TECTONOSTRATIGRAPHY OF THE WESTERN DOLOMITES IN THE CONTEXT OF THE DEVELOPMENT OF THE WESTERN TETHYS

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In the Dolomites, the transition from the post-Variscan to the Alpine orogen cycle generally takes place in a domain of lithospheric stretching, which is recorded in several plate tectonically controlled megacycles in the sediment sequences. Early Permian and Middle Triassic magmatism are associated with this development. In contrast to the "post-Variscan" magmatism, however, the Middle Triassic magmatism gives rise to numerous discussions due to its orogenic chemistry in the extensional setting of the Dolomites. A new analysis of the tectonostratigraphic development now revealed an interpretation of the processes that differs from the general opinion. Within the general extensional development in the Permo-Mesozoic there are four distinct unconformities caused by compressive or transpressive tectonic intervals.

1ST TECTONOSTRATIGRAPHIC MEGACYCLE (UPPER CARBONIFEROUS TO LOWER PERMIAN)

In the Dolomites, the cycle includes the Athesian Volcanic Group, which spanns the period between 285 - 274 Ma (Marocchi et al., 2008). In the Carnic Alps, this cycle begins with the Auernigg Group already in the Kasimovium and reaches into the Kungurium with the Trogkofel Limestone at the top (Krainer et al., 2009). After the late Variscan overthrust at the Val Bordaglia line (later extensionally reactivated) in the lower Moskovium (Brime et al., 2008), the hiatus (sedimentary gap) at the base covers a much shorter period than that in the Dolomites (see also Cassinis et al., 2018 with further citations). In both cases, the basin formation occurred in the context of the general Lower Permian thinning of the crust, which affects large areas of the former Variscan orogen. The significantly earlier beginning of sedimentation in the Carnic Alps implies a NW-directed back-stepping of the basin formation, which is accompanied by increasing exhumation and erosion of the Variscan basement. Pohl et al. (2018) succeeded for the first time in measuring a top to SE extension direction (according to current coordinates) in early Permian Mylonites of the central Southern Alps ("Grassi Detachment Fault"). This is an important benchmark for the reconstruction of the western Tethys realm, which questions or modifies previous models, e.g. those of Muttoni et al. (2009). Further localities for such detachment faults can be assumed in the area of the Giudicaria line (at the top of the Ifinger granodiorite), as well as at the Val Bordaglia line in the Carnic Alps. The lithospheric thinning reaches far into Central Europe ("Central European Extensional Province", Kroner et al., 2016) and is accompanied by the widespread thermal event ("Permian metamorphic event", Schuster & Stüwe, 2008).

2ND TECTONOSTRATIGRAPHIC MEGACYCLE (MIDDLE PERMIAN TO LOWER ANISIAN)

With the cooling of the crust, continental and marine sedimentation starts in large areas in the Middle and Upper Permian, which overlaps the graben-like extensional tectonics relief like mantle (see Wopfner, 1984 and Italian IGCP 203 Group, 1986). This was preceded by a strong erosional phase ("Middle Permian stratigraphic gap"), which is widespread in Southern Europe (Cassinis et al., 2018). The unconformity resembles a break-up unconformity indicating the formation of a Permian ocean. According to the upper limit of the tectonostratigraphic cycle with signs of compressive tectonics in the Lower to Middle Anisian, this ocean should range into the Middle Triassic. However, only deep-water faunas dated from a few localities are known in the western Tethys region (see Catalano et al., 1991; pers. comm. Leo Krystyn, Vienna). In the Dolomites the megacycle ranges from the continental Gröden/Val Gardena Fm to the shelf facies of the Lower Sarldolomite. The upper limit is formed by a clear erosional unconformity, which reaches in the area of Colfuschg/Colfosco down to the Bellerophon Fm. Here the more than 500 m thick sediment sequence of the Werfen Fm and the Lower Sarldolomite was eroded. The unconformity is overlain by conglomerates, sandstones and siltstones of the continental to marginal marine Peres Formation (incl. Richthofen Conglomerate), which interfingers with the marine sediments of the Prags/Braies Group in three cycles. Detailed mapping yields a asymmetrical anticline of a large wavelenght which shows high-angle westward dipping reverse faults at the side of the Gader/Val Badia Valley. In the following period, these faults of Anisian age were tectonically reactivated several times, so that the original shear sense is difficult to recognize. This is also the reason for the different interpretations of the type of Anisian tectonics: tectonic uplift, transpression/transtension, tectonically controlled sedimentation process (Bosellini, 1965, Brandner 1984, De Zanche & Farabegoli, 1988, Broglio-Loriga et al., 1990) or extensional block tilting (Brandner et al., 2016). The majority of authors are focused only on Middle Triassic rifting in general. However, this begins only after the compressive tectonics in the Upper Anisian, at the beginning of the 3rd megacycle. In the wider surroundings of the western Tethys area the meaning of this Molasse-like facies becomes clearer. It reaches from the Drauzug (Brandner, 1972) over the Dolomites and Montenegro (Budva - Cukali zone: Ciric, 1965, Brandner et al., 2016) up to Crete (Zulauf et al., 2018) and is accompanied until the Upper Ladinian by magmatites with calcalkaline affinity (Bébien et al., 1978). This indicates a subduction of a Permo-Triassic ocean beginning in the Lower Anisian at the active continental margin of Eurasia. The passive continental margin of this ocean is found at the margin of Gondwana (Baud et al., 2012).

3RD TECTONOSTRATIGRAPHIC MEGACYCLE (UPPER ANISIAN TO LOWER CARNIAN)

This cycle starts with several phases of strong subsidence. In the western Dolomites there are three subsidence phases: (1) the flooding of the Etsch-Gadertal high zone with deposition of the Peres Formation and subsequently of the Morbiac and Contrin Formations, which represent the sea level highstand of the Upper Anisian sequence, (2) the break-up of the shallow marine Contrin-platform and subsequently the developement of intraplatform basins with deposition of the Moena Formation and Plattenkalk of the Buchenstein Formation and (3) newly strong subsidence at the transition of the Plattenkalk Member to the Knollenkalk Member of the Buchenstein Formation in a deep sea basin with depths of more than 800 m. In the development of the carbonate platform of the Schlern Group, this subsidence phase has been preserved as a "downlapsurface" at the top of the Tschamin-Member. The "downlapsurface" is equivalent to the drowning of the Cernera platform in the eastern Dolomites during the Reitzi/Secedensis zone of the Upper Anisian (Brack et al., 2007). There is a clear increase in the subsidence rate in the direction to SE. This subsidence period is a widespread phenomenon outside the Southern Alps and can still be found in the Northern Calcareous Alps, in the Dinarides and Hellenides (see e.g. Gawlick et al., 2012 with further citations). The quick change from Anisian compressional tectonics to Upper Anisian extensional tectonics is most comparable to a "backarc" development. A roll-back of the subducted plate causes extensional deformation in the upper plate (Doglioni et al., 1999). The general configuration of the western Tethys in the Middle Triassic indicates a NW directed (today's coordinates) subduction in the front of the Southern Alps, which is accompanied by calcalkaline shoshonitic magmas occuring from the Dolomites to the Hellenides. Similar considerations have already been published by Marinelli et al. (1980), but in the assumption of a completely different spatial constellation. The real high subsidence rates of 800-1000 m/ Ma in the Upper Anisian are also generally characteristic for W-directed subductions (Doglioni et al., 1999).

A special tectonic feature of the Dolomites is the evolution of transpressive tectonic structures during the Upper Ladinian. Doglioni (1984) discribed this for the first time in the area of the Stava line and the Cima Bocche anticline. This sinistral WSW-ENE trending fault segment (trending NW after back-rotation) continues in the palaeo-Antelao line towards E (Picotti & Prosser, 1987). The structure is sealed in the West by the magmatites of Predazzo and Monzoni (Abbas et al., 2018). Also the somewhat older siliciclastic detritus fillings of the Zoppé Sandstone in the Upper Fassanian are attributed to the period of transpressive tectonics. The sandstones originate from a tectonically exhumed metamorphic basement south of today's Southern Alps.

On the Geological Map of the Western Dolomites the Schlernplateau fault is a Ladinian transpressive structure too, which is sealed by Upper Ladinian volcanites. The southern, above-mentioned, transpressive antiformal structure collapsed before the onset of the main volcanic extrusion in the Upper Ladinian. Folding close to the surface and gravitational sliding of huge stacks of strata took place in the 800 m deep sea basin at the southern margin of the prevolcanic reef of Rosengarten Fm at Langkofel/Sassolungo. At Col Rodela, south of the Duron Valley as well in the northern Fassa Valley, strata complexes of Bellerophon, Werfen and Contrin Formations (Contrin Dolomite), as well as of Buchenstein Formation are stacked locally in several sheets, sealed by Caotico Eterogeneo and Upper Ladinian volcanic rocks. The diapiric tectonics favoured by Castellarin et al. (1998 and 2004) could not be confirmed. The pile of stacked strata is called "Rodela-Olisthostrom". It is assumed that this zone continues as far as Slovenia. As a result of the superposition of the southern antiformal structure with huge amounts of volcanic rocks, islands were formed (Bosellini, 1998), which were quickly eroded. Large quantities of debris of Marmolada Conglomerate were transported to the offshore marine depressions and sealed the Rodela-Olisthostrom as well as the Caotico Eterogeneo and the volcanites. Similar conglomerates can also be found in the Ladinian strata of Montenegro.

Transfer faults can also be assumed for the necessary decoupling of the backarc basin of the Southern Alps from the Hallstatt-Meliata ocean basin, contemporaneously developed. The latter lacks signs of orogenic magmatism (Kozur, 1991). This presumably broad zone of strike slip faults is concealed in a "Paleo-Insubric Transfer Zone", which probably already originated in the Permian.

The subsidence history of the Middle and Upper Triassic is recorded in the geometry of the carbonate platforms. The general trend is very similar in the Dolomites as in the Northern Calcareous Alps as well in the High Karst Dinarides: in the Anisian and Ladinian there predominates aggradational deposition, whereas in the Lower Carnian strong progradation took place. The platforms were partially exhumed and subaerically exposed, after them they demised and drowned due to environmental reasons. Karstic surfaces of Schlern Dolomite and Wetterstein Limestone are the evidence. The "Carnian pluvial episode" with the sedimentation of large amounts of siliciclastic material immediately follows (Hornung et al., 2007, Dal Corso et al., 2018). At the northern margin of the Tethys this phenomenon is widespread and is related to eo-kimmerian orogeny (Şengör, 1979). West of Turkey, however, it is not clear which colliding Cimmerian continent it is.

4TH TECTONOSTRATIGRAPHIC MEGACYCLE (UPPER TRIASSIC TO UPPER JURASSIC)

With the eo-kimmerian orogeny a major plate boundary reorganization took place in the Tethys area during the opening of the Alpine Tethys (Piedmont Ocean) and the Vardar Ocean, or Maliac Ocean (after Stampfli & Kozur, 2006). This transition period is characterized in the western shelf area by the extensive development of the Hauptdolomit/Dachstein Limestone platform.

Extensive tectonics in the Western Dolomites already starts in the Upper Carnian with graben-like extensional basins of parts of the Raibl Group along N to NW trending normal faults, associated with scarp breccias (Keim & Brandner, 2001). These were mapped on Langkofel/Sassolungo, Sella and Gardenacia. The extensional tectonics continue into the Jurassic with backstepping at the margins of the Belluno Basin and the Slovenian Basin. It is particularly evident with the drowning of the shallow water carbonates of the Graukalk/Calcari Grigi Group occuring from the Pliensbachian until the Bajocian. The condensed facies of the Fanes Encrinit and the Rosso Ammonitico Veronese was developed on the Trento Plateau until the Upper Jurassic (Picotti & Cobianchi, 2017 with further citationes). It is noticeable that the strike of the E-dipping normal faults tends towards NW. This could be interpreted as an indication for the proximity of the Slovenian basin at the margin of the Maliac Ocean.

In the period from Upper Jurassic to ?Lower Cretaceous we find a clear erosional unconformity with karstic phenomena on the plateaus of Gardenacia and Sella. The map situation and the cross sections show a wide-span antiformal structure, which can be easily recognized by the more complete Upper Triassic to Jurassic stratigraphic succession of the Fanes area in the East and Northeast. In the highest parts of the Puez plateau the entire Jurassic sequence is missing and the Hauptdolomit is reduced erosively to a thickness of about 170 m. At Piz Boé, where still reduced Dachstein Limestone outcrops exist, deep reaching poljes and other karst landforms produced by solution are filled with Cretaceous sediments. On the Puez plateau the shallow water Gardenacia Fm. transgreeds the erosional unconformity. The deposition of the overlying Puez Formation (Lukeneder et al., 2016) begins in the ?Upper Valanginian/Lower Hauterivian. The tectonic uplift occurs between 157-153 Ma during the period of closure of the Maliac Ocean and the obduction of the oceanic crust of the western Vardar Ocean (Schmid et al., 2008). Far-field compression with wide-span folding in front of the Dinaric obduction could have thus involved the north-eastern Jurassic continental margin of the Southern Alps. This probably explaines the developement of the tectonic bulge (see also Picotti & Cobianchi, 2017).

5TH TECTONOSTRATIGRAPHIC MEGACYCLE (VALANGINIAN TO CAMPANIAN WITH THE FOLLOWING PALEOGENE ALPINE BACK THRUST AND NEOGENE DOLOMITES INDENTATION.

The shallow water sediments of the Gardenacia Formation are followed by a new drowning sequence with the condensed lithofacies of Rosso Ammonitico and Maiolica at the base, overlain by marls of the Puez Formation. Their age ranges until the Lower Cenomanian (Lukeneder et al., 2016). The subsidence after the Upper Jurassic uplift was newly active. Probably it was induced by a roll back of the slab of the subducted oceanic plate of the Western-Vardar ocean (Stampfli & Kozur, 2006).

In the area of Antruilles, north of Cortina d'Ampezzo (outside the map sheet, see CARG sheet 029 Cortina), the highly pelagic Cretaceous sequence reaches Campanian age. Turbidites with siliciclastic material deriving from basement areas in the North announce the Alpine orogeny (Stock, 1994).

On the Gardenacia and Sella plateaus, the Raibl beds and the Hauptdolomit outcrop in the hangingwall of the "summit overthrusts", while the footwall consists of the Puez Formation. The hangingwall represents well preserved cliffs of the frontal area of a Palaeogene overthrust. This Doglioni (1992) attributed to the Dinaric Overthrust Belt due to their direction of hangingwall movement to WSW-SW. Folding and thrusting were obviously reactivated along the structures of the previous Jurassic extensional continental margin development, wich occured at the margin of the Maliac and Vardar oceans. However, at the time of the Palaeogene overthrusts, the Southern Alps were already largely separated from the Dinarides by the dextral Alps-Dinarides transfer zone (Handy et al., 2015). Therefore the overthrusts can only correspond to Alpine reverse thrusts, wich are comparable to the pre-Adamello overthrusts of the Central Alps (cf. Schönborn, 1992).

The mapping campaign of the project "Geological Base Map South Tyrol" discovered that the summit overthrusts correspond to the frontal area of a large overthrust. It is called "Kreuzkofel-Nappe". The overthrust can be traced from the footwall flat in the evaporites of the Bellerophon Fm of the western Olang Dolomites via a ramp to the hangingwall flat of the Raibl beds at the base of the Kreuzkofel (2,912 m). The overthrust ends on Gardenacia summits with the large erosional gap of the Gader/Badia Valley in between. The same structural system is to be considered for the summit overthrusts on the Sella plateau.

In the front of the Alpine overthrust, relics of Molasse sediments of the Oligocene-Miocene Parei Conglomerate crop out at Col Bechei in the Eastern Dolomites (outside the map sheet; Keim & Stingl, 2000) and at the W-dipping slope of the Plattkofel/Sasso Piatto in the Western Dolomites. The important outcrop at Col Bechei shows an S-directed overthrust with the conglomerates in the footwall. The well-dated overthrust is part of the widespread Valsugana overthrust system (Castellarin et al., 1998a), which overlays and cuts through the Palaeogene back thrust system. The Neogene, Southalpine overthrust belt develops in the course of the indentation of the Dolomites into the northern Alps. Especially the southern part of the overthrust belt is still active today, as the continuing earthquake activity shows (Viganò et al., 2015; Reiter et al., 2018).

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