow water origin are intercalated only at the base of the section and become more pronounced upward. The calciturbidites are arranged in two thickening and coarsening upward cycles (Fig. 42). Proximality is indicated by channel filling and slumping (Fig. 43) Few greenish ash layers, indistinguishable from Pietra Verde of the Buchenstein Fm, have been found by Mietto et al. (2012) in the Rio Nigra section SW of Tschapitbach near the Schlernbödelehütte/Rif. Malghetta Sciliar. An ash layer 24 metres above the top of Fernazza volcanics was dated to 237,77 ± 0,14 Ma.



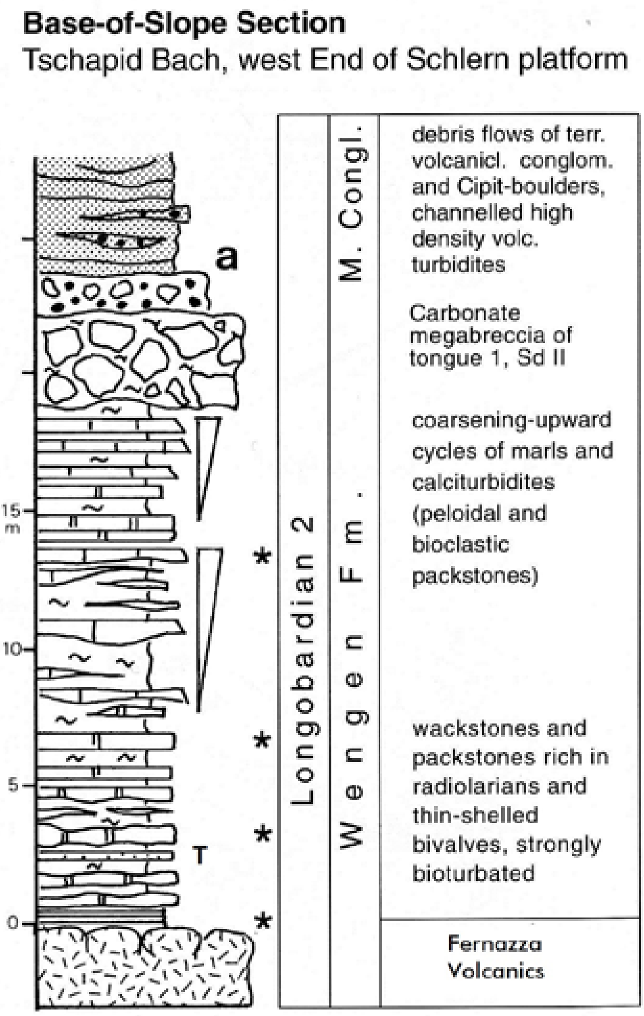


Fig. 42: Measured sections of postvolcanic sedimentation at the toe-of-slope and basin on the Seiser Alm/Alpe di Siusi (after Brandner, 1991). Note the different scale of the sections. Asteriks indicate biostratigraphical control. New findings of ammonoids by Mietto et al. (2012) updated the base of the *Regoledanus* Subzone and placed it a few metres above the top of the volcanics. The succession between the top of the volcanics and the Marmolada Conglomerate is now designated as *Frommer Mb.* (part of the Fernazza Fm). The Wengen Fm starts with the first occurrence of the Marmolada Conglomerate at the base of the depositional sequence Car 1. a, b, c: FU-cycles in the basinal section are to be correlated to the base-of-slope cycles of the Molignon section (see Stop 3.5). T: greenish tuff layer.

The deposition of Pietra Verde type tuffs of rhyolitic to rhyodacitic composition persisted over a time span from Upper Anisian to Late Ladinian, whereas the huge calcalkaline basalts of the central Dolomites accumulated during a short "intermezzo" in the Upper Ladinian with a duration of less than 200 Ka. This underlines the provenance of the extrusives from different magma chambers. Pietra Verde tuffs appear to have been derived from a belt of volcanics south of the Valsugana line below the Po Plain (Cros & Houel, 1983).

To emphasise the obvious facial differences to the Wengen Fm, Mietto et al. (2012) introduced (without comment!) the new name "*Frommer Mb*" (which could be a Member of the Aquatona Fm). The distribution of the Frommer Mb is very local, depending on a strong relief on top of the volcanics (see Fig. 26). N of the Seiser Alm/Alpe di Siusi, the Frommer Mb pinches out, onlapping a steep slope of volcanics. The same applies toward the E of the Seiser Alm/Alpe di Siusi, where the Frommer Mb is lacking in the Molignon section (see Stop 3.5).

The CU-cycles of the calciturbidites are part of the first platform progradation of the postvolcanic Schlern/Sciliar platform (number 1 of SD II (Rosszähne Fm) in Fig. 48) The carbonate grain composition of the calciturbidites indicates a source area of the flooded platform-top in a HST situation (highstand shedding). The CU-cycles are overlain by a carbonate megabreccia of the prograding slope composed of Cipit boulders. These beds are suddenly followed by debris flows and channelled high density flows of volcaniclastic sandstones and conglomerates (*Marmolada Conglomerate* of the Wengen Fm) mixed with layers of Cipit boulders. Distal representatives of the Marmolada Conglomerate are also known by the name "Pachycardientuffe" with a highly diverse invertebrate fauna. The remarkable change in the composition of sediment is interpreted as a lowering of the sea-level which forced the erosion of a volcanic island near the Marmolada (Fig. 44). The sequence boundary of La 3 and Car 1 is placed at the contact between the megabreccia and the Marmolada Conglomerate.

Fig. 43: View of the lower part of the Tschapitbach section with channel-filling and slumping of calciturbidites of the prograding platform tongue 1 of the Schlern/Sciliar platform.

Sedimentation at the toe-of-slope along the northern margin of the Schlern platform/Altipiano dello Sciliar is characterised by repeated progradation of the platform alternating with prograding volcaniclastic sandstones and conglomerates. The sediment production in the two different source areas and the shedding of the material into the basinal area may have been controlled by sea-level changes (discussion see Stop 3.5).

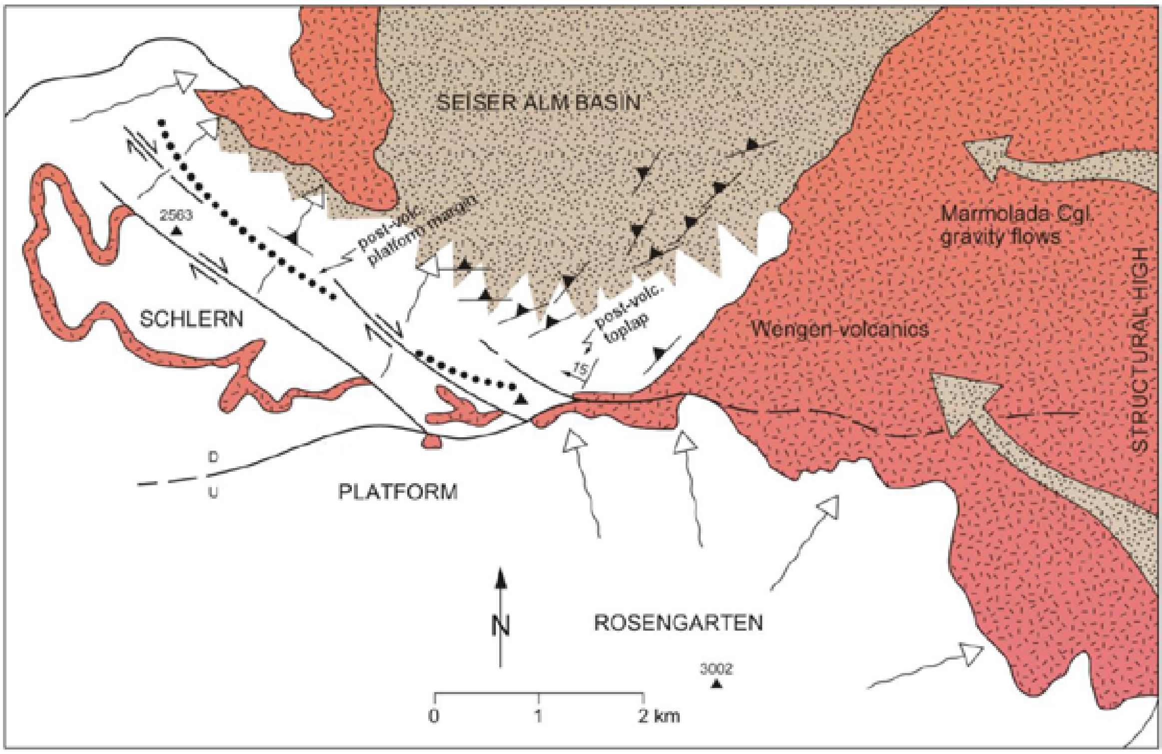


Fig. 44: Generalized geological map showing the distribution of Upper Ladinian platform, slope and basinal facies. Long arrows indicate the directions of pre-volcanic slopes, whereas post-volcanic carbonate and volcaniclastic foreslopes are implied by there strike and dip. Arrows with the dotted signatur marc the direction of high density flows of volcaniclastics (*Marmolada Conglomerate*) deriving from emergent volcanic terranes in the SE. Note the 15° NW dip of post-volcanic toplap with regard to the tectonical steepening of foreslopes. The dip direction clearly changes toward NW according to the development of the post-volcanic foreslope which nucleated in the SE. Transcurrent faults are possibly inherited post-volcanic Upper Ladinian faults. After Brandner (1991), coloration by Riva, AAPG-field guide Dolomites, N. Italy, 2015.

4 Field trip day 3, Middle and Upper Triassic successions at the Schlern/Sciliar platform (Schlern plateau/Altipiano dello Sciliar) and the NE margin of the platform (Mahlknecht wall)

(Rainer Brandner, Alfred Gruber)

Crossing the platform from NW toward SE we will see well preserved topset facies, with interfingering of lagoonal facies and reef flat ("coral garden"), as well as Upper Ladinian and Carnian karstification and local palaeosol sections with bean ore. The last stop of the excursion is a mega-outcrop with the impressive palaeoslope section of the Rosszähne/Denti di Terrarossa carbonate platform down to the Mahlknecht-wall toe-of-slope. Sea-level or tectonically forced cycles show the interfingering of prograding reef tongues with Cipit boulders and terrigenous volcaniclastic sandstones and conglomerates derivating from a volcanic island in the SE.

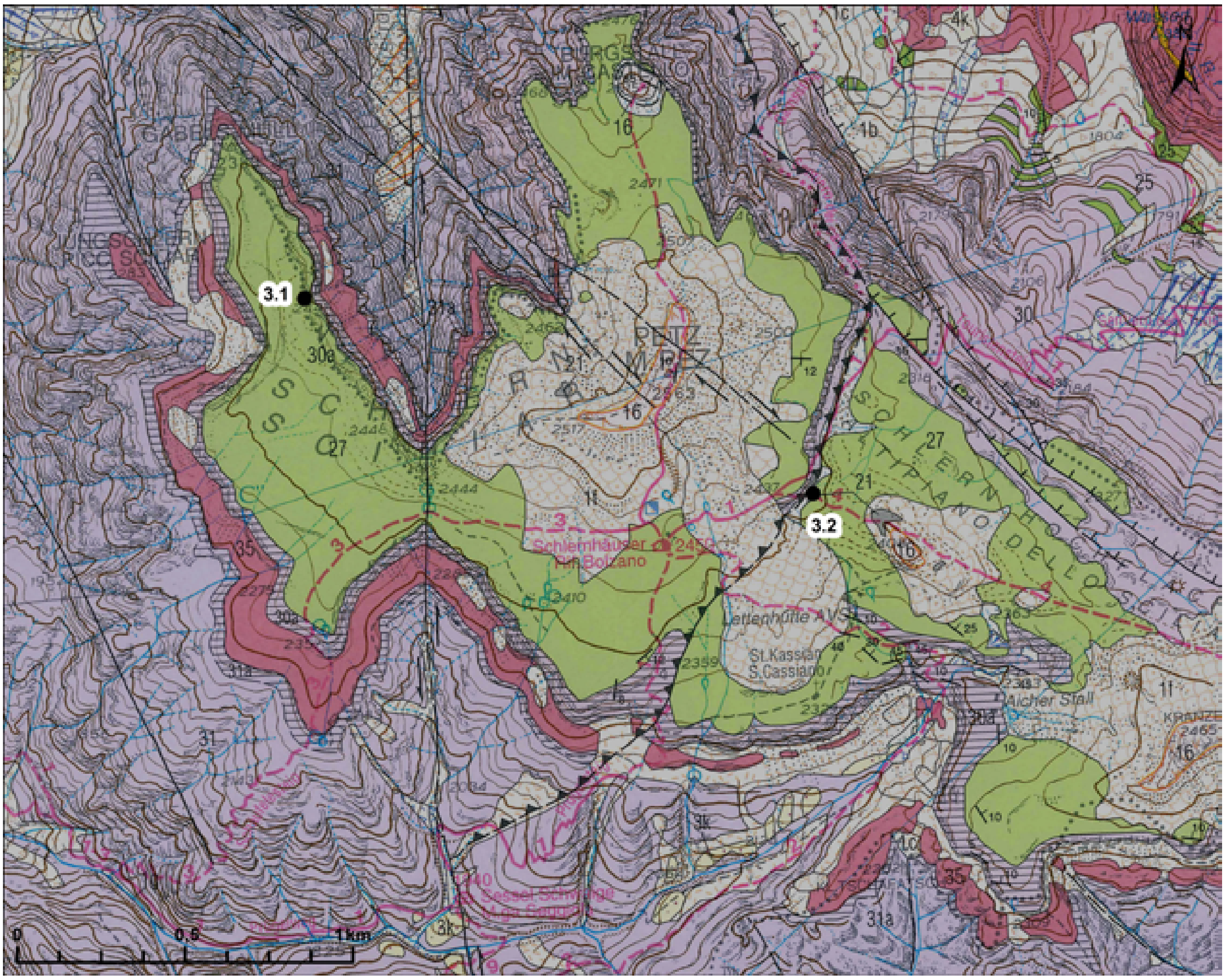


Fig. 45: Geological map (enlarged view of the Geologische Karte der Westlichen Dolomiten 1:25.000, 2007) of the western Schlernplateau/Altipiano dello Sciliar with location of the stops. Signatures: 35, Fernazza volcanics; 31, Rosengarten Fm; 30, Rosszähne Fm; 27, Schlernplateau Fm; 21, Raibl Group (Fedares Mb); 16, Hauptdolomit/Dolomia Principale.

4.1 Excursion route and Field trip stops (Fig. 45)

Stop 3.1 – Gabels Mull (NW Schlernhäuser/ Rif. Bolzano); platform-top succession of the Schlernplateau Formation

On the eastern flank of the Gabels Mull, as well as on the western flank of Petz/Pez mountain peak, the entire succession of pre-volcanic Schlern-dolomite of the Rosengarten Fm, up to 40 m thick volcanics and the post-volcanic Rosszähne Fm is exposed (Figs. 46 and 47). The bedded dolomites of the Rosszähne Fm ("Rosetta Dolomit") are overlain by reddish, highly fossiliferous, lagoonal sediments of the Schlernplateau Fm. In earlier times, the Schlernplateau beds were assigned to the "Raibler Schichten" of Carnian age. Findings of biostratigraphically important ammonoides as *Protrachyceras archelaus* indicate a precise age up to the Regoledanus Zone (Brandner, 1991, Urlichs & Tichy, 2000). The uppermost 6 m of the Schlernplateau section are assigned to the Lower Carnian Canadensis Zone based on the occurrence of *Myophoria kefersteini kefersteini* (Urlichs, 2014). Thus, the Schlernplateau beds span the same period of time as the postvolcanic succession of the Seiser Alm/Alpe di Siusi basin with the interfingering Rosszähne/Denti di Terrarossa platform development.

The top of the Rosetta Dolomite is characterised by a distinct unconformity with karstification and reddish volcaniclastic sandstones and conglomerates with cm-sized well rounded pebbles. Above 50 cm dolomitic grainstone red sandstones, conglomerates and shales with bean ore grains (pisolithic iron ore) indicating the first palaeosol horizon were deposited. Further palaeosol horizons with similar volcaniclastic grain compositions occur on top of the Schlernplateau Fm in transition to the Raibl Group (Fig. 48). In between, the transgressive Schlernplateau Fm is composed of several cycles of red marls, clayey dolosparite, white fossiliferous dolomitic grainstones and limestones with oncoids and ooids, coated grains and coquinas of bivalves and gastropods. The thickness of the sequence varies from 40 m to a few metres toward the platform margin where it interfingers with a reef flat facies (see Stop 3.3).

It is important to note that the intercalated volcaniclastic sandstones and conglomerates were transported from the platform interior in the W,

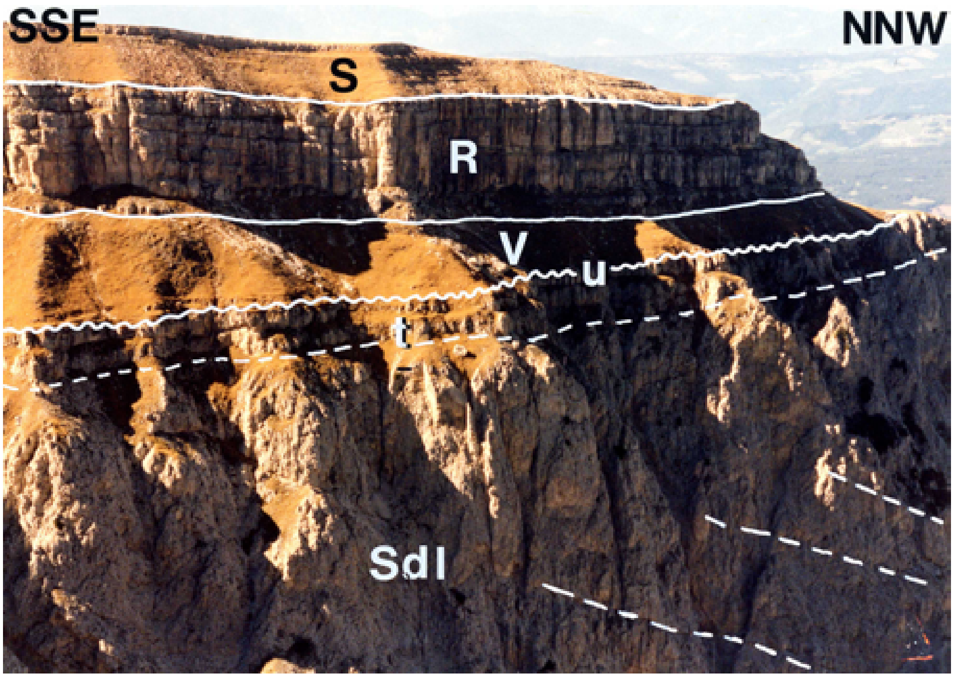


Fig. 46: View of the eastern flank of Gabels Mull (2.389 m) with the complete succession above the Rosengarten Fm. SD I: clinoforms with well bedded toplapping dolomite (t), u: unconformity, V: volcanics, R: "Rosetta Dolomite" (cycles of well bedded dolomite of platform interior facies of Rosszähne Fm). Note that the top of the Rosetta Dolomite locally displays karstic features and is unconformably overlain by Schlernplateau Fm (S). After Brandner (1991).

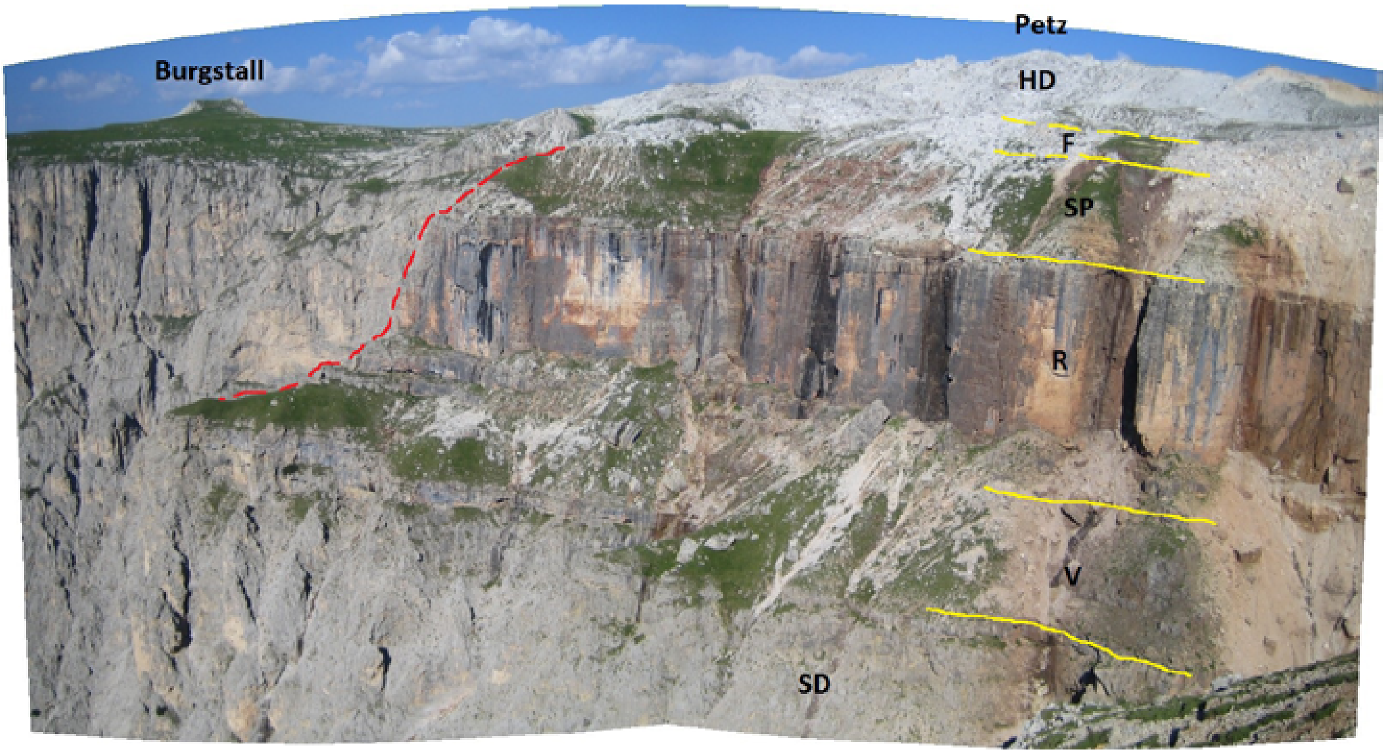


Fig. 47: View of the western flank of the Petz/M. Pez-Burgstall/M.Castello crest. We observe the same succession as in Fig. 46 completed here by Fedares Mb (F) of the Raibl Group and the overlaying Hauptdolomit/Dolomia Principale (Petz/Pez and Burgstall/Castello mountain peaks). Active mass movements mask the base of Hauptdolomit/Dolomia Principale (Hd). To the N the succession is cut by a NW-SE striking ?dextral strike-slip fault. Below the Hauptdolomit of the Burgstall/M. Castello we observe a well bedded sequence without the typical reddish Schlernplateau beds (SP), as well as no volcanics (V). Rosetta Dolomit of the Rosszähne Fm (R) overlays directly the Schlerndolomit (SD) of the Rosengarten Fm (R).

i. e. from the area of the Mendel/Mendola near Bozen/Bolzano. Here, the Ruffrè Conglomerate (Avanzini et al., 2007) correlates with the times of subaerial exposures of the Schlernpateau Fm. A transport from the above-mentioned source area in the SE, as proved for the Marmolada Conglomerate, is impossible due to the existence of a basinal area in between. It is therefore reasonable to assume that the Schlern/Sciliar and the Rosengarten/Catinaccio are the margins of a vast, expansive platform located on the Trento-Bolzano-high.

Stop 3.2 – E of Schlernhäuser/Rif. Bolzano, near quota 2.408 m; short section of palaeosol horizons on top of Schlernplateau Fm.

In general, there are only few outcrops of sections of palaeosol horizons. Usually pisolithic iron ore (Fig. 49) is dispersed over the Schlernplateau/Altipiano dello Sciliar through recent resedimentation. Clear depositional relationships are visible in a little creek south of the path. A colourfull succession of ca. 30 m thickness overlays a gray dolosparite bed of the Schlernplateau Fm. The succession at the transition from Late Ladinian Schlernplateau beds to Upper Carnian Raibl beds is composed of gray to black shales with few plant remains and irregularly intercalated reddish volcaniclastic sandstones and fine conglomerates. Well rounded grains of pisolithic iron ore ("bean ore") occur at the top of a 80 cm thick, fine conglomerate bed. The bean ore grains have a size of few millimetres up to 20 mm. Core and concentric crusts are composed of hematite, goethite and magnetite (Fig. 50). At the base of the section, 30 cm thick red sandstone is overlain by a cm thick iron crust and a rootlet horizon. Bean ore concretions are a product of subtropic climate with alternating moist and arid periods.

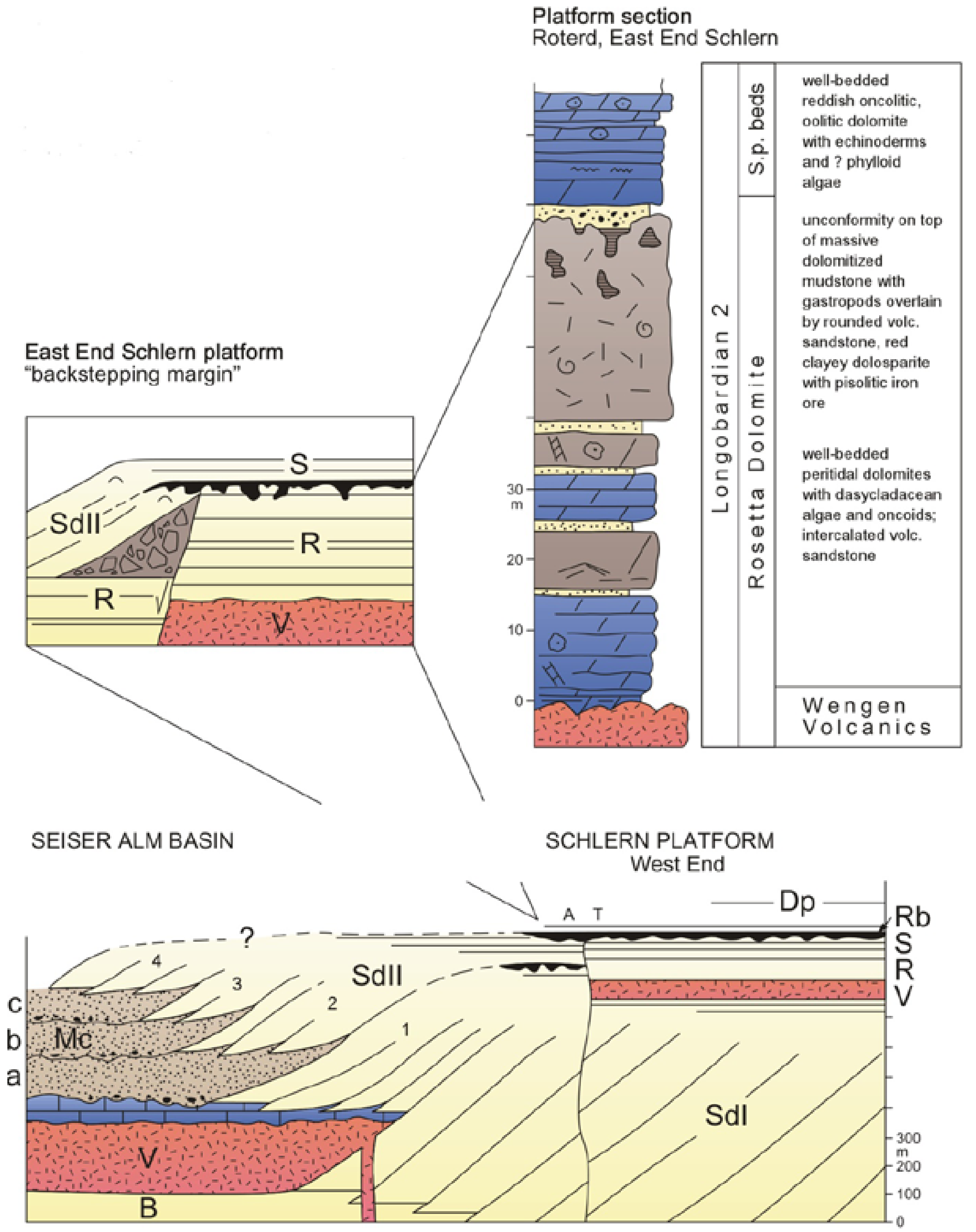


Fig. 48: Interpretative cross section and measured sections of the restored Middle Triassic Schlern/Sciliar platform and coeval basinal sediments of the Schlern/Sciliar-Seiser Alm/Alpe di Siusi region. Note differences between the western (see Fig. 42) and eastern part of the Schlern/Sciliar platform margin and foreslope. B: Buchenstein Fm, Dp: Dolomia Principale/ Hauptdolomit, V: volcanics, Mc: Marmolada Conglomerate (Wengen Fm), R: "Rosetta Dolomite" (=platform interior facies of Rosszähne Fm), Rb: Raibl Group (Fedares Mb), S: Schlernplateau Fm, SD I: pre-volcanic Schlerndolomit (Rosengarten Fm), SD II: post-volcanic Schlerndolomit (Rosszähne Fm), 1, 2, 3, 4: foreslope tongues of Rosszähne Fm, a, b, c: volcaniclastic sequences of Marmolada Conglomerate (Wengen Fm). After Brandner (1991), coloration by Riva, AAPG-field guide Dolomites, N. Italy, 2015.

Fig. 49: Grains of pisolithic iron ore ("bean ore") are widely dispersed on the Schlernplateau/ Altipiano dello Sciliar by resedimentation. They derive from Upper Carnian palaeosol horizons.

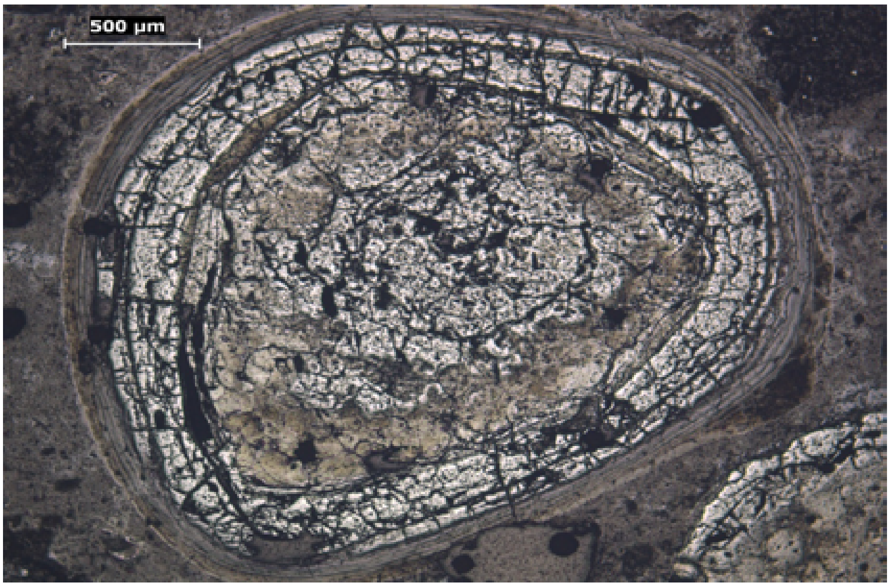


Fig. 50: Thin section of a pisolithic iron ore grain. Core and concentric crust consist of hematite, goethite and magnetite.

4.2 Excursion route and field trip stops (Fig. 51)

Stop 3.3 – W Roterdspitz/Cima di Terrarossa; quota 2.551 m; interfingering of Schlernplateau beds with reef flat and platform margin.

This is one of the few places where it is possible to observe the transition from backreef to forereef. The lagoonal sediments of the Schlernplateau Fm are represented by cycles of gray and reddish dolomites with strikingly large oncoids (*"Sphaerocodium"*, Fig. 52) and intercalated red dolomitic shales. Laterally toward the platform-margin there is a transition to gray dolomites with brushy colonies of *Thecosmilia* like corals in growth position ("coral garden") and microbial mounds. In most cases, the skeletal grains are totally recrystallized and often show micritic encrustations.

Descending to Tierser Alpl/Alpe di Tires we pass the fault zone of the backstepping platform-margin of the Rosszähne/Denti di Terrarossa reef. Clinoforms of the Rosszähne/Denti di Terrarossa slope downlap on the horizontal bedded topset layers of Rosetta Dolomite (Fig. 48). The clear geometry is better seen from a viewpoint in the E (south of Tierser Alpl/Alpe di Tires, Fig. 53).

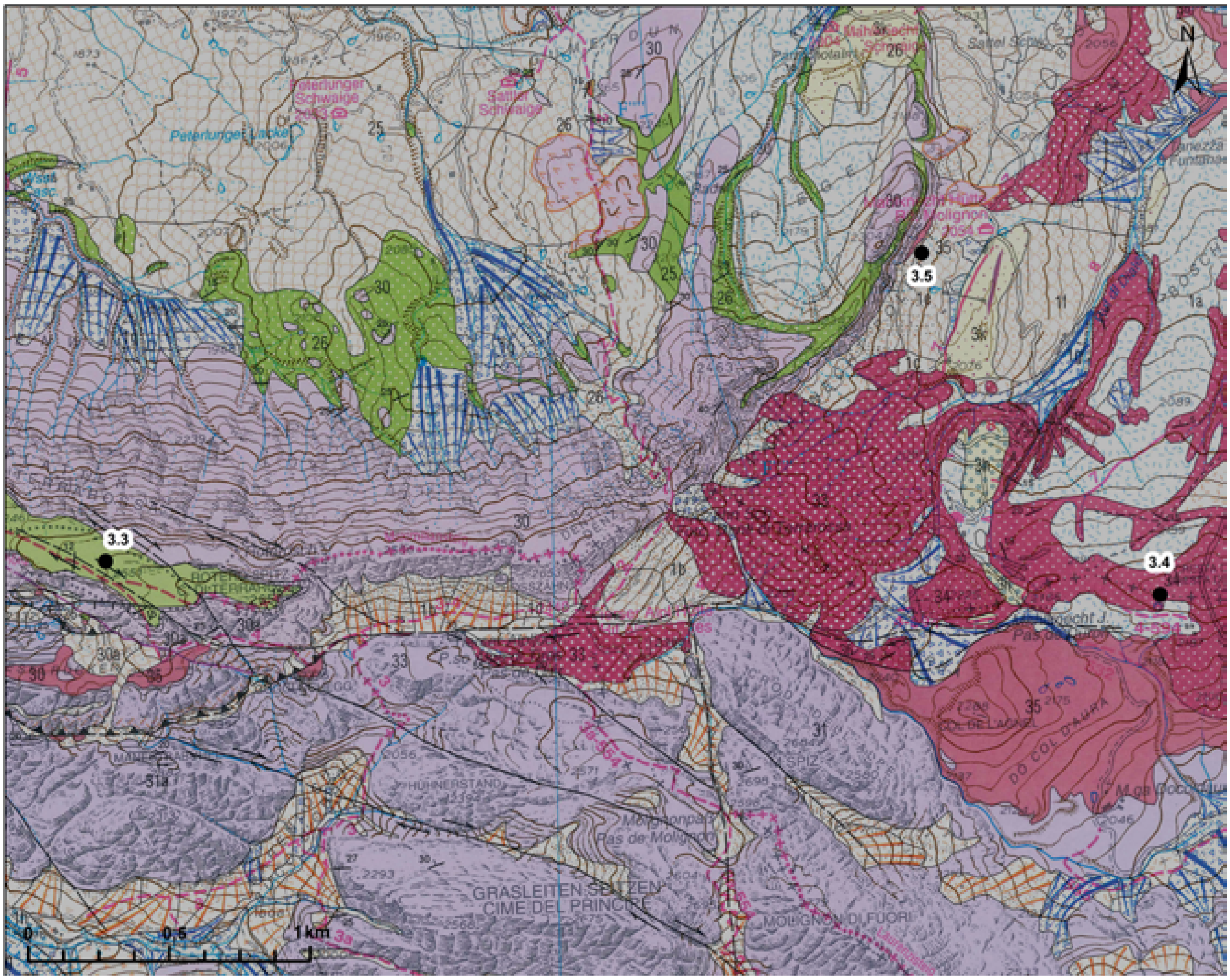


Fig. 51: Geological map (enlarged view of the Geologische Karte der Westlichen Dolomiten 1:25.000, 2007) of the eastern Schlernplateau/Altipiano dello Sciliar – Rosszähne/Denti di Terra Rossa area with location of the stops. Signatures: 25, Wengen Fm; 26, Marmolada Conglomerate; 30, Rosszähne Fm; 31, Rosengarten Fm; 33, volcanic breccias; 34, lava (both Fernazza Group).

Stop 3.3/1 – Tierser Alpl Hütte/Rif. Alpe di Tires and Rosszahn Scharte/Forc. Denti di Terrarossa (optional)

Here, the spectacular panorama and of the isolated Langkofel/Sassolungo-Plattkofel/Sasso Piatto carbonate platform with its W dipping

Fig. 52: Strongly dolomized large oncoids (*"Sphaerocodium"*) intercalated in red dolomitic marls. Schlernplateau beds below Roterdspitz/Cima di Terrarossa.

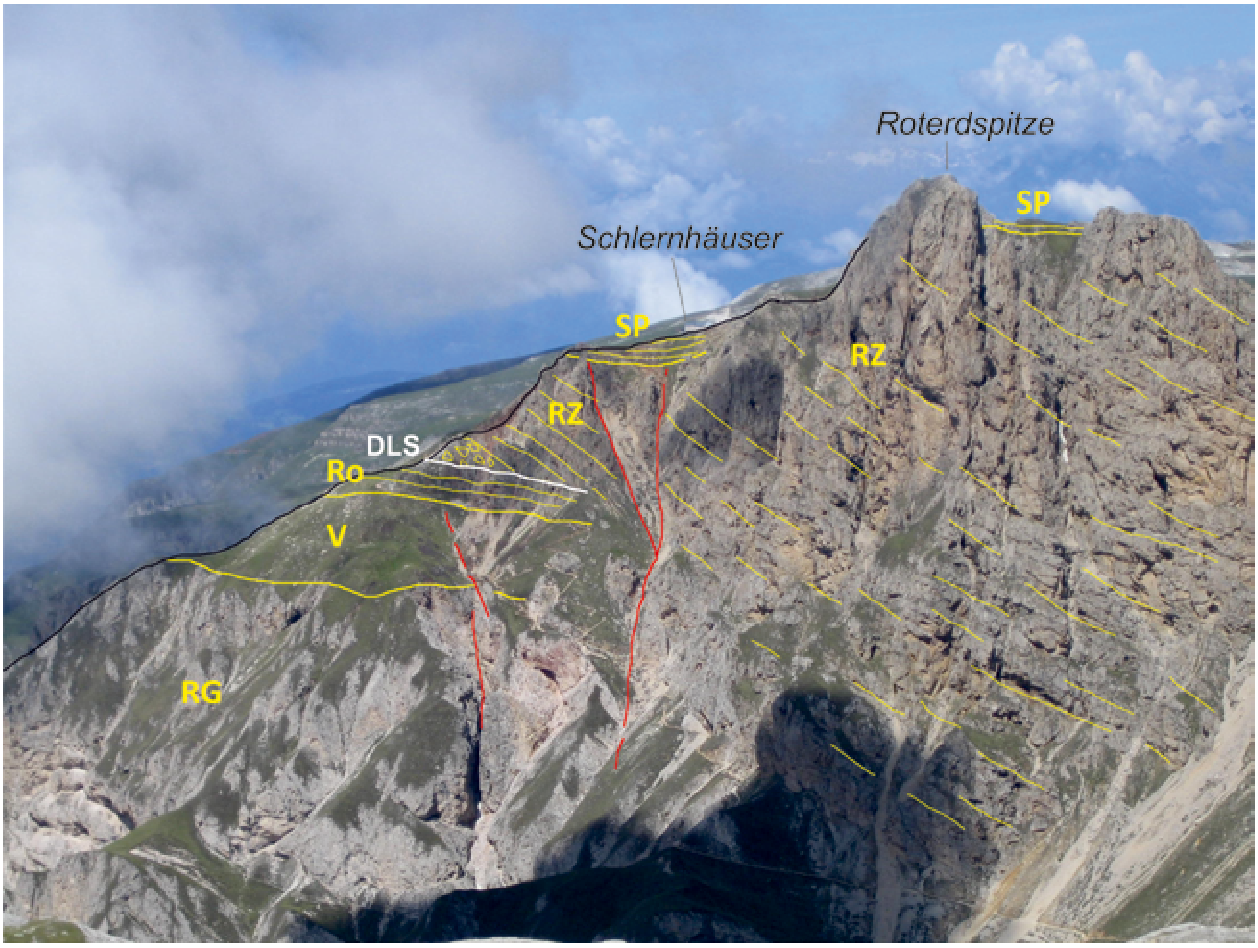


Fig. 53: View from SE to the wall of the Roterdspitz/Cima di Terrarossa-crest. Backstepping of Rosszähne Fm-slope on top of horizontal bedded inner-platform facies ("Rosetta Dolomite"). Faults are sealed by Rosszähne Fm and Schlernplateau Fm. RG: Rosengarten Fm, V: volcanics, Ro: "Rosetta Dolomite", RZ: Rosszähne Fm, SP: Schlernplateau Fm.

paleoslope is explained. Between the Rosengarten/Catinaccio-Schlern/Sciliar and the Langkofel/Sassolungo-Plattkofel/Sasso Piatto 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/Sassolungo-Plattkofel/Sasso Piatto platform was sheared off its underground and thrusted towards the north.

At the Rosszahn Scharte/Forc. Denti di Terrarossa the ca. 30° steep NW dipping paleoslope with the above described phenomena of gravitative submarine sliding of carbonate banks and megabreccia formation can be observed (Fig. 54, 55). 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 connected carbonate tongues, which were permeable for dolomitization fluids. Boulders transported further into the basin were isolated by a fine grained sedimentary matrix and thus escaped the dolomitization.

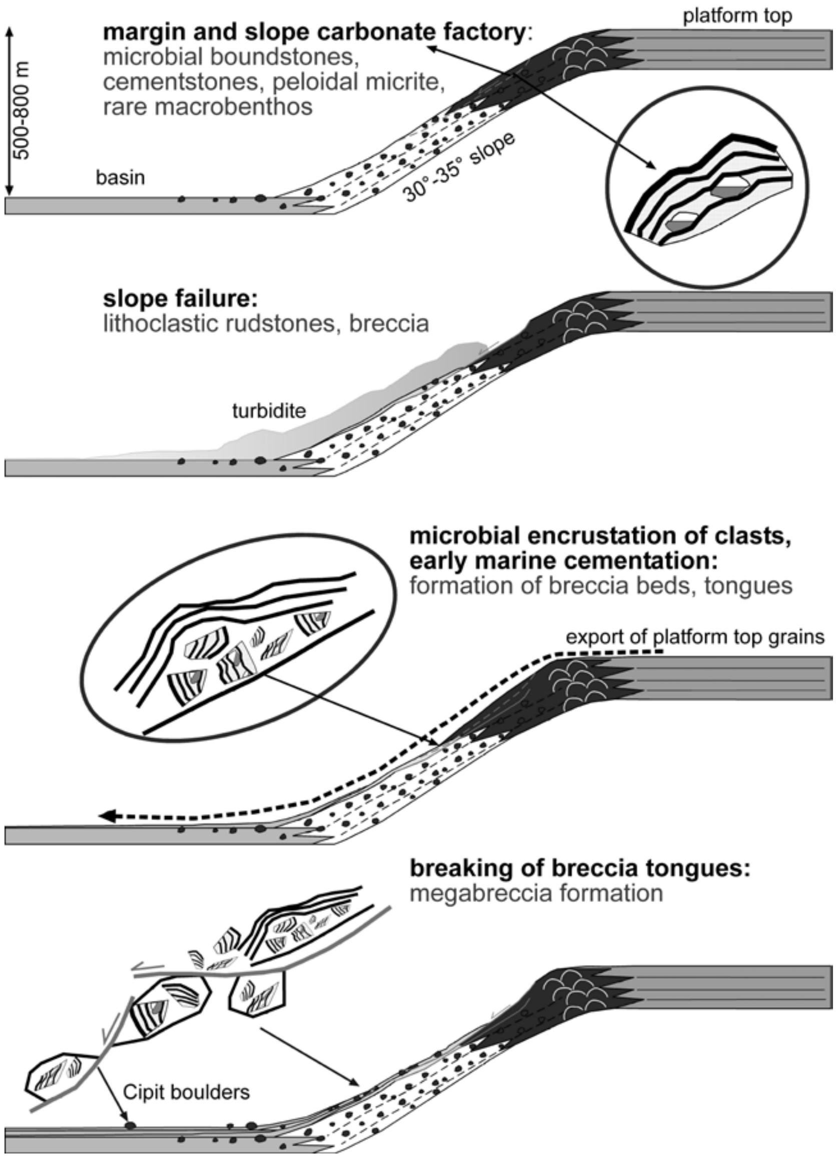


Fig. 54: Schematic model for steeply dipping, prograding carbonate slopes. The formation of breccias and megabreccias on the slope requires multiple interactions of platform shedding, *in situ* carbonate precipitation and microbial encrustation, geopetal infill, early cementation, break up of already 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. After Brandner & Keim, 2011b.

Fig. 55: Outcrop photo of steeply NW-dipping clinoforms west of the Rosszahn Scharte/ Forc. Denti di Terrarossa with typical slope breccia tongues.

Stop 3.4 – **Auf der Schneid/Cresta di Siusi**

Panorama of the seismic-scale outcrops of the entire slope domain of the post-volcanic Rosszähne/Denti di Terrarossa platform (Fig. 56). The volcaniclastic sequence pinches out on the post-volcanic carbonate slope at the transition to red beds at the Roterd Spitz/Cima di Terrarossa, which may reflect intermittent subaerial exposure of the platform top. The downlap surface of the prograding Rosszähne/Denti di Terrarossa reef tongues of the early highstand follows above. South of the Tieser Alpl/Alpe di Tires the onlap of the volcanics is well exposed within the Rosengarten/Catinaccio group.

Stop 3.5 – **Mahlknechthütte/Rif. Molignon**

The spectacular outcrop (Fig. 57) of the Mahlknecht wall shows the sedimentation on the slope and toe-of-slope of the Rosszähne/Denti di Terrarossa reef. A varicoloured succession of megabreccias, calcarenites, volcaniclastic sandstones and conglomerates (Marmolada Conglomerate) directly overlie well-preserved pillow lavas (Fig. 58) that occur on top of a thick volcanic sequence, which itself succeeds the Buchenstein Fm and the Rosengarten Fm.
In the interstitial pores and cooling cracks of the pillows radiolarian micrites with sponge spiculae occur locally. These remnants of pelagic deposits correspond to a ca. 20 m thick succession of the lowermost Wengen Fm (now Frommer Mb of Fernazza Group) in a similar facies as in the Tschapit creek, located ca. 2.5 km to the west (see Stop 2.6), with conodonts and *Daonellae* of the Longobardian substage (*Archelaus/Regoledanus* zone, Brandner, 1991). The thickness variation results from an onlap geometry onto the very irregular, ca. NW-dipping surface of the volcanites. The sedimentary succession is dominated by mega-breccias 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 showing 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 micrite crusts, various festooned crusts as well as masses of *Tubiphytes*

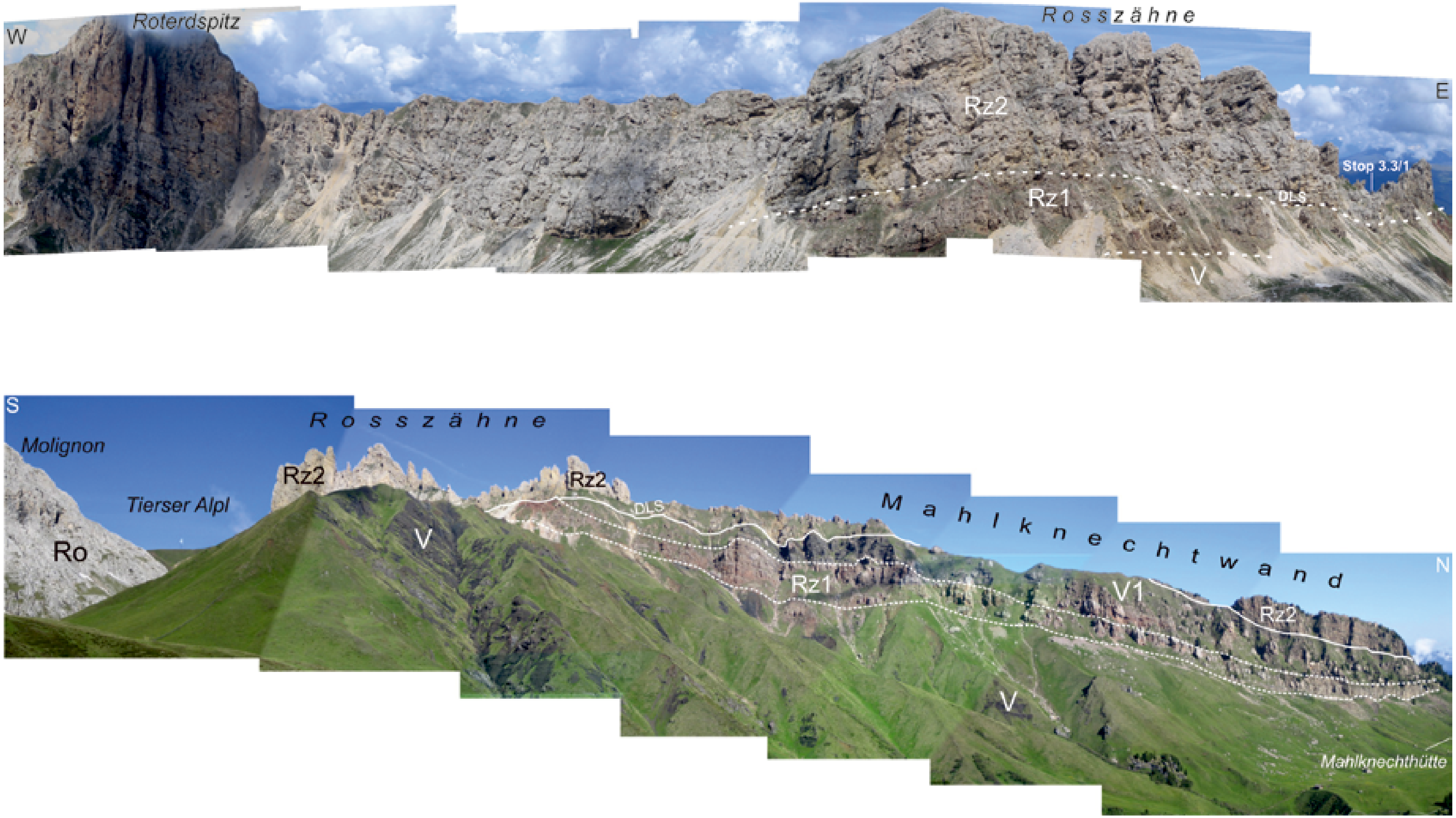


Fig. 56: TOP - Panoramic view from SE to the Roterdspitz/Cima di Terrarossa and Rosszähne/Denti di Terrarossa wall. Note the change in slope orientation of Rosszähne/Denti di Terrarossa slopes from N-dipping (Roterdspitz) to NW-dipping (Rosszähne). This indicates that the NW-dipping foreslopes nucleated on a possible volcanic high (now eroded) in the SE (see also Yose, 1991). BOTTOM - Panoramic view from "Auf der Schneid"/Cresta di Siusi (Stop 3.4) to the Rosszähne/Denti di Terrarossa and Mahlknecht wall showing the interfingering between prograding reef slope deposits of the Rosszähne Fm (Rz1 and 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 Mahlknecht wall 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/Alpe di Siusi (after Brandner et al., 2007.

Fig. 57: View of the famous Mahlknecht wall with the post-volcanic base-of-slope deposits.

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 filled with internal sediments in various phases (tilted geopetals), and fibrous and botryoidal cements are common (Fig. 59). 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. This points 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. 54).

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 show 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 different rheological characteristics and thus instability of the slope succession. The rapidly cemented carbonate breccia beds overlie water-saturated volcaniclastic sediments which were not yet cemented. This alternation distinctly reduces the shear strength and any earthquake may have led to the downslope sliding of rigid

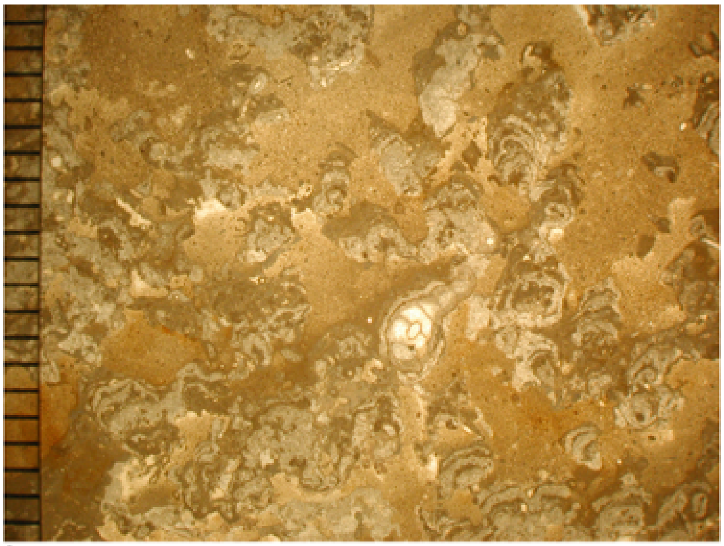
Fig. 58: Behind the students well preserved pillow lavas are exposed which are sharply overlain by megabreccias of reef slope deposits of the Rosszähne Fm (Rz 1). Note the lacking of bedded basinal sediments of the Frommer Mb in the Tschapit creek section (see Stop 2.6).

carbonate layers ("hard" on "soft") along a discrete shear surface (= clinostratification). At the frontal side of the mass movement body single boulders were deposited instead of carbonate banks. In the distal part the megabreccias turn into dm bedded calciturbidites with shallow-water derived grains. Ooids and coated grains testify the provenance from the flooded platform top.

Well-bedded sedimentary intervals with volcaniclastic detritus overlie the platform tongues (Fig. 59) and form an onlap geometry on the paleo-slope (see also Stop 3.4). The succession is made 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 re-deposition. The volcaniclastic intervals are repeatedly but not randomly interbedded with the reef tongues. The carbonate/volcaniclastic succession shows a certain rhythmicity, the control mechanisms of which 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/Denti di Terrarossa platform itself, whereas the volcaniclastic sediments were transported from a volcanic island situated far away (surroundings of Marmolada?).

The regularity of the sedimentary successions suggests that sea-level fluctuations controlled the timing of deposition. 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 feel that arguments favour the transport of volcaniclastics during a sea-level lowstand, whereas the progradation of the reef tongues with shallow water grains (oolites) occurred during sea-level highstands.

Fig. 59: Thin section photomicrographs of Cipit boulders from the Mahlknecht wall:
(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.



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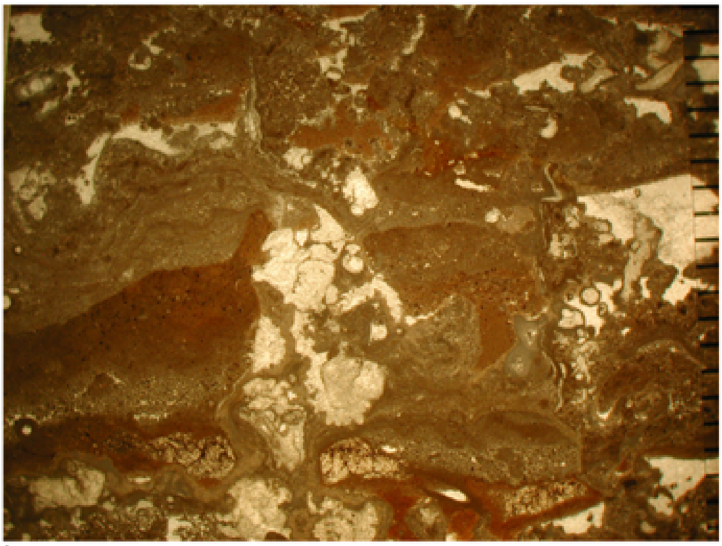

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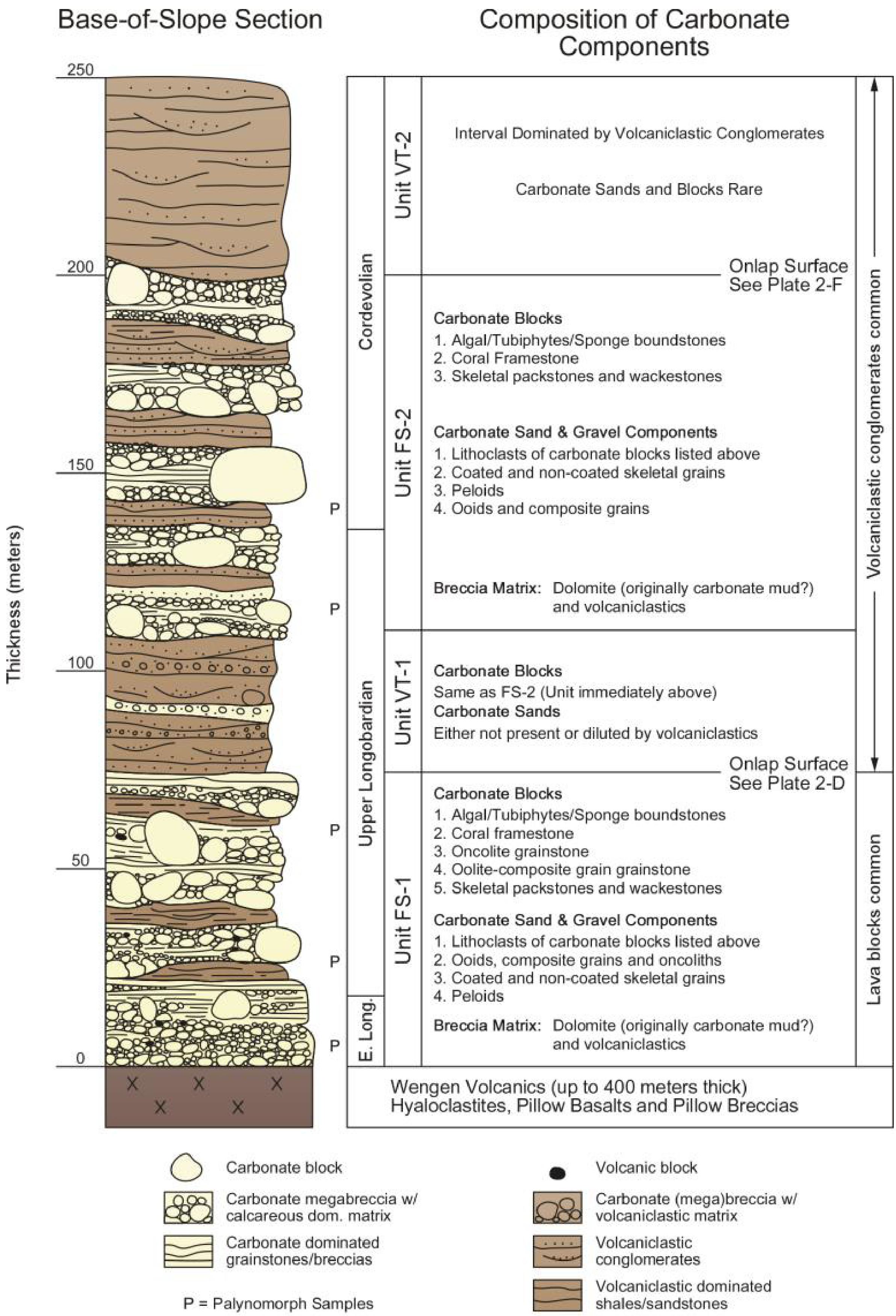

Fig. 60: Measured section of post-volcanic base-of-slope sediments of the Mahlknecht wall (after Yose, 1991, coloration by Riva, AAPG-field guide Dolomites, N. Italy, 2015). Unit FS-1 corresponds "Rz1" in Fig. 55, unit VT-1 = "V1" and Unit FS-2 = "Rz2". Volcaniclastic-rich tongues onlap the Rosszähne/Denti di Terrarossa reef foreslopes. Note that new biostratigraphic data indicate an Upper Ladinian age for the whole section.

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