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The Palaeozoic of the Carnic Alps: an overview

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Introduction

The Carnic Alps are located along the Italian-Austrian border (Fig. 1). One of the better preserved Palaeozoic sequences of the world, ranging from the Middle Ordovician to the Permian/Triassic boundary up to the Upper Triassic, is exposed here.

Figure 1. Location of the Carnic Alps.

The "Palaeocarnic Chain" is considered as a part of the Variscan ancient core of the Eastern Alps in the Southalpine domain, and extends as a narrow strip for more than 100 km in a W-E direction, with a N-S width that rarely exceeds 15 km (Fig. 2). To the North it is bordered by the Gailtail Line, part of the Periadriatic Lineament, separating the Austroalpine from the Southalpine domains; towards the South it is unconformably covered by Upper Palaeozoic and Triassic successions (Venturini & Spalletta, 1998; Schönlaub & Forke, 2007). The Palaeocarnic Chain can be subdivided into two parts (Text-Fig. 3), separated by the Val Bordaglia thrust (Brime et al., 2008), a prominent NE-SW trending fault: the western zone is made of greenschist facies metamorphic rocks, the eastern zone mainly consists of sedimentary successions (Schönlaub, 1980, 1985, 1997; Venturini &

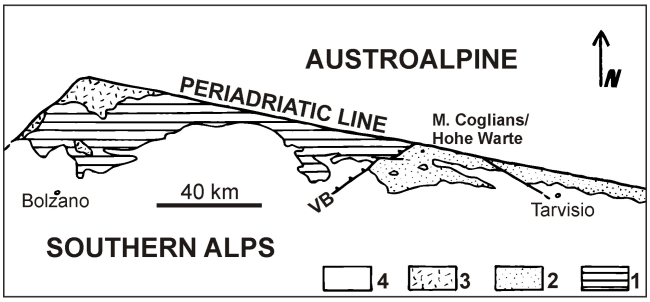

Figure 2. Simplified geological map of the Southern Alps showing the partition of the Palaeocarnic Chain into a West and an East Zone (after Venturini & Spalletta, 1998, modified). VB: Val Bordaglia thrust. 1. Low to middle grade metamorphic basement. 2. Non- to anchi-metamorphic units. 3. Variscan intrusive bodies; 4: post-Palaeozoic units.

Spalletta, 1998; Brime et al., 2008) except for the northernmost part where banded limestones occur.
The Carnic Alps underwent compressional as well as extensional deformational events during Variscan and Alpine times, which originated a complex structural framework including some low metamorphic terrains of Variscan age (Fig. 3) (Brime et al., 2008; Barthel et al., 2014).
According to Venturini (1990), Variscan compression originated roughly N120°E trending top to the south thrusts and folds. The first Alpine compression of Chattian-Burdigalian age is coaxial with the Variscan one, thus reactivating the older structures and enhancing their shortening (Venturini, 1990). The two more recent Alpine events (Tortonian-Serravallian and Plio-Pleistocene respectively) depict a strike-slip stress regime also with some compressional and extensional features (Venturini, 1990). These phases were very important to originate pluri-kilometer-scale vertical folding along the Gailtal and Bordaglia lines while in the rest of the Carnic Alps they fragmented the previously formed structural setting mostly by high angle strike-slip faults.

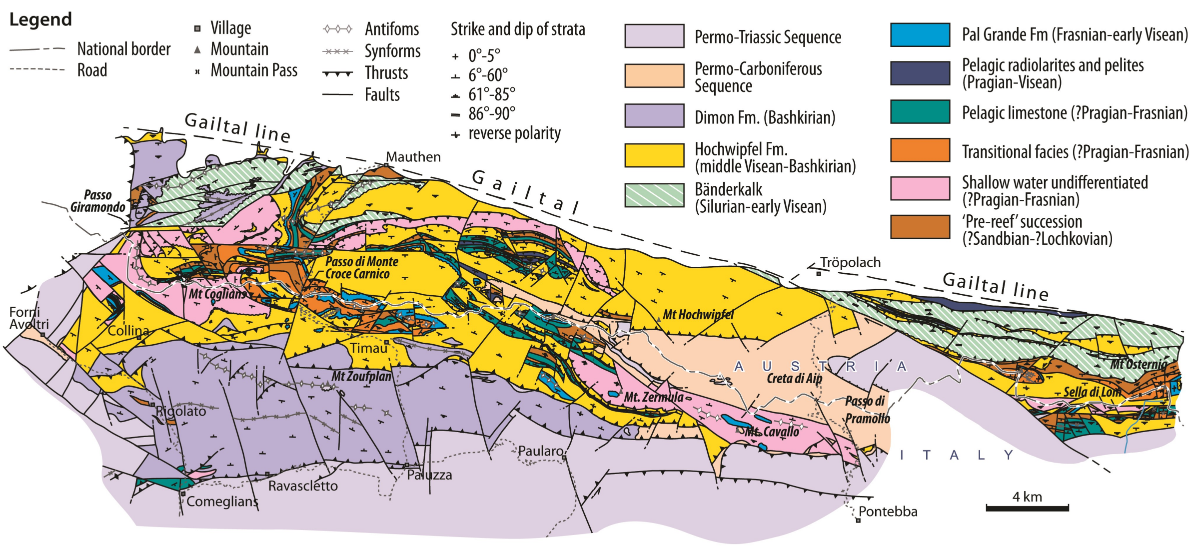

Figure 3. Sketch of the geology of the Carnic Alps (after Brime et al., 2008, simplified).

According to Barthel et al. (2014) in a N-S profile along the axis of maximum shortening between the Drau Range and the Friuli Southalpine wedge five kinematic groups can be distinguished: (1) N-S compression; (2) NW-SE compression; (3) NE-SW compression, σ_3 changes gradually from subvertical to subhorizontal; (4) N-S compression; and (5) NW-SE compression. The authors concluded that the deformation sequence on either side of the PAF (Periadriatic Fault) is similar.

Palaeogeographic overview

During the early Palaeozoic the Carnic Alps belonged to a group of terrains that detached from the northern Gondwana margin within the Ordovician, and moved northward faster than the main continent (Fig. 4a). These terranes, often indicated as Galatian terrane assemblage (von Raumer & Stampfli, 2008), include among others the Pyrenees, Montagne Noire, Sardinia, the Graz Palaeozoic, Barrandian and Saxothuringian, beside the Carnic Alps (Fig. 4b). However, the mutual position of these areas and their distance from the emerged continents is not completely clear.
Important is to note that the drift from about 50°S in the Late Ordovician, to 35°S in the Silurian and to tropical belt in the Devonian (Schönlaub, 1992) is reflected in clear evident differences in litho- and biofacies along the Carnic Alps.

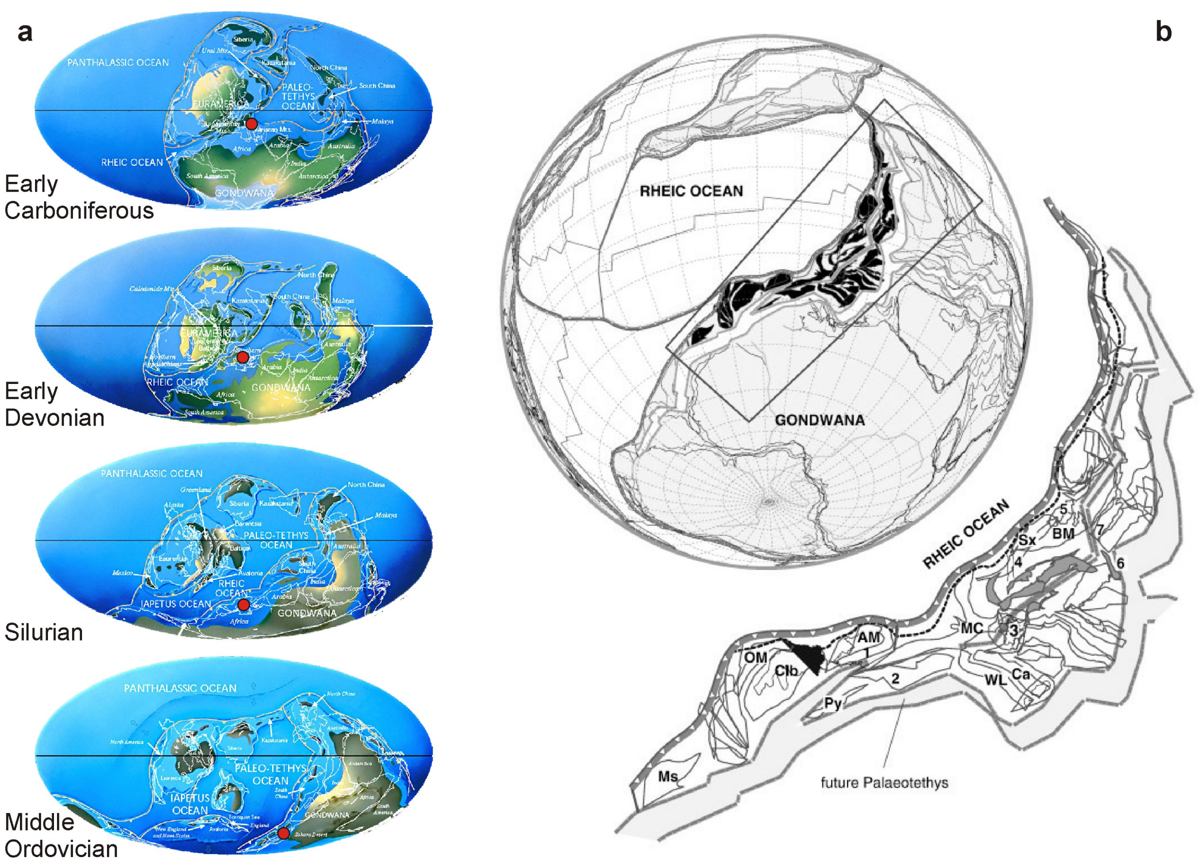

Figure 4. Palaeogeography of the Carnic Alps. **A.** position of the Carnic Alps (red circle) from the Ordovician to the Lower Carboniferous (maps after www.scotese.com). **B.** Global tectonic situation at the beginning of the Devonian (After von Raumer & Stampfli, 2008) and detail of the Galatian terrane assemblage. 1: Southern Brittany; 2: North Spain; 3: Sardinia; 4: S. Black Forest; 5: Barrandian; 6: Carnic Alps; 7: Graz Palaeozoic. AM: Armorican Massif; BM: Moldanubian part of the Bohemian Massif; Ca: Cantabrian Zone; CIb: Central Iberia; MC: French Massif Central; Ms: Meseta; OM: Ossa Morena Zone; Py: Pyrenees; Sx: Saxothuringian; WL: Westasturian Leonese Zone.

The Pre-Variscan sequence

Rocks from the Middle Ordovician to the lower Pennsylvanian that were affected by the Variscan orogeny during the late Bashkirian and Moscovian (Venturini 1990, Schönlaub and Forke 2007) constitute the so-called Pre-Variscan sequence. The lithostratigraphy of this sequence was recently revised and 36 formations were finally discriminated in the Pre-Variscan sequence of the Carnic Alps (Corradini and Suttner 2015).

The oldest rocks of the Carnic Alps are Middle Ordovician in age (Fig. 5) and crop out west of the Val Bordaglia Line. They are represented by phyllitic schists and quartzites, with subordinate conglomeratic layers (Val Visdende Fm.), followed by porphyroids (Comelico Fm.) and volcano-clastic sediments (Fleons Fm.).

With the exception of local fossil occurrences in the Fleons Fm., the most ancient fossiliferous rocks of the Carnic Alps belong to the Valbertad Fm. (Katian). They are represented by up to 100 m of shallow-water pelites, sandstones and rare conglomerates deposited at medium-high southern latitudes. Fossils, mainly bryozoans, brachiopods, echinoderms, trilobites and gastropods, are abundant. In the central part of the basin a coarser grained sandstone unit (Himmelberg Fm.) crops out. The basal clastic sequence is followed by an encrinitic parautochthonous limestone (Wolayer Fm.) in the central part of the chain and by the coeval slightly-deeper-water limestones of the Uqua Fm. Both these units are late Katian in age, even so an extension to the basal Hirnantian cannot be excluded. The global glacially-induced regression of the Hirnantian is documented by the calcareous sandstone of the

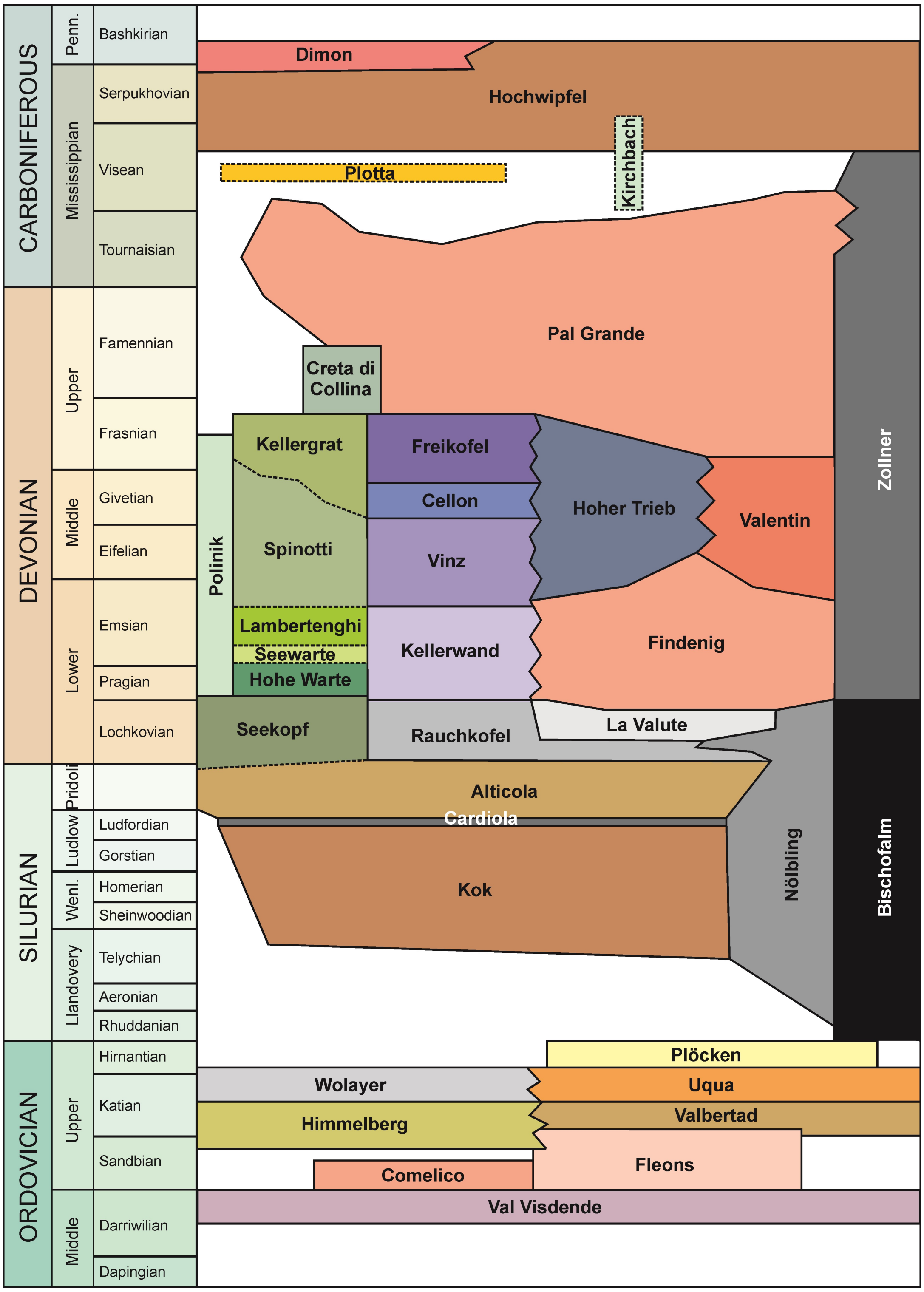

Figure 5. General lithostratigraphic scheme of the Pre-Variscan sequence of the Carnic Alps. (after Corradini & Suttner, 2015, modified).

Plöcken Fm., providing evidence of the HICE $\delta^{13}C$ excursion (Schönlaub et al., 2011). It resulted in erosion and local non-deposition, as also indicated by Silurian strata resting disconformably upon the Upper Ordovician sequence (Schönlaub & Histon, 1999; Brett et al., 2009; Hammarlund et al., 2012; Pondrelli et al., 2015).

Silurian deposits are irregularly distributed within the Carnic Chain, and range from shallow water bioclastic limestones to nautiloid-bearing limestones, interbedded shales and limestones to deep-shelf or basinal black graptolitic shales and cherts ("lydites"). The overall thickness does not exceed 60 m. The Silurian transgression started at the base of the Llandovery, and, due to the disconformity separating Ordovician and Silurian strata, an unknown thickness of sediments is locally missing, which corresponds to several conodont zones of Llandovery to Ludlow age (Schönlaub & Histon, 1999; Brett et al., 2009; Štorch & Schönlaub, 2012; Corradini et al., 2015a).

Three calcareous units are vertically developed in the proximal parts of the basin: The Kok Fm. (Telychian-lower Ludfordian), the Cardiola Fm. (Ludfordian) and the Alticola Fm. (upper Ludfordian-basal Lochkovian). These units mostly correspond to the "*Orthoceras* limestones" of earlier authors, and are represented by bioclastic wackestones-packstones. Nautiloid cephalopods are very abundant. Trilobites, bivalves and conodonts are common; crinoids, gastropods and some few ostracods, brachiopods and chitinozoans are present as well (Brett et al., 2009; Corradini et al., 2010, 2015a; Histon, 2012); ferruginous ooids were reported by Ferretti (2005). In the deeper part of the basin, the Bischofalm Fm. was deposited. It consists of a tripartite succession, up to 60 m thick, of black siliceous shales, with interbedded cherts, clay-rich alum shales, and black graptolitic shales. Graptolites are generally abundant (Jaeger, 1975; Jaeger & Schönlaub, 1977, 1994; Schönlaub, 1997). Intermediate sedimentary conditions between calcareous and shaley facies are represented by the Nölbling Fm., composed of alternating black graptolitic shales, marls and limestone beds (Jaeger & Schönlaub, 1980; Schönlaub, 1997).

The Silurian of the Carnic Alps is subdivided into four lithological facies representing different depths of deposition and hydrodynamic conditions (Schönlaub, 1979, 1980; Wenzel, 1997). The Wolayer facies is characterized by proximal sediments, while the Bischofalm facies corresponds to deep water euxinic deposits. The Plöcken facies and the Findenig facies are intermediate between the ones mentioned above.

During the Lochkovian (Lower Devonian) in the Carnic basin the calcareous part of the succession started to differentiate more noticeably (Kreutzer, 1990, 1992; Schönlaub, 1992; Kreutzer et al., 1997; Suttner, 2007; Corriga et al., 2012). The Seekopf Fm. was deposited in moderately shallow water, and the Rauchkofel Fm. and La Valute Fm. on the outer platform. In the deeper parts of the basin the Nölbling Fm. and the Bischofalm Fm. continued up to the top of the stage (*M. hercynicus* graptolite Zone).

Starting from the upper Lochkovian, the differences within the sedimentary basin increased: "the Devonian Period is characterized by abundant shelly fossils, varying carbonate thicknesses, reef development and interfingering facies ranging from near-shore sediments to carbonate buildups, lagoonal and slope deposits, condensed pelagic cephalopod limestones to deep oceanic off-shore shales" (Schönlaub & Histon, 1999: p. 15). From the Pragian to the lower Frasnian, within short distances a strongly varying facies pattern developed, indicating highly diverse depths in the basin. More than 1000 m of reef and near-reef limestones (Hohe Warte Fm., Seewarte Fm., Lambertenghi Fm., Spinotti Fm., Kellergrat Fm.) and various intertidal lagoonal deposits (Polinik Fm.) are time equivalent to less than 100 m of pelagic limestones (Findenig Fm. and Valentin Fm.). In the intermediate fore-reef areas thick piles of mainly gravity-driven deposits accumulated (Kellerwand Fm., Vinz Fm., Cellon Fm., Freikofel Fm.). Pelites and cherts were deposited in the deeper part of the basin (Zollner Fm.). Between the fore-reef and the deeper part of the basin the gravity driven deposits alternated with pelagic limestone and black shales (Hoher Trieb Fm.).

Reefs reached their maximum extension during the Givetian and early Frasnian, when the present Carnic Alps were at a latitude of about 30° S (Schönlaub, 1992). Four major reef areas developed, now represented by the cliffs of Mt. Coglians/Hohe Warte, Mt. Zermula, Mt. Cavallo/Roßkofel and Mt. Oisternig, beside several minor buildups. The fossil content is always very high: stromatoporoids, tabulate and rugose corals, brachiopods, crinoids, gastropods, ostracods, bivalves, cephalopods, trilobites, algae, calcispheres, and foraminifers (Kreutzer, 1990, 1992; Kreutzer et al., 1997; Schönlaub, 1992; Rantitsch, 1992).

Starting from the early Frasnian, the basin was subjected to a combination of extensional tectonic activity and eustatic fluctuations, which combined effects caused reefs extinctions. From the upper Frasnian (Upper *rhenana* conodont Zone) a uniform pelagic environment developed, which continued up to the lowermost Visean (Schönlaub, 1969; Schönlaub & Kreutzer, 1993; Perri & Spalletta, 1998): The Pal Grande Fm. is represented by a greyish, pinkish, reddish wackestone with cephalopods. At places cherty sediments (Plotta Fm.) unconformably capped the Pal Grande Fm. indicating at least a paleokarstic event in the lowermost Carboniferous (Schönlaub et al., 1991, Corradini et al., 2017).
Starting from the upper Visean, up to 1000 m of arenaceous pelitic turbidites of the Hochwipfel Fm. were deposited. It is interpreted as a Variscan Flysch sequence (Vai, 1963; Amerom et al., 1984; Spalletta & Venturini, 1988 and references therein). These deposits indicate a Variscan active plate margin in a collisional regime following the extensional tectonics during the Devonian and the Early Carboniferous (Schönlaub & Histon, 1999). The Hochwipfel Fm. consists of quartz-sandstones and greyish shales, turbidites, with intercalations of mudstones, chaotic debris flows and chert and limestone breccias. At place plant remains are present and rare trace fossils can be found (Amerom et al., 1984; Amerom & Schönlaub, 1992). Short local episodes of carbonatic deposition during the Lower Visean to the Serpukhovian boundary are represented by the Kirchbach Fm. In the upper part of the Early Carboniferous, the basic volcanites and volcanoclastic deposits of the Dimon Fm. occur. They are related to crustal thinning associated to a rifting episode (Vai, 1976; Rossi & Vai, 1986; Läufer et al., 1993, 2001). These conditions continued up to the Late Bashkirian (Late Carboniferous), when the Variscan orogeny in the Carnic area marked the end of the deposition of the Pre-Variscan sequence (Venturini, 1991).

The Variscan orogeny and the post Variscan rocks

The Variscan orogeny had its climax during the Moscovian and affected the Variscan sequence, producing different systems of asymmetric folds, faults and thrusts distributed along a N 120°-140°E direction (Venturini, 1990).
The uplift of the Palaeocarnic chain generated an erosional-depositional sedimentary hiatus. In places (Forni Avoltri, Pramollo and Tarvisio sectors) this gap lasted until the latest Moscovian, where, because of subsidence related a to strike-slip tectonic system, the Permo-Carboniferous Sequence deposited in disconformity on top of the Variscan Sequence. It consists of alternating cycles of fluvio-deltaic and marine deposits, caused by frequent eustatic sea level changes due to the Permo-Carboniferous glaciation. The sequence starts with basal breccias and conglomerates, resulting from the erosion of the Paleocarnic Chain.
The basal conglomerates (attributed by Venturini, 1990 to the Bombaso Fm) are overlaid by sediments subjected to frequent transgressive-regressive cycles, with alternating fluvio-deltaic clastic sediments and calcareous shallow water deposits. Different authors discriminate five formations belonging to the Auernig Group (Venturini, 1990), or several members within the Auernig Fm (Forke et al., 2006; Schönlaub & Forke, 2007).
Across the Carboniferous-Permian boundary and in the lower Permian, calcareous facies are dominant; the three formations (Schulterkofel Fm., Val Dolce Fm. and Zweikofel Fm.), grouped in the Rattendorf Group (Venturini, 1990) indicate a general transgression with more stable marine conditions. The transgressive trend continues throughout the lower Permian, and ends with the Trogkofel Group (Venturini, 1990) (Trogkofel Fm., Forke et al., 2006), characterized by reefs up to 400 metres thick.
Within the middle Permian, a transpressional tectonic phase causes extensive emersion and karstification. In the upper Permian an extensional phase starts, controlling the deposition of a sequence of continental ruditic deposits (Tarvisio Breccia and Sesto Conglomerate) followed by marine to terrigenous (Val Gardena Sandstones), and finally evaporitic, lagoonal and shallow marine deposits (*Bellerophon* Fm.). This sequence was deposited in an environment characterised by alluvial fans (Tarvisio Breccia and Sesto Conglomerate), alternating with alluvial plains with irregular braided rivers deposited a thick sequence of pelites and sandstones (Val Gardena Sandstones). The *Bellerophon* Fm, marking the end of the Carnic Palaeozoic, indicates a slow rise in sea level, and is

characterized by gypsum, graywackes and evaporitic dolostone in the lower part of the succession and by dolostone and black limestone in the upper part.

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