The Palaeozoic of the Southern Alps

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Summary

In this article the present knowledge about the classic Palaeozoic sequence of the Austrian part of the Southern Alps is summarized. The available faunal, floral and sedimentological data are derived from a continuous record of Middle to Upper Ordovician through end-Permian fossiliferous strata exposed in both the Carnic Alps and its eastward continuation in the Karawanken Alps. These data supplemented by palaeomagnetic measurements suggest a constant movement from more temperate regions of some 50° southern latitude in the late Ordovician to the equatorial belt during the Permian (Fig. 1)[2].

Although direct evidence is missing it may be concluded that the Southern Alps like other regions in Southern and Western Europe, belonged to the northern margin of the African part of Eastern Gondwana during the Cambrian. Initiation of rifting indicated by basic volcanism in parts of the Central Alps, may have occurred during the Lower Ordovician leading to fragmentation and northward drifting of small microcontinents. In fact, during the late Ordovician the supposed former close spatial relationship to northern Africa decreased.

Instead the faunistic and lithic pattern suggest a warm water influx from Baltica and even Sibiria. The following biota, in particular bivalves, nautiloids, trilobites and corals from the Silurian and Devonian shows close affinities to coeval faunas and floras from southern, central and southwestern Europe. However, the relationships to the Atlantic bordering continents and microplates in low latitudinal position such as Baltica, Avalonia and also Sibiria were also remarkably close suggesting a setting of about 35°S for the Silurian and within the tropical belt of some 30° or less for the Devonian. Whether or not Sardinia, the Montagne Noire, Iberia and the Armorican Massif occupied a similar palaeolatitudinal position or were attached to Northern Africa remains open. In any case, exchange of faunas between these regions and the Southern Alps seems well documented and may have been aided through currents.

During the Visean Stage of the Lower Carboniferous the Lower Palaeozoic sequence of the Southern Alps collided with the Central Alps and migration paths developed across the accreted Alpine terranes. Both Lower and Upper Carboniferous faunas and floras appear of limited biogeographic significance as they exhibit either cosmopolites or represent a general humid equatorial setting. Nevertheless they provide key elements for correlating continental deposits and shallow marine sequences. Progressive northward drifting during the Late Carboniferous and the Permian resulted in semi-arid and arid conditions which started in the Central Alps in the Lower and in the Southern Alps during the Middle Permian indicating that

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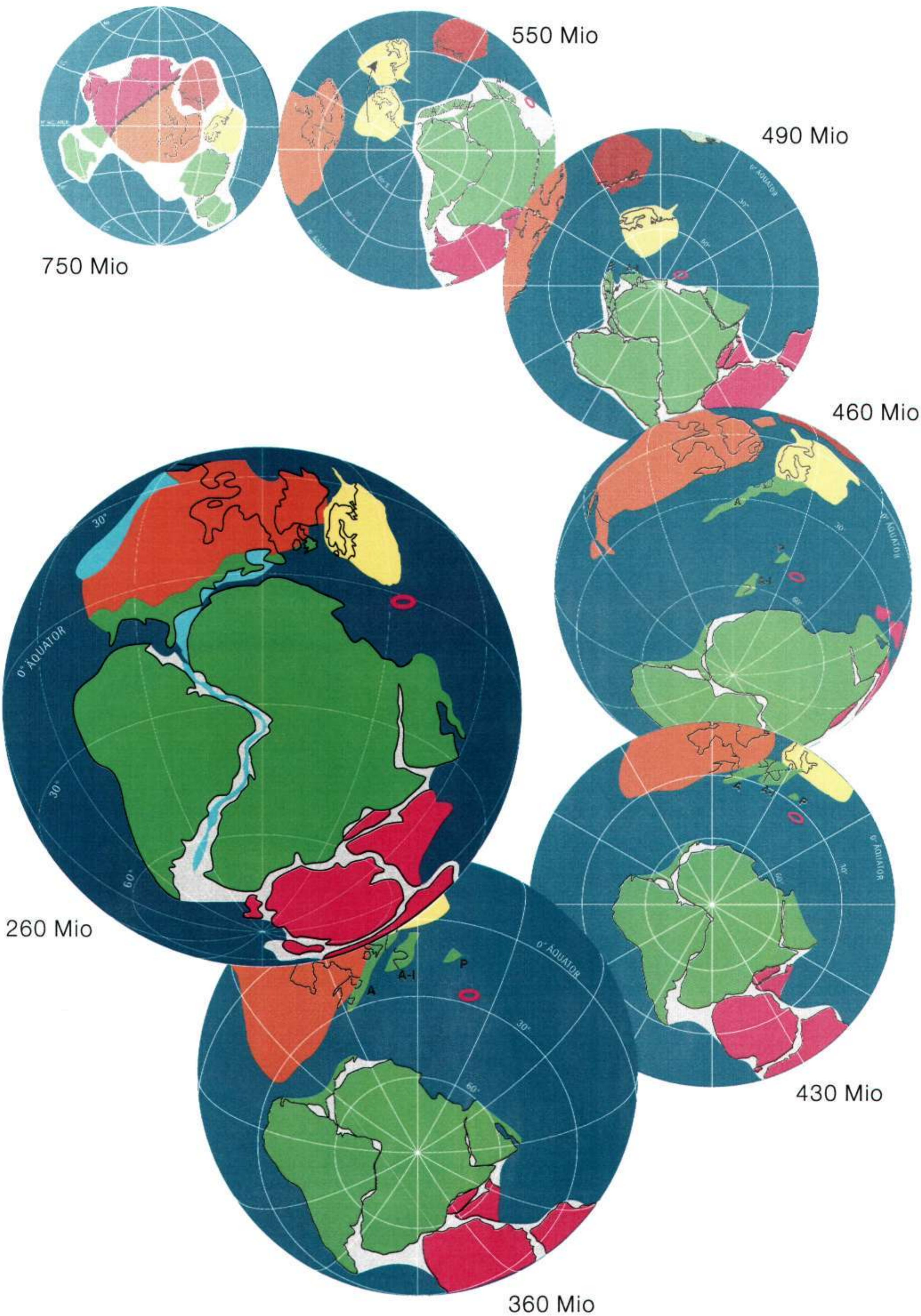
[2] Fig. 1. (Facing page – colour insert) Wander path of continents between 750 and 260 Ma. Circle indicates approxoimate position of the Proto-Alps. Main plate configration after I. W. D. DALZIEL 1995, T. H. TORSVIK et al. (1996) and L. R. M. COCKS & C. R. SCOTESE 1991.



750 Mio
550 Mio
490 Mio
460 Mio
430 Mio
360 Mio
260 Mio
0° ÄQUATOR
30°
60°
A
A-I
P

the forerunner of the Alps may have crossed the equator at different times during the Upper Palaeozoic.

In the Southern Alps the spatial distribution of the different Upper Ordovician to Lower Carboniferous litho- and biofacies indicates a SW-NE directed polarity from shallow water environments to an open marine and deep-sea setting. The latter must be assumed further north of the present Carnic and Karawanken Alps which, however, are fault-bounded. At least during the Lower Carboniferous this northern counterpart comprised an extensive shallow water carbonate platform of which, however, only small remnants and exotic limestone clasts have been preserved embedded mainly in the flysch-type Hochwipfel Formation. Therefore, any conclusion about the width of this intervening area and the nature of the rocks separating different Alpine terranes, remains a matter of speculation.

On a larger scale these Alpine blocks represent peri-Gondwanide terranes and arcs similar to Avalonia, Armorica-Iberia, Perunica, Mixteca, Zapoteca, Famatina and others which originally formed the northern and western margin of Gondwana. Some of these may have been permanently or loosely attached to Africa while others including the Southern Alps split off in the early Ordovician to drift northward more or less rapidly until they successively collided and accreted with Laurentia and Baltica, respectively, during the Devonian and Carboniferous.

Introduction

The Carnic Alps of Southern Austria and Northern Italy represent one of the very few places in the world in which an almost continuous fossiliferous sequence of Palaeozoic age has been preserved. They extend in a W-E-direction for over 140 km from Sillian in Tyrol to Arnoldstein in central Carinthia. Continuing into the Western Karawanken Alps the Variscan sequence is almost completely covered by rocks of Triassic age. Further in the east, however, Lower Palaeozoic rocks are excellently exposed in the Seeberg area of the Eastern Karawanken Alps south of Klagenfurt, the capital of Carinthia. Differing from the Carnic Alps, in this region the Lower Palaeozoic strata are distributed on either side of the Periadriatic Line (Gailtal Fault) which separates the Southern and the Central or Northern Alps (Fig. 2). These rocks have been subdivided into a northern and a southern domain, respectively. The latter extends beyond the state border to northern Slovenia.

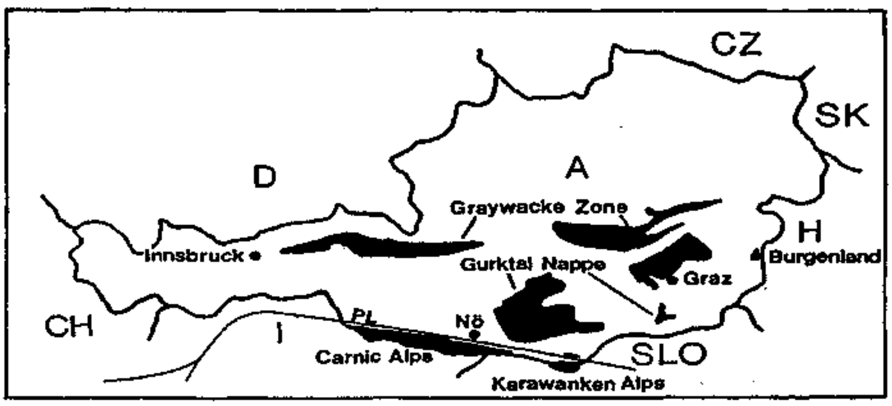


Fig. 2. Main occurrences of fossiliferous Palaeozoic rocks in the Eastern and Southern Alps (PL = Periadriatic Line, Nö = Carboniferous of Nötsch).

In both the Carnic and Karawanken Alps systematic research started soon after the foundation of the Geological Survey of Austria in the middle of the last century. Interestingly, the equivalents of the Lower Palaeozoic were first found in the Karawanken Alps and not in the more fossiliferous Carnic Alps (E. SUESS 1868, F. TIETZE 1870). In this latter area the main emphasis was drawn on marine Upper Carboniferous and Permian rocks. At the end of the 19th century this initial phase was followed by the second mapping campaign carried out mostly by G. GEYER from the Geological Survey of Austria and detailed studies by F. FRECH. During the first half of this century F. HERITSCH and his research group from Graz University revised the stratigraphy on the Austrian side while M. GORTANI from Bologna University and others worked on the Italian part of the mountain range. One of the outstanding contributions of that time focusing on the Lower Palaeozoic was provided by H. R. von GAERTNER (1931). The detailed knowledge of Upper Carboniferous and Permian rocks resulted mainly from studies by F. KAHLER beginning in the early 1930s. Since that time many students of geology started to visit both regions. During this third campaign study of various microfossil groups began and other techniques were also applied. This research culminated in the publication of detailed maps, a new stratigraphic framework, and revisions of old and discoveries of new faunas and floras (see e. g., H. P. SCHÖNLAUB 1971, 1980, 1985, 1997, H.P. SCHÖNLAUB & L. H. KREUTZER 1994).

Review of Stratigraphy

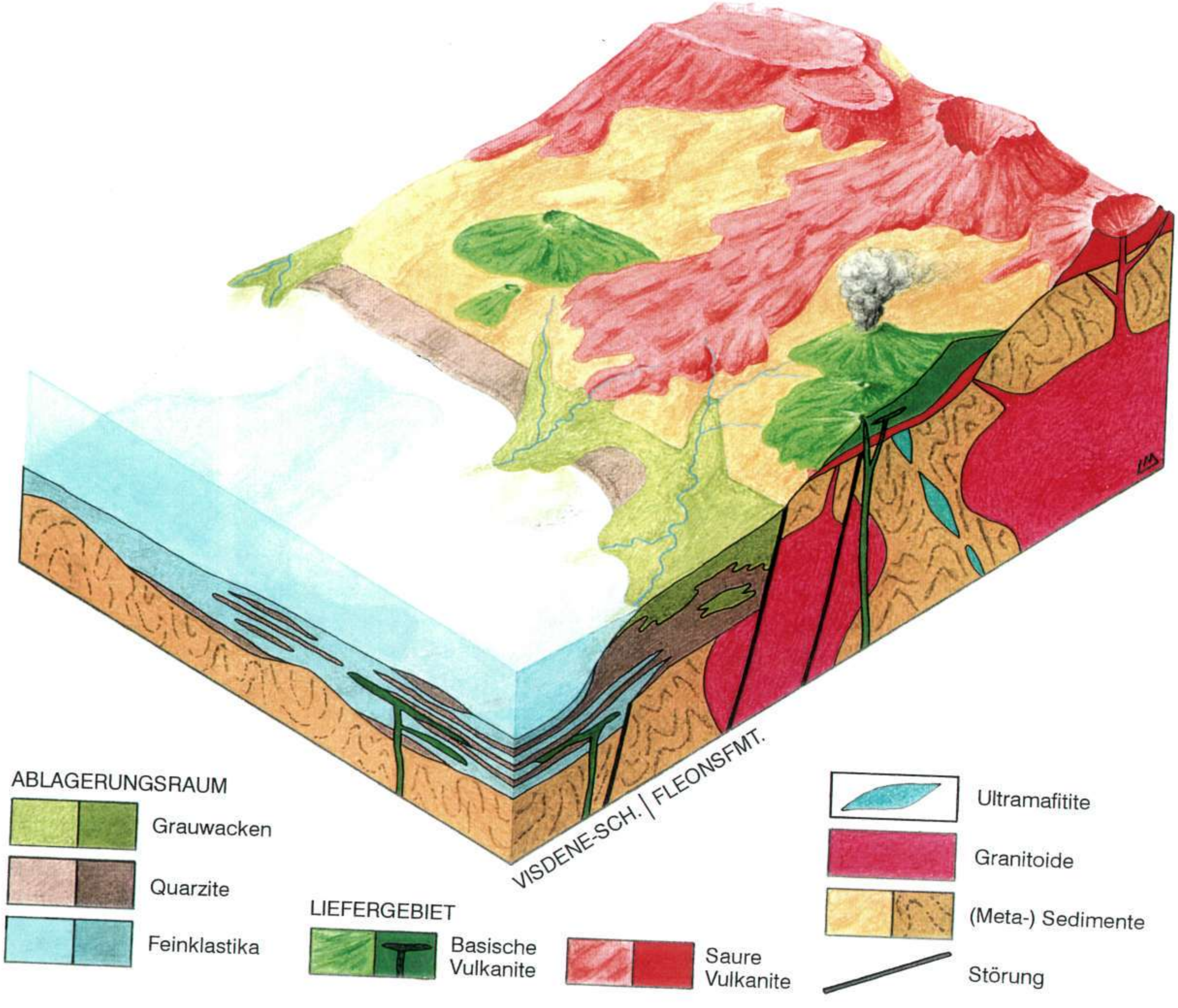
Fig. 4 summarizes the stratigraphy and facies distribution of the sedimentary sequences of the Carnic Alps. With minor modifications this framework can also be applied to the Karawanken Alps (H. P. SCHÖNLAUB 1980, B. MOSHAMMER 1989).

Ordovician

The oldest megafossil-bearing strata of the Southern Alps indicate an early Upper Ordovician age. In the western Carnic Alps and in the Brixen Phyllite Complex even older rocks occur the age of which, however, is not precisely known. Presumably, the oldest part of this sequence may be attributed to the Cambrian or Lower Ordovician.

In the Austrian part of the Southern Alps the Ordovician succession comprises weakly metamorphosed fine and coarse clastic rocks named the Val Visdende Group. This more than 1000 m thick sequence is well exposed in the westernmost part of the Carnic Alps on both sides of the Austrian-Italian border on the topographic sheets Obertilliach and Sillian. The lithology ranges from shales and slates to laminated siltstones, sandstones, arkoses, quartzites and greywackes. They are overlain by more than 300 m thick acidic volcanites and volcanoclastic rocks named the "Comelico-Porphyroid" and "Fleons Formation" respectively (Fig. 3) [3], and their lateral equivalents comprising the Himmelberg Sandstone and the Uggwa Shale. Locally, the latter contain rich fossils such as bryozoans, trilobites, hyoliths, gastropods and cystoids indicating a Caradocian age (V. HAVLICEK et al. 1987). According to R. D. DALLMEYER & F. NEUBAUER (1994) detrital muscovites from the sandstones are

[3] Fig. 3. (Facing page – colour insert) Sketch of Upper Ordovician volcanism in the western Carnic Alps (modified from M. HINDERER 1992).



VISDENE-SCH. | FLEONSFMT.
ABLAGERUNGSRAUM
Grauwacken
Quarzite
Feinklastika
LIEFERGEBIET
Basische Vulkanite
Saure Vulkanite
Ultramafitite
Granitoide
(Meta-) Sedimente
Störung

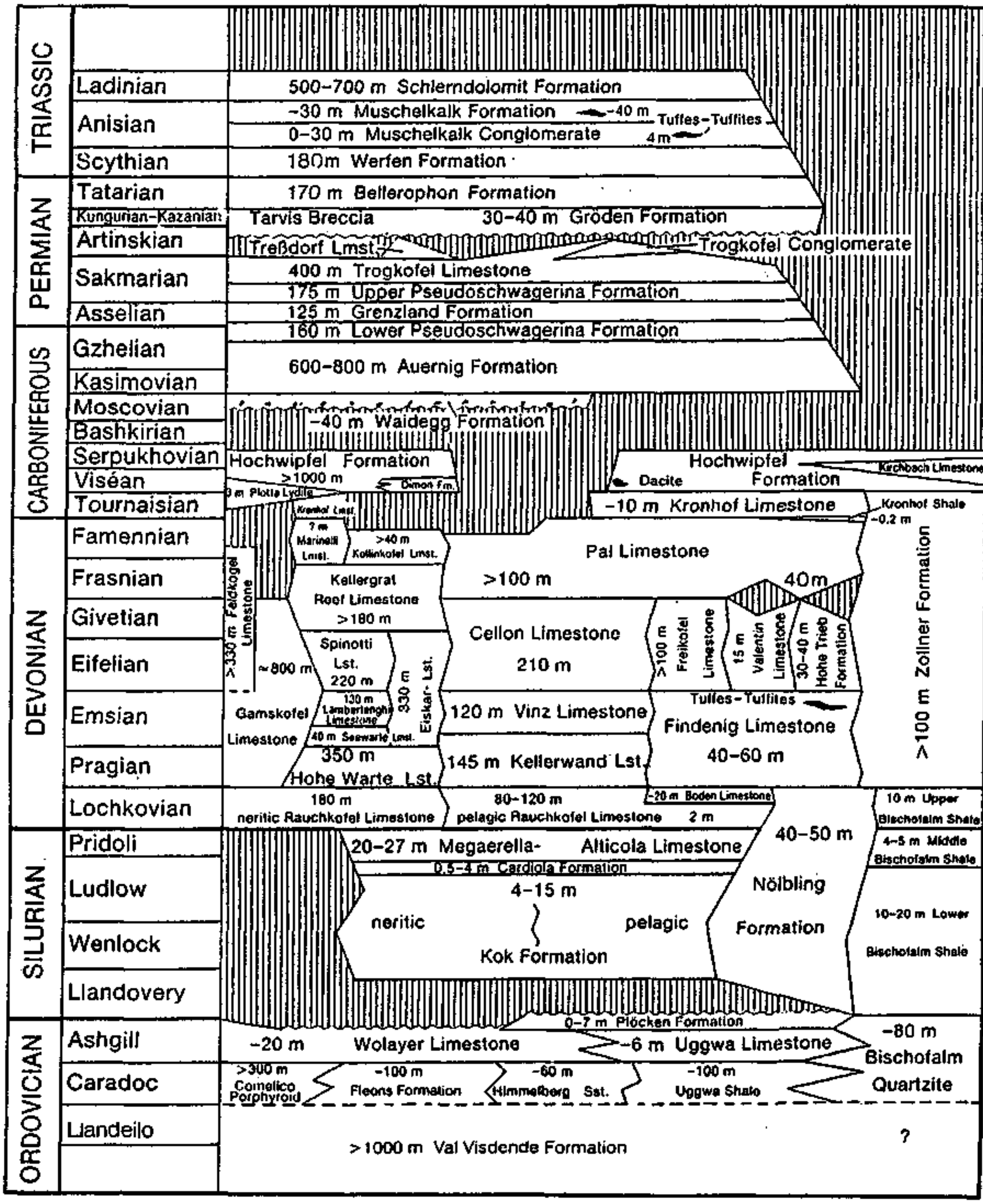


Fig. 4. Biostratigraphic scheme of the Palaeozoic sequence of the Carnic Alps. With only minor modifications this subdivision can also be applied in the Karawanken Alps (after H. P. SCHÖNLAUB 1985, modified).

characterized by appparent ages (40Ar/39Ar) of c. 600 to 620 Ma and may thus be derived from a source area affected by late Precambrian (Cadomian) metamorphism.

This basal clastic sequence is capped by an up to 20 m thick fossiliferous limestone horizon of early Ashgillian age. It displays two lithologies, namely the massive "Wolayer Limestone" composed of parautochthounous bioclasts from cystoids and bryozoans which laterally grades into the bedded wackestones of the "Uggwa Limestone" representing a more basinal setting with reduced thicknesses.

In the Carnic Alps the global glacially induced regression during the Late Ashgillian Hirnantian Stage is documented by marly intercalations and arenaceous bioclastic limestones of the Plöcken Formation which presumably corresponds to the graptolite zone of *Gl. persculptus* (H. P. SCHÖNLAUB 1996). If so it may have lasted during the early and middle Hirnantian Stage for not more than 0.5 to 1 million years. It resulted in channeling, erosion and local non-deposition. In fact, the succeeding basal Silurian strata generally disconformably rest upon the late Ordovician sequence.

Initiation of the fore-mentioned rifting and subsequent movements from higher to lower latitudes may be marked by basic volcanism occurring at various places in the Eastern Alps in pre-Llandeillian strata (for references see H. P. SCHÖNLAUB 1992). In the Southern Alps such rocks have not yet been recognized. The Upper Ordovician faunal affinities, e.g. brachiopods, nautiloids, cystoids, ostracods, conodonts and vertebrate remains indicate links with Bohemia, Thuringia, Baltoscandia, Sardinia and the British Isles (H. P. SCHÖNLAUB 1992, A. FERRETTI & C. R. BARNES 1998, A. FERRETTI 1997, G. BAGNOLI et al. 1998, O. BOGOLEPOVA & H. P. SCHÖNLAUB 1998). Moreover, the appearance of carbonate rocks in the Upper Ordovician suggests a position within the broader carbonate belt for this time. However, also a temporary cold-water influx from northern Gondwana may have existed as can be concluded by certain elements of the Hirnantia fauna, e.g. the genus *Clarkeia* appearing in uppermost Ordovician strata of the central Carnic Alps (H. JAEGER et al. 1975). Based on the available evidence from the Ordovician of the Southern Alps H. P. SCHÖNLAUB (1992) inferred a palaeolatitudinal position at roughly 50°S. Originally this conclusion was based solely on lithic and faunal data but subsequently was confirmed by palaeomagnetic measurements (M. SCHÄTZ, J. TAIT, V. BACHTADSE & H. SOFFEL 1997).

Silurian

The Silurian strata of Austria are irregularly distributed within the Alpine nappe system with occurrences in the Gurktal Nappe of Middle Carinthia and southern Styria, the surroundings of Graz and the Graywacke Zone of Styria, Salzburg and Tyrol while to the south of the Periadriatic Line they occur in the the Carnic and Karawanken Alps. The main differences on either side of the Periadriatic Line being the distribution of fossils, the facies pattern, rates of subsidence, supply area, amount of volcanism and the spatial and temporal relationship of climate sensitive rocks (H.P. SCHÖNLAUB 1992)

The Silurian of the Carnic Alps is subdivided into four lithological facies representing different depths of deposition and hydraulic conditions suggestive of a steadily subsiding basin and an overall transgressional regime from the Llandovery to Ludlow (Fig. 5). Uniform limestone sedimentation during the Pridoli suggests that more stable conditions were

developed at this time (H.P. SCHÖNLAUB 1997). Silurian deposits range from shallow water bioclastic limestones to nautiloid-bearing limestones, interbedded shales and limestones to black graptolite-bearing shales and cherts with overall thicknesses not exceeding 60m. The available data for the Carnic and Karawanken Alps suggest a complete but considerably condensed succession in the carbonate-dominated facies and a continous record in the graptolite-bearing sequences something which is not possible to demonstrate in other areas of the Eastern Alps due to bad preservation, lack of fossils and metamorphic overprints.
In the Carnic Alps the Silurian transgression started at the very base of the Llandovery, i.e. in the graptolite zone of *Akidograptus acuminatus*. Its forerunner from the latest Ordovician, *Gl. persculptus* was reported from the western Karawanken Alps (H. JAEGER et al. 1975). Due to the disconformity separating the Ordovician and the Silurian at many places a varying pile of sediments is locally missing, which corresponds to several conodont zones of Llandoverian to Ludlovian age in both the Carnic and Karawanken Alps. At some places even uppermost Pridolian strata may disconformably rest upon Upper Ordovician limestones.

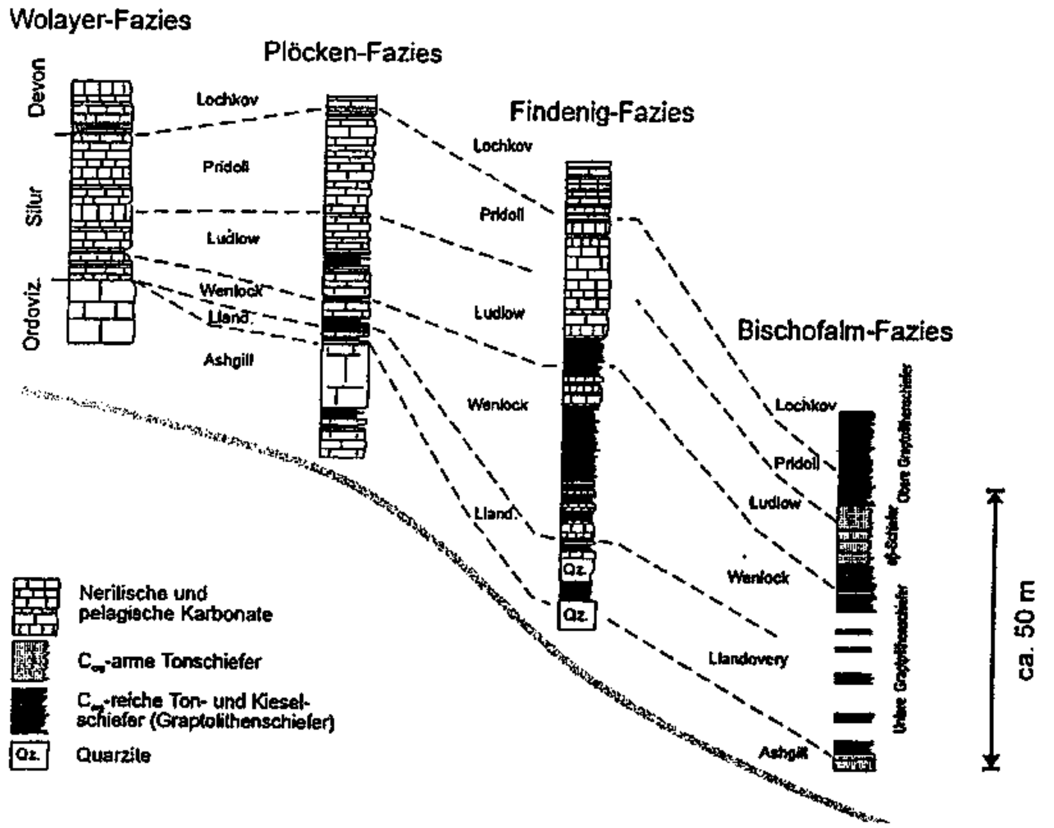


Fig. 5. Lithology of Silurian sediments of the four different lithofacies of the Carnic Alps. Brickstone reflects carbonates, black corresponds to C_{org} rich graptolite-bearing shales and cherts and C_{org} rich carbonates of the Wolayer facies. Light gray represents C_{org} poor shales. Columns from left to right show the sections Rauchkofel Boden, Cellon, Oberbuchach 1-2 and Nölblinggrabe-Graptolithengraben. In the latter composite section Lower Silurian sediments are not continuously exposed. From B. WENZEL 1997.

The Rauchkofel Boden section is one of the best known and most fossiliferous Upper Silurian sections of the Carnic Alps corresponding to the "Wolayer facies", an apparently shallower marine environment. The contact with the underlying massive cystoid Wolayer Limestone (Upper Ordovician) and the Mid Wenlock bioclastic limestones with a rich fauna of nautiloids, bivalves, brachiopods and trilobites representing the neritic Kok Formation is marked by an iron-oolitic concentration. Development of microstromatolites is also evident in the lower levels of the sequence. In the Wenlock / Ludlow transition thinly developed cyclic micritic limestone beds of bioclastic accumulations are separated by stylolites and sometimes iron-oolitic concentrations which may mark the end of depositional regimes. Concentrations of apparently juvenile and equidimensional articulate brachiopods, nautiloids and gastropods alternate with the dominantly nautiloid beds (the classic *Orthoceras* limestone) in the lower Ludlow demonstrating the changing energy and oxygen levels of the formation while the preservation and orientation of the fauna indicate many accumulated levels with intermittent changes in sea level particularly towards the top of the sequence. The overlying *Cardiola* Formation, Ludlow in age, comparable with the well-known cephalopod limestone deposited in Bohemia and along the North Gondwana margin is represented by a thinly developed dark limestone showing lateral variation in its outcrop. Nautiloids and bivalves are the dominant fauna in this micritic limestone which represents more current-ventilated conditions. The Alticola Lst., Pridoli in age, is a fine grey micritic limestone with abundant micritised bioclasts, frequent stylolites and an abundant nautiloid fauna throughout the formation. The associated shallow water fauna is similiar to the Kok Formation except for the presence of ruguse corals. A *Scyphocrinites* bed bearing complete specimens caps the formation and marks the Silurian /Devonian boundary and the shallowest level of the sequence.

The Cellon section represents the stratotype for the Silurian of the Eastern and Southern Alps (WALLISER,1964) and the "Plöcken facies" is developed here as a shallow to moderately deep marine carbonate series (FLÜGEL *et al.*, 1977). The condensed nature of the sequence of the Cellon is clearly demonstrated when correlated with the thicknesses of the same intervals of the more basinal facies of mainly graptolitic shales of the Oberbuchach section and the even more condensed Rauchkofel Boden section. Underlain by the Uggwa Limestone and clastic Plöcken Fm. the carbonate sequence of the Plöcken Facies were deposited in a relatively shallow environment, periodically effected by storm currents, with intervals of reduced deposition and non-sedimentation in an overall transgressive sequence. The pelagic Kok Formation consists of a transgressive carbonate series with alternating black shales and dark grey to slightly red micritic lenticular limestones occuring at the base of the formation in the upper Llandovery and brown-red ferruginous limestones with abundant nautiloids and frequent stylolites in the Wenlock - lower Ludlow. Two deepening events are documented within the formation: at the transition between the Llandovery and Wenlock and between the Wenlock and Ludlow (SCHÖNLAUB 1997). WENZEL (1997, fig. 7) also illustrates several variations of the oxygen Isotope ratio throughout the Kok Formation in particular at the transition of the Llandovery/Wenlock and Wenlock/Ludlow. Frequent levels showing bioturbation and condensed brachiopod accumulations also demonstrate changes in hydrodynamic regime (K. AZMY et al. 1998).

The alternating rapid deposition of black shales and laminated micrites with more time-rich light grey nodular micrites with an abundant nautiloid fauna of the Cardiola Formation (Ludlow) indicate a slightly deeper offshore environment with probable contemporary non-deposition taking place. Current activity of varying hydrodynamic regime is evidenced by

these accumulations and periodic increases in oxygen content throughout the sequence may be implied from the concentrations of brachiopods /bivalves and pockets of *chondrites*.
A more stable pelagic environment is developed in the Alticola and Megaerella Limestones from the upper Ludlow continuing into the Prídolí (SCHÖNLAUB, 1997) represented by a transgressive carbonate series of grey to dark pink micritic limestones with a variety of bed thickness and frequent stylolites The beds decrease in thickness in the Pridoli and alternate with interbedded laminated micrites with a dominant nautiloid and brachiopod fauna. Several deepening events marked by the development of black shales have been documented within the uppermost levels of the Pridoli. An offshore setting frequently ventilated by currents of varying energy is envisaged for the upper Ludlow and Pridoli sequences of the Alticola Limestone. The Megaerella Limestone (Pridoli in age) comprises the upper Pridoli and Silurian / Devonian boundary transgressive sequences of biodetritus-rich carbonates, lenticular micrites and black shales. The boundary between the Silurian and Devonian is drawn based on conodonts with the first occurrence of *Icriodus woschmidti* (WALLISER, 1964). However, the first evidence from graptolites of Lochkovian age is found in bed 50 with the occurrence of *M. uniformis* (JAEGER, 1975).
There appears to be a distinct gradation of beds upwards towards the Silurian / Devonian boundary indicating that the hydrodynamic regime is constantly changing with the shallowest point being reached at the base of the Rauchkofel limestone (Lochovian) with the occurrence of a bryozoan fauna.
The large oxygen isotope ratio excursion shown by WENZEL (1997) at the boundary may be supported by the more ventilated setting implied by the bryozoan fauna. PRIEWALDER (1997) indicates a rich chitinozoan fauna from the Pridoli - Lochkovian interval therefore the depositional environment was of a low hydrodynamic regime favorable for their preservation.

The intermediate "Findenig Facies" occurs between the shallow water condensed sequences outlined above and the starving basinal facies. It consists of the interbedded black graptolitic shales, marls and blackish carbonates of the Nölbling Formation which is locally underlain by a quartzose sandstone.
The stagnant water graptolitic "Bischofalm Facies" is represented by black siliceous shales, lydites and clayish alum shales. The transgressional regime in both of these more basinal facies continued from the Llandovery to the Ludlow when a slight decrease in the subsidence of the basin is documented by the green-gray shales of the Middle Bischofalm Shale Formation. A return to the deeper water graptolitic sequence is seen in the late Pridoli to Lochkov.

The evidence from the Silurian indicates faunal affinities, e.g. conodonts, trilobites, brachiopods, molluscs, chitinozoa and architarchs with Baltica and Avalonia as opposed to loose relationships with Africa and southern Europe. In addition, first occurrences of rugose and tabulate corals, ooids and stromatolites indicate a moderate climate. An overall island setting may be inferred by a generally condensed and reduced sedimentary pattern without significant clastic imput. These data suggest an ongoing drift towards lower latitudes and consequently a paleolatitudinal position between 30 and 40°S. In the central Alps rifting-related basic volcanism underpins these inferred plate movements.

A sea-level curve for the Llandovery-lower Ludlow interval of the Cellon (Plöcken Facies) and Oberbuchach (Findenig Facies) sections of the Carnic Alps has been elaborated by C.E. BRETT and H.P. SCHÖNLAUB based on a sequence stratigraphy study of the sections (Fig. 6). The variations in sea-level compare quite well with those inferred by M.E. JOHNSON

(1996) and D. K. LOYDELL (1998) for the global sea-level changes during the Lower Silurian. A correlation of the sequence boundaries and sea-level changes determined for the Carnic Alps with those of N.E. America and Britain (C.E. BRETT et al. 1990, W.M. GOODMAN and C.E. BRETT 1994) suggests proximity also with Laurentia and Avalonia during this time interval as the global eustatic changes effecting the Gondwana-derived terranes to the east and Laurentia to the west are quite similiar.

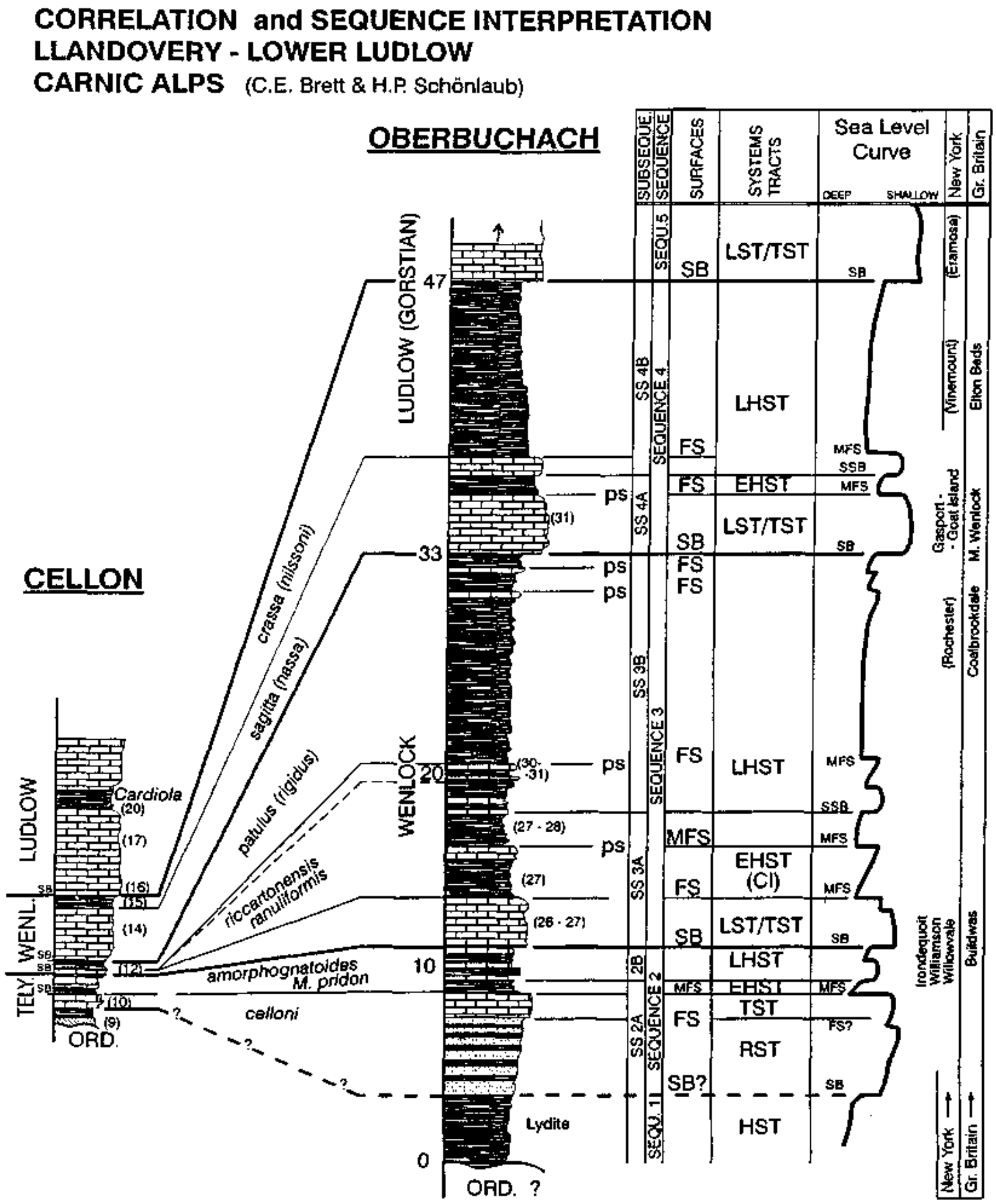


Fig. 6. Correlation and sequence interpretation Llandovery - Lower Ludlow, Carnic Alps. (C.E. BRETT & H. P. SCHÖNLAUB)

Devonian

In the Southern Alps 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. The ratio of thicknesses between shallow-water limestones and contemporary cephalopod limestones approximates 1200 : 100 m and thus indicates differentially subsiding mobile basins affected by extensional tectonics. This regime lasted until the early Lower Carboniferous. Rifting-related volcanism, however, is only known in the Central Alps, e.g., in the Graywacke Zone and the surroundings of Graz.

The Lower Devonian is characterized by a transgressional sequence including the neritic Rauchkofel Lst. (up to 180 m thick) which corresponds to some 20 m of pelagic limestones (Boden Lst.). During the Pragian and Emsian Stages the differences even increased. Within short distances of less than 10 km a strongly varying facies pattern developed indicating a progressive but not uniform deepening of the basin. It was filled with thick reef and near-reef organodetritic limestones including different intertidal lagoonal deposits of more than 1000 m thickness in the Carnic Alps and some 300 m in the Karawanken Alps. They are time-equivalent to some 100 m of pelagic cephalopod limestones and the pelitic Zollner Formation:

During the Upper Ordovician and the Silurian, reef evolution never exceeded a pioneer faunal stage with pelmatozoans suggesting flat biostromes and a weak tendency to form low topographic carbonate buildups. In the Lochkovian and Pragian Stages, the appearance of corals and stromatoporoids indicate more favourable life conditions and first patch reefs accumulated. Main reef builders were stromatoporoids, tabulate corals and calacareous algae such as *Renalcis*.

According to L. H. KREUTZER 1992a,b in the Carnic Alps five north-northeast to south-southwest directed facies belts developed in the Devonian Period. During later orogenic events these belts were strongly deformed, being distributed in different nappes and tectonic slices which from top to base can be subdivided into the following units (Fig. 7):

1. Southern shallow-water facies of the Cellon-Kellerwand nappe
   a: Intertidal subfacies at Biegengebirge and Gamskofel
   b: Back reef subfacies at Upper Kellerwand, Hohe Warte, Biegengebirge
   c: Reef subfacies at Hohe Warte and Upper Kellerwand
   d: Reef debris subfacies at Hohe Warte and Upper Kellerwand
2. Transitional facies of Cellon nappe
3. Pelagic limestone facies of Rauchkofel nappe
4. Pelagic off-shore basinal facies of Bischofalm nappe
5. Northern shallow water facies.

In the Carnic Alps the approximately 1300 m high cliffs of the Kellerwand and of Hohe Warte (2784 m above sea level) represent the depocenters of the Devonian reef building which reached the climax during the Givetian and Frasnian Stages. The strongly varying thicknesses of all facies belts during the Devonian contrasts markedly with the foregoing Silurian Period. In the interval from the Lockovian to the Frasnian in facies belt 1 more than 1100 m of limestones accumulated corresponding to some 100 m of cephalopod limestones in facies belt

3. Between both facies belts an intermediate environment developed in facies belt 2. According to L. H. KREUTZER 1990, 1992b at least 13 different carbonate microfacies types can be recognized for the Devonian.

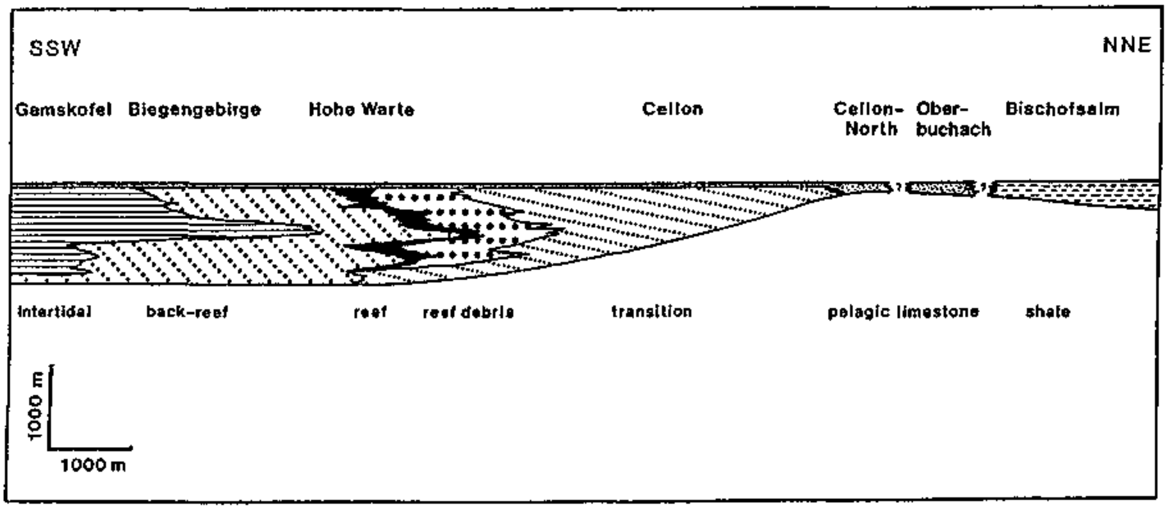


Fig. 7. Palinspastic profile of the Carnic Alps at the Devonian/Carboniferous boundary. Gamskofel, Biegengebirge, Hohe Warte: Southern shallow water facies (Kellerwand nappe. Cellon: Transitional facies (Cellon nappe). Cellon-North, Oberbuchach: Pelagic limestone facies (Rauchkofel nappe). Bischofalm: Offshore pelagic basinal facies (Bischofalm nappe). Further to the north the northern shallow water facies of the Feldkogel nappe occurs. After L. H. KREUTZER 1992a.

The reef development ended in the Late *P. rhenana* conodont Zone of the upper Frasnian. At the Frasnian/Famennian boundary the reefs drowned and a uniform pelagic environment developed which lasted across the Devonian/Carboniferous boundary. During the Famennian the reddish, pinkish and greyish Pal Limestone was deposited followed by the Kronhof Lst. in the Tournaisian which both represent cephalopod-trilobite-ostracod-bearing wackestones.

Northeast of facies belt 3 the almost carbonate-free facies 4 occurred attaining a thickness comparable to the cephalopod limestone facies. This siliciclastic facies comprises mainly black and greenish shales, siltstones and siliceous shales and massive and well bedded variegated cherts together named the Zollner Formation. It succeeded the Silurian to Lochkovian graptolite-bearing black Bischofalm Formation at the base of the Pragian and continued into the Lower Carboniferous. So far, in these rocks only a few conodont data from bedding planes and interbedded limestone lenses provide age assignements and hence pose some problems to infer the actual thickness of the Zollner Formation.

For the Karawanken Alps G. RANTITSCH (1990) concluded an arrangement of reefs resembling present-days atolls as opposed to the Carnic Alps with its barrier-type reefs (L. H. KREUTZER 1990, 1992a). Depending on adequate subsidence the location of the reef core shifted spatially and temporarily during the Devonian. Differing from the Carnic Alps with its 150 m thick reefs of Givetian age, in the Karawanken Alps there are no good records from the Middle Devonian. In both areas, however, the reef development ended in the Frasnian when the former shallow sea subsided being followed by a drowning and erosion of the reefs.

Similar to the Carnic Alps in the Karawanken Alps these shallow water deposits were also replaced by uniform pelagic goniatite and clymeniid limestones.

During the Devonian Period faunal exchange between the peri-Gondwanide microcontinents, including those possibly attached to northern Africa, and affinities to the equatorial warm-water realm in the vicinity of Baltica increased suggesting the continued approach of the Southern Alps towards lower latitudes. In particular, Lower Devonian brachiopods, corals, gastropods, trilobites and algae reflect close relationships with southern, central and western Europe but also to the Ural-Tienshan region as opposed to northern Africa (H. P. SCHÖNLAUB 1992, B. HUBMANN & A. FENNINGER 1993). In addition, equatorial gyres may have aided the distribution of several planctonic groups of organisms.

As mentioned above the Devonian of the Southern Alps is particularly characterized by thick carbonate deposits which locally have formed buildups containing a highly diversified fauna and flora. Within short distances of only a few kilometers these shallow water deposits grade into coeval sequences with reduced thicknesses. This facies pattern implies spatially and temporary enhanced rates of subsidence in an extensional regime and thus characterizes a passive plate margin prior to the collison with a land area to the north. In the whole Southern Alps evidence for rifting-related volcanism is generally very weak and may only occur in the Karawanken Alps.

In conclusion, the combined lithic and fossil data from the Devonian Period suggest that the Southern Alps were placed within the tropical belt of some 30° S or less (SCHÖNLAUB 1992). This estimation seems well constrained by palaeomagnetic data (SCHÄTZ et al. 1997).

Carboniferous

According to H. P. SCHÖNLAUB et al. (1991) in the Carnic and Karawanken Alps the vertical range of the Variscan limestone successions varies considerably. Some end close to the Frasnian/Famennian boundary, others in the middle or upper Famennian, and others range within different levels of the Lower Carboniferous (Fig. 8). Yet, at some localities the uppermost beds have yielded diagnostic conodonts and ammonoids of the *anchoralis-latus*-conodont zone, thus indicating an age at the Tournaisian/Visean boundary. Recenty, a slightly younger age has been inferred from additional sections from the Italian side of the Carnic Alps, west of Plöckenpaß, which provided a "post-*Scaliognathus*" conodont fauna corresponding to the Pericyclus IIγ Stage of the uppermost Tournaisian or lowermost Visean Stage of the Lower Carboniferous (H.P. SCHÖNLAUB & L. H. KREUTZER 1993, M. C. PERRI & C. SPALLETTA 1998a,b, C. SPALLETTA & M. C. PERRI 1998).

The nature of the transition from the above mentioned limestones to the overlying siliciclastics of the Hochwipfel Formation raised a long lasting controversy about the significance of tectonic events in the Lower Carboniferous (Fig. 9).

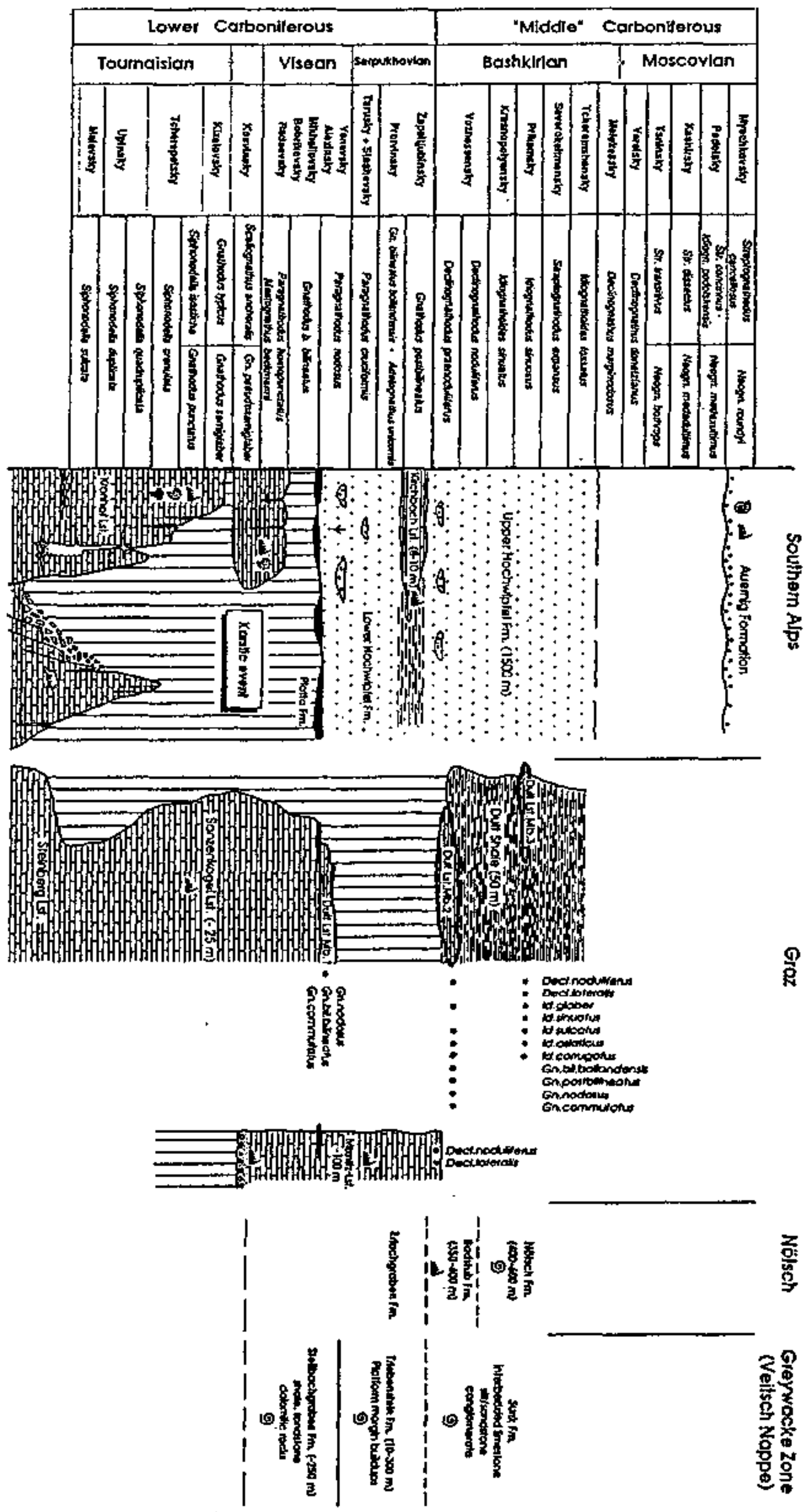
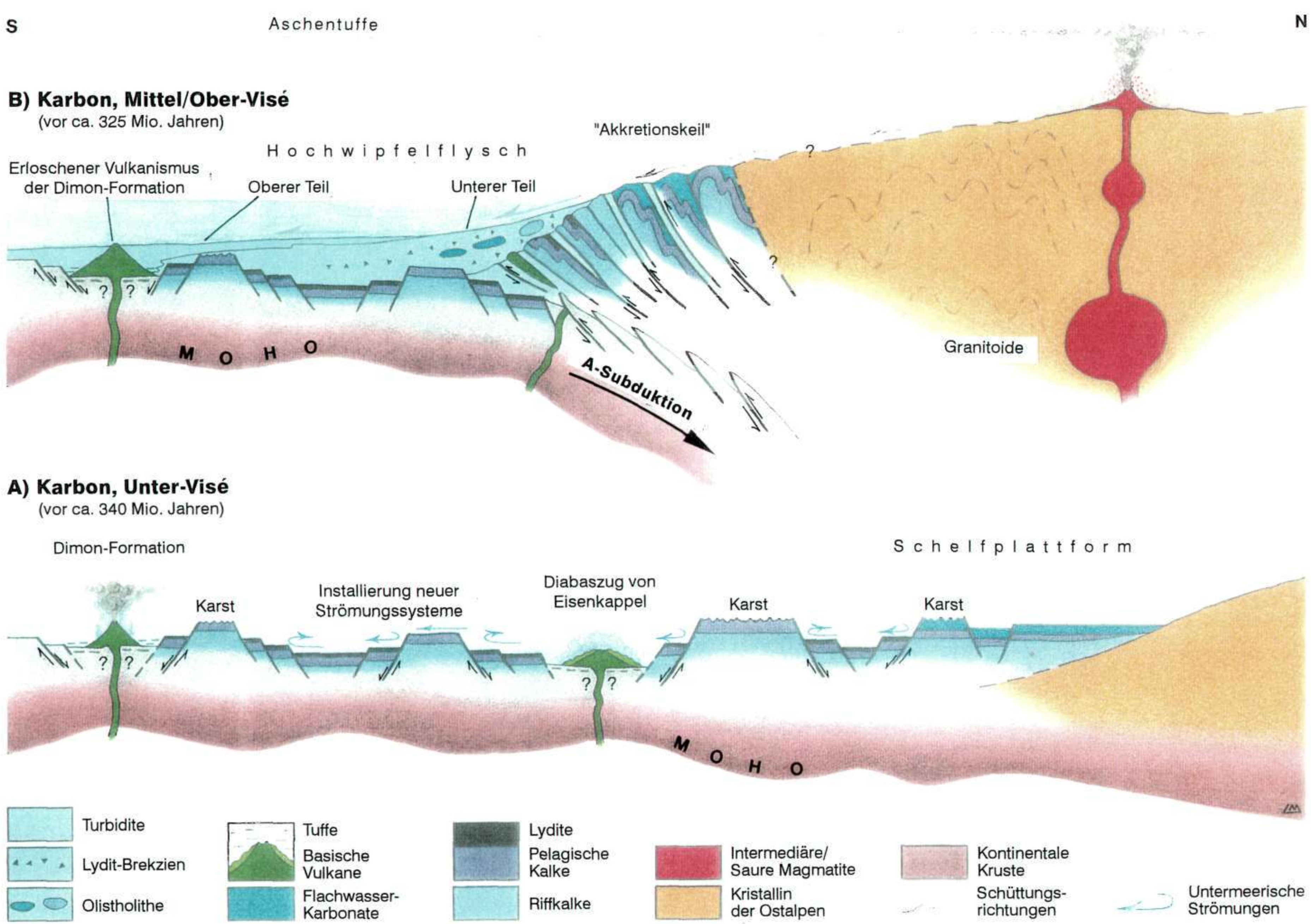


Fig. 8. Correlation of Lower Carboniferous squences of the Southern and Eastern Alps. Note the palaeokarst event.[4]

[4] Fig. 9. (Facing page-colour insert) Geodynamic model of the tectonic and sedimentary history of the Southern and Central Alps during the Lower Carboniferous transition from a passive to an active plate margin regime (after A. LÄUFER et al. 1993, modified).


S
N
Aschentuffe
B) Karbon, Mittel/Ober-Visé
(vor ca. 325 Mio. Jahren)
"Akkretionskeil"
H o c h w i p f e l f l y s c h
Erloschener Vulkanismus
der Dimon-Formation
Oberer Teil
Unterer Teil
M O H O
A-Subduktion
Granitoide
A) Karbon, Unter-Visé
(vor ca. 340 Mio. Jahren)
Dimon-Formation
S c h e l f p l a t t f o r m
Karst
Installierung neuer
Strömungssysteme
Diabaszug von
Eisenkappel
Karst
Karst
M O H O
Turbidite
Lydit-Brekzien
Olistholithe
Tuffe
Basische
Vulkane
Flachwasser-
Karbonate
Lydite
Pelagische
Kalke
Riffkalke
Intermediäre/
Saure Magmatite
Kristallin
der Ostalpen
Kontinentale
Kruste
Schüttungs-
richtungen
Untermeerische
Strömungen

Apparently, this has been settled after recognition of a wide variety of distinct palaeokarst features in the Karawanke and the Carnic Alps (F.TESSENSOHN 1974, H.P. SCHÖNLAUB et al. 1991) including an extensive palaeorelief with surface-related collapse breccias, fissures, strata-bound ore carbonate deposits, a silcrete regolith ("Plotta Lydite"), and formation of caves with cave sediments, speleothems and palaeokarst-related cements in the subsurface . The palaeokarst was caused by a drop in sea-level during the Tournaisian. Rise of sea-level and/or collapse of the basin promoted the transgression of the Hochwipfel Formation which presumably started in the Lower Visean .

Based on its characteristic lithology and sedimentology F. TESSENSOHN 1971, 1983, C. SPALLETTA et al. 1980, H. W. J. van AMEROM et al. 1984, C. SPALLETTA & C. VENTURINI 1988 and others interpreted the 600 to more than 1000 m thick Hochwipfel Formation as a Variscan flysch sequence. In modern terminology the Kulm deposits indicate a Variscan active plate margin in a collisional regime following the extensional tectonics during the Devonian and Lower Carboniferous Periods. The main lithology comprises arenaceous to pelitic turbidites with intercalations of several tens of meters of thick pebbly mudstones, chaotic debris flows and chert and limestone breccias in its lower part which may represent submarine canyon fillings or inner fans. In addition to these lithologies, along the northern margin of the region up to 10 m thick plant-bearing sandstone beds consitute a prominent member of the Hochwipfel Formation. Except for trace fossils the palaeontological evidence of the flysch sediment is very poor. However, plant remains are locally very common suggesting a Middle Visean to Namurian age for its formation (H. W. J. van AMEROM et al. 1984, H. W. J. van AMEROM & H. P. SCHÖNLAUB 1992). Other stratigraphic data are derived from the fore-mentioned underlying limestone beds and locally occurring intercalations of the Kirchbach Limestone which provided index conodonts of the Visean/Namurian boundary (E. FLÜGEL & H. P. SCHÖNLAUB 1990). Also of great interest are limestone clasts within the debrites which comprise a broad spectrum of shallow water carbonate shelf types with stratigraphically important fossils such as the coral *Hexaphyllia mirabilis*, the algae *Pseudodonezella tenuissima*, the foraminfera *Howchinia bradyana* and early fusulinids. These clasts were supplied from a shelf-like source area localted originally to the north of the present Southern Alps but which was completely destroyed by later tectonic events.

According to A. LÄUFER et al. 1993 the volcaniclastites and basic volcanics of the Dimon Formation occur at the base of the Hochwipfel Formation and not as its lateral equivalents or as a succeeding event. They represent intraplate alkalibasalts indicating the climax of the rifting immediately before the onset of the deposition of the Hochwipfel Formation.

In the Southern Alps the Variscan orogeny reached the climax between the Late Namurian and the Late Westphalian Stages. This time corresponds to the interval from the Early Bashkirian to the Middle or Late Moscovian Stages. According to F. KAHLER (1983) the oldest post-Variscan transgressive sediments are Late Middle Carboniferous in age and, more precisely, correspond to the *Fusulinella bocki* Zone of the Upper Miatchkovo Substage of the Moscovian Stage of the Moscow Basin (for more details see K. KRAINER 1992). In particular between Stranig Alm and Lake Zollner they rest with a spectacular angular unconformity upon strongly deformed basement rocks including the Hochwipfel Formation, the Silurian-Devonian Bischofalm Formation and different Devonian limestones. This basal part named the Waidegg Formation consists mainly of basal conglomerates, disorganised pebbly siltstones and arenaceous and silty shales with thin limestone intercalations. Even meter-sized limestone boulders reworked from the basement were recognized at the base of the transgressive sequence (A. FENNINGER et al. 1976) and which was named Malinfier Horizon by Italian geologists (C. VENTURINI 1989, 1990).

The lower part of the Bombaso Formation south of Naßfeld, i.e., the Pramollo Member, has also long been regarded as the base of the Auernig Group in this area (C. VENTURINI et al 1982, C. VENTURINI 1990). Based on new field evidence, however, for this member a clear relationship with the Variscan Hochwipfel Formation is suggested.

In the Naßfeld region the transgressive molasse-type cover comprises the 600 to 800 m thick fossiliferous Auernig Group. Although the oldest part may well correspond to the late Moscovian Stage (M. PASINI 1963) the majority of sediments belong to the Kasimovian and Ghzelian Stages. Based on rich fusulinid evidence from the Schulterkofel section west of Rattendorf Alm the Carboniferous/Permian Boundary has recently been drawn by the first appearance of the genera *Pseudoschwagrina* and *Occidentoschwagerina* in the upper part of the Lower Pseudoschwagerina Lst. and not at its base as previously was suggested (F. KAHLER & K. KRAINER 1993).

Permian

In the Lower Permian the Auernig Group is succeeded by a series of more than 1000 m thick shelf and shelf edge limestones and clastics (K. KRAINER 1992, 1993, H. C. FORKE 1995). They characterize a differentially subsiding carbonate platform and outer shelf setting which were affected by transgressive-regressive cycles from the Westphalian to the Artinskian Stages. This cyclicity may be explained as the response to the continental glaciation in the Southern Hemisphere (K. KRAINER 1991, E. SAMANKASSOU 1997).

Upper Permian sediments rest disconformably upon the marine Lower Permian or its equivalents, and farther west, on the Ordovician Val Visdende Formation and quartzphyllites of the Variscan basement. They indicate a transgressive sequence starting with the Gröden Formation and followed by the Bellerophon Formation of Late Permian age (K. BOECKELMANN 1991, W. T. HOLSER et al. 1991, K. KRAINER 1993).

Upper Carboniferous and Permian molasse-type sediments also occur in the Seeberg area of the Eastern Karawanken Alps (F. TESSENSOHN 1983, F. BAUER 1983). Although strongly affected by faults the general lithology and the fossil content resemble that of the Auernig Group of the Carnic Alps being dominated by interbedded fusulinid and algal bearing limestones, areanceous shales, sandstones and massive beds of quartz-rich deltaic conglomerates. Equivalents of the Permian are represented by the Trogkofel Lst., its coeval detritic Trogkofel Formation and the Gröden Formation. The Bellerophon Formation is only locally preserved.

In the Eastern Karawanken Alps, north of the Periadriatic Line, rocks of Palaeozoic age have long been known. They belong to the so-called "Diabaszug von Eisenkappel" (Fig. 10). This narrow belt extends in a W-E direction from Zell Pfarre via Schaidasattel to east of

Eisenkappel and continues further east to Slovenia. In Austria this zone has a length of more than 25 km and a maximum width of 3,5 km. The 650 m thick Palaeozoic sequence comprises up to 350 m of volcanic and volcaniclastic rocks and sediments. According to K. LOESCKE 1970-1977, 1983, J. LOESCHKE et al. 1996) the first group is dominated by basic tuffs and tuffitic rocks, massive pillow lavas and basic sills of hawaiitic composition with ultrabasic layers. Sills and pillow lavas represent spilites which differentiated from alkali olivine basalts, the original geotectonic setting of which is yet not known. Subsequent low-temperature metamorphism associated with devitrification and metasomatic replacement processes caused the spilitic mineral composition in these rocks. The sedimentary rocks are monotonous gray shales and slates with intercalations of conglomeratic graywackes, quartzitic and graphitic sandstones and thin limestone beds. The definite age of this succession is yet not exactly known although some poorly preserved single cone conodonts recovered from the limestone intercalations are rather in favour of an Ordovician than any younger age (F. NEUBAUER, pers. comm.).

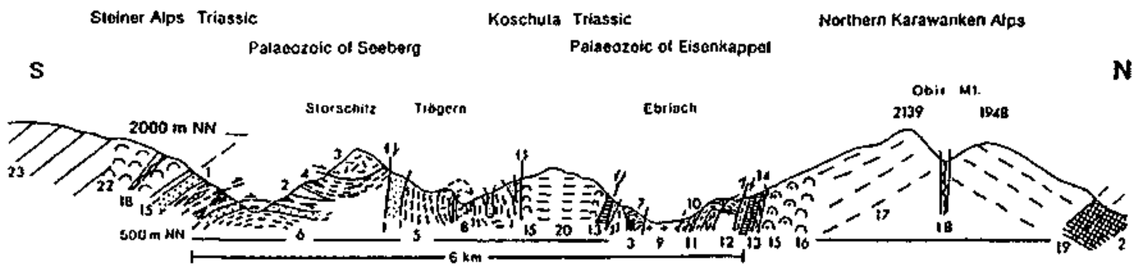


Fig. 10. N-S directed section through the Eastern Karawanken Alps. Numbers indicate (1) post Variscan Permian and Late Carboniferous, (2) banded limestone thurst sheets in imbricate structure, (3) Devonian limestones, (4) undated volcanics, (5) Hochwipfel Fm., (6) Seeberg Shale, (7) Upper Ordovician and Silurian rocks, (8) volcanics of the Upper Ordovician, (9) Granite of Eisenkappel, (10) pillow lava of the "Diabaszug of Eisenkappel", (11) sills, (12) Werfen Fm., (13) Muschelkalk Fm., (14) Partnach Fm., (15, 16, 17) Wetterstein Lst., (18) Raibl Fm., (19) Rhätian to Jurassic deposits, (20) Schlern Dolomite, (21) Tertiary, (22, 23) Dachstein Lst. (from H. P. SCHÖNLAUB 1979).

Tectonic Remarks

The Palaeozoic sequence of the Carnic and Karawanken Alps represents a strongly compressed WNW-ESE running thrust sheet complex composed of isoclinally folded anchi-to epimetamorphic Palaeozoic rocks. The Palaeozoic and Triassic succession was affected by both the Variscan and Alpine orogenic cycles. Based on illite crystallinities from the Carboniferous Hochwipfel Formation and K-Ar ages A. L. LÄUFER 1996 concluded that Variscan epizonal metamorphism was equal or slightly higher than the Alpine overprint. Thus, Variscan deformations were not completely destroyed. In contrast the less intensely folded late Carboniferous to Triassic cover in the central and eastern Carnic Alps reached mainly anchizonal conditions with temperatures roughly between 235 and 270°C. The northernmost tectonic units adjacent to the Periadriatic Line reveal two deformation events. The younger epizonal metamorphism and ductile deformation is of late Alpine age and is related to Tertiary activities along the Periadriatic Line and exhumation by transpression (A. L. LÄUFER 1996).

The south-verging fold-and-thrust belt developed during the Variscan orogeny in the Late Namurian or Early Westphalian. It is sealed by the post-Variscan cover overlying the deformed basement with a distinct angular unconformity. Paraconformities occur at different levels within the Palaeozoic sequence, for example, at the end of the Ordovician, in the late Middle and early Upper Devonian and in the Lower Carboniferous. Presumably, they were caused by sea-level changes related to the glaciation of parts of Gondwana at the end of the Ordovician, to seismic shock events, and to a palaeokarstic event, respectively. Lowering of sea-level and/or block faulting may also have acted at the end of the Trogkofel Stage being responsible for extensive erosion and accumulation of reworked limestones, stratigraphic gaps, formation of fissures and local karstification.

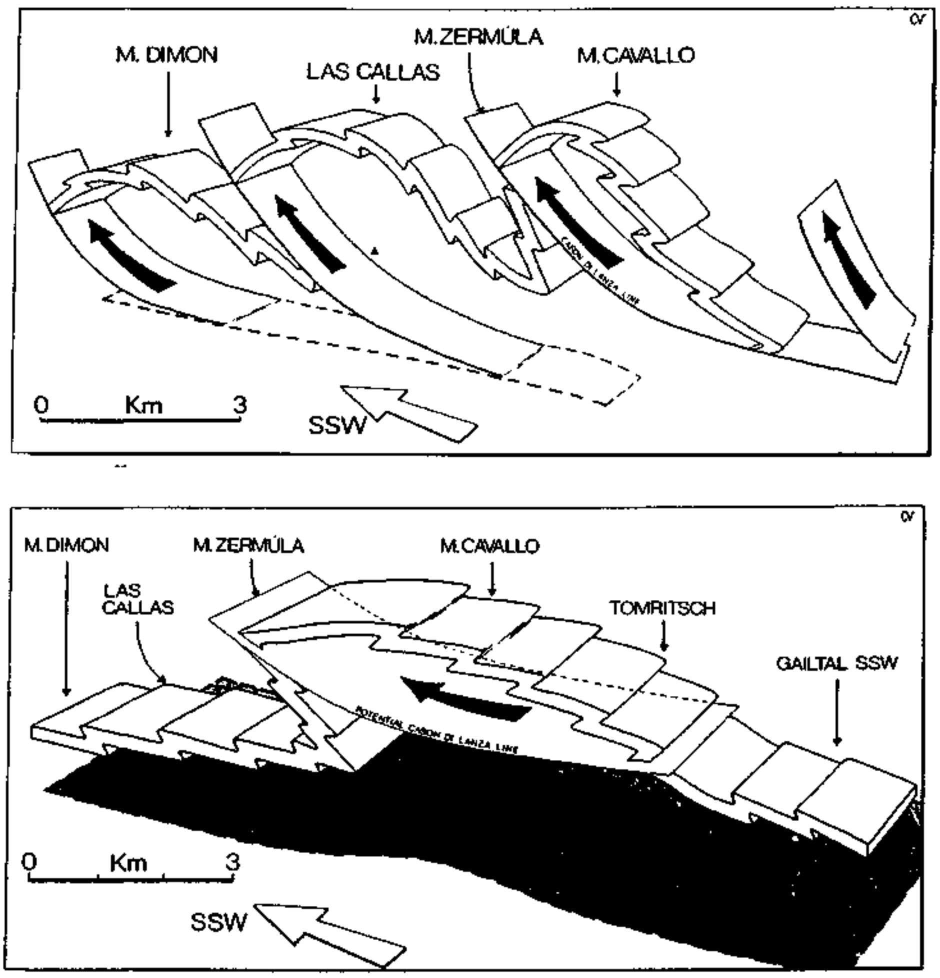


Fig. 11. Hercynian deformation of the Carnic Alps. The 1st and 3rd (Figure above) deformative phases are shown. The huge asymmetric fold affected the whole Palaeozoic belt. The 3rd phase formed thrusts with open folds which re-folded the older structures of the 1st and 2nd deformative stages (from C.VENTURINI 1990).

For many years the complicated tectonics of the Carnic Alps was explained in terms of 9 nappes produced during the Variscan orogeny. Each north verging nappe consisted of a more or less continuous Ordovician to Devonian sequence and was separated from the next by the clastics of the Hochwipfel Formation. The extent of Alpine overprints on this pile of nappes was difficult to decipher. With respect to the less deformed post-Variscan cover, however, it was concluded that the intensity of the Variscan tectonics was much stronger than the Alpine deformation. Nevertheless, the latter resulted in interferences between both and was responsible for a complex deformative pattern in the Southern Alps (A. CASTELLARIN & G. B. VAI 1981)

According to G. B. VAI 1979 the horizontal shortening of the Carnic Alps during the Variscan deformation is estimated to 75-80% of its original width. This value does not consider the assumed detachment from pre-Ordovician basement rocks.

Based on new field data, mainly from the Naßfeld area, the old concept was challenged by C. VENTURINI (1990, 1991) who proposed a new structural model. He speculated on three distinct and interacting phases that resulted in different systems of asymmetric folds and faults distributed along a N 120° - 140° E direction (Fig. 11):

1. Middle or early Upper Carboniferous compressional tectonics caused a huge SSW-verging fold that affected the whole belt. Synkinematically a back fold system with clear northern vergence developed behind it. Such smaller-scale syn-and anticlines can be recognized, for example, on Roßkofel, at Hoher Trieb, at Plöckenpaß-Kleiner Pal-Piz Timau. Perhaps even the fold structure separating the Cellon subnappe from the Kellerwand-subnappe (L. H. KREUTZER 1990) can be attributed to this deformation.

2. In response to uplifting brittle deformation occurred with development of flat fault planes along shale horizons. As a result the huge asymmetrical fold was cut into smaller tectonic slices.

3. The third phase occurred during further uplift. It produced huge open antiforms following new thrust planes and older folded structures. These were later reactivated during the Alpine compression.

The formation of sedimentary basins in the Upper Carboniferous was governed by extensional tectonics (C. VENTURINI 1990). They were related to 120° to 130° directed fault zones, forming thus an elongated trough with an original width of not more than 15 km, shortened today to a narrow zone of some 10 km.

With regard to the Alpine deformation of the Carnic Alps the reader is referred to P. EICHÜBL (1988) and C. VENTURINI (1990, 1991).

The tectonic framework of the Eastern Karawanken Alps is characterized by the north verging anticlinal structure of the central and southern part (Fig. 12). Its axis dips gently towards southwest. The whole area may be subdivided into two superimposed allochthonous units. In addition, north of the Seeberg anticline the folded Trögern area further complicates the deformation style.

1. In the area around the Seeberg Pass the uppermost part is represented by the Reef Unit. Rocks of the core are well exposed near the Pass. They comprise reef and near-reef limestones, e.g., north of Plasnik (P.1257), at Rapold, Pasterk, Storschitz and at the Grintoutz localities. Laterally this facies grades into forereef and pelagic deposits. Generally, the

sequence within this unit consists of different limestones of Devonian age, followed locally by the Carboniferous Hochwipfel Formation and transgressive sediments of Late Carboniferous and Permian age. At the southern limb geologically well known outcrops are located such as Paulitschwand, Leßnik and Sadnikar, while on the northern side Sadonighöhe, Stanwiese, Grintoutz and Hirschfelsen have long been famous. The lateral movement of the Reef Unit is estimated to be some 4,5 km.

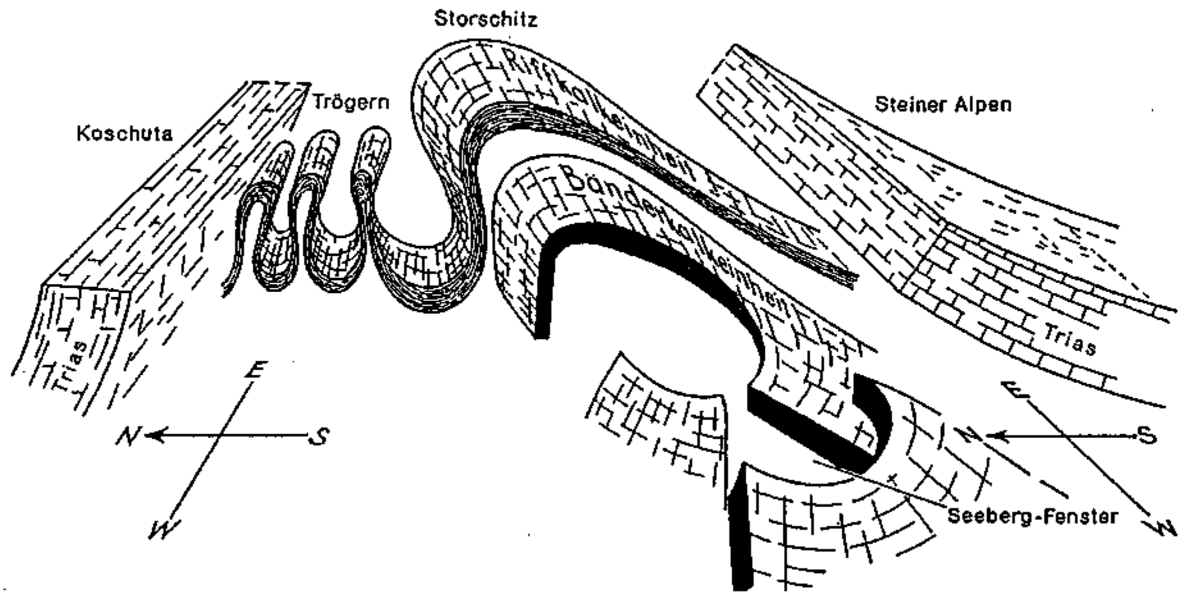


Fig. 12. Diagram showing the main tectonic units of the Seeberg area of the Eastern Karawanken Alps (from J.ROLSER & F.TESSENSOHN 1974).

2. The above mentioned uppermost unit is underlain by the Bänderkalk Unit ("Striated banded limestone Unit"). It is dominated by banded limestones as well as over and underlying clastics. Locally, at its base nautiloid bearing Silurian limestones and Lower Devonian tentaculite bearing limestones occur. The amount of thrusting in this unit does not exceed 1,5 km.

3. The Basal Unit is well distributed between the village of Bad Vellach und the locality "Steiner". Structurally, this unit can be regarded as a tectonic window (Fig. 13). Its sequence consists of the so-called "Seeberg Shale" the age of which has not yet been ascertained and its transgressive cover formed by the equivalents of the Auernig Group, i.e., fusulinid bearing limestones, shales, sandstones and quartz-rich conglomerates.

To unravel the complicated tectonic deformation of the Eastern Karawanken Alps the above mentioned Late Carboniferous sediments are of critical importance as they provide clear evidence of the age of nappe-forming processes. Due to the fact that the post-Variscan molasse-type sediments are also involved in the nappe pile the main deformation in this area must be of Alpine age.

North of the anticline formed by the above mentioned nappes the folded zone of Trögern occurs. It is characterized by a steep to vertical dipping sequence dominated by clastic rocks of the Hochwipfel Formation. Locally also the Devonian substratum and the post-Variscan cover are exposed showing a mushroom and drop-like appearance due to squeezing of competent rocks between clastic layers. This zone may locally attain a width of more than 3 km.

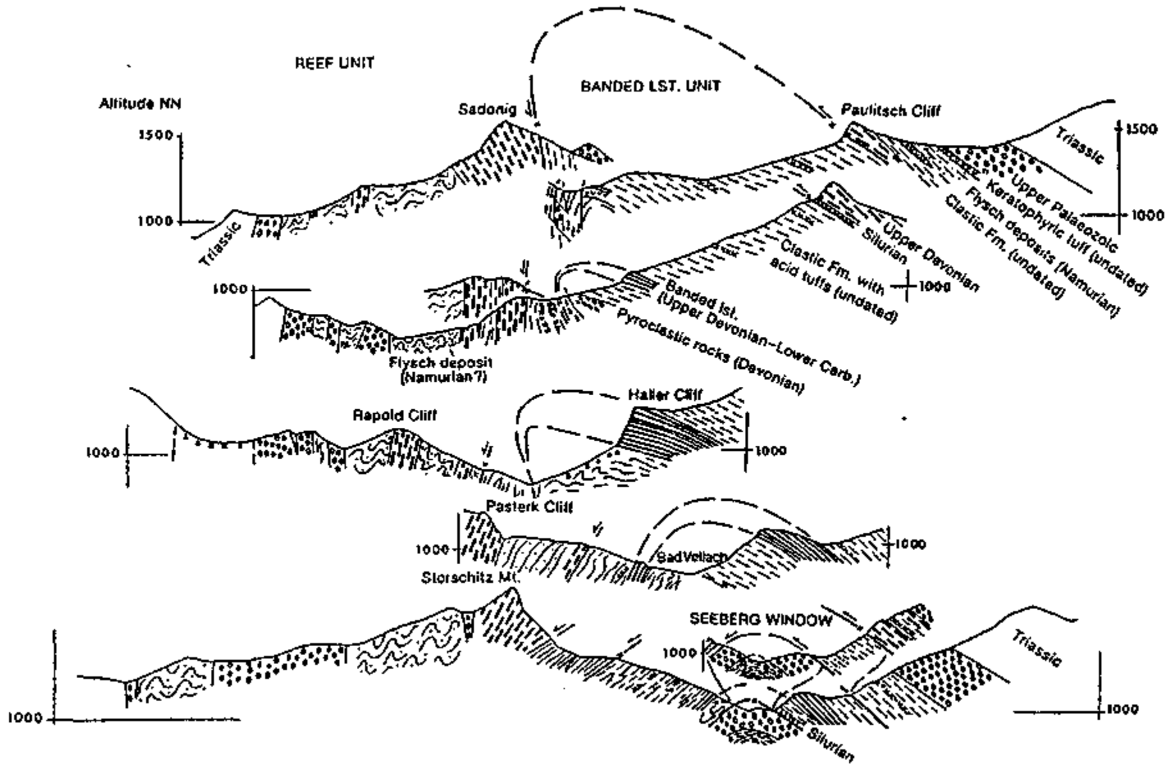


Fig. 13. N-S running sections through the Palaeozoic of the Seeberg area of the Eastern Karawanken Alps (after J.ROLSER & F.TESSENSOHN 1974, modified)

In addition to the huge fold structures with amplitudes of several hundreds of meters small-scale folding is very common in the Seeberg area. It mainly affects those regions which are occupied by shales, i.e. the Seeberg Shale and the Hochwipfel Formation. Finally, steep faults have further subdivided the whole area into numerous small blocks. During the uplift of the area the Triassic cover of the Koschuta belt and the Steiner Alps detached from the underlying Late Carboniferous and Permian rocks.

The narrow belt of the "Diabaszug of Eisenkappel" north of the Periadriatic Line is fault bound to the north and the south (Fig. 10). It represents a highly compressed folded and faulted north verging zone showing several repetitions. To the north this belt of Palaeozoic rocks is thrust upon Late Permian and Triassic rocks. Most probably they formed the original cover of the Lower Palaeozoic volcaniclastic sequence suggesting thus a Variscan deformation for this Palaeozoic series. The southern boundary is formed by the northward thrusted Karawanken Granite. According to radiometric dating it was formed during Late Variscan times (R. A. CLIFF et al. 1975). During intrusion the Diabase of Eisenkappel and its accompanying metamorphic rocks were marginally affected by contact metamorphism (C. EXNER 1972).

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