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The Palaeozoic Evolution of the Southern Alps

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Abstract

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 Upper 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.

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 (Fig. 1). 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 Fault (Gailtal Fault) which sep-

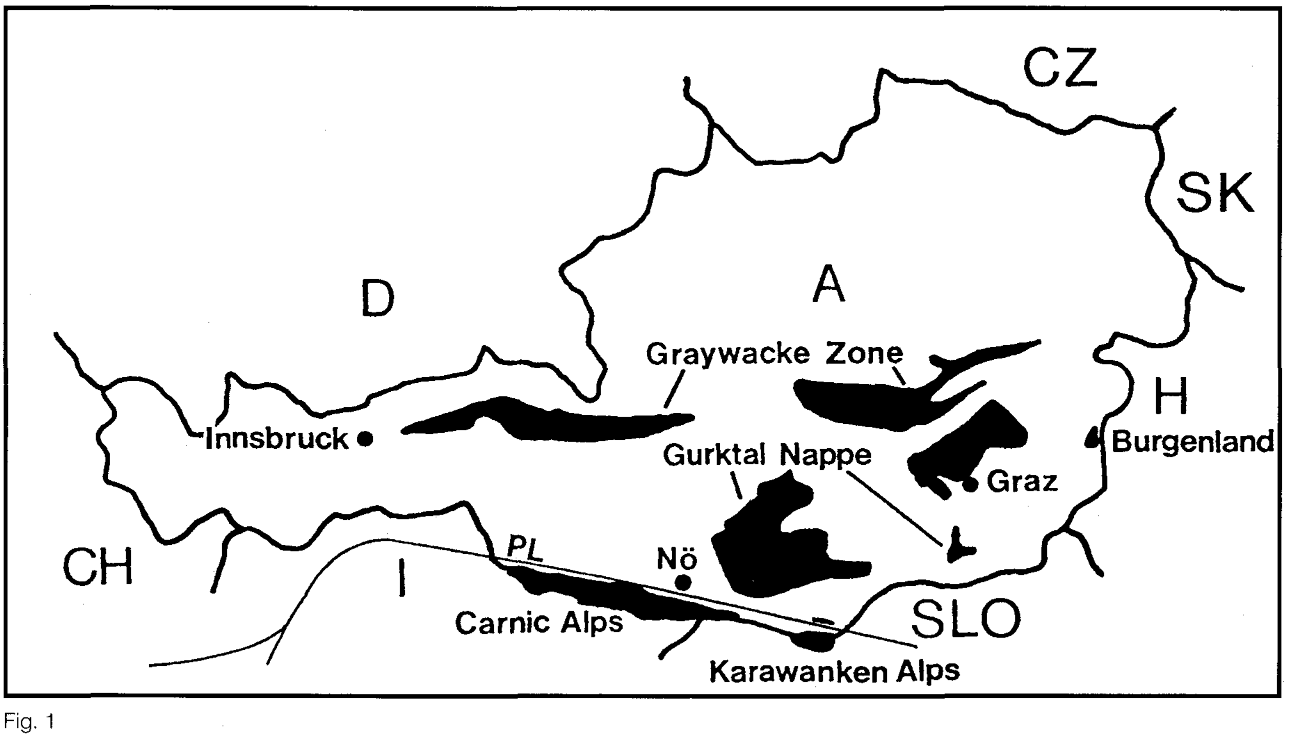

Fig. 1
Main occurrences of fossiliferous Palaeozoic rocks in the Eastern and Southern Alps (A = Austria, CH = Switzerland, CZ = Czech Republic, D = Germany, H = Hungary, I = Italy, SK = Slovakia, SLO = Slovenia, PL = Periadriatic Fault, Nö = Carboniferous of Nötsch).

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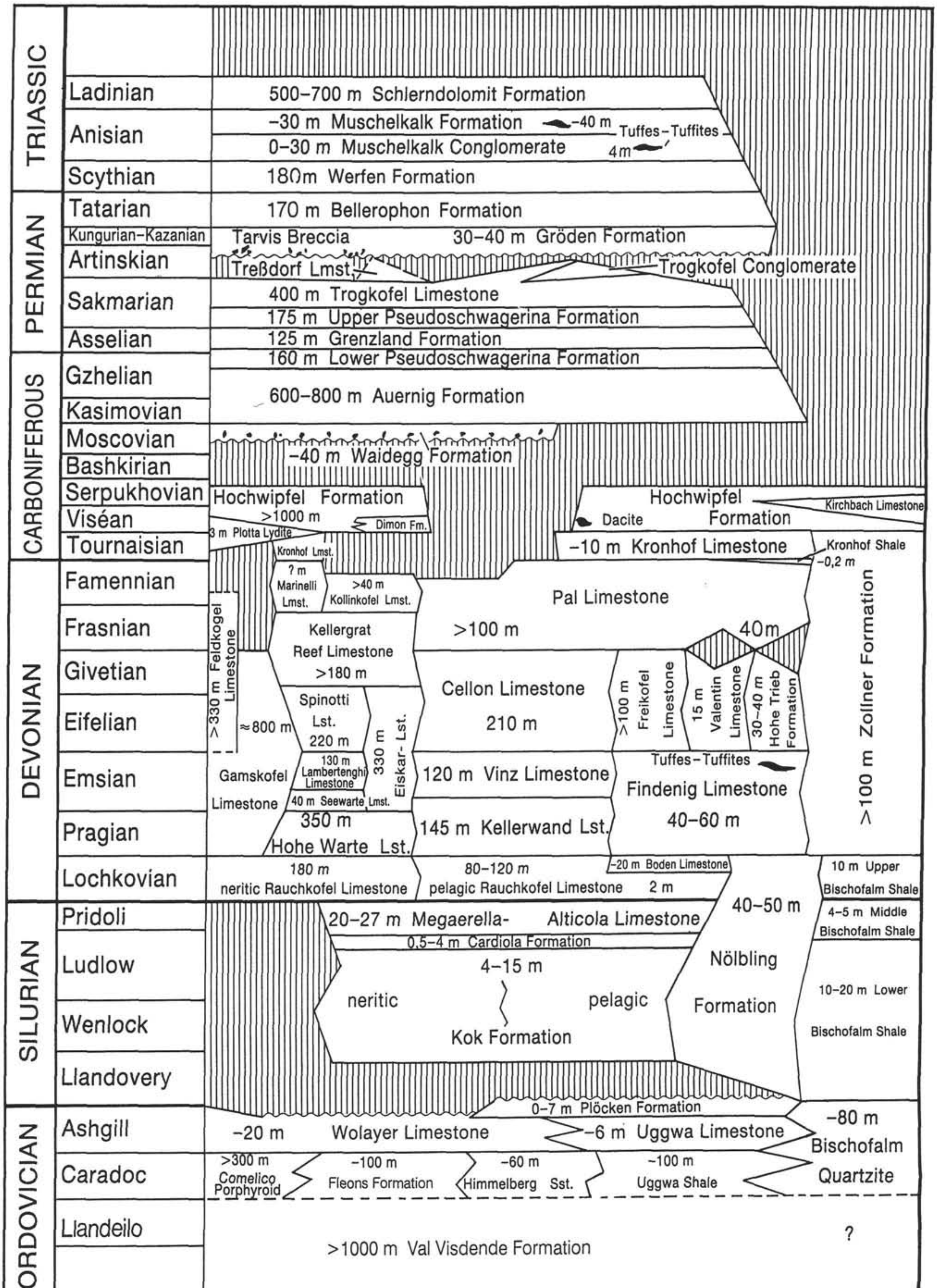

TRIASSIC
Ladinian
Anisian
Scythian
PERMIAN
Tatarian
Kungurian-Kazanian
Artinskian
Sakmarian
Asselian
CARBONIFEROUS
Gzhelian
Kasimovian
Moscovian
Bashkirian
Serpukhovian
Viséan
Tournaisian
DEVONIAN
Famennian
Frasnian
Givetian
Eifelian
Emsian
Pragian
Lochkovian
SILURIAN
Pridoli
Ludlow
Wenlock
Llandovery
ORDOVICIAN
Ashgill
Caradoc
Llandeilo
500-700 m Schlerndolomit Formation
-30 m Muschelkalk Formation
-40 m
Tuffes-Tuffites
0-30 m Muschelkalk Conglomerate
4m
180m Werfen Formation
170 m Bellerophon Formation
Tarvis Breccia
30-40 m Gröden Formation
Treßdorf Lmst.
Trogkofel Conglomerate
400 m Trogkofel Limestone
175 m Upper Pseudoschwagerina Formation
125 m Grenzland Formation
160 m Lower Pseudoschwagerina Formation
600-800 m Auernig Formation
-40 m Waidegg Formation
Hochwipfel Formation
>1000 m
Dimon Fm.
3 m Plotta Lydite
Hochwipfel Formation
Kirchbach Limestone
Dacite
Kronhof Lmst.
-10 m Kronhof Limestone
Kronhof Shale
-0,2 m
? m Marinelli Lmst.
>40 m Kollinkofel Lmst.
Pal Limestone
>100 m
40m
>330 m Feldkogel Limestone
Kellergrat Reef Limestone >180 m
Cellon Limestone 210 m
>100 m Freikofel Limestone
15 m Valentin Limestone
30-40 m Hohe Trieb Formation
>100 m Zollner Formation
Spinotti Lst. 220 m
≈800 m
330 m Eiskar- Lst.
130 m Lambertenghi Limestone
Gamskofel Limestone
40 m Seewarte Lmst.
120 m Vinz Limestone
Tuffes-Tuffites
Findenig Limestone 40-60 m
350 m Hohe Warte Lst.
145 m Kellerwand Lst.
180 m neritic Rauchkofel Limestone
80-120 m pelagic Rauchkofel Limestone
-20 m Boden Limestone
2 m
10 m Upper Bischofalm Shale
40-50 m
20-27 m Megaerella- Alticola Limestone
4-5 m Middle Bischofalm Shale
0.5-4 m Cardiola Formation
4-15 m
neritic
pelagic
Kok Formation
Nölbling Formation
10-20 m Lower Bischofalm Shale
0-7 m Plöcken Formation
-20 m Wolayer Limestone
-6 m Uggwa Limestone
-80 m Bischofalm Quartzite
>300 m Comelico Porphyroid
-100 m Fleons Formation
-60 m Himmelberg Sst.
-100 m Uggwa Shale
>1000 m Val Visdende Formation
?

arates the Southern and the Central or Northern Alps. These rocks have been subdivided into a northern and a southern domain, respectively. The latter extends beyond the state border to northern Slovenia.

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 (SUESS, 1868, 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 (1936) 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 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 have 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., SCHÖNLAUB, 1971, 1980, 1985, 1997; SCHÖNLAUB and KREUTZER, 1994).

Review of Stratigraphy

Figure 2 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 (SCHÖNLAUB, 1980; MOSHAMMER, 1989).

Ordovician

The oldest megafossil-bearing strata of the Southern Alps indicate an early Late 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 Early 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. 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 volcaniclastic rocks named the "Comelico Porphyroid" and "Fleons Formation" respectively (Fig. 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 (HAVLICEK et al., 1987). According to DALLMEYER and NEUBAUER (1994), detrital muscovites from the sandstones are characterized by apparent ages ($^{40}Ar/^{39}Ar$) of c. 640 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 parautochthonous bioclasts from cystoids and bryozoans, which laterally grades into the bedded wackestones of the "Uggwa Limestone" representing a more basinal setting with reduced thickness.

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* (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 aforementioned rifting and subsequent movements from higher to lower latitudes may be marked by mafic volcanism occurring at various places in the Eastern Alps in pre-Llandeillian strata (for references see SCHÖNLAUB, 1992). In the Southern Alps such rocks have not yet been recognized. The Late Ordovician faunal affinities, e.g. brachiopods, nautiloids, cystoids, ostracods, conodonts and vertebrate remains indicate links with Bohemia, Thuringia, Baltoscandia, Sardinia and the British Isles (SCHÖNLAUB, 1992; FERRETTI and BARNES, 1997; FERRETTI, 1997; BAGNOLI et al., 1998; BOGOLEPOVA and SCHÖNLAUB, 1998). Moreover, the appearance of carbonate rocks in the Late Ordovician suggests a position within the broader carbonate belt for this time. However, also a temporary coldwater 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 (JAEGER et al., 1975). Based on the available evidence from the Ordovician of the Southern Alps 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 (SCHÄTZ et al., 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, while to the south of the Periadriatic Fault they occur in the the Carnic and Karawanken Alps. The main differences on either side of the Periadriatic Fault being the distribution of fossils, the

← Fig. 2
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 SCHÖNLAUB, 1985, modified).

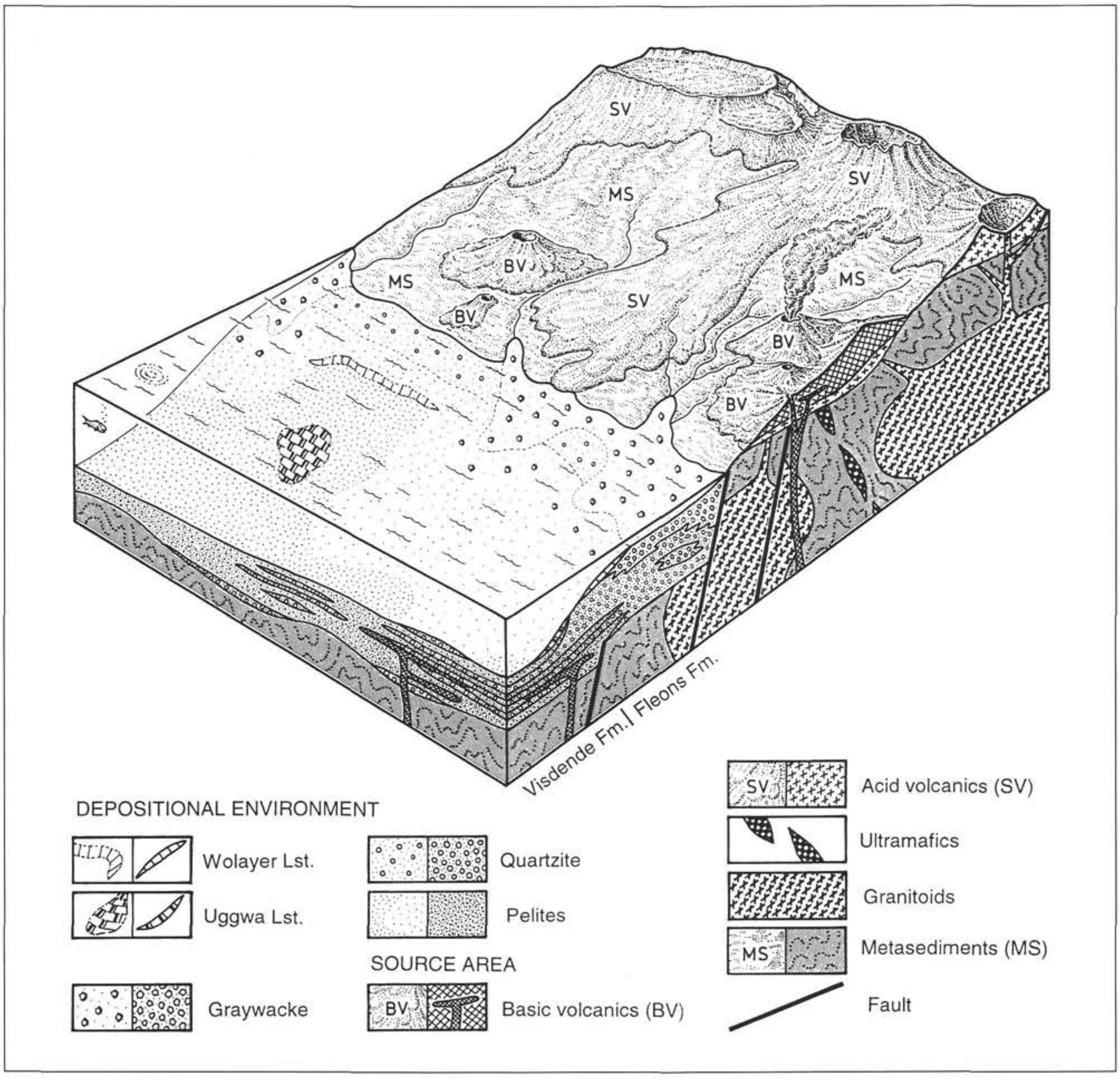


Fig. 3
Sketch of Upper Ordovician volcanism in the western Carnic Alps (modified from HINDERER, 1992).

facies pattern, rates of subsidence, supply area, amount of volcanism and the spatial and temporal relationship of climate-sensitive rocks (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. 4). Uniform limestone sedimentation during the Pridoli suggests that more stable conditions were developed at this time (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 60 m. The available data for the Carnic and Karawanken Alps suggest a complete but considerably condensed succession in the carbonate-dominated facies and a continuous 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 (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 Late Ordovician limestones.

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 shallow marine environment. The contact with the underlying massive cystoid-bearing 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 to 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 Limestone, 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 rugose 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 sequence (FLÜGEL et al., 1977). The condensed nature of the sequence of the Cellon section 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 Formation the carbonate sequence of the "Plöcken Facies" were deposited in a relatively shallow environment,

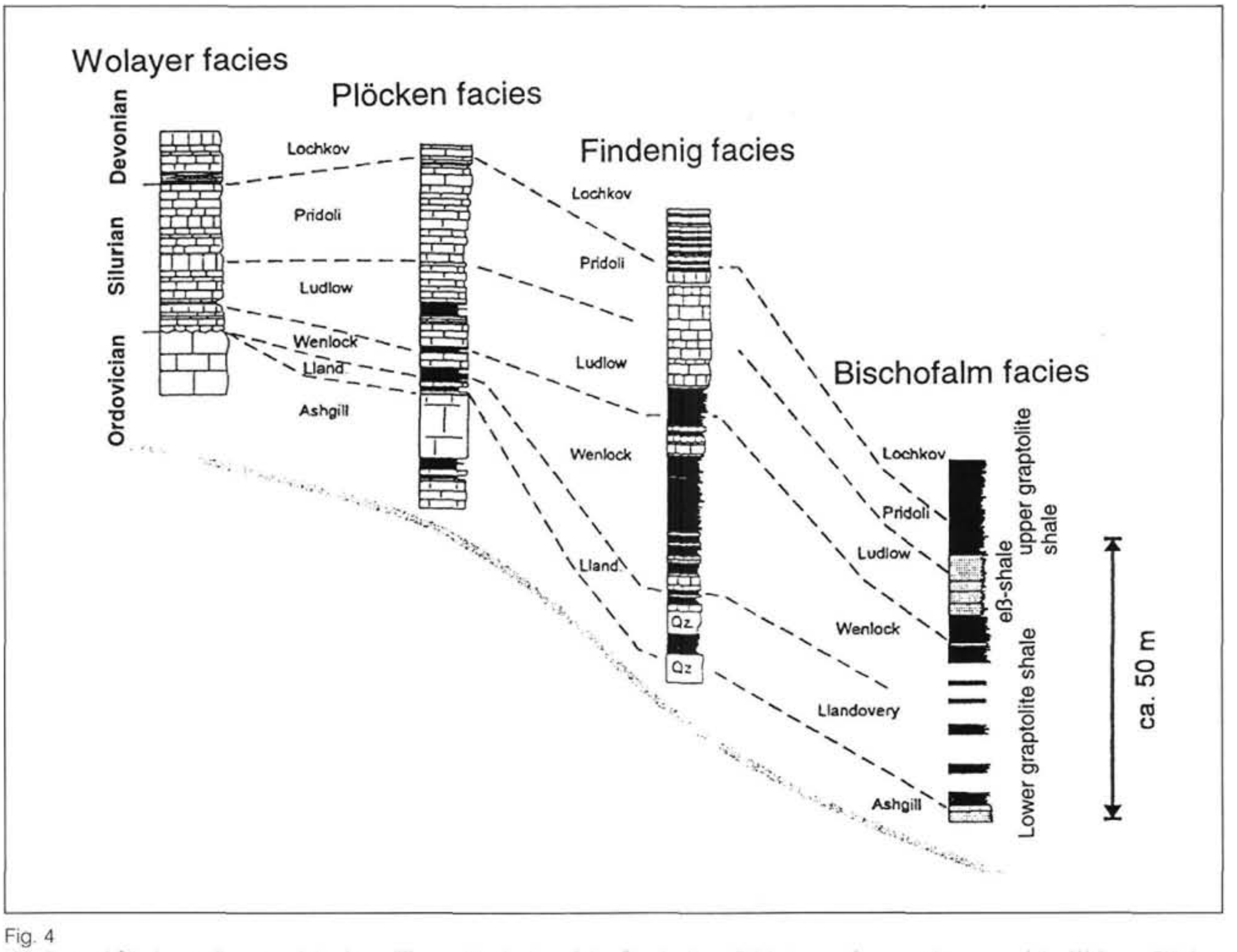


Fig. 4
Lithology of Silurian sediments of the four different lithofacies of the Carnic Alps. Brickstone reflects carbonates of the Wolayer, Plöcken and Findenig facies, black corresponds to C_{org} rich graptolite-bearing shales and cherts and C_{org} rich carbonates. Light gray represents C_{org} poor shales. Qz. indicates quartzite beds. Columns from left to right show the sections Rauchkofel Boden, Cellon, Oberbuchach 1-2 and Nölblinggraben-Graptolithengraben. In the latter composite section Lower Silurian sediments are not continuously exposed. From WENZEL, 1997.

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 occurring at the base of the formation in the Late Llandovery and brown-red ferruginous limestones with abundant nautiloids and frequent stylolites in the Wenlock – Early 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. 6) 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 (AZMY et al., 1998).

The alternating rapid deposition of black shales and laminated micrites with 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 Pridoli (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 late Pridoli and Silurian/Devonian boundary transgressive sequences of bioodetritus-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 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 (Lochkovian) 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 palaeolatitudinal position between 30 and 40°S. In the central Alps rifting-related mafic 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 BRETT and SCHÖNLAUB (1998) based on a sequence stratigraphy study of the sections (Fig. 5). The variations in sea-level compare quite well with those inferred by JOHNSON (1996) and 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 northeastern America and Britain (BRETT et al., 1990; GOODMAN and 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.

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 earliest 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 Limestone (up to 180 m thick), which corresponds to some 20 m of pelagic limestones (Boden Limestone). 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

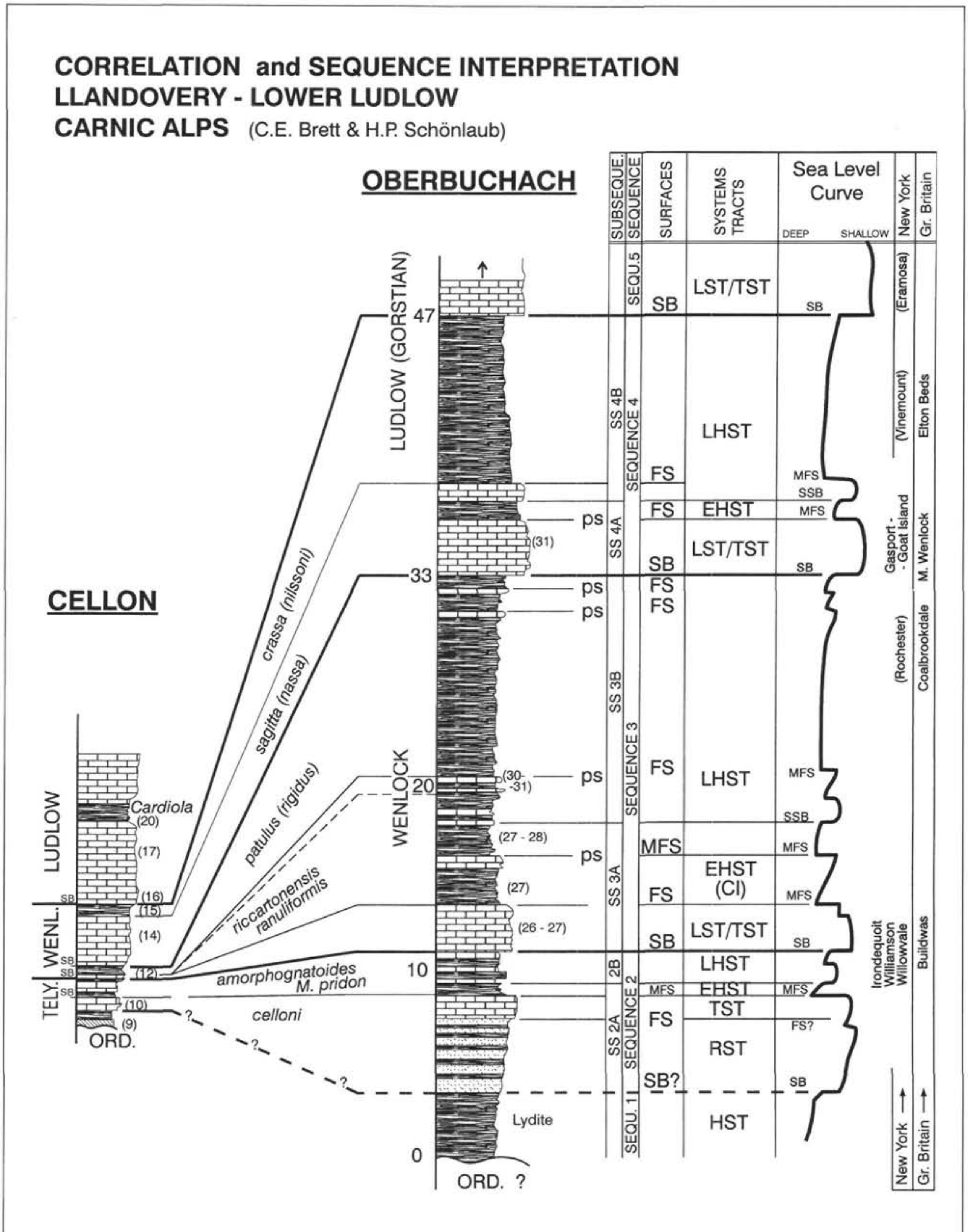


Fig. 5

Correlation and sequence interpretation of Llandovery – Lower Ludlow succession, Carnic Alps (BRETT and SCHÖNLAUB, 1998). Ord. = Ordovician, Tely. = Telychian, Wenl. = Wenlock, SB = Sequence boundary, PS = Parasequence, SS = Subsequence, FS = Flooding surface, MFS = Maximum flooding surface, HST = highstand systems tract, RST = Regressive systems tract, TST = transgressive systems tract, EHST = early highstand systems tract, LHST = late highstand systems tract, CI = condensed interval, LST = lowstand systems tract, SSB = subsequence boundary, M.Wenlock = Much Wenlock.

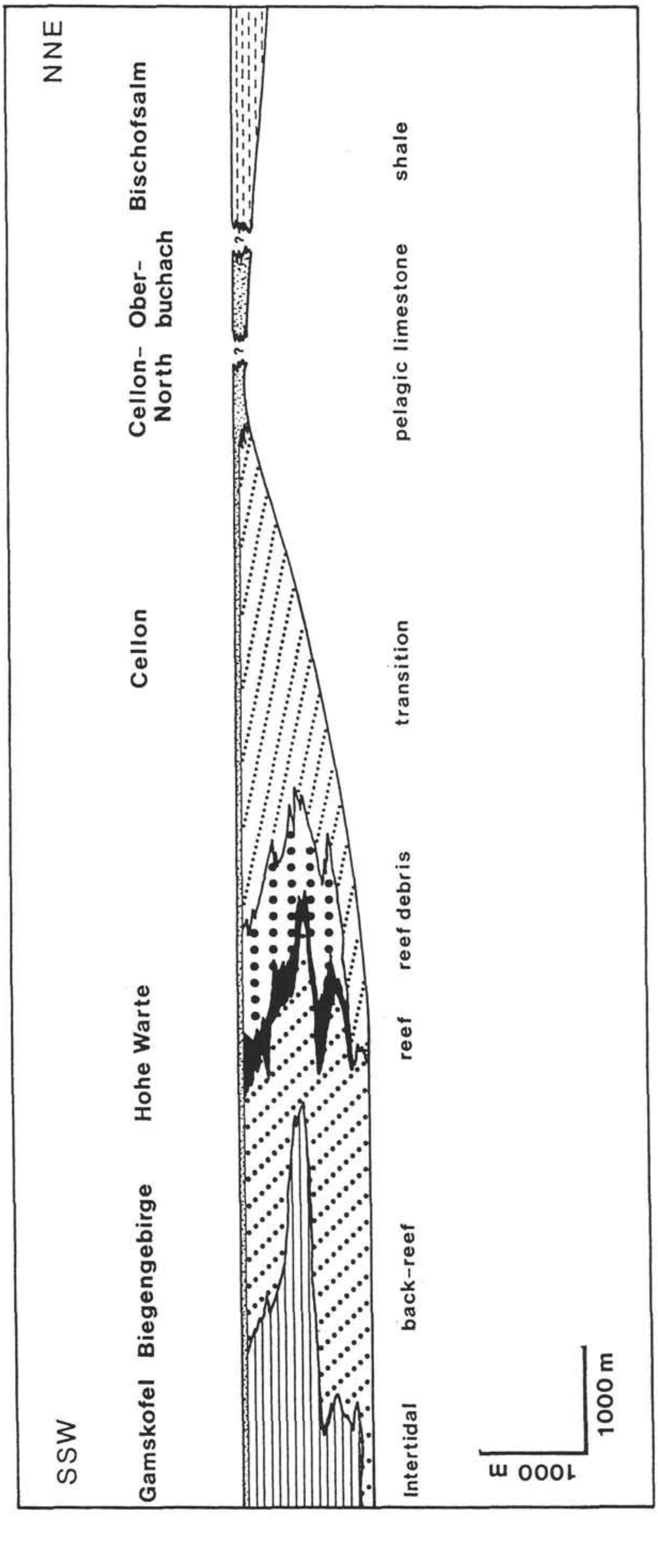


Fig. 6
Palinspastic profile of the Carnic Alps at the Devonian/Carboniferous boundary. Gamskofel, Biegengebirge, Hohe Warte: Southern shallow water facies (Kellerwand nappe. Cellon: Transitional facies (Cellon nappe). Cellon-North, Oberbuchach: Pelagic limestone facies (Rauchkofel nappe). Bischofalm: Offshore pelagic basinal facies (Bischofalm nappe). Further to the north the northern shallow water facies of the Feldkogel nappe occurs. After KREUTZER, 1992a.

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 Late 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 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. 6):

(1) Southern shallow-water facies of the Cellon-Kellerwand nappe with (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 1,300 m high cliffs of the Kellerwand and of Hohe Warte (2,784 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 contrast markedly with the foregoing Silurian period. In the interval from the Lochkovian to the Frasnian in facies belt 1 more than 1,100 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 KREUTZER (1990, 1992b), at least 13 different carbonate microfacies types can be recognized for the Devonian.

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 Limestone 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 Early 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 (SCHÖNLAUB, 1985; HERZOG, 1988).

For the Karawanken Alps RANTITSCH (1990) concluded an arrangement of reefs resembling present-days atolls as opposed to the Carnic Alps with its barrier-type reefs (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 these shallow water deposits in the Karawanken Alps 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 with the Ural-Tienshan region as opposed to northern Africa (SCHÖNLAUB, 1992; HUBMANN and FENNINGER, 1993). In addition, equatorial gyres may have aided the distribution of several planktonic 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 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 Late Famennian and others range within different levels of the Early Carboniferous (Fig. 7). 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. Recently, 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 II-Stage of the uppermost Tournaisian or lowermost Visean Stage of the Lower Carboniferous (SCHÖNLAUB and KREUTZER, 1993; PERRI and SPALLETTA, 1998a, b; SPALLETTA and 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. 8). Apparently, this has been settled after recognition of a wide variety of distinct palaeokarst features in the Karawanken and the Carnic Alps (TESSENSOHN, 1974; SCHÖNLAUB et al., 1991) including an extensive palaeorelief with surface-related collapse breccias, fissures, stratabound ore 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 carbonate basin promoted the transgression of the Hochwipfel Formation, which presumably started in the Lower Visean.

Based on its characteristic lithology and sedimentology TESSENSOHN (1971, 1983), SPALLETTA et al. (1980), VAN AMEROM et al. (1984), SPALLETTA and 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 constitute 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

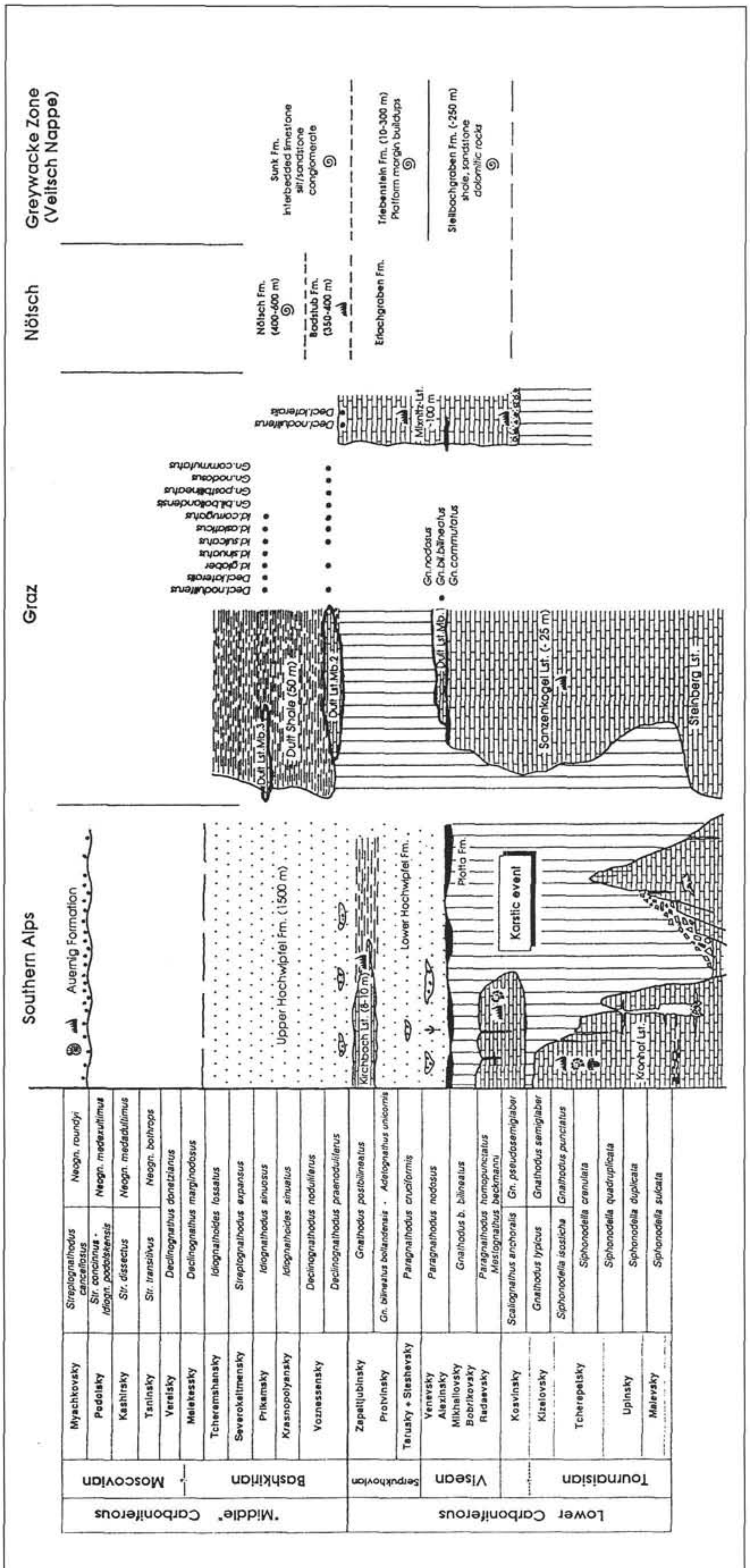


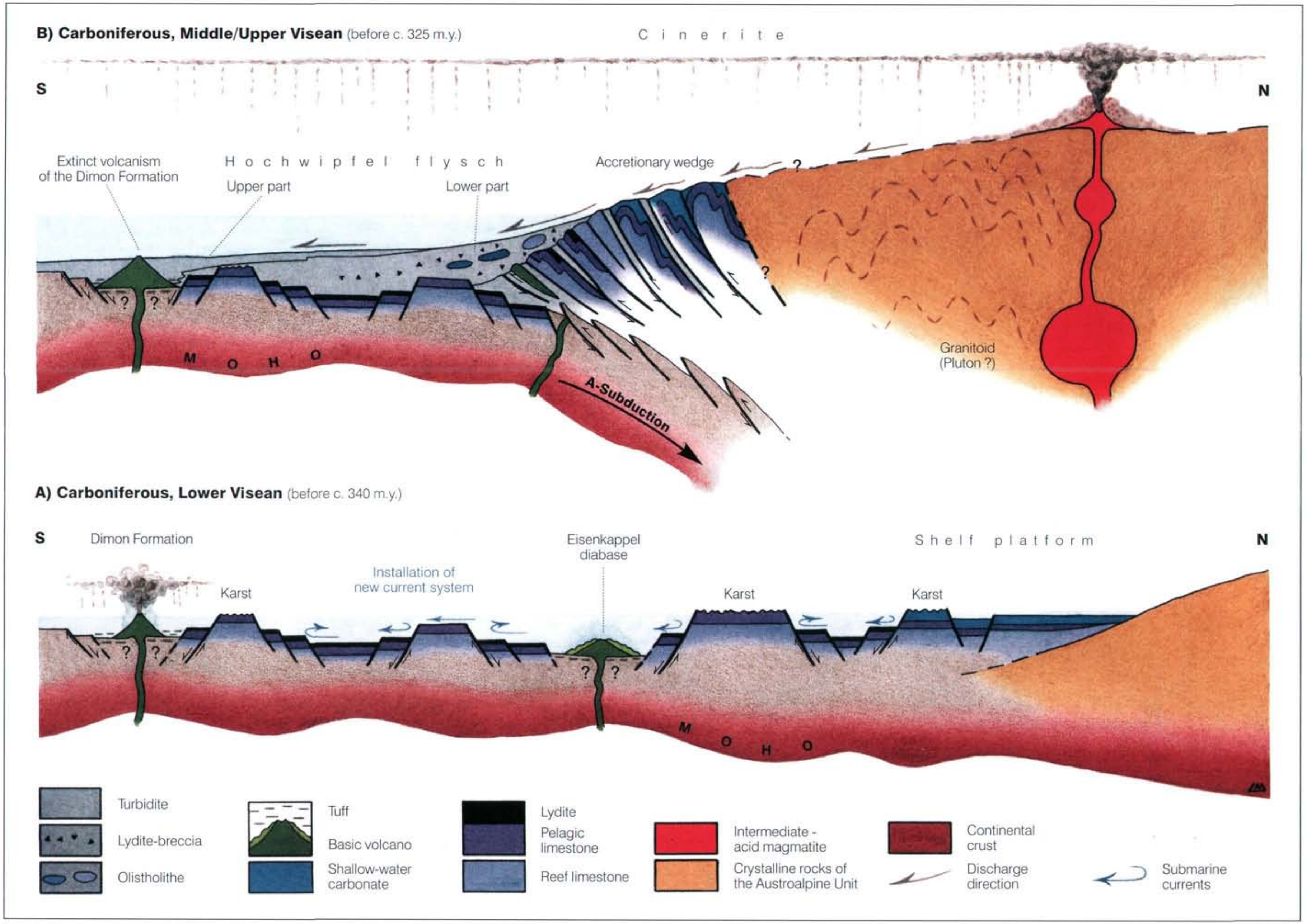
Fig. 7
Correlation of Lower Carboniferous squences of the Southern and Eastern Alps. Note the palaeokarst event.

very common suggesting a Middle Visean to Namurian age for its formation (VAN AMEROM et al., 1984; VAN AMEROM and SCHÖNLAUB, 1992). Other stratigraphic data are derived from the aforementioned underlying limestone beds and locally occurring intercalations of the Kirchbach Limestone which provided index conodonts of the Visean/Namurian boundary (FLÜGEL and 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 located originally to the north of the present Southern Alps but which was completely destroyed by later tectonic events.

According to 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 KAHLER (1983) the oldest post-Variscan transgressive sediments are late Middle Carboniferous in age and, more precisely, correspond to the *Fusulinella bocki* Zone of

Fig. 8 →
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 LÄUFER et al. 1993, modified).



B) Carboniferous, Middle/Upper Visean (before c. 325 m.y.)
Cinerite
S
N
Extinct volcanism of the Dimon Formation
Hochwipfel flysch
Upper part
Lower part
Accretionary wedge
?
MOHO
A-Subduction
Granitoid (Pluton ?)
A) Carboniferous, Lower Visean (before c. 340 m.y.)
S
Dimon Formation
Karst
Installation of new current system
Eisenkappel diabase
Karst
Karst
Shelf platform
N
MOHO
Turbidite
Lydite-breccia
Olistholithe
Tuff
Basic volcano
Shallow-water carbonate
Lydite
Pelagic limestone
Reef limestone
Intermediate - acid magmatite
Crystalline rocks of the Austroalpine Unit
Continental crust
Discharge direction
Submarine currents

the Upper Miatchkovo Substage of the Moscovian Stage of the Moscow Basin (for more details see KRAINER, 1992). In particular between the 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 (FENNINGER et al., 1976) and which was named Malinfier Horizon by Italian geologists (VENTURINI, 1990; 1991).

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 (VENTURINI et al., 1982; 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 (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 *Pseudoschwagerina* and *Occidentoschwagerina* in the upper part of the Lower Pseudoschwagerina Limestone and not at its base, as previously was suggested (KAHLER and KRAINER, 1993).

Permian

In the Lower Permian the Auernig Group is succeeded by a series of more than a 1,000 m thick shelf and shelf edge limestones and clastics (KRAINER, 1992, 1993; 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 (KRAINER, 1991; 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 (BOECKELMANN, 1991; HOLSER et al., 1991; KRAINER, 1993).

Upper Carboniferous and Permian molasse-type sediments also occur in the Seeberg area of the Eastern Karawanken Alps (TESSENSOHN, 1983; 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, arenaceous shales, sandstones and massive beds of quartz-rich deltaic conglomerates. Equivalents of the Permian are represented by the Trogkofel Limestone, 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 Fault, rocks of Palaeozoic age have long been known. They belong to the so-called "Diabaszug von Eisenkappel". 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 LOESCKE (1970, 1977, 1983, 1989a, b) and LOESCKE 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 (NEUBAUER, pers. comm.).

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 anchito 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 LÄUFER (1996) concluded that Variscan epizonal metamorphism was equal to 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 activity along the Periadriatic Fault and exhumation by transpression (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 Late Devonian and in the Early 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

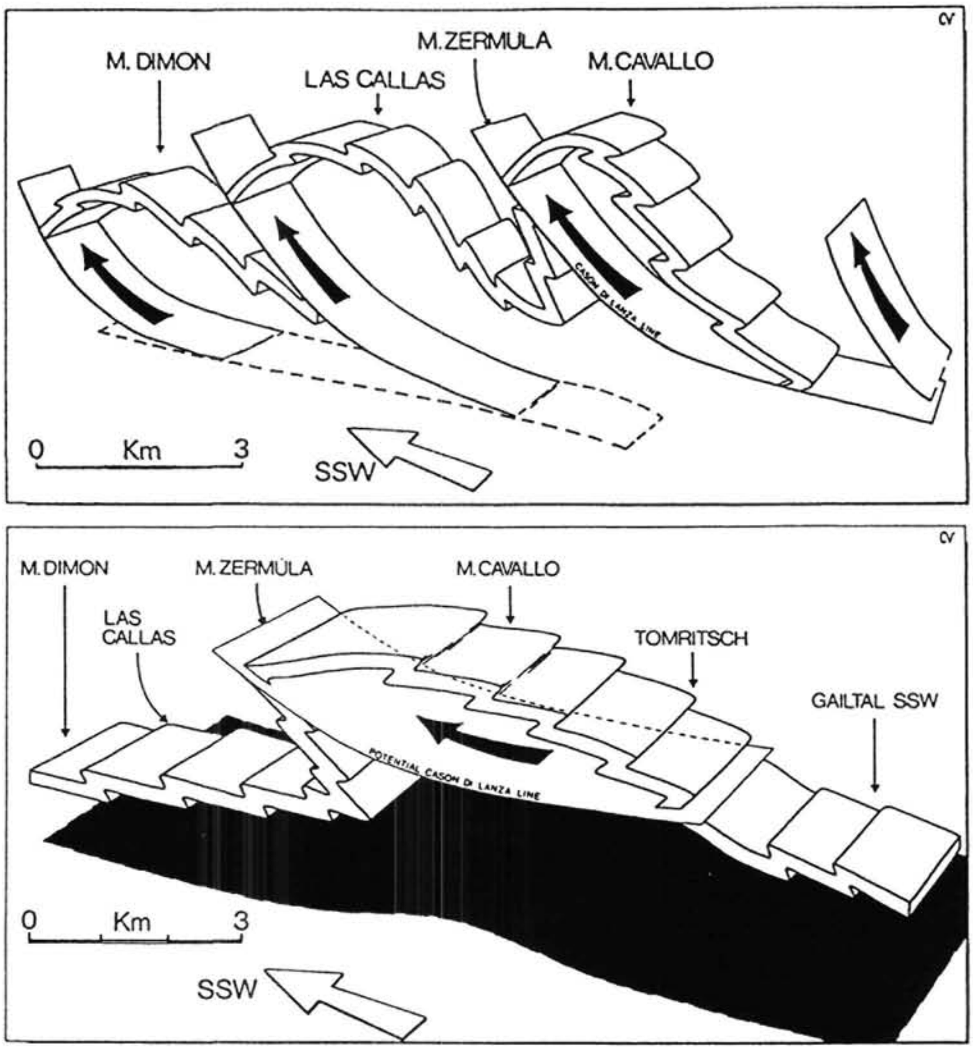


Fig. 9
Hercynian deformation of the Carnic Alps according to VENTURINI, 1990. The first and third (Figure above) deformation stages are shown. The huge asymmetric fold affected the whole Palaeozoic belt. The third stage formed thrusts with open folds which re-folded the older structures of the first and second deformation stages (from VENTURINI, 1990).

accumulation of reworked limestones, stratigraphic gaps, formation of fissures and local karstification.

For many years the complicated tectonics of the Carnic Alps was explained in terms of nine 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 deformation pattern in the Southern Alps (CASTELLARIN and VAI, 1981).

According to 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 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. 9):

1. Middle or early Late 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 (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 Late Carboniferous was governed by extensional tectonics (VENTURINI, 1990; SCHÖNLAUB, 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 EICHHÜBL (1988), VENTURINI (1990, 1991) and LÄUFER (1996).

The tectonic framework of the Eastern Karawanken Alps is characterized by the north verging anticlinal structure of the central and southern part (Fig. 10). 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 (Fig. 11). Rocks of the

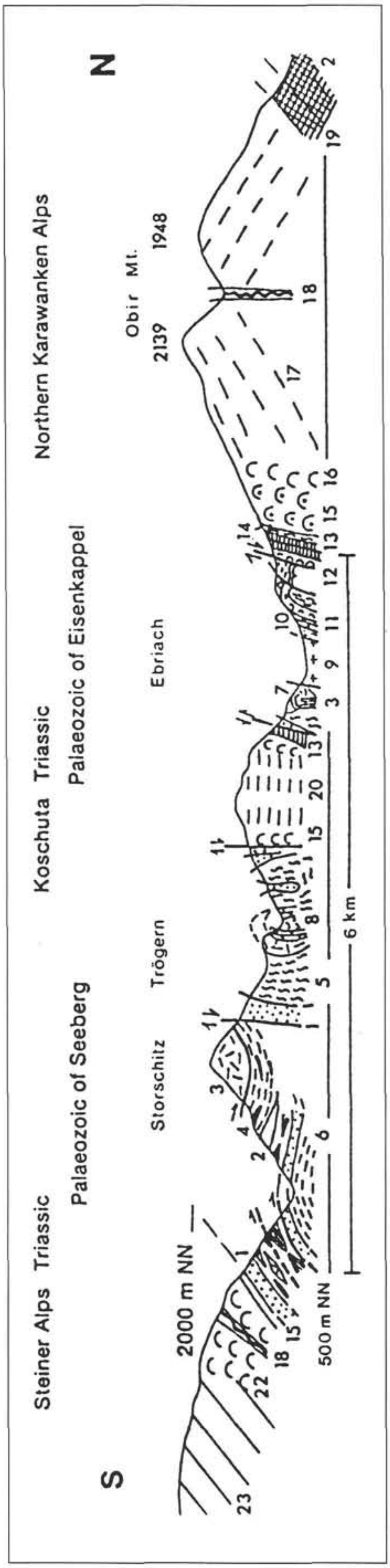


Fig. 10
N-S directed section through the Eastern Karawanken Alps. Legend: 1 – post Variscan Permian and Upper Carboniferous, 2 – banded limestone thrust sheets in imbricate structure, 3 – Devonian limestones, 4 – undated volcanics, 5 – Hochwipfel Formation, 6 – Seeberg Shale, 7 – Upper Ordovician and 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 – Muschel limestone Formation, 14 – Partnach Formation, 15, 16, 17 – Wetterstein Limestone, 18 – Raibl Formation, 19 – Rhätian to Jurassic deposits, 20 – Schlern Dolomite, 21 – Tertiary, 22, 23 – Dachstein Limestone. (from SCHÖNLAUB, 1979).

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.

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. 12). 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 Upper 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.

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 fault 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, thus suggesting 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 (CLIFF et al., 1975). During intrusion the Eisenkappel Diabase and its accompanying metamorphic rocks were marginally affected by contact metamorphism (EXNER, 1972).

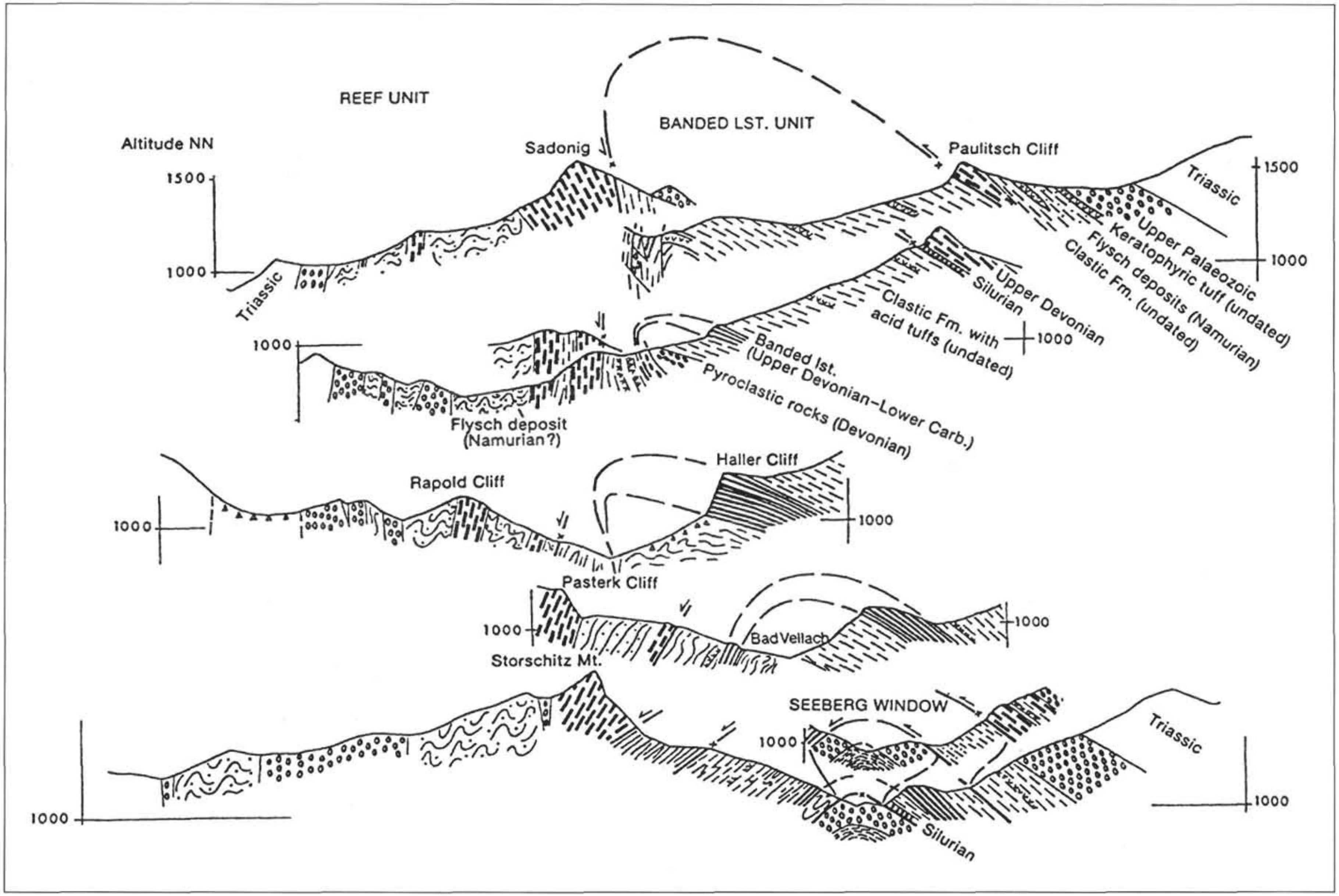


Fig. 11
N-S running sections through the Palaeozoic of the Seeberg area of the Eastern Karawanken Alps (after ROLSER and TESSENSOHN, 1974, modified).

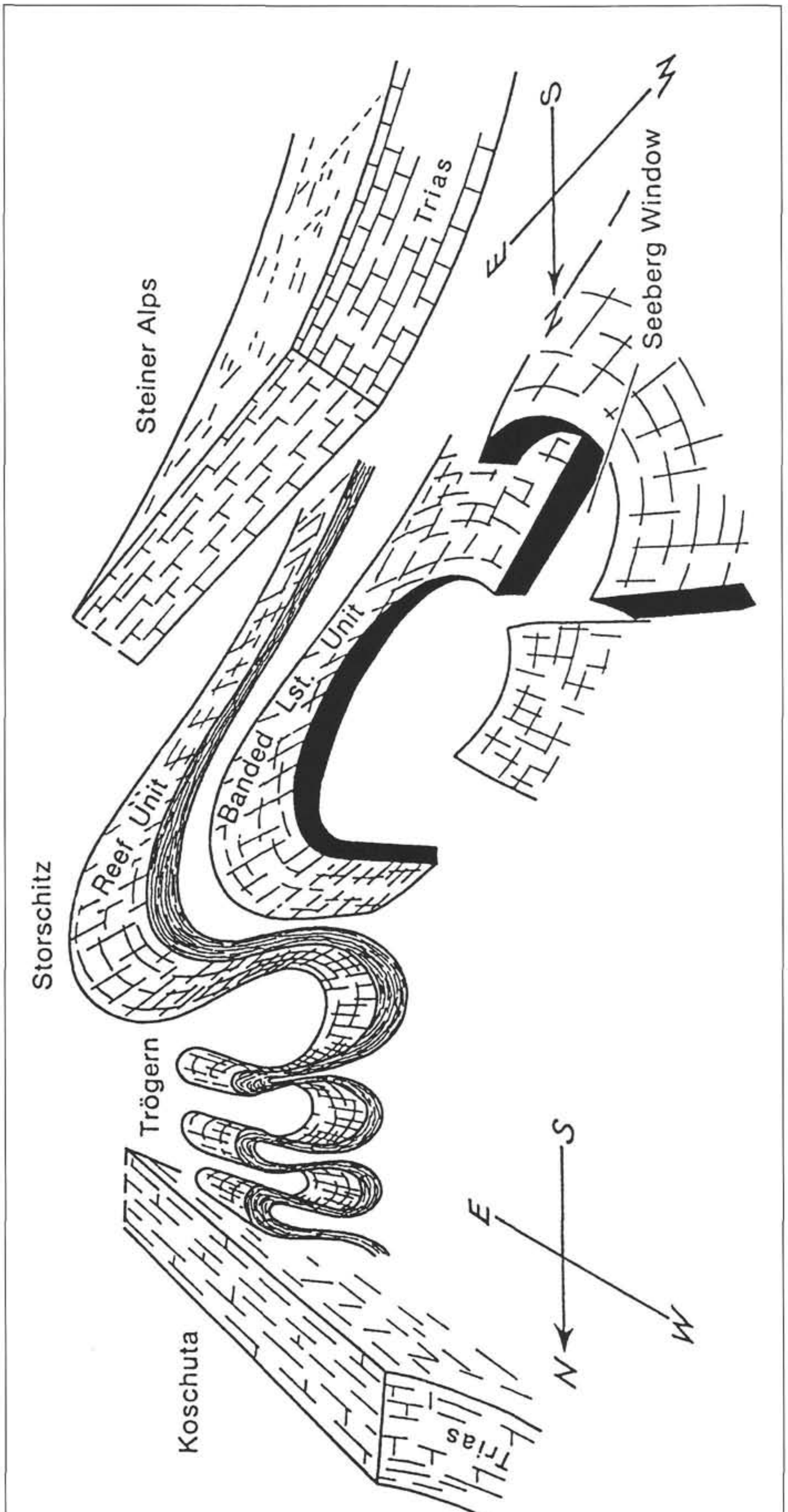
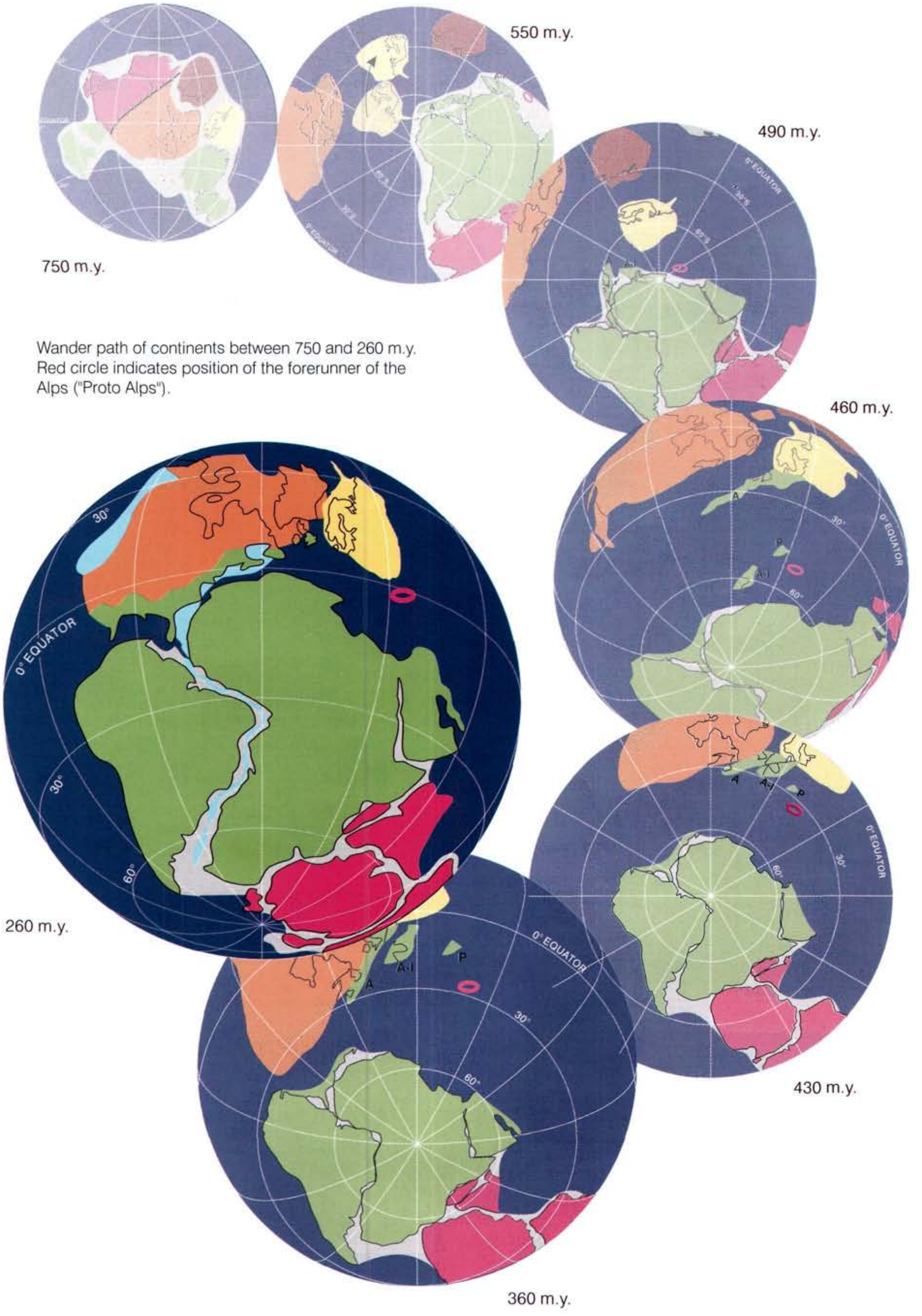


Fig. 12
Diagram showing the main tectonic units of the Seeberg area of the Eastern Karawanken Alps (from ROLSER and TESSENSOHN, 1974).

Conclusion

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 Early 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 Siberia. The following biota, in particular bivalves, nautiloids, trilobites and corals from the Silurian and Devonian show 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 Siberia 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

Fig. 13 →
Wander path of continents between 750 and 260 Ma. Circle indicates approxoimate position of the Proto-Alps. Main plate configuration after DALZIEL 1995, TORSVIK et al. (1996) and COCKS and SCOTESE 1991. A – Armorica, A-I – Armorica-Iberia, P – Perunica.



Wander path of continents between 750 and 260 m.y. Red circle indicates position of the forerunner of the Alps ("Proto Alps").

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 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 Early 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 (Fig. 13).

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