The Silurian of Austria[2]

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with 8 figures

Geography

In the Austrian Alps fossiliferous Silurian strata are irregularly distributed (Fig. 1). They form a mosaic-like pattern of dismembered units incorporated into the Alpine nappe system. Such areas include the Gurktal Nappe of Middle Carinthia and southern Styria, the surroundings of Graz and the Graywacke Zone of Styria, Salzburg and Tyrol. Corresponding rocks are also exposed along the northern margin of the Southern Alps to the south of the Periadriatic Line, i. e. in the Carnic and Karawanken Alps. In addition, a certain portion of the sedimentary precursor sequences of quartzphyllites and even amphibolite-grade metamorphic rocks may also have been deposited during the Silurian Period but due to lack of fossils it is as yet not possible to correlate these series with the so-called "classical Paleozoic areas" (Fig. 1).

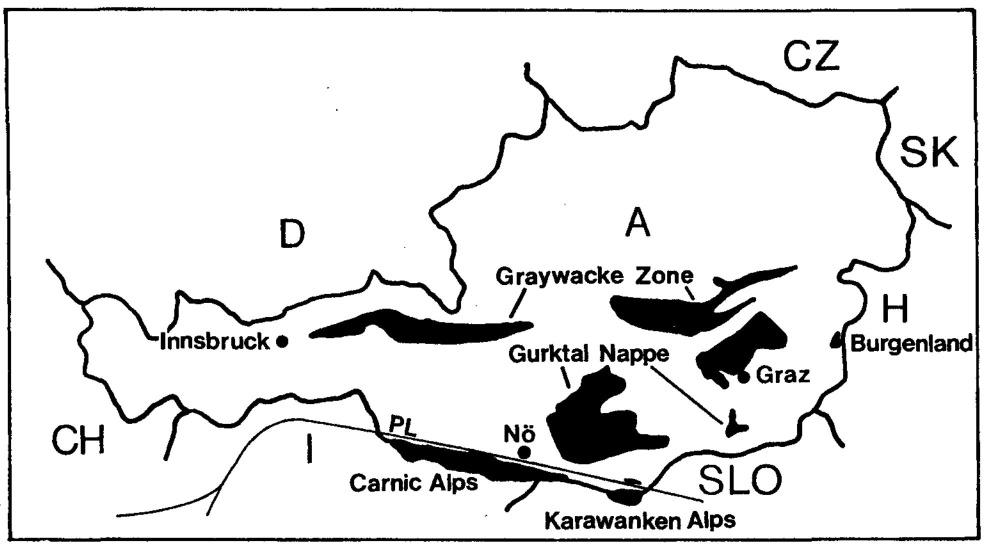

Fig. 1. Main regions with fossiliferous Paleozoic strata in the Eastern and Southern Alps (PL = Periadriatic Line, Nö = Nötsch).

Geology - Main Features

Since the discovery of Silurian fossils in the Alps by F. v. HAUER in 1847 the knowledge of rocks and organic remains has considerably increased. Largely responsible for this progress was the introduction of research method to investigate the micro and nannofossil content of strata but also on many collection campaigns of different

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2 Pre-print of a joint publication for the Proceedings of The James Hall Symposium: Second International Symposium on the Silurian System, Rochester, N.Y. 1996 entitled "Silurian Lands and Shelf Margins" (eds. M. S. JOHNSON & C. E. BRETT).

working groups to elaborate a more detailed biostratigraphic framework as well as to assess the lithological characteriscs of different Silurian strata.

Silurian deposits range from shallow water carbonates to graptolitic shales. Thicknesses are overall similar and generally do not exceed some 60 m. Main differences on either side of the Periadriatic Line concern 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 1993).

Biostratigraphical important fossil groups include primarily graptolites and conodonts; of almost equal importance with a supposedly great potential for correlation are trilobites, bivalves, chitinozoans and acritarchs, the latter, however, only in the Lower Silurian (upper Llandovery to lower Wenlock). Brachiopods and nautiloids provide further data and are useful for paleoecological and paleogeographical considerations.

The stratigraphic record of the Southern Alps comprises Ordovician to Middle Triassic strata. The Ordovician Series are characterized by mainly clastic rocks with minor participation of acid and basic volcanics. This facies resembles other areas in the Mediterranean region. Also, in the Carnic Alps the widespread end-Ordovician (Hirnantian) glacial event has been recognized being responsible for sedimentary gaps in the basal part of the succeeding Silurian. During this period a considerable variety of different lithologies developed which, however, exhibit some common features outlined in more detail in the following chapters. Due to extensional tectonics and highly different rates of subsidence the facies pattern changed significantly during the following Devonian. This is documented by more than 1200 m of shallow water limestones which are time equivalent to some 100 m of condensed nodular limestones. After drowning of the reefs limestone sedimentation was more uniform and continued during the Famennian and early Lower Carboniferous when a phase of emersion and karstification occurred near the end of the Tournaisian Stage. The final collapse of the Variscan basin started in the Visean and resulted in more than 100 m flysch deposits indicating an active margin at the northern part of the Southern Alps culminating in the main deformation stage in the Upper Carboniferous Westphalian Stage. The transgressive Late Carboniferous to Middle Triassic cover comprises thick shelf deposits ranging from near-shore siliciclastics to fossiliferous algal and fusulinid limestones.

The area north of the Periadriatic Line has only few rocks in common with the Southern Alps. This concerns thick piles of siliciclastic rocks in the interval from the Ordovician to the Devonian, a contemporaneous local reef development during the Silurian and the Devonian Periods, basic magmatism in the Ordovician, Lower Silurian and in the Middle Devonian. The inccreased input of clastic material suggests a proximity to a land area. On the other hand intense volcanism may be related to crustal extension. However, this activity may also be responsible for the different facies development which occurred in most areas north of the Periadriatic Line during the Silurian and parts of the Devonian.

The Carnic and Karawanken Alps

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 part of the Karawanken Alps near Villach. Due to the unconformity relationship which separates the Ordovician from the Silurian in both the Carnic and Karawanken Alps a varying thick sedimentary pile is locally missing which corresponds to several conodont zones in the Llandovery and Wenlock. At a few places even basal Lochkovian strata may disconformably rest upon Upper Ordovician limestones.

The Silurian lithofacies is subdivided into four major facies reflecting different depths of deposition and hydraulic conditions (Fig. 2). A moderately deep marine environment represents the Plöcken Facies characterized in succeeding order by the pelagic Kok Formation, the Cardioala Fm. and the Alticola-Megaerella Limestones. The classical section is the 60 m thick Cellonetta profile well known for its merits for the Silurian conodont zonation established by O. H. WALLISER in 1964.

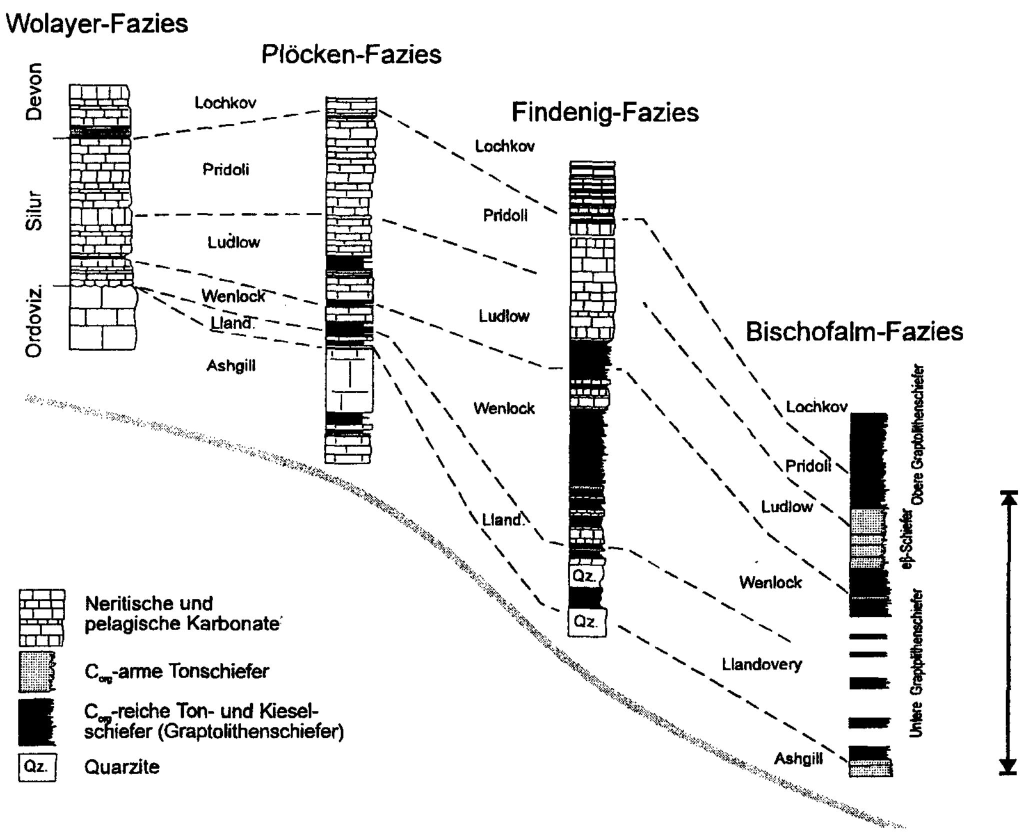

Fig 2. Lithology of Silurian sediments of the four different lithofacies of the Carnic Alps. Brickstone drawing reflects carbonates; black colour corresponds to C_{org} rich graptolite-bearing shales and cherts and C_{org} rich carbonates of the Wolayer Facies. Light gray areas represent C_{org} poor shales. Columns represent from left to right the sections "Rauchkofel Boden", "Cellon", "Oberbuchach 1-2" and "Nölblinggraben-Graptolithengraben". In the latter composite section Lower Silurian sediments are not continuously exposed. From B. WENZEL 1997 (in press).

The Wolayer Facies represents an apparently shallower environment. It is characterized by fossiliferous limestones with abundant orthoconic nautiloids, trilobites, bivalves, small brachiopods, gastropods, crinoids and few corals. Due to a hiatus at the base this facies is represented by only 10 to 15 m thick variegated limestones. The classical sections are located in the Lake Wolayer region of the central Carnic Alps.

The stagnant water graptolite facies is named Bischofalm Facies. It is represented by 60 to 80 m thick black siliceous shales, black cherty beds ("Lydite") and clayish alum shales which contain abundant graptolites. Their distribution has been clearly outlined by the comprehensive work of Herman Jaeger in the past (H. JAEGER 1975, H. W. FLÜGEL et al. 1977, H. JAEGER & H. P. SCHÖNLAUB 1980, 1994, H. P. SCHÖNLAUB 1985). According to H. JAEGER the Bischofalm Facies can be subdivided into three members, i. e. the Lower, Middle and Upper Bischofalm Shales.

The Findenig Facies represents an intermediate facies between the shallow water and the starving basinal environment. It comprises interbedded black graptolite shales, marls and blackish limestone beds. At its base a quartzose sandstone may locally occur.

The four Silurian lithofacies reflect different rates of subsidence. From the Llandovery to the beginning of the Ludlow sedimentation suggests a steadily subsiding basin and a transgressional regime. This tendency decreased and perhaps stopped during the Pridoli to form balanced conditions with uniform limestone sedimentation. Simultaneously, in the Bischofalm Facies black graptolitic shales were replaced by greenish shales and grayish shales named Middle Bischofalm Shale. At the base of the Devonian in the Bischofalm Facies the deep-water graptolitic environment was restored until the end of the Lochkovian Stage.

Lithostratigraphy, Biostratigraphy, Depositional Environment

In the Carnic Alps the Cellon section has served since the study of O. H. WALLISER (1964) as a standard for the worldwide applicable conodont zonation which, however, has been further detailed and partly revised in other areas. In fact, this section represents the stratotype for the Silurian of the Eastern and Southern Alps. The conformable sequence suggests continuity from the Ordovician to the Devonian. However, in recent years several small hiatuses have been recognized which reflect sea-level changes within an overall shallow to moderately deep environment. From top to base the Silurian part is subdivided into the following formations (Fig. 3):

- 8 m Megaerella Lst. (greyish and partly fossiliferous limestone; Pridoli)
- 20 m Alticola Lst. (grey and pink nautilod bearing limestone; Ludlow to Pridoli)
- 3.5 m Cardiola Fm. (alternating black limestone, marl and shale; Ludlow)
- 13 m Kok Fm. (ferruginous nautiloid limestone, with shaly interbeds at the base; upper Llandovery to Wenlock)
- 4.8 m Plöcken Fm. (calcareous sandstone; Ashgill, Hirnantian Stage).

According to H. P. SCHÖNLAUB (1985, 1988) the Ordovician/Silurian boundary is drwan between the Plöcken and Kok Formations. Conodonts and graptolites from the basal part of the Kok Fm. indicate that at least the equivalences of six graptolite

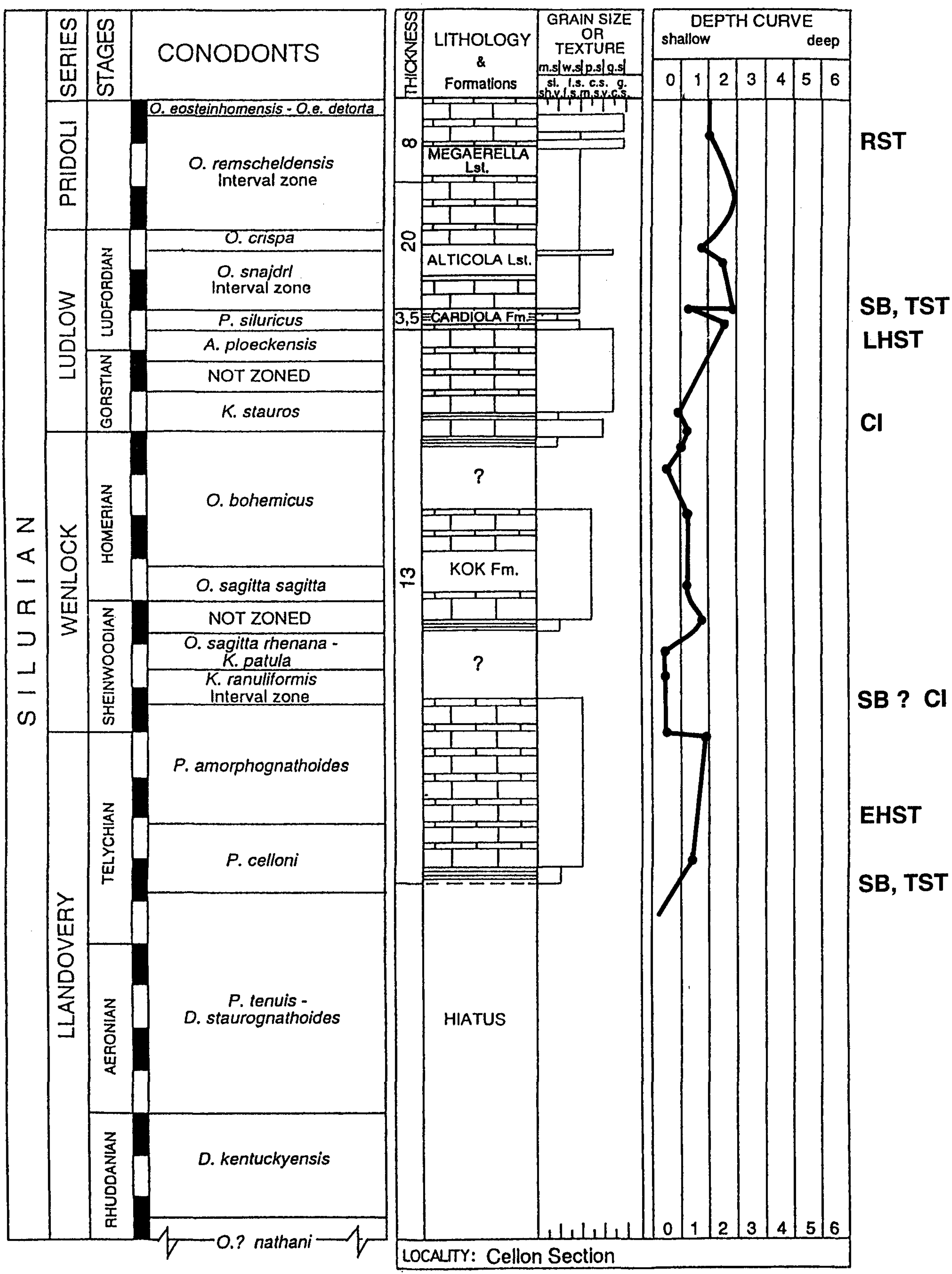

Fig. 3. Conodont stratigraphy, lithology, grain size and depth curve of the Silurian portion of the Cellon section (CI - condensed interval, EHST - early highstand system tract, LHST - late highstand (regressive) system tract, RST - regressive system tract, TST - transgressive system tract, SB - sequence boundary).

and two conodont zones are missing in the Lower Silurian. Sedimentation started in the upper Llandovery within the range of the index conodont *Pterospathodus celloni.*

At present in the Cellon section the precise level of theLlandovery/Wenlock boundary can not be drawn. Based on graptolites and conodonts this boundary should be placed between sample nos. 11 and 12 of O. H. WALLISER's conodont-based subdivision. As a consequence, the thickness of the exposed Llandovery strata does not exceed some three meters.

The boundary between the Wenlock and Ludlow Series is precisely drawn between the conodont sample numbers 15B1 and 15B2. This level most closely corresponds to the stratotype at quarry Pitch Coppice near Ludlow. For the entire Wenlock an overall thickness of some 5 m is thus concluded. By comparison with the Bohemian sections strata equivalent to the range of the index conodont *Ozarkodina bohemica* are extremely condensed at Cellon suggesting that sedimentation occurred mainly during the lower part of the Homerian Stage. As stated by H. P. SCHÖNLAUB 1994 with regard to the foregoing Sheinwoodian Stage it may be inferred that at its base the corresponding strata are also missing or they are represented as the thin shaly interbed between sample nos. 12A and 12C. At this horizon the *M. rigidus* Zone clearly indicates an upper Sheinwoodian age.

Correlation with the Bohemian sequences and the occurrence of the index graptolite *M. parultimus* for the base of the Pridoli indicates the position of the Ludlow/Pridoli boundary a few cm above the conodont sample no. 32 (see H. P. SCHÖNLAUB in J. KRIZ et al. 1986). This level lies 8m above the base of the Alticla Lst. suggesting that the thickness of Ludlow strata is about 16.45 m.

At Cellon the Silurian/Devonian boundary is placed at the bedding plane between sample nos. 47A and 47B. At this latter horizon the first representatives of the index conodont *Icriodus woschmidti* occur. The first occurrence of diagnostic index graptolites for the base of the Lochkov Stage is however some 1.5 m higher. H. JAEGER (1975) recorded in sample no. 50 the lowermost occurrence of *M. uniformis*, *M.* cf. *microdon* and *Linograptus posthumus.* In total, the Pridoli part of the Cellon section may this reach a thickness of some 20 m.

Data about the distribution of acritarchs, chitinozoans, brachiopods, bivalves and unrevised occurrences of nautiloids and trilobites are included in the SSS-Field Meeting and summary report edited by H. P. SCHÖNLAUB & L. H. KREUTZER (1994).

Depositional environment: In the Carnic Alps as early as in the Upper Ordovician a twofold facies development can be deduced. According to W. DULLO (1992) the Wolayer Lst. represents the near-shore parautochthonous cystoid facies and the Uggwas Lst. its off-shore basinal debris counterpart. Follwing a sedimentary gap at the base of the Silurian caused by glacially-induced sea-level fall renewed sedimentation started in a moderately shallow environment which may have lasted until the very beginning of the Wenlock. This is testified for example in sample no.11 indicating a bioturbated wackestone with algae and lumachelles suggesting a very shallow to intertital environment. During the following Wenlock time there is a progressing transgressive tendency. However, at the Wenlock/Ludlow boundary some strata are missing.

During deposition of the Cardiola Formation an pelagic off-shore environment is indicated by radiolarian-bearing black marly inderbeds and pelagic limestones containing a diverse Cardiola community. The following Alticola Lst. reflects stable conditions in a pelagic setting which terminated in a short regressive pulse at sample no. 40, i. e. laminated grainstones with lumachelles. A further transgressive trend can be assumed at the base of the Megaerella Limestone. For more details see L. H. KREUTZER in H. P. SCHÖNLAUB 1994.

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Graptolites have been known in the Alps since the first discovery of G. STACHE in 1872. The pure graptolitic facies is best exposed in the so-called "Graptolithengraben" north of the upper Bischofalm in the central Carnic Alps. Lithologically, the graptolite-bearing rocks form a monotonous sequence of interbedded radiolarian bearing cherts and alum shales. The first dominate in the Llandovery and Wenlock part of the succession, the latter prevail in the upper part. The intermediate green and grey shales yield only few graptolites in tiny layers.

The composite thickness of the graptolite-bearing Silurian to Lochkov sequence ranges from 50 to 100 m. It is thus an extremely condensed sequence due to a very low but nevertheless continuous rate of deposition. This conclusion is supported by the very complete graptolite zonal succession. The environmental conditions were extremely euxinic except for a short interval when the Middle Bischofalm Shale was deposited (Fig. 4).

Graptolites and few conodonts on bedding planes are the only fossils to be found in this facies. The graptolites are common in many layers both in the alum shales and in the cherts. Some intervals, however, are almost barren of graptolites.

Due to intense Variscan and Alpine tectonics larger undisturbed sections are very rare. By far the best exposed and least disturbed section is displayed in the "main section", named the Hauptprofil and has been studied in great detail bei H. JAEGER starting in 1965. The tectonic block is almost 20 m thick and covers the interval from the vulgaris Zone of the Ludlow to the Lower Devonian hercynicus Zone. In the vicinity of the section older strata are as well exposed but they are fault-bounded with the main section.

The main graptolite section is virtually undisturbed except for a fault at the critical horizon between the *M. uniformis* and the *M. transgrediens* Zones , i. e. at the Silurian/Devonian boundary. By comparison with other sections it is concluded that there is no significant loss of strata at this fault.

According to H. JAEGER in H. W. FLÜGEL et al. 1977 the following points are of more than local interest:

- The Silurian/Devonian boundary is within a homogeneous black shale facies. Obviously, there was no physical break at this boundary.
- A distinct change in facies from green and grey shales to black shales preceded the faunal change at the boundary by one graptolite zone.
- There is no evidence that *M. transgrediens* and *M. uniformis* overlap.
- The Middle Bischofalm Shales occupy the same stratigraphic position as the non-graptolitic Ockerkalk of Thuringia and presumably also of Sardinia.

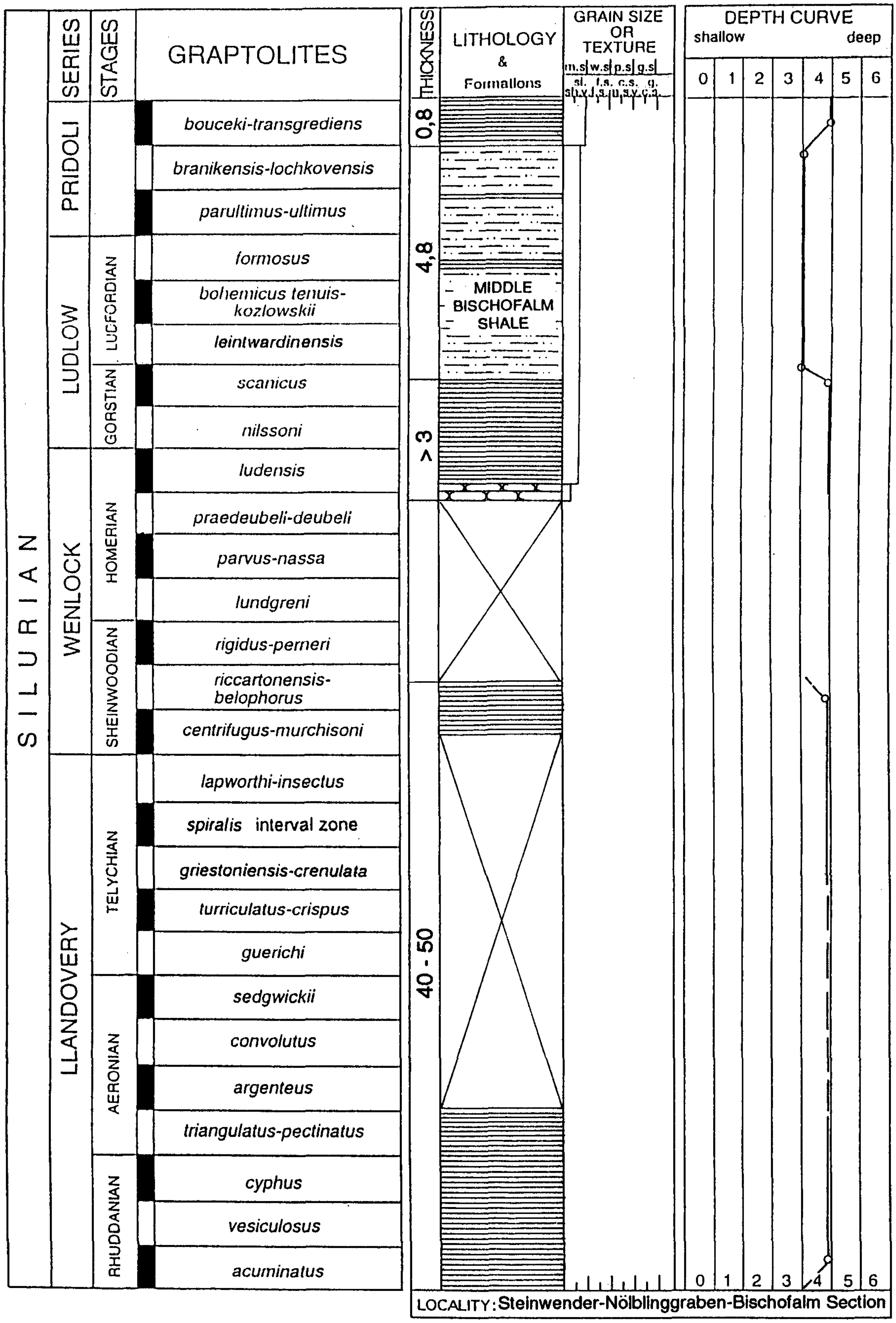

Fig. 4. Composite section of the Silurian Bischofalm facies at Steinwender Hütte, Nölblinggraben and north of upper Bischofalm with indication of lithology, grain size and depth.

The intermediate facies between the foregoing shallow water and basinal settings is best developed at the section Oberbuchach (Fig. 5). This facies is termed "Findenig facies". The Silurian strata represent a mixed argillaceous-calcareous lithology named Nölbling Formation. The almost 50 m thick sequence of Llandovery to Ludlow age are underlain by the Upper Ordovician Uggwa Lst. and the 10 m thick clastic Plöcken Fm. of Hirnantian age. This formation is overlain by interbedded laminated pyritic sandstones, black bedded chert layers and black argillaceous shales containing a graptolite fauna of the zone of *M. gregarius*, subzone of *M. triangulatus* of early Aeronian age (= early Middle Llandovery). Yet, it is not clear whether the equivalents of the Lower Llandovery are missing at this section or whether this portion is barren of fossils.

In the late Llandovery a second horizon of graphitic sandstones occur; its age is inferred from diagnostic conodonts of the *Pterospathodus celloni* Zone in limestones overlying the clastic member. These limestones are followed by an alternating sequence of dark argillaceous limestones, black argillaceous graptolite shales and cherts ranging through the Wenlock to the Ludlow. In this interval conodonts are associated with index graptolites of uppermost Llandovery to Wenlock age. In the shales above graptolites occur at several levels starting off with the zone of *Monograptus riccartonensis* in the Sheinwoodian Stage and ending in the zone of *Monograptus nilssoni* at the base of the Gorstian Stage, i. e. at the beginning of the Ludlow. The Wenlock/Ludlow boundary may thus be placed some 40 m above the base of the graptolite bearing sequence.

At this locality other fossils than graptolites and conodonts are very rare. Conodonts are dominated by simple tooth-shaped cones like *Dapsilodus* and *Decoriconus* whereas ramiform elements only occur in the lower portion of the section.

Strata corresponding to the remaining part of the Ludlow and Pridoli Series consist of up to 20 m thick, lithologically very distinct grey and almost unfossiliferous pyritiferous limestones showing a very characteristic weathered surface which may have originated from solution processes.

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The Rauchkofel Boden section represents the Silurian Wolayer facies which is characterized by the Upper Ordovician cystoid bearing Wolayer Lst. overlain by highly fossiliferous Middle to Upper Silurian limestones (Fig. 6). Strata corresponding to the Hirnantian Stage of the late Ordovician and Lower Silurian respectively are missing in this facies. The sedimentary gap may be ascribed to the glacial-induced end-Ordovician eustatic sea-level fall and the inherited topography.

The Wolayer Lst. is disconformably overlain by grey fossiliferous cephalopod bearing limestones, named "Orthoceras Lst." and being equivalent to the Kok Limestone. Besides the dominating nautiloids trilobites and bivalves are quite common (H. R. v. GAERTNER 1931, H. RISTEDT 1968, J. KRIZ 1979, H. P. SCHÖNLAUB, ed., 1980). In addition conodonts occur fairly abundant and represent the *Ozarkodina sagitta* Zone of the Wenlock Series (basal Homerian Stage). About 1.20 m above the unconformity the index conodont *Kockelella variabilis* appears suggesting the base of the Ludlow Series by comparison with Bohemia (H. P. SCHÖNLAUB in J.

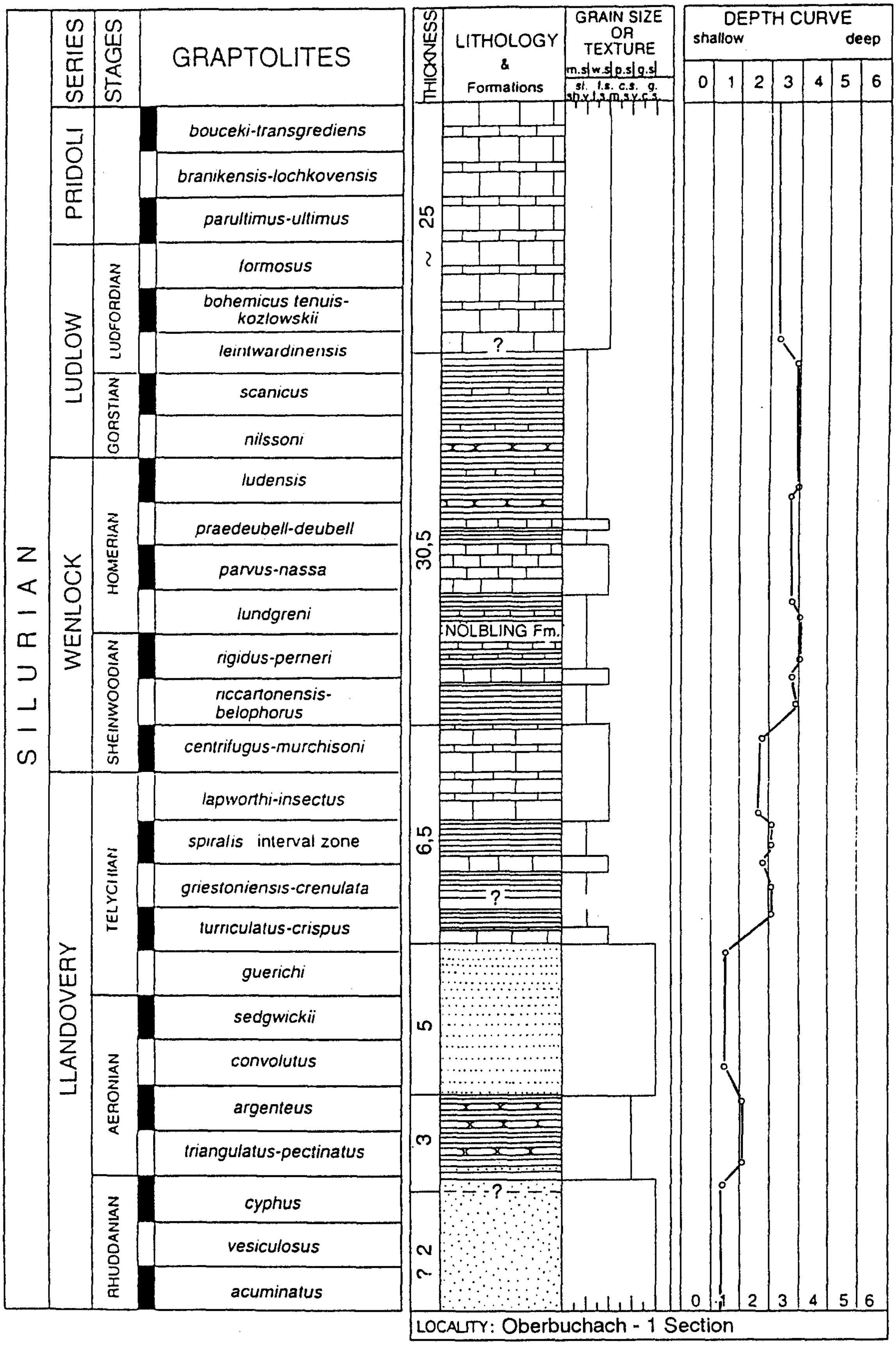

Fig. 5. Section Oberbuchach 1 representing the mixed carbonate - graptolitic shale facies of the Carnic Alps with indication of graptolite biostratigraphy, lithology, grain size and depth curve.

KRIZ et al. 1993). The following equivalent of the Cardiola Fm. corresponds to the *Polygnathoides siluricus* conodont Zone of the Cellon section. It is succeeded by pinkish and greyish limestones corresponding to the Alticola and Megaerella Limestones. However, diagnostic conodonts have yet not been found except in the uppermost level which contains *Scyphocrinites* sp. and common representatives of *Ozarkodina remscheidensis eosteinhornensis*. Based on new field data recently acquired by an international team including J. KRIZ, A. FERRETTI, C. HISTON, O. BOGOLEPOVA and the author the Silurian/Devonian boundary is suggested on top of the *Scyphocrinites* bed, i. e. at the base of the reference sample no. 199.

Preliminary paleoecological and paleogeographical analysis of the Wenlock to Pridoli succession have indicated a local hydraulic behaviour in a transgressive shallow water regime controlled by the South Equatorial Current who may have been responsible for the exchange of faunas between widely separated areas such as northern Sibiria, Perunica, the Carnic Alps and Sardinia (J. KRIZ & O. BOGOLEPOVA 1995). Indeed, there is a preferable trend in the orientation of orthoconic cephalopods from SW to NE in the Kok Lst. changing to a N-NE to S-SW direction in the overlying Lochkov strata (O. BOGOLEPOVA in H. P. SCHÖNLAUB & L. H. KREUTZER 1994).

The Gurktal Nappe

The Gurktal Nappe is composed of a several 100 m thick succession of volcanic and clastic rocks with intercalations of limestones. Strata corresponding to the Silurian comprise coral-bearing organodetritic limestone lenses at the passage from the Llandovery to the Wenlock and a few occurrences of 5 to 10 m thick limestones and dolomites of Late Silurian age. Due to lack of fossils and weak exposures it is as yet not possible to reconstruct a composite Silurian section. However, the facies development suggests a subdivision into a carbonate dominated and a carbonate-poor facies (M. F. BUCHROITHNER 1979, F. EBNER et al. 1990, H. P. SCHÖNLAUB & H. HEINISCH 1994).

The Lower Paleozoic sequences of the Gurktal Nappe System are also characterized by volcanic activities. Volcanism occurred at different times, varying intensities and different geochemical behaviour reflecting different paleotectonic settings (J. LOESCHKE & H. HEINISCH 1993).

The surroundings of Graz

The Palaeozoic history of the area of Graz is best displayed in the sequence of the Rannach Nappe which represents the uppermost nappe of the Graz Thrust Complex. The Silurian part of the sequence is dominated by alkaline mafic lavas and pyroclastics which suggest an initial rift stage. These volcano- and siliciclastics are succeeded by progressive carbonate production during the late Silurian and Devonian.

According to H. FRITZ & F. NEUBAUER 1988, F. NEUBAUER 1989 in the Silurian Kehr Fm. sedimentation was mainly controlled by volcanism. During the early Ludlow a more eastern area was characterized by a proximal shallow water setting with lavas and coarse lapilli tuffs while the western section represented the distal facies

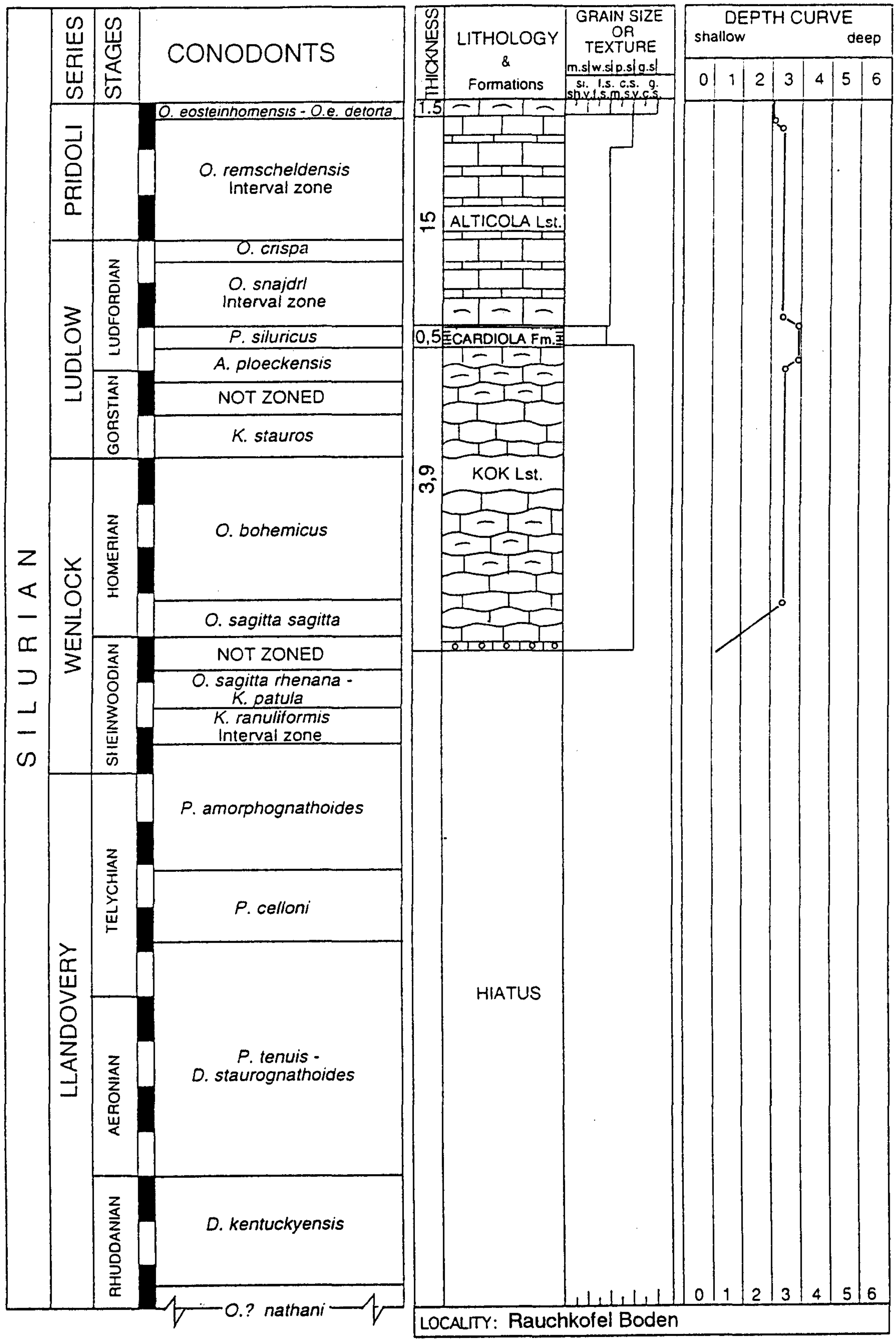

Fig. 6. The Silurian part of the Rauchkofel Boden section with indication of conodont stratigraphy, lithology, grain size and depth curve.

exhibiting cinerites with intercalations of lapilli-rich beds, agglomerates, shales and pelagic limestones. The interesting Kehr Agglomerate consists of 1 to 3% quartzites, dolomites, cherts and reworked limestones.

During the upper Silurian the volcanic centers were buried by fossiliferous carbonates consisting of approx. 4 m thick bedded dolomites with lenses of bioclastic (crinoids, brachiopods, trilobites, nautiloids) dolomitic limestones interbedded with tuffs and tuffitic shales. Based on conodonts for this sequence the Ludlow (Ludfordian) to Pridoli age is concluded (F. EBNER 1994).

Overall similar environmental conditions are suggested for the upper Silurian of the other nappes of the Graz Paleozoic in which pelagic nodular limestone sedimentation persisted from the Upper Silurian to the Devonian.

Lithostratigraphy, Biostratigraphy, Depositional Environment

In the Eggenfeld section the Silurian history of the Graz Paleozoic is best displayed (Fig. 7). In this area the distribution of upper Silurian and lower Devonian sediments is controlled by the Silurian volcanism. In spite of poor outcrops a well constrained lithostratigraphic framework can be established which includes the following rocks (F. EBNER 1994, Fig. 7):

- Massive green diabases interfingering with pinkish to greenish tuffs
- First horizon of well bedded dark dolomites (D/1) containing common crinoids, brachiopods, nautiloids and tabulate corals (*Favosites* sp.)
- Tuffs and tuffitic shales
- Second horizon of well bedded dark dolomites (D/2) with lenselike bioclastic accumulations of crinoids, brachiopods, trilobites, nautiloids and few corals (*Syringaxon* sp.)
- Tuffs and tuffitic shales with intercalations of dark dolomitic beds (D/3) with bioclastic accumulations of crinoids, brachiopods, trilobites and nautiloids.

Biostratigraphic important macro- and microfossils include conodonts and brachiopods. Conodonts are fairly abundant in all carbonatic levels. Diagnostic species include *Polygnathoides siluricus, Polygnathoides emarginatus* and *Kockelella variabilis* in the dolomites immediately overlying the diabases and thus indicate a Ludfordian or earlier age for the end of the basic volcanism. In the second carbonate level (D/2) *Ozarkodina snajdri* has been identified which represents the *Ozarkodina snajdri* Interval zone of the Ludfordian Stage. The index conodont is associated with *Ozarkodina remscheidensis eosteinhornensis*. In addition, at this level there is a common occurrence of the brachiopod species *Septatrypa subsecreta* which, however, also occurs in small carbonate layers intercalated in the overlying tuffitic shales. Based on the occurrence of *Icriodus woschmidti* the latter, however, belong to the lowermost Lochkovian. Yet, index conodonts of the *Pedavis latialata* and *Ozarkodina crispa* zones were not recorded.

The Eggenfeld section is of particular importance for the proof and dating of Silurian volcanic activity in the Eastern Alps. Based on its fossil record this section represents an excellent example of a volcanic island surrounded and buried by

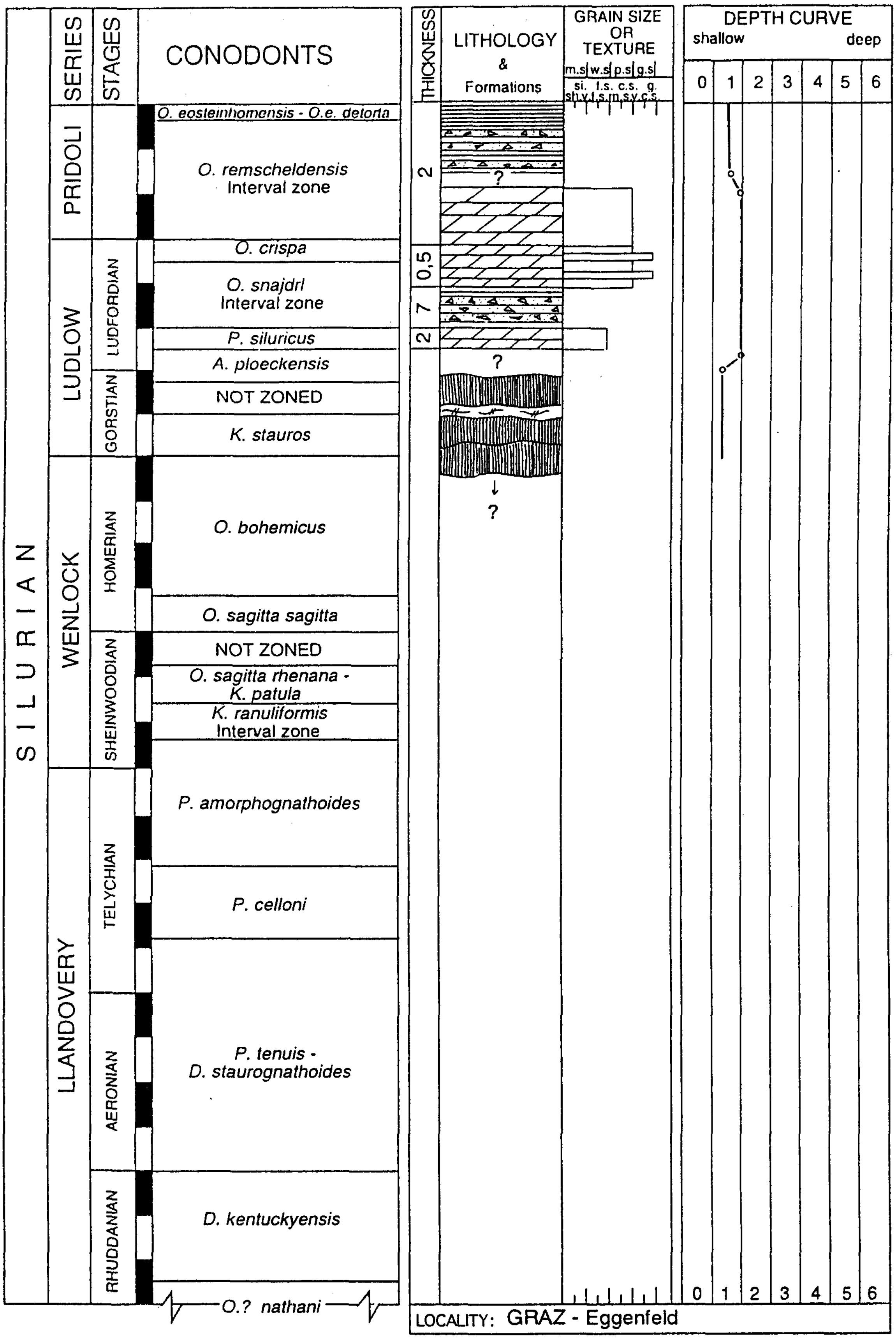

Fig. 7. The Eggenfeld section north of Graz with indication of conodont biostratigraphy, lithology, grain size and depth curve.

bioclastic carbonate accumulations during the upper Silurian. Carbonate production and volcanism progressed during the Devonian.

The Graywacke Zone

According to H. P. SCHÖNLAUB 1979 and H. P. SCHÖNLAUB & H. HEINISCH 1994 the Silurian part of the thick Lower Paleozoic succession of the Graywacke Zone of Styria exhibits a distinct facies differentiation which ranges from some 50 m thick crinoid and nautiloid bearing limestones to black graptolitic shales. Vertically and also laterally, they grade into interbedded limestones and shales followed by a pure limestone development during the Late Ludlow and Pridoli. Locally intercalations of basic volcanics of Llandovery age occur near its southern margin.

The above mentioned facies heterogenity seems to be valid also for the Tyrol and Salzburg segments of the Graywacke Zone. According to H. HEINISCH 1988 within short distances two distinct facies can be distinguished. They are preserved in two nappes named Wildseeloder and Glemmtal Unit, respectively. In the Silurian, the general facies pattern ranges from black shales with local occurrences of graptolites to cherts, siliceous pelagic limestones, condensed cephalopod limestones and even dolomitic rocks.

The Wildseeloder Unit is characterized by a thick pile of the Upper Ordovician Blasseneck Quartzporphyry which is overlain by several meters of pelagic limestones in the middle and upper Llandovery followed by the so-called "Dolomit-Kieselschiefer-Komplex" (Bedded Dolomite-Chert Fm.). In the upper Silurian a carbonate platform developed which lasted until the early Upper Devonian.

The Glemmtal Unit comprises more than 1000 m of mainly siliciclastic sequences which are summarized as Wildschönau Group. Locally up to 50 m thick intercalations of condensed pelagic limestones, marls, interbedded cherts, siliceous shales and basaltic layers occur which have been named Klingler Kar Formation. Based on conodonts for the lower part an upper Silurian age is indicated. Laterally this facies grades into a turbiditic facies named Löhnersbach Fm. In the latter, however, age assignments are as yet missing.

Lithostratigraphy, Biostratigraphy, Depositional Environment

With few exceptions from Styria the Silurian succession of the Graywacke Zone of Tyrol and Salzburg is fairly well known due to occurrences of conodonts and some other fossils such as graptolites. Yet, no detailed biostratigraphic data are available concerning the exact placement of the Ordovician/Silurian boundary.

The Spießnägel section south of Kirchberg/Tyrol is one of the few relevant sections in which the transition of presumably late Ordovician graywackes into basal Silurian strata is exposed. According to N. AL-HASANI & H. MOSTLER 1969 the Silurian sequence starts with 0.85 m thick arenaceous and tuffitic limestones containing diagnostic conodont of the *Pterospathodus celloni* Zone. The lower part of these limestones comprises bioturbated mudstones with varying amount of clastic and tuffaceous material. Some 0.70 m above the base they grade into wackestones. Of special interest is the occurrence of superficial ooids in the upper part of this bed. Their nucleus is formed by crinoid-stems or shell debris which were superficially coated.

The basal part is succeeded by 1.10 m of well bedded limestones with interbedded shale layers containing thin lenses of limestones. This part represents packstones with lumachelle-like debris of bivalves, brachiopods, ostracods and echinoderms. They exhibit a sharp contact to the overlying greyish laminated dolomites which are assigned to the *Kockellella patula* Zone of the lower Wenlock.

The sequence mentioned above corresponds to the interval from the *Ptersopathodus celloni* to the *Pterospathodus amorphognathoides* Zone, i. e., they reflect the environment of the upper Llandovery and the basal Wenlock in this segment of the Graywacke Zone.

Another important lower Silurian section has long been known as "Lachtal-Grundalm section" near the village of Fieberbrunn. The graptolite bearing sequence represents one of the classical outcrops of the Silurian of the Graywacke Zone. It comprises a mixed shale-limestone succession known in the literature as "Lydit-Kieselkalk-Komplex" at the base and the 5 m thick "Dolomit-Kieselschiefer-Komplex" above (H. MOSTLER 1966, Fig. 8).

The basal cherty formation is formed by black massive cherts known as "Lydite" in the Alpine terminology, radiolarian bearing dolomites and reddish cherty limestones which grade vertically into crinoidal limestones. The total thickness does not exceed 5 m. The accompanying microfauna consists of remains of ostracods, foraminifers, brachiopods, radiolarians, conodonts and echinoderms. In addition bivalves, solitary corals, trilobites and orthocone nautiloids sparsely occur in the lower part of the 1.40 m thick crinoid limestone member. Based on conodonts the lower 2.10 m of the limestone succession can be assigned to the *Pterospathodus celloni* Zone; the upper part belongs to the *Pterospathodus amorphognathoides* Zone.

According to H. JAEGER 1978 the only identifyable graptolites occur in the upper part of the Lachtal-Grundalm section known as "Dolomit-Kieselschiefer-Komplex". The lithology resembles the Nölbling Fm. of the Silurian of the Carnic Alps. Representatives of *Monograptus bohemicus* are most abundant in an upper horizon. They are characteristic for the *Monograptus nilssoni* Zone at the base of the Gorstian Stage of the lower Ludlow Series. Co-occurring conodonts are long ranging elements which permit no further age assignment. Other graptolites are *Monograptus dubius* cf. *frequens* and *Monograptus* sp. indet. ex gr. *colonus.*

In the Tyrolean part of the Graywacke Zone the "Dolomit-Kieselschiefer-Komplex" is overlain by dolomitic rocks and magnesites. According to H. MOSTLER 1966 the base of these carbonates can be assigned to the conodont zone of *Ozarkodina crassa* or to the base of the following *Ancoradella ploeckensis* Zone, i. e. to the boundary between the Gorstian and the Ludfordian Stages of the Ludlow Series.

In summary, the available data from the Lachtal-Grundalm section represent a composite succession through the major part of the Silurian. Biostratigraphically dated rocks start in the middle Llandovery and can be followed up through the Wenlock to the middle of the Ludlow Series. In the Tyrolean part of the Graywacke Zone no

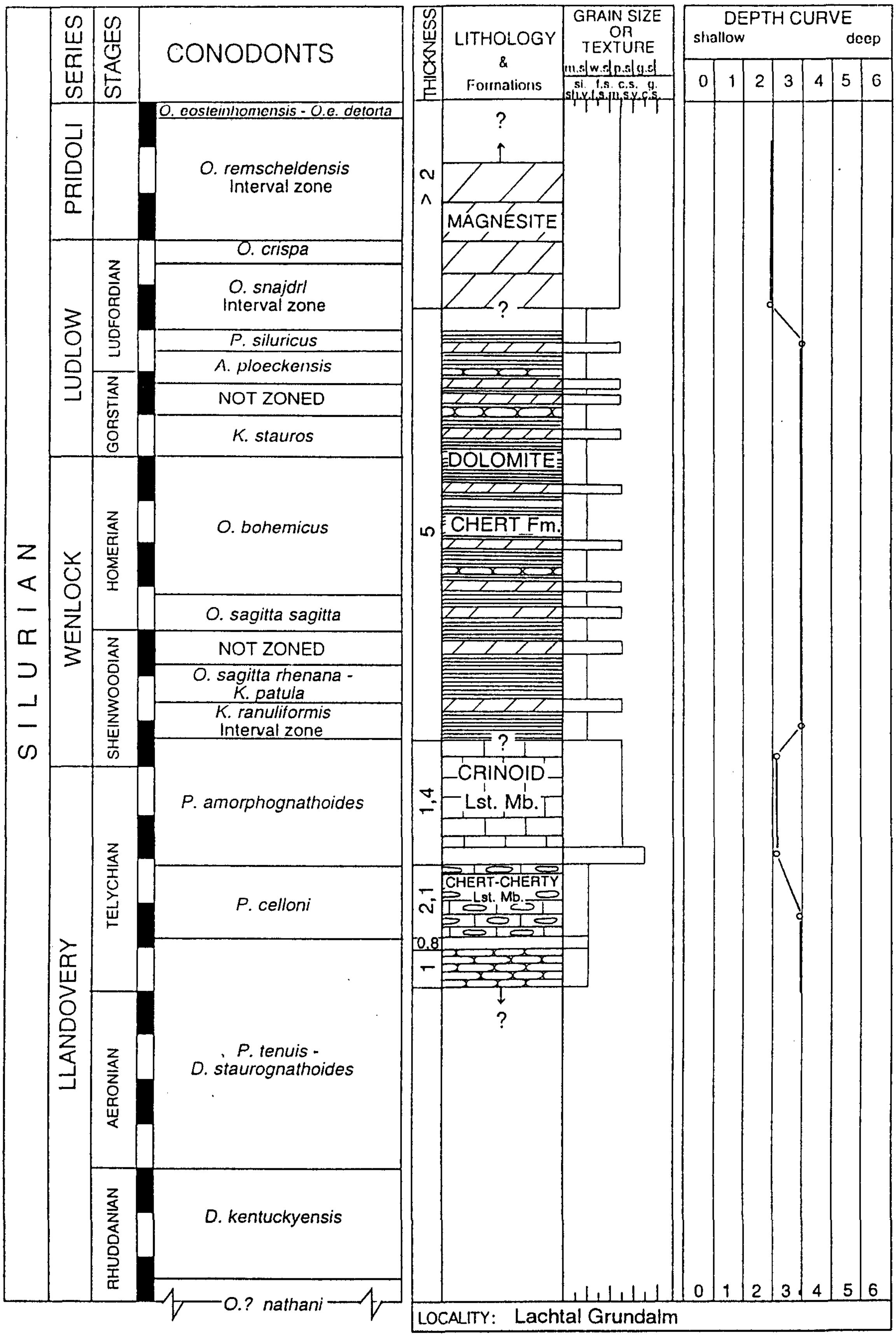

Fig. 8. The Lachtal Grundalm section south of the village Fieberbrunn/Tyrol with indication of conodont stratigraphy, lithology, grain size and depth curve.

records from the Pridoli Series are yet available which, however, may be represented by recrystallized dolomites.

Faunal relationships and climatic implications

As mentioned in the chapters before the Silurian Period is characterized in the Alps by a wide range of different lithofacies. The corresponding strata are locally very fossiliferous and contain each a distinct faunal assemblage consisting of varying abundances of nautiloids, trilobites, bivalves, brachiopods, graptolites as well as conodonts, foraminifera, acritarchs, chitinozoans and ostracods. During the last decades most but by far not all groups have been revised or are being studied presently. The available data suggest a complete but considerably condensed succession in the carbonate-dominated facies and a continuous record in the Silurian graptolite-bearing sequences. In particular this is true for the Carnic and Karawanken Alps; in other areas, however, continuity has as yet not been demonstrated and it seems uncertain to assess this aim due to bad preservation, lack of fossils and metamorphic overprints.

Silurian faunas following the end-Ordovician mass extinction are generally regarded as cosmopolitans and hence provide only little evidence to reconstruct the latitudinal position of individual plates. In combination with lithic data and a highly diversified fossil assemblage, however, this matter may be improved.

Conodont evidence from the Silurian of the Alps suggests a close affinity to coeval faunas from central, southern and southwestern Europe. Britain and Gotland occupied a more equatorial position and, hence, corresponding conodonts are more diversified.

The distribution of acritarchs suggest an intermediate position between the high latitude *N. carminae* and the tropical *Domasia-Deunffia* biofacies. The available data on chitinozoans show close relationships to those from Bohemia the connection of which is even stronger supported in upper Ludlow to lower Lochkov deposits (P. DUFKA 1992, J. KRIZ 1992, J. KRIZ et al. 1986, F. PARIS & J. KRIZ 1984).

Silurian trilobites from the Carnic Alps are closely related to Bohemia and other central European regions. Affinities to Morocco exist but are as yet not studied in detail.

According to W. B. N. BERRY 1979 Silurian graptolites show only little endemism suggesting that interplate dispersal was possible. Their distribution may have mainly been controlled by the surface water and oceanic currents which operated between the individual Silurian microcontinents and volcanic islands. As noted by H. JAEGER (1976, 1988) during the Ludlow and Pridoli an essentially uniform graptolite fauna developed in Europe. The changing environment of this time is portrayed in a contemporaneously shifting lithofacies between Africa and Baltica which displays a characteristic vertical change from black graptolitic shales to limestones and back to shales. Sea-level rise and fall are considered to have been responsible for these changes.

Beginning in the Upper Llandovery nautiloids became the dominating organisms in the carbonate facies of the Alps with rich abundances of orthoceratids in the

Wenlock and Ludlow and decreased numbers in the Pridoli (H. RISTEDT 1968, 1969). The diversified fauna seems closely related to Bohemia and Sardinia (J. KRIZ & E. SERPAGLI 1993). Ongoing studies have also shown that the Silurian cephalopod biofacies reflects even close links to northern Sibiria. Supposedly, this relationship resulted from the South Equatorial Current that operated during the Silurian along the southern margin of Sibiria and Laurussia (J. KRIZ & O. BOGOLEPOVA 1995).

The distribution of other mollusks, in particular bivalves resembles grossly that of nautiloids. According to J. KRIZ (1979) Silurian cardiolids from the Carnic Alps and the western Graywacke Zone inhabitated a warm equatorial belt or were dispersed through currents.

J. KRIZ (1996 in press) recognized in the Carnic Alps the oldest Silurian Bivalvia dominated community of the *Cardiola* Community Group, i. e. the *Carnalpia nivosa* Community in the rigidus Biozone (Wenlock). Other recurring communities of the *Cardiola* Community Group are also known from Bohemian Prague Basin and from other regions in Europe. In the Wenlock (lundgreni Biozone) of the Rauchkofel section the *Slava fibrosa* Community occurs which is closely related to the *Cardiola agna* Community known from other European regions.

The Cardiola Formation is characterized by the *Cardiola docens* Community, which is known from the Prague Basin (Bohemia), Sardinia, Eastern Serbia, Montagne Noire (France), Spain and Morocco.

At the base of the Prídolí (parultimus Biozone) in the Cellon section the *Cardiolinka bohemica* Community occurs known also from Nagelschmieddpalfen near Dienten in the Graywacke Zone of Tyrol, from the Prague Basin (Bohemia) and Elbersreuth, Frankenwald (Germany). In the uppermost Prídolí of the Rauchkofel Section the *Dualina - Patrocardia* Community occurs which is related to the Lower Devonian (Lochkovian) *Patrocardia evolvens evolvens* Community of the *Patrocardia* Community Group known from the Prague Basin in Bohemia, from Sardinia and from the South Armoricain Domain (La Meignanne) in France.

The *Cardiola* Community Group is characterized by epibyssate bivalves which were adapted to the cephalopod limestone biofacies indicating a temporally ventilated, relatively shallow bottom (Boucot´s Assemblage 2 - 3). The *Patrocardia* Community Group is characterized by epibyssate (*Patrocardia*), infaunal and reclining (*Dualina*) forms living also in the temporally ventilated cephalopod limestone biofacies.

In our view Silurian corals from the Alps were prominent constituents of a shallow water environment in the broader tropical belt (Fig. 9). During the early Silurian only weak indications of provincialism is indicated among tabulate and rugose corals at the generic level. However, long-living teleplanic larvae might also have been transported by ocean currents over long distances (J. W. PICKETT 1975, R. A. McLEAN 1985, D. L. KALJO & E. KLAAMANN 1973, A. E. H. PEDDER & W. A. OLIVER 1990).

Rugose and tabulate corals occur in the late Llandovery of Middle Carinthia, in the Upper Silurian (Ludlow) of Graz and very rare in shallow water and locally superficial ooid bearing limestones in the late Llandovery of the Graywacke Zone of Tyrol (H. P.

SCHÖNLAUB 1994, with additional references). Recently, the working team on cephalopod limestones has discovered also in the Carnic Alps a yet undescribed pioneer rugose coral fauna in rocks of Ludlow and Pridoli age.

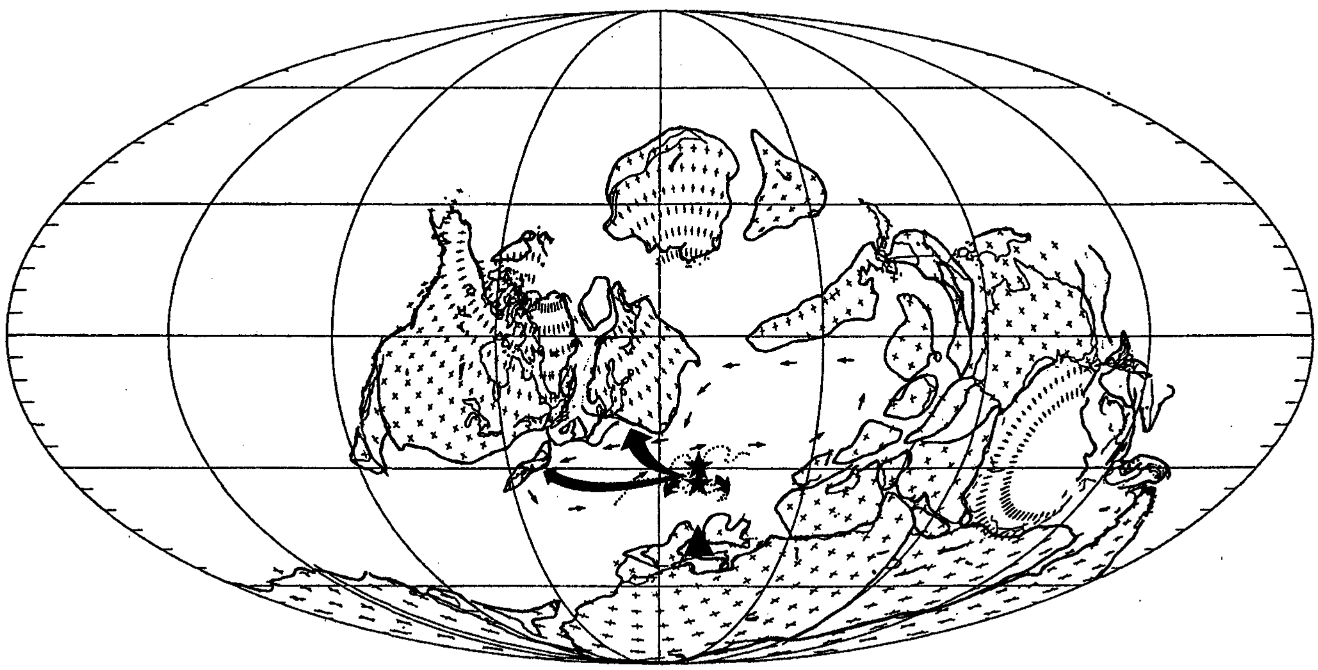

Fig. 9. Middle Silurian (Wenlockian) paleogeography with indication of latitudinal settings of Silurian rocks in the Alps shown as stars. Faunal relationships are shown by heavy arrows, the oceanic current system in the mid-European ocean by small arrows. Triangle represents position of the Alps as suggested by C. R. SCOTESE & W. S. McKERROW (1990). From H. P. SCHÖNLAUB (1992).

In summarizing, we believe that the above mentioned lithic and faunistic data of the Alps can be used to infer not only the climatic conditions during the Silurian but also provide some insights into such parameters as light, temperature, salinity, water agitation and other agents controlling the distribution of different organims. Hence, it is concluded that during the Silurian Period the Alpine occurrences continued to shift from higher to lower latitudes. Paleomagnetic data from Gondwana seem to support the assumption of rather rapid northward plate movements. Based on the evidences presented above we thus estimate for the Alpine occurrences of Silurian deposits a position at approx. 30 to 40° southern latitude. During this period close faunal relations existed to northern Europe but minor links were also directed to southern Europe (see Fig. 9).

References

AL-HASANI, N., and MOSTLER H., 1969, Zur Geologie der Spießnägel südlich Kirchberg (Nördliche Grauwackenzone, Tirol): Veröffentl. Univ. Innsbruck, 9, Alpenkundl. Stud., 5, 5 - 26.

BOGOLEPOVA, O. K., and KRIZ, J., 1995, Ancestral forms of Bohemian type Bivalvia from the lower Silurian of Siberia (Tungusskaja Syneclise, Russia): Geobios, 28, 6, 691 - 699.

BUCHROITHNER, M. F., 1979, Biostratigraphie und fazielle Untersuchungen im Paläozoikum von Mittelkärnten: Carinthia II, 169, 71 - 95.

DUFKA, P., 1992, Lower Silurian Chitinozoans of the Prague Basin (Barrandian, Czechoslovakia). Preliminary Results: Rev. Micropaléont., 35/2, 117 - 126.

DULLO, W. C., 1992, Mikrofazies und Diagenese der oberordovizischen Cystoideenkalke (Wolayerkalk) und ihrer Schuttfazies (Uggwakalk) in den Karnischen Alpen: Jb. Geol. B. - A., 135, 317 - 333.

EBNER, F., 1994, Section 1, Silurian/Devonian boundary section of Eggenfeld/Paleozoic of Graz. In: Field Trip Program IUGS Subcomm. Silurian Stratigraohy, Field Meeting 1994: Ber. Geol. B. - A., 30/1994, 77 - 82.

EBNER, F., FENNINGER, A., GOLLNER, H., HOLZER, H. L., NEUBAUER, F., NIEVOLL, J., RATSCHBACHER, L., STATTEGGER, K., TSCHELAUT, W., THALHAMMER, O. , and ZIER, C., 1990, Stratigraphic Correlation Forms of Paleozoic units in Austria. In: Sassi, F. P., and Zanferrari, A., (eds.) Pre-Variscan and Variscan Events in the Alpine-Mediterranean Belts, Stratigraphic Correlation Forms: Rend. Soc. Geol. Ital., 12, 213 - 239.

FLÜGEL, H. W., JAEGER, H., SCHÖNLAUB H.P. , and VAI G. B., 1977, Carnic Alps. In: Martinsson A (ed) The Silurian-Devonian Boundary: IUGS Series A, No 5, 126 - 142

FRITZ, H. and NEUBAUER, F. , 1988, Geodynamic aspects of the Silurian and Early Devonian sedimentation in the Paleozoic of Graz (Eastern Alps): Schweiz. Mineral. Petrogr. Mitt., 68, 359 - 367.

GAERTNER, H. R. von, 1931, Geologie der zentralkarnischen Alpen: Denkschr. Österr. Akad. Wiss., 102, 113 - 199.

HAUER, F. von, 1847, Versteinerungen von Dienten in Salzburg: Haidingers Berichte, 1, X.

HEINISCH, H., 1988, Hinweise auf die Existenz eines passiven Kontinentalrandes im Altpaläozoikum der Nördlichen Grauwackenzone - Ostalpen: Schweiz. Mineral. Petrogr. Mitt., 68, 407 - 418.

JAEGER H., 1975, Die Graptolithenführung im Silur/Devon des Cellon-Profils (Karnische Alpen): Carinthia II, 165/85, 111 - 126.

JAEGER, H., 1978, Graptolithen aus dem Silur der Nördlichen Grauwackenzone (Ostalpen): Mitt. Österr. Geol. Ges., 69 (1979), 89 - 107.

JAEGER H., 1988, Devonian Graptoloidea. In: McMillan NJ, Embry AF, Glass DJ (eds) Devonian of the World. - Proc. 2nd Internat. Symp. Devonian System Calgary Canada, 3, 431 - 438.

JAEGER, H., and SCHÖNLAUB, H. P., 1980, Silur und Devon nördlich der Gundersheimer Alm in den Karnischen Alpen (Österreich): Carinthia II, 170/90, 403 - 444.

JAEGER H., and SCHÖNLAUB, H. P., 1994, Section 4 "Graptolithengraben" (graptolite gorge) north of Upper Bischofalm. In: Field Trip Program IUGS Subcomm. Silurian Stratigraphy, Field Meeting 1994: Ber. Geol. B. - A., 30/194, 97 - 100.

KALJO, D. L., and KLAAMANN, E., 1973, Ordovician and Silurian corals. In: Hallam A (ed) Atlas of Palaeobiogeography: Elsevier Amsterdam, 37 - 45

KRIZ, J., 1979, Silurian Cardiolidae (Bivalvia): Sb. Geol. VED Paleont., 22, 1 - 157.

KRIZ, J., 1992, Silurian Field Excursions. Prague Basin (Barrandian), Bohemia: Geol. Ser. Nat. Mus. Wales, 13, 111 p.

KRIZ, J. (1996, in press), Bivalvia dominated communities of Bohemian type from the Silurian and Lower Devonian carbonate facies: Cambridge Univ. Press.

KRIZ, J. and BOGOLEPOVA, O. (1995), *Cardiola signata* Community (Bivalvia) in cephalopod limestones from Tajmyr (Gorstian, Silurian, Russia): Geobios, 28, 573 - 583.

KRIZ, J., JAEGER, H., PARIS, F. & SCHÖNLAUB, H. P. (1986): Pridoli - the Fourth Subdivision of the Silurian: Jb. Geol. B. -A., 129/2, 291 - 360.

KRIZ, J., and SERPAGLI, E., 1993, Upper Silurian and lowermost Devonian Bivalvia from Western Sardinia: Boll. Soc. Paleont. Italiana, 32, 289 - 347.

KRIZ, J., DUFKA, P., JAEGER, H. and SCHÖNLAUB, H. P., 1993, The Wenlock/Ludlow Boundary in the Prague Basin (Bohemia): Jb. Geol. B. - A., 136/4, 809 - 839.

LOESCHKE, J, and HEINISCH, H. 1993, Palaeozoic Volcanism of the Eastern Alps and Its Palaeotectonic Significance. In: Pre-Mesozoic Geology in the Alps, J. F. von RAUMER and F. NEUBAUER, eds, Springer Verl., 441 - 455.

McLEAN, R. A., 1985, New Early Silurian rugose corals from the Panuara area, central New South Wales: Alcheringa, 9, 23 - 34.

MOSTLER, H., 1966, Zur Einstufung der "Kieselschiefer" von der Lachtal-Grundalm (Fieberbrunn, Tirol): Verh. Geol. B. - A., 1966, 157 - 170.

NEUBAUER, F., 1989, Lithostratigraphie und Strukturen an der Basis der Rannachdecke im zentralen Grazer Paläozoikum (Ostalpen): Jb. Geol. B. - A., 132, 459 - 474.

PARIS, F., and KRIZ, J., 1984, Nouvelles especes de chitinozoaires a la limite Ludlow/Pridolien Tchecoslovaquie: Rev. Palaeobot. Palyn., 43, 155 - 177.

PEDDER, A. E. H., and OLIVER, Jr., W. A., 1990, Rugose coral distribution as a test of Devonian palaeogeographic models. In: McKerrow W. S. and Scotese, C. R. (eds) Palaeozoic Palaeogeography and Biogeography: Geol. Soc. London, Mem., 12, 267 - 275.

PICKETT, J. W., 1975, Continental reconstructions and the distribution of coral faunas during the Silurian: J. Proc. Roy. Soc. New South Wales, 108, 147 - 156.

RISTEDT, H., 1968, Zur Revision der Orthoceratidae: Abhandlungen Akademie Wissenschaften Mainz, math. naturw. Kl., 1968 No 4, 213 - 287.

RISTEDT, H., 1969, Orthoceren als Leitfossilien des Silurs: Carinthia II, SH 27, 25 - 28.

SCHÖNLAUB, H. P., 1979, Die Nördliche Grauwackenzone. In: Das Paläozoikum von Österreich: Abh. Geol. B. - A., 33, 76 - 97.

SCHÖNLAUB, H. P., 1980, Carnic Alps. Field Trip A. In: Schönlaub, H.P. (ed) Second European Conodont Symposium ECOS II, Guidebook-Abstracts: Abh. Geol. B. - A., 35, 5 - 57.

SCHÖNLAUB, H. P. 1985, Das Paläozoikum der Karnischen Alpen. In: Arbeitstagung der Geologischen Bundesanstalt 1985: Geol. B. - A., 1985, 34 - 52.

SCHÖNLAUB, H. P., 1988, The Ordovician-Silurian boundary in the Carnic Alps of Austria. In: Cocks, L.R.M., and Rickards, R. B., eds., A global analysis of the Ordovician-Silurian boundary: Bull. Brit. Mus. Nat. Hist. (Geology), 43, 107 - 115.

SCHÖNLAUB, H. P., 1994, The Faunal Relationship of the Silurian of the Alps. In: IUGS Subcomm.Silurian Stratigraphy , H. P.Schönlaub and L. H. Kreutzer (eds.): Ber. Geol. B. - A., 30, 52 - 60.

SCHÖNLAUB, H. P., 1994, Section 2 Cellon Section, Lithology, Paleontology and Stratigraphy. In: Field Trip Program IUGS Subcomm. Silurian Stratigraphy, Field Meeting 1994: Ber. Geol. B. - A., 30/1994, 83 - 84.

SCHÖNLAUB, H. P. 1993, Stratigraphy, Biogeography and Climatic Relationships of the Alpine Palaeozoic. In: J.F. von Raumer and F. Neubauer, eds., Pre-Mesozoic Geology in the Alps: Springer Verlag, 65 - 91.

SCHÖNLAUB, H. P., and HEINISCH, H., 1994, The Classic Fossiliferous Palaeozoic Units of the Eastern and Southern Alps. In: IUGS Subcomm. Silurian Stratigraphy, Field Meeting 1994: Ber. Geol. B. - A., no. 30/1994, 6 - 51.

SCHÖNLAUB, H. P., and KREUTZER, L. H., eds., 1994, Subcommission on Silurian Stratigraphy Field Meeting Eastern + Southern Alps, Austria 1994, Guidebook + Abstracts: Ber. Geol. B. - A., no. 30, 1 - 156.

STACHE, G., 1872, Entdeckung von Graptolithenschiefer in den Südalpen: Verh. Geol. R. - A., 1872, 234 - 235.

WALLISER, O. H., 1964, Conodonten des Silurs: Abh. hess. L. Amt Bodenf., 41, 1-106.