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ORIGINAL PAPER

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Variscan geodynamic evolution of the Carnic Alps (Austria/Italy)

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Abstract The South-Alpine Carnic Alps are part of the southern flank of the European Variscides and display a continuous sedimentary record from Late Ordovician to Devonian times followed by Carboniferous S-directed nappe stacking and Late Carboniferous to Early Permian post-collisional collapse. The tectonometamorphic and sedimentary evolution of the Carnic Alps resembles a continuous process where pre- and syn-orogenic volcanism, syn-orogenic flysch sedimentation, deformation including nappe stacking, metamorphism and tectonic collapse shift in age from internal zones in the N towards external zones in the S. New structural, petrological and sedimentological data are presented concerning the tectonometamorphic history of the Carnic Alps. We distinguish three thrust sheets or tectonic nappes differing in their stratigraphic, sedimentological, deformational and metamorphic histories which were thrust over each other in Carboniferous times. Our data lead to a new geodynamic model showing an evolution from rifting or back-arc spreading in the Late Ordovician to the establishment of a mature passive continental margin in the Late Devonian/Early Carboniferous, flysch sedimentation in an active continental margin setting during the Visean/Namurian and finally collision during the Late Carboniferous between the northern margin of Gondwana and a microcontinent to the N.

Keywords South-Alpine basement · Carnic Alps · Variscan geodynamics · Kinematics · Metamorphism · Sedimentology

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Introduction

The Carnic Alps are situated at the southern margin of the European Variscides (Fig. 1) and S of the Periadriatic Lineament (PL) along the Austrian–Italian border (Fig. 2). They belong to the South-Alpine Variscan basement units, reveal a more or less continuous geological record from the Late Ordovician to the Permo-Carboniferous and can be divided into the western Carnic Alps with stronger deformation and higher metamorphic overprint and into the central and eastern Carnic Alps which show a lower-grade Variscan tectonometamorphic history. The boundary between the western and central Carnic Alps is approximately located in the area of the Bordaglia fault (Fig. 3) which is a late-Alpine left-lateral conjugate fault to the PL.

In the Variscan edifice of the Carnic Alps, classic studies by von Gaertner (1931) and Heritsch (1936) distinguished ten tectonic nappes. However, in later studies a reduced number of nappes was suggested (Selli 1963; Schönlaub 1985). Recent concepts interpret the differences in lithology and facies of the central and eastern Carnic Alps as well as the Paleozoic South-Alpine Karawanken Mountains in terms of olistoliths within a Carboniferous flysch sequence rather than complex nappe tectonics (Läufer et al. 1993; Kullmann and Loeschke 1994). Low-grade metamorphic zones close to the PL in the eastern Carnic Alps, which were originally interpreted as separate Variscan nappes (e.g. Eder nappe), were proven to represent late-Alpine tectonic blocks genetically linked to the structural evolution of the PL (Läufer et al. 1997). Venturini and Spalletta (1998) distinguish two Variscan "zones" W and E of the Bordaglia fault differing in their tectonometamorphic evolution with two Variscan deformation events in the western and one event in the eastern zone. Similarly, this zonation and its Variscan age was reported by Hubich and Läufer

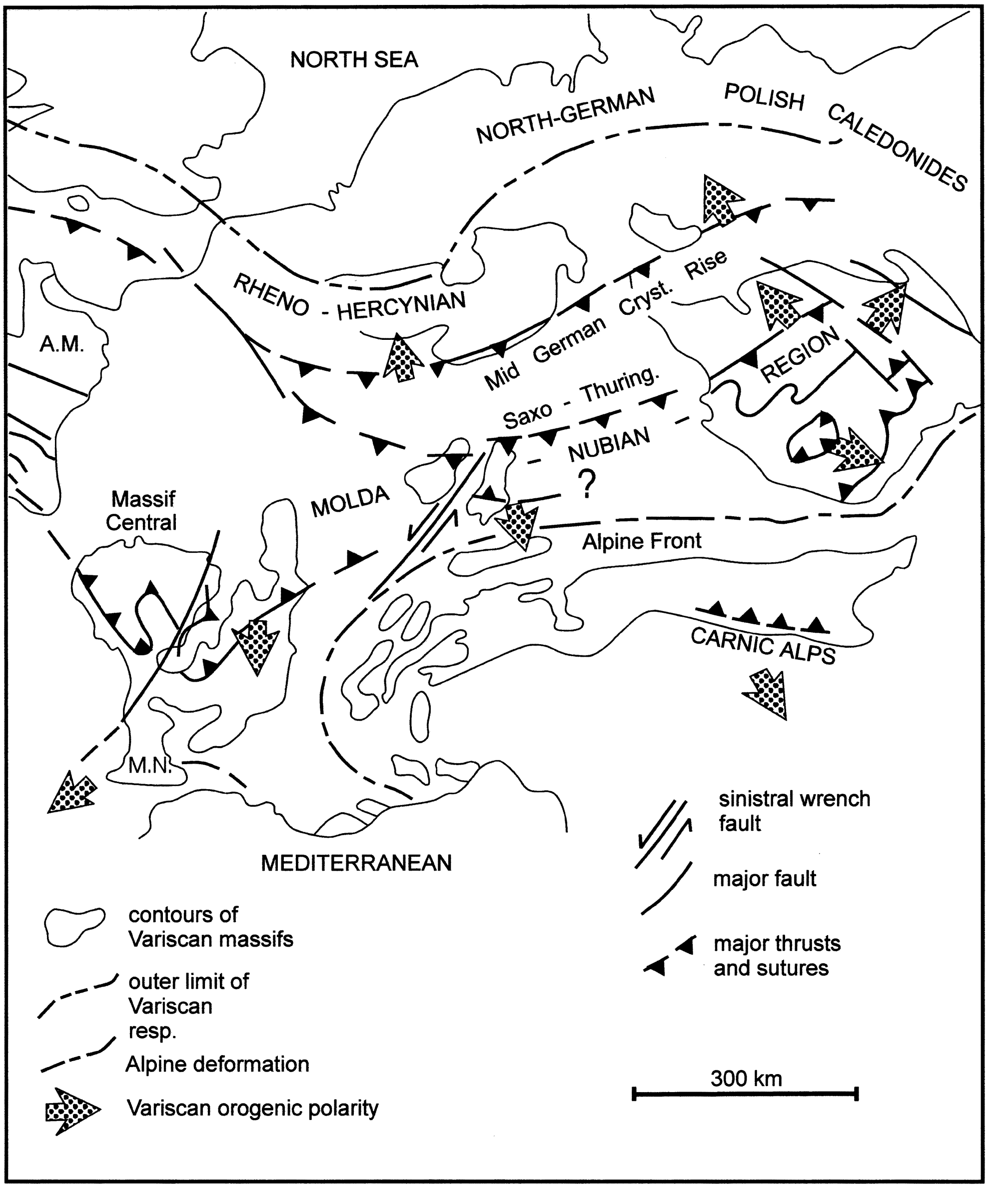


Fig. 1 Generalized map of the Variscan units in central Europe, slightly modified after Franke et al. (1995). *A.M.* Armorican Massif; *M.N.* Montagne Noire

(1996, 1997) who in turn interpreted the two zones as Variscan tectonic nappes based on modern structural analyses and studies of the metamorphic evolution of the region.

The aim of this paper is to decipher the Variscan tectonometamorphic evolution of the Carnic Alps, to describe the Variscan nappe tectonics and to interpret the Variscan evolution of the Carnic Alps in a geodynamic model. To approach this aim, the following methods were applied:

1. Detailed geological mapping and construction of cross sections in selected key areas
2. Analyses of the stratigraphic and sedimentological record to detect different lithostratigraphic and tectonic units
3. Detailed kinematic analyses of rocks deformed under both ductile and brittle regimes to obtain information on tectonic transport directions
4. Determination of illite crystallinity combined with other methods (e.g. deformational behaviour of minerals, index minerals) to study metamorphic grades

We distinguish four major tectonic units (Fig. 3): Late-Alpine transpressive blocks along the PL; the Fleons nappe in the western Carnic Alps; the Cellon-Kellerwand nappe in the central Carnic Alps; and the Hochwipfel nappe in the central and eastern Carnic Alps. These four tectonic units differ from each other in their stratigraphy, metamorphism and deformation. The transpressive blocks consist of Paleozoic rock units but show an intense late-Alpine tectonometamorphic overprint.

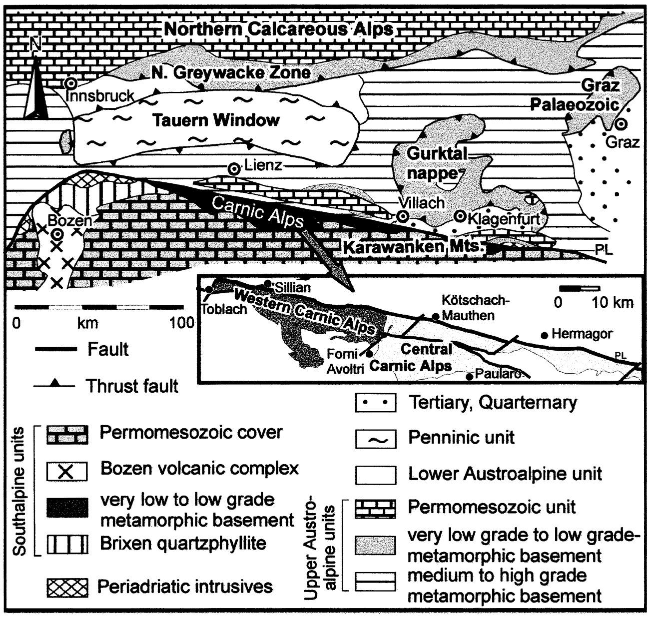


Fig. 2 Geological map of the Eastern Alps showing the study area of the Carnic Alps. *PL* Periadriatic Lineament

Late-Alpine transpressive blocks

Figure 4 shows the location of the transpressive blocks along the PL. These are the Eder unit in the E, the Mauthner Klamm unit in the centre and the Luggau unit in the W. All these blocks have certain aspects in common. They are built up mainly of phyllites and marbles in varying proportions which show steeply dipping foliation planes with an E/W-trending stretching lineation of quartz and calcite. Shear sense indicators prove right-lateral ductile shear subparallel to the PL. Illite crystallinity values are generally less than 0.25° $\Delta 2\theta$, thus indicating epizonal metamorphic grades. These structures and the low-grade metamorphic imprint are of late-Alpine age indicated by K–Ar and Ar–Ar geochronology of fine clay fractions and micas separated from rocks of the Eder unit (Läufer et al. 1997). The ductile structures are overprinted by steeply dipping faults subparallel to the PL revealing a first increment of thrusting and a second increment of dextral strike-slip movement. These distinct zones adjacent to the PL do not represent separate Variscan nappes. They represent, instead, fault-bounded blocks genetically linked to late-Alpine transpression along the PL. However, the deformational and metamorphic influence of the PL decreases gradually towards the S.

Fleons nappe

The eastern border of the Fleons nappe (Fig. 3) is in the vicinity of the Bordaglia fault. Its western border is less evident but located somewhere in the Toblach region based on the occurrence of the medium-grade Pustertal crystalline basement in this area. The Fleons nappe, hence, covers the whole western Carnic Alps. It consists of low-grade metamorphic rock units with a stratigraphic range from the upper Ordovician through the Silurian/Devonian and probably into the lower Carboniferous. Unambiguous palaeontological control of the various units is not always found but in some places is well known (Schönlaub 1979; Schönlaub and Flajs 1993). The sedimentary record of the Fleons nappe, published in detail by Hinderer (1992), is shown in Fig. 5. The base of the continuous sequence is built up by Ordovician phyllites and quartzites of the Val Visdende schists. These metasedimentary rocks show a facies differentiation from shallow marine environments in the S to deeper marine environments in the N. The quartzites represent coastal deposits in the S and the phyllites were deposited close to the shelf edge. In the upper part of the Ordo-

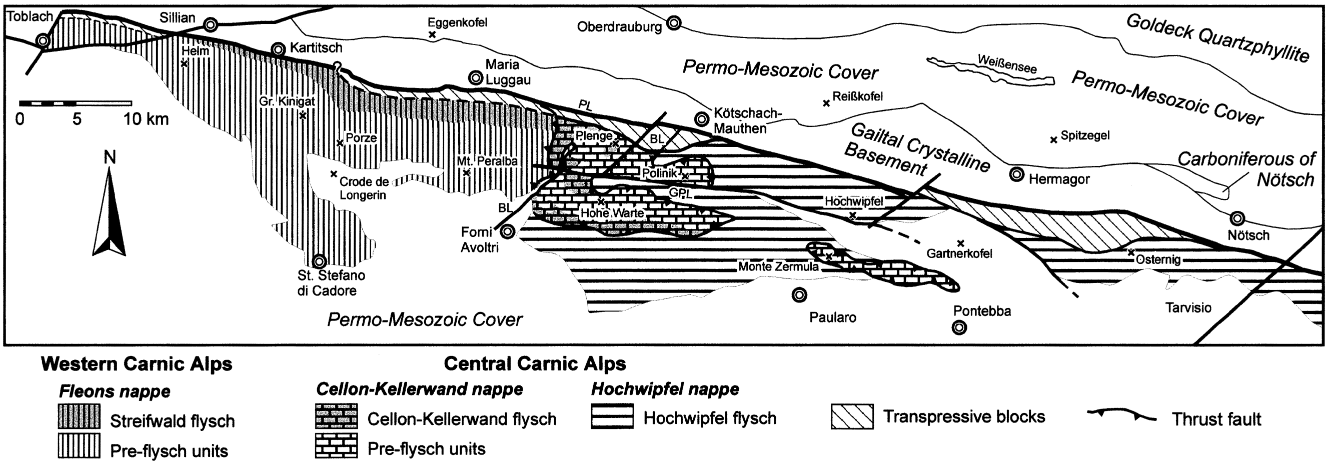


Fig. 3 Tectonic map of the Carnic Alps with their four tectonic units (Fleons nappe, Cellon-Kellerwand nappe, Hochwipfel nappe, transpressive blocks along the Periadriatic Lineament). *PL* Periadriatic Lineament; *BL* Bordaglia Fault; *GPL* Gamskofel-Polinik Fault

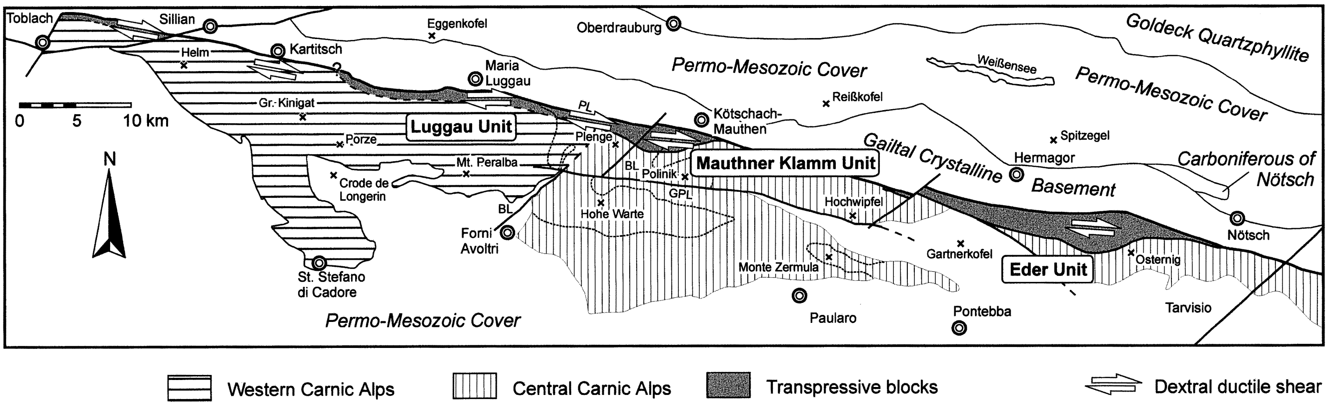


Fig. 4 Location of the late-Alpine transpressive blocks along the Periadriatic Lineament (Eder unit, Mauthner Klamm unit, Luggau unit)

vician, a facies transition between the Val Visdende schists and greywackes, sandstones and conglomerates of the Fleons formation deposited in a deltaic environment is evident (Hinderer 1992; Hubich et al. 1999). There is also a facies transition between the Fleons formation and calcalkaline metavolcanic rocks which are mostly ignimbrites and known as Comelico Porphyroid (Hubich and Loeschke 1993; Hubich et al. 1999). Zircons of these rocks have recently been dated by Söllner et al. (1997) and indicate an age of 455 m.y. The greywackes of the Fleons formation have a bimodal composition of clasts. They contain corroded quartz grains which originated from the "Comelico Porphyroid", basic volcanic clasts and clastic clinopyroxene grains which prove that basaltic and rhyolitic volcanic rocks existed in the source area. From the general situation, especially the facies differentiation from N to S and the bimodal composition of the volcanic rocks in the source area of the greywackes, we deduce a tectonic situation for the Late Ordovician of the Carnic Alps which might have been similar to a rifted continental margin or a back-arc environment, respectively. This conclusion is based on our field observations and is discussed in greater detail later.

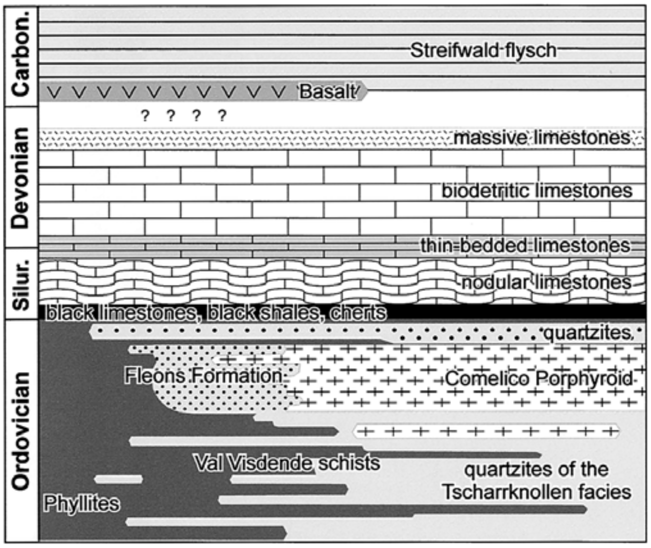


Fig. 5 Stratigraphic sequence of the Fleons nappe, without scale for thicknesses

In the uppermost Ordovician, quartzites follow on top of both the Fleons formation and the Comelico Porphyroid which consist of reworked clasts of the basement. The Silurian comprises black limestones, black shales, cherts and nodular limestones. The latter have been dated by Schönlaub and Flajs (1993) because they contain conodonts of late Silurian to early Devonian age. The Lower Devonian is represented by dark, thin-bedded limestones and the middle Devonian by massive reef limestones which contain in some places Devonian corals (Stache 1884; Hubich 1992). The boundary between the Upper Devonian and the Lower Carboniferous is not documented. In Fig. 6 which shows a geological section from N to S in the central part of the western Carnic Alps in the area of Schulterhöhe, a major fault line separates nodular limestones and chert layers of probably Silurian age from a sequence which consists of fine-grained turbidites and sills of basaltic composition and probably also basalt flows and hyaloclastites (Raabtal metabasalts). This fault line can be traced over several kilometres in an E–W direction and represents a major tectonic break between flysch turbidites in the N and a shelf sequence in the S. We interpret the turbidites as a newly discovered flysch sequence of probably early Carboniferous age which rests on top of alkali basaltic rocks (Czischek 1999). The turbiditic sequence contains also olistostromes (Fig. 5) and is named Streifwald flysch after the type locality in the western Carnic Alps S of Kartitsch. The contact between the stratigraphically underlying alkali basaltic rocks, which are metamorphosed under greenschist facies conditions, and the turbidites is of sedimentary nature. The turbidites have a green colour at their base because they contain fragments of metabasaltic composition and the turbidity currents, which produced the flysch sequence, must have reworked

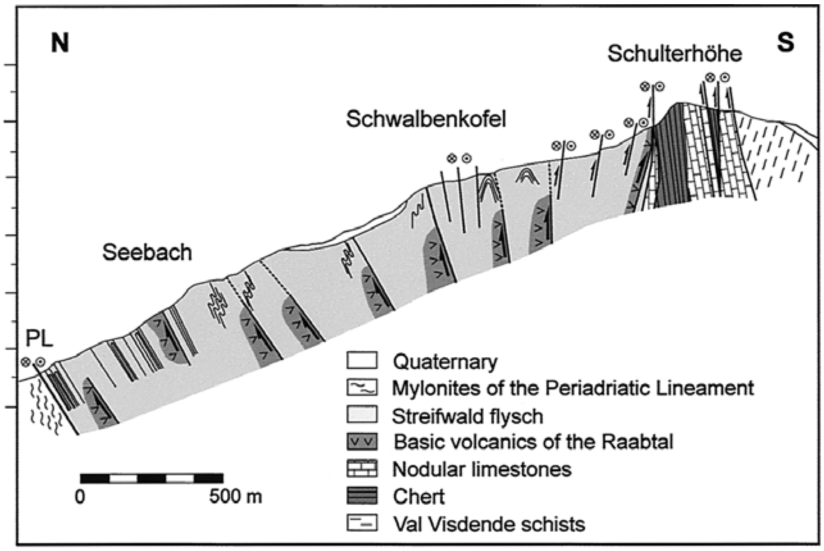


Fig. 6 Geological section through the western Carnic Alps S of Maria Luggau showing the tectonic situation of the Streifwald flysch and the underlying meta-basalts. *PL* Periadriatic Lineament

the underlying volcanic fragments which might have been hyaloclastites. Their original volcanic nature is unrecognizable due to the metamorphic overprint. The flysch turbidites and the alkali basaltic rocks are intensively imbricated and partly overturned due to the late-Alpine tectonics along the PL. In Variscan times, they must have represented a thrust complex (Fig. 6) because they show Variscan deformations as well, e.g. thick quartz mobilisates on thrust planes which are not present in the post-Variscan cover. The Streifwald flysch represents a northern flysch basin which borders the PL. The underlying basalts are similar to within-plate alkali basalts in their geochemical composition (Czischek 1999) which is presently found on seamounts or oceanic islands. Their age is unknown. Similar alkali basaltic rocks occur in the Dimon formation on the Italian side of the central Carnic Alps (Läufer et al. 1993) and in the Eisenkappel area in the Karawanken Mountains (Loeschke 1975).

Cellon-Kellerwand nappe

The Cellon-Kellerwand nappe is structurally below the Fleons nappe near the Bordaglia fault (Fig. 3). A tectonic klippe of the Cellon-Kellerwand nappe occurs further to the E in the area of M. Zermula where it rests with a tectonic contact on top of the Hochwipfel flysch. The stratigraphic sequence starts with upper Ordovician sediments, but it differs completely in its facies from the upper Ordovician in the Fleons nappe. Thin limestone and sandstone beds occur at the base and both metavolcanic rocks and greywackes are missing (Fig. 7). The Silurian is represented by black shales and pelagic limestones and the Devonian by platform carbonates which reveal a widespread facies differentiation (Schönlaub 1979) and form the highest peaks and a very steep morphology in the central Carnic Alps. In the upper Devonian and lowermost Carboniferous, pelagic limestones prevail with radiolarian chert on top indicating a deeper water environment and the breakup of the carbonate platform. At this time, a mature passive continental margin has been established accompanied by a general thinning of the continental crust and increasing subsidence of the shelf. The pelagic limestones show submarine dissolution phenomena by CO_2-rich currents in a deeper-water environment. These dissolution phenomena have previously been described as palaeo-karst by Schönlaub et al. (1991). Vai (1998) disagrees with this interpretation as we do and interprets the features as due to submarine dissolution. The sequence is covered by lower Carboniferous turbidites which represent a typical flysch sequence and is named Cellon-Keller-

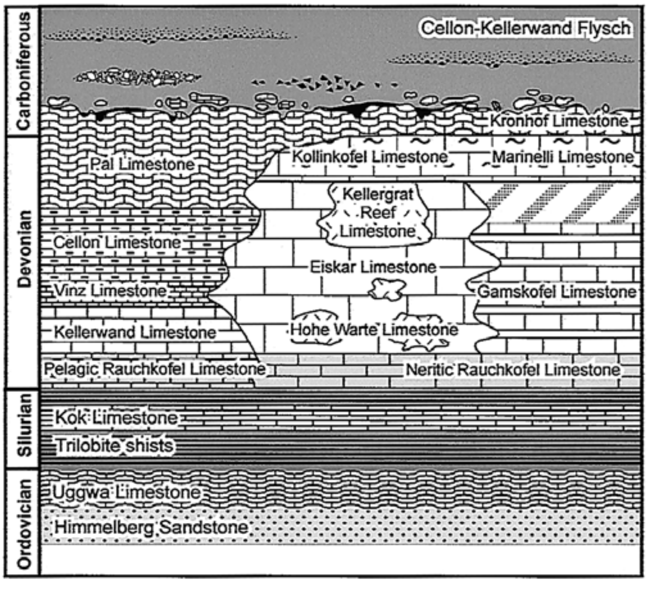


Fig. 7 Stratigraphy of the Cellon-Kellerwand nappe, no scale for thicknesses

wand flysch. It has a Middle (-Late?) Visean age (Van Ameron and Schönlaub 1992) and differs from the Streifwald flysch by higher contents of modal feldspar (Schmalholz 1998). It contains breccias built up of chert fragments and smaller olistostromes as well (Fig. 7). It differs, furthermore, from the Hochwipfel flysch sensu stricto which is more mature and richer in quartz and chert fragments. The Hochwipfel flysch, however, is restricted to the Hochwipfel nappe.

Hochwipfel nappe

The Hochwipfel nappe covers the central part of the Carnic Alps from the Bordaglia fault to the area S of Nötsch and stretches further to the E into the Karawanken Mountains (Fig. 3). It consists exclusively of Hochwipfel flysch which contains numerous olistostromes and partly huge olistoliths (Fig. 8). The geological maps of Kötschach and Weissbriach (Schönlaub 1985, 1987), therefore, show numerous older sedimentary blocks and packets within the Hochwipfel flysch which vary in age from the Late Ordovician to the Early Carboniferous. They are completely enclosed by Hochwipfel flysch and locally show a "chaotic" orientation compared with the flysch strata. These blocks must be interpreted as olistoliths in various proportions (Kullmann and Loeschke 1994). The situation is very similar to the Visean/Namurian flysch deposition in the Montagne Noire (Franke and Engel 1986; Matte 1986). Since the age of the youngest olistoliths in the Hochwipfel flysch is Late Visean to Early Namurian, its deposition probably did not start before the early Late Carboniferous (latest Namurian A; Kullmann and Loeschke 1994). Therefore, the Hochwipfel flysch is interpreted to be slightly younger than the Cellon-Kellerwand flysch. Facies differentiations within the Hochwipfel flysch indicate proximal conditions in the N and distal conditions in the S so that its source area must have been positioned in the N, probably in the neighbourhood of the Austro-Alpine crystalline complexes. The sedimentary basement of the Hochwipfel flysch, such as Devonian carbonates (? Eder limestone), is nowhere known. The Hochwipfel flysch has probably been deposited by turbidity currents and submarine gravity slides in a deep-sea trench in front of S-migrating nappes or thrust sheets at an active continental margin, an environment where numerous blocks of different sizes and ages could glide down into the trench. The question as to whether the crust on top of which the Hochwipfel flysch has been deposited was of oceanic or continental character is still disputed. There is only one place known in the whole of the Carnic Alps where a probably sedimentary contact between the Hochwipfel flysch and older rocks is observed. This outcrop is located on the Italian side of the Carnic Alps N of Paularo. There, the contact between turbidites of the Hochwipfel flysch and basaltic rocks of the Dimon formation is visible within a S-verging syncline unconformably capped by Permo-Carboniferous molasse units (Läufer et al. 1993). The situation is shown in Fig. 9 at the southern end of the section. The section is cut by various S-verging thrusts and the overall tectonic situation is complex. From field observations it is concluded that there the Hochwipfel flysch rests on top of basaltic pillow lavas of the Dimon formation which represents the youngest formation of the pre-flysch sequence. Its age is unknown and there is a discussion about it (Vai and Cocozza 1986; Spalletta and Venturini 1988; Läufer et al. 1993). In comparison with other Paleozoic orogens, such as the European Caledonides, and in concordance with field evidence, these pillow lavas must belong to the pre-flysch sequence because they indicate the climax of crustal extension. The deposition of the flysch turbidites marks the beginning of orogenic compression, e.g. the plate tectonic reorganization from the stage of a mature passive continental margin with possible ocean-floor development to the stage of compression and possible subduction of thinned continental or oceanic crust; therefore, the pillow lavas of the Dimon formation are regarded as older and as the primary basement of the Hochwipfel flysch (Fig. 8).

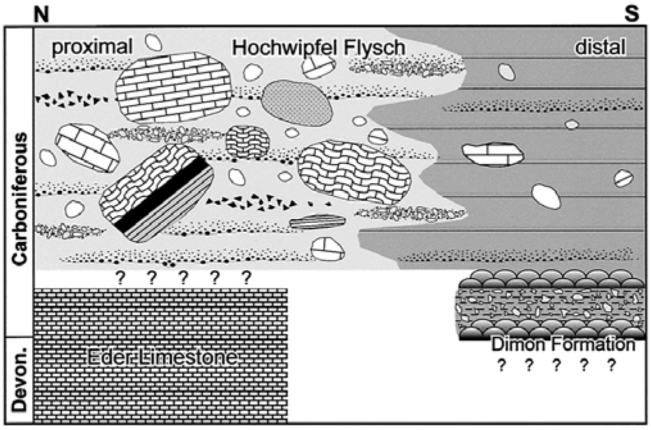


Fig. 8 Stratigraphy of the Hochwipfel nappe, no scale for thicknesses

Structural geology and metamorphism

The structural–geological results are shown in Figs. 10 and 11. The tectonometamorphic evolution is different for the three lithotectonic units described previously. A ductile deformation event D_1 under low-grade metamorphic conditions affected only the Fleons nappe (western Carnic Alps). It is missing in both the Cellon-Kellerwand nappe and the Hochwipfel nappe, respectively. Corresponding structures of D_1 are first-generation isoclinal folds F_1 and a down-dip oriented stretching lineation Str_1 of both calcite and quartz grains within E–W to SE/NW-striking penetrative foli-

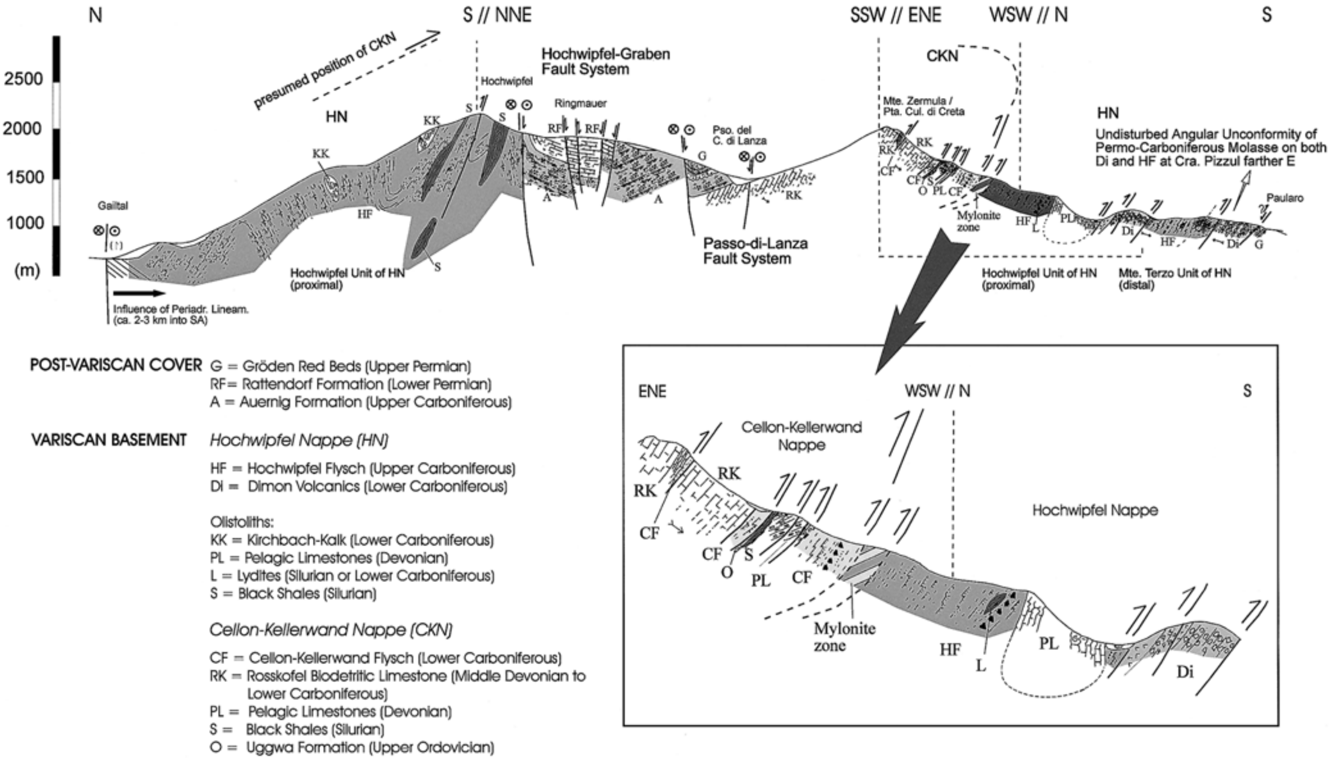
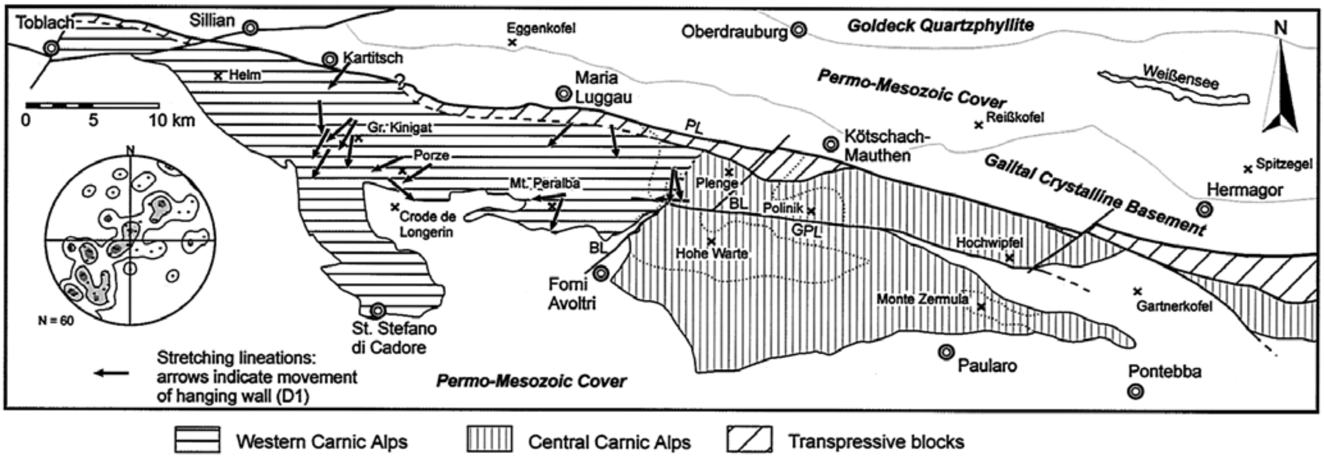


Fig. 9 Geological cross section through the central Carnic Alps with *inset* showing the tectonic boundary between Cellon-Kellerwand nappe and Hochwipfel nappe

ation planes S_1 which developed due to crystal-plastic deformation processes. The foliation is oriented parallel to the axial planes of the F_1 folds which probably deformed an initial schistosity parallel to S_0. Shear sense indicators in the XZ plane of the finite-strain ellipsoid indicate approximately S-directed sense of shear (see arrows in Fig. 10). Quartz grains show strong undulose extinction, deformation lamellae and partly dynamic recrystallization. In contrast to calcite and quartz, both feldspar and dolomite reveal cataclastic deformation and white mica is not recrystallized. The behaviour of these minerals indicates temperatures in the range of 300–450 °C for D_1. While D_1 is present only in the western Carnic Alps and totally missing in the central and eastern Carnic Alps, a second deformation event D_2 affected the whole Carnic Alps, i.e. the Fleons nappe, the Cellon-Kellerwand nappe and the Hochwipfel nappe. Corresponding D_2 structures are more or less S-verging thrusts with locally thick quartz mobilisates and large close to tight folds F_2 with approximately E/W-trending axes and an axial planar cleavage S_2. The vergence of these folds is again approximately S directed (triangles in Fig. 11). A stretching lineation, as during D_1, did not develop

Fig. 10 Tectonic transport direction in the western Carnic Alps during the first deformation event D_1. *PL* Periadriatic Lineament; *BL* Bordaglia Fault; *GPL* Gamskofel-Polinik Fault



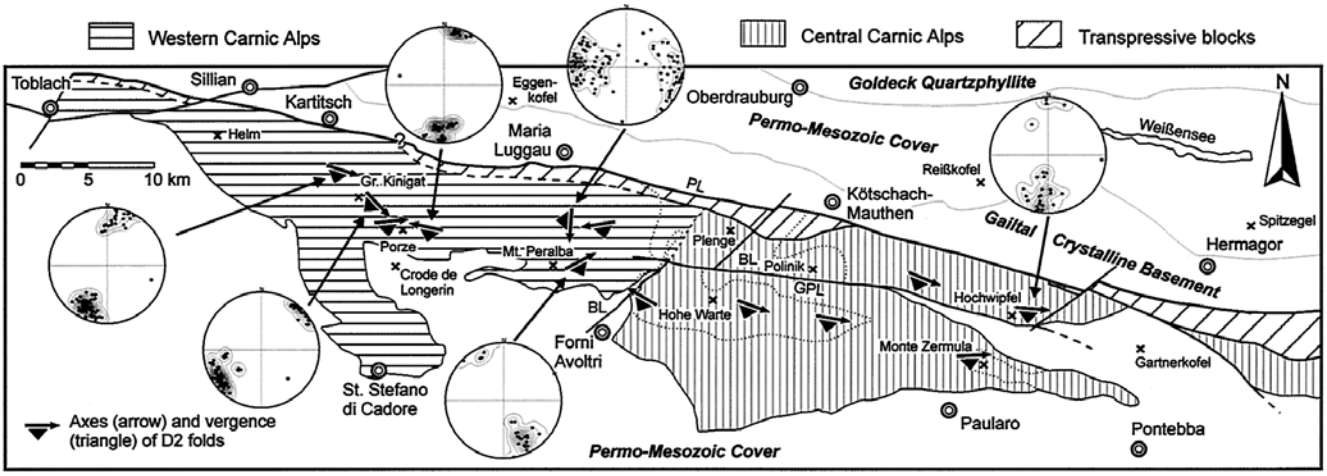
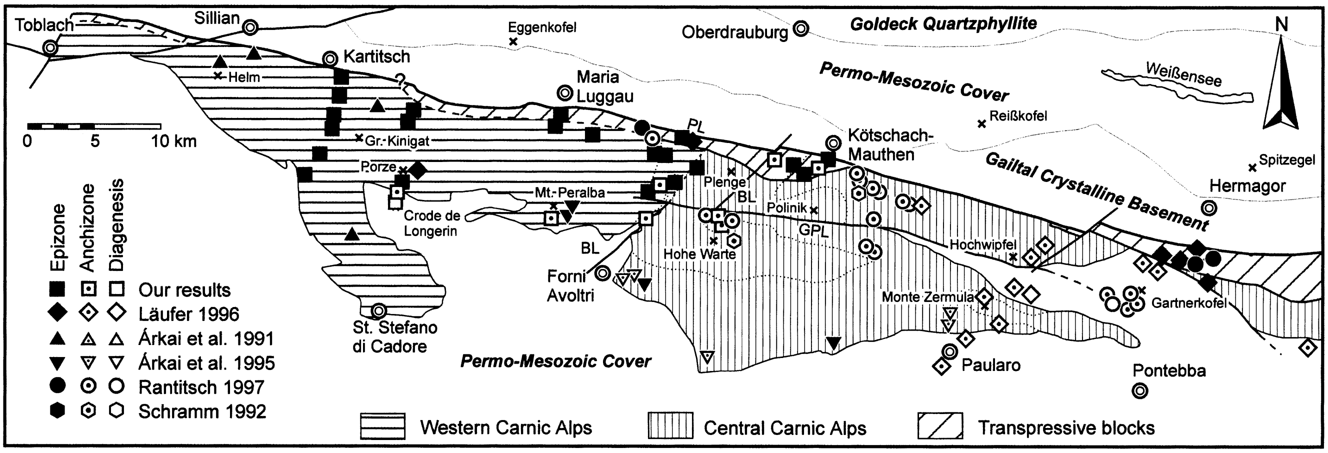


Fig. 11 Fold axes and thrusting in the Carnic Alps during the second deformation event D2

either in the Fleons nappe or in the other two nappes; quartz is not recrystallized. Therefore, peak temperatures must have been somewhat lower than during D_1. Kink bands, which occur abundantly in the Fleons nappe and only locally in the Cellon-Kellerwand nappe, are interpreted as late-orogenic structures linked to the uplift of the nappes into higher crustal levels. That both D_1 and D_2 are of truly Variscan age is clearly indicated by the unconformably overlying, less intensively deformed post-Variscan cover units (upper Carboniferous and Permian sedimentary rocks in the Hochwipfel graben fault system; see Fig. 9).

The regional distribution of illite crystallinity (IC) values (Frey 1986; Mullis et al. 1995) of the Carnic Alps are shown in Fig. 12. Measurements of this study are shown as squares and those of other authors as the symbols indicated in the legend of Fig. 12. Rocks of the western Carnic Alps yield epizonal values, whereas rocks of the central and eastern Carnic Alps, with the exception of the late-Alpine transpressive blocks, are dominated by anchizonal values. The transpressive blocks show epizonal values. The map indicates clear differences in metamorphism between the western and the central to eastern Carnic Alps. Samples from the post-Variscan cover units yield IC values which plot into the high-diagenetic and anchizonal range. There is a clear difference in metamorphic grade between the Variscan basement units of the western Carnic Alps and the post-Variscan cover units which are best seen in the area of Porze and Crode de Longerin in the western half of Fig. 12. In the central Carnic Alps, this difference in metamorphism is less well documented, but it is stated that the Variscan anchizonal metamorphism was at least as high or slightly higher than the Alpine metamorphic overprint (Läufer et al. 1997; Rantitsch 1997).

Fig. 12 Distribution of various metamorphic grades in the Carnic Alps based on illite crystallinity data



Determinations of IC were concentrated at the border between the western and central Carnic Alps directly W of the Bordaglia fault (Fig. 3). The structures there are shown in two cross sections, one running approximately N–S along Runseck-Stallon-Säbelspitz and the other NW–SE through Säbelspitz (Fig. 13; Schmalholz 1998). The IC results are presented in a diagram in which the relation between

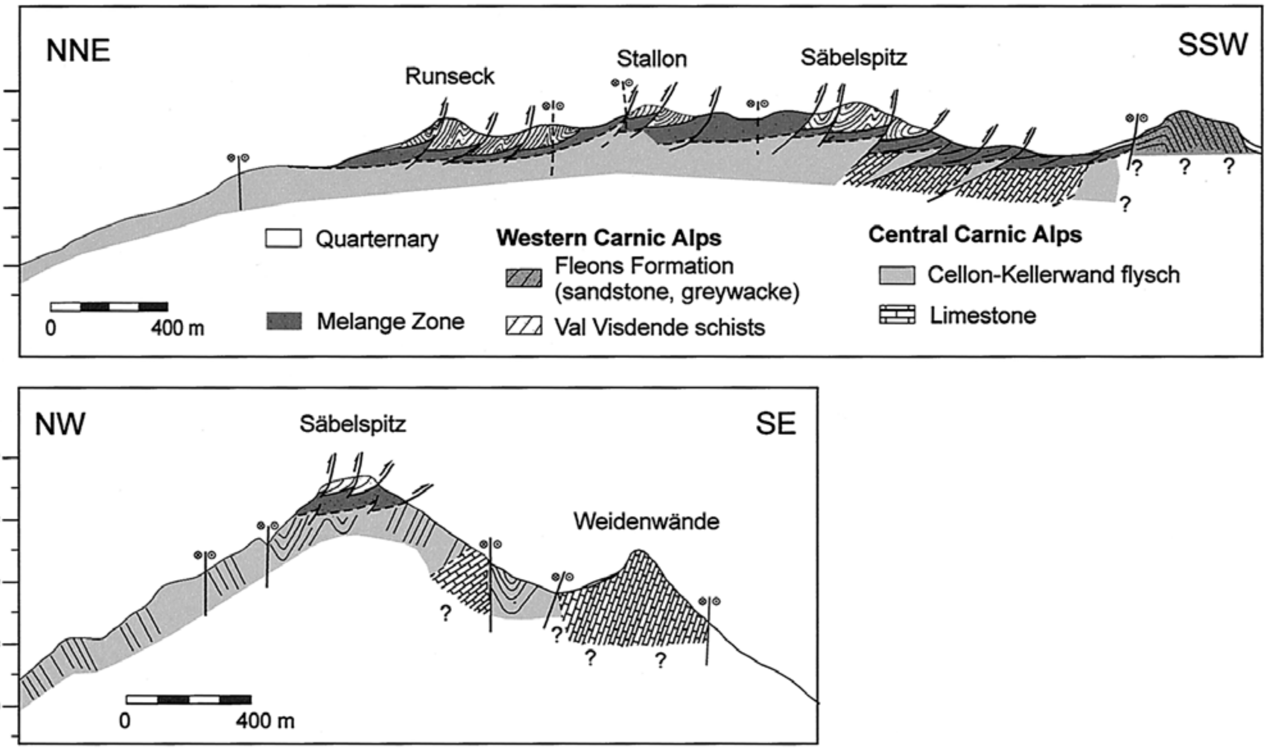


Fig. 13 Two geological cross sections immediately W of the Bordaglia fault (see Fig. 3) showing the thrust plane and the melange zone between Fleons nappe and Cellon-Kellerwand nappe

degree of metamorphism and topographic altitude has been plotted in these sections (Fig. 14).

Three tectonic units are discerned in Fig. 13. Carboniferous flysch units that belong to the Cellon-Kellerwand flysch occur at lower altitudes. They are characterized by abundant feldspar grains and volcanic detritus and rest stratigraphically on Devonian to lower Carboniferous limestones. The highest peaks are formed by Ordovician metasedimentary rocks of the Fleons nappe showing all the structural elements of the western Carnic Alps. These two tectonic units are separated by a tectonic melange zone where both the flysch clastics and the Val Visdende schists are intensively mixed and imbricated. Both base and top of this melange zone are formed by thrust planes dipping moderately to the NW. Several steep thrust planes originate at the floor thrust and run upwards through the melange zone in an approximately southeastern direction separating the section into several imbricated thrust slices. Whereas quartz grains in the flysch units at lower altitudes do not show any signs of internal deformation, the internal deformation increases upwards from undulose extinction, grain boundary migration to recrystallization in the Val Visdende schists in the crest area. Furthermore, quartz grains show increasingly N/S- and NW/SE-trending stretching lineations within generally northward-dipping foliation planes. Shear sense indicators within the melange zone and the Val Visdende schists indicate S- to SE-directed thrusting.

The results of IC measurements support the structural observations: in Fig. 14, IC values of samples taken at different altitudes are plotted against topographic altitudes of sample locations. Metamorphic

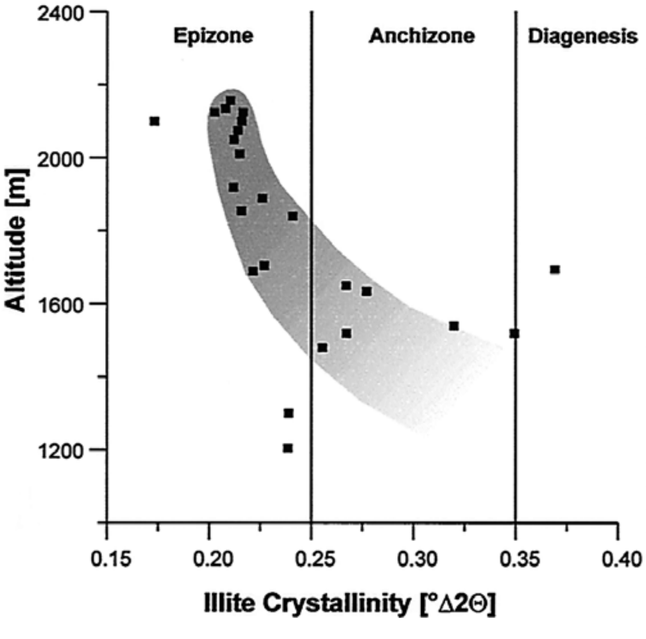


Fig. 14 Relationship between metamorphic grade (illite crystallinity values) and topographic altitude immediately W of the Bordaglia fault (sections of Fig. 13)

grades increase from the anchizonal Cellon-Kellerwand flysch, the lower epizonal melange zone into the epizonal Val Visdende schists. The epizonal values of two samples taken at 1200- and 1300-m altitude at a locality near the Bordaglia fault are probably due to Alpine overprint.

The structures shown in Fig. 13 are the result of the formation of a large-scale thrust duplex zone where the higher metamorphic and older rocks of the Fleons nappe have been thrust over the lower metamorphic and younger rocks of the Cellon-Kellerwand nappe. At the crest of the section, the Val Visdende schists represent a klippen zone which rests as an erosional remnant on top of a melange zone which again rests on top of the Cellon-Kellerwand flysch. Both deformation and metamorphism increase with increasing topographic altitude.

Geochronological studies to date the two tectonometamorphic events are still in progress; however, preliminary results point to an age of approximately 340 m.y. for metamorphism in the Fleons nappe and 320–300 m.y. for the younger Cellon-Kellerwand and Hochwipfel nappes (K–Ar on white mica and clay fractions; analyst: Y. Harlavan, Jerusalem).

Geodynamic evolution and discussion

To discuss the Variscan geodynamic evolution of the Carnic Alps, five sections are presented in Figs. 15 and 16 showing the situations in the Late Ordovician, Early-Middle Devonian, Late Devonian–Early Carboniferous, Visean-Namurian and Late Carboniferous–Early Permian. The figures are based on field observations but include certain hypothetical aspects.

The Late Ordovician situation (Fig. 15) is clearly documented in the Fleons nappe (western Carnic Alps). The eruption of acidic pyroclastic rocks of the Comelico Porphyroid and the deposition of the clastic Fleons formation in a coastal to deltaic environment is indicated on the right (southern) side according to Hinderer (1992). Both eruption of the porphyroid (455 m.y.; Söllner et al. 1997) and deposition of the clastics were contemporaneous indicated by the fact that both sequences grade into each other laterally. In addition, the clastics contain corroded quartz grains derived from the porphyroid and clastic pyroxenes as well as basic volcanic fragments proving bimodal volcanism in the source area. In the N, the Fleons formation grades laterally into the fine-grained Val Visdende schists. The ignimbrites of the Comelico Porphyroid are of calcalkaline nature (Hubich and Loeschke 1993). They are very similar in composition and age to the ignimbrites of the Northern Greywacke Zone (Blasseneck Porphyroid; Loeschke et al. 1990). Since the stratigraphic sequences above the ignimbrites of both areas are nearly identical, it is generally

Fig. 15 Tectonic situation in the Late Ordovician of the western Carnic Alps (*right side*) indicating the beginning of rifting which leads to the separation of the Carnic Alps from northern Africa. The *left side* shows the corresponding situation in the Northern Greywacke Zone and the Gurktal unit

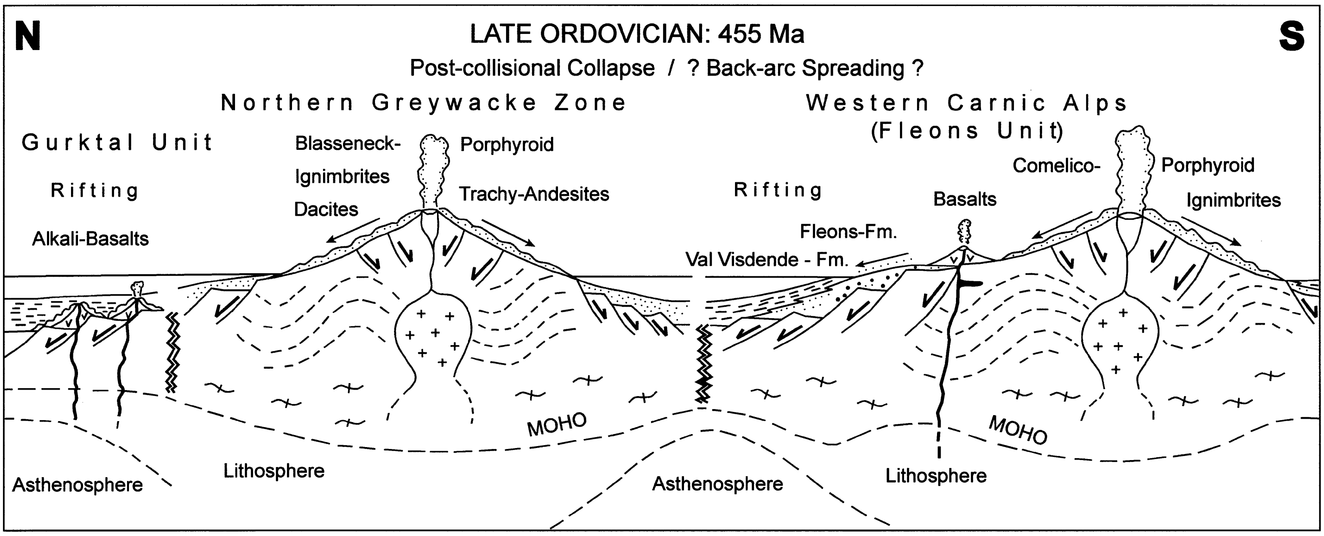
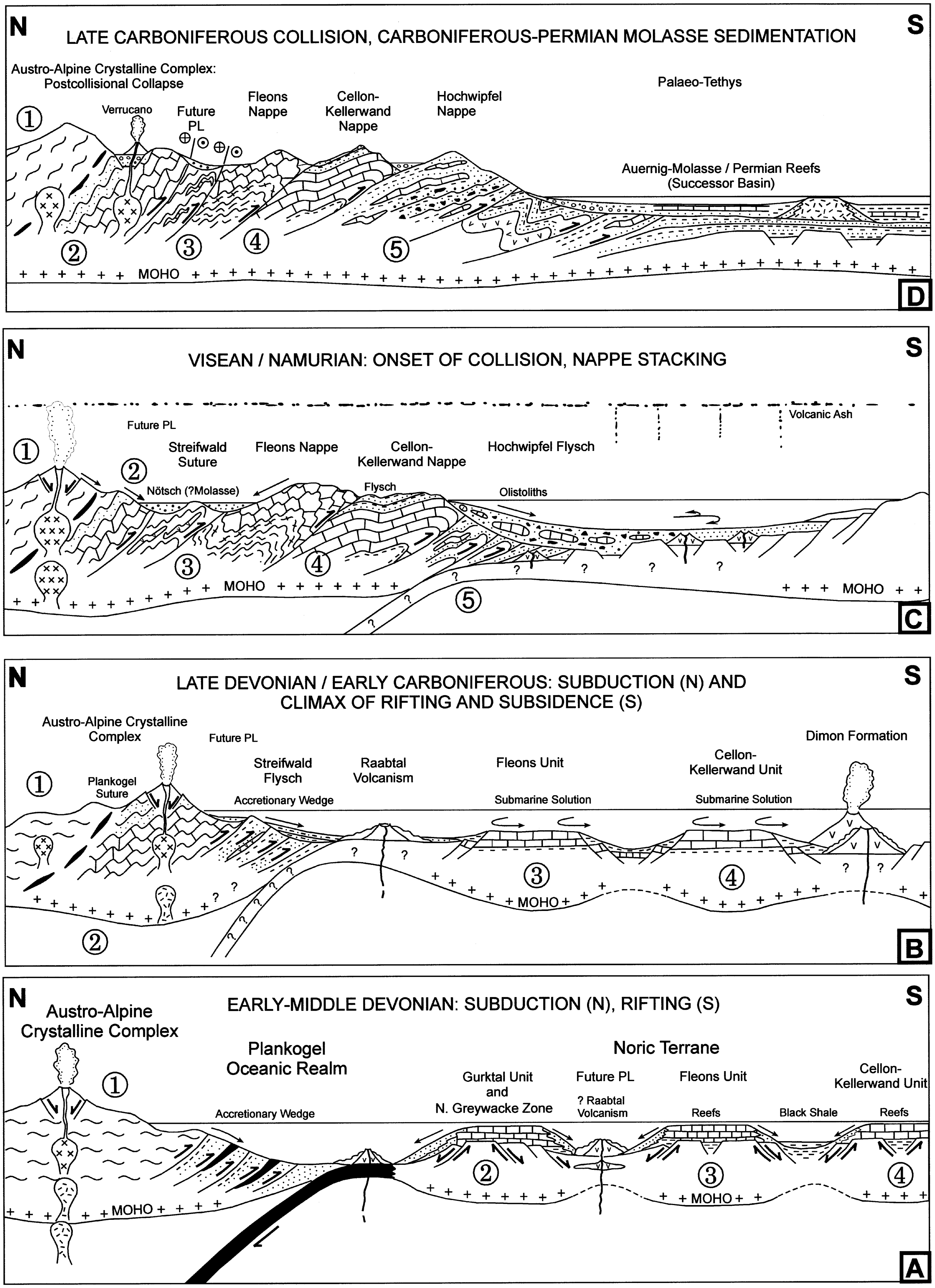


Fig. 16A–D Tectonic situations in the Carnic Alps from Devonian to Permo-Carboniferous times. **A** Early to Middle Devonian. Rifting in the S and subduction in the N. The age of the Raabtal volcanism is unknown. **B** Late Devonian to Early Carboniferous. Establishment of a mature passive continental margin, eruption of submarine basalts, breakup and subsidence of the middle Devonian carbonate platform and submarine solution by new ocean currents. **C** Visean/Namurian. Increasing crustal shortening, formation of a S-migrating fold-and-thrust belt, deposition of turbidites and olistoliths in front of S-verging nappes. **D** Late Carboniferous to Early Permian. Collision, uplift and erosion of the nappe pile and deposition of clastic sediments and reef growth in the molasse foredeep in the S. *PL* supposed position of future Periadriatic Lineament. *Numbers 1–5* refer to the different crustal blocks in the model


N
LATE CARBONIFEROUS COLLISION, CARBONIFEROUS-PERMIAN MOLASSE SEDIMENTATION
S
Austro-Alpine Crystalline Complex:
Postcollisional Collapse
Verrucano
Future PL
Fleons Nappe
Cellon-Kellerwand Nappe
Hochwipfel Nappe
Palaeo-Tethys
Auernig-Molasse / Permian Reefs
(Successor Basin)
①
②
③
④
⑤
MOHO
D
N
VISEAN / NAMURIAN: ONSET OF COLLISION, NAPPE STACKING
S
Volcanic Ash
Future PL
Streifwald Suture
Fleons Nappe
Cellon-Kellerwand Nappe
Hochwipfel Flysch
Nötsch (?Molasse)
Flysch
Olistoliths
①
②
③
④
⑤
?
MOHO
C
N
LATE DEVONIAN / EARLY CARBONIFEROUS: SUBDUCTION (N) AND CLIMAX OF RIFTING AND SUBSIDENCE (S)
S
Austro-Alpine Crystalline Complex
Future PL
Streifwald Flysch
Raabtal Volcanism
Fleons Unit
Cellon-Kellerwand Unit
Dimon Formation
Plankogel Suture
Accretionary Wedge
Submarine Solution
Submarine Solution
①
②
③
④
?
MOHO
B
N
Austro-Alpine Crystalline Complex
EARLY-MIDDLE DEVONIAN: SUBDUCTION (N), RIFTING (S)
S
Plankogel Oceanic Realm
Noric Terrane
Gurktal Unit and N. Greywacke Zone
Future PL
? Raabtal Volcanism
Fleons Unit
Cellon-Kellerwand Unit
Accretionary Wedge
Reefs
Black Shale
Reefs
①
②
③
④
MOHO
A

assumed that the Ordovician palaeogeographic position of the Northern Greywacke Zone was in the vicinity of the Carnic Alps (Schönlaub 1979) as indicated in Fig. 15 as well. Further Late Ordovician volcanic sequences of the Eastern Alps occur in the Gurktal nappe (Magdalensberg and Kaser series; Loeschke 1989); these comprise alkali within-plate basalts typical of areas of crustal extension (left side of Fig. 15). The interpretation of the geodynamic setting in the Late Ordovician of the Eastern and Southern Alps is ambiguous. Calcalkaline volcanic rocks are on the one side typical of active plate marins, but they can, on the other side, also occur in areas of crustal extension, e.g. in the Basin and Range province of western North America (Lipman 1992). Von Raumer (1998; Fig. 5) reports a supposed Ordovician suture zone characterized by eclogites and granitoids in the Penninic and Helvetic realm. It is possible that the Late Ordovician ignimbrites and alkaline within-plate basalts of the Eastern and Southern Alps indicate a back-arc extensional regime which may have belonged to this suture zone. However, the Late Ordovician situation in the Carnic Alps clearly reflects a rift environment. It probably represents the onset of rifting which started after the Late Ordovician glaciation according to Von Raumer (1998, p 420). In this connection, it is interesting to note that a tillite horizon occurs beneath the Blasseneck Porphyroid in the Northern Greywacke Zone (Kalwang Gneiss Conglomerate; Loeschke et al. 1990). The eruption of the ignimbrites could, therefore, mark the beginning of the detachment of the Noric Terrane (Frisch and Neubauer 1989) from the northern margin of Gondwana in the Late Ordovician. The scenario could, however, also be the consequence of post-collisional collapse of a Cambrian to Early Ordovician arc at the northern margin of Gondwana (Stampfli et al. 1999). This interpretation is in accordance with the generally accepted development during the Late Ordovician: the Noric Terrane (Frisch and Neubauer 1989) and the South-Alpine basement belonged to the North African continental margin. These crustal blocks started to become detached during the Late Ordovician and drifted as microcontinents northwards into the realm of the central European Variscides during the Silurian and Devonian (Franke et al. 1995; Tait et al. 1997; Von Raumer 1998).

The Early to Middle Devonian situation is shown in Fig. 16A. In the southern part of the section, three crustal blocks are assumed to be present separated by major faults and belonging to the Noric Terrane of Frisch and Neubauer (1989). We discern the Cellon-Kellerwand unit, the Fleons unit and a third unit to the N with similar stratigraphy as in the other two blocks which could possibly represent the Gurktal nappe and/or the Paleozoic sequences of the Northern Greywacke Zone in the Eastern Alps. They contain a widespread facies differentiation with thick reef limestones on top of the crustal blocks and black shale deposition in the basins in between which is typical of the Devonian in the Eastern and Southern Alps. During this time, rifting has been intensified and the transition to the formation of a passive continental margin was in progress. The occurrence of submarine basaltic volcanism is suggested in the basin between the Fleons unit and the block situated to the N (Raabtal volcanism). This assumption is hypothetical, but the basalts could represent early precursors of the alkaline within-plate basalts occurring directly beneath the Streifwald flysch turbidites. Numerous alkaline within-plate basalts of Silurian/Devonian age are found in other places of the Eastern Alps (Loeschke 1989) and generally indicate crustal stretching and intensified rifting of continental crust during the Silurian and Devonian (Loeschke and Heinisch 1993).

The subduction of an ocean and the formation of an accretionary wedge is shown on the northern side of the section of Fig. 16A. The ocean is named "Plankogel ocean" and could be a temporal continuation of the Prototethys or Palaeotethys. It is represented by the Plankogel rock association of the crystalline basement of the Saualpe (Frisch and Neubauer 1989). The Plankogel association is partly of true oceanic nature and contains highly metamorphosed ophiolitic rocks, alkalic seamounts, shelf carbonates and manganese chert in a pelitic matrix. It is a disrupted terrane and has a melange-like character. It can be followed as a distinct rock assemblage over 70 km in the metamorphic complexes of eastern Carinthia. The accretionary complex and active continental margin could in a broad sense be a continuation of the Ligerian Cordillera of the French Massif Central to the E into the Alpine domain (Pin and Peucat 1986; Von Raumer 1998). The accretionary wedge characterized by the Plankogel Terrane could be an early Variscan precursor of the main Variscan orogenic belt. This is supported by the fact that the Plankogel Terrane lies in the more internal parts of the Eastern Alps and that there is generally a gradual shift of the deformation front within the southern part of the Variscan orogen from the internal more northern parts of the Alps to the external parts in the S (Schönenberg 1970). The magmatic arc in the N of Fig. 16A is not very well known and there are only some Devonian radiometric data available indicating metamorphism and intrusion of granites in the crystalline basement of the Eastern Alps (Neubauer and Frisch 1993; Neubauer et al. 1999). In comparison with the palaeogeographic maps of Ziegler (1989), the Plankogel Terrane could have been located at the southern margin of the Intra-Alpine Terrane. The position of the Raabtal volcanism could have been in the Prototethys S of the Austro-Alpine Terrane; however, we do not know any true ophiolite assemblages there.

The sedimentary record of the Late Devonian and Early Carboniferous indicates that the climax of crustal stretching has been reached and a mature passive continental margin has been established (Fig. 16B).

Generally, deeper-water deposits prevail like pelagic nodular limestones and chert with slow sedimentation rates. Figure 16B thus shows the subsidence of the middle Devonian carbonate platform of the Fleons and Cellon-Kellerwand units, the reduction of the thickness of the continental crust and the eruption of submarine basalts N of the Fleons unit on the Austrian side (Raabtal volcanism) and S of the Cellon-Kellerwand unit on the Italian side (Dimon formation). These basalts are typical akali within-plate basalts which are presently found on seamounts and oceanic islands or in continental rift zones. They are similar in their composition to the basalts of the Eisenkappel area in the Karawanken Mountains. Seen from the aspect of plate tectonics and in comparison with the evolution of other Phanerozoic orogenic belts, they must belong to the pre-flysch stage and indicate the maximum of crustal extension and isostatic subsidence of thinned continental crustal blocks prior to contraction. Whether the basalts erupted on thinned continental or oceanic crust is open to question. The field observations show that there is no single outcrop known where the normal sedimentary stratigraphic basement of the basalts is seen. The basalts are imbricated with flysch turbidites and are in some localities stratigraphically overlain by these turbidites. They represent the normal basement of the flysch turbidites. This means that the basement of the basalts is unknown and could easily have been the lower oceanic crust and/or mantle; therefore, question marks are indicated in Fig. 16B below the submarine volcanoes to show that the nature of the underlying crust is unknown. The basalts could represent former oceanic islands or seamounts, which have been obducted during the Variscan collision, and could mark smaller oceanic basins which are now present as tectonically reduced slices in smaller suture zones between the crustal blocks. Oceanic islands and seamounts have the best chance to be obducted and preserved in continental crust because they form a morphological rise and tectonic obstacle in a subduction zone and have a thicker and lighter underlying crust than normal oceanic crust. They can, therefore, easily be incorporated into an accretionary wedge or nappe pile during later collision. The non-existence of true ophiolite assemblages in the Carnic Alps is no argument against the possible former presence of oceanic crust. By far the greatest part of normal oceanic crust is always subducted due to its higher density.

The left side of Fig. 16B indicates the presence of an accretionary wedge and an active continental margin. The accretionary wedge is deduced from the structural configuration of the Streifwald flysch and its imbricated basalts (see Fig. 6). The discovery of this new flysch unit is very important because flysch deposits were not known in the western Carnic Alps until now. The section of Fig. 6 conveys the impression that this sequence could represent a former accretionary wedge which has obviously been tectonically shortened and disrupted in the right-lateral transpressional regime of the Periadriatic Lineament (PL) but can still be recognized as such. Very similar turbidites follow on top of submarine within-plate alkali basalts in the Karawanken Mountains (Eisenkappel area) to the E directly N of the PL (Kullmann and Loeschke 1994; Sonntag et al. 1997). Since these flysch deposits are further to the N than the typical Hochwipfel flysch, and since flysch basins migrate from N to S in the southern half of the Variscan orogen due to the S-directed migration of the orogenic front (Schönenberg 1970), it is presumed that the Streifwald flysch and the flysch turbidites of Eisenkappel in the Karawanken Mountains are older than Cellon-Kellerwand and Hochwipfel flysch and may stratigraphically be regarded as belonging to the lower Carboniferous. This is also indicated by the fact that the Streifwald flysch contains the older and higher-temperated deformation event (D_1) of the Fleons nappe which is not present in both Cellon-Kellerwand and Hochwipfel flysch. The next Variscan flysch basin to the N outside the Alpine realm is located in the southern Black Forest (Fig. 1) and has a pre-Late Visean, probably Late Devonian to Early Carboniferous age (Loeschke et al. 1998).

An active continental margin is located N of the accretionary wedge. It is built up by the Austro-Alpine crystalline complex where the Plankogel ocean has been closed and a corresponding suture zone has been formed. The precursor of the PL is clearly visible. This lineament separates the Austro-Alpine crystalline complex from the Carnic Alps in form of the accretionary wedge of the Streifwald flysch already during the Late Devonian/Early Carboniferous. The PL had probably a Paleozoic precursor because the Streifwald flysch is directly S of the lineament and the Raabtal basalts mark deep-reaching faults and perhaps a small oceanic basin. The continuation of this flysch with its imbricated basalts can be found in the Karawanken Mountains near Eisenkappel further to the E where it is positioned N of the PL. The two flysch/basalt units have been separated by the late-Alpine PL and offset by right-lateral movements for approximately 140 km, a distance which is generally accepted for the offset along this lineament (Polinski and Eisbacher 1992). The PL apparently follows more or less a Paleozoic suture zone; however, it cuts this suture zone at a very small angle so that the within-plate basalts and the overlying flysch units are in one case S (Streifwald flysch) and in the other case N of the lineament (Eisenkappel flysch).

Figure 16B clearly shows the co-existence of subduction in the N and extension in the S whereby the deformation front migrates within the southern parts of the central European Variscides from N to S, i.e. from the internal to the external side of the orogen. In comparison with the palaeogeographic maps of Ziegler (1989), the basin of the Streifwald flysch and the Raabtal volcanism could have been located between the Austro-Alpine and South-Alpine Terrane, a position which is clearly indicated in Fig. 3.

The Visean/Namurian is the time of the beginning of nappe stacking and collision at the southern margin of the European Variscides. Figure 16C thus indicates nappes or thrust sheets prograding from N to S and the Variscan collision in its early stage. The crustal blocks of the Fleons and Cellon-Kellerwand units have been incorporated into a S-verging nappe or fold-and-thrust complex due to subduction of thinned continental crust from the S. In the N (left side of Fig. 16C), intense granitic plutonism and corresponding volcanism is documented by numerous radiometric age determinations (Gebauer 1993; Neubauer and Frisch 1993). Pyroclastic sediments of this volcanism are found within the turbidite sequences of the Hochwipfel flysch in the form of ash layers. Intense crustal shortening creates the S-verging fold-and-thrust belt indicative of the collision of the northern margin of Gondwana with a complex collage of composite terranes of the Variscan realm. Uplift and erosion of the prograding nappes due to intense compression expose stratigraphically older rock sequences which glide into the southern foredeep in the form of olistoliths. The thinned continental crust of northern Gondwana is forced down under the S-verging orogenic front and an accretionary wedge is formed consisting of the intensely imbricated Hochwipfel flysch. Turbidites of the Hochwipfel flysch cover the volcanic rocks of the Dimon formation further to the S beyond the accretionary wedge and the basaltic volcanism ceases because the tectonic regime changes from extension to contraction.

The Carboniferous basin of Nötsch (Schönlaub 1979) is interpreted as an early internal molasse-type deposit which is positioned in a depression between the S prograding nappes and the Austro-Alpine hinterland. Therefore, the highest peaks of the nappes could have formed islands which were located between the foredeep in the S and the basin of Nötsch in the N. Relics of a cryptic suture zone in the form of the accretionary wedge of the Streifwald flysch may have been present under the Nötsch basin because it is directly at the northern border of the PL and, therefore, near to the structural position of the Streifwald flysch.

In comparison with the palaeogeographic maps of Ziegler (1989), the Hochwipfel flysch basin is positioned at the southernmost end of the Variscan orogen in Central Europe. The turbidites were deposited on the tectonically thinned North African shelf, but they may also have been deposited on oceanic crust further to the E. A similar plate-tectonic scenario as in Fig. 16C can also be observed outside the Alpine domain at the southern margin of the European Variscides in the Montagne Noire of southern France during the Visean/Namurian (Engel et al. 1981; Franke and Engel 1986; Matte 1986).

During the Late Carboniferous, the collision between Gondwana and Variscan terranes has been completed; however in the E, a marine gulf, the Tethys ocean, is still present in which Late Carboniferous to Permian marine sediments are deposited (Stampfli et al. 1999). The situation is presented in Fig. 16D. It shows the increasing crustal shortening, the uplift of the Hochwipfel nappe, the tectonic imbrication of the Dimon volcanic rocks within the accretionary wedge of the Hochwipfel flysch and the sedimentation of clastic debris in the Auernig basin (Schönlaub 1979) in the S. This debris is derived from the nappes of the Carnic Alps and the metamorphic hinterland of the Eastern Alps. Eustatic sea-level changes caused marine conditions from time to time and the deposition of marine limestones and reef complexes. The Auernig basin is interpreted as a successor of the Hochwipfel flysch basin. An unconformity between the Auernig formation and the Hochwipfel flysch is evident only in some places of the Carnic Alps. These localities are either in an internal position on top of the folded Hochwipfel nappe or Cellon Kellerwand nappe or on top of huge olistoliths within the Hochwipfel nappe. Concordant relationships between distal turbidites of the Hochwipfel flysch and the Auernig formation should very likely prevail in a more external position which is shown on the southern side of Fig. 16D. This is one reason why finding a throughgoing Variscan unconformity is so difficult in the Carnic Alps and the Karawanken Mountains. Another reason is the Alpine deformation which overprinted the Variscan unconformity as well and disguises it.

Between the Fleons nappe and the Austro-Alpine crystalline complex, two major dextral horizontal strike-slip faults bordering the Steifwald flysch on both sides are shown on the left side of Fig. 16 (D). In the field, the Streifwald flysch is between the PL in the N and a major throughgoing E/W-trending fault in the S. It is assumed that both faults probably have a Paleozoic history. This can be deduced from the palaeogeographic maps of Ziegler (1989) and the work of Arthaud and Matte (1977) who show that during the Late Carboniferous and Early Permian various E/W-oriented right-lateral strike slip systems were active in Central Europe caused by the western drift of northern Gondwana at that time (Neugebauer 1988). The volcanism of the Verrucano in the Eastern Alps, shown in Fig. 16D as well, is probably the result of post-collisional collapse of the Variscan orogen.

Conclusion

By comparing Figs. 15 and 16, the following basic processes are deduced from the geology of the Carnic Alps:

1. The separation of the Carnic Alps from the North African continental margin started in the Late Ordovician, probably after the Late Ordovician glaciation.

2. From the Early to Middle Devonian onwards extension with the formation of a passive continental margin prevails in the S and subduction in the N.
3. The deformation front migrates from N to S with time and crustal shortening increases until the Late Carboniferous.
4. Small crustal blocks are being welded together by contraction and possible subduction of small basins between the blocks during the Devonian and Carboniferous. These basins are formed on thinned continental or even oceanic crust. By these processes, a complicated pattern of small terranes, nappe complexes and thrust sheets with different stratigraphies is being produced which are constituents of the mega-suture between Central Europe and northern Africa.
5. Figures 15 and 16, which are deduced primarily from field observations and after that from generally valid geodynamic considerations, can be brought into line with the palaeogeographic maps of Ziegler (1989) and the palaeogeographic reconstructions of Stampfli et al. (1999) without any problems. They should therefore be considered as realistic even if no scale has been added to the drawings, which is impossible on those hypothetical models anyway.

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