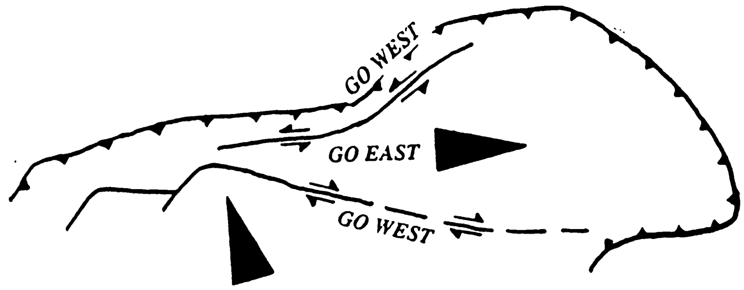

ALCAPA

Geological evolution
of the internal Eastern Alps and Carpathians
and of the Pannonian Basin

June 27 - July 6, 1992

ALCAPA Field Guide

THE EASTERN CENTRAL ALPS OF AUSTRIA

edited by F. NEUBAUER

with contributions from

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PREFACE

This field guide provides an overview on the internal tectonic zones of the eastern Central Alps. This region has been the goal of detailed research since a long time, much data have been collected, and many models of tectonic processes are based on these data. However, major portions of this region have been re-examined during the last decade resulting in many new insights and models both for pre-Alpine evolution of Penninic and Austro-Alpine basement units and Alpine geodynamics. Therefore, we believe that a new excursion guide is an useful tool to present recent data and models on the evolution of this region and to trigger discussion, evaluation and further research. These data have been provided by many different working groups of Austrian, German, English and Italian universities and of the Austrian Geological survey. However, major parts of this region, although critical for interpretation of the entire Alpine, Carpathian and Pannonian region, are not known to geologists from other countries.

The field guide is devoted to basement geology and Alpine tectonics of the eastern part of the Eastern Alps and touches all major tectonic units in an east-west section, starting with the Tauern Window, crossing the entire Austro-Alpine nappe pile, and going down again to the Penninic Rechnitz window. Furthermore, Cretaceous and Neogene overstep sequences will be likewise touched, discussing modes of basin formations.

The excursion guide is also written for future visitors of this region. Therefore, we included more stops than we will see during the ALCAPA excursions. Furthermore, we refer to additional field guides and topographic maps. As apparently common Austrian usage, some contributions came very late, some other planned contributions too late or have never been written. Therefore, there are some inconsistencies, missing descriptions and many errors in English grammar and spelling which derived from last minute submissions. The user may take into account these incoherent portions of the field guide.

I acknowledge the help of many students which helped me to finish the field guide in time. I especially thank Michael Brandmayr and Werner Kness who patiently gave the final lay-out to this field guide, then Waltraud Antonitsch, Harry Fritz, Hans Genser, Martin Huber, Gerd Rantitsch, Barbara Russegger, Eckart Wallbrecher and my wife Heidemarie Neubauer-Thurmaier who did many little helps and read many contributions for last minute corrections.

Graz, end of May, 1992.

F. Neubauer

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OVERVIEW OF THE EASTERN ALPS

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Introduction

This contribution provides a short overview of the tectonostratigraphy of the Eastern Alps with special emphasis on the internal, often metamorphic zones. Details of all these units are given in other contributions of the field guide.

Tectonostratigraphy of the Eastern Alps

A cross section through the eastern Alps displays the following major tectonic units from the North to the South, respectively from the footwall to the hangingwall (Fig. 1, 2; Janoschek and Matura, 1980; Oberhauser, 1980):

1) The European crust, exposed in the Bohemian Massif, which is sinking down to the South below the Eastern Alps. The European continental crust is covered by incomplete autochthonous Permian to Jurassic sediments, and the Oligocene - Neogene sediments of the molasse basin, a wedge-shaped foredeep.

2) The Molasse basin is overlain by the Helvetic Nappe Complex, a foreland thrust and fold complex which contains detached Jurassic to Eocene cover sediments from the southern margin of the European crust.

3) The Rhenodanubian Flysch Zone includes Cretaceous to Eocene orogenic flysch deposits.

4) The Penninic Nappe Complex which is exposed exclusively in tectonic windows in the central Eastern Alps (Tauern Window, Engadin Window, Rechnitz window). The Penninic Nappe Complex, always metamorphosed to greenschist to amphibolite facies, contains a lower unit with Variscan continental crust, only exposed in the Tauern Window, with a subautochthonous Permo-Mesozoic cover, and a higher unit with Mesozoic basinal deposits including ophiolites which form the essential suture zone in this part of the Alpine edifice.

5) The flat-lying Austro-Alpine Nappe Complex forms the backbone of the Eastern Alps, veiling all other units. The Austro-Alpine nappe complex largely contains basement units and few relics of Permo-Mesozoic cover sequences in the Central Alps, and an imbricated complex with Permo-Mesozoic cover sequences in the Northern Calcareous Alps.

6) The Periadriatic lineament separates the Austro-Alpine nappe complex from the South-Alpine tectonic unit south of it. The South-Alpine unit is basically regarded as an extension of the Austro-Alpine Nappe Complex. The South-Alpine unit is tilted to the South resulting in basement exposure along the Periadriatic lineament and southerly adjacent cover sequences (Late Carboniferous to Neogene).

In the Austrian usage, the Central Alps are the area between the Periadriatic Lineament and the Greywacke Zone, the northernmost Austro-Alpine basement unit.

Internal stratigraphy of the Penninic Nappe Complex

The lower portion of the Penninic Nappe Complex is composed of often foliated Variscan granitoids which are exposed in several domes within the Tauern window (Fig. 1). The granitoids are

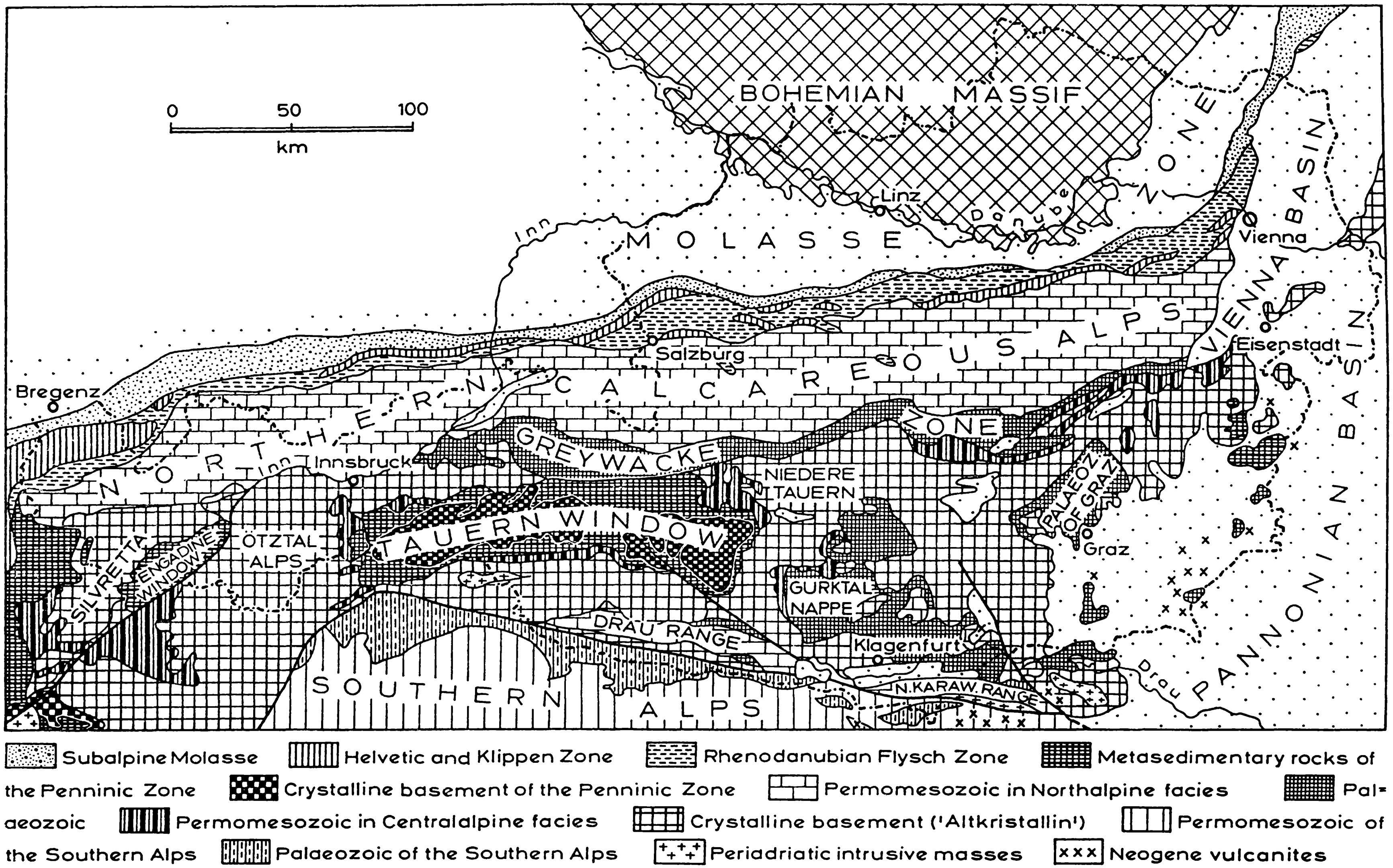
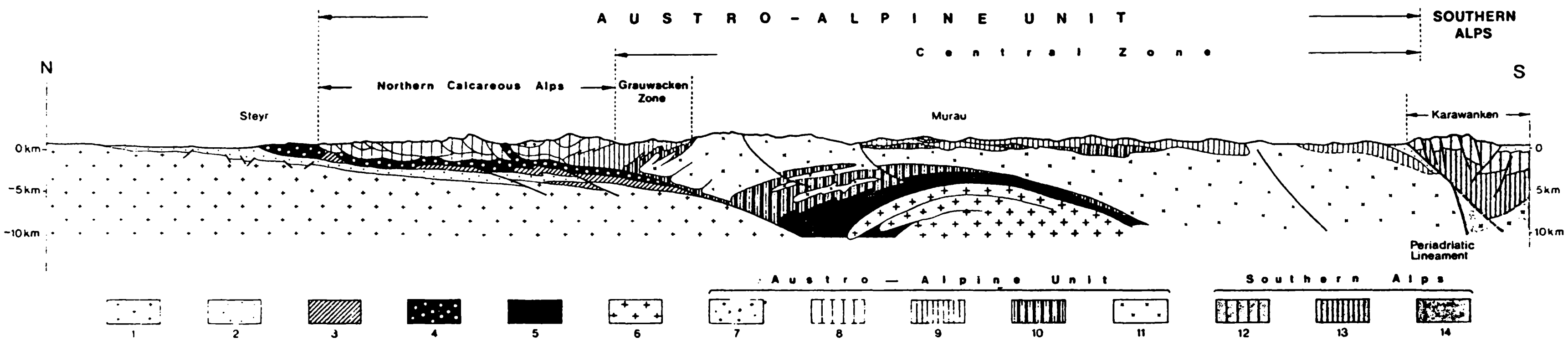


Fig. 1: Schematic structural map of the Eastern Alps (from Flügel and Faupl, 1987, p. 10).



Schematic cross-section of the Eastern Alps along the line Linz — Klagenfurt (modified after S. Prey, 1976; for exact position of the cross-section see fig. 1). 1 = Extra-Alpine basement of the Bohemian Massif; 2 = Molasse Zone and intra-Alpine Tertiary (post-upper-Eocene); 3 = Helvetic Zone and Klippen Zone; 4 = Flysch Zone; 5 = Metasedimentary rocks of the Penninic Zone; 6 = Crystalline basement of the Penninic Zone; 7—11 = Austro-Alpine Unit: 7 = Gosau Formation; 8 = Permomesozoic (unmetamorphic) in North-Alpine facies; 9 = Palaeozoic (low-grade metamorphic); 10 = Permomesozoic (low-grade metamorphic) in Central Alpine facies; 11 = Crystalline basement ("Altkristallin"); 12—14 = Southern Alps: 12 = Permomesozoic; 13 = Palaeozoic; 14 = Crystalline basement.

Fig. 2: Schematic cross section through the Eastern Alps (from Janoschek and Matura, 1980).

largeley surrounded by pre-Variscan basement units into which the granitoids intruded. The most important units are the Habach complex in the western part of the Tauern Window which basically contains a late Proterozoic to early Paleozoic island arc sequence, and the Storz complex in the eastern Tauern window which is interpreted as a migmatitic correlate to the Habach complex in the central and western Tauern window.

Mesozoic ophiolites are exposed in all major Penninic Windows occurring in a high structural level within these windows mostly. Deeper levels are composed of Mesozoic sediments which have been deposited, in part, on basement rocks.

Internal stratigraphy of the Austro-Alpine Nappe Complex

The Austro-Alpine Nappe Complex is composed of several thrust sheets which contain both pre-Late Carboniferous basement units and Late Carboniferous to Mesozoic cover sequences. For descriptive purposes we can use a conventional subdivision into a strongly imbricated Lower Austro-Alpine unit (LAA) with several internal nappes, a thick Middle Austro-Alpine unit (MAA) which is mainly composed of polymetamorphic basement rocks, the "Altkristallin", and the Upper Austro-Alpine unit (UAA). The MAA forms a coherent backbone of the entire Austro-Alpine body, the UAA occurs along the northern margin of the MAA (Greywacke Zone) and in large klippens (Graz Nappe Complex; Gurktal Nappe Complex). An alternative terminology and tectonostratigraphy (Fig. 3) was proposed by Frank (1987). The Austro-Alpine basement is divided into several units with distinct lithology and histories (Fig. 4).

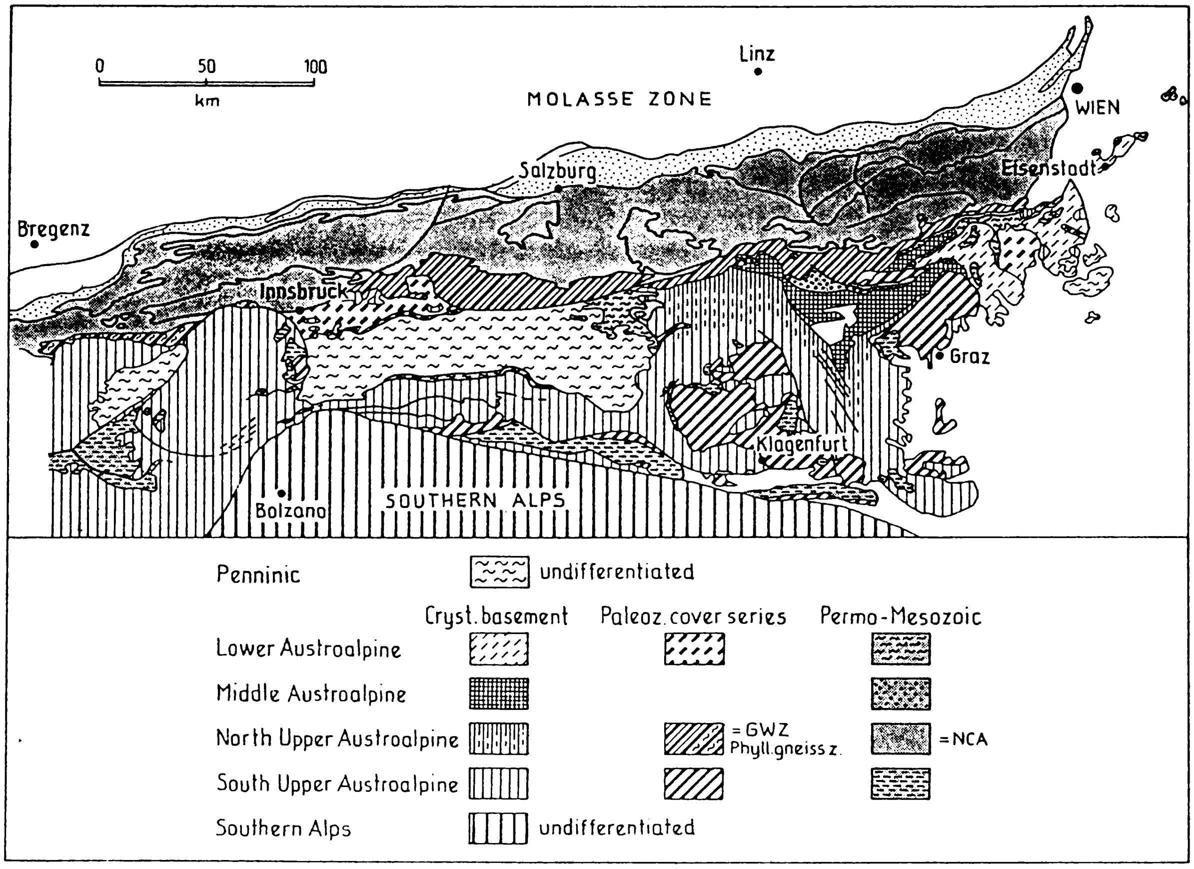


Fig. 3: Alternative structural map of the Eastern Alps (Frank, 1987).

Basic features of the internal structure of all these units are the occurrence of conformable cover sequences along the northern to northwestern edge of individual units and the increasing intensity of the Alpine metamorphic overprint from greenschist facies along the northern and upper units to amphibolite facies in lower units and central to southern parts (Fig. 4). The geochronological ages of this metamorphic event vary from Early to Late Cretaceous (Frank et al., 1987).

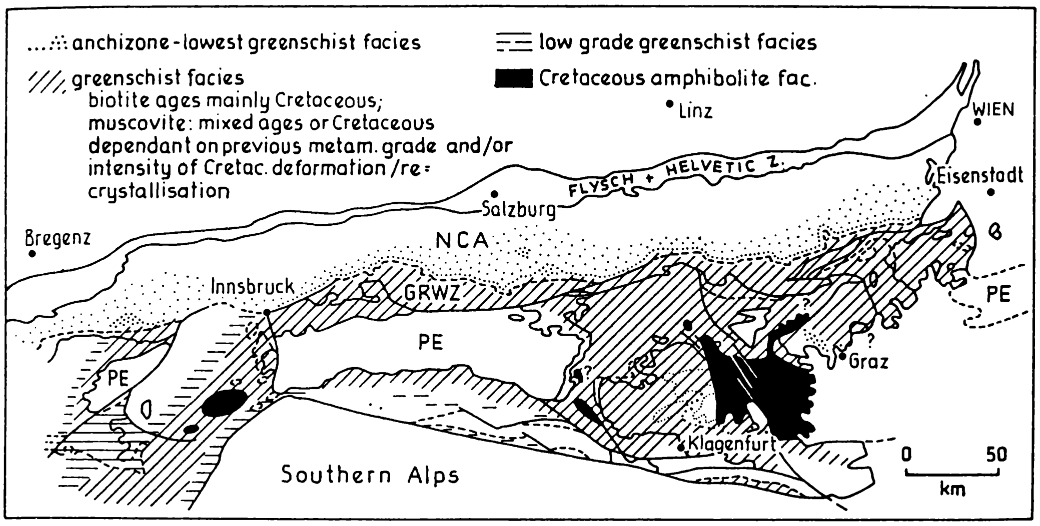


Fig. 4: Distribution of Cretaceous metamorphism in the Austro-Alpine Nappe complex.

Lower Austro-Alpine units

The Lower Austro-Alpine unit occurs in a rim around the Tauern Window and in the Grobgneiss/Wechsel/Waldbach units along the eastern margin of the Alps.

The Radstadt/Katschberg quartzphyllites mainly contain monotonous metapelites, black schists with some intercalations of greenschists, and calcitic and dolomitic marbles. The latter yielded conodonts of mainly Late Silurian age.

The cover sequences start with Permo-Scythian (?) Lantschfeld Quartzites, followed by dolomites and marbles of a Triassic platform sequence. The Jurassic sequence contains calcareous-schists, crinoidal limestones, breccias and metacherts mainly.

The Wechsel Window and several further windows east of it (Fig. 1) expose three distinct basement units: (Fig.5)

* the Wechsel Gneiss Complex,
* the Waldbach Complex,
* the Wechsel Phyllite.

These basement complexes are overlain by Permo-Triassic cover sequences, together forming the Wechsel System.

The Wechsel System is structurally overlain by the Semmering System which includes Semmering Permo-Triassic sequences and the polymetamorphic "Grobgneiss"/Raabalpen complex.

The Middle Austro-Alpine units

The Middle Austro-Alpine units (Fig. 5) contain polymetamorphic units with general amphibolite facies metamorphic overprint and minor, incomplete Permo-Scythian cover rocks along the northern margin and below the Gurktal Nappe System (Fig. 1).

The lithological composition of basement units varies within a broad range which allows to define distinct tectonostratigraphic units with distinct geodynamic histories. These units occur in a stack of thrust sheets which vary in composition from the West to the East.

East of the Wechsel window, the "Grobgneis" complex is overlain by some klippen of the Sieggraben complex. The Middle Austro-Alpine basement west of the Wechsel Window is composed of several tectonostratigraphic units, especially the deeper Muriden complexes and the higher Koriden complexes.

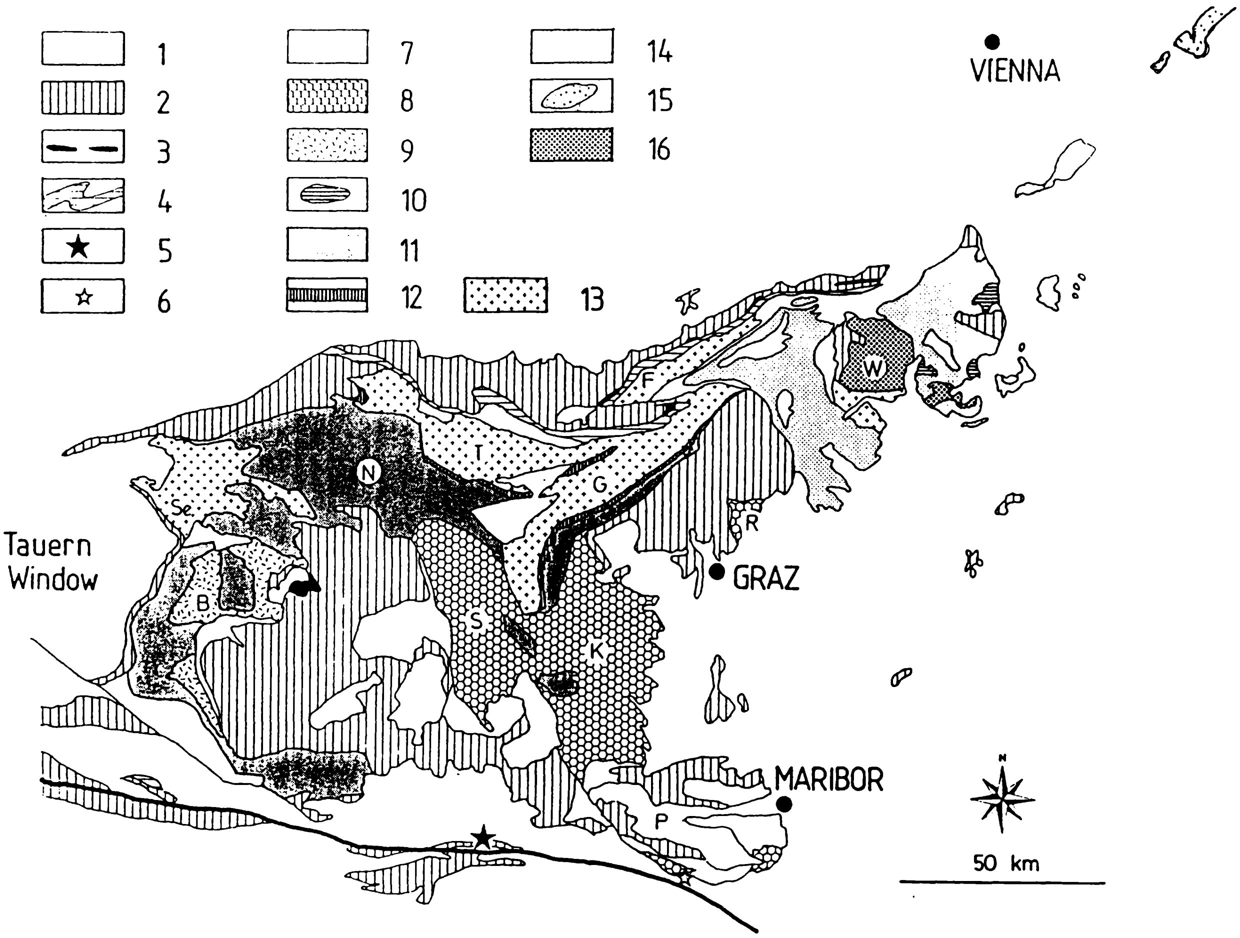


Fig. 5: Simplified map of Austro-Alpine basement units east of the Tauern window. Alpidic structures not shown. Legend: 1 - Permian to Cenozoic formations; 2 - fossiliferous Paleozoic formations and quartzphyllites; 3 - Kaintaleck slices and Ackerl complex (A); 4 - Carboniferous and Permian of the Veitsch nappe; 5 - Eisenkappel crystalline complex; 6 - Pohorje garnet-peridotite-granulite complex; 7 - Plankogel complex and related micaschist complexes; 8 - Koriden gneiss complex; 9 - Bundschuh complex; 10 - Sieggrabener complex; 11 - Micaschist-Marble complex; 12 - Speik complex; 13 - Core complex; 14 - "Grobgneis" complex; 15 - Tatric unit; 16 - Wechsel gneiss complex. Geographic signatures: B - Bundschuh; F - Troiseck-Floning mountains; G - Gleinalm; Gu - Gurktaler Alpen; K - Koralpe; L - Leithagebirge; N - Niedere Tauern; P - Pohorje mountains; R - Rennfeld; S - Saualpe; Sc - Schladminger Tauern; T - Seckauer Tauern; W - Wechsel.

The term Murides was created for basement units which differ from Koriden and Raabiden (Raabalpen Complex). This complex contains three major lithotectonic units, from top to bottom (Fig. 1, 3):

* the Micaschist-Marble Complex,
* the Speik Complex,
* the "Core Complex" which appears in several structural domes or cores below the first two complexes in the area east of the Tauern window.

The Koriden Complex is an eclogite-bearing basement complex ("Gneiss Group"), exposed in Koralpe and Saualpe mainly. It is overlain by the "Micaschist Group" which includes the ophiolitic Plankogel Complex. The "Micaschist Group" grades into a Phyllitic Micaschist which makes the distinction from UAA tectonic units uncertain often, especially if, as usual in southern portions of Austro-Alpine units, Permo-Mesozoic cover sequences are missing.

The MAA units are primarily covered by Permo-Triassic sequences of which only basal portions are preserved in the Rannach Fm. along the northern margin and by the Stangalm Group west of the UAA Gurktal Nappe System. The cover sequence includes basal clastic formations ("Alpine Verrucano", quartzite), rauhwacke, and Middle Triassic marbles and dolomites.

The Upper Austro-Alpine units

The Upper Austro-Alpine units contain several, mostly weakly metamorphic, often fossiliferous basement units which range from Middle Ordovician to Mid-Carboniferous (Gurktal Nappe Complex, Graz Nappe Complex, Noric Nappe of the Greywacke Zone). All these units, except the Paleozoic of Graz are covered by Late Carboniferous to Mesozoic sequences. Such covers occur along the northwestern margin of the Gurktal Nappe System and in the eastern part of this unit (Eberstein and St. Paul Permo-Triassic). A further polymetamorphic basement complex is the Kaintaleck Complex in the eastern Greywacke Zone which occurs underneath the Noric Nappe. Other metamorphic basement complexes also occur in the Gurktal Nappe System (Ackerl Complex and Pfannock gneiss).

Carboniferous sequences which occur in the Veitsch Nappe of the Greywacke Zone (constituted by Early Carboniferous to Permian sequences) and near Nötsch (Carboniferous) have a special importance because of otherwise not occurring marine clastic/carbonatic sequences.

Timing of Alpine metamorphism

Geochronological ages for timing of the Alpine metamorphic overprint are known since the Sixties. Geochronology yielded clear evidence that major portions of the southern Middle Austro-Alpine basement (e.g., the Koralm Gneiss Group, major portions of the Micaschist-Marble Complex) have been overprinted within Cretaceous amphibolite facies (Fig. 4; Frank et al., 1987b). Cyanite-bearing paragneisses are often associated with eclogites. Finally, Sm-Nd mineral isochrons of the Koralm eclogites clearly suggest a Cretaceous age of eclogite metamorphism (Thöni and Jagoutz, 1991).

However, the distribution of metamorphic isogrades is not well established although the boundary between Alpine amphibolite to greenschist facies is approximately known (Fig. 4).

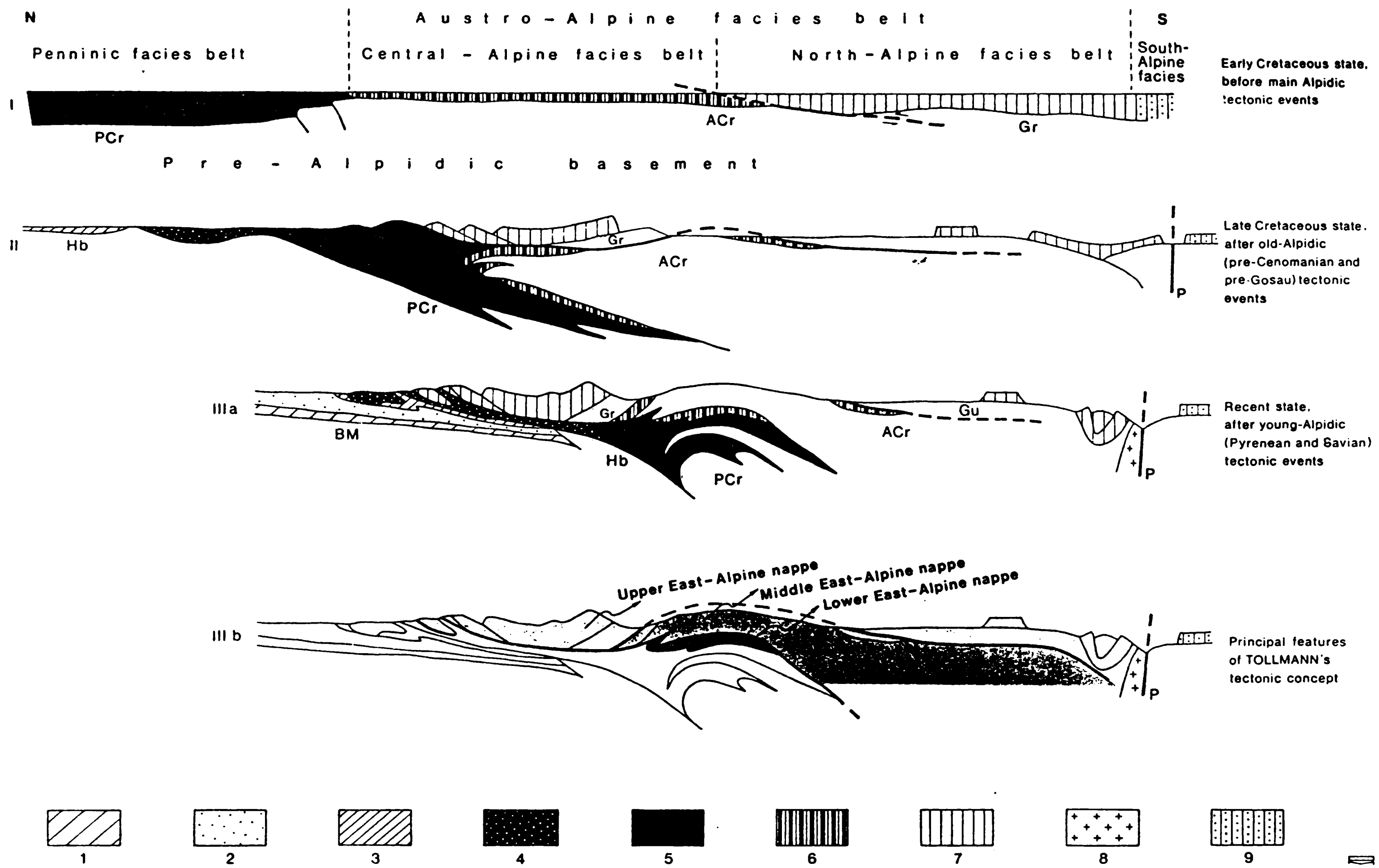
Of major interest is the feature that ages of post-metamorphic cooling varies in a systematic way from higher to lower tectonic levels. The white mica ages of the greenschist facies areas of the Upper Austro-Alpine tectonic units range from 140 to 120 Ma. These ages can be interpreted as formation ages because temperatures did not exceed 400°C. In the Middle Austroalpine unit the white mica cooling ages cluster at around 80 Ma (Frank et al., 1987b).

In contrast,the climax of metamorphism in the Penninic units is of Paleogene age, imprinting high pressure assemblages which are commonly interpreted to represent the high pressure belt to the Austro-Alpine medium pressure belt (see Frank et al., 1987a).

Paleogeographic and structural evolution

The Alpine geodynamics are interpreted in the following way: Permotriassic rifting resulted in subsidence and thinning of the Austro-Alpine crust. The open, Tethyan oceanic realm is thought to have been situated towards the Southeast. A second period of rifting during Jurassic times formed the South Penninic oceanic realm between the (Middle) Penninic continental crust and the LAA units (Frisch, 1979). Consumption of distinct units started with intra-Austro-Alpine nappe stacking during Early Cretaceous times (Fig. 6, 7).

The Alpine deformation within the Austro-Alpine and Penninic units is polyphase with large complexities by inversions on displacement surfaces. A sequence of Alpine deformation events is



Hypotheses of the tectonic evolution of the Eastern Alps (sections I, II, and III a; modified after E. Clar, 1973) and a schematic section (III b) showing the subdivision of the "East-Alpine" (= Austro-Alpine) Unit supported by A. Tollmann (1963).

Legend for the sections I, II, and III a: 1 = Tertiary rocks of the Molasse Zone; 2 = Extra-Alpine post-Variscan sedimentary rocks; 3 = Helvetic Zone and Klippen Zone; 4 = Flysch Zone; 5 = Permomesozoic of the Penninic Zone; 6 = Permomesozoic of the Central-Alpine facies belt; 7 = Permomesozoic of the North-Alpine facies belt; 8 = Periadriatic Intrusion; 9 = South Alpine facies; BM = Bohemian Massif; Hb = Basement of the Helvetic Zone; PCr = Crystalline Basement of the Penninic Zone; Gr = Palaeozoic rocks of the Grauwackenzone; Gu = Palaeozoic rocks of the Gurktal Sheet; ACr = Crystalline basement of the Austro-Alpine Unit; P = Periadriatic Lineament.

Fig. 7: Interpretation of the tectonic evolution of the Eastern Alps (from Janoschek and Matura, 1980).

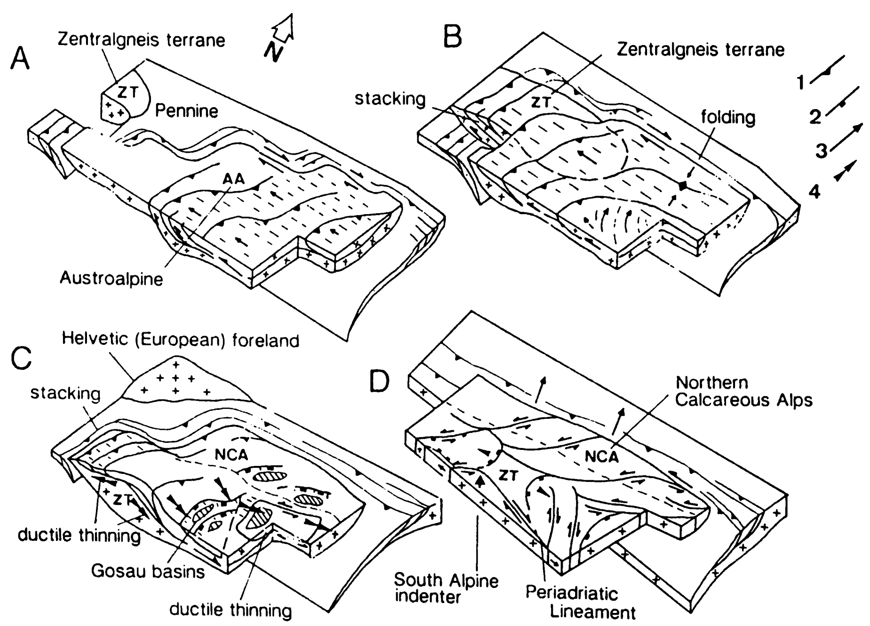
recognized with the following major steps (Ratschbacher et al., 1989; Neubauer and Genser, 1989; Behrmann, 1990):

The oldest structures are ductile thrusts which climb from within southern basement areas to basement-cover contacts into the cover rocks in the north (Fig. 6). The general displacement direction of Austro-Alpine units is towards the W, varying from WSW to WNW. The essential arguments for this interpretation are both stratigraphic distributions (climbing of the thrust surface to higher stratigraphic levels towards NW) and meso- to microscale structures.

Most of the important internal thrust surfaces within the Austro-Alpine unit are reactivated by subsequent ductile low-angle normal faulting during the Late Cretaceous. A system of normal faults with predominant top-to-the NE displacement is interconnected by steep sinistral shear zones. The Middle Austro-Alpine unit has been uplifted in domes. Therefore cooling, operation of normal and strike-slip faults and exhumation of metamorphic domes are coeval with subsidence of the Late Cretaceous Gosau basins.

Structures which are associated with the subsidence of Eocene basins are not known with certainty. Some N-S trending cataclastic fault zones may belong to such a system.

The next system of structures is a set of E-W to NE-SW trending faults. These faults form a broad sinistral wrench corridor along the northern part of the Austroalpine unit and led to the escape, respectively extrusion of the eastern Central Alps towards east against the Carpathians.



Orogenic wedge evolution in eastern Alps. A: Stacking and orogen-parallel extension during simple shear crustal imbrication. B: Underplating of Zentralgneis terrane. C: Unroofing extension and formation of Gosau basins. D: Continental escape. 1—Thrusts and shear zones. 2—Normal faults and extensional shear zones. 3—Thrust and shear directions during compression. 4—Motion directions during crustal thinning.

Fig. 6: Steps of Alpine kinematic evolution (from Ratschbacher et al., 1989).

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PRE-MESOZOIC GEOLOGY OF THE MIDDLE AND UPPER AUSTRO-ALPINE METAMORPHIC BASEMENT EAST OF THE TAUERN WINDOW

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Introduction

In contrast to the Austro-Alpine basement west of the Tauern window, the eastern part is highly diverse. Its metamorphic grade ranges from nearly unmetamorphosed, fossiliferous Paleozoic sequences through low grade rocks in the so-called quartzphyllite units to medium and high grade metamorphic units in the "Altkristallin".

In this contribution we review fossil-free lithotectonic units of the Altkristallin of the Middle and Upper Austro-Alpine tectonic units which underwent pre-Alpine and/or Alpine, medium to high grade metamorphism (Fig. 1).

The lithotectonic units occur at different tectonic levels within the Alpine nappe edifice. Some of the major Alpine units are separated by Permo-Mesozoic rocks mainly along their northern margins. The following major Alpine basement nappes are distinguished (Tollmann, 1977):

* Upper Austro-Alpine nappes which include the crystalline Kaintaleck basement slices and the Ackerl complex,

* the Middle Austro-Alpine nappes which consist of distinct lithotectonic basement units, in particular the Muriden complexes, including the "Core", the Speik and the Micaschist-Marble complexes, and the Koriden gneiss complex, with its associated micaschist complexes, in particular the Plankogel complex,

* and the Lower Austro-Alpine units which include the higher "Semmering system" with the "Grobgneis" or "Raabalpen" unit (corresponding to the Tatric unit at the northeastern margin of the Eastern Alps) and the lower "Wechsel system" with the Waldbach and Wechsel gneiss complexes (see Neubauer et al., this volume).

Cretaceous metamorphism affected nearly all these Altkristallin rocks. It reached greenschist facies in most parts, and up to amphibolite facies and possibly eclogite facies in the central and southern part of the Middle and Lower Austro-Alpine units (Deutsch, 1988; Frank, 1987; Frank et al., 1987; Miller, 1990; Schimana, 1986; Dallmeyer et al., this volume). Therefore, pre-Alpine P-T paths have not yet been established in detail.

Lithostratigraphic units

We describe the different lithotectonic basement units from the Middle and Upper Austro-Alpine units. Geochronological data are presented in Table 1. Representative chemical analyses from various basement complexes are compiled for comparison in Table 1.

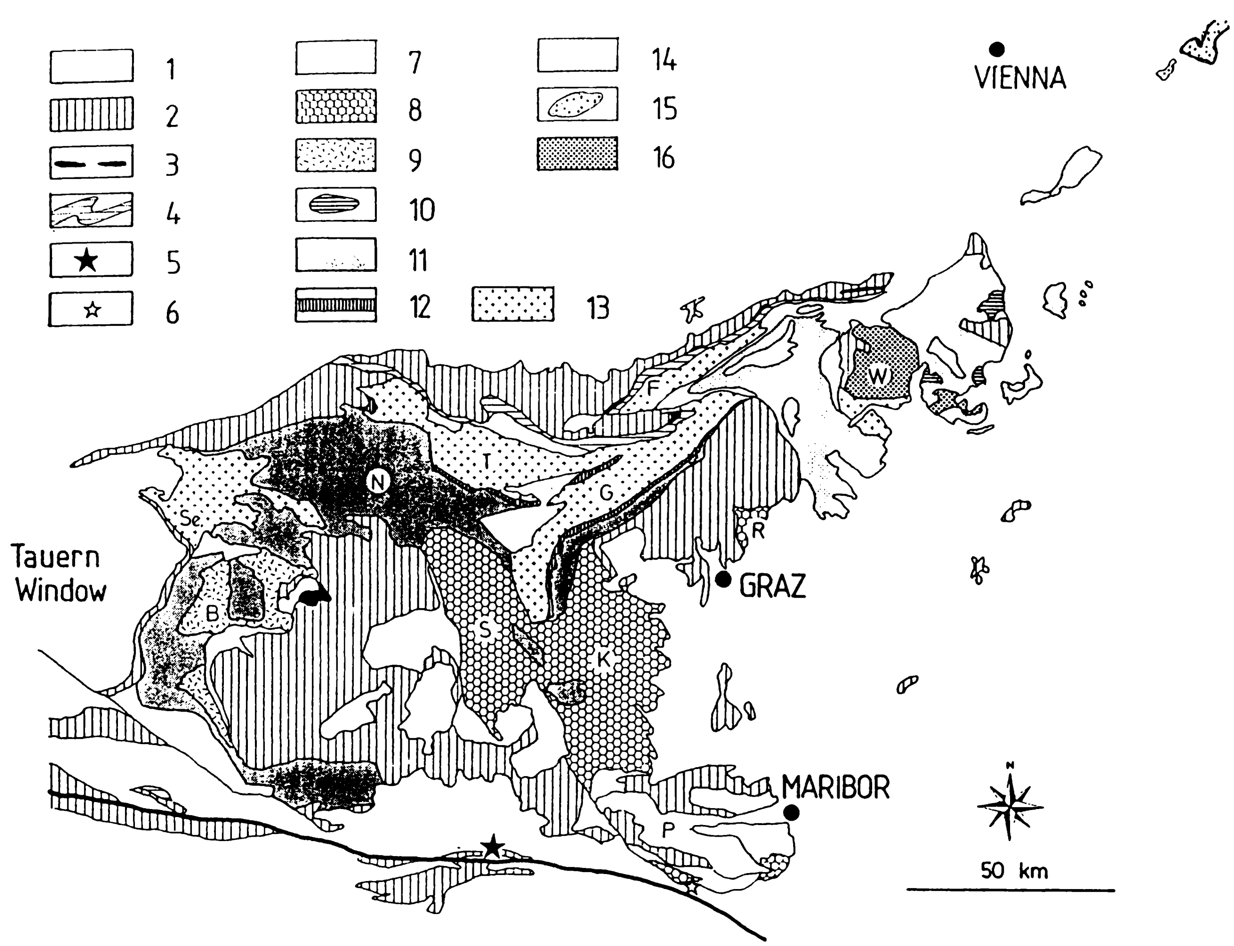

Fig. 1: Simplified map of Austro-Alpine basement units east of the Tauern window. Alpidic structures not shown. Legend: 1 - Permian to Cenozoic formations; 2 - fossiliferous Paleozoic formations and quartzphyllites; 3 - Kaintaleck slices and Ackerl complex (A); 4 - Carboniferous and Permian of the Veitsch nappe; 5 - Eisenkappel crystalline complex; 6 - Pohorje garnet-peridotite-granulite complex; 7 - Plankogel complex and related micaschist complexes; 8 - Koriden gneiss complex; 9 - Bundschuh complex; 10 - Sieggrabener complex; 11 - Micaschist-Marble complex; 12 - Speik complex; 13 - Core complex; 14 - "Grobgneis" complex; 15 - Tatric unit; 16 - Wechsel gneiss complex. Geographic signatures: B - Bundschuh; F - Troiseck-Floning mountains; G - Gleinalm; Gu - Gurktaler Alpen; K - Koralpe; L - Leithagebirge; N - Niedere Tauern; P - Pohorje mountains; R - Rennfeld; S - Saualpe; Sc - Schladminger Tauern; T - Seckauer Tauern; W - Wechsel.

Muriden

The term Muriden was created for basement units which differ from the Koriden and Raabiden (Raabalpen complex) (e.g., Kober, 1938). The Muriden complex contains three major lithotectonic units (Fig. 1, 2):

* the Micaschist-marble complex as the uppermost unit,
* the Speik complex and
* the "Core complex" which appears in structural domes or cores as the lowermost unit.

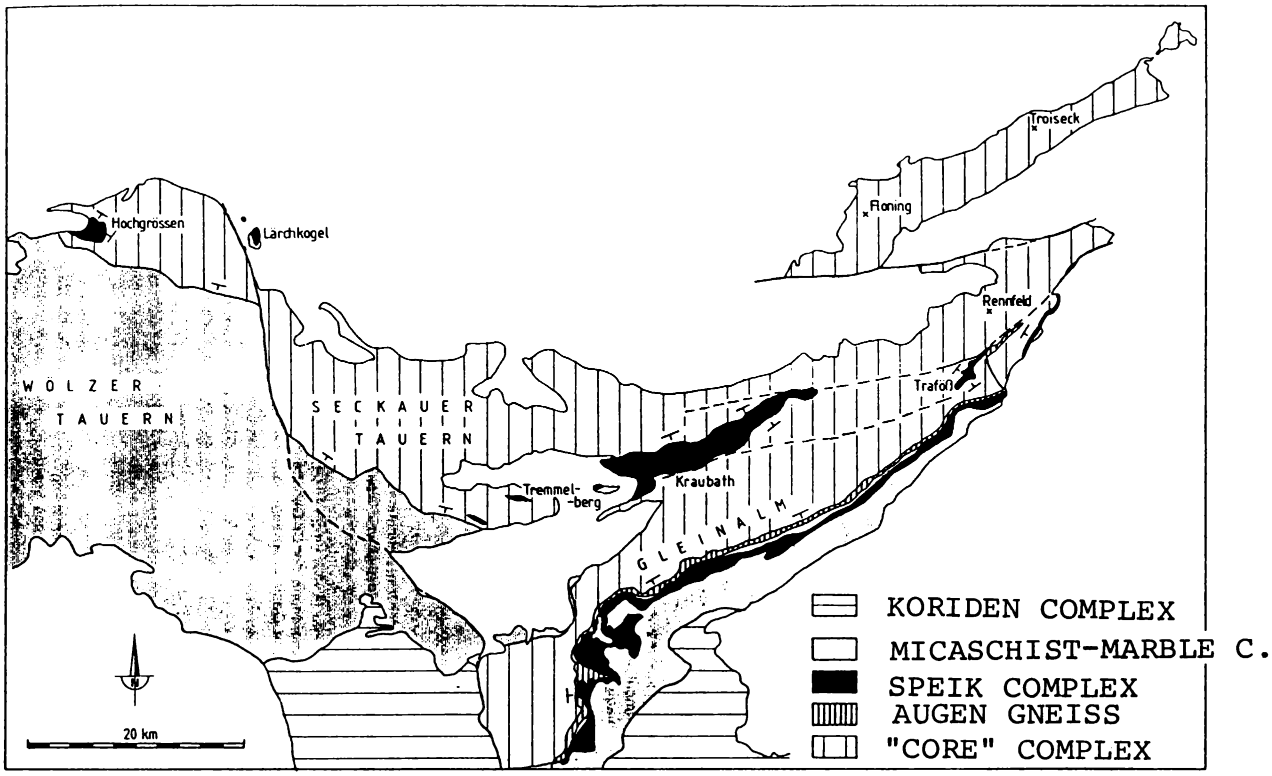

Fig. 2: Simplified geological map of the Gleinalm-Rennfeld-Mugel area which exposes Muriden complexes (modified from Neubauer, 1988a).

"Core complex"

The "Core complex", best studied in the Gleinalm and Rennfeld-Mugel areas, is also exposed in the Troiseck-Floning, the Seckauer Tauern and Bösenstein, and the Schladminger Tauern (Fig. 1).

In each locality, the "Core complex" consists of the following lithological units (see, for example, Fig. 2):

* A thick pile of strongly foliated biotite plagioclase paragneisses form the country rocks of all the other magmatic lithological units.

* Plagioclase orthogneisses appear in large cuppolas mantled by biotite plagioclase paragneiss.

* Large masses of various amphibolites are enclosed within plagioclase paragneiss and orthogneiss (Becker, 1981; Frisch et al., 1987; Haiss, 1991; Neubauer, 1988a; Schedl, 1981). The most common amphibolite type is a banded amphibolite which includes orthogneiss layers on the scale of centimetres to metres (Frank et al., 1976; Frisch et al., 1987). This amphibolite strongly resembles the leptinite-amphibolite complexes of Variscan basement massifs in western Europe (e.g., Santallier et al., 1988). The banded amphibolite is in close spatial relationship to the plagioclase orthogneiss (Fig. 2).

* A layered metatonalite complex ("metablastic amphibolites") is accompanied by ultramafic rocks, metagabbros and rare acidic rocks (Becker and Schumacher, 1970; Frisch et al., 1987); Neubauer, 1988a; Teich, 1987a, b).

* Major plutons of granitic, granodioritic and tonalitic rocks occur in all domes. A sheet-like augen gneiss forms the hangingwall boundary of the "Core complex".

The biotite plagioclase paragneiss contains thin marbles, calcsilicate rocks and garnet micaschists, which include manganese quartzites and carbonates (Paul and Neubauer, 1992), as marker horizons. The gneiss itself exhibits a locally well-preserved sedimentary layering which may reflect graded bedding of graywackes (Neubauer 1988a). Both the geochemistry and the zircon habitus suggest that the paragneiss may be derived from volcanogenic graywackes (Frisch et al., 1987; Haiss, 1991; Neubauer, 1988a). U-Pb zircon data suggest late Proterozoic to early Palaeozoic origin of the clastic zircons (Neubauer et al., in prep.). We interpret the plagioclase paragneiss sequence as graywacke prism on the margin of a magmatic arc complex which has been interrupted by sedimentation on an abyssal plane with pelites and siliceous, manganese-bearing rocks.

The plagioclase orthogneisses form a major pluton in the Gleinalm area (Fig. 2) with a Rb-Sr whole rock errorchron of 518 ± 50 Ma (Frank et al., 1976). Haiss (1991) found a U-Pb minimum age of approximately 500 Ma based on nearly concordant zircons. These rocks, in association with the banded amphibolites, were interpreted as a bimodal volcanic sequence (Frank et al., 1976). However, the dome-like form of the orthogneisses crosscutting other lithologies (Fig. 2), the rock distribution, the occurrence of amphibolite xenoliths and mappable discordant contacts between plagioclase orthogneiss and country rocks argue for a plutonic origin (Neubauer, 1988a; Neubauer, 1989b). The layering is the result of mylonitization and ductile shearing of both rock types after the intrusion of the orthogneiss protoliths into the amphibolites (Neubauer 1989b).

The amphibolites display a wide range of petrographic and chemical compositions. Because of intense ductile deformation, relics of magmatic mineralogy are preserved in only a few bodies. Well-preserved gabbros are mainly related to the suite of the "metablastic amphibolite", e.g. the Utschgraben meta-gabbro (Schatzmayer et al., 1990). These bodies contain relics of orthopyroxene and clinopyroxene (Hermann, 1972). In contrast, Haiss (1991) has described amphibolites which are derived from subalkaline basalts with an intraplate component. Other major amphibolite bodies show a more calcalkaline composition according to their major, minor, trace and REE chemistry (Fig. 3). Cumulate gabbroic rocks may form a major portion of the amphibolites as suggested by rare relict minerals, strong positive Eu anomalies, low Ti contents and other chemical features (Fig. 4). Gabbro-derived amphibolites dominate volumetrically within both the plagioclase paragneiss and the orthogneiss. All these data indicate different origins and variable ages of the amphibolites. Protolith ages of these amphibolites are uncertain. An unusual, highly differentiated garnet amphibolite yielded a U-Pb zircon age of ca. 425 Ma (lower intercept age; Neubauer et al., in prep.).

Some major amphibolite bodies exhibit migmatitic fabrics near contacts to country rocks (Neubauer, 1988a). Trondhjemite gneisses form leucosomes, hornblende felses the palaeosomes. The association is interpreted as result of partial melting of amphibolites (Neubauer, 1988, 1992). Nearly concordant U-Pb zircons at 353 ± 2 Ma indicate a Variscan age of trondhjemite formation, and, therefore, of high-grade metamorphism (Neubauer et al., in prep.).

The plutonic suite of the "metablastic amphibolite", a metatonalite, is widespread throughout the Core complex. It outcrops over a distance of 70 km mostly at the boundary between biotite plagioclase paragneiss and the banded amphibolite. The most prominent rock type of this suite is a medium-grained, massive plagioclase amphibolite or hornblende gneiss which includes lenses of metapyroxenite, metawehrlite, hornblendite, metagabbros and augengneisses which are derived from porphyric biotite granites. This augengneiss differs from the sheet-like augen gneisses at the hangingwall boundary of the Core complex. The plutonic suite is probably derived from more than one magma. The average metatonalite shows differentiation to more hornblende-poor types and to mafic and ultramafic cumulates. Own unpublished Sr isotopic data indicate contamination with radiogenic Sr of some metagabbros which are enclosed within the metatonalite. The trace element signature of the augengneiss is different from, and the REE contents are lower than, those of the metatonalite. The lower intercept U-Pb zircon age of the metatonalite is 356 ± 5 Ma (Neubauer et al., in prep.) which is interpreted as the age of Variscan metamorphism. The upper intercepts of the metatonalite near 3 Ga and of the augengneiss at 2.25 Ga indicate contamination by old, Archaean to Proterozoic zircons derived from continental crust during melt formation and magma rise. One of the augen gneiss lenses yielded a lower intercept U-Pb zircon age of ca. 425 Ma. A preliminary Rb-Sr errorchron with 390 ± 49 Ma contradicts the U-Pb zircon age of the metatonalite.

Most granitic, granodioritic and rare tonalitic and dioritic orthogneisses postdate formation of other lithologies. An orthogneiss from the Seckauer Tauern with unknown contact with the country rocks yielded a Rb-Sr age of 432 ± 16 Ma (Scharbert, 1981). A nearly concordant U-Pb zircon age (ca. 500 Ma) from a tonalite gneiss is interpreted as the minimum formation age (Haiss, 1991). Other

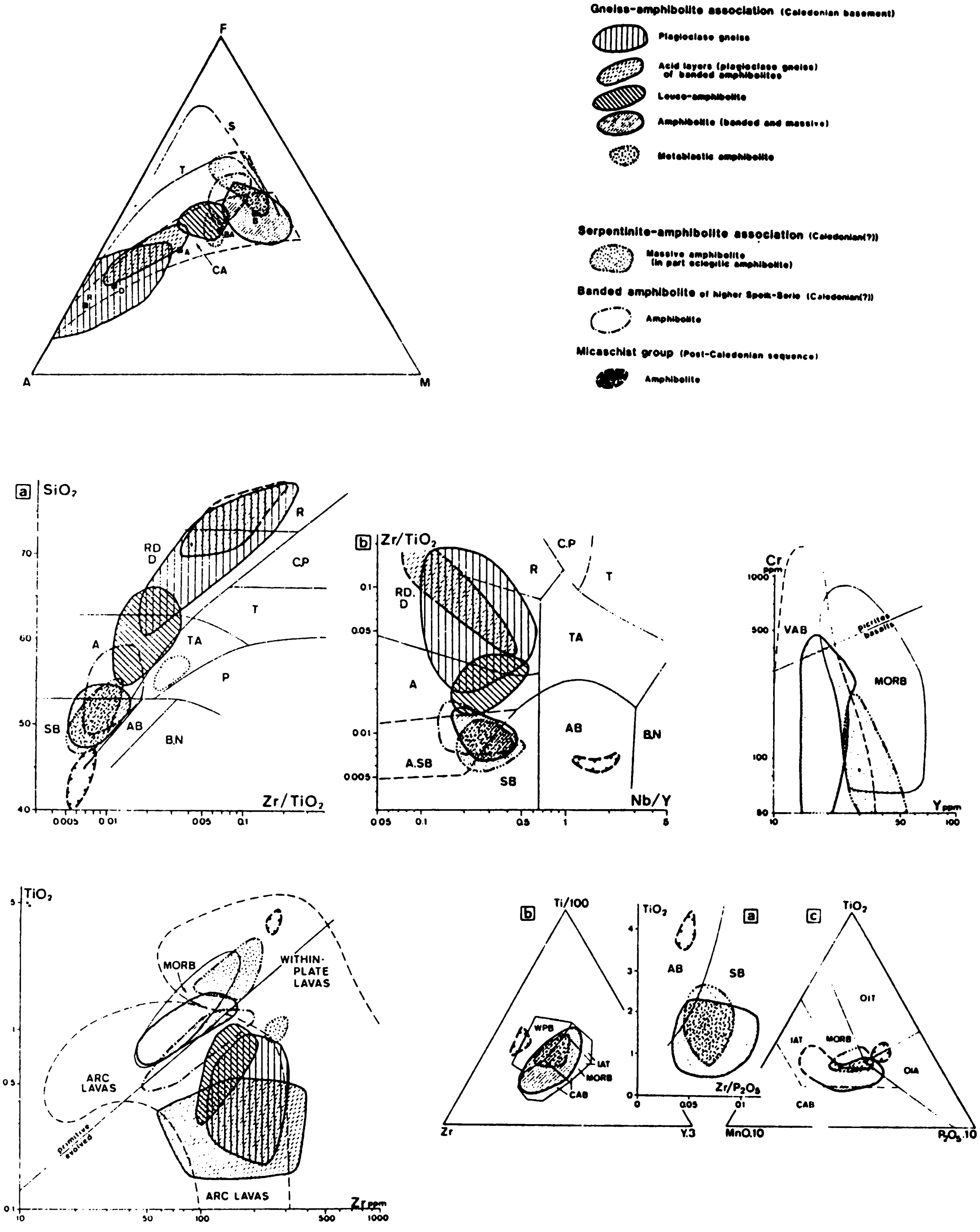

Fig. 3: Geochemical discrimination of amphibolites of the Murides units (after Frisch et al., 1987).

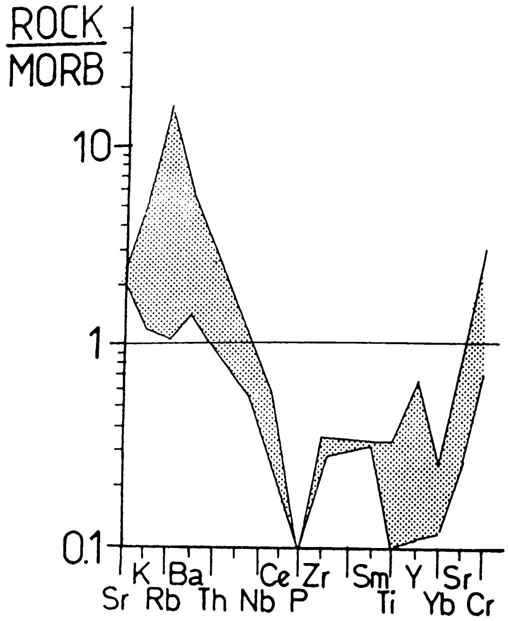

Fig. 4: Spidergram of a major metagabbroic amphibolite body from the "Core complex" (from Schatzmayer et al., 1990).

granitoids are fine-grained granite and granodiorite gneisses which form discordant plutons and sheet-like augengneisses (Neubauer, 1988a; Teich, 1979). A characteristic two-mica augengneiss forms the hangingwall boundary of the Core complex in the Gleinalm, Seckauer Tauern and Schladminger Tauern (Becker, 1981). The Gleinalm augengneiss yielded a Rb-Sr errorchron of 330 ± 30 Ma (Frank et al., 1983). The widespread granitoids in the Gleinalm and Rennfeld area are mostly mica-poor. Various flaser granite gneisses and two-mica granites like the Zinken granite occur in the Seckauer Tauern (Metz, 1976a; Scharbert, 1981). The Zinken metagranite yielded a Rb-Sr age of 354 ± 16 Ma (Scharbert, 1981) indicating an early Carboniferous age of intrusion. The source of early Variscan granitic rocks is uncertain because detailed investigations have not been made yet. The presence of white mica in some granitoids argues for a S-type origin.

We interpret the "Core complex" as a late Proterozoic to early Palaeozoic root of a magmatic arc which was flanked by sedimentary basins. The protoliths of the biotite plagioclase paragneiss may have formed in an arc-related basin which was later buried and intruded by mafic and acidic magmas. A major step in evolution is indicated by the most frequent age group in the range of 460 - 425 Ma which is exclusively related to magmatic rocks. Granites intruded during this period for the first time (orthogneiss in the Seckauer Tauern). Crustally-derived radiogenic Sr isotopic composition as well as Archaean and early Proterozoic memories in magmatic zircon indicate the presence of old continental crust underlying the "Core complex" during this time. Therefore, the subduction process ceased during this time by subduction of or collision with a plate composed of old continental crust which provided the Precambrian isotopic signature of the calcalkaline melts. We do not know whether there is a continuous transition of plutonism to the Carboniferous granitoids. The Carboniferous granitoids are related to final collision of the Core complex with other basement units of the Eastern Alps, e.g. the Speik complex.

Speik complex

The Speik complex (Fig. 2, 5) consists of a package of several hundred metres thick garnet amphibolites and banded amphibolites (meta-basaltic rocks), garnet-zoisite and plagioclase amphibolites (meta-gabbroic rocks), thin augengneiss or serpentinite lenses up to 20 kilometers in length, and rare metasedimentary rocks (El Ageed et al., 1980; Frisch et al., 1987; Haditsch et al., 1981; Neubauer, 1988a; Neubauer et al., 1989b). The complex is exposed along the southern

Gleinalm, at Kraubath, Traföß and Hochgrößen. An eclogite occurrence is also reported from the Hochgrößen (Wieseneder, 1969; Richter, 1973). All these rocks are intensely foliated.

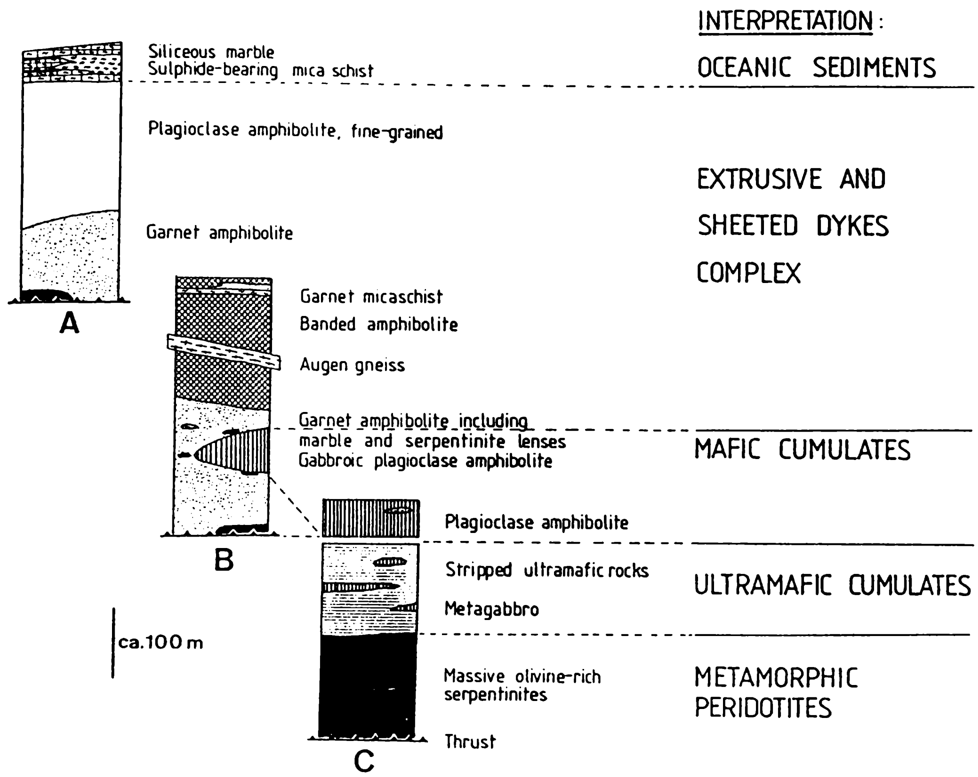

Fig. 5: Lithostratigraphy of the Speik complex (after Neubauer et al., 1989a).

Petrographic and chemical data provide evidence that the Speik complex contains all members of an ophiolite. Refractory ultramafic rocks are mainly exposed at Kraubath and Hochgrößen (El Ageed et al., 1980). Ultramafic and mafic cumulates are common within the Traföß body (Neubauer, 1988a). The chemical patterns of garnet amphibolites of the southern Gleinalm are close to those of back arc basin ocean floor basalts (Neubauer et al., 1989b). Locally occurring sulphide-rich quartzites and impure marbles are interpreted as the oceanic sedimentary layer (Neubauer, 1988a).

The Speik complex has not yet been dated by geochronological methods. Its age is presumed to predate the Micaschist-Marble complex in the hangingwall for which a late Ordovician to Devonian age is assumed based on lithostratigraphic correlations (see below).

Micaschist-Marble complex

The Micaschist-Marble complex is widespread throughout the Middle Austro-Alpine basement (Fig. 1). It occurs along the southern margin of the Gleinalm, within the Niedere Tauern, and is again widespread southeast of the Tauern window and in the Kreuzeck Mts. south of the Tauern window (Becker, 1981; Hoke, 1990; von Gosen, 1989a) (Fig. 1). Feldspar-rich and quartz-rich micaschists dominate in the structurally lower part. The middle portion contains garnet micaschists, pale-coloured quartzites, thin amphibolites and black schists (Becker, 1981; Becker and Schumacher, 1970; Metz, 1976b; Neubauer, 1988a). Siliceous and pure marbles, which are also intercalated with biotite amphibolites, some garnet micaschist and sheet-like pegmatites, dominate the upper portion of the sequence (Fig. 6). The transition of micaschist to carbonates is characterized by calcsilicate rocks, and sometimes by scheelite-bearing tourmalinites and dolomitic marbles (Becker, 1977, 1981; Neubauer, 1988a; Raith, 1988).

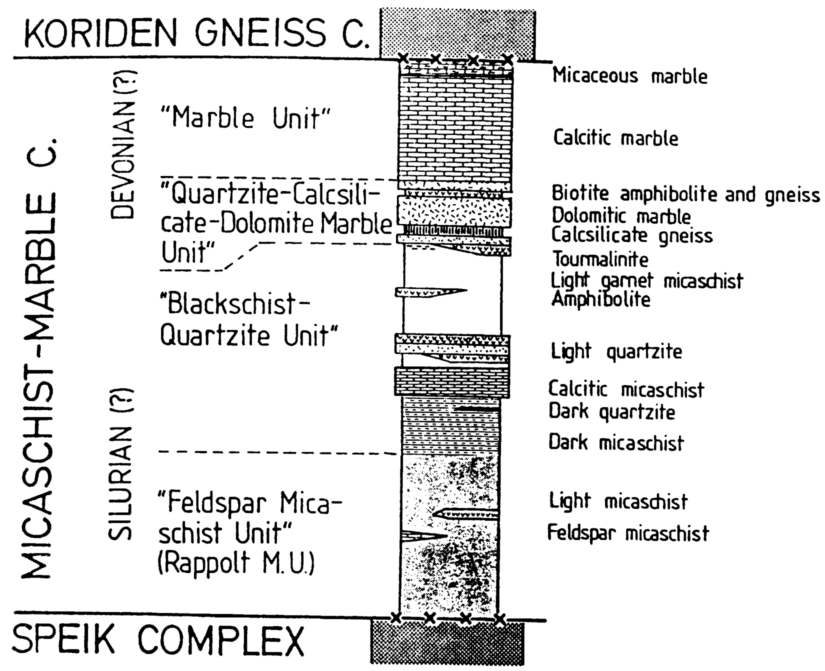

Fig. 6: Lithostratigraphy of the Micaschist-Marble complex, Gleinalm area (modified from Neubauer, 1988a).

Geochronological data of protolith ages are not available. The sequence can be correlated with the fossil-bearing late Ordovician to early Carboniferous sequences of the Eastern Alps: the micaschists are presumed to be of late Ordovician to early Devonian age, the marbles of mainly mid-Devonian age (Becker, 1977, 1981; Neubauer, 1988a).

The field relationship of the augengneiss in the lower Muriden complex and pegmatites in the Micaschist-Marble complex suggest cogenetic, early Carboniferous formation (Neubauer, 1989a). The Li- and Be-mineralizations of some pegmatites (e.g., Koller et al., 1983) classify them as highly fractionated melts derived from a major granite.

Pre-Alpine tectonothermal evolution of the Muriden

The Core complex, the Speik complex and the Micaschist-Marble complex have a common Variscan thermal history. The "Caledonian thermal event" is evidenced only in the "Core complex" by U-Pb zircon lower intercept data of the augengneiss within the metatonalite suite, and the garnet amphibolite between 450 and 425 Ma (Tab. 1). In addition, scattered paragneiss zircons are close to the discordia of this intercept (Neubauer et al., in prep.). The same age is found in an orthogneiss of the Seckauer Tauern (Scharbert, 1981). All these data indicate magma crystallization during this time. Evidence of deformation and metamorphism during this time span is lacking.

The superposition of both Speik and Micaschist-Marble complexes on the Core complex most probably predates peak thermal conditions of pre-Alpine metamorphism.Thrusting is accompanied by intrusion of granites, the protoliths of the augengneiss on top of the Core complex and within the Speik complex, into the zone of thrusting (Neubauer, 1988b; 1989a, b). Ductile deformation of hot granites and amphibolitic country rocks is attributed to large shear strain which caused the mylonitic fabric and the layering of gneisses and most banded amphibolites (which derived most probably from veined amphibolites). The fact that the augengneiss horizon climbs southwestwards from the top of the Core complex through the Speik complex into the Micaschist-Marble complex indicates top-to-the-

Koriden complex ("Gneiss group")

The Koriden Gneiss complex is exposed in the Koralpe (Beck-Mannagetta, 1970; Frank et al., 1983), Saualpe (Weissenbach, 1975) and Pohorje mountains (Hinterlechner-Ravnik and Moine, 1977)

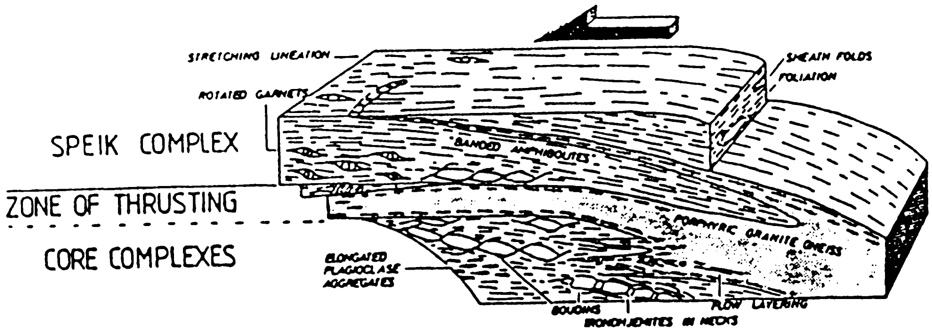

Fig. 7: Model for Variscan melt-enhancend emplacement of the Speik ophiolite nappe (modified from Neubauer, 1989b).

and consists of a thick sequence of kyanite-bearing paragneiss, paragneiss with kyanite paramorphs after andalusite, enclosing up to kilometre-sized lenses of eclogite and amphibolitic eclogite (Fig. 1). Intercalations of rare relics of metagabbro, marbles, manganese quartzites, calcsilicate rocks, and widespread pegmatites are observed (Hinterlechner-Ravnik and Moine, 1977; Raith, 1988; Weissenbach, 1975).

The age and evolution of the Gneiss group is the subject of lively discussion. The paragneiss is interpreted as metamorphosed graywacke and shale (Pacher and Riepl, 1978; Heritsch, 1980). The eclogites are derived from two different protoliths: Kyanite-bearing, low-Ti eclogites from gabbros (clinopyroxene-bearing cumulates), kyanite-free, high-Ti eclogites from N- and E-type MOR basaltic rocks (see, Tab. 2; Miller, 1990; Miller et al., 1988; Manby and Thiedig, 1988). The nature of the protolith and the metamorphic ages are uncertain. Manby and Thiedig (1988) and Manby et al. (1989) argued for late Precambrian eclogite metamorphism based on a Sm-Nd garnet-whole rock age of 693 Ma. Thöni and Jagoutz (1991) favour a Permian age of one of the gabbroic protoliths and an Alpine age of eclogite metamorphism. A pegmatite within the eclogite amphibolite, however, yielded a Permian Rb-Sr age (Scharbert, cited in Göd, 1989). Coarse-grained pegmatitic muscovite from pegmatite in paragneissic country rock yielded Rb-Sr ages in the range of 267 - 244 Ma (Frank et al., 1983; Morauf, 1981). These ages are considered to be slightly rejuvenated due to Alpine metamorphic overprinting under amphibolite facies conditions (Frank, 1987; Frank et al., 1987; Krohe, 1987; Rittmann, 1983). Rb-Sr thin slab isochrons of the mylonitic "Plattengneis" also gave intra-Permian ages (Frank et al., 1981, 1983) somewhat younger than U-Pb zircon ages (Paquette and Gebauer, 1989). Most workers agree that a Variscan metamorphic complex with low pressure characteristics (andalusite stability) was intruded by numerous pegmatites in late Variscan time (Becker et al., 1987; Frank et al., 1983; Göd, 1989). The crucial relationship of pegmatites to eclogites suggests a Permian or post-Permian age of eclogitization (for further discussion, see Neubauer, 1991).

East of the Wechsel window, the "Grobgneis" complex is overlain by several klippen of the "Sieggrabener complex" (Kümel, 1935) (for location, see Fig. 1). Their superposition on the "Grobgneis" complex is eo-Alpine in age. The Sieggrabener complex is composed of biotite-garnet paragneiss, kyanite gneiss, eclogite amphibolite, calc-silicate rocks, marble, and a large, kilometre-scale serpentinized peridotite body (Kümel, 1935; Richter, 1973). Most authors correlate the sequence with the gneiss complex in the Koralpe and Saualpe. The data base is poor. The chemistry of the eclogites to that of N-type MOR basaltic rocks (Kiesl and Weinke, cited in Koller, 1990) Garnet-clinopyroxene thermometry indicates a temperature of approximately 630° C, and phengite and pyroxene composition a pressure of ca. 10 kb (Kiesl and Weinke in Koller, 1990).

The serpentinite body has in general a normative harzburgitic composition. It contains spinel pyroxenite and rodingite (Evren, 1972; Koller and Richter, 1980).

Rock	Method	Age (error)	Rb-Sr initial ratio (error)	Reference
Murides, core complex				
Plagioclase gneiss	Rb-Sr WR	518 (44)	.7044 (.7012)	Frank et al. (1976)
Orthogneiss	Rb-Sr WR	432 (16)	.71158 (.00235)	Scharbert (1981)
Garnet amphibolite	U-Pb z.l.	c.435		Neubauer et al. (in prep.)
Augen gneiss	U-Pb z.l.	c.425		Neubauer et al. (in prep.)
Metatonalite ("Metablastic amphibolite")	U-Pb z.l.	356		Neubauer et al. (in prep.)
Two-mica metagranite (Zinken granite)	Rb-Sr WR	354 (16)	.7047 (.0007)	Scharbert (1981)
Trondhjemite gneiss	U-Pb z.c.	353 (2)		Neubauer et al. (in prep.)
Augen gneiss	Rb-Sr WR	331 (25)	.7058 .0029	Frank et al. (1983)
	Rb-Sr mu	258 (1)		Frank et al. (1983)
Metagranite	Rb-Sr mu	331 (7)		Scharbert (1981)
Pegmatite	Rb-Sr mu	329 (12)		Scharbert (1981)
Pegmatite	K-Ar mu	347 (7)		Hejl (1984)
Pegmatite	K-Ar mu	340 (18)		Hejl (1984)
Biotite amphibolite	K-Ar bio	276 (15)		Hejl (1984)
Pegmatite	K-Ar mu	265 (14)		Hejl (1984)
Plagioclase gneiss	K-Ar mu	282 (15)		Hejl (1984)
Murides, Micaschist-Marble complex				
Villach orthogneiss	Rb-Sr WR	445 (44)	.7122 (.0014)	Frimmel (1988)
Wolfsberg granite	Rb-Sr WR	258 (11)	.7046 (.0028)	Morauf (1980)
Pegmatite	Rb-Sr mu	347 (6)		Frank et al. (1983)
Pegmatite	Rb-Sr mu	277 (1)		Frank et al. (1983)
Pegmatite	Rb-Sr mu	256 (30)		Jäger and Metz (1971)
Bundschuh area				
Bundschuh orthogneiss	Rb-Sr WR	372 (29)	.738 (.002)	Hawkesworth (1976)
	Rb-Sr mu	352 (4)		Frimmel (1986)
"Kaintaleck slices"				
Hornblende-garnet gneiss	U-Pb z.u.	2,530		Neubauer et al. (1989)
	U-Pb z.l.	516		
Paragneiss	U-Pb z.l.	391 (2)		Neubauer et al. (in prep.)
Aplitic orthogneiss	U-Pb z.u.	365 (20)		Neubauer et al. (in prep.)
Orthogneiss boulder	U-Pb z.u.	502 (6)		Neubauer et al. (1987)
Orthogneiss boulder	U-Pb z.u.	500 (20)		Neubauer et al. (1987)
Eisenkappel				
Karawanken granite	K-Ar hb	252 (9)		Cliff et al. (1974)
	Rb-Sr bio	232 (9)		Scharbert (1975)

Korides

Eclogite	Sm-Nd WR-gt	693 (39)		Manby and Thiedig (1988)
Micaschist	U-Pb zi.u.i.	1200 (60)		Paquette and Gebauer (1989)
"Plattengneis"	U-Pb zi.u.i.	2015 (49)		Paquette and Gebauer (1989)
	l.i.	297 (3)		
	Rb-Sr t.s.i.	256 (35)	.7158 (.0012)	Frank et al. (1981)
	Rb-Sr t.s.i.	249 (6)		Frank et al. (1983)
Metagabbro	Sm-Nd m.i.	275 (18)		Thöni and Jagoutz (pers. comm.)
Pegmatite	Rb-Sr WR	ca. 280		Scharbert, cited in Göd (1990)
	Rb-Sr mu	277 (5)		Frank et al. (1983)
	Rb-Sr mu	265 (25)		Morauf (1981)
	Rb-Sr mu	263 (25)		Morauf (1981)
	Rb-Sr mu	263 (25)		Frank et al. (1983)
	Rb-Sr mu	258 (16)		Morauf (1981)
	Rb-Sr mu	249 (16)		Morauf (1981)
	Rb-Sr mu	247 (15)		Morauf (1981)
	Rb-Sr mu	246 (16)		Morauf (1981)
	Rb-Sr mu	246 (32)		Morauf (1981)
	Rb-Sr mu	244 (26)		Morauf (1981)
Pegmatite (St. Radegund)	Rb-Sr WR	313 (18)	.7147 (.0010)	Neubauer and Stattegger (unpubl. data)
	Rb-Sr mu	308 (16)		Neubauer and Stattegger (1981)
	Rb-Sr mu	303 (65)		Neubauer and Stattegger (1981)

Tab. 1: Compilation of significant geochronological data of Middle and Upper Austro-Alpine basement rocks east of the Tauern window. Older data are recalculated with lambda = 1.42 x $10^{-1}1$ a^{-1}. Explanation: WR - whole rock age, z.l. - zircon lower intercept age; z.u. - zircon upper intercept age; m.i. - mineral isochron; t.s.i. - thin slab isochron; mu - muscovite, gt - garnet, hb - amphibole, bio - biotite.

southwest shear. Because of the early Carboniferous age of the augengneiss, a Variscan age is presumed for thrusting (Neubauer, 1989a, b). The Speik complex is, therefore, considered by Neubauer (1988a) to be a large Variscan ophiolite nappe (Fig. 7) because of the Variscan age of granite emplacement into the zone of thrusting and the Variscan age of penetrative fabrics. The age of the Speik complex is assumed to be pre-Silurian. The metamorphic conditions are assumed to have reached the stability field of staurolite in the early Carboniferous.

No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Sample	R146	RF115	RF143	RF118	RF145	556	23	SK1	GE2	34	333b	GR-D	GR115
SiO_2	49.88	48.30	47.87	53.68	47.12	48.56	48.88	42.40	48.74	48.91	49.28	44.65	48.05
TiO_2	1.18	1.62	0.64	1.12	0.15	1.30	3.44	0.42	2.54	1.35	3.18	1.30	2.22
Al_2O_3	15.09	15.12	19.98	16.85	19.75	13.28	14.58	28.78	14.55	14.77	14.22	16.15	14.22
Fe_2O_3	2.02	2.99	1.03	1.29	0.45	2.10	1.48	0.80	1.27	1.26	2.07	11.04*	12.57
FeO	6.76	7.44	5.45	5.38	6.50	11.44	10.05	6.00	9.30	9.24	10.96	n.d.	n.d.
MnO	0.18	0.21	0.12	0.14	0.15	0.25	0.16	0.09	0.18	0.22	0.31	0.17	0.17
MgO	6.80	6.96	9.68	5.11	9.99	6.67	6.54	4.59	8.13	10.19	5.76	5.57	5.83
CaO	9.27	11.63	9.65	7.93	12.55	9.91	7.19	15.10	12.10	10.90	8.61	11.93	11.31
Na_2O	3.71	2.81	3.00	3.54	1.21	3.00	3.94	1.10	2.88	0.88	3.07	3.14	3.11
K_2O	0.10	0.31	0.47	2.08	0.13	0.20	--	0.06	0.09	0.15	0.21	0.42	0.52
P_2O_5	0.19	0.21	0.15	0.62	0.19	0.12	0.50	0.05	0.18	0.06	0.44	0.13	0.22
L.O.I.	2.78	1.74	1.71	2.23	1.64	0.48	1.00	1.07	1.23	1.18	0.46	4.69	1.24
Cr	180	200	143	116	135	72	372	248	206	282	54	111	175
Nb	<2	n.d.	n.d.	12	n.d.	n.d.	68	8	5	<5	45	<7	18
Ni	13	101	219	<5	81	54	123	59	73	149	29	74	125
Rb	6	2	16	73	3	<3	11	7	<4	10	7	12	11
Sr	366	183	255	766	232	112	554	271	182	98	347	291	368
Y	18	26	18	34	14	28	24	17	38	24	25	22	16
Zr	100	91	54	281	15	81	307	35	130	68	211	84	158

*Tab. 2: Representative chemical analyses of Austro-Alpine amphibolites. Major and minor element oxides in weight percent, trace elements in ppm. n.d. - not determined; * - Fe_2O_3 as total Fe.*
1: Epidote amphibolite from the Wechsel gneiss complex (own unpubl. analysis).
2: Plagioclase amphibolite from the "Core" complex with supposed calcalkaline basaltic origin (From Neubauer, 1988a).
3: Plagioclase amphibolite from the "Core" complex with supposed gabbroic origin (from Neubauer, 1998a).
4: "Metablastic amphibolite" (metatonalite) from the "Core" complex (from Neubauer, 1988a).
5: Metagabbro of the Speik complex (Neubauer, 1988a).
6: Garnet amphibolite of the Speik complex (from Schlöser, 1987).
7: Alkalic garnet amphibolite of the Micaschist-Marble complex (from Schlöser, 1987).
8: Low-Ti eclogite of the Koriden complex (Miller et al., 1988).
9: High-Ti eclogite of the Koriden complex (Miller et al., 1988).
10: Garnet amphibolite of the Plankogel complex (Schmerold, 1988).
11: Biotite amphibolite of the Plankogel complex (Schmerold, 1988).
12: Garnet-zoisite amphibolite of the Ritting complex (own unpublished analysis).
13: Amphibolite of the Frauenberg complex (own unpublished analysis).

Plankogel complex and accompanying micaschists

A package of micaschist units overlies the gneiss group along the southern margin of the Saualpe and Koralpe (Weissenbach, 1975; Kleinschmidt and Ritter, 1976) and in the Pohorje Mountains (Hinterlechner-Ravnik and Moine, 1977). The most prominent units are the Plankogel complex at the bottom and the Kräuping complex above it which in turn is structurally overlain by phyllitic micaschists.

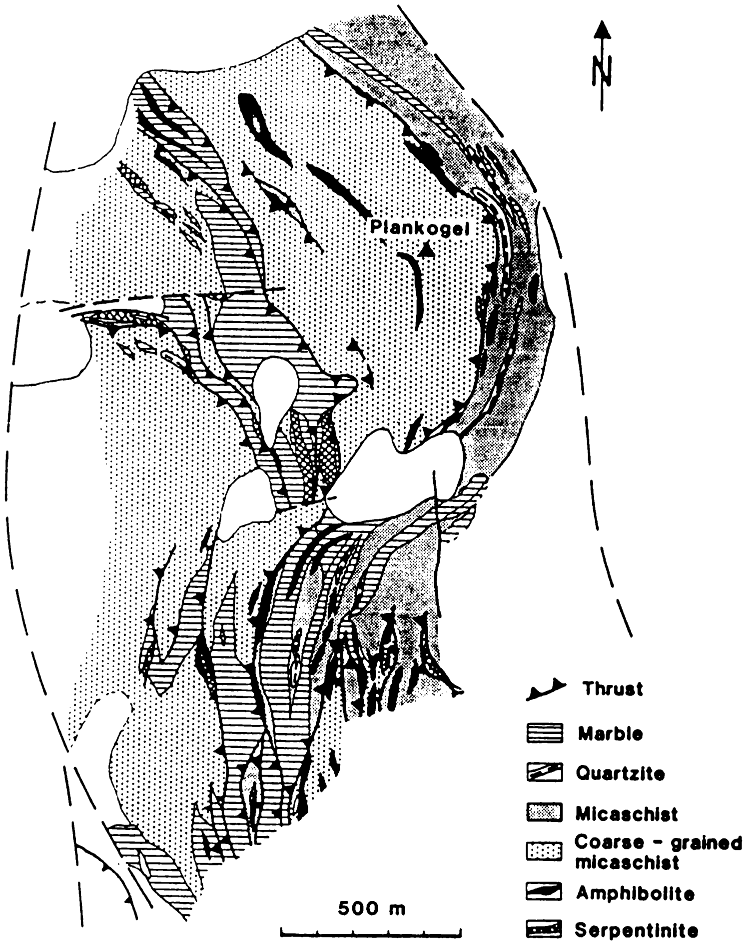

Fig. 8: Map showing the internal structure (ophiolitic melange) of the Plankogel complex (modified after Neubauer et al., 1989a).

The Plankogel complex consists of a staurolite-garnet micaschist matrix in which up to kilometre-sized lenses of marbles, amphibolites, manganese quartzites and ultramafic rocks are embedded (Kleinschmidt, 1975; Weissenbach, 1975). Schmerold (1988) subdivided the Plankogel complex into two subunits (Fig. 8, 9): (1) The "manganese quartzite unit" contains plagioclase and biotite micaschists, amphibolites with an alkali basaltic chemistry, silicate-rich marbles and manganese-bearing quartzites. This unit is interpreted in terms of an oceanic island environment. (2) The "serpentinite-bearing unit" is characterized by coarse-grained micaschists, serpentinites, amphibolites with an ocean-floor tholeiitic chemistry and pure marbles. The normative mineral contents of the serpentinites argue for harzburgite, lherzolite, olivine orthopyroxenite and olivine websterite protoliths (Schmerold, 1988). The Plankogelcomplex is interpreted as a an ophiolitic melange zone marking a pre-Alpine ophiolitic suture zone (Frisch et al., 1984; Neubauer et al., 1989b). Both protolith age and the age of metamorphism are uncertain.

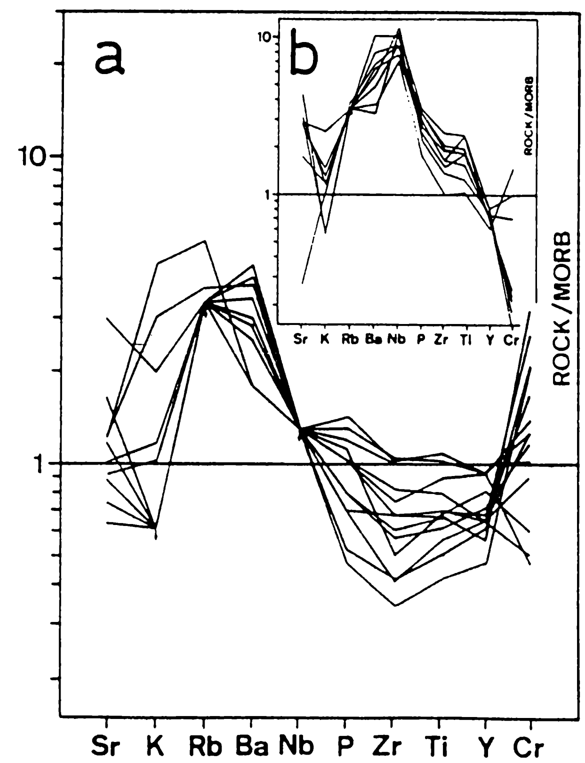

Fig. 9: Spidergram of Plankogel complex amphibolites displaying differentiation into two units with tholeiitic and alkali basaltic trends.

The Kräuping complex consists mainly of light-coloured micaschists, thin quartzitic layers and thick bodies of amphibolites (Weissenbach, 1975). The amphibolites have a predominantly alkali-basaltic chemistry (Schmerold, 1988).

Bundschuh-Einach complex

In the area between the Tauern window and the Gurktal thrust system, the Micaschist-marble complex is overlain by monotonous paragneiss (Einach-Priedröf complex) which contains lenses of Bundschuh orthogneiss (Fig. 1). The Einach-Priedröf paragneiss may be correlated with the gneisses of the Koriden because of their lithological similarities. The protolith's nature and age are unknown. The Bundschuh orthogneiss, a granitic to granodioritic gneiss, differs strikingly from other Austro-Alpine orthogneisses in its high content of muscovite, its high Sr_0 value of 0.738 and its Silurian/ Devonian Rb-Sr model age (Hawkesworth, 1976; Frimmel 1986a,b; 1988).

"Kaintaleck slices" and Ackerl complex

The "Kaintaleck slices" occur within the eastern Graywacke zone along 70 km of a thrust surface (Hauser, 1938; Cornelius, 1941). The thrust surface separates the lower Veitsch nappe with mainly Carboniferous formations (Ratschbacher, 1987) from the upper Noric nappe of Ordovician to early Carboniferous rocks. The structural thickness of the Kaintaleck slices does not exceed two hundred metres. In some areas these slices are intensely imbricated with footwall and hangingwall rocks (Neubauer et al., 1987). Lithology, geochronological data, geological relationships and structural position suggest that the Kaintaleck slices consist of various lithotectonic units (Fig. 10).

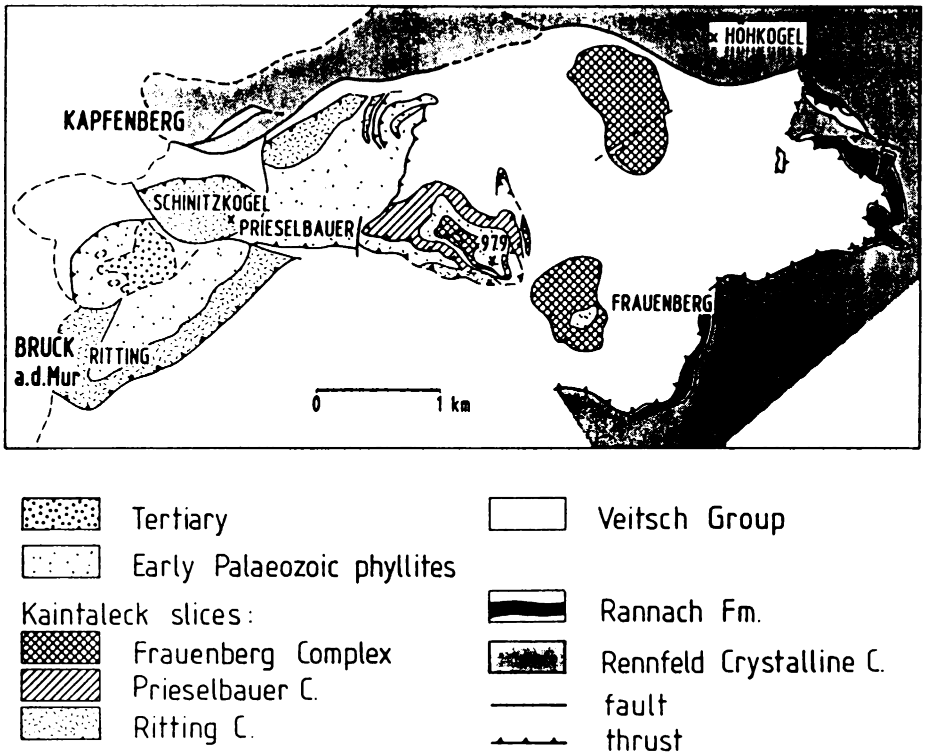

Fig. 10: Map showing internal structure of the Kaintaleck slices near Bruck/Mur (modified after Neubauer et al., 1987).

(1) The Ritting complex occurs near Bruck/Mur, at the Kaintaleck and west of Vöstenhof. It is composed of garnet-zoisite amphibolite, serpentinite, micaschist and thin marble layers. The chemistry of the amphibolites corresponds to tholeiitic basalts (Neubauer et al., 1989b). They contain a disseminated Cu mineralization. Chromite occurs in the serpentinites (Neubauer and Thalhammer, 1989). The protolith age of the Ritting complex is uncertain.
Amphibole concentrates yielded a disturbed total gas $^{40}Ar/^{39}Ar$ age which reflects post-metamorphic cooling prior to 420 Ma (Dallmeyer et al., this volume).

(2) The Frauenberg complex is mainly composed of paragneiss containing plagioclase amphibolite and marble lenses. The petrographic characteristics contrast with those of the Ritting complex. The amphibolites exhibit a mildly alkaline trend. A hornblende-garnet gneiss which is included in the plagioclase amphibolite contains numerous rounded zircon crystals with smooth surfaces which are interpreted as the result of high grade metamorphism. Pressure and temperature conditions are uncertain, but a high pressure event is indicated by the high pyrope content of garnet (ca. 40 mole percent pyrope). The zircons yielded a U-Pb upper intercept age of ca. 2.53 Ga and a lower intercept age of 516 Ma (Neubauer et al., 1989b). Because of the highly discordant pattern the upper intercept age is considered to be the protolith age, assuming an igneous source for the hornblende-garnet gneiss, and the lower intercept the late Cadomian age of metamorphism (Neubauer et al., 1989b). Brown, metamict zircons yielded a different upper intercept age of approximately 2.8 Ga. These zircons are interpreted as representing crustal contamination of the igneous source.

(3) The Prieselbauer complex is composed of migmatitic augen paragneiss and micaschists which include minor occurrences of amphibolite as well as concordant and discordant aplites. The paragneiss yielded a lower intercept U-Pb zircon age of ca. 391 Ma which is interpreted as the approximate age of metamorphism. A discordant aplitic vein yielded an upper intercept zircon age of 363 Ma which reflects the zircon crystallization within the protolith (Neubauer et al., 1987; in prep.). The Prieselbauer complex is interpreted as the basement of the Carboniferous sediments of the Veitsch nappe (Neubauer et. al., 1987).

The Ritting and Frauenberg complexes are transgressively covered by the Kalwang gneiss conglomerate which forms the stratigraphic base of the fossiliferous sequence of the eastern

Graywacke zone (Daurer and Schönlaub, 1978; Neubauer, 1985). Apart from various basement fragments such as amphibolites and serpentinites, trondhjemitic orthogneiss components dominate in the conglomerate. The orthogneiss is interpreted to derive from a source in a supra-subduction zone environment because of its geochemical patterns, especially those of the REEs. The U-Pb zircon upper intercept ages of two boulders from different localities are approximately 500 Ma (Neubauer et al., 1987). The predominance of the orthogneiss clasts suggest the presence of a major pluton in the hinterland of the conglomerates. This orthogneiss is not known from the Kaintaleck slices.

Recent mineral ages (Rb/Sr and 40Ar/39Ar muscovite and amphibole) of all three complexes resulted in ages ranging between 470 and 360 Ma with no significant difference between these three complexes. Therefore, a major Mid Paleozoic tectonothermal event affected major portions of the "Kaintaleck slices".

The Ackerl complex at the northwestern margin of the Upper Austro-Alpine Gurktal thrust system (Fig. 1) is another medium-grade metamorphic complex in a similar tectonic position to the Kaintaleck slices. The Ackerl complex is composed of staurolite-bearing biotite plagioclase gneisses, partly phyllonitized micaschists, rare amphibolites, acidic orthogneisses and quartzites (Neubauer, 1980). The Ackerl complex is derived from a thick clastic wedge with predominant graywackes and and basalts with within plate basaltic composition. Protolith ages are unknown. 40Ar/39Ar muscovite plateau ages with ca. 310 Ma record the Variscan metamorphic overprint (Dallmeyer et al., this volume). The Ackerl complex seemingly escaped a major Alpine metamorphic overprint.

Eisenkappel and eastern Gailtal crystalline

A small tectonic segment of crystalline basement rocks occurs immediately north of the Periadriatic lineament in the eastern Karawanken (Exner, 1972). It consists of a metamorphic sequence and the Karawanken granite pluton. The metamorphic sequence comprises biotite plagioclase paragneiss as the main lithology, with graphite-rich quartzites and gneisses, amphibolites and microcline orthogneiss (Exner, 1972; von Gosen, 1989a, b). Protolith ages and metamorphic history are unknown.

The Karawanken granite pluton is composed mainly of granite with subordinate granodiorite, diorite and gabbro as well as granodiorite dykes, pegmatite, aplite and lamprophyre dykes. The age of the pluton is poorly constrained. A K-Ar amphibole age (252 9 Ma; Cliff et al., 1974) and a Rb-Sr biotite age (232 Ma; Scharbert, 1975) reflect late Permian/ early Triassic cooling after intrusion.

Granite, diorite and augengneiss which are comparable to metagranitoids of the eastern Karawanken occur as tectonic slices along shear zones in the eastern Gailtal crystalline (Exner, 1985).

Garnet peridotites and granulites of the Pohorje Mountains

Although first described long ago, no attention has been paid to the granulites and associated garnet peridotites on the southern slopes of the Pohorje mountains in Slovenia. This unit is situated immediately to the north of the Periadriatic lineament in a comparable tectonic position to other Austro-Alpine granulitic and high-pressure ultramafic rocks (Frisch et al., 1990). A redescription of the Pohorje mountains was provided by Hinterlechner-Ravnik (1982, 1988) and Hinterlechner-Ravnik and Moine (1977). The metaperidotite-bearing sequence is composed of serpentinized dunite, harzburgite and garnet peridotite enclosed within eclogitic rocks. Kyanite-bearing eclogite typically associated with the garnet-peridotites suggests a relationship with the eclogite-bearing Koriden complex (Hinterlechner-Ravnik, 1982, 1988). The garnet peridotite suffered polyphase metamorphism: a metamorphic event with pressures higher than 12 to 15 kbar is postulated which was overprinted under amphibolite and greenschist facies conditions (Hinterlechner-Ravnik, 1988). Protoliths and metamorphic ages are unknown. The garnet peridotite and granulite have a position comparable to that of the garnet peridotites and granulites in the Ulten valley for which Variscan metamorphism is constrained by U-Pb zircon data.

Discussion

The medium- to high-grade metamorphic basement units east of the Tauern window exhibit a high degree of diversity with respect to their lithological composition, the age of granitoid intrusions, and metamorphism. The lithotectonic complexes have different positions within the Alpine nappe pile. During the early Alpine orogeny lithotectonic units accumulated in certain levels. This is espescially true for the Kaintaleck slices.

Protolith ages for the metasedimentary sequences are largely a matter of speculation. Several major groups of units are distinguished with regard to their tectonothermal histories according to their geochronological ages (Tab. 1):

(1) Rock units which were mainly affected by early Paleozoic magmatism and metamorphism (550 - 500 Ma) such as the Ritting and Frauenberg complexes, which escaped Variscan metamorphic overprint;

(2) rock units with Ordovician to Silurian, "Caledonian" ages (450 - 425 Ma) which were later affected by early Carboniferous metamorphism and intrusions;

(3) rock units which underwent Devonian metamorphism and magmatism (400 - 360 Ma), e.g. the Prieselbauer slice, the Bundschuh area and possibly the Tatric unit;

(4) rocks with early Carboniferous ages of metamorphism; these units are the most widespread;

(5) units such as the Koriden gneiss group for which the data base is uncertain or the lithological association is different from adjacent units, and whose history is not constrained by age determinations.

The geodynamic settings of most of these units appear to be different:

One set of units is regarded as the product of a late Precambrian/early Palaezoic subduction system. This system includes units derived from an ensialic magmatic arc such as the Core complex, and from ocean floor (Ritting and Speik ophiolite complexes) related to it. Some portions of this system suffered Cambrian metamorphism and accompanying deformation with subsequent uplift. Parts of the newly consolidated crust acted as the basement to an Ordovician to early Carboniferous shelf and rise sequences of a new sedimentary cycle. This is constrained by data from some Kaintaleck slices which show basement-cover relationship. The Micaschist-Marble complex is correlated by its lithostratigraphy to the fossiliferous late Ordovician to Carboniferous sequences. We interpret all units which contain this late Ordovician to Carboniferous cover sequence including its highly metamorphic equivalents as members of the Noric composite terrane (Frisch and Neubauer, 1989).

The Tatric unit, the Wechsel unit (see Neubauer et al., this volume), the Bundschuh-Einach complex, and major portions of the Kaintaleck slices define a completely different setting. Evidence of Devonian metamorphism and magmatism are not compatible with the evolution of a Devonian shelf and slope sequence in the Noric composite terrane. These units are, therefore, interpreted as parts of another terrane, the Pannonian terrane (Frisch and Neubauer, 1989), which formed a continental collisional belt in the Devonian as part of the West-European Ligerian cordillera.

The evolution of the other lithotectonic units is badly constrained. The Plankogel complex is interpreted to be the Variscan ophiolitic suture which separates the foreland sequences from Variscan metamorphic internides, especially from those of the Pannonian terrane (Frisch and Neubauer, 1989).

Geochronological data indicate an early Carboniferous climax of metamorphism and magmatism for the Murides, the Wechsel gneiss complex, and the Grobgneiss complex. S- and I-type granitoids of early Carboniferous age are widespread in the Grobgneis and Core complexes. These data suggest that the lower lithotectonic units within the Alpine nappe pile were involved in early Carboniferous plate collision which amalgamated different Austro-Alpine basement units. Burial, deep-crustal thrusting under the influence of melts, and uplift shortly after the metamorphic peak are the evolutionary steps recorded in this zone. The collisional event is also indicated by Visean flysch sedimentation in the Austro-Alpine/Southalpine foredeep (Frisch et al., 1990).

Only little evidence is available for the late Carboniferous evolution. Permian radiometric data obtained from pegmatitic muscovites, granite and gabbro intrusions, and Rb-Sr thin slab errorchrons are widespread. The meaning of these data is not clear. A reliable explanation is a major late Carboniferous to Permian rift event which resulted in intrusion of gabbros and formation of tholeiitic basaltic melts, high temperature/low pressure metamorphism in a regime of crustal thinning. The rifting led finally to formation of the Tethys. However, most mineral data were interpreted by previous authors as the result of partial resetting of Carboniferous ages by Cretaceous metamorphism. Well-documented magmatic activity, which is also preserved in acidic tuffs in Permian overstep sequences (see Krainer, this volume), indicates high heat flow within the Variscan crust, and the mineral ages may, therefore, reflect postmetamorphic cooling caused by crustal extension and uplift.

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LATE PALEOZOIC PLUTONISM IN THE EASTERN ALPS

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Introduction

Granitoid gneisses with late Paleozoic intrusion ages turn out more and more to be an extraordinary typical constituent of the Alpine-Carpathian basement. They are known to occur in numerous bodies over the entire length of the Alpine-Carpathian arc, from the French Alps down to Slovakia. In the Austrian Alps, more than 20 % of the exposed pre-Mesozoic crust is built up of such granitoids, and they form metaplutonic complexes of considerable extent in the lower Penninic unit and the structurally higher Austroalpine nappe system.

The four main metaplutonic terrains of the **Austroalpine realm** are (from east to west) the *Raabalpen-Semmering-Wechsel complex*, located between Vienna and Graz, the *Gleinalm complex* west of Graz, the *Seckau-Bösenstein complex* of northern Styria, and the *Schladminger Tauern complex*, which is situated ca. 70 km SSE of Salzburg (Fig.1).

The largest and so far best understood metaplutonic terrain of the Eastern Alps is, however, exposed in the **Penninic Tauern Window** (*Hohe Tauern Batholith*). It can be divided into three largely independent sectors, a western, a central and an eastern sector, each consisting of somewhat different suites of granitoids (Fig.1).

The eastern sector of the Hohe Tauern Batholith lies along the excursion route, which is described in the second part of this excursion guide.

Granitoid types

It has been pointed out recently by Finger and Steyrer (1990) that the Late Paleozoic plutonism of the Alps has chemically much in common with the calc-alkalic plutonism of continent margin orogenic belts. This appears to be especially valid for the Austrian Alps: Here, typical calc-alkaline tonalite-granodiorite-granite associations are present in all major regional plutonic complexes. The granitoids are, with only few exceptions, sodium-rich and metaluminous to weekly peraluminous rocks, and therefore I-type granites (s.l.) in terms of the Australian classification (Chappell and White, 1974). Furthermore, nearly all of the granitoids display the characteristic trace element signatures of volcanic-arc granites in the sense of Pearce et al. (1984). The ε_{Nd} - ε_{Sr} covariations are also in the typical range of continental margin I-type batholiths, indicating involvement of sources with mantle isotopic composition and mature crustal sources (cf. Figs. 2,3).

Current work in the **Hohe Tauern Batholith** (Haunschmid et al., 1991; Schermaier, 1991; Finger et al., 1992) has revealed the presence of at least three different suites of I-type granitoids:

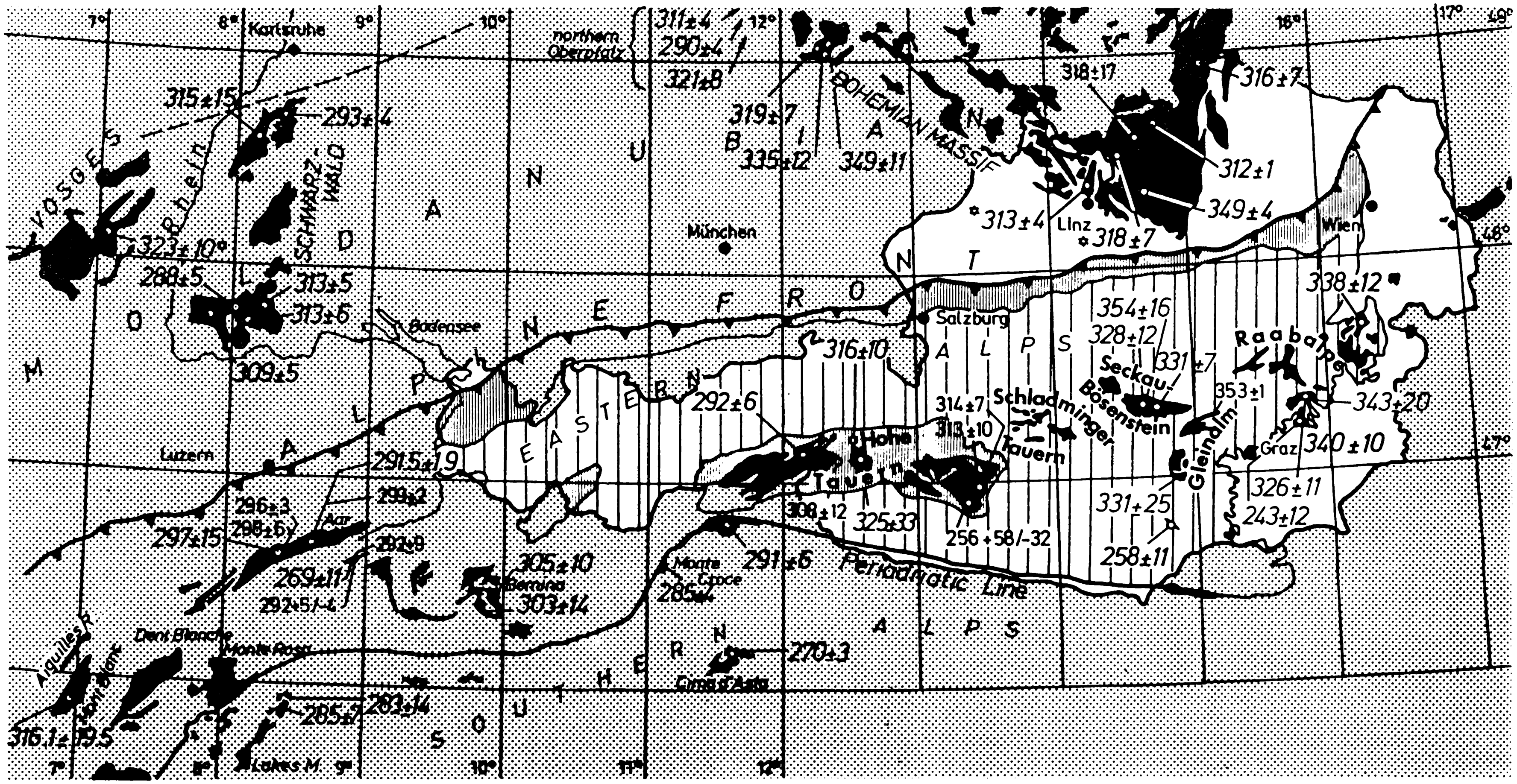


Fig.1: Distibution of late Paleozoic granitoids (black) in Austria and neighbouring areas (map slightly modified after Finger and Steyrer, 1992). Shown age data refer to published Rb-Sr WR ages (big numerals) and U/Pb ages (small numerals). Tectonic subdivision of Alps in Austria: wide vertical hatching = Austroalpine, narrow hatching = Penninic (partly Helvetic).

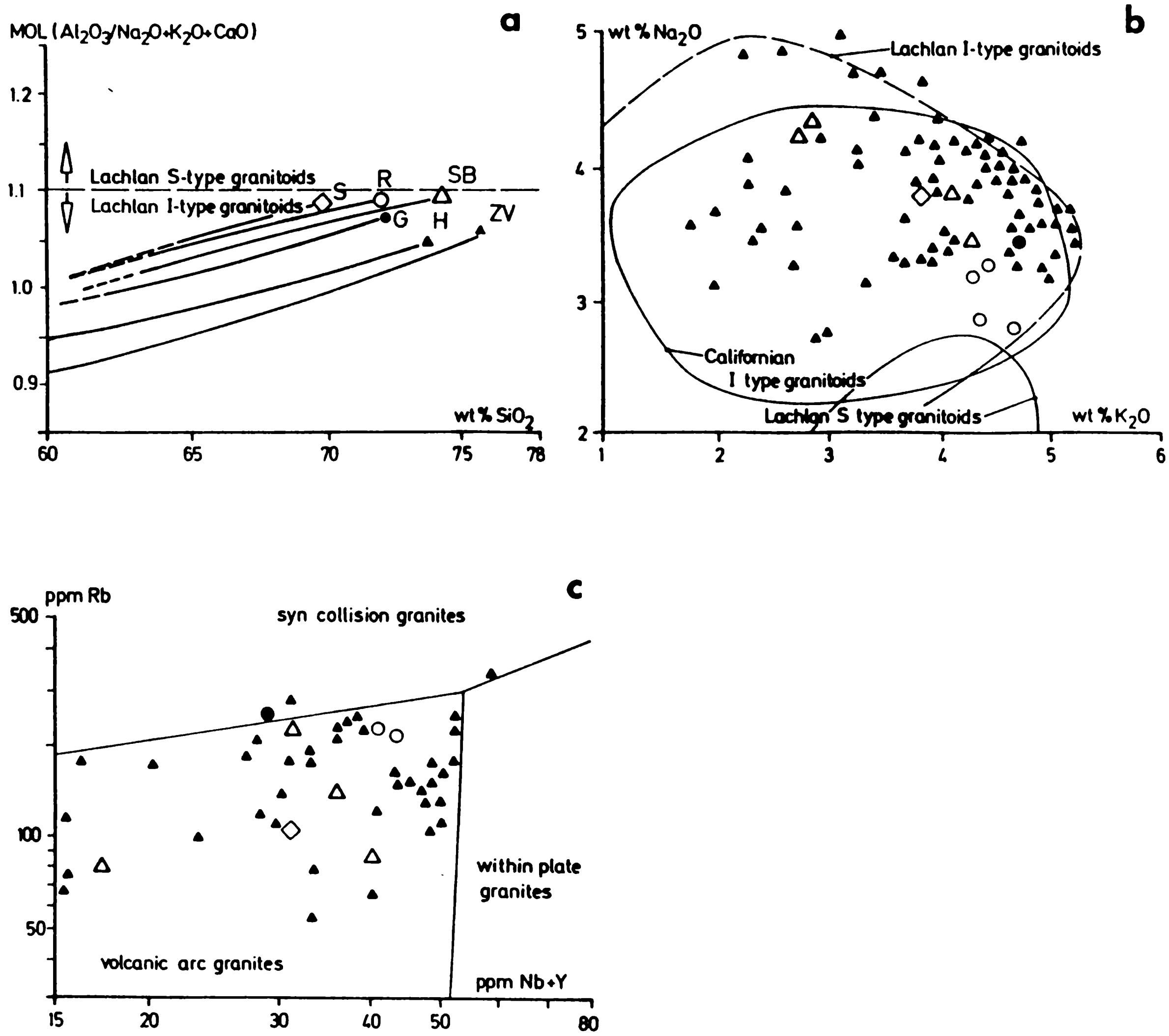


Fig.2: Three conventional diagrams for the classification of granitic rocks with plots and trends of the intra-Alpine late Paleozoic granitoids of Austria. Fig. 2C is after Pearce et al. (1984). Black triangles: Hohe Tauern Batholith (undiff.). Other symbols see Fig.5. Fields of Lachlan and Californian granites after Finger and Steyrer (1990) and references therein.

The *Zillertal-Venediger Suite* of the western Tauern Window and the *Hochalm Suite* of the eastern Tauern Window are typical calc-alkaline suites and they both comprise a wide variety of granitoids, ranging from medium grained tonalitic rocks over granodiorites to (sometimes coarser grained) granitic end members. Together these calc-alkaline rocks make up ca. 80 % of the Hohe Tauern Batholith.

The Zillertal-Venediger Suite is tonalite-granodiorite dominated. It follows a trondhjemitic differentiation trend (Lameyre and Bowden, 1982) and appears to be chemically quite primitive, with high CaO and low K_2O, Sr, Ba and Rb contents (Figs.4,5; Tab.1).

The Hochalm Suite is on average more felsic and granodiorite-granite dominated. In the Streckeisen diagramm (Fig.5), it spans a calc-alkaline granodioritic trend in the sense of Lameyre and Bowden (1982). When compared to the Zillertal-Venediger Suite, the Hochalm Suite is considerably lower in CaO, but higher in alkalies, Sr and Ba, at a given SiO_2. (Figs.4,5; Tab.1).

A third suite can be roughly outlined as *high-K_2O I-type granitoids*. These rocks are volumetrically of minor importance and make up not more than 20 % of the Hohe Tauern Batholith. However they can be found in every sector (e.g. Romate gneiss, see Stop 00). They are always coarse grained and range in composition from syenitic over monzonitic and monzodioritic to granitic. Major element chemistry is usually metaluminous (therefore: I-type) and only moderately felsic with SiO_2

contents between 60 and 68 %. In their trace element spectrum, the rocks are distinctly enriched in Rb, Ba, Sr, Th and Zr (Fig.4).

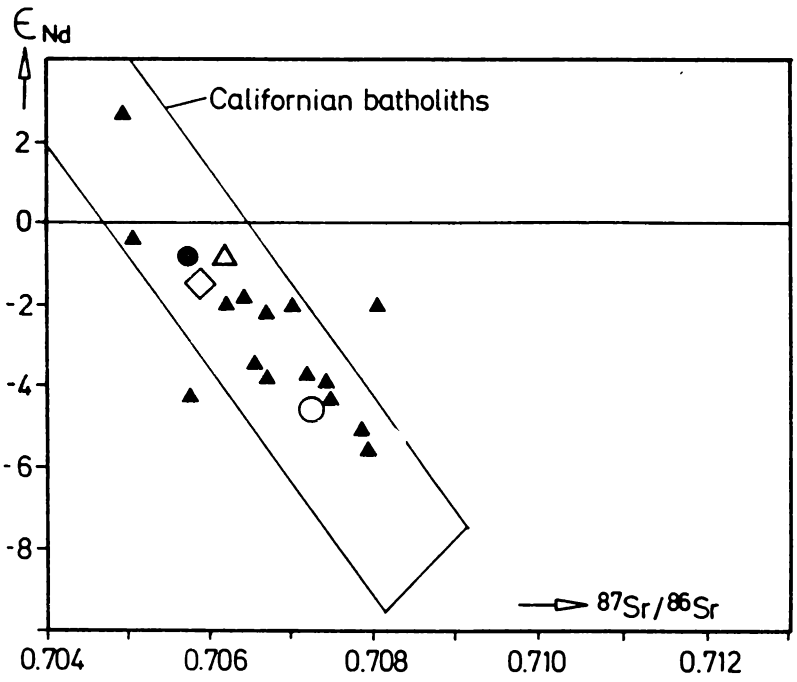


Fig.3: $^{87}Sr/^{86}Sr$ vs ε_{Nd} diagram with model initial ratios of intra-Alpine granitoids. Black triangles: Hohe Tauern Batholith (undiff.). Other symbols as in Fig.5. Field of Californian batholiths after De Paolo (1981).

Where contacts to the calc-alkaline intrusions are exposed, the high-K_2O granitoids were always found to be older. Furthermore, the high-K_2O granitoids very often turned out to be closely associated with meta- to diatectic country rocks. This implies that they were formed during large scale crustal anatexis, which obviously stood at the beginning of the evolution history of the Hohe Tauern Batholith. Geochronological data suggest an age between 330 and 310 Ma for this anatectic event, while the bulk of the calc-alkaline granitoids intruded probably between 315 and 290 Ma (see review of age data in Finger et al., 1992). Unlike the high-K_2O group, the calc-alkaline intrusions solidified usually as high level plutons. This means that the migmatitic crust was uplifted and cooled in the meantime.

Apart from the three I-type granitoid suites mentioned above, the Hohe Tauern Batholith comprises also some minor plutonic bodies of granitoids with affinities to *S-type* and *A-type* granites.

The most important example of an S-type granite suite is the Granatspitz massif of the central Tauern Window, which consists mainly of a leucocratic, medium to coarse grained and more or less porphyritic two mica metagranite with pseudomorphs after cordierite. The granite is likely to have formed during the same anatectic event which generated also the high K_2O I-type granitoids.

Those granites considered to approach A-types in composition, are usually small leucocratic intrusions, which have been found throughout the batholith to crosscut the calk-alkaline granitoids (see Stop 00, Haunschmid et al. 1991). Maybe, an early Permian age should be envisaged for them (Vavra, 1989; Vavra and Hansen, 1991). The most distinctive features of the "A-type" granites lie in their trace element spectrum, which shows systematic enrichment in Y and HREE and a distinct negative Ba and Eu anomaly (see Fig.4, Tab.1).

Although only relatively little data are presently available from the **Austroalpine realm**, there is some evidence that granite typology in that area is in many ways similar to the Hohe Tauern Batholith. Clearly, the bulk of the granitoids belongs again to calc-alkaline I-type suites.

For the *Seckau-Bösenstein area*, it has been already stated by Metz (1976) that the dominant plutonic lithology is tonalitic/granodioritic, associated with minor amounts of diorites and gabbros (Fig.5). Our preliminary set of chemical data suggests that many plutonic

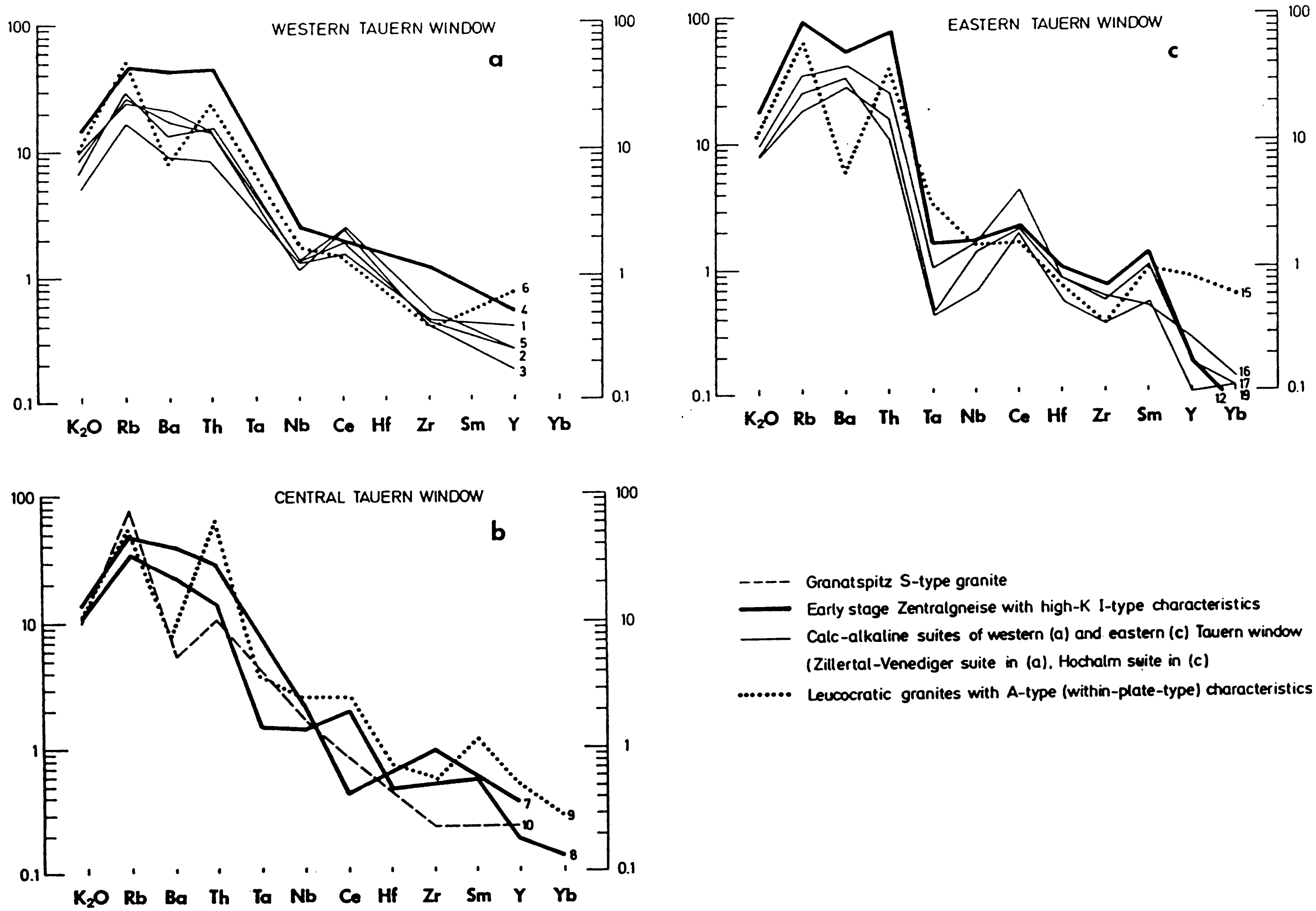
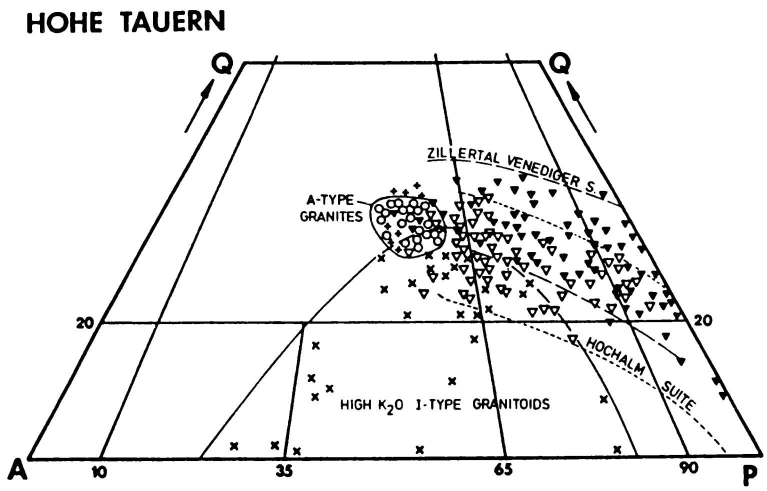


Fig.4: HORG-normalized trace element patterns of different granitoid suites of the Hohe Tauern Batholith (HORG = hypothetical ocean ridge granite, see Pearce et al. 1984). Sample numbers and locations see Tab.1.



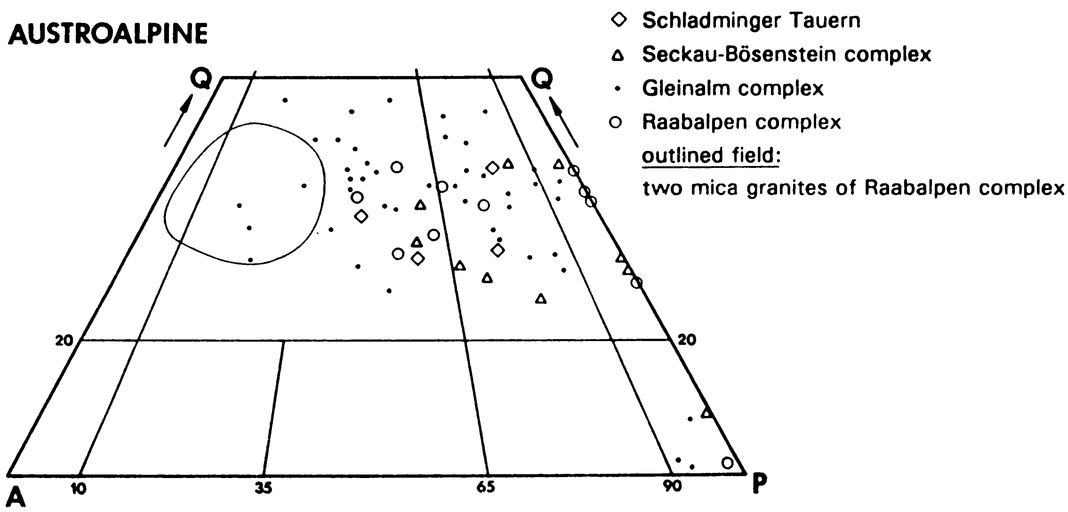


Fig.5: Streckeisen diagrams with plots of intra-Alpine granitoids. Data sources: Finger et al. (1992 and references therein), Formanek (1964), Metz (1976), Neubauer (1988), Peindl et al. (1990), Wieseneder (1968) and unpublished University of Salzburg data.

rocks of the Seckau-Bösenstein area are compositionally quite similar to the Hochalm Suite of the Eastern Tauern Window (see Tab.1).

The same seems to be valid for the Schladming complex, as far as we can conclude from the few presently available data (Fig.5, Tab.1).

The Gleinalm complex was investigated by Neubauer (1988) and found to consist dominantly of granodiorites and granites, but also of some tonalites and diorites (Fig.5).

For the Raabalpen-Semmering-Wechsel complex, new data have been recently presented by Peindl et al. (1990). These imply the presence of a calc-alkaline suite with trondhjemitic differentiation trend. Furthermore, Peindl et al. (1990) described a distinct group of very felsic two-mica granites (Fig.5), which could be similar to the A-type granites of the Hohe Tauern Batholith.

An important but as yet not completely resolved question is, whether the Austroalpine plutonic complexes are of the same age as the Hohe Tauern Batholith or not. Presently available Rb-Sr isotope data (Fig.1) seem to indicate that they are slightly older. However, more data, including high quality zircon data, will be necessary to work out the overall timing of the Late Paleozoic plutonism of the Austrian Alps.

		HOHE TAUERN											SCHLADMINGER TAUERN	SECKAU BÖSENSTEIN		
		high K_2O I-type granitoids			Granatsp. massiv	Zill.- Venediger suite		Hochalm suite		A-type granitoids						
	Nr.:	4	7	12	10	1	5	16	18	20	15	6	21	22	23	24
	SiO2	60.85	62.37	62.39	74.28	60.73	73.93	60.60	70.20	73.23	74.54	75.22	70.08	63.63	67.55	71.56
	TiO2	0.76	0.65	0.54	0.12	0.57	0.23	0.48	0.23	0.27	0.21	0.13	0.36	0.75	0.55	0.35
	Al2O3	15.80	17.86	15.83	14.64	16.40	14.30	18.39	15.20	13.85	13.12	13.45	14.95	16.66	15.90	14.57
	FeOtot	5.20	3.20	2.40	1.22	6.55	1.89	4.24	1.67	1.89	1.49	1.52	2.52	4.45	3.22	2.35
	MnO	0.08	0.05	0.05	0.07	0.20	0.00	0.23	0.04	0.02	0.05	0.07	0.06	0.09	0.06	0.06
	MgO	3.87	1.92	1.61	0.29	3.34	0.33	2.43	0.45	0.28	0.29	0.23	0.88	2.17	1.25	0.84
	CaO	2.93	2.58	2.21	0.73	5.82	1.40	3.98	1.96	1.25	1.17	0.88	2.03	3.59	2.72	1.67
	Na2O	3.35	3.88	3.87	3.21	3.08	4.73	4.64	4.32	3.69	3.23	3.90	3.72	4.18	4.20	3.80
	K2O	5.61	5.31	7.05	4.94	1.98	3.48	3.16	3.30	4.73	4.68	4.50	3.95	2.72	2.84	4.02
	P2O5	0.57	0.26	0.50	0.26	0.24	0.07	0.36	0.10	0.08	0.05	0.01	0.19	0.28	0.21	0.15
	L.O.I.	0.70	1.86	1.84	0.89	1.08	1.02	1.50	1.60	0.87	0.82	1.28	0.80	0.80	0.80	0.80
	tot	99.72	99.94	98.29	100.65	99.99	101.38	100.01	99.07	100.16	99.65	101.19	99,54	99.32	99.30	100.17
	A/CNK	0.93	1.06	0.88	1.22	0.92	1.01	1.01	1.07	1.03	1.05	1.04	1.06	1.02	1.07	1.07
XRF	Nb	24	22	17	15	13	13	14	bdl	16	15	17	11	12	9	13
XRF	Zr	380	315	244	78	152	164	200	142	189	125	123	171	246	230	161
XRF	Y	35	24	12	16	27	18	19	11	47	58	49	20	28	8	23
XRF	Sr	347	450	1074	70	287	128	882	520	119	92	84	305	645	530	286
XRF	Ba	1970	1775	2736	264	456	812	1492	1127	511	197	389	1111	1023	1031	909
XRF	Rb	182	188	368	285	65	102	108	117	244	281	195	105	84	81	139
XRF	Cr	127	55	37	bdl	17	bdl	49	bdl	3	bdl	1	104	102	167	179
XRF	Ni	47	23	40	10	11	1	23	bdl	16	20	10	7	10	7	8
XRF	Th	33	22	55	8	6	11	13	19	20	31	17	11	6	8	8
INAA	Ba	-	1735	2632	-	382	774	1609	1018	601	273	-	-	-	-	-
INAA	Rb	-	192	356	-	60	105	98	100	244	257	-	-	-	-	-
INAA	Cr	-	29	35	-	23	2	10	3	3	4	-	-	-	-	-
INAA	Th	-	23	58	-	6	11	9	9	23	31	-	-	-	-	-
INAA	U	-	4.9	12.3	-	1.1	2.6	3.0	2.3	10.3	15.0	-	-	-	-	-
INAA	Hf	-	9.0	9.1	-	4.8	6.5	7.4	3.0	7.6	6.2	-	-	-	-	-
INAA	Sc	-	6.9	7.3	-	20.0	4.0	4.8	3.1	5.3	4.8	-	-	-	-	-
INAA	Co	-	9.4	7.7	-	17.0	2.2	7.9	1.8	2.3	2.0	-	-	-	-	-
INAA	Ta	-	1.64	1.12	-	0.85	0.85	0.31	1.01	2.30	2.30	-	-	-	-	-
INAA	La	-	42.2	36.7	-	27.6	34.2	46.0	31.5	40.5	25.6	-	-	-	-	-
INAA	Ce	-	76.4	77.1	-	51.5	62.9	75.1	57.5	81.4	55.5	-	-	-	-	-
INAA	Nd	-	34.4	46.3	-	22.8	24.2	23.0	21.6	34.4	28.5	-	-	-	-	-
INAA	Sm	-	6.94	11.72	-	6.70	5.15	4.38	3.77	10.76	9.15	-	-	-	-	-
INAA	Eu	-	1.92	1.95	-	1.41	0.80	1.31	1.02	0.94	0.46	-	-	-	-	-
INAA	Tb	-	0.74	0.48	-	0.73	0.55	0.34	0.36	1.16	1.14	-	-	-	-	-
INAA	Yb	-	2.17	0.60	-	2.35	1.80	1.09	0.90	4.22	4.95	-	-	-	-	-
INAA	Lu	-	0.32	0.12	-	0.37	0.28	0.18	0.15	0.60	0.68	-	-	-	-	-
	$\epsilon Nd(320)$	-	-4.63	-4.39	-4.83	-3.78	-1.66	-1.94	-	-1.18	-3.98	-2.25	-1.38	-	-0.94	-4.08

Tab.1: Representative XRF and INNA analyses of selected late Paleozoic granitoids of the Austrian Alps. A/CNK= mol $Al_2O_3/(CaO+Na_2O+K_2O)$.Sample locations:

1 - metatonalite, southern rim of Venediger core; 4 - biotite-rich Augen gneiss, inner Krimml valley; 5 - "Augen- und Flasergneis", mittlere Gfrorene Wand Spitze, near Olperer; 6 - "Augen- und Flasergneis", quarry in the outermost Obersulzbach valley; 7 - Hochweißenfeld gneiss, S of Abretterkopf; 10 - metagranite, W Tauernmoos lake; 12 - Romate gneiss, near Mallnitz; 15 - leucogranite, tunnel from Gastein valley to Mallnitz; 16 - "Hochalmporphyrgranit", NNW Hochalmspitze, near Osnabrücker Hütte; 18 - Malta tonalite, Malta valley, bifurcation to Katowitzer Hütte; 20 - leucogranite, Gößbach valley, Untere Thomanbauernalm; 21 - Schladming granite gneiss, Pötten; 22 - metagranodiorite, Bösenstein, Mühle St. Johann; 23 - Kraubath orthogneiss, Pressnitzgraben; 24 - Seckau granite, Rannachgraben.

Geodynamic interpretation of the Late Paleozoic I-type plutonism in the Alps

During the past years, several attempts were made to fit the intra-Alpine basement into an overall Variscan plate tectonic concept (e.g. Frisch and Neubauer, 1989; Frisch et al., 1990). Generally, there is agreement on the point that the Paleozoic units of the Alps were once situated somewhere along the southern flank of the Variscan orogen (see e.g. Franke, 1989). However, the locations of single units relative to each other and to the actual Variscides on the north of the Alpine front (e.g. the Moldanubian unit; see Fig.1) prior to the Alpine tectonics can be only very tentatively inferred, and the evolution and paleogeography of the Alpine basement during and before the Variscan Gondwana-Laurasia continent collison event, which started in the Devonian (Matte, 1986) is still more uncertain.

Frasl (1987) stressed pronounced lithological contrasts between the Moldanubian zone of the Bohemian Massif (Fig.1) and the Paleozoic formations of the Tauern Window and emphasized that most of the intra-Alpine Variscan units are obviously not the simple straightforeward continuation of the Moldanubian zone. Considering the important dextral shearing event, that affected much of the central European crust at the end of the Variscan orogeny (Arthaud and Matte, 1977), it appears to be quite possible that the intra-Alpine Variscan units of Austria were formerly situated much more to the southeast of the Bohemian massif.

However, like the southern (extra-Alpine) Variscan units of western Europe, the Alpine basement comprises fragments of ophiolites (see e.g. Neubauer et al., 1989), which are remnants of early Paleozoic or late Proterozoic oceanic domains extending in the Gondwana foreland. Furthermore, Frisch and Neubauer (1989) presented convincing evidence that these oceanic domains were strongly shortened (Early Carboniferous) and at least partly closed by northward subduction in the course of the Variscan convergence of Gondwana and Laurasia, just like their counterparts in western Europe (Matte, 1986). Frisch and Neubauer (1989) also proposed that, along with this process, Gondwana derived terranes attached from the south stepwise to the Variscan orogen.

Certainly, it would be most tempting to relate the calc-alkaline I-type plutonism of the Alps to such a subduction scenario along the southern Variscan fold belt flank. On the other hand, there is faunal, facies and paleomagnetic evidence that the megacontinents Gondwana and Laurasia were long linked and formed a nascent Pangea, when the late Paleozoic I-type plutonism occurred in the Alps (see e.g. review in Neugebauer, 1988). Consequently, one might argue that the plutonism is rather collision- than subduction-related, and that its I-type features are merely a consequence of a collision-induced anatectic remagmatization of infra-crustal I-type sources, e.g. volcanic arc material of older sutures (see e.g. Vavra, 1989).

It is , however, still an open question, how the Alpine units were actually involved in the Variscan megacontinent collision event. Namely, it appears possible that they were situated in a southeastern section of the Variscan fold belt, where Gondwana and Laurasia did not fully touch and where previous oceanic domains between these continents remained open. Thus, a continental margin type orogeny might have survived in this southeastern realm from the early to the late Paleozoic, while the actual Variscan continent collision, i.e. the docking of the megacontinents, was restricted to the western sector of the Variscan belt (see also Ziegler, 1986).

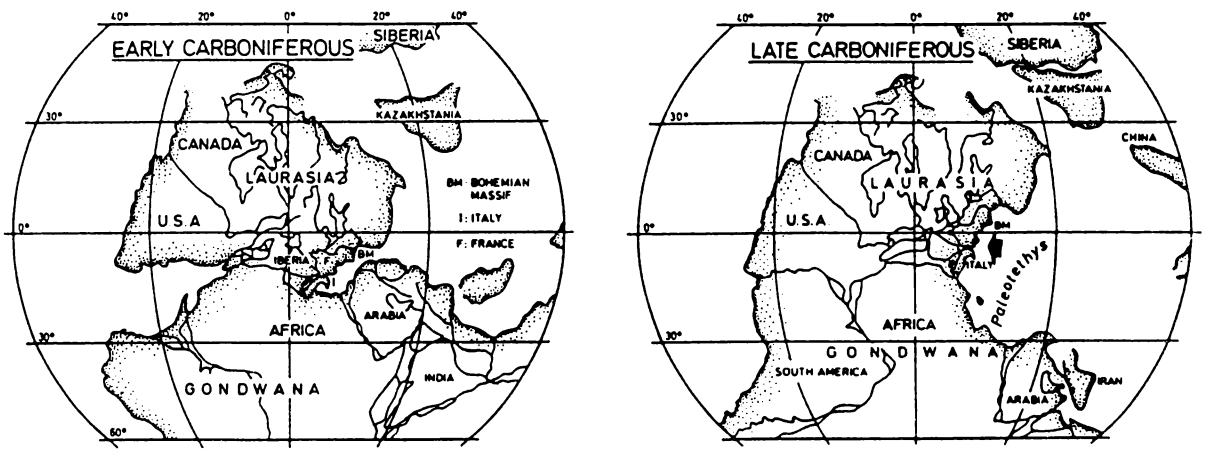


Fig.6: Paleogeographic base maps for the early and late Carboniferous after Scotese (1984). Finger and Steyrer (1990) hypothesized that the palaeo-Tethys ocean was subducted in the late Paleozoic below the Variscan fold belt, which is in front of the northern Laurasian part of the nascent Pangea megacontinent (black arrow). This plate configuration probably formed first in the course of the Carboniferous westward drift of Gondwana relative to central Europe. The map for the early Carboniferous suggests a more or less intracontinental position of the Variscan fold belt between Gondwana and Laurasia.

Finger and Steyrer (1990) have argued that the well documented late Paleozoic west drift of Gondwana relative to Laurasia and the simultaneous opening of the Pangea golf (Arthaud and Matte, 1977) could have resulted in a marked "post-collisional" Cordilleran type orogeny along the southern flank of the Variscan orogen, giving rise to a vast production of granitoids (Fig.6). One argument in favour of such a concept is that the Variscan orogen exhibits a significant active continent margin type zonation of its late stage granitoids with a southern belt of predominantly I-type plutons in the Alps (outer arc ?) and a northern belt of predominantly S-type plutons (inner arc ?) in the Moldanubian unit.

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40Ar/39Ar AND Rb-Sr MINERAL AGE CONTROLS FOR THE PRE-ALPINE AND ALPINE TECTONIC EVOLUTION OF THE AUSTRO-ALPINE NAPPE COMPLEX, EASTERN ALPS

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Introduction

The Austro-Alpine Nappe Complex (AANC) represents a classical thick-skinned fold and thrust belt interpreted to have comprised the upper continental plate during the Tertiary collision of the European foreland/Penninic continental crust and Adriatic microplate. The AANC is composed of several regional internally imbricated thrust units which are structurally interlayered with Permo-Mesozoic sequences along northern margins (Fig. 1). Southwards, basement units from various thrust sheets are in mutual contact. Three major internally imbricated subcomplexes may be distinguished, within the AANC (Tollmann, 1959, 1987). Those include 1) the Lower Austro-Alpine Unit (LAA), 2) the Middle Austro-Alpine unit (MAA), and 3) the Upper Austro-Alpine unit (UAA). These units are characterized by a distinction in basement lithology, nature of protolith formation and/or degree of metamorphic overprint of basement units (Fig. 2). The MAA contains units which record an amphibolite facies overprint of Alpine/pre-Alpine age. The UAA is represented by weakly metamorphosed units and several thin units with amphibolite facies assemblages of pre-Alpine age (e.g., Kaintaleck Complex, Ackerl Complex). The LAA basement exposed along eastern margins ranges from units which display greenschist facies assemblages (Wechsel Gneiss, Wechsel Phyllite, both forming together with the Waldbach complex the Wechsel window basement) to predominantly amphibolite facies ("Grob gneiss"/Raabalpen Complex).

This contribution constitutes an overview of the timing of pre-Alpine and Alpine tectonic processes which affected the AANC east of the Penninic Tauern Window. The structure of this region is discussed in Frank (1987), Neubauer and Genser (1989), Ratschbacher (1986), Ratschbacher et al. (1987), Tollmann (1959, 1977, 1987). This have been evaluated by $^{40}Ar/^{39}Ar$ and Rb-Sr mineral dating. The main emphasis has been an evaluation of: (1) the presence of pre-Variscan tectonothermal events; (2) the sequence of thrusting within the Austro-Alpine thrust complex and, (3) the timing of post-metamorphic cooling of the Austro-Alpine complex.

Previous geochronological work in this area has been compiled by Frank et al. (1987) and Neubauer and Frisch (in press).

Analytical methods

Mineral concentrates for $^{40}Ar/^{39}Ar$ measurements were wrapped in aluminium-foil packets, encapsulated in sealed quartz vials, and irradiated for 40 hr in the central thimble position of the TRIGA Reactor at the U.S. Geological Survey, Denver. Variations in the flux of neutrons along the length of the irradiation assembly were monitored with several mineral standards, including MMhb-1 (Samson and Alexander, 1987). The samples were incrementally heated until fusion in a double-vacuum, resistance heated furnace. Temperatures were monitored with a direct-contact thermocouple and are controlled to 1°C between increments and are accurate to 5°C. Measured isotopic ratios were corrected for total blanks and the effects of mass discrimination. Interfering isotopes produced during irradiation were corrected using the factors reported by Dalrymple et al. (1981) for the TRIGA Reactor. Apparent $^{40}Ar/^{39}Ar$ ages were calculated from corrected isotopic ratios using the decay constants and isotopic abundance ratios listed by Steiger and Jäger (1977) following the methods described in Dallmeyer and Keppie (1987).

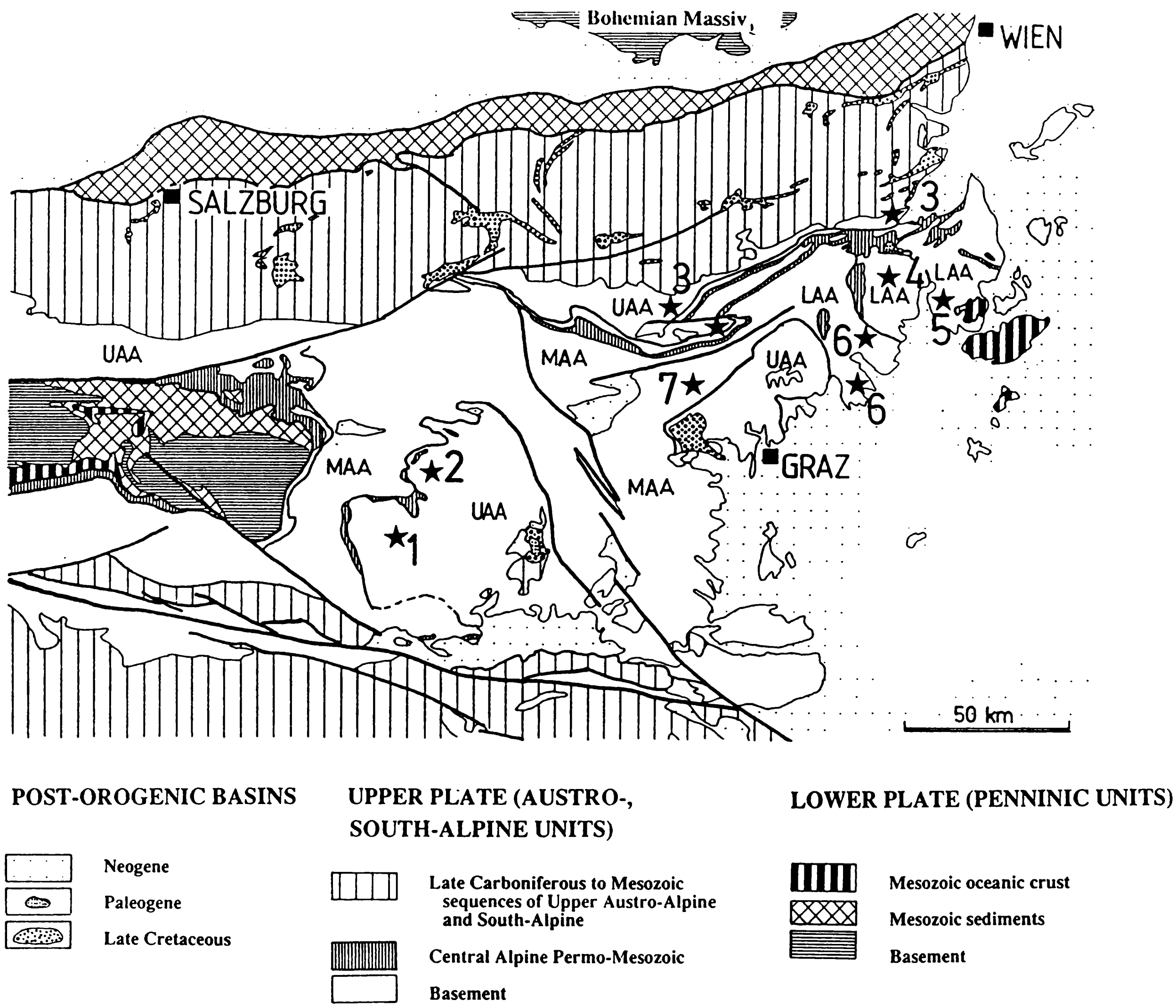

Fig. 1: Simplified tectonic map of the Eastern Alps with locations of $^{40}Ar/^{39}Ar$ and Rb-Sr mineral dating: 1 - Ordovician/Silurian sandstones of the Gurktal Thrust System; 2 - Ackerl Complex; 3 Kaintaleck Complex; 4 - Wechsel Complex incl. surrounding Raabalpen Complex; 5 - Sieggraben Unit; 6 - southern Raabalpen Complex; 7 - Gleinalm dome. LAA - Lower Austro-Alpine unit; MAA - Middle Austro-Alpine Unit; UAA - Upper Austro-Alpine Unit.

Two categories of uncertainties are encountered in $^{40}Ar/^{39}Ar$ incremental release dating. One group involves intralaboratory uncertainties related to measurement of the isotopic ratios used in the age equation. The other group considers interlaboratory uncertainties in the other parameters used in the age equation (monitor age, J-value determination, etc.), and are the same for each gas increment evolved from a particular sample. Therefore, to evaluate the significance of potential incremental age variations within a sample, only intralaboratory uncertainties should be considered. These are reported here, and have been calculated by statistical propagation of uncertainties associated with measurement of each isotopic ratio (at two standard deviations of the mean) through the age equation. Interlaboratory uncertainties are c. +/- 1.25 - 1.5% of the quoted age. Total-gas ages have been computed for each sample by appropriate weighting of the age and percent ^{39}Ar released within each temperature increment. A "plateau" is considered to be defined if the ages recorded by two or more contiguous gas fractions each representing > 4% of the total ^{39}Ar evolved (and together constituting > 50% of the total quantity of ^{39}Ar evolved) are mutually similar within a +/- 1% intralaboratory uncertainty. Analysis of the MMhb-1 monitor indicates that apparent K/Ca ratios may be calculated through the relationship 0.518 +/- 0.005 x $^{39}Ar/^{37}Ar$ corrected.

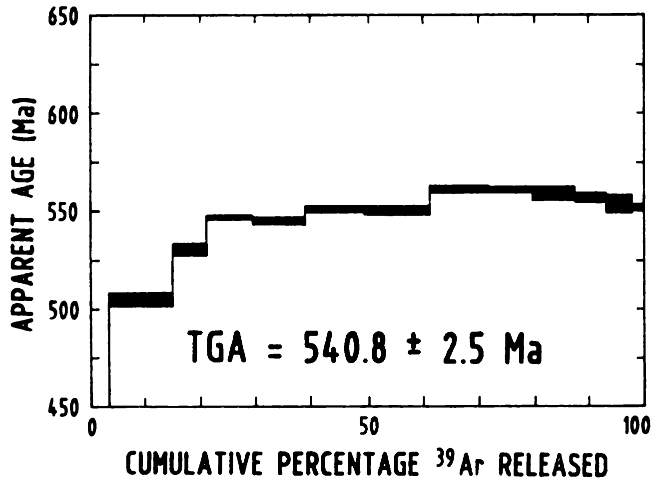

Fig. 2: $^{40}Ar/^{39}Ar$ release spectrum of detrital muscovites from a Late Ordovician/Silurian(?) sandstone of the Gurktal Thrust System. TGA - total gas age.

Plateau portions of the analyses have been plotted on $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlation diagrams (Roddick et al., 1980, Radicati de Brozolo et al., 1981). Regression techniques followed the methods of York (1969). A mean square of the weighted deviates (MSWD) is the statistical parameter which has been used to evaluate isotopic correlations. Roddick (1978) suggests that an MSWD > c. 2.5 indicates scatter about a correlation line greater than that which can be explained only be experimental errors.

The Rb-Sr mineral dating was carried out at the Laboratory of Geochronology, Arsenal, Vienna. For analytical methods, see Thöni (1986).

Age of detrital micas in Early Paleozoic sandstones (UAA)

Detrital muscovite within Late Ordovician sandstones exposed in the Carnic Alps (South-Alpine Unit), yielded convincing evidence of Cadomian (ca. 620 Ma) cooling in the source region (Dallmeyer and Neubauer, in prep.). In continuation of this study, a muscovite concentrate from an Ordovician/Silurian sandstone of the the Gurktal Thrust System was examined. The $^{40}Ar/^{39}Ar$ analysis yielded an internally discordant age spectrum (Fig. 2). Intermediate and high-temperature increments recorded mutually similar aparent ages corresponding to a c. 560 Ma plateau. Systematically increasing ages were recorded at low experimental temperatures. These suggest that a slight loss of 40Ar occurred during a relatively low-grade thermal overprint in the late Paleozoic. We interpret the high temperature increments as the minimum age of post-metamorphic cooling after a late Cadomian tectonothermal event in the source region and the low temperature increments as combined effects of Variscan/Alpine metamorphic overprints. The Variscan/Alpine metamorphic overprints apparently did not exceed c. 375 - 400^{o} C.

Timing of pre-Alpine tectonothermal events in the eastern Greywacke Zone (UAA)

Mineral dating within the pre-Variscan Kaintaleck Complex was carried out to evaluate previous U-Pb zircon data which recorded tectonothermal events at ca. 520-500 Ma and ca. 390-360

Ma (for compilations, see, Neubauer and Frisch, in press). However, $^{40}Ar/^{39}Ar$ and Rb-Sr mineral dating on muscovites and amphiboles confirm a middle Paleozoic event in the Kaintaleck Complex (Fig. 3). For example, a highly discordant amphibole spectrum yielded a total gas age of ca. 547 Ma. Amphiboles of two further samples yielded more or less similar Ar release spectra but with quite younger ages. Both analyses suggest cooling after amphibolite facies metamorphism at or about 420 Ma. Therefore, the high age of the 547 Ma amphibole mentioned above is caused by a high component of extraneous ^{40}Ar.

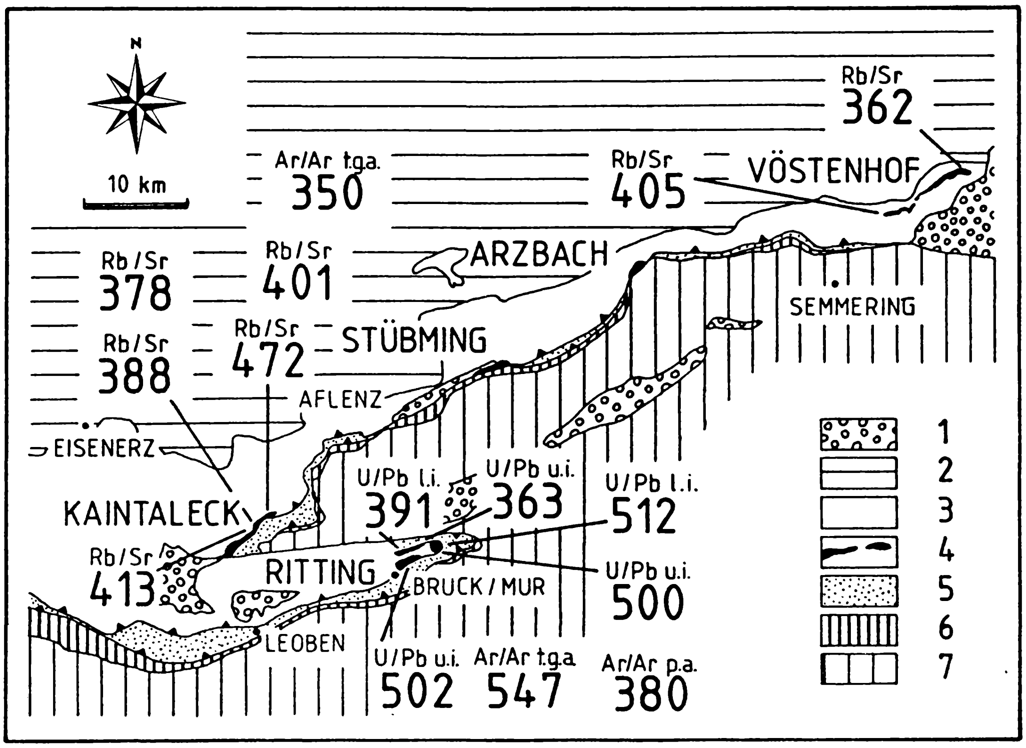

Fig. 3: Mineral ages [Ma] of the Kaintaleck Complex. Legend: 1 - Neogene basins, 2 - Mesozoic cover of the Upper Austro-Alpine Unit, 3 - Noric Nappe, 4 - Kaintaleck Complex, 5 - Silbersberg and Veitsch Nappe, 6 - Mesozoic cover of the Middle Austro-Alpine unit, 7 - Middle Austro-Alpine basement. Rb/Sr: two-point isochron age; Ar/Ar: p.a. - plateau age, t.g.a. - total gas age; U/Pb: u.i. - upper intercept, l.i. - lower intercept.

Muscovite from a foliated micaschist yielded a 472 +/-2 Ma Rb-Sr age, which probably reflects a "Cadomian Sr memory". All other muscovites from micaschists yielded Rb-Sr whole-rock mineral ages between 413 +/-3 Ma and 401 +/-3 Ma. $^{40}Ar/^{39}Ar$ analysis from the same samples displays an internally discordant age pattern, ranging from c. 375 Ma in high temperature portions to c. 290 Ma low-temperature portions of the experiment. A total gas age of 350 +/-2 Ma is similar to the Rb-Sr age. Muscovites of pegmatites within these crystalline slices yielded Rb-Sr two point isochron ages of 388 +/-4 Ma and 378 +/-4 Ma. That suggests intrusion of the pegmatites postdated penetrative ductile deformation and metamorphism. The significance of a muscovite Rb-Sr age from a highly deformed aplitic gneiss (362 +/-13 Ma) is uncertain.

These data argue for a peak of amphibolite-facies metamorphism in the Ritting and the Prieselbauer Subunits reached prior to c. 410 Ma (the time when the closure temperature of 500-550°C for Rb-Sr in phengitic white micas which was reached). Peak metamorphic conditions were followed by slow cooling to ca. 250-350°C (Ar-closure temperature for muscovites at c. 380 Ma. This was followed by intrusion of pegmatites and aplitic veins. The amphibolite-facies metamorphism was preceeded by a high-pressure event with formation of the eclogites in Ritting Subunit. The age of this metamorphic event has not been constrained.

The data indicate a possible paleogeographic linkage of protoliths Carboniferous clastic sequences of the Veitsch Nappe with portions of the Kaintaleck Complex. This is indicated by the age of detrital white micas which were deposited in phyllitic sequences of the Veitsch Nappe during the Carboniferous.

Timing of tectonothermal events in the Wechsel Window and surrounding units of the Raabalps (LAA)

The eastern part of the LAA is characterized by two contrasting tectonostratigraphic subunits. The Wechsel Unit forms the footwall and the Raabalpen Unit comprised the hangingwall. Both consist of Variscan basement and Permo-Mesozoic cover rocks (Tollmann, 1977). They are separated by an Alpine thrust fault (Mesozoic slices occur within this fault). Because of the lower greenschist facies metamorphism recorded in all cover rocks (quartzites and marbles), the metamorphism of the basement rocks in both units has also been considered to be of Alpine age. However, new Rb/Sr and $^{40}Ar/^{39}Ar$ mineral age data led to the following conclusions (Fig. 4):

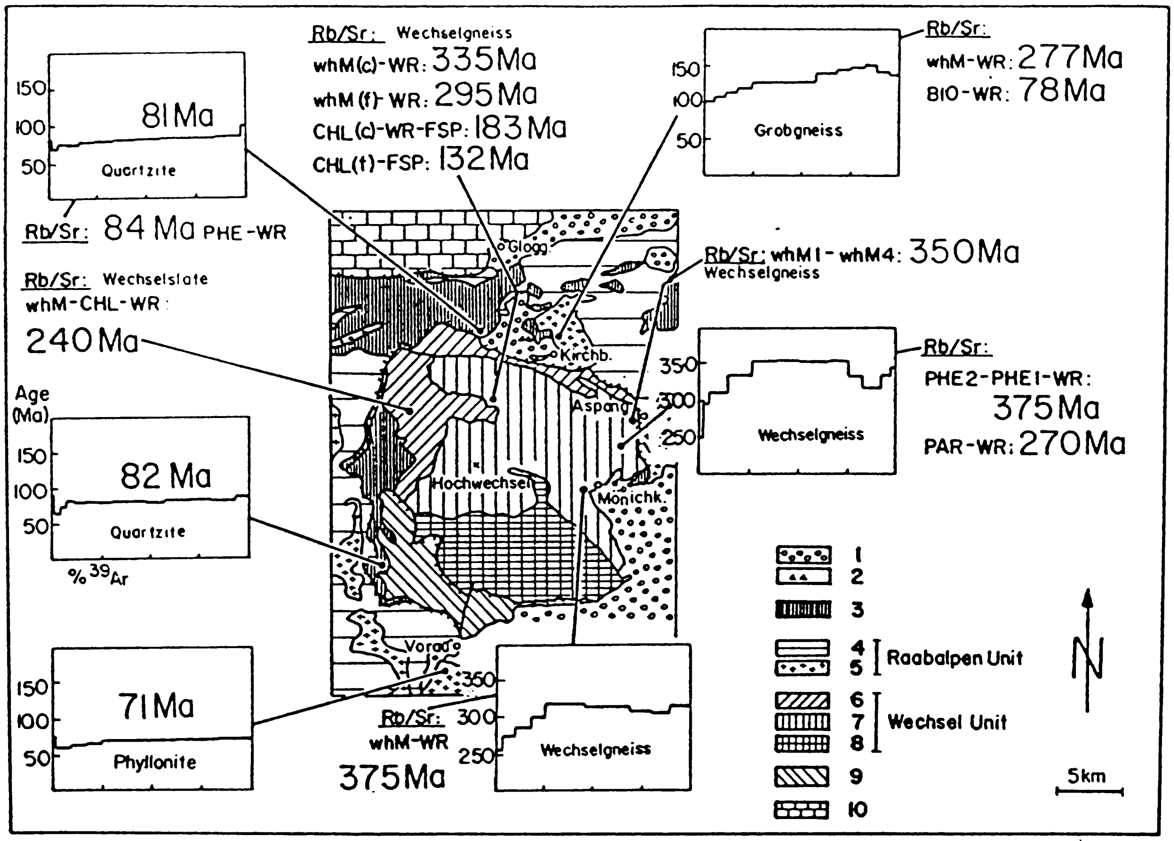

Fig. 4: Sketch map of the Wechsel Window and the surrounding Raabalpen Unit with recent Rb-Sr and $^{40}Ar/^{39}Ar$ mineral ages. Legend: 1 - Neogene deposit; 2 - Eocene limestone; 3 - Permo-Mesozoic cover (both units); 4 - phyllitic micaschist; 5 - Grobgneiss; 6 - Wechsel Phyllite; 7 - Monotonous Wechsel Gneiss; 8 - Variegated Wechsel Gneiss; 9 - Waldbach Unit; 10 - Northern Calcareous Alps. whM - white Mica; PHE - phengite; PAR - paragonite; BIO - biotite; CHL - chlorite; FSP - feldspar; WR - whole rock; 1,2,4 - different magnetic fractions; f - fine-grained; c - coarse-grained.

1) Phengitic white mica (Si content 3.5 (core) and 3.25 (rim)) indicate an initial high pressure metamorphism at c. 370 - 380 Ma (Late Devonian). This is represented by the highest Rb/Sr ages, recorded within the Wechsel Unit.

2) A large scatter of Rb/Sr (same Sr initial ratios of 0,71) and $^{40}Ar/^{39}Ar$ ages is interpreted to reflect very slow cooling rates (closing temperatures reached at different places at different times).

3) A late "Variscan" (270-240 Ma, Upper Permian) metamorphism can be inferred from: 1) Rb/Sr ages of paragonitic white mica (Wechsel gneisses); 2) Rb/Sr mineral isochron (white mica - chlorite - whole rock of the Wechsel Phyllites); 3) c. 250 Ma $^{40}Ar/^{39}Ar$ ages recorded by low temperature increments of discordant age spectra.

4) The age of ductile, top-to WNW shearing recorded both in basement and cover rocks remains unknown. Despite similar kinematics, an Alpine age appears unlikely because of the undisturbed Variscan mineral ages recorded in the basement.

5) Alpine metamorphic conditions in the Raabalpen Unit must have been slightly higher than in the Wechsel Unit because: 1) Alpine Rb/Sr ages recorded in biotite; 2) more strongly rejuvenated $^{40}Ar/^{39}Ar$ white mica system; 3) growth of small garnets within instable Ca-rich plagioclase.

7) Early Alpine metamorphism of the cover rocks is recorded in similar Rb/Sr and 40Ar/39Ar ages of c. 80 Ma, which are interpreted to date formation of new-grown phengitic white mica (Si content approximately 3.3).

Timing of metamorphism in the Ackerl Gneiss Complex (UAA)

The Ackerl Gneiss is part of a UAA amphibolite facies basement nappe in the northwestern Gurktal Thrust Complex (UAA; Fig. 1; Neubauer, 1980). $^{40}Ar/^{39}Ar$ release spectra of two muscovite concentrates yield corresponding plateaus of ca. 310 Ma with minor Alpine loss of radiogenic argon (Fig. 5). The data prove Late Carboniferous cooling of the Ackerl Gneiss Complex and Early Alpine emplacement of this basement nappe as one of highest nappes within the AANC.

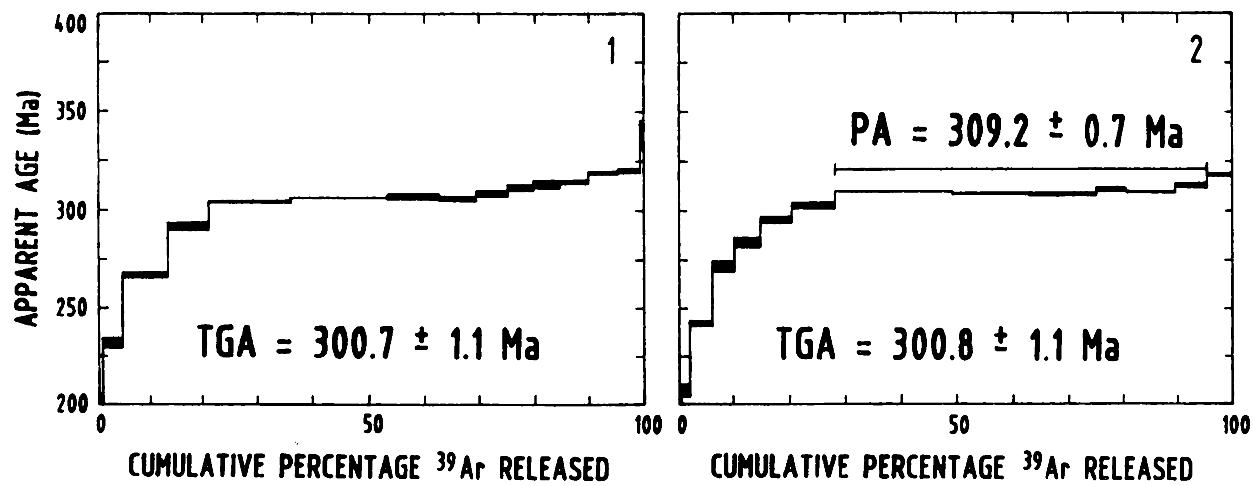

Fig. 5: $^{40}Ar/^{39}Ar$ release spectra of two white mica concentrates of the Ackerl Gneiss Complex. ICA - isotope correlation age; PA - plateau age; TGA - total gas age.

Timing of Early Alpine metamorphism and thrusting sequence in the AANC

The AANC is a large-scale internally imbricated thick-skinned nappe stack comprised of both thick basement and thin cover sequences (Fig. 1). Three major nappe complexes are distinguished from paleogeographic south to north: Upper Austro-Alpine (UAA), Middle Austro-Alpine (MAA), Lower Austro-Alpine (LAA). As already mentioned above, although these individual nappe complexes include distinct basement units which are covered by similar "Central Alpine" Permo-Triassic terrestrial and shelf sequences, these units record contrasting Alpine tectonothermal evolution.

Previous models have explained intra-Austro-Alpine nappe imbrication in terms of a Middle-Cretaceous collision between a Middle-Penninic microcontinent and the Apulian microplate (with its northern extension, the Austro-Alpine unit). Of special interest are, therefore, our new results from the Sieggraben Structural Unit. The Sieggraben Structural Unit is a tectonic klippe of the MAA exposed along eastern margins of the Alps (Fig. 1, location 5; Tollmann, 1978). It is a tectonic melange which includes eclogite-bearing metamorphic units containing both ophiolite-like fragments (retrogressed N-MORB type eclogites and serpentinites) and supracrustal, probably pre-Alpine continental rocks. Inclusions of hornblende and epidote in eclogite-facies garnets suggest that an initial epidote amphibolite facies assemblage dehydrated to eclogite. P-T conditions maintained during eclogite formation were c. 670-750° C and 14-16 Kb (based on garnet-clinopyroxene and jadeite-bearing assemblages). Retrogression of eclogite included: 1) replacement of eclogitic omphacite by sodic augite; 2) development of sodic plagioclase symplectite; and, 3) formation of epidote-hornblende bearing assemblages. The symplectite formed at c. 500-600° C and c. 6-9 Kb.

$^{40}Ar/^{39}Ar$ analyses of two concentrates of hornblende within retrograde assemblages yield similar internally-discordant age spectra (Fig. 6). Most intermediate-temperature increments record similar apparent ages. Isotope correlation of these data yielded plateau isotope correlation ages of 136.1 +/- 0.5 Ma and 108.2 +/- 0.3 Ma. These date the last cooling through c. 500° C.

Alternative models to explain similar late Jurassic - Cretaceous mineral ages which are recorded throughout the Austro-Alpine Thrust Complex include: 1) The Sieggraben Unit represents a basement nappe which was buried and remetamorphosed during Cretaceous A-subduction and associated imbrication within the Austro-Alpine Nappe Complex; and, 2) The Sieggraben Unit initiated within a Permo-Mesozoic ophiolitic suture zone during Mesozoic plate collision. The record of Cretaceous ages and high-pressure assemblages argue for development of the Sieggraben Unit within a Jurassic-Cretaceous subduction zone which likely entrained significant portions of Austro-Alpine crust.

New $^{40}Ar/^{39}Ar$ and Rb-Sr mineral ages (white mica, biotite and amphibole) together with previously reported geochronological results from other AANC units (Frank et al., 1987; Fritz, 1988) range between c. 140 to 70 Ma (Figs. 3, 4, 6, 7, 8, 9). Systematic regional variatios in mineral ages combined with characteristics of Alpine metamorphic zonation display the following trends:

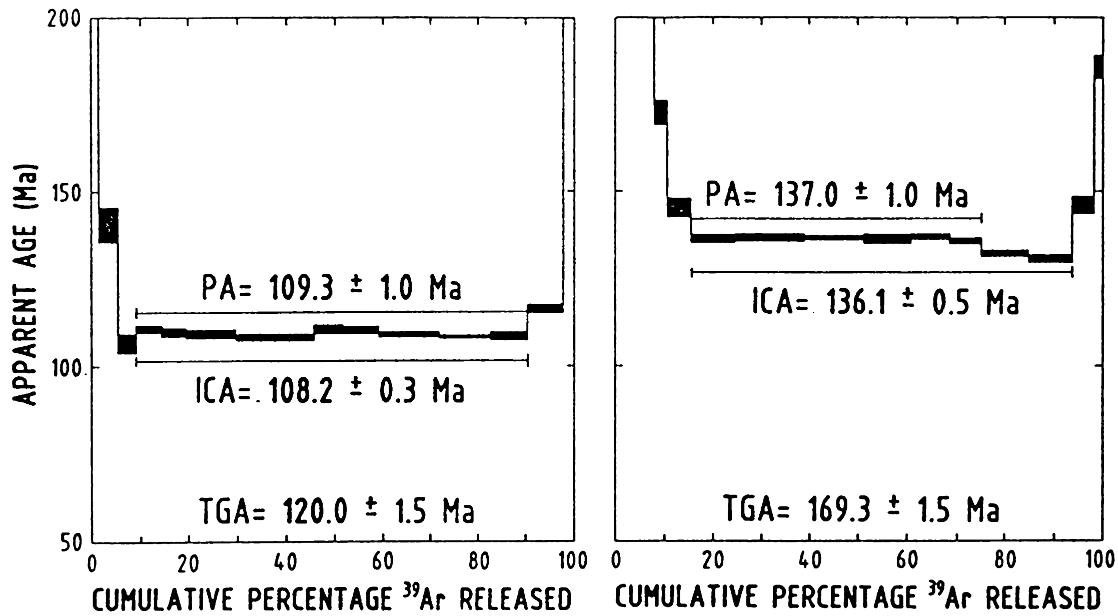

Fig. 6: $^{40}Ar/^{39}Ar$ amphibole age spectra of two retrogressed eclogites from the Sieggraben unit (Zöberndorf quarry; Schäffern klippe). ICA - isotope correlation age; PA - plateau age; TGA - total gas age.

(1) The extent of Alpine metamorphic overprint increases from greenschist metamorphic facies (north) to amphibolite facies conditions (south) in both LAA (Fig. 7) and MAA units. Correspondingly, confining thrust surfaces climb NW-ward from basement units to cover sequences. These relationships may reflect thrust propagation by splays of a deep-crustal, intra-continental master thrust.

(2) Mineral ages generally young from hangingwall to footwall nappe units (UAA: 140 - 125 Ma; MAA: 140 - 80 Ma; LAA: 125 - 70 Ma). This pattern likely reflects footwall propagation of the master fault and associated piggy-back transport of hangingwall structural units.

(3) Both, the basal MAA thrust and an important internal thrust within the LAA (between the Wechsel Unit in the footwall and the Raabalpen unit in the hangingwall) must represent an out-of-sequence thrusts, because they transported deep-crustal Alpine metamorphic sequences over units which were not penetratively affected by Alpine tectonothermal activity.

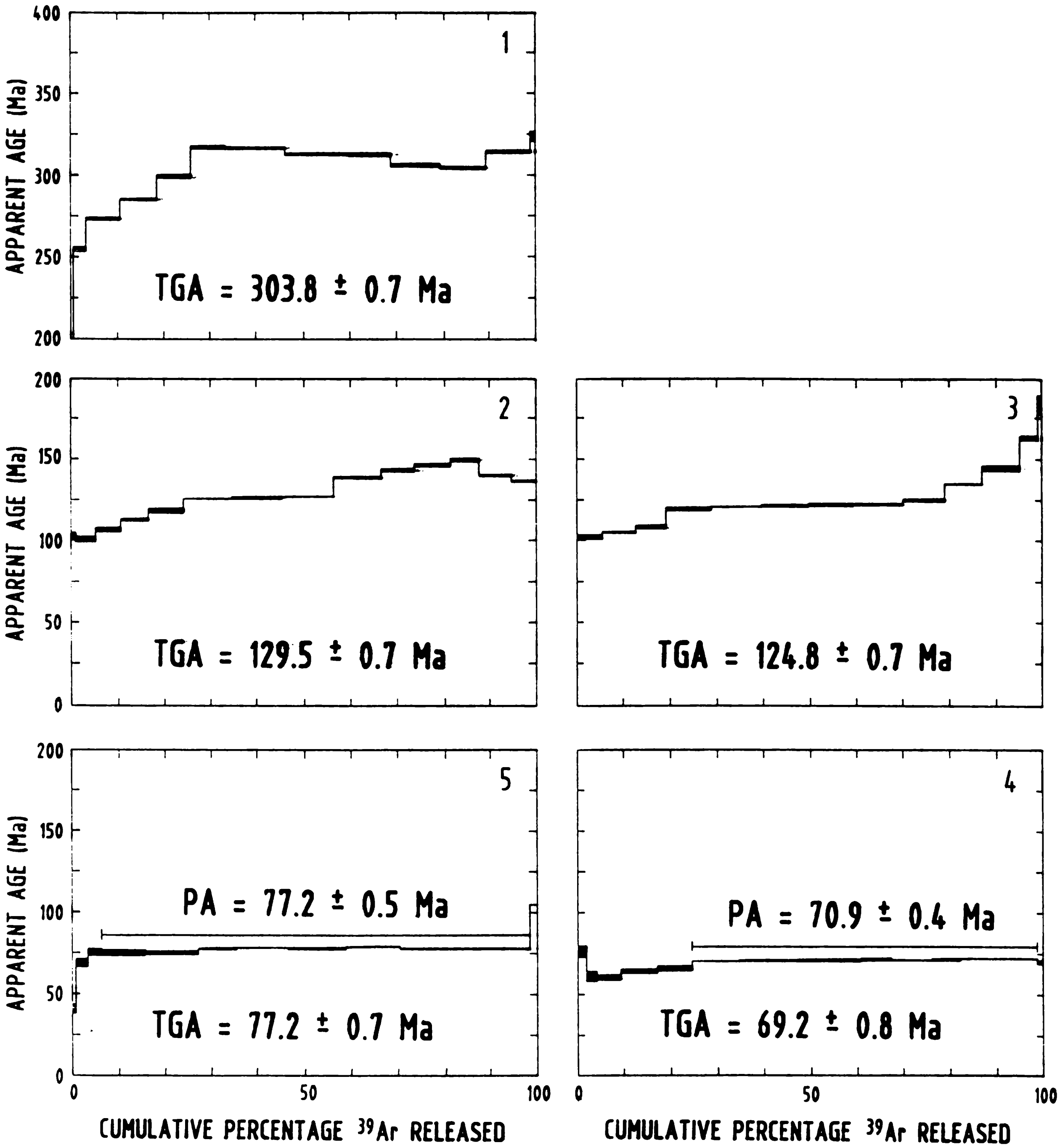

Fig.7: $^{40}Ar/^{39}Ar$ release spectra of the Raabalpen Unit (LAA). ICA - isotope correlation age; PA - plateau age; TGA - total gas age.

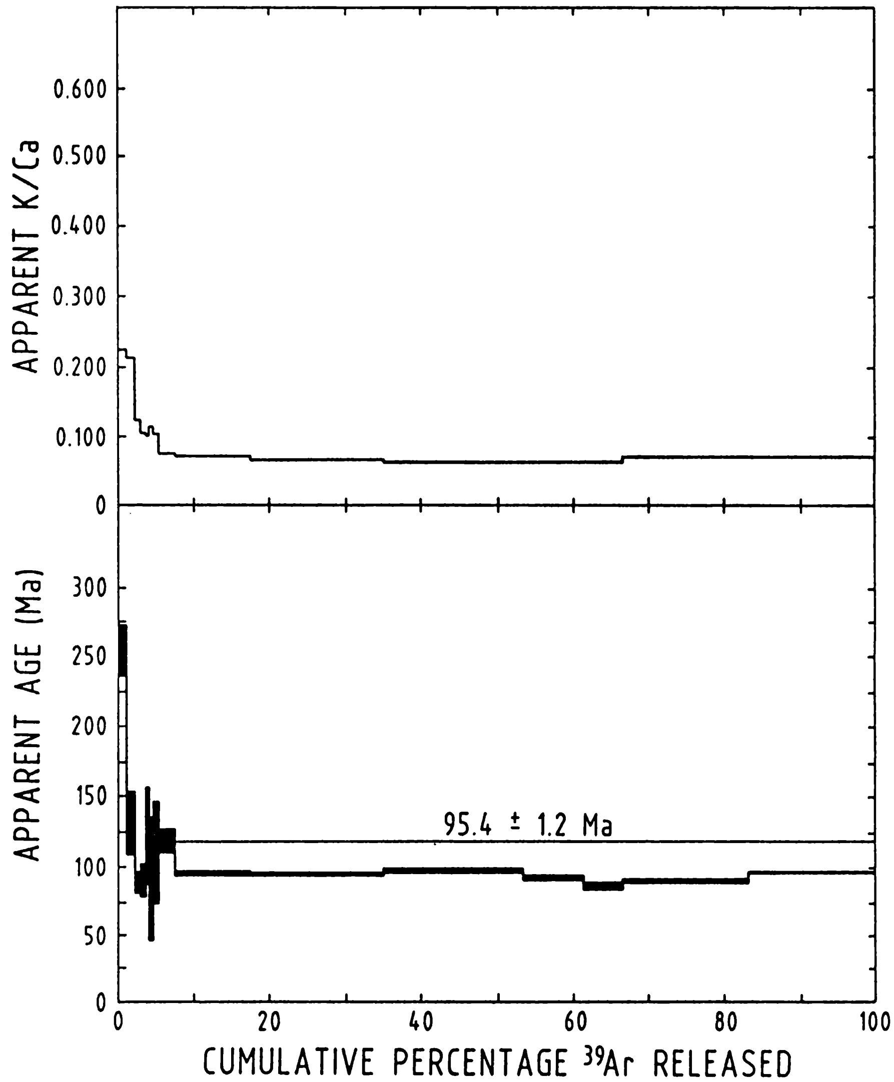

Fig. 8: $^{40}Ar/^{39}Ar$ release spectrum of a hornblende from the Humpelgraben quarry, Gleinalm dome.

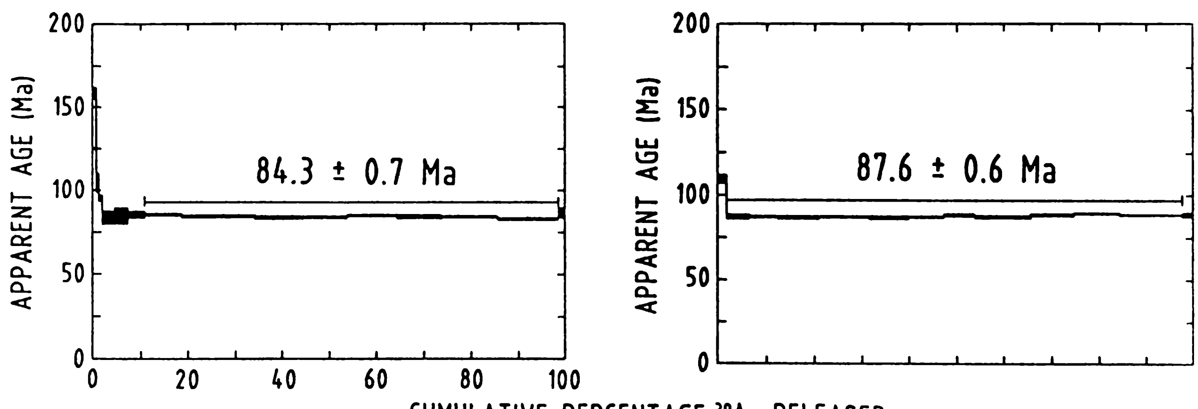

Fig. 9: $^{40}Ar/^{39}Ar$ release spectra of two muscovites (1 - Humpelgraben quarry; 2 - Neuhof valley), Gleinalm dome.

All these data suggest that the Austro-Alpine unit records Alpine metamorphism and deformation typical for a lower continental plate position during continent-continent collision. This is compatible with accepted paleogeographic restorations which indicate that a Triassic/Jurassic basin (probably associated with oceanic crust) developed SE of the Alpine continental fragment (e.g., Decker et al., 1987). Additionally, a zone of probable crustal thinning may occur between LAA and MAA units. Major Alpine thrust surfaces may correspond to pre-Alpine faults, which initially separated contrasting basement tectonic units and which were variably reactivated as Alpine thrust faults.

Cretaceous cooling of the Gleinalm metamorphic dome (MAA)

The metamorphic Gleinalm dome, part of the Middle Austro-Alpine Nappe Complex of the Eastern Alps, was exhumed during the Late Cretaceous in an overall sinistral wrench corridor (Fig. 10). Confining ductile shear zones form a system of low angle faults which is bounded by steep sinistral tear faults forming a large relais with the metamorphic dome in the center (Neubauer and Genser, 1988). Fabrics within all ductile shear zones suggest development during a decreasing temperature regime (from lower amphibolite/upper greenschist facies conditions with crystal plastic fabrics of quartz to cool temperatures below 300°C with exclusively cataclastic fabrics without crystal annealing; Neubauer, 1988). A cooling path based on $^{40}Ar/^{39}Ar$ ages of amphibole (Fig. 11), muscovite (Fig. 12) and fission track ages of sphene and zircon together with Rb-Sr mineral ages from Frank et al. (1976) indicate cooling through c. 500°C at 94 Ma to below c. 225°C at 65 Ma (Fig. 11).

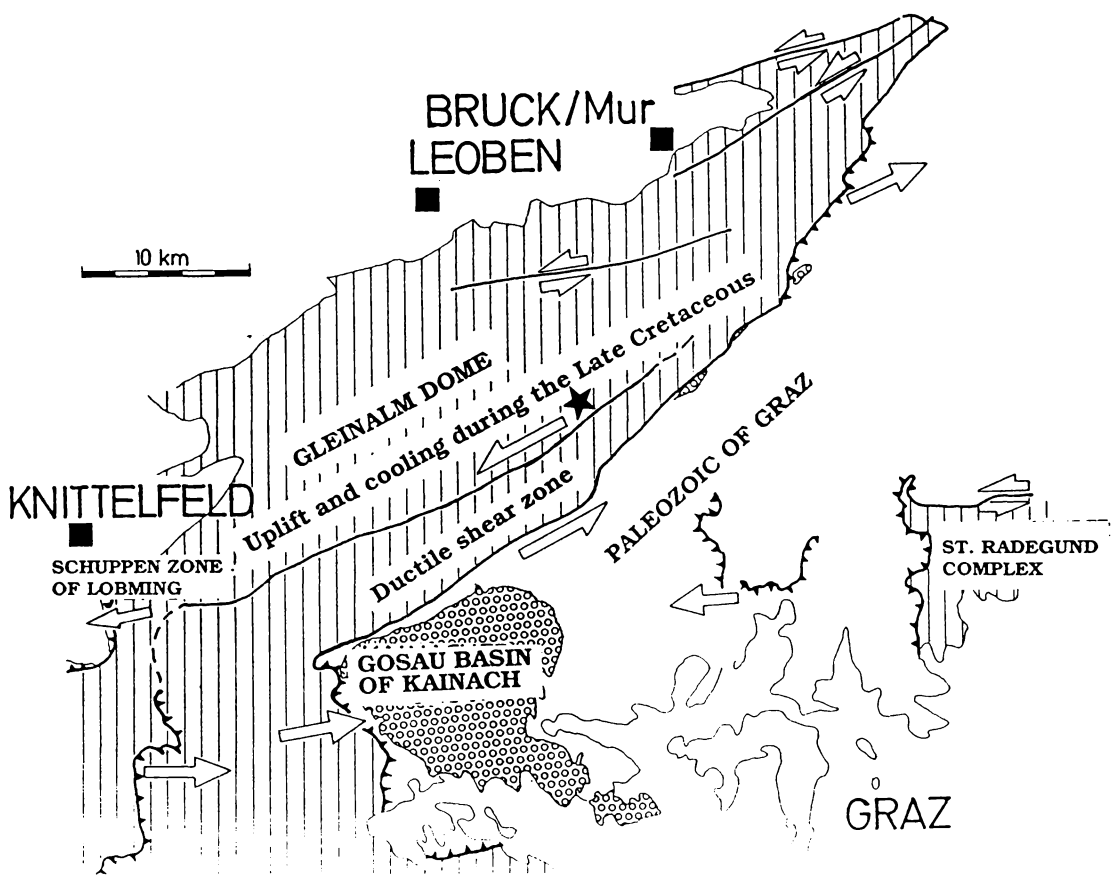

Fig. 10: General structure of the Gleinalm metamorphic dome and adjacent areas including the Late Cretaceous basin of Kainach. Asterisk marks location of samples which are used for construction of the cooling path of Fig. 11.

Subsidence of the adjacent Late Cretaceous Kainach basin (the Gosau basin within the same tectonic frame) was synchronous with cooling and exhumation of the Gleinalm dome. Internal depositional patterns display sharp subsidence at the time of cooling with internal synsedimentary block rotation.

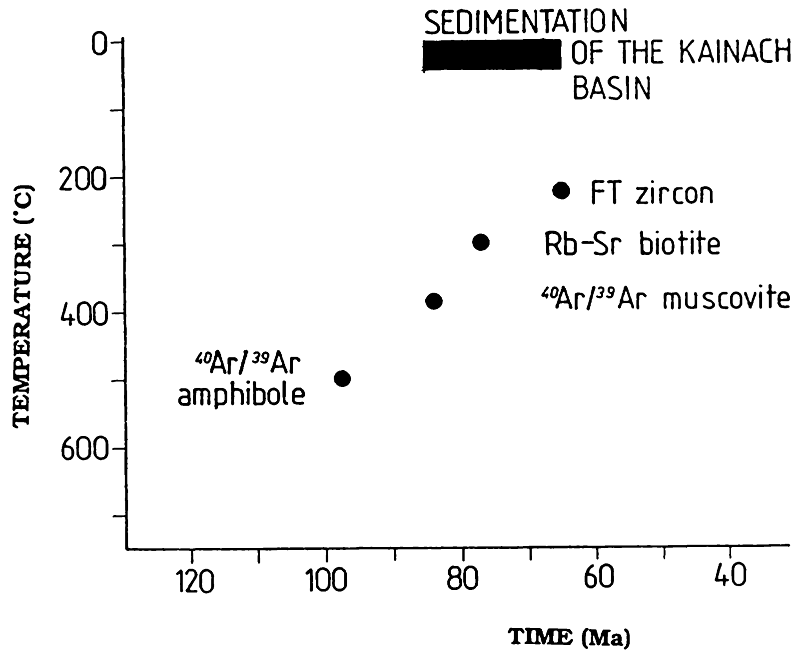

Fig. 11: Cooling path of the Core complex of the Gleinalm dome. All data are from one locality (Humpelgraben quarry).

Discussion

$^{40}Ar/^{39}Ar$ and Rb-Sr mineral ages suggest that several distinct tectonothermal events affected the Austro-Alpine Nappe Complex. $^{40}Ar/^{39}Ar$ ages of detrital muscovite from the Carnic Alps and the Gurktal Thrust System emphasize the significance of Late Precambrian (Cadomian) metamorphic and/or plutonic sequences in the source regions of Early Paleozoic shelf deposits (part of the Noric terrane: Frisch and Neubauer, 1989). However hints of significant differences in precise ages (early and late Cadomian) may reflect distinct Cadomian basement structural units. Neubauer (1985) interpreted the Kaintaleck Complex as a basement to Ordovician to Early Carboniferous shelf sequences of the Noric terrane. U-Pb zircon analyses from several rocks of the Kaintaleck Complex indicated two distinct complexes with two age groups (520 - 500 Ma, and 400 - 360 Ma) which were interpreted as two distinct metamorphic complexes. Rb-Sr white mica, hornblende and muscovite $^{40}Ar/^{39}Ar$ ages range from 470 to 360. These suggest a tectonothermal evolution for major portions of the Kaintaleck Complex which, thus, cannot constitute a primary basement to the Noric composite terrane. Lithologies of the Kaintaleck Complex are part of a contrasting terrane ("Pannonian terrane" of Frisch and Neubauer, 1989) which is defined by a record of Silurian/Devonian metamorphism. The new data from the Wechsel Gneiss Complex (intra-Devonian ages) confirm correlation of this tectonostratigraphic unit with the "Pannonian" terrane.

The "classical" timing of the Variscan orogeny (Late Variscan orogeny) with c. 310 Ma is confirmed by the muscovite ages of the Ackerl Gneiss Complex. This unit might have been part of a Variscan lower plate which collided during Carboniferous with other Austro-Alpine basement complexes.

Permian ages (ca. 260 - 240 Ma) are recorded in the Wechsel and Raabalpen units and might have been related to post-Variscan extension leading to formation of the Tethyan shelf (Late Permian - Triassic). In this sense, the Wechsel data may record low temperature activity along a ductile shear zone (low angle normal fault) which separates Wechsel gneisses from Wechsel phyllites. Permian volcanic, and also plutonic activity, could have resulted in higher geothermal gradients.

Alpine tectonothermal activity recorded within the Austro-Alpine Nappe Complex reflects a long-lasting compression history more characteristic of a lower continental plate structural position than that of the upper plate suggested by previous geodynamic interpretations. Evidence for Alpine (pre-Late Cretaceous eclogite metamorphism with eclogites with pressures raging from 10 - 18 Kb (for data compilation, see Dallmeyer et al., in prep.).

The distribution of mineral data support footwall propagation of thrusts from early thrusting (ca. 140 - 110 Ma) within the UAA, and later overriding the LAA by the MAA thrust sheets between ca. 110 and 90 Ma which is followed by a period of extension in both MAA and LAA units (ca. 85 - 65 Ma).

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LATE PALEOZOIC OVERSTEP SEQUENCES OF THE EASTERN AND SOUTHERN ALPS

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Introduction

In the Eastern and Southern Alps Late- to Post-Variscan sedimentation processes started during the Late Carboniferous (Late Moscovian/Cantabrian). The Late- to Post-Variscan Molasse sediments of the Eastern and Southern Alps were deposited in NE - SW and E - W to ESE - WNW oriented intramontane basins which probably formed as a result of crustal thinning associated with strike-slip tectonics along megashear zones due to the eastward drift of the Eurasian plate and westward drift of the African plate respectively.

Tectonic processes and climate, respectively climatic changes, were the most important controlling factors of sedimentation processes, and based on major tectonic and climatic events as well as on fossil assemblages a close correlation between the Late- to Post-Variscan sequences of the Eastern and Southern Alps is possible.

The Late- to Post-Variscan sequence of the Eastern and Southern Alps is divided into two evolutionary cycles, which are separated by a major intra-Permian tectonic event.

The lower cycle (Late Carboniferous/Early Permian) is characterized by the formation of intramontane basins which were filled with sediments of different environments including volcanic rocks. Transgressive-regressive clastic-carbonate cycles within the shallow marine sequence of the Carnic Alps (Southern Alps) are related to eustatic sea-level fluctuations caused by the Gondwana glaciation. The climatic shift from humid to semiarid conditions near the Carboniferous/Permian boundary caused a significant change in sedimentary processes in the continental sequences of the Eastern Alps.

During the upper cycle (?Middle - Late Permian to Early Triassic) sedimentation patterns were more uniform and similar sequences developed in the Southern and Eastern Alps. During this time sedimentation was characterized by the transgression of the Tethys Sea from SE to NW and interfingering of shallow marine sediments with continental deposits. Sedimentation processes were also influenced by a climatic shift near the Permian/Triassic boundary and sedimentary cycles of the Scythian are probably caused by different spreading rates of midoceanic ridges.

The question where to draw the boundary between the Late- to Post-Variscan Molasse sediments and the following Alpidic sedimentation cycle still remains open.

Eastern Alps

In the Eastern Alps, Late- to Post-Variscan sediments are found in all major tectonic units (Penninic Unit, Lower Austroalpine, Middle Austroalpine = Central Austroalpine, and Upper Austroalpine Unit). In the Penninic (Upper Schieferhülle), Lower and Middle Austroalpine Units the Late- to Post-Variscan sequence is very similar and composed of coarse- to fine-grained clastic sediments, in the lower (?Permian) part with intercalated rhyolithic volcanic rocks and reworked volcanic clasts.

All Late- to Post-Variscan sequences of the units mentioned above have been deformed and overprinted by Alpine metamorphism to phengite- and sericite-schists, arkose-schists and arkose-gneisses, quartzites and porphyroides.

Age and depositional environment of all these metasediments are not exactly known due to strong deformation and metamorphic overprint. Further informations are found in Frasl and Frank

(1966), Frank (1972) (Penninic Unit); Tollmann and Faupl (1972), Tollmann (1964) (Lower Austroalpine Unit); Claasen et al. (1987), Krainer (1984), Krois and Stingl (1989), Schünemann et al. (1982) (Middle Austroalpine Unit), for summaries see also Tollmann (1964, 1972, 1977), Oberhauser (1980).

Upper Austroalpine Units

Although Late to Postvariscan sedimentation within the Upper Austroalpine Unit of Carboniferous (Stephanian) age are known from a few places (at the NW-margin of the Gurktal Nappe, the Steinach Nappe), bulk sedimentation did not start before the Earliest Permian (see Fig. 1).

Major progress in stratigraphy and depositional history has been achieved by extensive investigations in recent years (for example Angerer et al. 1976, Haditsch et al. 1978, Niedermayr and Scheriau-Niedermayr 1982, Stingl 1982, 1983, 1984, 1987, 1989, Mostler and Rossner 1984, Krainer 1982, 1985, 1987a,b, 1989a,c,d, 1990a,b, Krainer and Spötl 1989, Krainer and Stingl 1986, Niedermayr 1975, 1985, Poscher 1985, Sylvester 1989a,b).

Late Carboniferous - Early Permian (Lower Cycle)

The best exposed example of Late Carboniferous sediments, which has been intensively studied during the last years, is the Stangnock Formation at the NW-margin of the Gurktal Nappe (Krainer 1989a, c and references therein, Fritz, Boersma and Krainer 1990).

The Stangnock Formation comprises a sequence of more than 400m thick intramontane Molasse sediments and can be divided into 3 units:

A basal sequence consists of polymict conglomerates rich in gneiss clasts, and intercalated immature, coarse-grained sandstones (feldspathic lithic arenites). These sediments are interpreted as deposits of a proximal fluvial system.

The main part of the Stangnock Formation (Hauptserie) is built up by a few, indistinctly developed megasequences. At the base, these megasequences are characterized by a sharp, erosive boundary, starting with sediments of a gravelly braided river system, grading upwards into a gravel-sandstone facies, frequently showing features of a meandering river system. At the top of these sequences usually dark shales with thicknesses up to a few meters occur, which contain abundant, well preserved plant fossils. The shales, interpreted as overbank fines deposited on flood plains and in oxbow lakes, sometimes are overlain by thin anthracite seams.

Conglomerates are very rich in quartz clasts (>90%), sandstones are classified as moderately sorted, subangular lithic arenites and sublitharenites, subordinate lithic wackes, all containing high amounts of polycrystalline quartz.

The top sequence (Hangendserie) shows similar features, slight differences exist concerning the composition of the sediments: sandstones contain volcanic rock fragments, esp. volcanic quartz, referring to first volcanic activity during the Late Carboniferous in this area.

On account of current directions which show a significant eastward trend, it is concluded that the intramontane basin developed in an approximately east-west direction.

The sharp erosive base of the megasequences within the main sequence and top sequence is referred to synsedimentary fracture tectonics (block faulting).

Plant fossils (72 different taxa), which have been studied from more than 20 localities (summary in Fritz, Boersma and Krainer 1990) indicate that the Stangnock Formation is of Stephanian age.

The Stangnock Formation is overlain by Early Permian red beds (Werchzirm Formation).

Within the small Upper Austroalpine Steinach Nappe in western Austria (Tyrol) Late Carboniferous (Stephanian) sediments overlie the presumably Early Paleozoic Steinach Quartzphyllite, a diaphthoritic overprinted metamorphic complex (Frizzo and Visona 1981).

The poorly exposed Stephanian sequence is composed of various channel-, bar- and overbank sediments and thin anthrazite seams which have been mined. The composition is very similar to the sediments of the Stangnock Formation: Conglomerates are again very rich in quartz clasts. Sandstones are classified as lithic arenites, sometimes as lithic wackes (Krainer 1990a, see also Schmidegg 1949, Karl 1956).

According to the depositional history and composition the Late Carboniferous (Stephanian) sequence of the Steinach Nappe is very similar to the Stangnock Formation, especially to the conglomerate-sandstone facies of the main sequence.

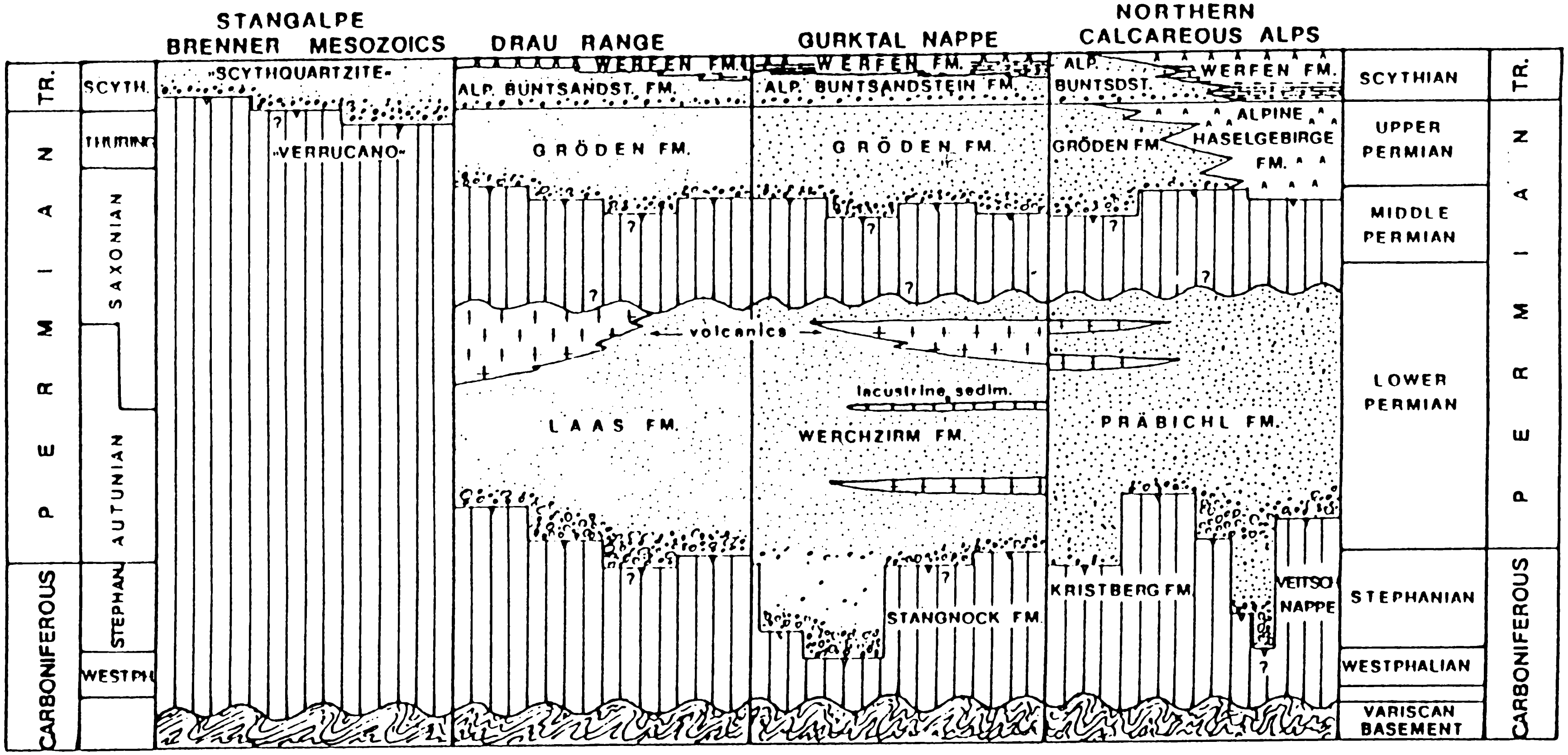

Fig.1: Schematic stratigraphic framework of late- to post-Variscan (Late Carboniferous to Early Triassic) sediments in some Austroalpine Units (Centralalpine and Upper Austroalpine). Legend see Fig. 3.

The Late Carboniferous sediments of the Steinach Nappe are also interpreted as intramontane Molasse sediments, which probably have been formed in the same basin system as the Stangnock Formation.

Shales contain plant fossils (about 30 different taxa are known) pointing to Early Stephanian (Cantabrian/Barruelian) age.

The Permian sequence of the Upper Austroalpine Unit, which rarely contains fossils, is divided into two lithostratigraphic units, separated by a major hiatus ("Saalian movements"): the Early Permian lithostratigraphic unit of the lower cycle, and the Late Permian lithostratigraphic unit of the upper cycle (see Fig. 2).

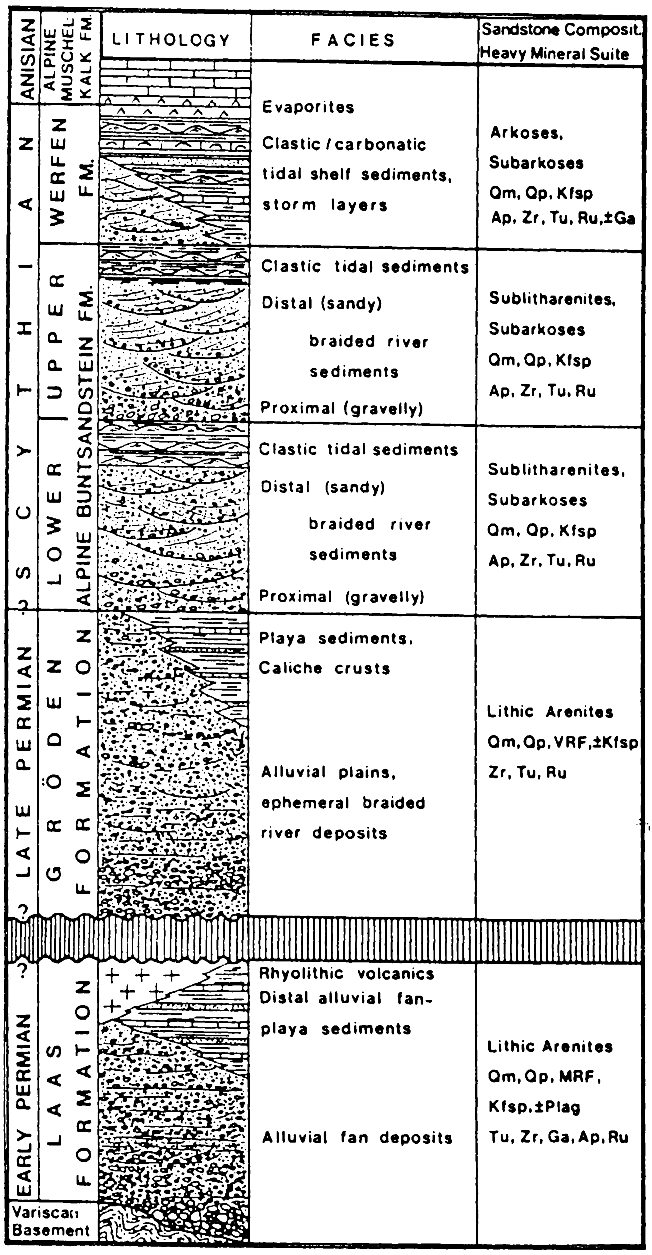

Fig.2: Generalized lithostratigraphic column of Permian and Early Triassic (Scythian) se-diments of the Drau Range with depositional environment, sandstone composition (Qm= monocrystalline, Qp= polycrystalline quartz, Kfsp= kalifeldspar, Plag= plagioclase, VRF= volcanic rock fragments, MRF= metamorphic rock fragments) and heavy mineral assemblages (Ap= apatite, Ga= garnet, Ru= rutile, Tu= tourmaline, Zr= zircon).

Proximal to distal alluvial fan sediments (red colored breccias, conglomerates, immature sandstones), grading into fine-grained sandflat-playa complexes with caliche-crusts and rare thin algal layers at some places, characterize the Early Permian throughout all tectonic units (Basalbreccia and Präbichl Formation in the Northern Calcareous Alps, Laas Formation in the Drau Range, Werchzirm Formation in the Gurktal Nappe, maximum thickness about 150m; see Krainer 1987b, 1989d, 1990b, Krainer and Stingl 1986 a,b, Niedermayr and Scheriau-Niedermayr 1982, Stingl 1983, Sylvester 1989a,b). In most cases, these sediments overlie the Variscan basement, which is formed of crystalline rocks. (schists, gneisses etc., Drau Range) or different, weakly metamorphosed Variscan sediments. At the NW-margin of the Gurktal nappe, Early Permian red beds overlie Late Carboniferous sediments (Stangnock Formation). The Early Permian sediments are rich in clasts derived from the local basement, especially weakly metamorphosed old Paleozoic rocks (polymict conglomerates, lithic arenites and wackes).

In some places plant fossils of the Callipteris conferta Zone are known from the base of this Early Permian sequence indicating lowermost Permian age (Van Amerom et al. 1982, Fritz and Boersma 1987a,b, 1988, Fritz, Boersma and Krainer 1990).

In the Drau Range, Gurktal Nappe and the westernmost part of the Northern Calcareous Alps, rhyolithic volcanics (ignimbrites and pyroclastic flows) with thicknesses up to about 100 m are widespread on top of this Early Permian sequence. From these volcanics no radiometric age determinations exist, but based on palynological data from lacustrine sediments within the equivalent Bolzano Volcanic Complex of the Southern Alps, the Early Permian sequence, including the rhyolithic volcanics, probably reaches up to Late Artinskian - Kungurian (Hartkopf-Fröder and Krainer 1990).

Late Permian - Early Triassic (Upper Cycle)

With a hiatus caused by block faulting ("Saalian movements"), Late Permian siliciclastic sediments (conglomerates, sandstones, shales of red bed type) of ephemeral braided rivers and playas termed Gröden Formation overlie Early Permian sediments and mark a sudden and significant change in sedimentation. This hiatus marks the boundary between the lower and upper cycle and is equivalent to that between the Bolzano Volcanic Complex and Gröden Formation or between the Trogkofel limestone and Tarvis breccia in the Southern Alps. The sediments of the Gröden Formation contain high amounts of reworked volcanic fragments derived from the volcanic rocks on top of the Early Permian sequence, and are lacking stratigraphically significant fossils (Krainer 1987b, 1989d, 1990b, Niedermayr and Scheriau-Niedermayr 1982, Stingl 1983, Sylvester 1989a,b). In the Drau Range and Gurktal Nappe the maximum thickness is about 350m, in the Northern Calcareous Alps about 800m.

In the central and eastern realm of the Northern Calcareous Alps a few hundred meters of halite-bearing marine evaporites were deposited in an approximately E-W-trending Late Permian rift, now represented by a strongly deformed decollement horizon at the base of the Northern Calcareous Alps (Spötl 1987, 1988a,b, 1989). Stratigraphical and paleoenvironmental data (S-isotopes of sulphate minerals, bromide content in halites, pollen and spores as well as scarce marine bivalves) unequivocally support a marine origin for this Late Permian evaporites ("Alpine Haselgebirge") (Spötl 1989).

The boundary between the late Permian Gröden Formation and Scythian Alpine Buntsandstein Formation is documented by an abrupt change in the depositional environment and composition of the sediments, caused by a climatic change to slightly more humid conditions. This boundary presumably corresponds to the Permian/Triassic boundary (Brandner et al. 1986, Krainer 1987a).

Based on transgressional and regressional events, the Scythian sequence of the Drau Range and Gurktal Nappe can be subdivided into three fining upward megasequences: Lower and Upper Alpine Buntsandstein Formation and Werfen Formation (Krainer 1985, 1987a).

Lower and Upper Alpine Buntsandstein Formations are built up by quartz- rich conglomerates of a gravelly braided river system, grading upward into small-scale fining-upward cycles of a sandy braided river system. Some sections contain clastic shallow-marine sediments developed on top. Compared to the Permian sandstones (uncemented, poorly sorted angular lithic arenites rich in volcanic fragments), Scythian sandstones are better sorted and rounded, well cemented by authigenic overgrowths of quartz and feldspar and carbonate cements in most cases, and contain more quartz and detrital feldspars. The heavy mineral composition also differs significantly. The regressive event at the base of the Upper Buntsandstein Formation can be compared with the regressive "Campill Event" in the Southern Alps based on palynomorphs. The dominantly siliciclastic sediments of the Werfen Formation, containing thin intercalated fossiliferous limestone beds, were deposited on a shallow-marine, tidally influenced epicontinental shelf.

Southern Alps

In the Southern Alps Late Carboniferous-Permian sediments lie on the variscan basement with a classical unconformity. This basement was folded and, in the western part, slightly metamorphosed during Westphalian times. Within the Late to Post-Variscan sedimentary sequence, two cycles can be recognized, which are separated by a main unconformity (Figs 3, 4; see Massari 1986).

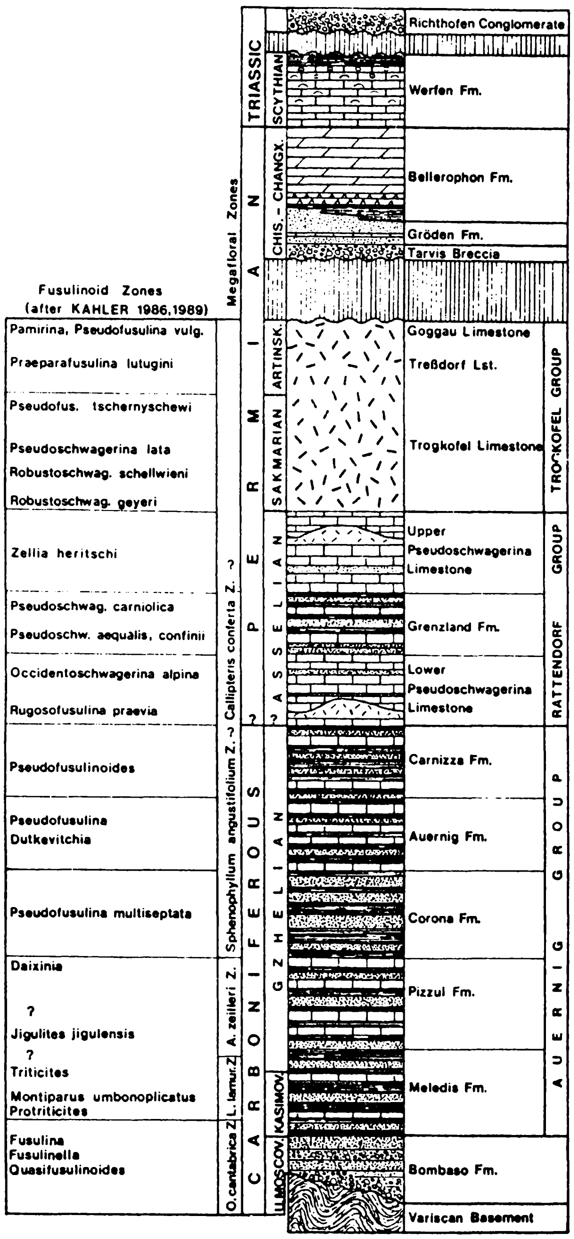

Fig.3: Generalized stratigraphic column through the late- to post-Variscan (Late Carboni-ferous to Early Triassic) sequence of the Carnic Alps in the Trogkofel - Gartnerkofel area.

The first cycle is characterized by Late Carboniferous-Early Permian sediments and volcanic rocks which were accumulated in intramontane basins formed by block- and wrench-faulting. In the Carnic Alps and Southern Karawanken Mountains, the sequence of the first cycle is represented by cyclic deltaic and shallow marine clastic and carbonate sediments, the Bombaso Formation, Auernig, Rattendorf, and Trogkofel Group, ranging from Late Moscovian to Late Artinskian.

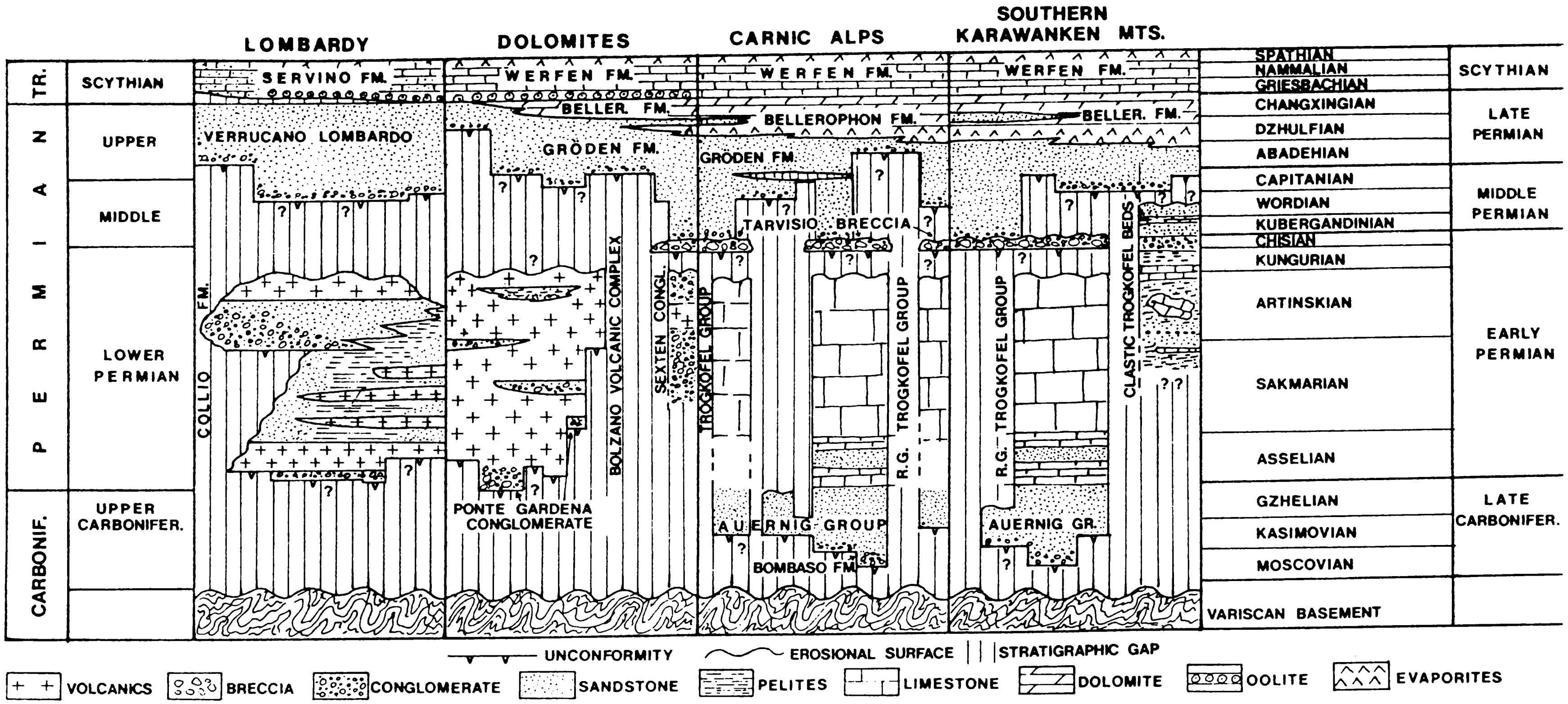

Fig.4: Schematic stratigraphic framework of late- to post-Variscan (Late Carboniferous to Early Triassic) sediments of the Southern Alps (after ITALIAN RESEARCH GROUP 1986, p.37 and Massari et al. 1988, varified and supplemented). RG = Rattendorf Group.

In the Dolomites, the first cycle is formed by the local development of thin alluvial fan sediments (Ponte Gardena/Waidbruck Conglomerate). It is followed by a thick volcanic sequence of latiandesitic to rhyolitic tuffs, ignimbrites and lavas with intercalated fluvial and lacustrine sediments (Bolzano Volcanic Complex) of Early Permian age. In the Lombardian Alps, south of the Adamello Massif, different intermontane basins formed, which were filled with thick sequences of volcanic rocks and clastic sediments (Collio Formation).

With a hiatus (?)Middle -Late Permian sediments of the second cycle, which are more widely distributed but not restricted to discrete basins, unconformably overlie Early Permian or even older rocks. In the Southern Karawanken Mountains, Carnic Alps and Dolomites, the second cycle starts with continental to shallow marine clastic sediments of the Gröden Formation which repeatedly interfinger with and grade upwards into the shallow marine evaporitic and carbonate sediments of the Bellerophon Formation. The Bellerophon transgression prograded slowly westwards over a very low-gradient and flat landscape. Sabkha-sediments formed on this very shallow and wide, evaproitic transition zone sabkha-sediments formed. During prograding transgressional events, fossiliferous limestones of open-lagoon shallow water environments were deposited. West of the Dolomites, the second cycle is represented by continental red beds of the "Verrucano Lombardo" and by shallow marine sediments of the Servino Formation (see summary in Krainer 1992).

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THE GURKTAL NAPPE COMPLEX

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Introduction

The Gurktal Nappe Complex (GNC), part of the Upper Austro-Alpine thrust sheet, mainly contains weakly metamorphic Ordovician to Early Carboniferous basement sequences and Late Carboniferous to Triassic cover sequences (Fig. 1). It is thrusted onto the Middle Austro-Alpine Nappe Complex from which Permo-Mesozoic sediments are preserved below the northern and western margin of the GNC (Fig. 1). The GNC extends from the Nockberge area to the foreland of the Karawanken and may be traced along the southern Saualpe and Koralpe to the Pohorje Mts. in Slovenia (Hinterlechner and Moine, 1977) (Fig. 1).

The existence of the thrust sheet and the scale of displacement played an important role for the interpretation of internal tectonics of the Austro-Alpine Nappe Complex (Clar, 1965; Frank 1987; Neubauer, 1987; Tollmann, 1959, 1977; von Gosen, 1982, 1989).

Internal stratigraphy

The Gurktal Nappe Complex is internally subdivided into two major nappes, both composed of Early Paleozoic rocks, which are distinguished by lithology and degree of metamorphic overprint. The lower Murau Nappe is composed of lithologies mainly in upper greenschist facies, the upper Stolzalpe nappe in lower greenschist facies (Becker et al., 1987). The Pfannock gneiss and accompanying cover sequences, probably a part of the Stolzalpe Nappe, occurs along the western margin. The Ackerl gneiss and micaschist complexes together with Permotriassic cover sequences form another local klippe, the Ackerl Nappe as apparently highest tectonic unit in northwestern Gurktal thrust complex (Fig. 1). The Paleozoic nappes, the Stolzalpe and Murau Nappes, contain a similar trend in stratigraphic evolution but striking differences in detail. The stratigraphy is largely based on rare conodont findings which are derived from minor dolomite lenses within metapelitic and metavolcanic sequences (for reviews, see Schönlaub, 1979; Neubauer and Pistotnik, 1984; Neubauer and Sassi, in press).

Stratigraphy

The stratigraphy of the Murau Nappe is uncertain because of the lack of continuous, fossil-bearing sections, and strong, partly unresolved deformation structures which include large-scale isoclinal folding, internal imbrication and transposition by large-scale shearing. As a rule, the stratigraphy follows that of the Schöckl Unit within the Paleozoic of Graz (see Fritz et al., this volume). Prasinites and greenschists derived from lava flows, sills and tuffs occur at the supposed stratigraphic base within a phyllite matrix (Fig. 2) (Neubauer, 1980a). Most of these greenschists show transitional to mildly alkaline basaltic chemical characteristics (unpublished data). A phyllite-rich unit overlay the greenstones. Carbonatic phyllites, black phyllites, and quartzites with minor greenstones and orthoquartzites build up the next higher stratigraphic unit. Along the southern margin of the Gurktal nappe, widespread acidic volcanics occur (Loeschke, 1989b). The stratigraphic higher level is made up by carbonates which exhibit lateral facies differentiation. Dolomites at the base of the

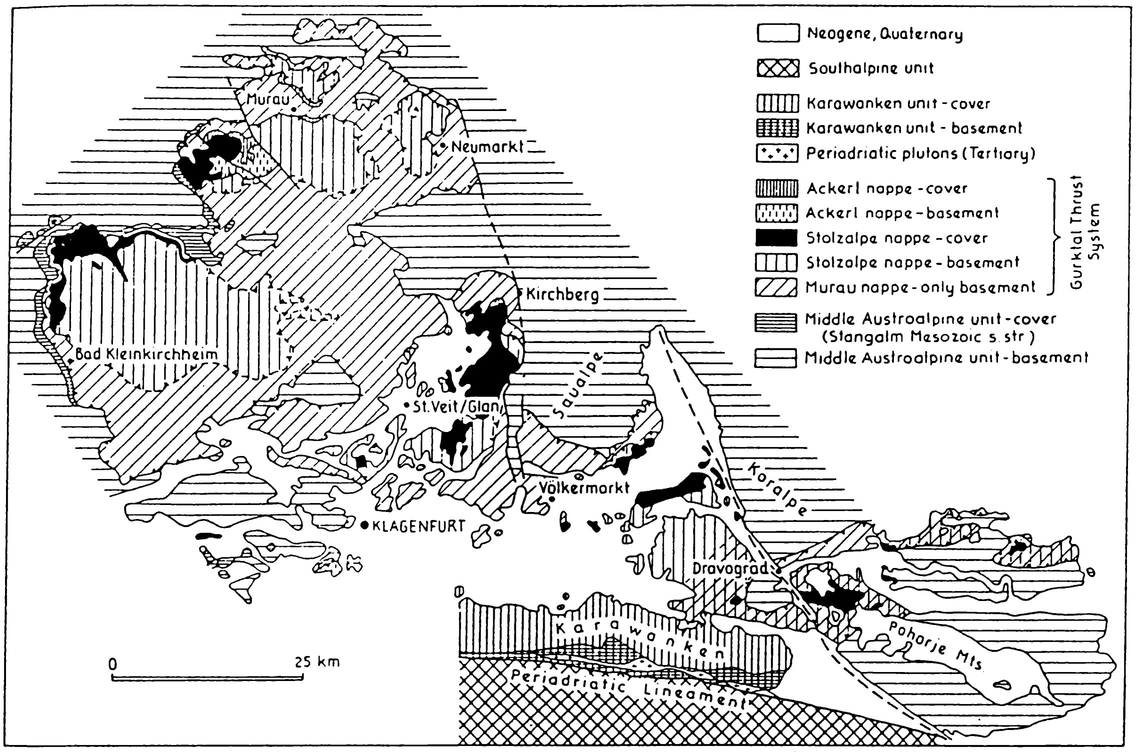


Fig. 1: Simplified map of the Gurktal thrust complex (from Neubauer, 1987).

carbonates in the more northern region yielded a Late Silurian to Early Devonian, respectively a Pragian to Zlichovian conodont fauna (Buchroithner, 1979; Neubauer, 1980a, b; Niederl, 1980; Schönlaub, 1979). Calcite marbles are widespread. A singular finding of a brachiopod support the late Silurian and/or early Devonian age of the carbonates in the southern Saualpe (Neugebauer, 1970). The marbles sometimes bear coarse-grained mafic dykes of transitional basalt affinity (Neubauer, 1989).

The Stolzalpe Nappe also exhibits an internal imbrication, and is composed probably of slices which differ in Late Silurian to Early Devonian facies. The separation from the Murau Nappe is uncertain in the interior of the GNC because of missing Permo-Mesozoic rocks along thrust surfaces and comparable lithologies, mainly quartzphyllites, in both units (e.g., von Gosen, 1982, 1989).

The differentiation of various stratigraphic levels within the Stolzalpe Nappe is well-constrained by stratigraphic valuable fossils. As a rule, thick mafic volcanic sequences occur at the stratigraphic base (Fig. 2). They are overlain by pelitic-psammitic dominated sequences, whereas pelagic limestones occur at the top. In detail, mafic dominated volcanics at the base are subdivided in two subunits: A late Middle Ordovician and Late Ordovician age, respectively, is proved for the Magdalensberg Fm. at the Magdalensberg by brachiopods (Havlicek et al., 1987) and conodonts (Riehl-Herwirsch, 1970). The Nock Series (Giese, 1988) occur in the late Ordovician (Neubauer and Pistotnik, 1984). The Kaserer Fm. is a further probably Ordovician volcanic unit with major basaltic sills and stocks. A pre-Silurian age is supposed for the Kaserer Fm. because of its superposition by the Silurian Eisenhut Fm. The earlier one is interpreted as a basaltic-keratophyric marine island volcanoe (Riehl-Herwirsch, 1970) with alkaline geochemical characteristics (Loeschke, 1989a, b). The Nock Series exhibit calc-alkaline affinities (Giese, 1988; Loeschke, 1989b).

These units are contrasted by Early to Mid Silurian volcanics, the Eisenhut Fm. at the northwestern edge of the GNC (Höll, 1970; Neubauer and Pistotnik, 1984), the Metadiabase Formation at the northern edge of the GNC (Schnepf, 1989), and the younger portion of the Magdalensberg Formation (West to the Saualm: Neubauer and Pistotnik, 1984). All these Silurian volcanic units have a coherent mildly alkaline geochemical characteristics (Giese, 1988; Schnepf, 1989; Antonitsch and Neubauer, 1992). However, Ordovician and Early Silurian volcanics are probably separated by a Late Ordovician unit of slates, quartzphyllites and sandstones which contain also lydites and thin carbonate layers (Neubauer, 1980a; Neubauer and Pistotnik, 1984).

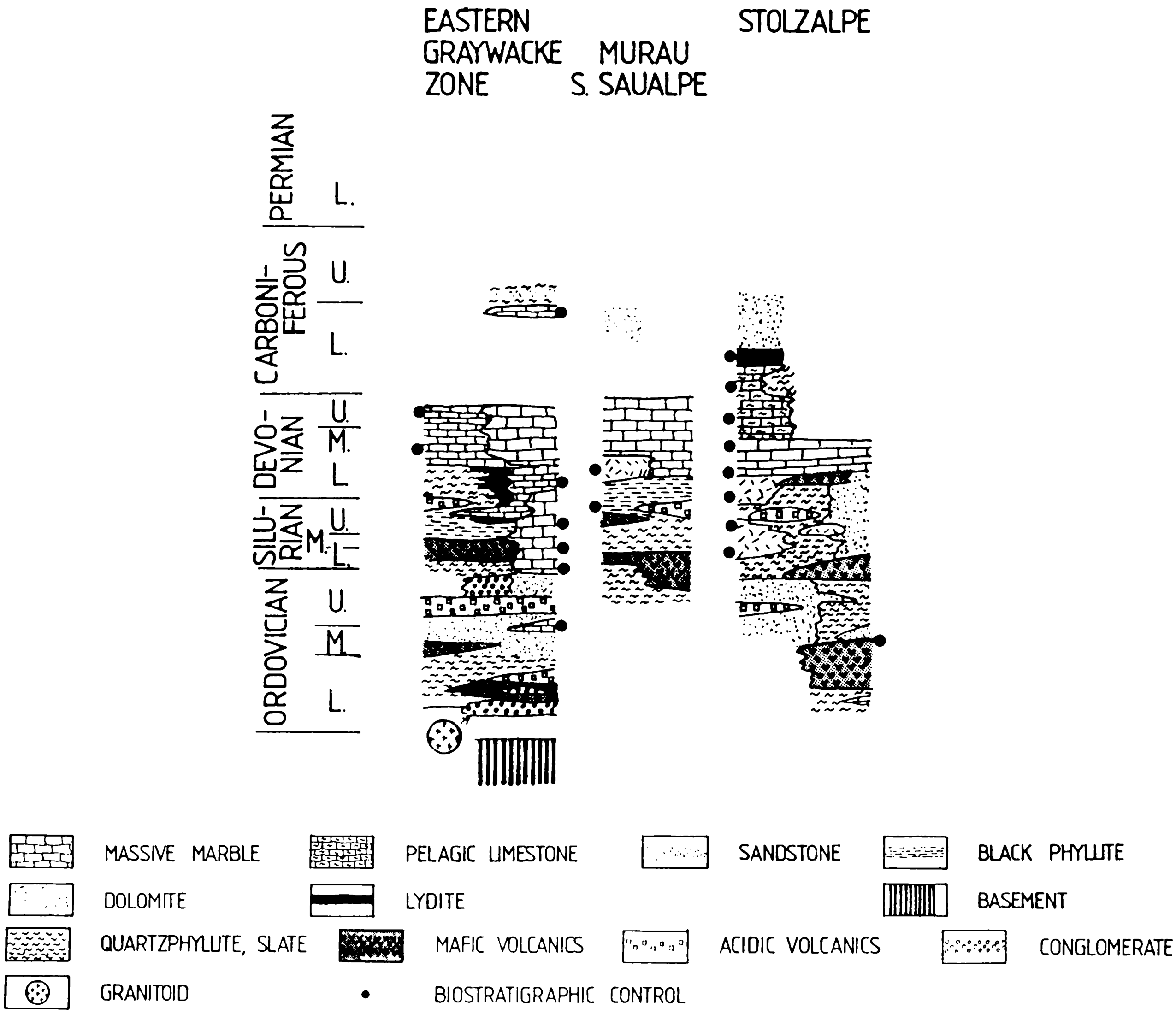


Fig. 2: Stratigraphic sections of the Murau and Stolzalpe Nappes (modified from Neubauer and Sassi, in press).

A slaty facies with cherts and allodapic limestones persists through the Wenlockian to the boundary of Lochkovian/Pragian (Magdalensberg facies; Fig. 2). On the other hand, thick sandstones, quartz wackes and quartz arenites (Fig. 3), occur locally covering the same time span. The composition of these Late Ordovician to Early Devonian sandstones varies from quartz arenites to quartz wackes and subarkoses. A preliminary 40Ar/39Ar age of a detrital muscovite yielded a fairly good plateau at ca. 560 Ma with minor later, probably combined Variscan/Alpine overprint (Dallmeyer et al., this volume). The siliciclastic sediments are contrasted by thin Late Wenlockian to Pragian dolomites, and pelagic limestones. At latest at the boundary Pragian/Zlichovian, comparable pelagic limestones occur in all units differentiated before. The Zlichovian to Pragian carbonate includes mafic volcanics (Neubauer, 1980b). These carbonates locally persist up to the Early Carboniferous and are overlain by cherts and graywackes. The cherts yielded conodont faunas from the Tournaisean/Visean boundary (Neubauer and Herzog, 1985). Rare diabase dykes and detrital modes of graywackes suggest felsic and mafic intrabasinal volcanoes (Neubauer and Herzog, 1988). Recent investigations show evidence for the presence of late Visean corals in carbonates within cover rocks on the stratigraphic top of quartzphyllites (Schlöser and others, 1990). Therefore, deformation and metamorphism occurred within a short intra-Visean time.

The Ackerl Nappe consists of a lower Ackerl micaschist unit with mainly micaschist and the upper Ackerl gneiss unit, a two-mica plagioclase paragneiss with minor aplite, pegmatite, amphibolite and orthogneiss (Neubauer, 1980c). The age of metamorphism of both complexes is pre-Alpine with an eo-Alpine, Cretaceous metamorphism in lower greenschist facies. 40Ar/39Ar muscovite plateau ages yielded ca. 310 Ma which is interpreted as the age of postmetamorphic cooling through the approriate closing temperature of ca. 350 - 400^{o}C (see Dallmeyer et al., this volume).

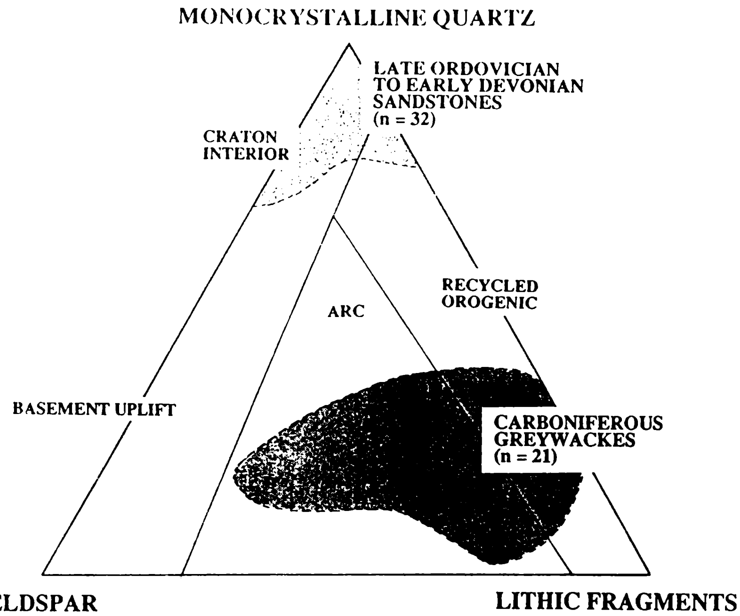


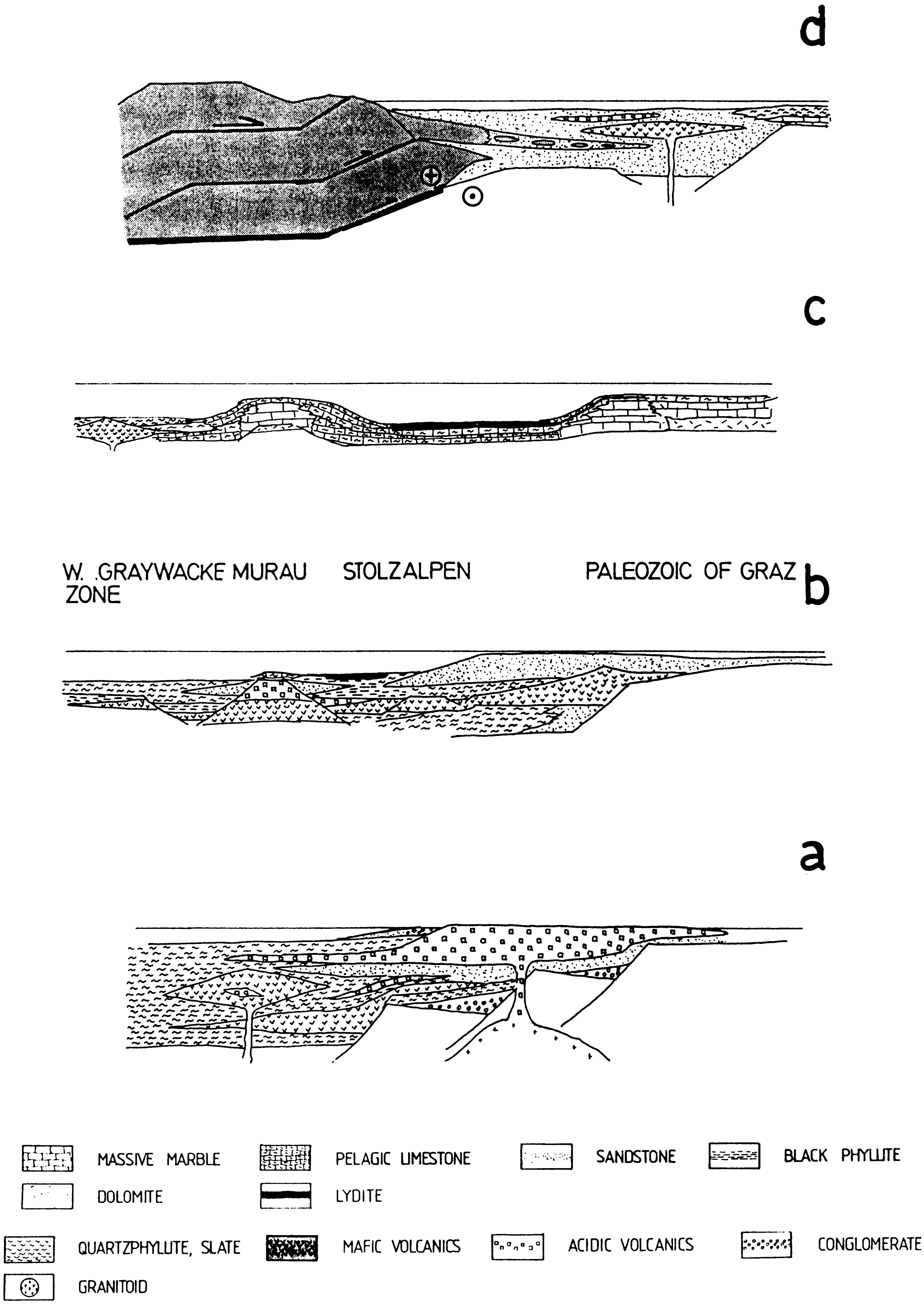
Fig. 3: Detrital modes of Late Ordovician and Early Carboniferous sandstones of the Stolzalpe Nappe.

Paleozoic geodynamic setting

The Early Paleozoic geodynamic evolution is a matter of controversies (Giese, 1988; Loeschke, 1989b; Neubauer and Frisch, 1988, Neubauer and Sassi, in press). Both, the sequences of the Murau and Stolzalpe Nappes, although distinct in sequence, are part of the same depositional system. It may regarded as an example for the evolution of the entire Upper Austro-Alpine Paleozoic sequences (see Fig. 4, from Neubauer and Sassi, in press).

A basement on which these were deposited is missing most probably due to detachment of the entire content. The Middle Ordovician to Silurian sequences are rich in volcanics which monitors a distinct evolution with early calc-alkaline mafic rocks (Kaserer and Nock series) and later mainly alkaline volcanism. The entire controlling factor is the evolution of a back-arc basin system. The accompanying sedimentation of siliciclastic sediments is controlled by low water energy, and variable

*Fig. 4: Evolution of Upper Austro-Alpine quartzphyllite sequences (from Neubauer and Sassi, in press) as models for the sedimentary and orogenic evolution of the Gurktal Nappe Complex. Assumed orientation of sections is ca. NW to SE in relation to the present-day geographic coordinates. Facies differentiation is shown for restricted stages. **a**: The Ordovician evolution is interpreted as time of the back-arc basin formation. The basin is formed on top of a Cadomian crust which has been consolidated during the Late Proterozoic and/or Cambrian. The basin is filled up with clastics and bimodal volcanic piles. **b**: The Silurian and basal Early Devonian is the time of renewed rifting, block faulting, alkalic mafic and acidic volcanism and SEDEX-type mineralization (e.g. Murau Nappe). Afterwards, the basin is filled up with clastic sediments derived from southeastern areas. **c**: During late stages of the Early Devonian until Early Carboniferous the siliciclastic input looses importance except in western areas. Near-shore carbonates, lagoonal dolomites and reefs dominate the southeastern margin (Paleozoic of Graz), and probably an intra-basinal high (Murau Nappe). The deeper part of the basin is filled up with pelagic limestones and cherts. Volcanism occurred along the northwestern margins. **d**: Contraction and basin closure by thrusting started during Mid-Visean times. Subsidence of the flysch basin may be explained by loading of incoming thrust sheets. The basin is filled up with partly volcanogenic graywackes which are derived mafic and acidic volcanics.*


d
c
W. GRAYWACKE ZONE
MURAU
STOLZALPEN
PALEOZOIC OF GRAZ
b
a
MASSIVE MARBLE
PELAGIC LIMESTONE
SANDSTONE
BLACK PHYLLITE
DOLOMITE
LYDITE
QUARTZPHYLLITE, SLATE
MAFIC VOLCANICS
ACIDIC VOLCANICS
CONGLOMERATE
GRANITOID

influence of terrigenous clastics (quartz-, feldspar-, and white mica-rich sandstones). The Late Silurian to Devonian evolution displays a gradual shift to the formation of a carbonate platform with more shallow water deposits in the Murau Nappe, and pelagic sediments in the Stolzalpe Nappe. During the Famennian, the entire carbonate platform subsided to pelagic levels. During Visean time, flysch-like greywackes followed, most probably accompanied by deformation. The exact timing of the Variscan deformation is uncertain, but must predate Westfalian B/C.

Cover sequences

The basement is overlain by Late Carboniferous to Triassic cover sequences which are preserved along the northwestern margin of the Gurktal thrust complex, and in the Eberstein and Griffen areas (Krainer 1984, 1987, 1989; Pistotnik, 1975; Sylvester, 1987).

Terrestrial Late Carboniferous to Permian sequences form some tectonically independent thrust slices of the Stolzalpe Nappe (Krainer, 1987, 1989; for detailed information, see Krainer, this volume). The Stangnock Formation is an about 400 metres thick intramontaneous coal-bearing molasse formation of Late Westfalian to Stefanian age (Krainer, 1989). It has been deposited by an approximately west to east fluent river system under humid climate conditions. The clasts are derived from gneisses which have apparent similar Rb-Sr model ages and isotopic signatures like the Bundschuh orthogneisses of the immediate tectonic footwall (Frimmel, 1986a, b; 1988). A single occurrence of Early Carboniferous limestone of uncertain origin, redeposited clast or conformable lense, is reported from one locality below the Stangnock Formation (Schlöser et al., 1990).

The Werchzirm Formation (Permian) with redbeds monitors the gradual transition to semi-arid climatic conditions. Basal portions contain acidic tuffs which are used for large-scale correlation with Early Permian formations in the Southalpine unit.

The depositional age of the Pfannock sequence, mostly interpreted as detached portion of the Stolzalpe Nappe, is a partly overturned sequence along the western edge of the Gurktal Nappe Complex (Tollmann, 1975) which range from Late Permian to Late Triassic (Norian). The similarity of the Anisian sandy/carbonatic alternations of the Pfannock sequence with such of the underlying Middle Austro-Alpine Stangalm unit is called for local derivation of the Gurktal Nappe System (Frank, 1987; Krainer, 1984).

The Ackerl nappe as well as the cover sequences along the thrust surface between the Murau and the Stolzalpe Nappe contain local redbeds (mostly purple-coloured silt- and sandstones), Semmering-Quartzite-type quartzarenites (or Gröden Fm.; late Permian to Scythian age ?), rauhwacke and minor dolomites (Anisian ?) (Neubauer, 1980c).

Both the Eberstein and Griffen Permo-Triassic sequence commence with terrestrial deposits of Permian age (Werchzirm Fm.) grading into quartzarenites (Gröden Fm.) of Late Permian to Scythian age. The transition to carbonate deposition is given by Anisian rauhwackes. The further sequence is apparently incomplete and tectonically disturbed. It contains Middle Triassic basinal limestones sequences, tectonically thickened Carnian siliciclastic Raibl beds and mainly Norian Haupt Dolomite (for details, see Appold, 1989; Lein, 1989).

Successor basins

Following a period of deformation and erosion, both Eberstein and Griffen Trias are overlain by Late Cretaceous basinal sequences of the Krappfeld and St. Paul Gosau basins. The sequence of the Krappfeld Gosau is more complete (van Hinte, 1963; Neumann, 1989) and ranges with an approximate thickness of 1,500 metres (Neumann, 1989) from Late Santonian (Herrmann and Wascher, 1972) to lower Late Maastrichtian (Thiedig and Wiedmann, 1976). The Krappfeld Gosau occurs in the Krappfeld graben, a Miocene structure. Basal conglomerates and dolomite arenites onlap the Triassic Haupt Dolomite (Neumann, 1989). Locally, a detrital reef limestone with rudists occurs (Fig. 5). The main sequence shows a turbiditic facies which is subdivided into several formations by lithology and the occurrence of olistolithic marker beds (Neumann, 1989). This lithofacies is composed of basinal pelagic marls and limestones with planctic foraminifera, inoceramens and ammonoideas. The pelagic sediments contain olistolitic beds with thicknesses ranging from metre to more than 30 metres which are essentially composed of shallow water rudist reef limestone clasts, which locally reach the size of several meters.

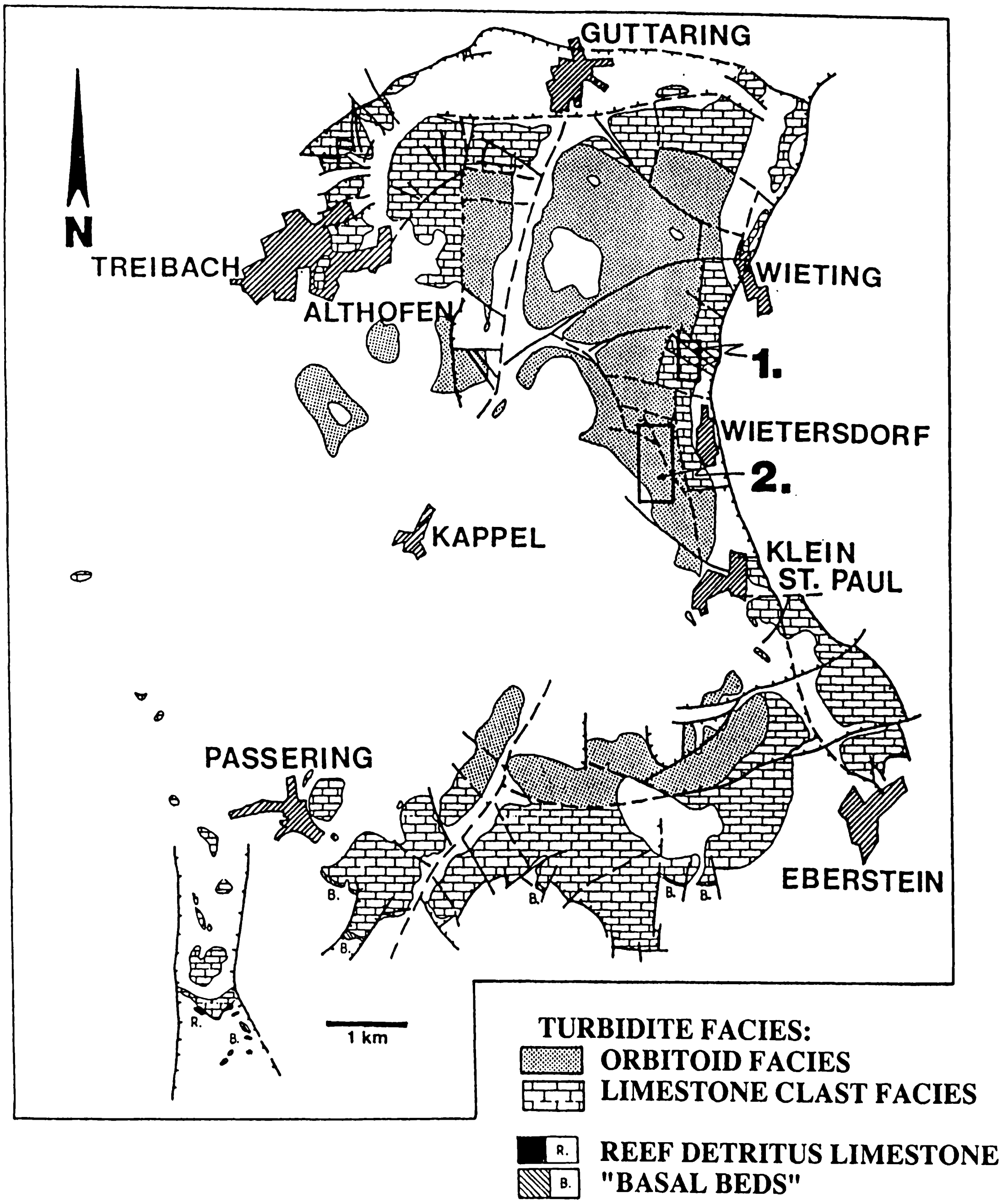


Fig. 5: Map of the Krappfeld Gosau basin (from Neumann, 1989).

The facies patterns of the Krappfeld Gosau basin monitors three major steps of evolution (Neumann, 1989):

After the Late Santonian transgression a carbonate platform developed in front of a terrestrial environment. After a period of lithification of platform sediments, rapid subsidence resulted in a turbidite facies with local debris flow sediments which contain mainly clasts derived of the earlier platform. This is interpreted as a dramatic collapse event in the platform area (Neumann, 1989; Thiedig, 1975). Thiedig (1975) suggested a source to the east on top of the metamorphic Saualpe region which cooled and uplifted during the Late Cretaceous.

A last phase resulted in the diminishing occurrence of limestone clasts, decreasing grain sizes and transition to more orbitoid-rich clasts of a submarine fan. For the first time clasts of basement rocks of the highest structural levels (Stolzalpe Nappe) occur.

Paleogene of the Krappfeld area

The Gosau beds are locally overlain by Paleogene sequences with an erosional unconformity. The sequences range from uppermost Paleocene to middle Eocene with a stratigraphic thickness of more than 1,000 metres (Wilkens, 1989). At the base red beds occur above an erosional relief with red clay, quartz gravels, local coal seams and rare horizons of black, marine detrital limestones (Fig. 6). It is suceeded by nummulite marls with only minor terrigenous clasts. A second formation with coal seams, and abundant siliciclastic sediments monitors enhanced terregenous input. Limestone-marl alternations are followed by nummulite limestones with decreasing content of siciliclastic material.

It should be noted that Paleogene clasts are abundant in Miocene gravels in the surroundings of the Krappfeld graben (Wilkens, 1989). Therefore, Paleogene sediments were most probably also present outside of the Krappfeld graben.

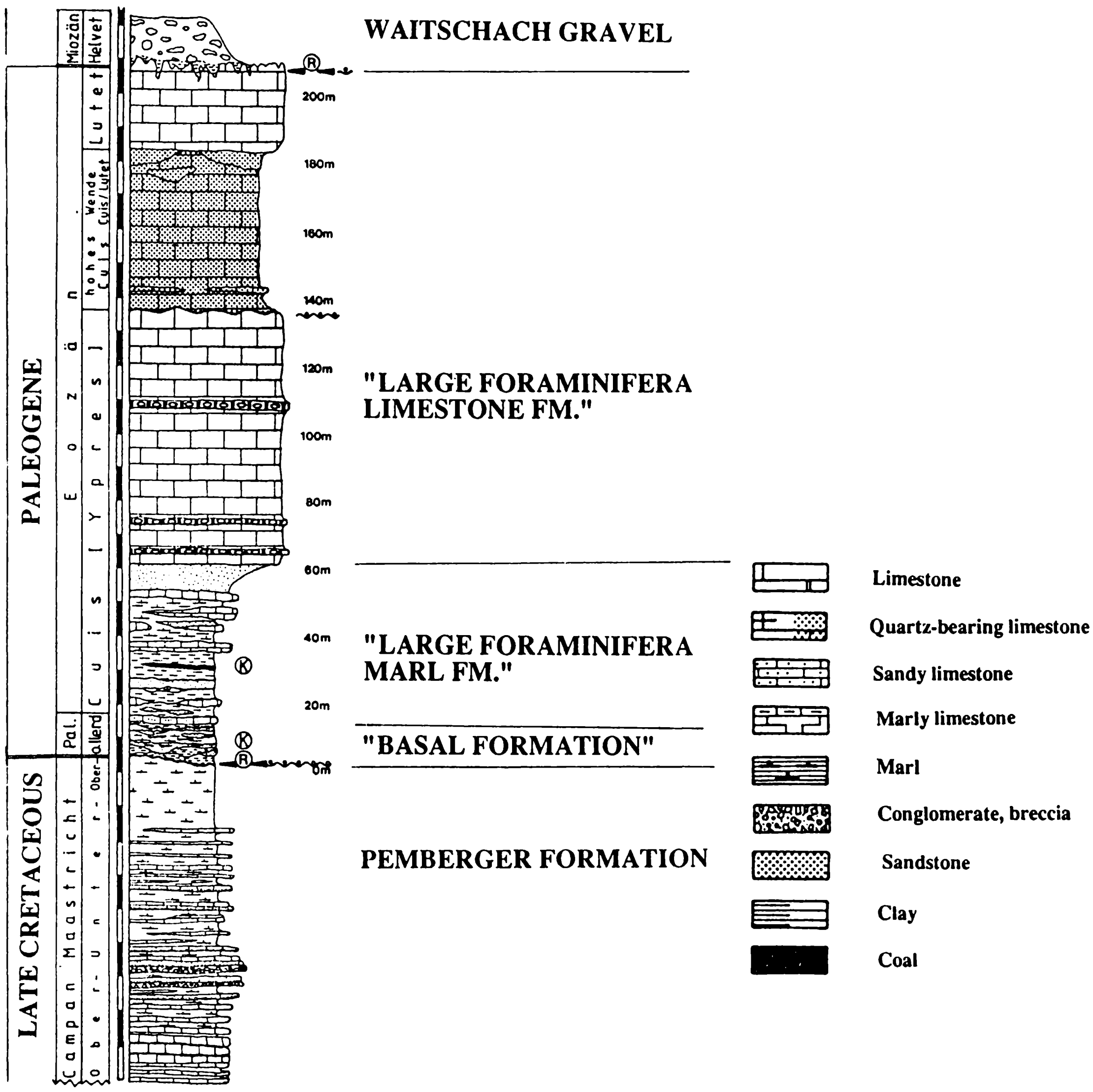
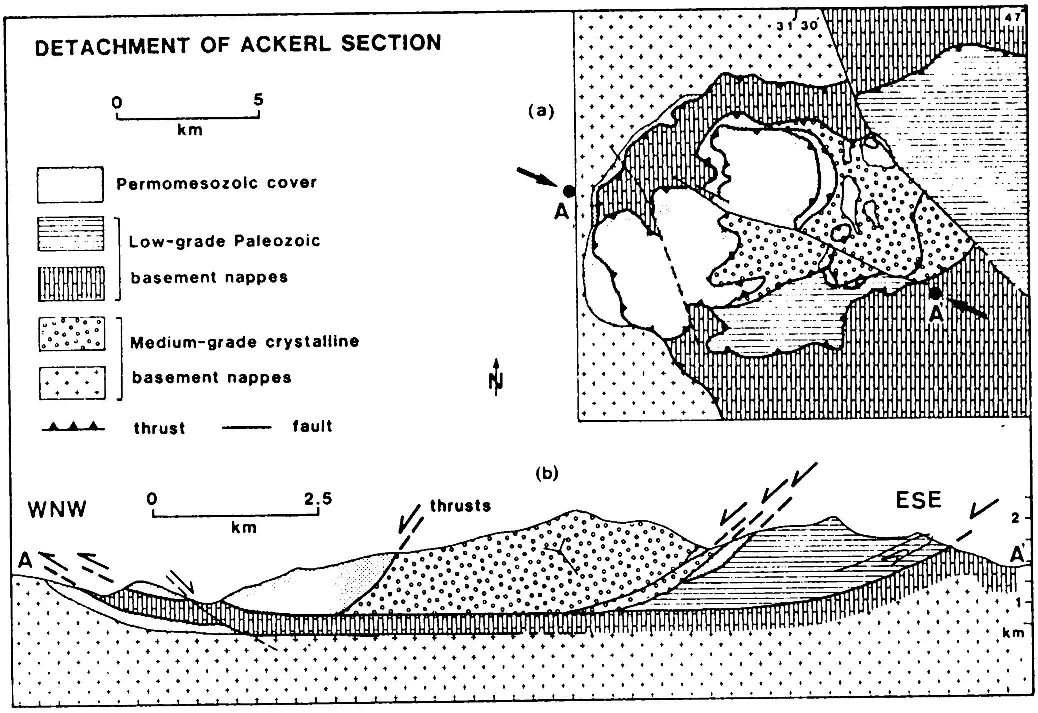


Fig. 6: Paleogene section of the Krappfeld (from Wilkens, 1989).



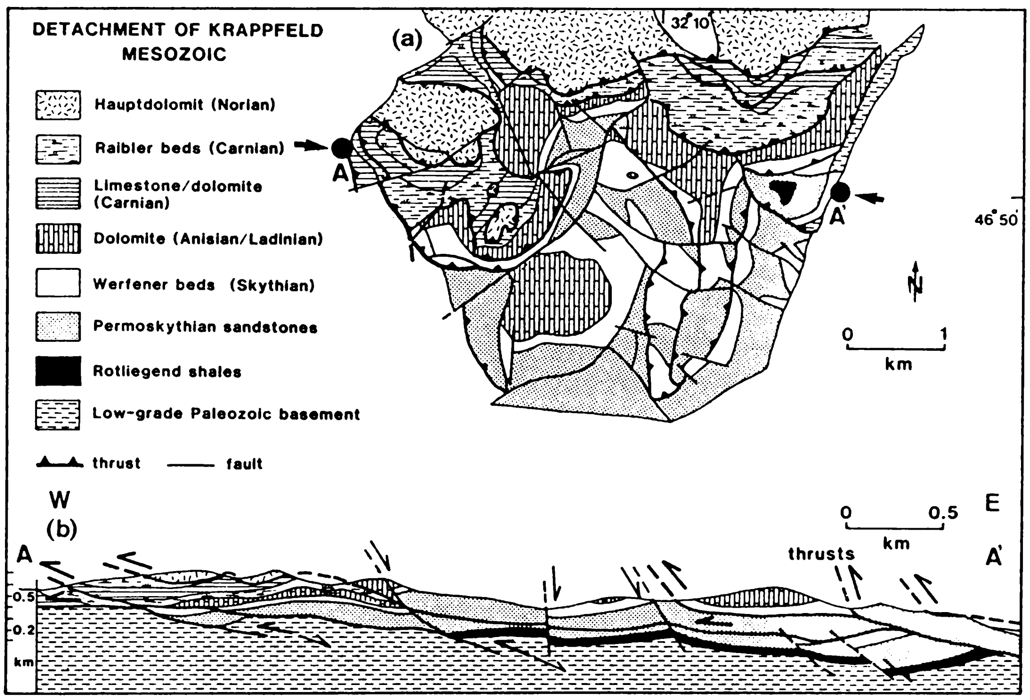
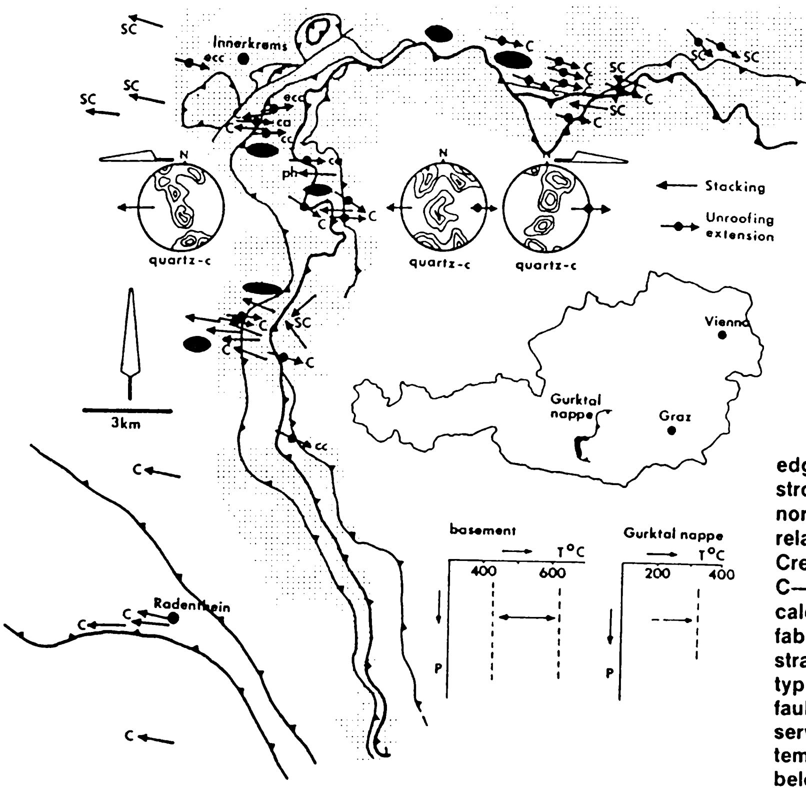


Fig. 7: Some structures related to nappe imbrication (from Ratschbacher and Neubauer, 1989).

The deposition of Paleogene sediments was followed by a period of erosion, karst formation and deposition of terrestrial red clays. During Middle Miocene, the thick gravels (e.g., Waitschach gravels) were deposited both west of the Saualpe region and along the southern edge of the GNC. These deposits resulted from a new period of faulting,especially along the Görtschitztal and Lavanttal fault zones. These basins includes both half grabens (Zollfeld graben) and pull apart basins, e.g., along the Lavanttal fault zone.

Deformation and metamorphism

The Late Carboniferous angular unconformity at the base of the Stolzalpe Nappe clearly separates Variscan and Alpine deformational and metamorphic events. Variscan metamorphism of the Stolzalpe Nappe apparently reached low grade metamorphic conditions largely overprinted by Alpine effects. All detailed pre-Alpine deformation structures are uncertain. The Alpine deformation of the GNC occurred under very low to low grade metamorphic conditions. Alpine metamorphic conditions regularly increase from hangingwall tectonic units the footwall. Only a few geochronological data are reported (Frank et al., 1987). The geochronological ages cluster around 120 Ma.



Simplified structural map, western edge of Gurktal nappe. Stippled area: zone of strong, Late Cretaceous, unroofing-related normal faulting. Arrows indicate displacement related to Early Cretaceous stacking and Late Cretaceous normal faulting. Kinematic criteria: C—quartz c-axis; cc—calcite c-axis; ca—calcite a-axis; ph—mica textures; SC—S-C fabrics; ecc—shear bands; ellipses—finite strain in foliation plate. Quartz c-axis textures: typical end-member (stacking and normal-faulting related) and superposition fabrics observed in east-west sections. Pressure (*P*)-temperature (*T*) diagrams record *T* fields below (left) and above (right) zone of normal faulting, based on geothermometry, phase equilibria, and illite crystallinity (e.g., Schimana, 1986).

Fig. 8: Late Cretaceous extensional structures along the western margin of the Gurktal Nappe Complex (from Ratschbacher et al., 1990).

A sequence of Alpine deformation events is reported from several areas. Interpreting all structures, the deformational sequence started at about peak temperature conditions with top to the west shearing and stacking of large nappes, such as the transport of the Stolzalpe Nappe onto the Murau Nappe (Fig. 1, 7), overriding Permotriassic sequences at the northern and northwestern margin of the GNC (von Gosen, 1989; Neubauer, 1987; Ratschbacher and Neubauer, 1989). The next deformation event was a NNE-SSW contraction by folding with about NNW-SSE fold axes. Ductile shear fabrics are largely overprinted by low-temperature mylonites and shear fabris which are due to top to the E and ESE, respectively, shearing and low-angle normal faulting (Neubauer, 1980b; Ratschbacher et al., 1989, 1990, Stock, 1989). This event reactivated the previous ductile thrust faults at the structural base and especially in the hangingwall of the Murau Nappe resulting in a break of the Alpine metamorphic section (amphibolite and lower greenschist facies conditions in the Middle Austro-Alpine unit vs. very low grade conditions in the higher Gurktal Nappe Complex; compare Gosen et al., 1987). Therefore, the present structure is a ductile low angle normal fault (Fig. 8). An age of about 80 Ma in the Middle Austro-Alpine units is called for starting of post-metamorphic cooling. The subsidence of the Krappfeld Gosau basins is approximately coeval with cooling and uplift of footwall units resulting in a dramatic collapse event in the Gosau beds. Direction of sediment transport as well as 80 Ma old Pb-Pb ages on galena within the Görtschitztal line favours first activity on this line during the Late Cretaceous. The significance of the Paleogene sediments are not well understood although the more than 1,000 m thick sequences call for activity of a major normal fault system.

The Miocene fault system is both related to large sinstral, E-W trending faults and NNW-SSE trending, sigmoidal dextral faults which are related to the Escape of Central Alps to the East.

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THE GRAZ THRUST-COMPLEX (PALEOZOIC OF GRAZ)

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Introduction

The Upper Austroalpine Graz Thrust Complex (GTC), the so-called Paleozoic of Graz (Fig. 1), is a nappe pile which includes weakly grade metamorphosed metasediments and metavolcanic rocks of Silurian to Carboniferous age. The internal structure is dominated by several thrust sheets with distinct Paleozoic facies. The upper limit of the age of thrusting is given by a late Cretaceous overstep sequence, the Kainach Gosau. The physical margins of the GTC are the metamorphic Koralm complex to the west, the metamorphic Gleinalm complex to the north (both Middle Austroalpine), and the metamorphic Raabalpen complex to the east (Lower Austroalpine). The present contact to the surrounding metamorphic complexes is a tectonic one, no primary basement of the GTC is known. The southern termination is built by onlap of the Tertiary sediments of the Styrian basin (Friebe et al., this volume) which is western continuation of the Pannonian Basin.

History of research

Fundamental stratigraphic work was done in the early decades of this century, especially by Heritsch (1911, 1915, 1917). The development of conodont stratigraphy in the sixties gave raise to a second period of intense stratigraphic research and detailed mapping by the school of Flügel (Flügel, 1975; Flügel in Flügel and Neubauer, 1984 cum lit.). The tectonic concept of a fold-and-thrust belt originates from Clar (1935) and was later improved by Boigk (1951) and Flügel (1958).

Tectonostratigraphy

Three major nappe systems can be distinguished within the Graz Thrust Complex which differ in sedimentary facies, stratigraphic range of sedimentary sequences and metamorphic overprint. Polyphase stacking and folding caused internal imbrications, recumbent folds and structures commonly observed in a fold-and-thrust belt. Stacking of the nappes is proved by detailed mapping combined with stratigraphic and structural investigations. The nappe systems contains the following thrust sheets from bottom to the top (Fig. 1):

Lower nappe system

The Schöckl Nappe system at the base of the GTC comprises the sedimentary sequences of the Schöckl Group, Passail Group and Anger Crystalline Complex. Late Silurian to middle Devonian sedimentation is recorded from the Schöckl- and the Passail Groups. Metavolcanics and pelites dominate the Late Silurian to Early Devonian sequences, carbonates the Middle Devonian section (Ebner and Weber, 1978; Tschelaut, 1985; Weber, 1990; Fritz, 1991). The stratigraphic section is truncated by the higher nappe complexes, the structural base of the nappe complex is not exposed. Alpine greenschist facies metamorphism is common, locally amphibolite facies conditions are reached in the eastern part of the Graz Thrust Complex (Neubauer, 1981), the so-called Anger Crystalline Complex (Fig. 1).

Intermediate nappe system:

The Laufnitzdorf Nappe and Kalkschiefer Nappe are defined by the sedimentary sequences of the Laufnitzdorf Group respectively Kalkschiefer Group and occur either in basal parts of the GTC or, due to two-step stacking, in an intermediate structural level.

The Laufnitzdorf Group consists of pelagic limestones, shales and volcanic rocks of Early Silurian to Late Devonian age (Gollner et al., 1982). The metamorphic overprint was in the range of very low-grade to low-grade metamorphic conditions. Truncated teconic slices with variable stratigraphic range occur mostly along the western part of the Graz thrust complex (Fig. 1).

The Kalkschiefer Group is an uniformly developed sequence of carbonatic/siliciclastic rocks of Devonian age, the metamorphism is very low to low grade (Gollner and Zier, 1985; Tschelaut, 1984a). Slices occur in northern and western parts of the GTC (Fig 1).

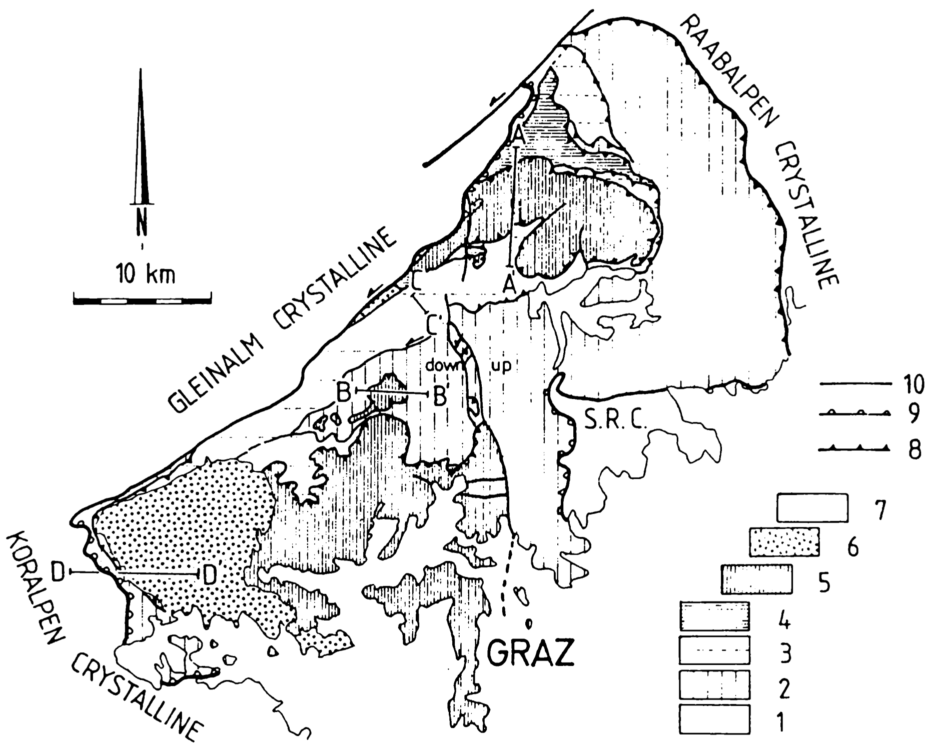

Fig. 1: Simplified tectonic map of the Graz Thrust Complex (after Fritz et al., 1991). Legend: 1 - Middle Austroalpine unit (S R C - St Radegund Crystalline); 2 - Lower nappe system; 3 - Kalkschiefer nappes and 4 - Laufnitzdorf nappe (both intermediate nappe system; 5 - Upper nappe system (Rannach nappe and Hochlantsch nappe; 6 - Kainach Gosau; 7 - Styrian/Pannonian basin (Neogene); 8 - thrust fault; 9 - ductile low angle normal fault; 10 - strike slip and high angle normal fault.

Upper nappe system:

The upper nappes, the Rannach and Hochlantsch Nappe, comprises the Rannach Group and Hochlantsch Group respectively, which are similar in stratigraphic range (Silurian to Carboniferous) and metamorphic overprint (very low-grade to low grade metamorphism, Hasenhüttl and Russegger, 1992). However, they differ in sedimentary/facial evolution. A very generalized section includes metavolcanic and clastic rocks from the Silurian to the Early Devonian and carbonates of platform and pelagic environments up to the Carboniferous (Fenninger and Holzer, 1978; Ebner et al., 1980; Poltnig, 1984; Gollner and Zier, 1985, Neubauer, 1989, 1991; Fritz, 1991; Hubmann, 1990). Rocks of the Rannach- and Hochlantsch Groups occur predominantly in western and northern parts of the GTC (Fig. 1).

Kainach Gosau basin (Late Cretaceous)

The internal nappe structure in the western part of the GTC is concealed by the Kainach Gosau sediments which unconformly overlie the nappe pile of Paleozoic rocks (Gräf, 1975). The sequence starts with conglomerates along the northern margin of the basin (Basiskonglomerat). Besides local detritus from the GTC, Mesozoic carbonates including few pebbles of probable Southalpine origin dominate the pebble spectrum (Gollner et al., 1987). The conglomerate is followed by limnic sediments (Bitumenmergel) and a thick turbiditic sequence, the so-called Hauptbeckenfolge.

Stratigraphy and Paleogeographic Evolution

A wide diversity of facies ranging from shallow marine to basinal pelagic environments is characteristic for the sedimentary evolution of the Graz Thrust Complex. The primary arrangement (Fig. 2) of the stratigraphic sequences, now dismembered by tectonic processes, is deduced from both structural and stratigraphic/facial investigations.

In spite of a facies differentiation the following general trends which are typical especially for the Schöckl Group, Kalkschiefer Group and the Rannach and Hochlantsch Groups can be observed. Numbers and formations in the description below refer to the stratigraphic/ sketch in Fig. 2.

-- The basal members of the stratigraphic sequences up to the late Silurian are dominated by alkaline mafic volcanoclastics which are interpreted as initial rift sequence (1: Lower Kher-Fm; Passail-Fm; Waldstein-Fm.) (Fritz and Neubauer, 1988; Loeschke, 1988).

-- An alternation of carbonates and fine grained siliciclastic sediments developed from the Late Silurian up to the Early Devonian. Characteristic is a progressive carbonate production and clastic input in subbasins of variable water depth (2: Upper Kher-Fm; 3: Parmasegg-Fm. [Crinoiden-Fm]; Arzberg-Fm.) (Ebner and Weber, 1978; Tschelaut, 1984b; Weber, 1990; Neubauer, 1991; Fritz, 1991).

-- Thick dolomites, coarse sandstones and partly fossil-rich limestones of a carbonate platform interfinger with lagoonal sandy coastal environments developed in lower to middle Devonian (4: Gschwendt-Fm; 5: Dolomit-Sandstein-Fm.; 6: Barrandei-Fm.; 7: Schöckl-Lmst.) (Fenninger and Holzer, 1978; Gollner and Zier, 1985; Hubmann, 1990).

-- A second climax of alkaline mafic volcanism occurd during the Givetian (8: Tyrnau-Fm.) (Gollner and Zier, 1985).

-- From Late Givetion to Early Frasnian the sedimentary environment changed from a platform setting (9: Kanzel-Lmst.; 10: Hochlantsch-Lmst.) to a conodont-rich, pelagic sequence including flaser limestones and cherts which continue locally to the Namurian A (11: Steinberg-Lmst.; 12: Sanzenkogel-Fm.) (Ebner, 1978, 1980, Ebner et al., 1980; Gollner and Zier, 1985).

-- In the Rannach and Hochlantsch Groups the stratigraphic sequence continues probably up to Westfalian/A. Significant stratigraphic gaps accompanied by erosion and karstification, characterized by mixed conodont faunas developed during Late Devonian and Early Carboniferous levels. A peculiarity of the Rannach Group are shales at the top of the sequence (13: Dult-shales) (Ebner, 1978, 1980; Ebner et al., 1980).

The Laufnitzdorf Group shows deviating characteristics with a continuous pelagic environment from the Early Silurian to Late Devonian (14: Hackensteiner-Fm; 15: Harrberger-Fm) probably interfingering with carbonatic/clastic shelf (16: Schattleiten-Fm;) and litoral environments (17: Dornerkogel-Fm) in the Devonian or probably Carboniferous times (Gollner et al., 1982; Gollner and Zier, 1985; Tschelaut, 1984a).

All these sequences reflect the evolution of a passive continental margin from the breakup of a Silurian continent with alkaline volcanism to the formation of shelf and platform sediments in the Devonian (Fritz and Neubauer, 1988; Loeschke, 1988). Facies heterogenities between the single

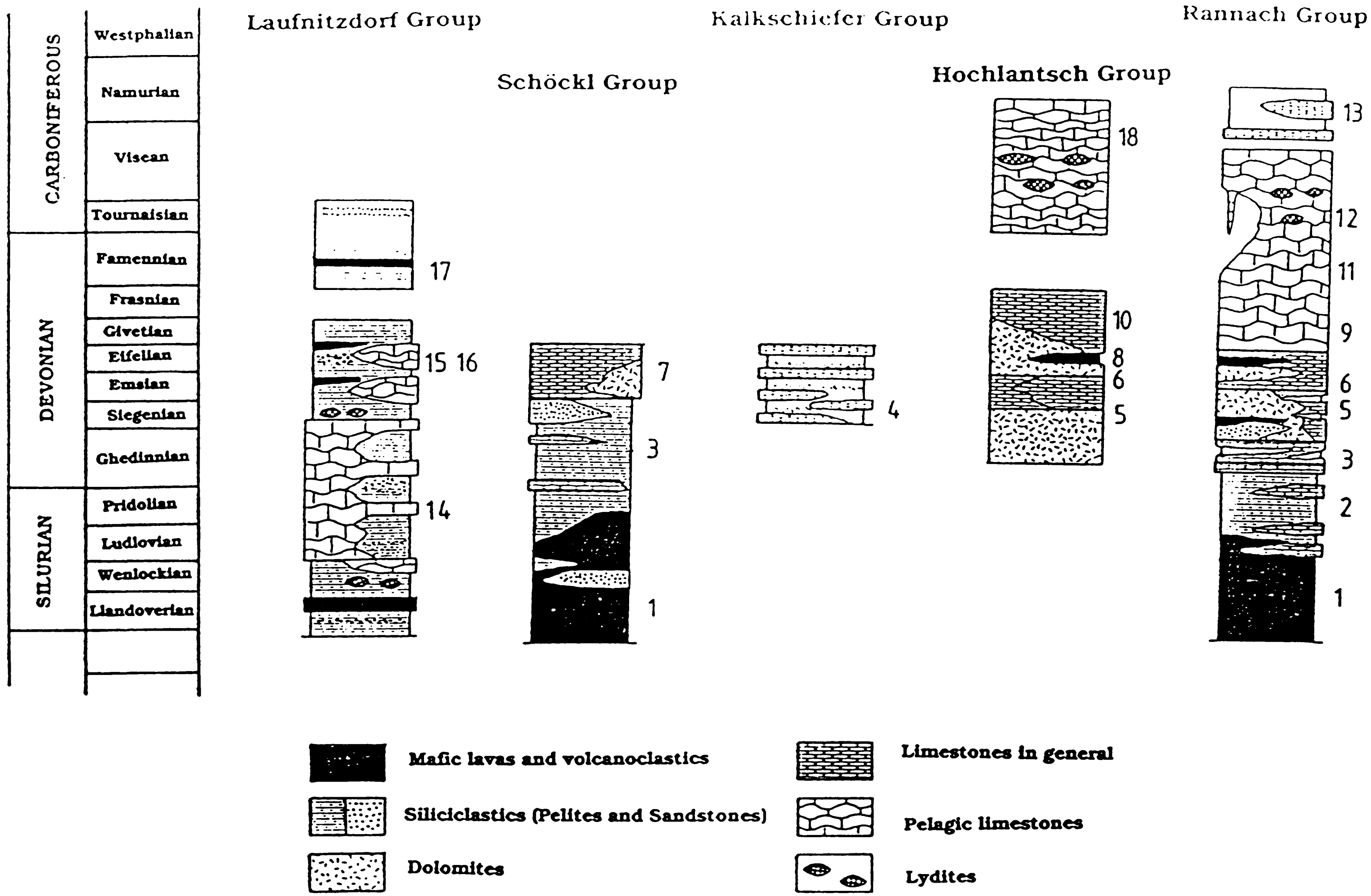

Fig. 2: Stratigraphic sketch of the Graz Thrust Complex: 1: Lower Kher Fm. (Rannach Group); Waldstein Fm. resp. Passail Fm. (Schöckl Group). 2: Upper Kher Fm.; 3: Parmasegg Fm. (Rannach Group); Arzberg Fm. (Schöckl Group). 4: Gschwendt Fm. 5: Dolomit-Sandstein Fm. 6 : Barandei Lmst. 7: Schöckl Lmst. 8: Tyrnau Fm. 9: Steinberg Lmst. 10: Hochlantsch Lmst. 11: Steinberg Lmst. 12: Sanzenkogel Lmst. 13: Dult Fm. 14: Hackenstein Fm. 15: Harrberger Fm. 16: Schattleitner Fm.17: Dornerkogel Fm. 18: Mixnitz "Carboniferous Lmst."

groups (Rannach-, Hochlantsch-, Schöckl-Group) indicating different bathymetric and hydrodynamic conditions reflect segmentation of the passive continental margin in subbasins and swells.

The sedimentary facies of the Devonian/Carboniferous carbonate shelf is controlled by eustatic sea level fluctuations and synsedimentary tectonics which caused stratigraphic gaps and the formation of conodont mixes faunas (Ebner, 1978).

However, the widely deviating sediments of the Laufnitzdorf Group do not fit into the concept of a single terrigenous hinterland. Recent investigations on detrital modes of Silurian/Devonian sandstones reveal clear differences between quartz arenites of the Rannach- Hochlantsch and Kalkschiefer Groups and the greywackes and arkoses of the Laufnitzdorf Group. The latter require a differnt source region which is incompatible with the former ones (Neubauer, in prep.).

Paleogeographic correlations to other extra- and intra-Alpine Paleozoic sequences are based on biogeography and stratigraphic/ facial comparisons. Algal floras suggest close relationships of the Graz Thrust Complex to the Rhenohercynien in the middle Devonian (Hubmann, 1990). In addition, the occurrence of widespread quartz arenites during the Early Devonian and red mature quartz arenites in the Middle Devonian Barrandei Limestone indicate possible relations to the Old Red-continent. A possible correlation to the Hungarian Uppony Mountains arises from strong similarities in the stratigraphic sequences and the fact that pelagic sedimentation continues up to the Westfalian and synorogenic flysch sedimentation is missing in both areas (Ebner et al., in prep.).

Structural Evolution

Structural association of the Graz Thrust Complex can be subdivided into structures which are related to Early Cretaceous crustal stacking, to Late Cretaceous extensional structures which are associated with the formation of the Gosau basin and to post-Gosauian faulting. Pre-Alpine structures are rarely preserved. However, there is some evidence for pre-Alpine static recrystallization under upper greenschist metamorphic conditions in the deeper nappes (Neubauer, 1981). All Alpine structures developed under decreasing temperature conditiones.

Early Cretaceous compressional structures

Shortening in the GTC resulted in structures which are known from fold-and-trust belts. Shortening directions are similar in all units, they reflect a two stage imbrication with approximately top-to-the WSW- (D1) to top-to-the NW (D2) directed thrusting (Fig. 3). Single displacement paths and structural associations, however, differ localy depending on rheological behaviour of minerals in different crustal levels and on the location within the thrust complex.

In the Schöckl nappe system deformation is concentrated in the Silurian to lower Devonian metapelites which include the most deformable rocks in this unit. These rocks formed the flats during nappe imbrication. Pressure solution and diffusional mass transfer are the dominant deformation mechanisms which developed during the first deformational event (D1). An intense stretching lineation is homogenousely east-west oriented. Rotational component of deformation is revealed by several shear sense indicators as asymmetrically pressure shadows around rigid objects, S-C surfaces, ecc-structures and structure in outcrop scale (thrust geometry) (Fritz, 1988, 1991; Fritz et al., 1991; Neubauer, 1989, 1991). The sense of shear is top-to-the W, the strain geometry is close to plane strain. This penetrative foliation was refolded in a second deformation increment (D2) (Neubauer, 1981; Agnoli, 1987; Fritz, 1988, 1991). Fold axes are parallel to stretching, strain geometry turns to flattening strain.

In the highest nappe, the Rannach nappe, the structures of the first deformation increment (D1) are very similar to those of the Schöckl nappe. Fabric asymmetries and large-scale sheath folds (Neubauer, 1991) again indicate shear towards top-to-the-W and top-to-the-WSW, respectively, as well as plane strain geometry. During the second increment of deformation (D2) the strain geometry persisted but the direction of stretching changed progressively towards NW. This is indicated by changing growth directions of synkinematic fibres behind rigid objects (Fritz, 1988). We interpret this feature as progressive change of nappe displacement from southwest towards northwest.

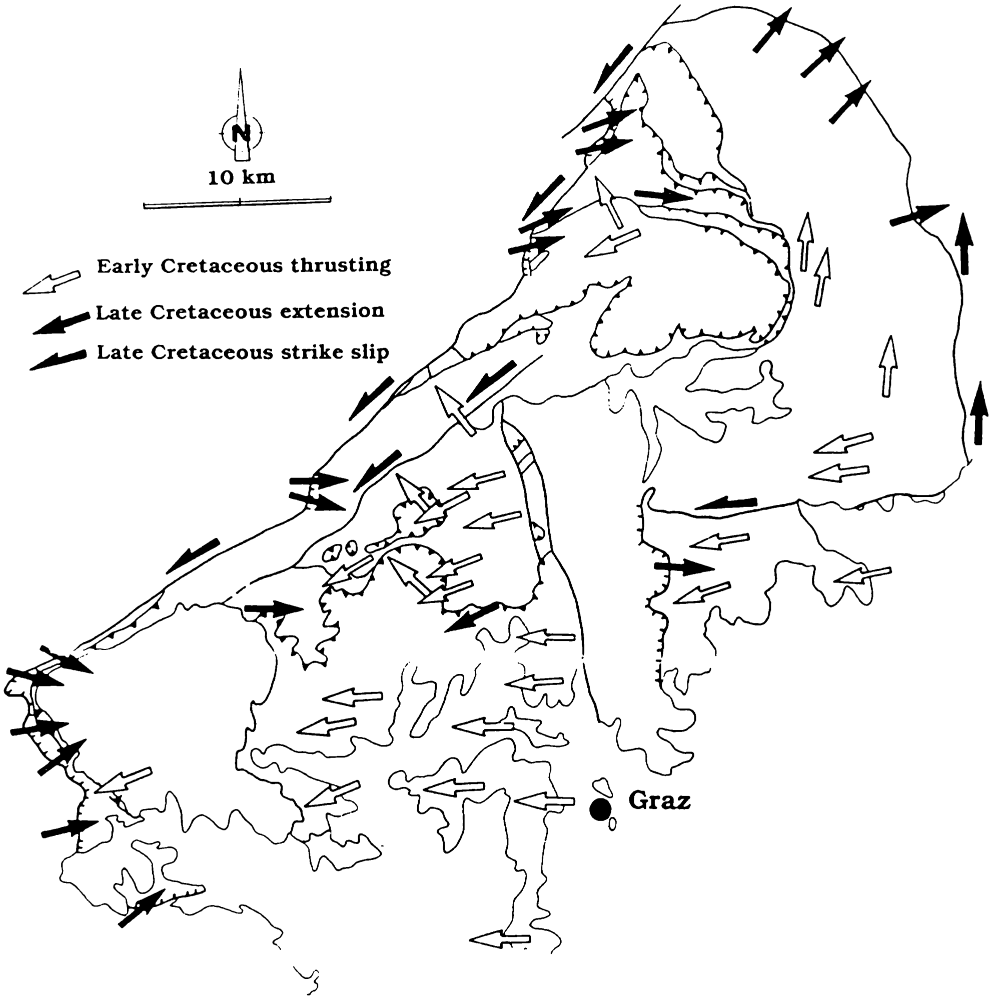

Fig. 3: Simplified structural map of the Graz Thrust-Complex.

Asymmetric fabrics in the Kalkschiefer Group indicate top-to-the-NW to top-to-the NE transport (D2) (Tschelaut, 1984b; Fritz et al., 1991). Decreasing temperatures caused progressive brittle behaviour and thrusting in a thin-skinned-tectonic manner (D2). Thrusts with ramps and flats developed in an outcrop scale, the direction of displacement persisted (top-to-the-W to top-to-the NE). NW-SE horizontal compression is supported by paleostress analyses (Fritz, et al. 1991).

On map-scale, arguments for a W-directed nappe stacking arise from the stratigraphic extend and spatial distribution of tectonostratigraphic units. Basal thrusts of the higher nappes are climbing towards higher stratigraphic levels during thrust-propagation. In western sections of the GTC the basal thrust planes cut the Devonian carbonates, whereas in eastern sections basal members of the stratigraphic column are preserved.

Macro-scale folding is best seen in the bedded limestones of the Kalkschiefer nappe. The relationships between bedding, axial plane foliation and minor second order folds point to NW-directed vergence (Tschelaut, 1984b). Large-scale recumbent folds developed mostly in the lowers nappe systems due to enhanced passive fold amplification (Clar, 1935; Neubauer, 1981).

An example for the two-phase stacking and the mode of thrust propagation is given from the northwestern parts of the GTC (Fritz, 1991). In a first step the Rannach nappe was thrusted onto the Schöckel nappe, later the whole nappe pile was involved into foreward propagation of thrusts (Fig. 4). Foreland dipping thrusts may be explained by duplex structures.

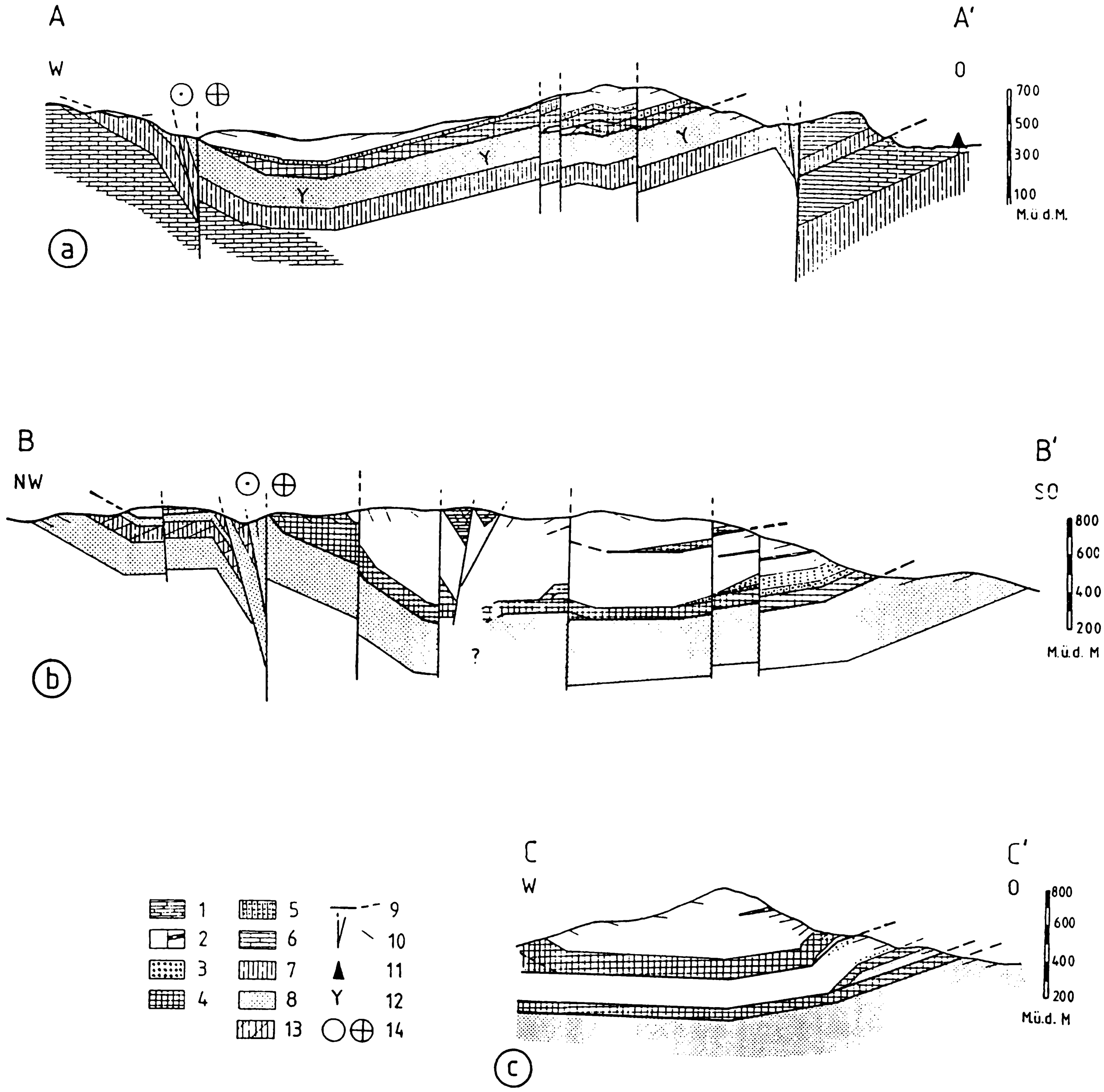

Fig. 4: Sections parallel to the direction of nappe emplacement in the northwestern part of the Graz Thrust Complex (after Fritz, 1991) shows mode of stacking. Fig. 4a is parallel to section B-B', Fig. 4b and 4c parallel to E-E' in Fig. 1. Legend: 1 - Barrandei-Fm; 2 and 3 - Dolomit-Sandstein-Fm; 4 and 5 - Parmasegg-Fm (all Rannach nappe); 6 - Schöckl-Lmst.; 7 - Arzberg-Fm; 8 - 13 Waldstein-Fm (all Schöckl nappe); 9 - thrust; 10 - strike slip fault and normal fault; 11 - well; 12 - inverted portions; 14 - sense of movement in strike slip zones.

Another example of two-phase stacking is seen along the northern margin of the GTC (Fig. 5). The section shows a double repetition of Early to Middle Devonian limestones of the Kalkschiefer nappe with Late Silurian and Devonian sediments of Laufnitzdorf nappe. This intermediate nappe pile is thrusted by Middle Devonian limestones of the Hochlantsch nappe. Again we interpret this special imbrication as a two-phase stacking with out-of-sequence thrusting. Thus, the Laufnitzdorf nappe was first thrusted onto the Kalkschiefer unit and stacking continued in further imbrication of both nappes and thrusting of the Hochlantsch nappe. The nappe transport inferred from stretching lineation and shear sense indicators is top-to-the-WSW to top-to-the-NW.

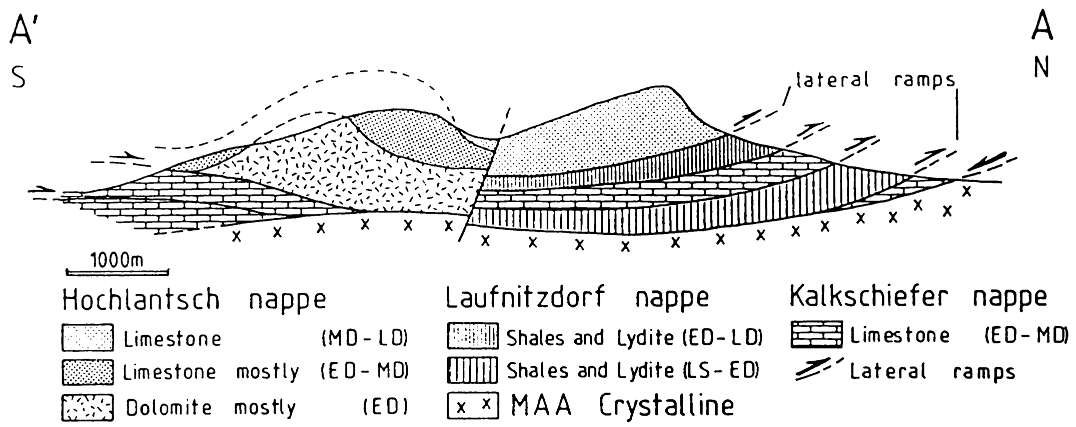

Fig. 5: Section parallel to A-A' in Fig. 1 modified after Gollner and Zier (1985) shows double stacking of nappes which is overprinted by extensional structures along the northern margin of the Graz Thrust complex.

Late Cretaceous extensional structures

Extensional structures are predominantly non-penetrative. Extension is accomplished by a system of NE-SW striking sinistral strike-slip faults and approximately N-S striking normal faults (Fig. 3). Examples for bulk extension arise from central parts of the Graz Thrust Complex and from the western margin (Neubauer, 1988; Fritz et al., 1991; Ratschbacher et al., 1991a) where extension resulted in the formation of the Gosau basin.

The western, northwestern and northern margins of the Graz Thrust Complex represent a system of NE-SW striking sinistral shear zones and East dipping decollements (Neubauer, 1988; Neubauer and Genser, 1990; Ratschbacher et al., 1991a). Arguments for extension on map-scale are the dramatically reduced lithotectonic profile, the oblique cut of nappes by the basal decollement zone, and the metamorphic break at the western and northern margin of the GTC. Confrontation of displacement directions, W-directed between internal nappes of the GTC and E-directed at the base to the Middle Austroalpine crystalline is interpreted in change of compression to extension (Fritz, et al. 1991). Extensional deformation continued in late Cretaceous time and affected also basal Gosau sediments which are incorporated in the sinistral shear zone along the northwestern margin of the GTC (Fig. 1).

Microfabrics indicating low temperature plasticity of quartz and calcite suggest that normal faults and sinistral shear zones were active under greenschist metamorphic conditions at the basal parts of the GTC . Textures indicate operation of sinistral strike slip displacement along NE-SW oriented faults together with E-dipping normal faults. Within the Gosau sediments respectively at the base of Gosau, paleostress analyses and the pattern of extension veins indicate E-W extension.

In the Schöckl nappe sinistral strike slip is achieved by semiductile steep shear zones. Widely spaced ecc surfaces cut the metamorphic layering which was created during previous deformations. In higher portions of the nappe pile discrete NE-SW striking faults are common.

Post-Gosauian faulting

Horst and graben structures north of Graz are bound to W-E striking faults. These faults are themselves cut by N-S striking normal faults with downward movement of the eastern blocks. The kinematic frame of these faults points to vertical shortening and E-W extension as commonly observed in Neogene faults of the Eastern Alps (Neubauer, 1988; Ratschbacher et al., 1991b). Continental scale extrusion of the consolidated Eastalpine block and formation of the Pannonian basin may be correlated with this system of faults commonly observed east of Tauern Window (Neubauer, 1988; Neubauer and Genser, 1990; Ratschbacher et al., 1991b).

Timing of the events

From the sedimentary record the upper limit of thrusting in the Graz Thrust-Complex is given by the overstep sequence of the Gosau with approximately 80 Ma. Although there is geochronological evidence for a pre-Alpine metamorphic event it is very likely that thrusting occurred during the Early Cretaceous (approximately 120 Ma) (Flügel et al. 1980; Fritz, 1991; Dallmeyer et al., in prep.). This is supported by geochronological data which point to Early Cretaceous compression in the Upper Austroalpine nappe pile (Kralik, et al., 1987; Frank et al., 1987, Ratschbacher et al., 1989).

Extensional regime is clearly connected with the formation of the Gosau basin. In addition, mineral ages of hornblende, biotite and white mica indicate rapid cooling of the metamorphic Gleinalm complex between 100 Ma to 80 Ma. This cooling is related to uplift in the metamorphic Gleinalm complex and relative down-dip movement of the Graz Thrust Complex during within a sinistral wrench corridor.

Discussion

Structural investigations indicates that the record of Variscan deformation in the Graz Thrust Complex was only minor. In addition, the continuous sedimentation up to the Westfalian in shallow marine facies suggests that this area had been in an external position relative to the main Variscan front.

Timing and evolution of Alpine structures is typically for the Upper Austroalpine nappe pile (e.g. Ratschbacher and Neubauer, 1989; Ratschbacher et al., 1989). Progressive change of extensional directions from approximately SW to NW is explained by transpressive collision between an Adriatic block and a segment of the Cimmerian terrane. The Graz Thrust Complex occupied an upper plate position during plate collision. Subsequent orogen-parallel extension and basin formation occured in two distinct periods and may be explained by lateral extrusion of crustal pieces in Late Cretaceous and Neogene times (e.g., Neubauer, 1988, Ratschbacher et al., 1989).

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REMARKS ON THE BIOGEOGRAPHICAL RELATIONSHIP OF THE GRAZ PALAEOZOIC UNIT

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Geologist's troubles to point out faunal relationships between the Palaeozoic of Graz and other remnants of the Palaeozoic, especially the Rhenish Slate Mountains date back to the last century (e.g. Suess, 1868). But till now all these efforts have been failed because of incorrect determinations, misinterpretations of taxonomy, macrobiosis of the referred organisms, etc.

Especially the strongly fossiliferous late Emsian to Eifelian formations of the Palaeozoic of Graz (particularly the Barrandei Limestone) seem to be designated to point out faunal relations. These successions have been studied by palaeontologists for more than 100 years. According to these studies a large number of fossils has been recorded (see Flügel, 1975):

Dasycladacean and Udoteacean Green Algae: 3 genera, 3 species
Stromatoporoids: 9 genera, 15 species
Rugose Corals: 18 genera, 21 species
Tabulate Corals: 11 genera, 30 species
Gastropodes: 7 genera, 13 species
Bivalves: 8 genera, 5 species
Cephalopods: 1 genus
Trilobites: 1 genus
Eridostraca: 2 genera, 2 species
Bryozoan: 1 genus
Brachiopodes: 28 genera, 37 species
Conodonts: 3 genera, 6 species

The usefulness of these fossils is somewhat limited by the fact that most of the identifications were carried out during the last century and revision is required urgently. Also, a great number of type localities is now inaccessible or cannot be found, so that re-sampling is curtailed: The typoids of the brachiopodes cannot be found thus precluding a revision.

Obviously it is quite easy to draw incorrect conclusions when one compares the listings of fauna - especially since the same or similar uncertainties could have affected other listings of faunas as well.

To achieve reliability of faunal correlations it is of paramount importance that only modern publications are consulted that are based on state-of-the-art taxonomy and systematic, otherwise any further statements of a more general nature will become pseudo-scientific fancies.

When you take these aspects into account it is impossible at this stage to establish quantitative patterns of faunal affinities or similarities (e.g. to calculate affinity indices after Johnson, 1971; or similarity coefficients after Clark and Hartleberg, 1983 or others). For this reason it is wise to restrict oneself to quantitative comparisons. But also in this case it is of crucial importance to use only well defined taxa. Likewise conodonts are nearly of no use because they are very abundant fossils distributed worldwide and therefore impracticable. Green Algae as well as some tabulate and rugose corals and the Brachiopod genus Zdimir of the Middle Devonian of Graz can be used because their taxonomy was subjected recently to detailed studies.

Zdimir, for example is a common fossil of the upper parts of the Barrandei Limestone Formation (Zdimir cf. hercynicus; Boucot and Siehl, 1962); it has been an essential fossil for biogeographical considerations for quite a long timespan of palaeontological and stratigraphical research and not least it is a leading fossil of the Eifelian of Belgium and the Harz area (cf. Flügel, 1975).

Currently some 15 species of Zdimir are known distributed worldwide from Spain, the Rhenohercynian zone, the Uralian area to China (Boucot and Siehl, 1962; Sapelnikov et al., 1981; Bai and Bai, 1988). This genus apparently lived in a special narrow environment (transitional between a dacryoconarid-ammonite biofacies and a spiriferid-coral-biofacies) and perhaps - following the assumptions by Bai and Bai (1988) - their occurrences are restricted to a well defined time span ranging from the seriotinus conodont zone of Upper Emsian to the partitus conodont zone of Lower Eifelian. However, Zdimir seems to be a good fossil for palaeobiogeographical studies (Fig.1a).

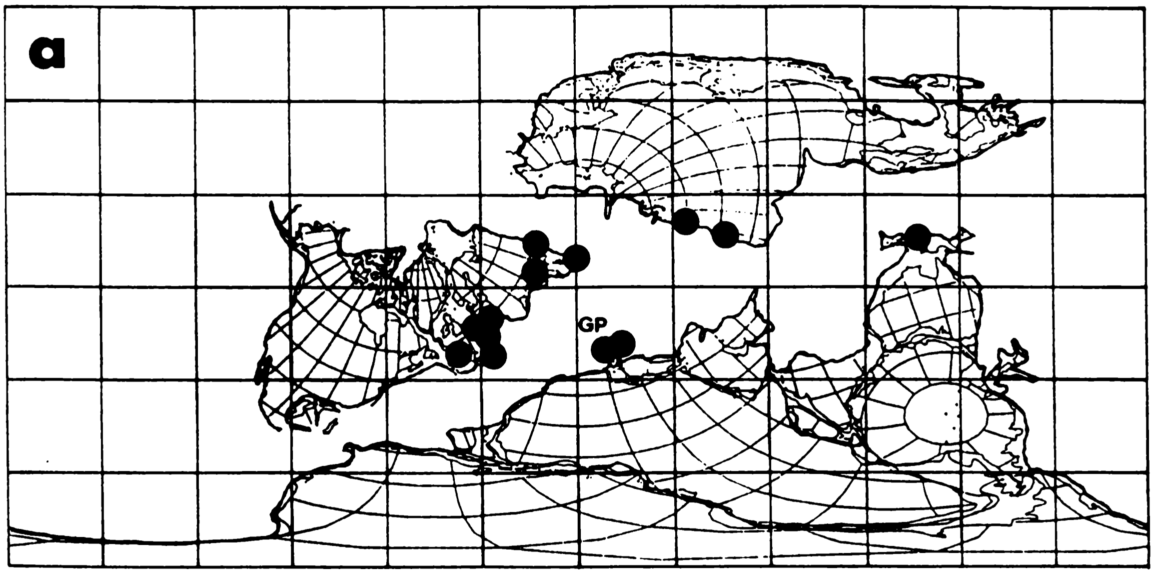

Fig.1a) Distribution of Zdimir. Middle Devonian base map of Smith, Hurley and Briden (1981). Cylindrical equidistant projection.

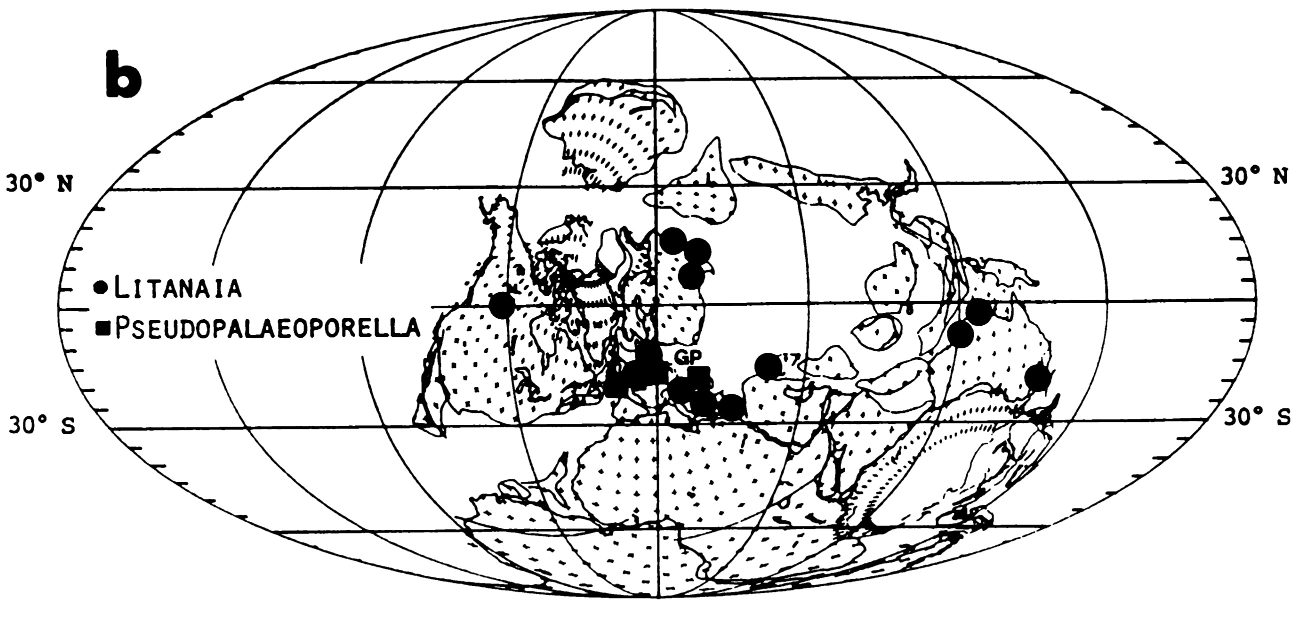

Fig.1b) Distribution of Litanaia and Pseudopalaeoporella. Middle Devonian base map after Scotese and McKerrow (1990). Mollwide projection.

Rugosa show no uniform trends (west-European forms may be predominant), but in particular the genus Thamnophyllum gives the coral fauna a certain appearence and show some affinities to the Devonian of Poland (cf. Flügel, 1975). Tabulate corals indicate connections with the Rhenohercynian zone, the Moravian Karst and the Cantabrian mountains (Hubmann, 1991). The former and the latter have also in common with the Devonian of Graz some floral elements (Pseudopalaeoporella lummatonensis; Hubmann, 199O). The Udoteacean genera Litanaia and Pseudopalaeoporella (calcified benthonic green algae) were also distributed worldwide within the intertropical climate zone

(3O°N and S of the palaeoequator) during (Middle) Devonian times (Fig.1b). Especially Pseudopalaeoporella lummatonensis is currently known only from 5 localities in the European realm. They all are known from the Rhenohercynian zone exept the ones of the Devonian of Graz which represent findings of the Gondwanian shelf (Fig.1c). Recently Pseudopalaeoporella lummatonensis was discovered in the Devonian of Cantabria/Spain (Herrmann and Hubmann, in prep.). Both occurrences, the Austrian and the Spanish indicate that these basins were in connection with the Rhenohercynian basin, which enabled gene drift over these areas.

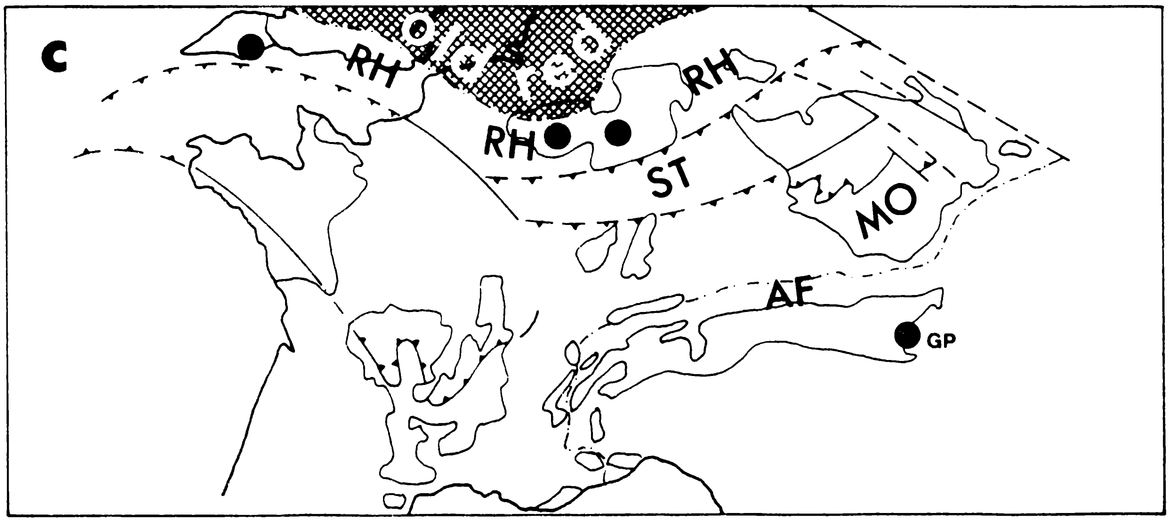

Fig.1c) Localities of Pseudopalaeoporella lummatonensis (ELLIOT) within the European realm. Tectonostratigraphic subdivision of the variscan belt after Franke and Engel (1986).RH: Rhenohercynian; ST: Saxothuringian; MO: Moldanubian; AF: Alpine front; GP: Graz Palaezoic

However, only few indisputable data are now available to allow reliable biogeographical interpretations and therefore the statement presented herein should be viewed as a preliminary rather than as a solidy based permanent one.

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EVOLUTION OF LOWER AUSTROALPINE UNITS ALONG THE EASTERN MARGINS OF THE ALPS: A REVIEW

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Introduction

Lower Austro-Alpine tectonic units are widespread along the eastern margins of the Alps (Fig. 1, 2). These units contain various polymetamorphic basement complexes and Permo-Triassic cover sequences, the latter mainly exposed along the northern margin of these tectonic units (Figs. 1, 2).

Tatric Units

In the transition zone of the Eastern Alps to the Carpathians, a basement complex is exposed which belongs rather to the Western Carpathians than to the Alps because of distinct facies in Permo-Mesozoic cover formations (Fig. 1). The Tatric basement is composed of paragneiss, staurolite-bearing micaschist, quartzitic biotite phyllite, and greenschist which include carbonatic layers (Tollmann and Spendlingwimmer, 1978; Wessely, 1961). The paragneiss and micaschist are intruded by a granitoid pluton which includes two-mica granite, granodiorite and leucogranite comparable to the Bratislava pluton of the Little Carpathians. The phyllite is correlated by Tollmann and Spendlingwimmer (1978) to the Lamac Fm. of the Little Carpathians. In the Little Carpathians, the age of metamorphism is probably Devonian constrained by a Rb-Sr isochron of 380 +/- 20 Ma (Cambel and Kral, 1989). The Bratislava pluton gave an age of 347 +/- 4 Ma (Cambel and Kral, 1989). In contrast to the Raabalpen Complex, the Alpine metamorphism and penetrative deformation is weak.

Wechsel gneiss complex

The Wechsel gneiss complex occurs within the Wechsel window and some additional isolated windows (Fig. 2) in the transition zone of the Eastern Alps to the Neogene Pannonian basin (Tollmann, 1978) (Fig. 3). A detailed correlation between different windows is not done up to now.

The Wechsel gneiss complex (Fig. 4)consists of a thick package of monotonous albite porphyroblast paragneiss ("Monotonous Wechsel gneiss complex") and a structural higher complex which includes other lithologies like quartzites, epidote amphibolites, acidic orthogneiss, black schists and black paragneisses ("Variegated Wechsel gneiss complex") (Faupl, 1970, 1972; Neubauer, 1990, Vetters, 1970). The footwall boundary of the Wechsel gneiss is not exposed. The hangingwall is formed by a series of quartzphyllite-like rocks, the Wechsel phyllites and Permo-Mesozoic cover rocks. In other windows, the Variegated Wechsel gneiss complex is dominates with regard to the wide range of lithologies from albite porphyroblast gneiss, black quartzites and gneisses, and the thick leucocratic Wiesmath orthogneiss (Fuchs, 1962; Pahr, 1980). In the more northern windows, the monotonous albite porphyroblast gneiss is prevailing up to the Leitha Mountains.

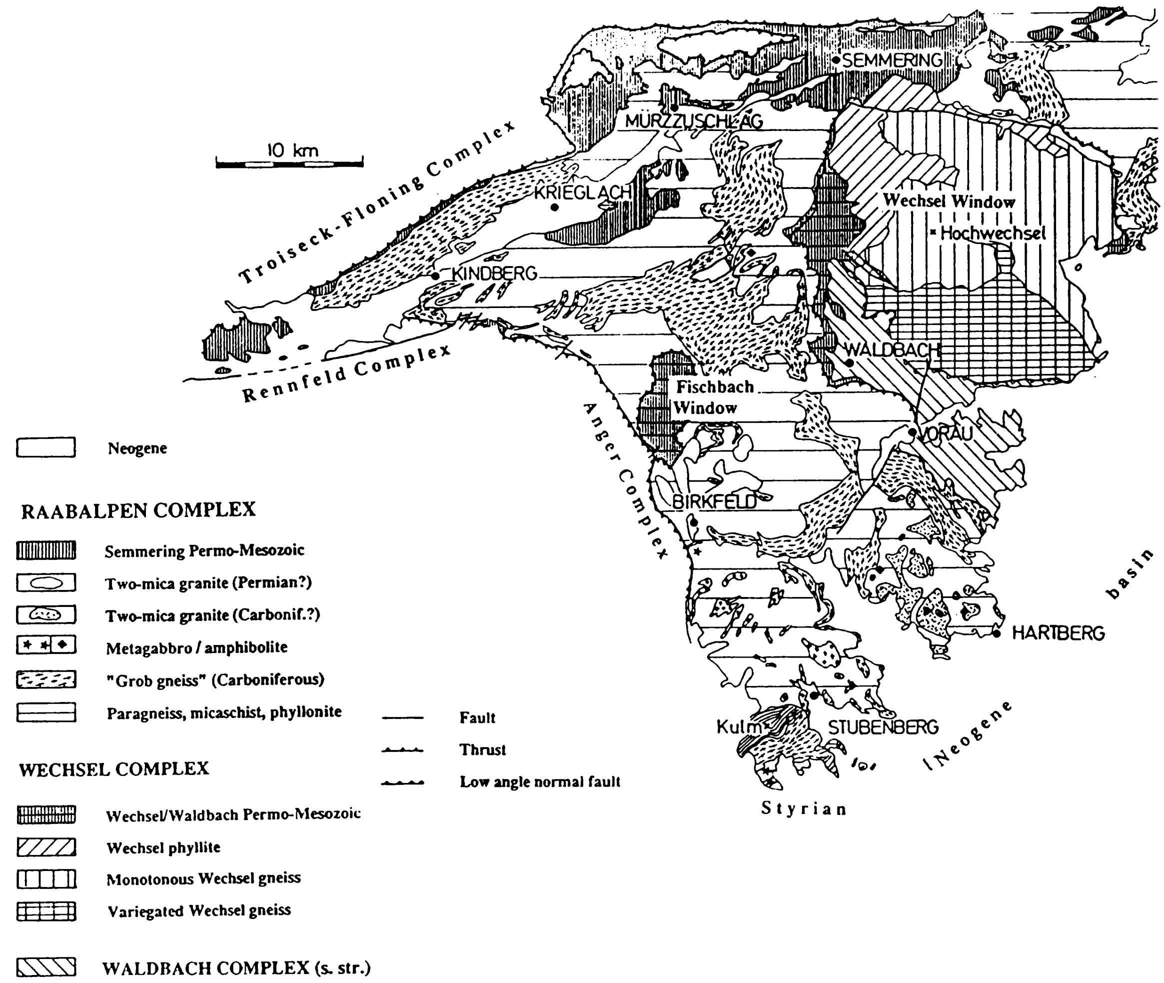

Fig. 1: Simplified tectonic map of the western part of Lower Austro-Alpine units along the eastern margin of the Alps.

The thick package of albite porphyroblast paragneiss exhibits petrographic and chemical features of somewhat altered graywackes and shales (Fig. 5; Neubauer, 1990). Based on major, minor, trace and rare earth elements, the mafic rocks have a mafic subalkaline chemistry comparable to that of a modern supra-subduction zone environment (Fig. 6). The sheetlike orthogneisses are strongly altered and have also some geochemical features comparable to those of suprasubduction zone environments. The protolith ages of all these rocks are uncertain.

Therefore, the Wechsel gneiss complex is interpreted as the product of an active continental margin (Neubauer, 1990). The essential arguments for this interpretation are the chemistry of igneous rocks, the presence of polycyclic, metasedimentary zircons in meta-quartz arenites, and the occurrence of massive Cu-sulphides at the hangingwall boundary of the Wechsel gneiss complex (Tufar, 1968).

The metamorphic overprint of the Wechsel gneiss complex is polyphase. Within the southern part there is evidence for a first epidote amphibolite facies stage later overprinted by retrogressive formation of albite porphyroblasts within higher greenschist facies conditions. Rb-Sr and 40Ar/39Ar ages with 380 - 370 Ma from phengitic white mica indicate an intra-Devonian age of a pressure-dominated metamorphic event (Müller et al., 1992; Dallmeyer et al., this vol.). The relationship of these white micas to the albite porphyroblast growth is uncertain. However, the metamorphism has been accompanied by polyphase folding suggesting approximately N-S compression within the present geographic framework.

The hangingwall boundary of the Wechsel gneiss complex to the Wechsel Phyllite is previously thought to be a possible primary contact. Recent investigations indicate that this boundary is a zone of ductile W to SW-directed thrusting or, more reliably, a ductile low angle normal fault

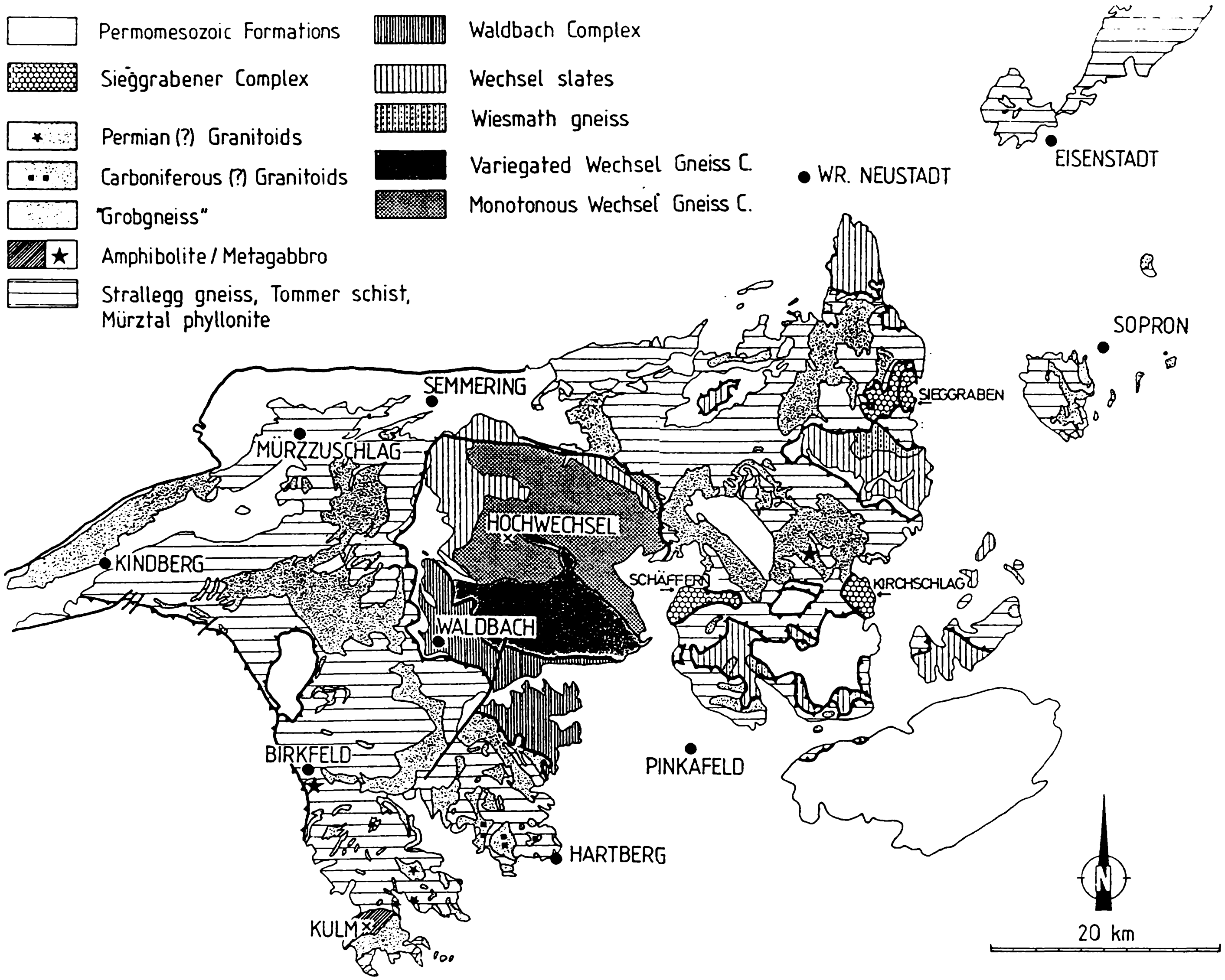

Fig. 2: Simplified tectonic map of the eastern part of Lower Austro-Alpine units along the eastern margin of the Alps.

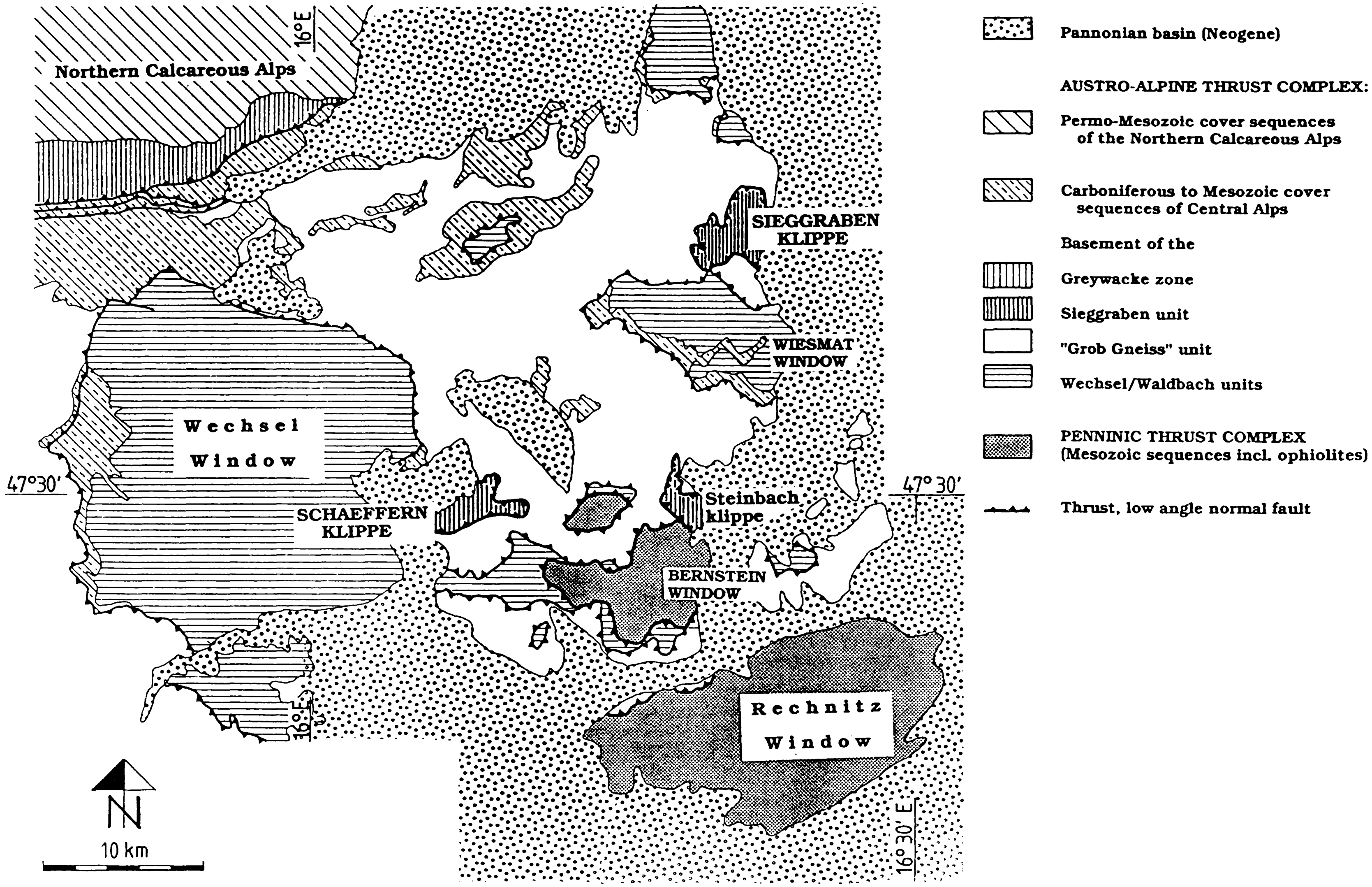

Fig. 3: Map of the Lower and Middle Austroalpine basement nappes at the eastern margin of the Eastern Alps (from Neubauer and Frisch, in press).

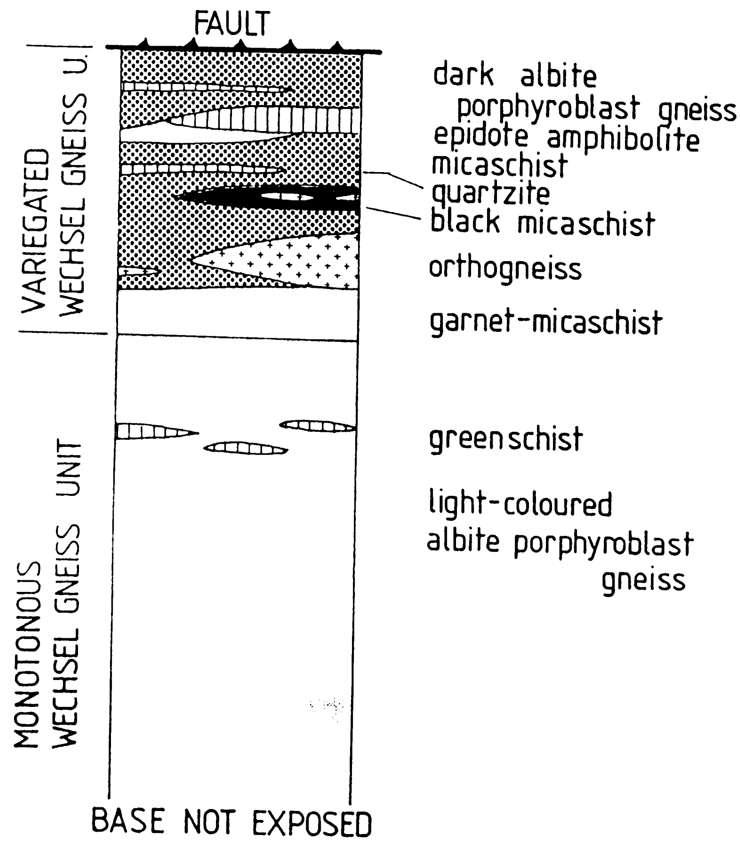

Fig. 4: Log of the Wechsel gneiss complex (from Neubauer, in prep.).

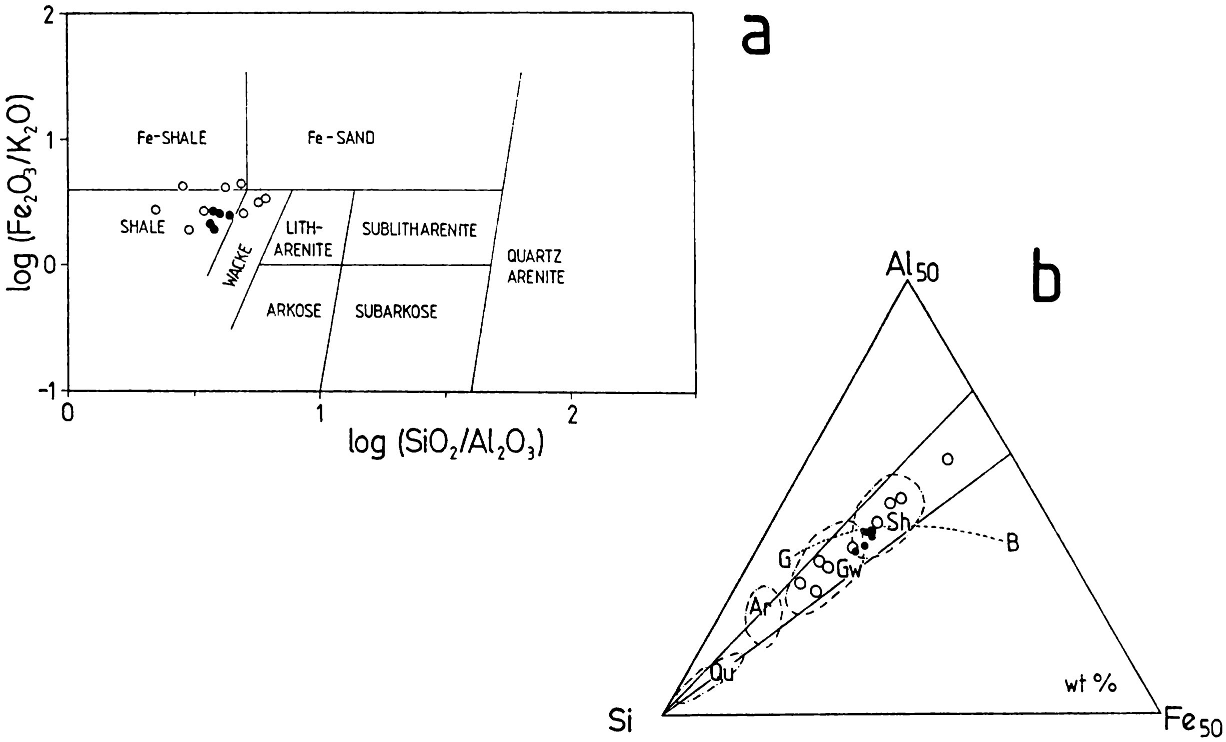

Fig. 5: Chemical discrimination of the Wechsel gneiss (from Neubauer, in prep.).

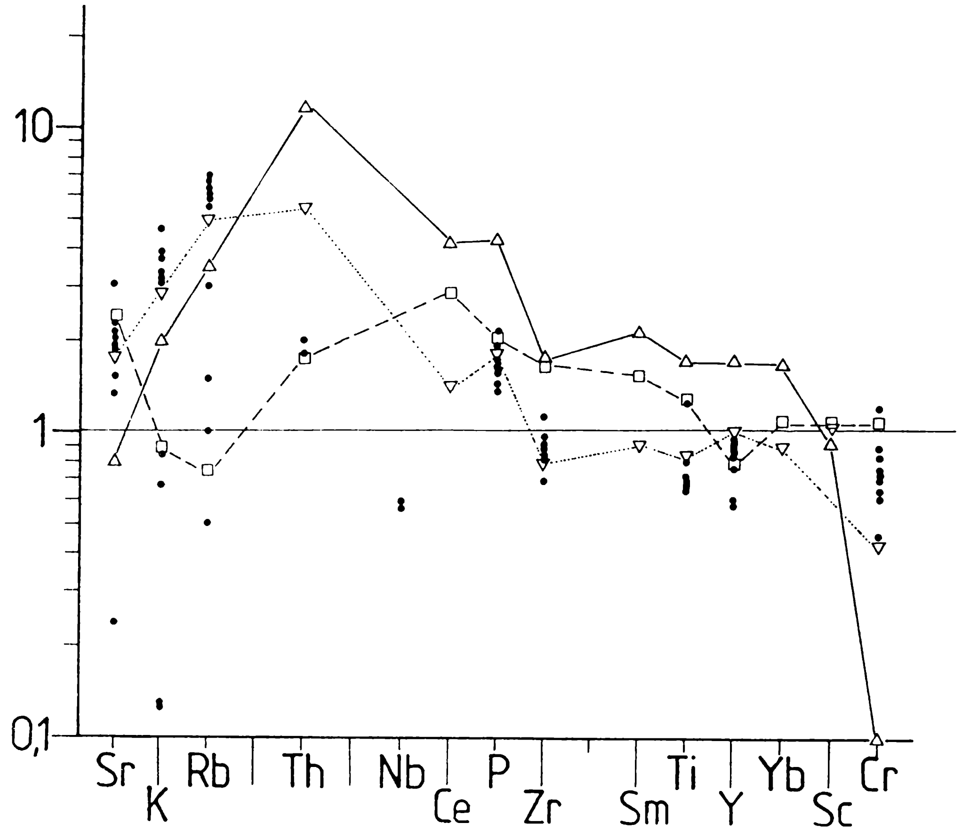

Fig. 6: Spider diagram of epidote amphibolites and greenschists from the Wechsel gneiss complex (from Neubauer, in prep.).

which indicates the emplacement of a Wechsel Phyllite nappe after raeching the metamorphic peak of the Wechsel gneiss complex (Neubauer and Pischinger, in prep.). A late Variscan age of retrogression (270 - 240 Ma, Late Permian) can probably be inferred from Rb-Sr ages of paragonitic white mica (Wechsel gneiss), Rb-Sr mineral isochrons (white mica - chlorite - whole rock) of the Wechsel Phyllite, and 40Ar/39Ar age spectra first increments at approximately 250 Ma. These ages may proof activity along the ductile fault mentioned above during Permian extension with ongoing subsidence and/or thermal influence by Permian volcanism.

The Fertörakos complex in westernmost Hungary has been correlated with the Wechsel gneiss unit by most authors (e.g., Kovach and Svinghör, 1981; Lelkes-Felvari et al., 1984). In that complex, amphibolites prevail besides phyllitic rocks and marble. A Rb-Sr age of a pegmatitic white mica is at 354 Ma (Kovach and Svinghör, 1981). These lithologies suggest major differences to the Wechsel gneiss complex.

Wechsel Phyllites

The Wechsel Phyllites occur within the Wechsel window and other comparable windows at the northeastern margin of the Eastern Alps. In the Wechsel window, the section comprises dark phyllites, black phyllites, volcanogenic graywackes and rare mafic schists and leucocratic metatuffites (Faupl, 1970; Vetters, 1970; Matura, 1990). In other windows, the Wechsel phyllites are accompagnied by the Wiesmath gneiss. The protolith age of the Wechsel phyllites is uncertain. Planderova and Pahr (1983) described mixed floras of sporomorpha which have a range from Silurian to earlymost Permian. These authors interpreted the protolith age of the Wechsel phyllite to be late Carboniferous to earlymost Permian. However, this age is unusual for quartzphyllite in the Eastern Alps and needs further proof.

Waldbach Complex

Along the southern margin of the Wechsel gneiss complex, the polymetamorphic Waldbach Complex is on the top of the former one, separated by a low angle normal fault. It consists of phyllitic micaschist at the structural base, intermediate orthogneisses (hornblende orthogneiss), various amphibolites, thin layers of garnet micaschists, ore-bearing black schists and quartzites, stratiform sulphides on the top of amphibolites (Faupl, 1972; Huska, 1970; Neubauer, 1983; Tufar, 1963). Limited petrographical and geochemical data suggest that major portions of amphibolites are derived from gabbros, hornblende gneisses from dacitic/tonalitic to granodioritic sequences. Therefore, these hornblende gneisses and amphibolites may represent an island arc magmatic sequence of unknown, pre-Alpine age. The widespread concordant polymetallic mineralization (Tufar, 1963) is in accordance with this interpretation. The pre-Alpidic metamorphic overprint reached amphibolite facies conditions, and locally, partial melting of rocks occurred (Faupl, 1972). Discordant pegmatites postdate peak conditions of pre-Alpine metamorphism and ductile deformation.

A relationship of the Waldbach crystalline complex to the Core complex of the Middle Austroalpine basement nappe is supposed because of comparable lithologies.

Although new grown staurolite, evidence for amphibolite facies conditions, can be locally observed within confining shear zones the Alpine metamorphic overprint is apparently within greenschist facies. Alpine deformation resulted in recumbent folds with E-W trending fold axes and related, steeply southerly dipping axial surface foliation fans. Confining shear zones operated within greenschist facies conditions during exhumation of the Wechsel Window.

"Grobgneis Complex"

The "Grobgneis" complex is exposed Northeast and West to the Wechsel window (Fig. 2). Other terms for this lithotectonic units are Raabalpen crystalline complex (west of the Wechsel window) or Eselsberg complex (east of the Wechsel window) (Flügel and Neubauer, 1984; Fuchs, 1965; Tollmann, 1978).

Metasedimentary and metavolcanic sequences

The "Grobgneis" complex is composed of migmatitic paragneiss (Strallegg gneiss), micaschist (Tommer schist), and phyllonite (Mürztal and Birkfeld quartzphyllites), respectively of minor intercalations like talc schists, clinopyroxene-bearing amphibolites, quartzites, kyanite-bearing quartzites and tourmalinites (Cornelius, 1952; Flügel and Neubauer, 1984; Moreau, 1981; Peindl, 1990). The age of deposition is uncertain but predates intrusion of various granites of Carboniferous age. Geochemical patterns of rocks surrounding the talc deposit Rabenwald argue for an evaporitic environment of the formation of country rocks (Moreau 1981).

The main metamorphic event is the pre-Alpine migmatitization of the metapelites in southern areas, and pre-Alpine amphibolite facies conditions within the stability field of staurolite in northern areas (Tommer micaschist). The intensity of (Early) Alpine metamorphism decreases from the amphibolite facies conditions in the southern areas of the Raabalps to a greenschist facies metamorphic overprint in the northern area.

The Strallegg Gneiss is a migmatitic, locally alumosilicate-bearing, biotite-rich paragneiss with a stromatitic foliation. Boudinage of the stromatitic foliation causes accumulation of leucosome in the necks being between the boudins (Peindl, 1990) indicating synkinematic anatexis.

The Alpine metamorphism causes a very strong change in the mineral contents of the melanosome: biotite is changed to sericite by the following reaction: biotite + K-feldspar + quartz + Tschermak-molecule = muscovite (Thompson, 1982). Well preserved Strallegg Gneiss occurs preferably in the southern part of the Raabalpen complex and in the area between Vorau and Birkfeld.

Amphibolites occur as metre- to decametre thick lenses within paragneisses and along margins of orthogneiss bodies. In the southeastern Raabalpen complex three amphibolite varieties occur:

(1) Clinopyroxene- and brown hornblende bearing amphibolites;

This group occurs always in combination with granitoids. This type is interpreted as being large xenoliths in the granites.

(2) Amphibolites and hornblende gneisses with brown hornblende but without clinopyroxenes occur within a few meters thick and a few hundred meters long lenses.
(3) Green and/or colourless hornblende-bearing amphibolites.
They are the retrograde metamorphic products of the two amphibolite types mentioned above.

Preliminary geochemical data of some further amphibolites from southwestern Raab Alps have geochemical signatures of continental within plate basalts based on low La_N/Yb_N ratios (ranging between 1.5 and 4), relatively high Nb and Th contents.

Although the Alpidic overprint reached regionally variable greenschist to amphibolite facies, the pre-Alpine mineral assemblages are well-preserved in some areas (Koller and Wieseneder, 1981). A recent estimate of the Alpidic metamorphic overprint of the southwestern area is 500 - 550^{0}C and 8 - 9 kb (Moine and others, 1989). Some stages of pre-Alpidic metamorphism may be recognized because of the relationship to Carboniferous and Permian intrusions (Peindl, 1990; Peindl and others, 1990). A first stage of metamorphism predates Carboniferous intrusions and reached partial melting in metapelites. The peak metamorphic conditions were reached after the intrusion of the muscovite-biotite granites by progressive decomposition of muscovite in granites to potash feldspar and sillimanite (Peindl, 1990). Therefore, the peak metamorphic conditions which can be described as localized granulite facies took place after intrusion of the first generation of two-mica granites between early Carboniferous and Permian.

Variscan plutonic suites

Granitoid gneisses are widespread within the "Grob gneiss" Complex. Recent field work and detailed Rb-Sr geochronologic work (see Tab. 2) exhibits an imagine of complex intrusional relationships. The most widespread rock, the "Grob gneiss", is a coarse-grained, porphyric, sheetlike granite gneiss which includes rare lenses of tonalite/diorite gneiss. Along margins of the Grob gneiss, well-preserved gabbros occur, e.g. the gabbros of Birkfeld and Landsee. Further metagabbros have been identified recently in the Kulm area at the southwestern margin of the "Grobgneis complex". The metagabbros of the Kulm may be of Permian age because they postdate the pre-Alpine metamorphism (see below). The Rb-Sr age of the "Grobgneis" is 338 +/- 12 Ma (Sr_0 = .7071 +/- .0006). A little body of fine-grained, porphyric hornblende to biotite metatonalite occurs in the southern area (Peindl, 1990; Peindl et al., 1990). The Rb-Sr age is 343 +/- 20 Ma with an Sr initial ratio of .7057 +/- .0003. A suite of isolated muscovite granite bodies is widespread in the southeastern Raabalpen crystalline complex. Further two-mica granite gneisses exhibit subsolvus granite mineralogy with often well-preserved discordant contact haloes to the country rocks. They are more differentiated in relation to the Grobgneis. A Rb-Sr isochrone of such rocks yielded an age of 326 +/- 11 Ma and a Sr initial ratio of .7068 +/- .0019 (Peindl, 1990; Peindl and others, 1990).

A further suite of isolated garnet-bearing muscovite-biotite granite gneisses occur in the area west of the former one (Fig. 2). The rocks yielded a Rb-Sr errorchrone of 243 +/- 12 Ma and a Sr initial ratio of ca. .7234 (Scharbert, 1990).

Detailed studies have been carried out in three regions: A detailed study about the "Grob gneiss" (Sassi, Zirpoli and Neubauer, unpubl. data), in the Masenberg - Hartberg section in the southeastern Raabalpen (Peindl, 1990) and in the Rabenwald - Kulm section of the southwestern ones (Moyschewitz, in prep.). Various granitoids and associated gabbros can be distinguished. The range of metagranitoids and metagabbros of the latter two areas in the Streckeisen diagram shows Fig. 7, the REE patterns are shown by Figs. 8 and 9. The location in the mol$Al_2O_3/(Na_2O+K_2O+CaO)$ versus SiO_2 diagram shows Fig. 10, the position in the log Rb versus log (Y + Nb) diagram Fig. 11, the position in the AFM diagram Fig. 12. Spider diagrams for the metatonalites and the Carboniferous two-mica granites are shown in Fig. 13.

(1) The **Grob gneiss** is a K-feldspar porphyroclasts-bearing augen gneiss. The size of the augen ranges between 1 and 15 cm. The modal composition is granitic, the groundmass consists of quartz, muscovite, plagioclase, some biotite, chlorite and epidote. Locally, there are intercalations of tonalitic/dioritic gneisses (Neubauer, 1983; Pahr, 1972). Geochemical data show the granitic composition of the Grobgneis. REE patterns (Kiesl et al., 1983; Peindl, 1990) show a strong enrichment of the light REE and a pronounced Eu-anomaly. A Rb-Sr isochron of the Grobgneis yielded an age of 338 $\pm$12 (Sr_0 = 0.7071 +/- 0.0006) (S. Scharbert, 1990).

(2) Some **Metagabbros** (Birkfeld, Landsee, Kulm, Pöllauberg) partly occur at the margins of the Grobgneis (Moyschewitz; in prep., Peindl, 1990; Schwinner, 1935). Some small lenses of

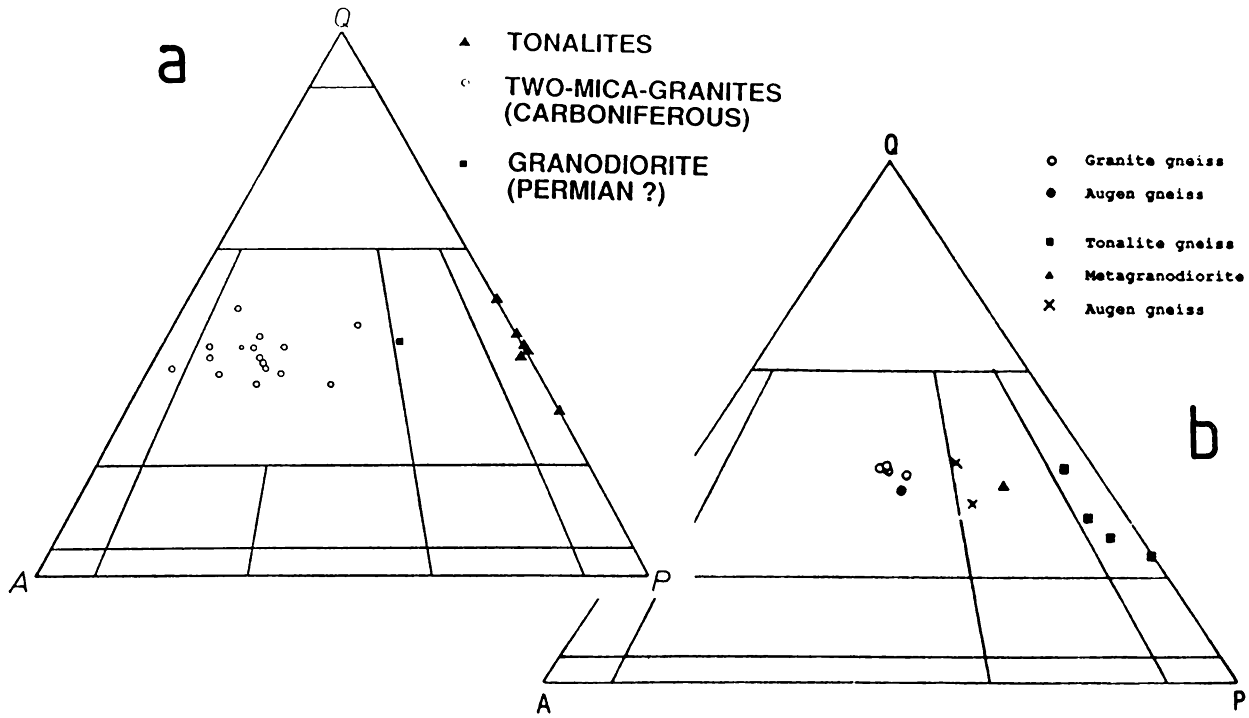

Fig. 7: Streckeisen diagram of the (a) granitoids in the area between Masenberg and Hartberg (Peindl, 1990), (b) granitoids and gabbros from the Kulm and Rabenwald (Moyschewitz, in prep.).

metagabbros can be found in the north of Birkfeld in the area between Ratten and Arzberg (Wieseneder, 1961), here called Eckberg Formation. This type often is completely altered to amphibolites which are to hardly distinguish from the amphibolites above mentioned. A small lens of a metagabbro with a very strong retrograde metamorphic imprint occurs 400 m SSE of the village Pöllauberg (Peindl, 1990).

(3) Small dykes of **metatonalites** not being connected with the Grobgneis occur only in one outcrop in the southeastern part of the Raabalpen (Peindl, 1990). Spider diagrams of the tonalites see Fig. 13. A Rb-Sr whole rock isochron yielded an intrusion age of 343 ± 20 Ma (Sr_0 = 0.7057 ± 0.0003) (Peindl, 1990).

Average modal composition:

	Hornblende-bearing	Biotite-bearing
Quartz	14 %	33 %
Plagioclase	34 %	45 %
Biotite	10 %	21 %
Hornblende	38 %	-
Accessories	4 %	1 %
	100 %	100 %

(4) **Two-mica granite gneiss**: The relatively fine-grained (maximum grain size about 5 mm) subsolvus-granites with varying modal compositions and textures appear in isolated bodies with sometimes clearly recognizable contacts with the country rock.

Geochemical features (Fig. 11) are similar to S-type syn-collisional granitoids. REE-patterns can be seen in Fig. 8.

Rb-Sr-dating (Peindl, 1990) yielded an intrusion age of 326 ± 11 Ma (Sr_0 = 0.7068 +/- 0.0019), see Fig. 15. Increasing temperature causes postintrusive desintegration of the magmatic muscovite, see below.

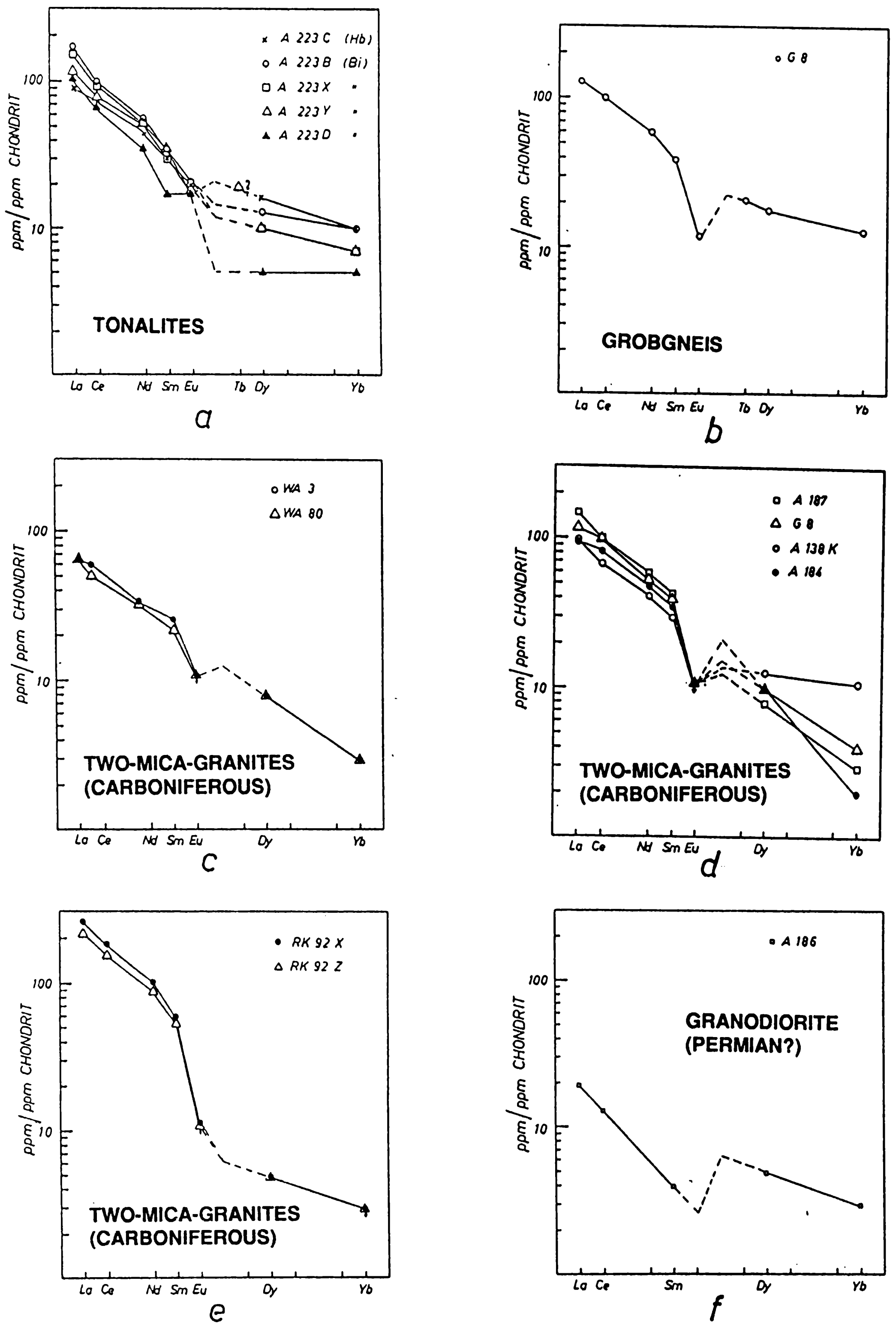

Fig. 8: REE patterns of the granitoids in the area between Masenberg and Hartberg (Peindl, 1990). (a) metatonalites; (b) Grob gneiss; (c), (d), (e) Carboniferous two-mica-granites; (f) Permian (?) granodiorite.

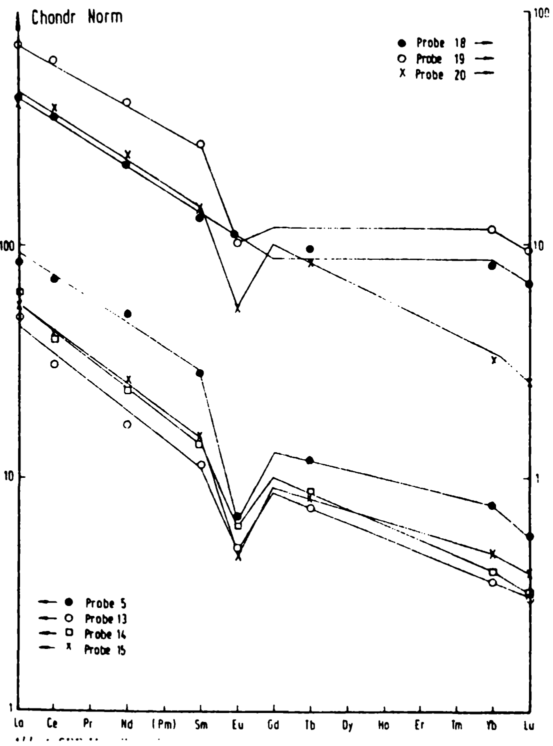

Fig. 9.: REE patterns of the Grobgneis (from Kiesl et al., 1983)

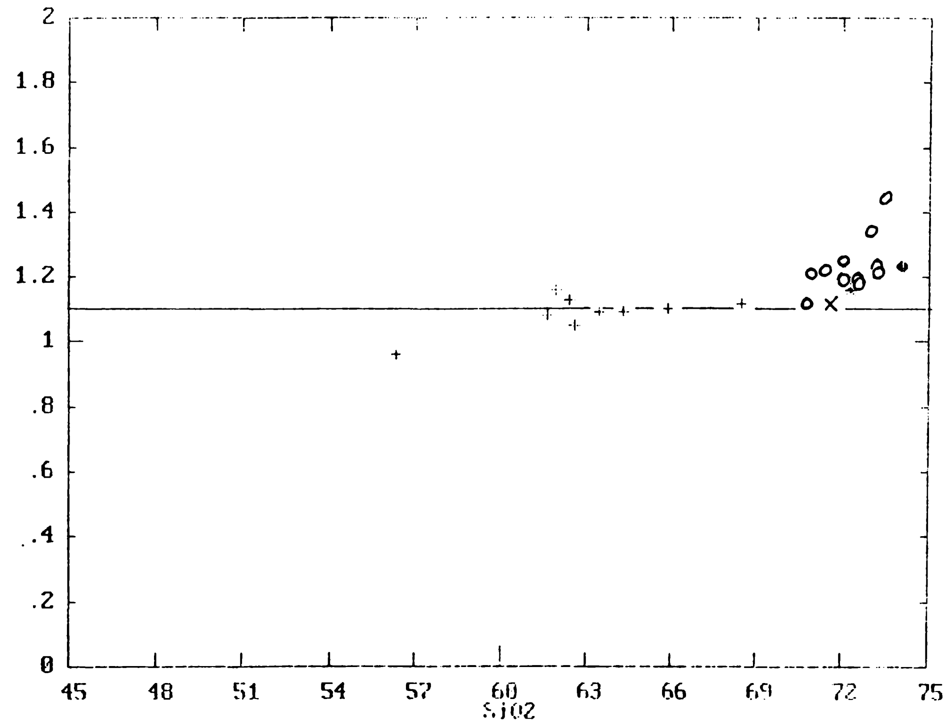

Fig. 10: Mol $Al_2O_3/(Na_2O+K_2O+CaO)$ versus SiO_2 diagram (Chappell and White, 1974) of the granitoids and of two metagabbroes (filled squares). Crosses: metatonalites; x: Grobgneis; open circles: two-mica granites (carboniferous); asterisk: Stubenberg granite; filled circle: granodiorite (Permian ?).

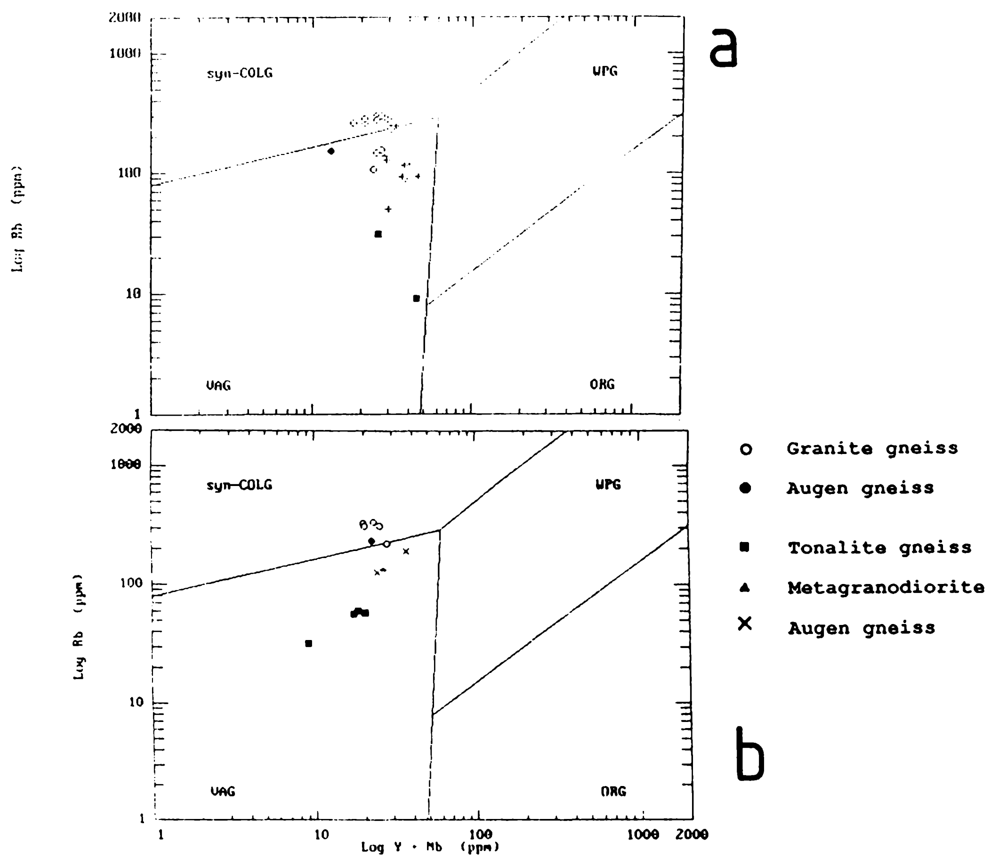

Fig. 11: Log Rb versus log (Y + Nb) diagram of Pearce et al. (1984) for the same rocks as in Fig. 7a, b. a) Granitoids from Hartberg - Masenberg; b) granitoids from Rabenwald - Kulm.

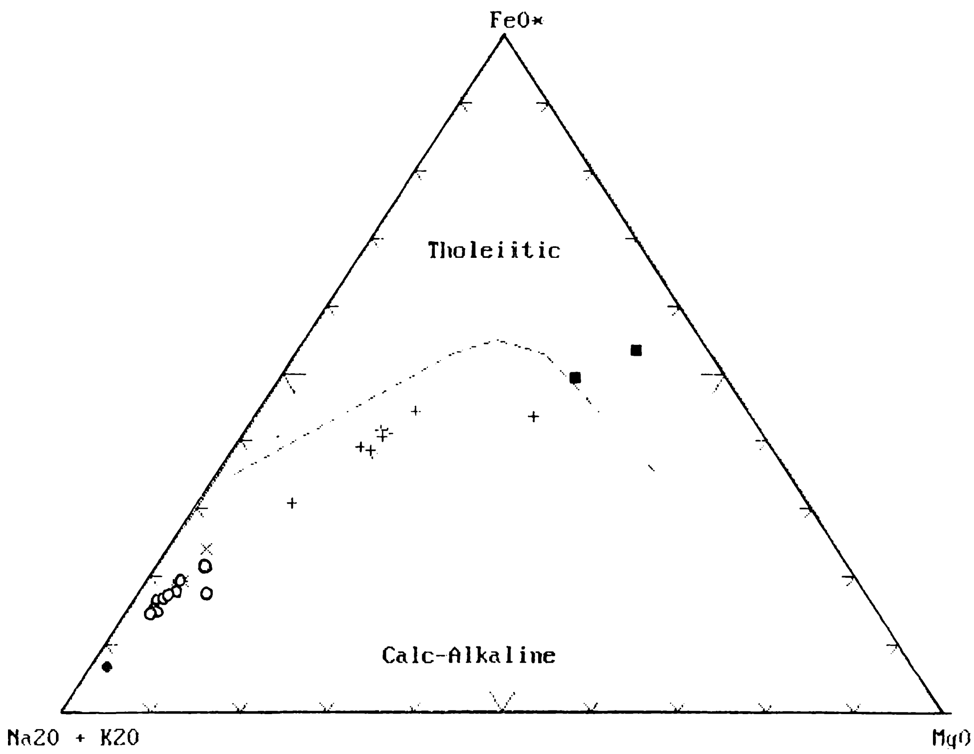

Fig. 12.: AFM diagramm of the same rocks as in Fig. 7a.

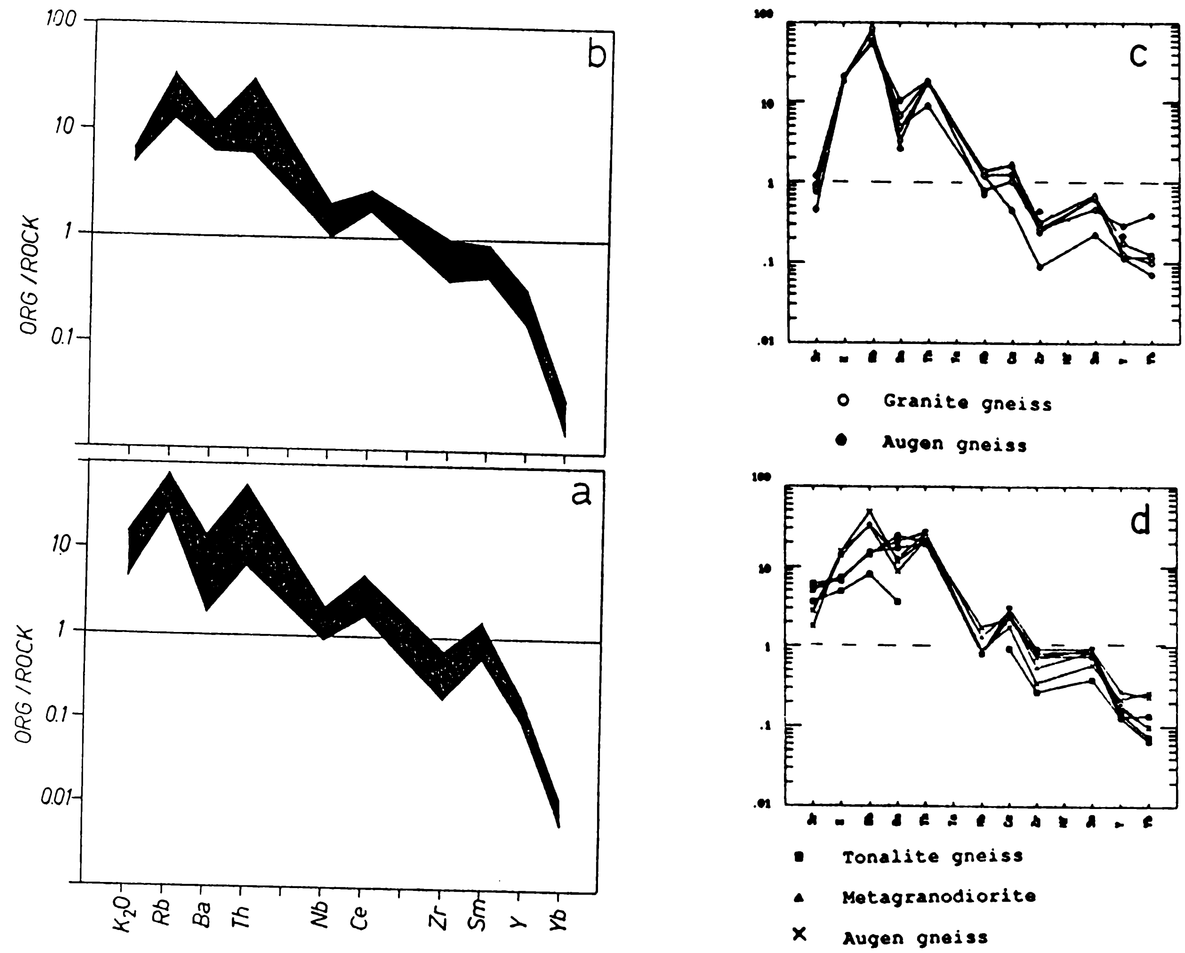

Fig. 13: Spider diagrams for the (a) Carboniferous two-mica granites, (b) metatonalites from the area between Masenberg and Hartberg, c) granites from the Kulm, d) granodiorites and tonalites from the southern Rabenwald. Normalization values from Pearce et al. (1984).

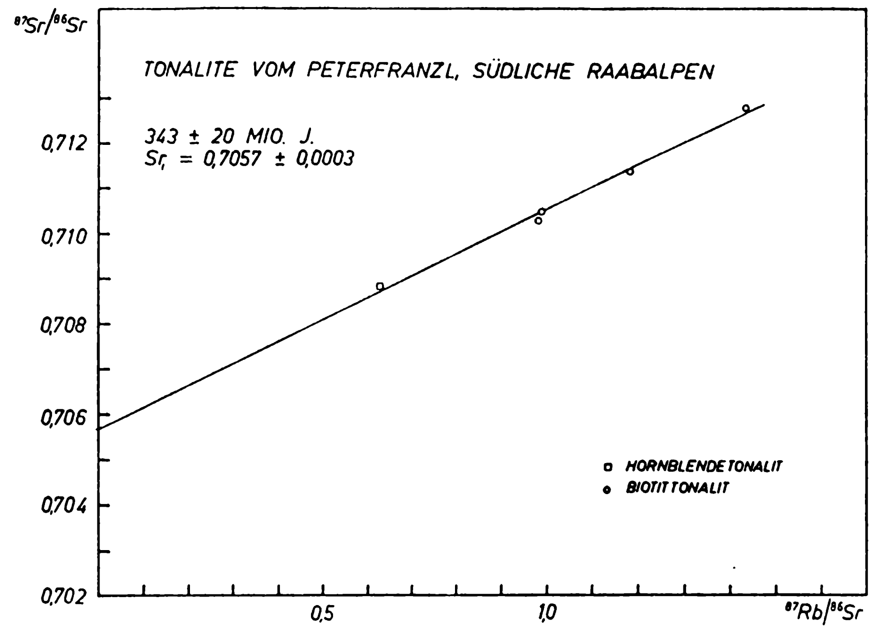

Fig. 14: Rb-Sr isochron of the tonalites (from Peindl, 1990).

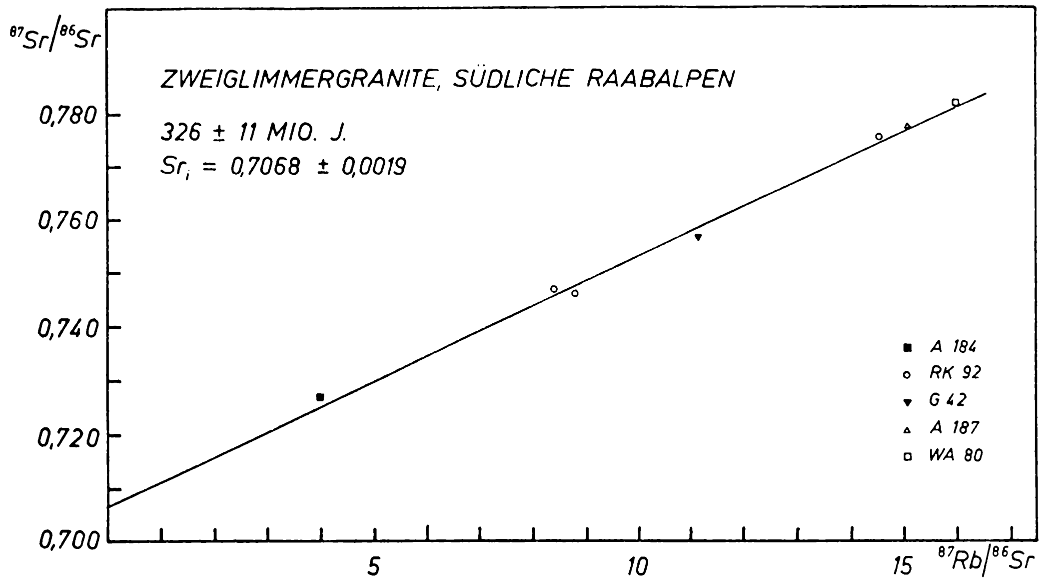

Fig. 15: Rb-Sr-isochron of the two-mica granites.

5) **Tonalite gneisses**, the **Buchkogel metagranodiorite** and biotite-rich augen gneisses of the Rabenwald/northern Kulm area, all with variable petrographic composition, are characterized by general calc-alkaline geochemical composition. High Al_2O_3 contents, highly fractionated geochemical patterns and low Sm/Nd ratios indicate limited crustal contamination.

(6) A **metagranodiorite** showing black patches occurs NW of Hartberg, at the southern slope of Wullmenstein. The black patches consist of magmatic muscovite with flakes of newly grown biotite.

There exists only one REE-analysis of this rock-type (Fig. 8) which yielded very low concentrations of the REE and a Th/U-ratio of 1 (Th = 2 ppm, U = 2 ppm). The content of Rb (153 ppm) and K_2O (5.58 %) is unexpected high. This rock type does not show the postintrusive high temperature metamorphism of the two-mica granites mentioned above. Similar rock types occur further in the W in the area between Rabenwald and the Stubenberg (Kiesl et al., 1983; Koller and Wieseneder, 1981). A Rb-Sr errorchron (S. Scharbert, 1990) yielded an age of these rocks of 243 ± 12 Ma (Sr_0 = 0.7234 ± 0.0017). The granodiorite from mount Wullmenstein is positioned exactly on this errorchron. A possible explanation for the genesis of this type is the contamination of a mantle-derived magma with crustal material.

7) **Two mica granite gneisses** and **microcline augen gneisses** form several bodies between Rabenwald and southern Kulm areas. Petrographic composition with high muscovite contents, high Rb contents ranging from 217 - 331 ppm, and the high Sr_0 ratio of 0.7234 mentioned above classify these granitoids as syn-collisional granites. The meaning of the errorchron is not really clear, but it is interpreted to show a possibly realistic, Permian intrusion age (S. Scharbert, 1990). Field relationships suggest that some of these two-mica-granite gneisses and the microcline augen gneiss may belong to the Carboniferous granitoids.

We interpret Early Carboniferous granitoids as syncollisional intrusions which are followed by late collisional I-type and H-type (hybrid) granitoids due to mixing of igneous and sedimentary sources. The Permian intrusions, granitoids and gabbros, are related to crustal extension, rifting and ongoing subsidence along the Tethyan margins. In addition, thin volcanic sequences in Permian cover sequences result from the same Permian plutonic/volcanic event.

Variscan P-T-path (Fig. 16)

The time of the migmatitization is unknown, but probably it happened at the time of the intrusion of the Carboniferous two-mica granites. Chilled margins in the granites and granite-dykes are missing, which is an argument for a higher temperature of the country rocks (migmatites). Arguments for a pressure of about 4 kb at the time of the anatexis/intrusion are (Peindl, 1990):

(1) the existence of sometimes slightly corroded magmatic muscovite in the two-mica granites (4 kb is the lower stability limit for muscovite in granitic melts (Hyndman, 1985)), and

(2) the existence of pseudomorphs of kyanite after andalusite in an contact aureole in the Waldbach valley.

The clinopyroxene-bearing amphibolites seem to be large xenoliths in the granites because of the following reasons:
Obviously following the reaction principle of Bowen, clinopyroxenes exist only in the central parts of the xenoliths. In the direction of the granite, the clinopyroxene disappears, brown hornblende can be found only.

A sign of the origin of the clinopyroxenes by a prograde metamorphic P-T-path is the appearence of hornblende with green core and a brown rim in one of these amphibolites. Consequently, this means an evolution from green hornblende to brown hornblende to clinopyroxene. In the clinopyroxene, there is growing brown hornblende. Finally, seams of green hornblende and of actinolite can be observed as the last step of the amphibolite growth.

Because there is a lot of biotite in the melanosome of the migmatites, the growth of the clinopyroxenes (far beyond the upper stability limit of biotite) can not have taken place in the vicinity of the migmatites.

A temperature rise follows the crystallization (dehydration) of the granites, which causes prograde replacement of magmatic muscovite by sillimanite + K-feldspar + quartz. Rare small green patches in the granites resulted from small frozen melts along grain boundaries and later grown green biotite (Peindl, 1990). Quartz grains beeing in these patches are corroded by the melt. If the

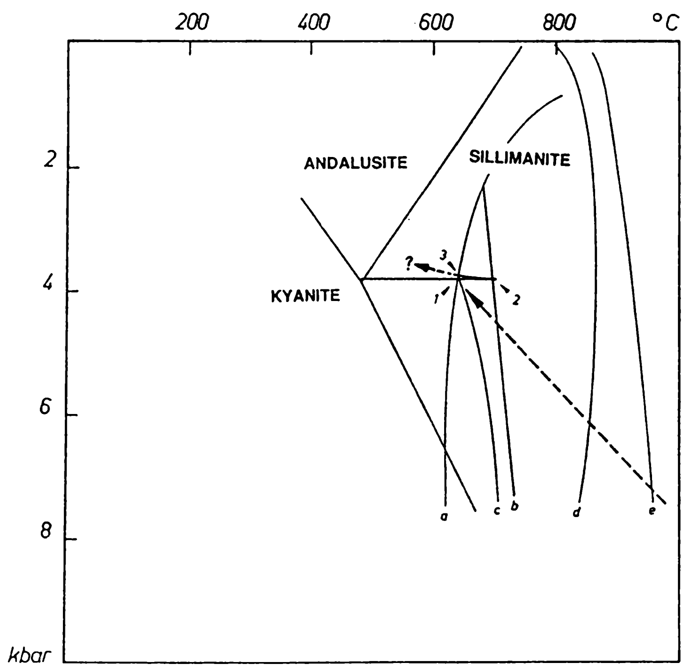

Fig. 16: Schematic Variscan metamorphic P-T-path of the southeastern part of the Raabalps (Peindl, 1990). Dashed line: P-T-path for the clinopyroxene-bearing amphibolites . Stages of evolution: 1: Anatexis of the migmatitic gneisses and intrusion of the Carboniferous two-mica-granites. 2: Increase of temperature, dehydration of muscovite, generation of H_2O-undersaturated liquids. 3: Intrusion of the Permian (?) granodiorite. Reaction curves: a: Anatexis of water saturated rocks. b: Anatexis of a water undersaturated rock. c: Upper stability limit of muscovite in a granitic liquid:muscovite + quartz + Na-rich plagioclase = alumosilicate + orthoclase + Ca-rich plagioclase + melt (Hyndman, 1985). d: Lower stability limit of biotite. e: Beginning of metamorphic growth of clinopyroxene (d, e after Wyllie, 1977).

tonalites/gabbroes intruded later than the two-mica granites, this could be the reason for the temperature rise. Otherwise, the volume of the tonalites/gabbros is much too small for releasing a sufficient amount of heat.

Before Triassic, but at latest at the Permian/Triassic boundary the granodiorite from the southern slope of Wullmenstein intruded. The muscovites are slightly corroded by the melt but they do not show any sign of a temperature rise following the crystallization of the magma.

Due to the strong overprint by the Alpine metamorphism, it is impossible until now to recognize the Variscan retrograde metamorphic P-T-path. Permo-Mesozoic sediments in the northern part of the Raab Alps proof the uplift of the Raabalpen complex at the end of the Variscan metamorphic P-T-path.

Permo-Triassic cover sequences

Permo-Triassic cover sequences are mainly exposed along the northern margin of the Tatric unit, the Wechsel/Waldbach units and the "Grob gneiss" unit (Semmering Group). The Semmering sequence commenced with the Alpine Verrucano Fm. (Permian ?) which consists of breccias, sericite schists and acidic tuffs as well as minor andesitic extrusive rocks (Tollmann, 1964, 1977). The Alpine Verrucano Fm. grades into the Semmering Quarzite of suggested Late Permian to Scythian age and greyish slates. Carbonate deposition started with rauhwacke (a gypsum-bearing yellowish limestone) and grades into light-coloured limestone and Anisian to Ladinian dolomite. Locally occurring dark slates and and coloured slates also including anhydrite/gypsum and dark dolomite belong to the Late Triassic. The Late Triassic sequence, called "Carpathian Keuper" (Tollmann, 1977), strongly differs from other Central-Alpine Triassic sequences.

The Wechsel/Waldbach cover sequence only includes basal Permo-Scythian and Anisian formations due to tectonic decapitation. This basal sequence is basically similar to the Semmering system (Faupl, 1970; Huska, 1970; Tollmann, 1977; Vetters, 1970).

Alpine Tectonic Evolution

The present tectonic structure of Lower Austro-Alpine tectonic units along the discussed section resulted from Cretaceous thrusting which led to the overriding of the Wechsel/Waldbach units by the nappes of the Semmering system. Thrust geometries with accumulated cover sequences in frontal recumbent folds along the northern margins of the Semmering System (Tollmann, 1964) and with basement only within southern areas combined with increasing metamorphic P-T conditions from North to the South which indicate a northward climbing of a basement-cover ramp. Metamorphic amphibolite facies conditions in the hangingwall nappe and in part upper greenschist facies conditions in the Wechsel/Waldbach nappes indicate an out-of-sequence thrust which brought up the Semmering nappes (Dallmeyer et al., this vol.). The internal structure of the Semmering system is dominated by splays of the basal master fault into mylonite zones which especially developed along Grob gneiss / paragneiss interfaces. These zones include broad mylonite zones with "white schists" which are mainly derived from orthogneisses due to access of hydrous fluids (Reindl, 1989; Prochaska, 1991). The direction of ductile thrusting varies over large areas (Fig 17). Limited data indicate top W to NW transport along northernmost Semmering areas, top N to NNE displacement in central portions (Reindl, 1991), and top N and NW displacement in southwestern areas (Moyschewitz, in prep.). Variations of the displacement pattern partly derived from ductile overprint within peak and decreasing metamorphic conditions which resulted from post-metamorphic extension. This later pattern mainly displays in E-W to NE-SW extension although detailed local studies monitor no preferred direction of extension (Peindl, 1990).

The exhumation of the dome-shaped Wechsel Window and probably of the Fischbach Window, both with a similar dome-like shape, ocurred in a two-step history. A first event probably followed Cretaceous metamorphism. Ductile to semiductile fabrics along western margin and semiductile fabrics along the eastern margin of the Wechsel Window record approximate E-W extension. In the interior, a weak flat-lying, widely spaced foliation is superimposed on earlier ones. The late foliation is related to folds with flat-lying axial surfaces due to subvertical shortening during extension. Semiductile shearing along E-W trending shear zones along northern and southern margins is apparently related to updoming. However, fission track data indicate that final cooling occurred during the Neogene (Dunkl, this vol.). Especially the northern portion of the Wechsel Window and

Permo-Mesozoic sediments are affected by brittle, ca. ENE trending folds. Related basins like the basin of Kirchberg am Wechsel proof the Neogene activity along these faults (Ebner et al., 1991).

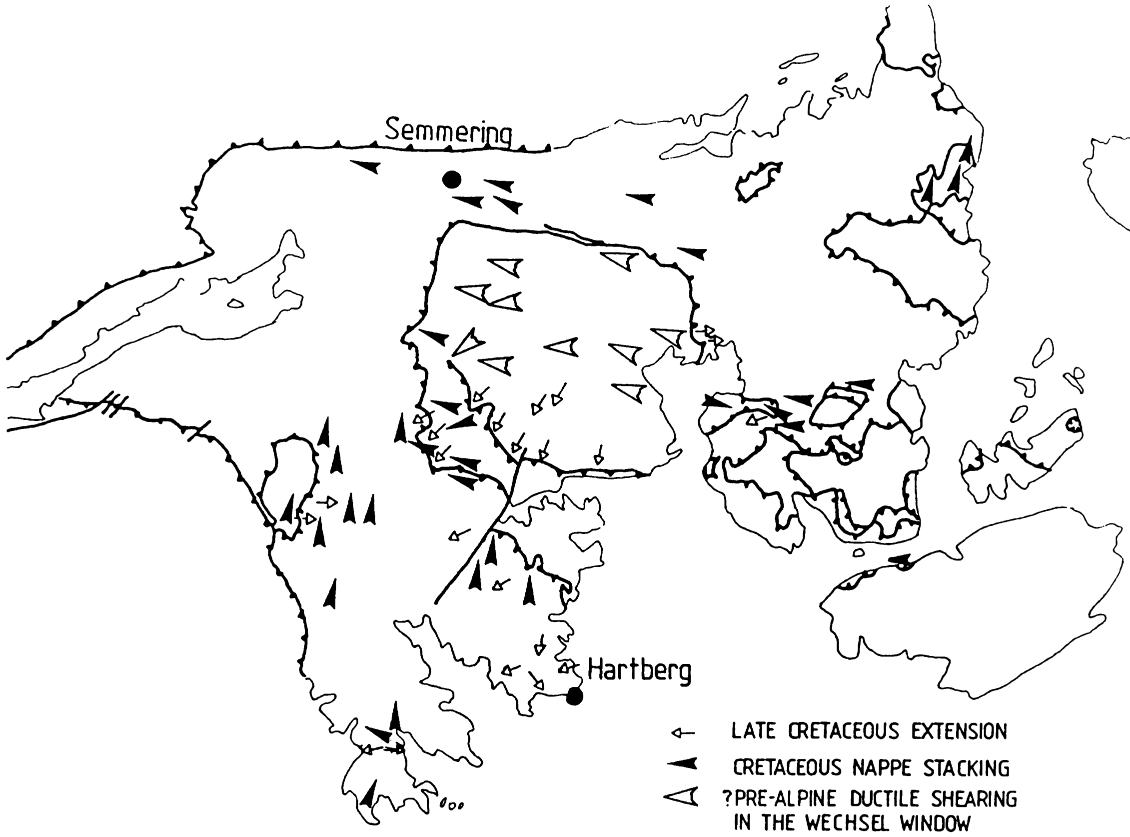

Fig. 17: Kinematic indicators in the Wechsel gneiss complex and Grob gneiss complex.

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THE MESOZOIC OPHIOLITES IN THE EASTERN ALPS - A REVIEW

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Abstract

Mesozoic ophiolites in the Eastern Alps are confined only to three tectonic windows of the Penninic zone: the Lower Engadin window, the Tauern window and the Rechnitz window group. They display an almost complete sequence with serpentinites, mafic and ultramafic cumulates, volcanics and a sedimentary cover of radiolarites and calcschists but lack a sheeted dyke complex. During the alpine orogeny they recorded a two stage metamorphic evolution with a high pressure facies event followed by a greenschist to amphibolite facies event. Non-ophiolitic volcanism is widespread.

The geochemical data of the metabasalts are consistent with a MOR - environment of a complex slow spreading ocean. Geological and petrological investigations indicate a polyphase evolution of the Penninic ocean. A rifting phase involving deposition of clastic sediments intruded by an early basaltic magmatism is probably followed by a phase of uplift and erosion of newly formed oceanic crust along fracture zones. A further episode generated the widespread basalts on top of the serpentinites and gabbros. At the same time off axis volcanism was active in the Tauern window. The duration of magmatic activity is not known but ceased with the onset of the subduction process during the Cretaceous.

Introduction

The ophiolites of the alps and especially those of the Eastern Alps provide a nice example that at least these ophiolite bodies in contrast to many other Tethyan or Cordillieran ophiolites (Moores 1982, Coleman 1984) formed in small extending ocean basins similar to the Red Sea or the gulf of California and are not related to any subduction processes.

Geological setting and lithology

Major occurrences of ophiolites and related rocks (except for the Reckner complex, which is part of the Lower Austroalpine nappe) in the Eastern Alps are virtually restricted to the Penninic windows, submerging below the Austroalpine units (Fig. 1). These are, from west to east: The Lower Engadin window, the Tauern window and the Rechnitz window group.

The age of the ophiolites within the Eastern Alps is not well documented because the intense alpine metamorphism and deformation destroyed all fossils and primary magmatic minerals. A contemporaneous origin with the Jurassic ophiolites of the Western Alps (Abbate et al., 1984) is very probable in view of their overall similarities and their comparable geological position.

In the following sections the ophiolites of each window will be treated separately. Tab.1 provides a synopsis of all for ophiolite complexes comparing lithological, geochemical, metamorphic and miscellaneous features.

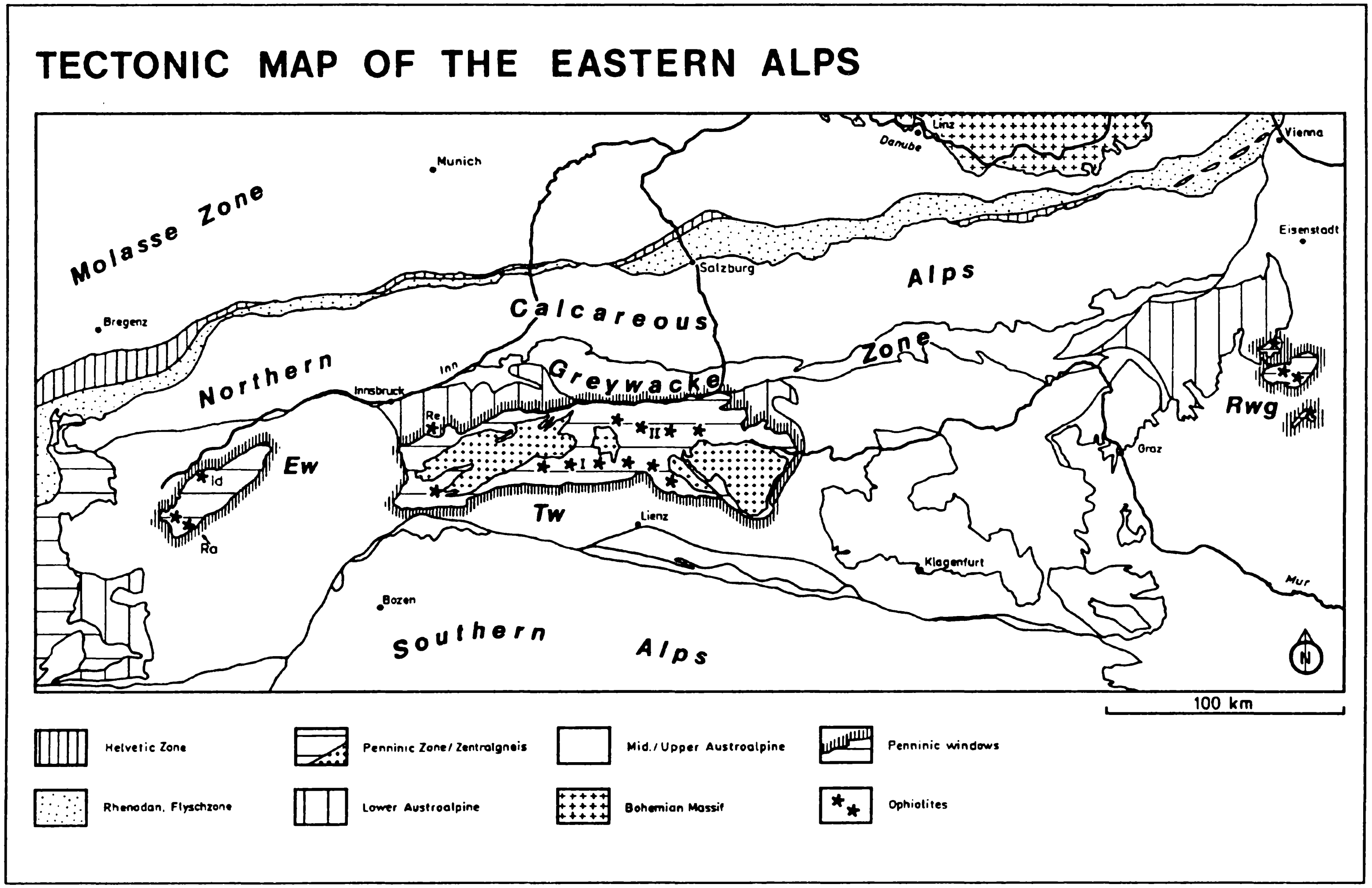

Fig.1: Geological-tectonic sketch map of the Eastern Alps showing the major occurrences of Mesozoic ophiolites

Ew	*Lower Engadin window, Id for Idalp and Ra for Ramosch ophiolite*
Tw	*Tauern window, I, II for ophiolite unit I and II*
Rgw	*Rechnitz window group*
Re	*Reckner complex, Lower Austroalpine nappe*

The Lower Engadin window

It is situated at the Swiss-Austrian border and consists of several tectonic units: The lower part, including the Ramosch ophiolite, is assigned to the north Penninic area; the Tasna nappe is middle Penninic and the highest structural unit, the Arosa zone, with the Idalp ophiolite (Daurer, 1980; Höck & Koller, 1987, 1989) is believed to be of south Penninic origin (Trümpy, 1972; Tollmann, 1977; Oberhauser, 1980; Frisch, 1984).

The Ramosch ophiolite is dominated by a serpentinized peridotite, which originated from a lherzolitic mantle (Vuichard, 1984a, b). The ultramafics are highly serpentinized and associated with ophicarbonates and serpentinite breccias. Basaltic and gabbroic partly rodingitized dikes crosscut the serpentinites. Metagabbros form lenticular bodies within the serpentinites. The volcanic complex (pillow basalts and minor sills) is tectonically emplaced upon the serpentinites. The presumed continuation of the Ramosch ophiolite towards the east is problematical. Only tuffs and some pillow lavas and pillow breccias are preserved. They show a geochemical composition which indicates some intense alterations especially in respect to the alkaline elements. Geochemical patterns of the immobile trace elements as well as from REEs indicate a generation either as T-type MORBs or as withinplate basalts.

The internal pseudostratigraphic pile of the Idalp ophiolite in the Arosa zone contrasts somewhat with the Ramosch ophiolite section (Höck & Koller, 1987, 1989). The sequence (Fig. 2; column A) starts with approximately 60 - 80 m thick serpentinites. They rest tectonically on the sediments of the Arosa zone. The overlying gabbros are in tectonic contact with the serpentinites and are intruded by rare diabase dikes. The volcanic section is in tectonic contact with the gabbros and starts with pillow lavas alternating with massive lava flows and hyaloclastites. The abundance of the hyaloclastites increases towards the upper levels. At the stratigraphic top tuffs with radiolarian schists were deposited. The volcanic pile (including the sediments) has a thickness of 250 to 300 meters.

Tauern window

In contrast to the other windows, the south Penninic Tauern window is characterized by a pervasive regional metamorphism in greenschist to amphibolite facies overprinting the older high pressure mineral assemblages. The original mineralogy, magmatic textures and possible remnants of an oceanic metamorphism are widely obliterated and only occasionally preserved.

Two coherent units (I and II) have been distinguished so far in the middle part of the Hohe Tauern (Höck, 1980, 1983; Höck & Miller, 1980, 1987) which comprise metamorphosed ophiolites including serpentinites, gabbros and basalts (unit I and II). Units I and II are situated in the central part of the Tauern window at its southern and northern margin respectively (Fig. 1). They rest tectonically on calcschists which grade into the more clastic metasediments (quartzites, breccias, black phyllites) of the Brennkogel facies, a deeper structural unit (Frasl & Frank, 1966; Frank, 1969). The latter is believed to have formed at the northern margin of the south Penninic ocean and comprises, in addition to the metasediments, some non-ophiolitic greenschists too. Other metamorphic volcanic rocks (former basalts, basaltic tuffs and thin banded tuffites) generated probably in an off-axis regime (Höck, 1983; Höck & Miller, 1987) are originally embedded in calcschists which overlie the ophiolites in the northeastern part of the Tauern window (unit III by Höck, 1983; Höck & Miller, 1980, 1987). They are, in turn, tectonically overlain by clastic sediments and coarse grained gabbroic rocks of the Fusch facies (Frasl & Frank, 1966; Frank, 1969), which has probably developed along the southern margin of the south Penninic ocean.

The ophiolitic sequence (Fig. 2; column B) starts with serpentinites at the base (maximum 100 m thick) which occur partly as foliated slivers, partly in stratigraphic contact with the overlying cumulate to gabbro sequence. The latter includes tremolite-chlorite-antigorite schists which are believed to be metamorphic remnants of ultramafic cumulates and ferrogabbros, forming small lenses in serpentinites, as well as leucogabbros. The 200 - 600meters thick extrusive series consists of metamorphosed basalts rarely showing features of pillows lavas, hyaloclastites and breccias. The ophiolite profile is completed with an up to 400 meters thick sedimentary cover of calc-mica schists and black phyllites sometimes interlayered with the volcanics at their base. Only occasionally a small quartzite horizon (metachert?) has formed on top of the extrusives.

	Lower Engadin Window (Arosa zone, Idalp)	Tauern Window	Rechnitz Window group	Reckner complex
Ophiolite type	high-Ti	high-Ti	high-Ti	high-Ti
Environment	MOR	MOR	MOR	
mantle composition	depleted	depleted, slightly variable	depleted, slightly variable	sligthly enriched
degree of melting	~ 10%	~ 10-15%	~ 10-15%	
MORB-type	N	N	N	
spreading rate	small	small	small	
Stratigraphy				
radiolarites	+	not clear	+	very common
tuffs/tuffites	+	+	+	?
hyaloclastites	+	+	+?	---
breccias	---	?	---	---
pillow lavas	+ (common)	+?	?	---
massive lavas flows	+	+?	+?	---
dikes within the gabbros	+	?	?	---
plagiogranites	---	---	+	---
ferrogabbros	very rare	rare	very common	---
cpx-plag-gabbros	+	+	+	very rare
ultramafic cumulates	?	+	+	+
rodingites	+	+	+	---
ophicarbonates	---	rare	+	very common
ultramafics	harzburgite	harzburgite	harzburgite	dominant lherzolite
Further Information				
transform-faults	?	?	+	+
non-ophiolitic volcanic activity	---	wide spread	+	---
oceanic metamorphism	poorly	overprinted by regional metamorphism	strong influence	strong influence
sedimentation rate	high	high	high	?
size of the oceanic basin	narrow	narrow	narrow	?
Alpidic metamorphism				
a) high pressure event	pumpellyite-actinolite-facies	eclogite/blue-schist-facies	pumpellyite-actinolite-facies	blueschist-facies
b) young Alpine metamorphism	low T green-schist-facies	greenschist-/am-phibolite-facies	greenschist-facies	greenschist-facies

Tab.1: Comparison of the more important features between the ophiolites of the Eastern Alps, compilation after Höck, (1983); Koller, (1985); Höck & Miller, (1987); Koller & Höck, (1987, 1990); Höck & Koller, (1987, 1989), Dingeldey, (1990).

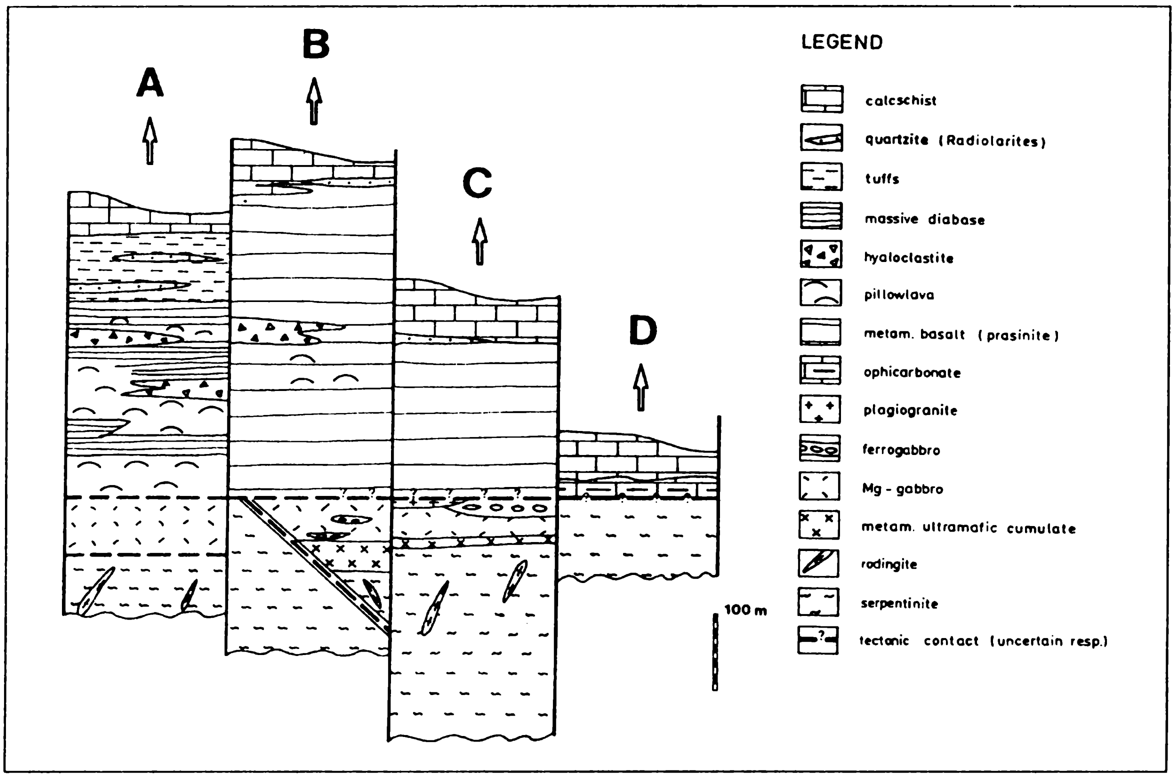

Fig.2: Generalized columnar sections through the ophiolites in the different windows:
A Aldalp ophiolite (Lower Engadin window)
B Tauern window
C Rechnitz window group
D Profile near Glashütten in the Rechnitz window and in the Reckner complex (Lower Austroalpine nappe). This is the only section with ophicarbonates on top of the serpentinites.

The Reckner complex

The Reckner ophiolite (Dingeldey, 1990; Dingeldey & Koller 1990) is situated in the upper parts of the Tarntal mountains near to the NW corner of the Tauern window. Tectonically it belongs to the higher parts of the Lower Australpine nappe (Fig.1). Besides a intensive oceanic metamorphism, a low temperature high pressure metamorphism overprinted by a regional themal event in greenschist facies is reported by Dingeldey (1990).

The ophiolitic sequence starts with ultramafic rocks mainly serpentinized lherzolites including small bodies of gabbros and ultramafic cumulates such as probable ilmenite-rich clinopyroxenites. The cover of these ultramafic rocks is formed by thin ophicarbonates, radiolarites and some questionable basaltic derivates which can not be used as geochemical markers. The thickness of this cover does not exceed more than 10 meters compared with more than 150 metres for the serpentinites. Dingeldey (1990) interpreted the metabasalts as transitional MORBs formed in the vicinity of a transform fault or in an incipient rifting zone. It is interesting to note, that the Reckner complex shows some striking similarities with the Ramosch ophiolite in the Lower Engadin window.

The Rechnitz window group

The Mesozoic Penninic rocks at the eastern end of the Alps forming several small windows are termed "Rechnitz Series". They comprise metasedimentary rocks together with several ophiolites (Koller, 1985; Koller & Höck, 1990; Höck & Koller, 1989). The following columnar sections can be established (Fig. 2; column C): serpentinites with a maximum thickness of 270 meters form the base. They are overlain by rare ultramafic cumulates, metaleuco- and ferrogabbros associated sometimes with metamorphosed plagiogranites and ferrodiorites. The maximum thickness of the plutonic sequence does not exceed 60 - 70 meters. Metamorphosed basalts including Fe-Ti-rich varieties and tuffs (up to 200 meters) form the extrusive section. Radiolarites (up to 10 meters) and calcareous sedimentary rocks terminate the whole sequence. Basic intercalations in the sediments are interpreted as tuffites.

It should be noted here that in contrast to the Tauern ophiolites and the Idalp ophiolite, but in accordance with the Ramosch ophiolite, ophicarbonates resting directly on the ultramafics play an important role in some ophiolitic profiles (Fig. 2; column D).

Geochemistry

The geochemistry will be treated here only briefly, a more detailed description is given elsewhere (Bickle & Pearce, 1975; Höck, 1983; Höck & Koller, 1987, 1989; Höck & Miller, 1987; Koller, 1985; Koller & Höck, 1990).

The generally serpentinized ultramafics in the Lower Engadin window are still recognisable as harzburgites from a petrographic point of view. The geochemistry with low Al_2O_3 contents, low TiO_2, Cr ranging from 2200 - 2700 ppm and Ni 1000 - 2700 ppm is consistent with the petrographic evidence. The serpentinites in the other windows show similar concentrations of major and trace elements. Only some metamorphosed ultramafic cumulates (antigorite - tremolite schists, diopside - chrysotile - chlorite and talc-tremolite schists) have lower MgO and high CaO and Al_2O_3 values than the normal serpentinites. The leucogabbros show higher MgO and Cr, low TiO_2, P, Nb, Zr, and Y concentrations. By contrast the ferrogabbros are depleted in Cr and enriched in Fe, Ti, V, Zr, Y, and P.

The chemical composition of all ophiolitic basalts is tholeiitic with a strong affinity to N-type MORB (Höck, 1983; Höck & Koller, 1987; Höck & Miller, 1987; Koller, 1985; Koller & Höck, 1987). The major elements as well as the trace elements including the REE (Koller, 1985) are in the typical MORB - range. According to the scheme of Beccaluva et al. (1983) they can be classified as high Ti - ophiolites. The effects of alteration are generally small.

In contrast to the uniform MORB characteristics of the ophiolitic basalts, the off-axis basalts and tuffs from the Tauern Window and some within plate metabasalts from the Rechnitz window group show a wider field of compositions. They range from tholeiites to mildly alkaline basalts with a significant enrichment in some trace elements such as Nb, Zr and the light REE, thus resembling T-type to E-type MORB (Höck & Miller, 1987; Koller, 1985).

As Höck & Koller (1989) have shown the variable Zr/Y ratios observed in the metabasalts from all Penninic windows cannot be explained by fractionation/accumulation mechanisms only. Other possibilities such as variation in source composition and different degrees of partial melting have to be considered. The petrogenetic evolution of the fractionated magmas will be dicussed briefly by means of the Zr/Y vs Zr diagram (according to Pearce & Norry, 1979). The non-cumulate magmas form two arrays in this diagram (Fig. 3) called field I and II, the latter having higher Zr/Y ratios at given Zr level. The distribution of lavas in these fields can be attributed to two factors: a variable mantle source and different degrees of partial melting. A somewhat depleted mantle, compared to a C3 composition (Pearce & Norry, 1979), partially melted to 10q5% (estimated degrees of partial melting are taken from Höck & Koller, 1989) gives rise to magmas which upon closed system fractionation of plag + ol + cpx (Fig. 3) can produce the basalts of field I. The tapping of a slightly more enriched mantle combined with a higher degree of partial melting (around 15%) and a similar fractionation history would account for the lavas of field II.

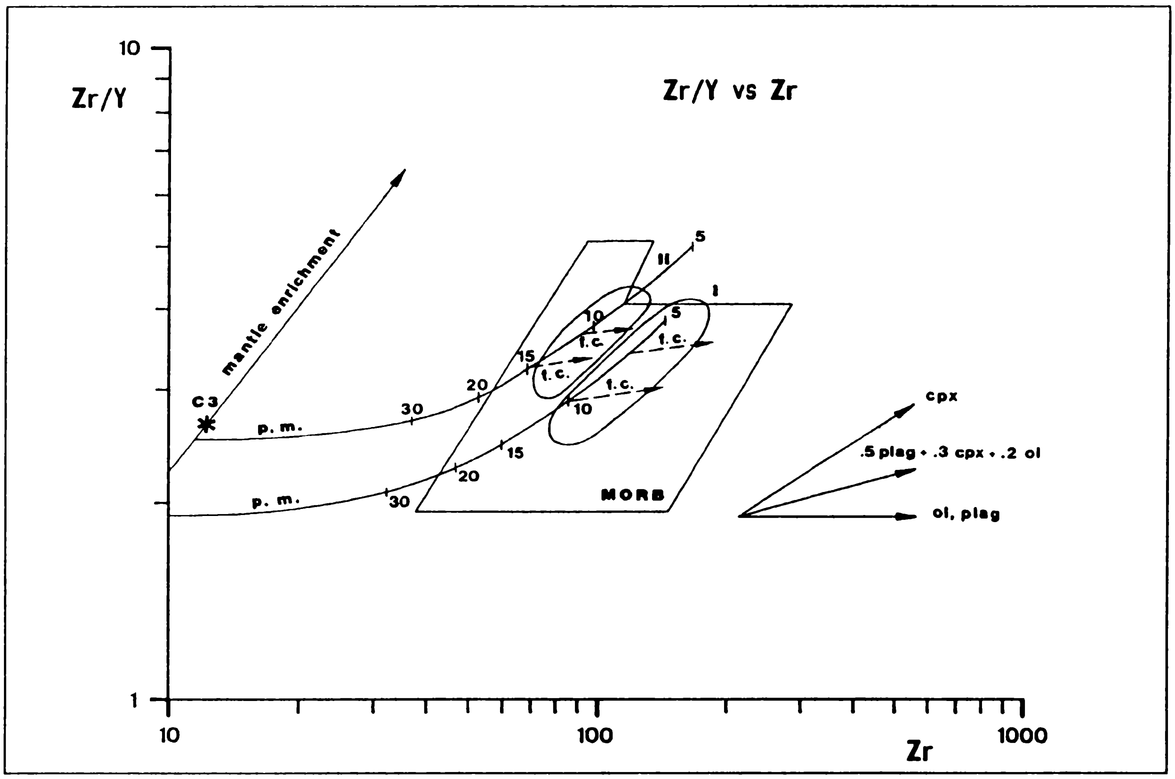

Fig.3: Zr/Y vs Zr diagram showing possible petrogenetic pathways for the two arrays I and II. The mantle enrichment and depletion trends starting from a C3 composition, partial melting curves (p.m.) and fractional crystallisation vectors (f.c.) are modelled according to Pearce & Norry (1979). Lavas from field I could have been formed by low partial melting (5 - 10%) of a depleted mantle with subsequent fractional crystallisation of plag + ol + cpx. Lavas of field II can be derived by 10 - 15 % partial melting of a less depleted mantle accompanied by 20-30 % fractional crystallisation of plag+cpx+ol. Fractionation trends for ol,pl,cpx for theoretical basaltic assemblage with ca. 50% crystallisation are inserted.

Höck (1983) and Höck & Miller (1987) have also shown utilizing several discrimination diagrams such as Zr-Ti/100-3*Y or Zr/Y vs Zr and MORB normalized multielement plots that the generation of the off-axis basalts and tuffs (unit III), of the coarse grained Fusch metabasics and of some eclogitic protoliths require a considerable variation (enrichment) in the mantle source to explain the high concentrations of some HFS elements and their ratios.

Geodynamic evolution

The internal structure of the ophiolites and their general geological situation is not only comparable within the Eastern Alps, common characteristics can be found over the whole range of the Alps from Eastern Liguria to the Austro/Hungarian border (Abbate et al.,1984; Höck & Koller 1989). The Mesozoic ophiolites in Austria compare quite well with the "Piedmont ophiolite composite nappe" as descibered by Monviso (1979); Abbate et al. (1984). Thus a similar geodynamic evolution can be expected for the entire Penninic realm. Nevertheless differences may occur.

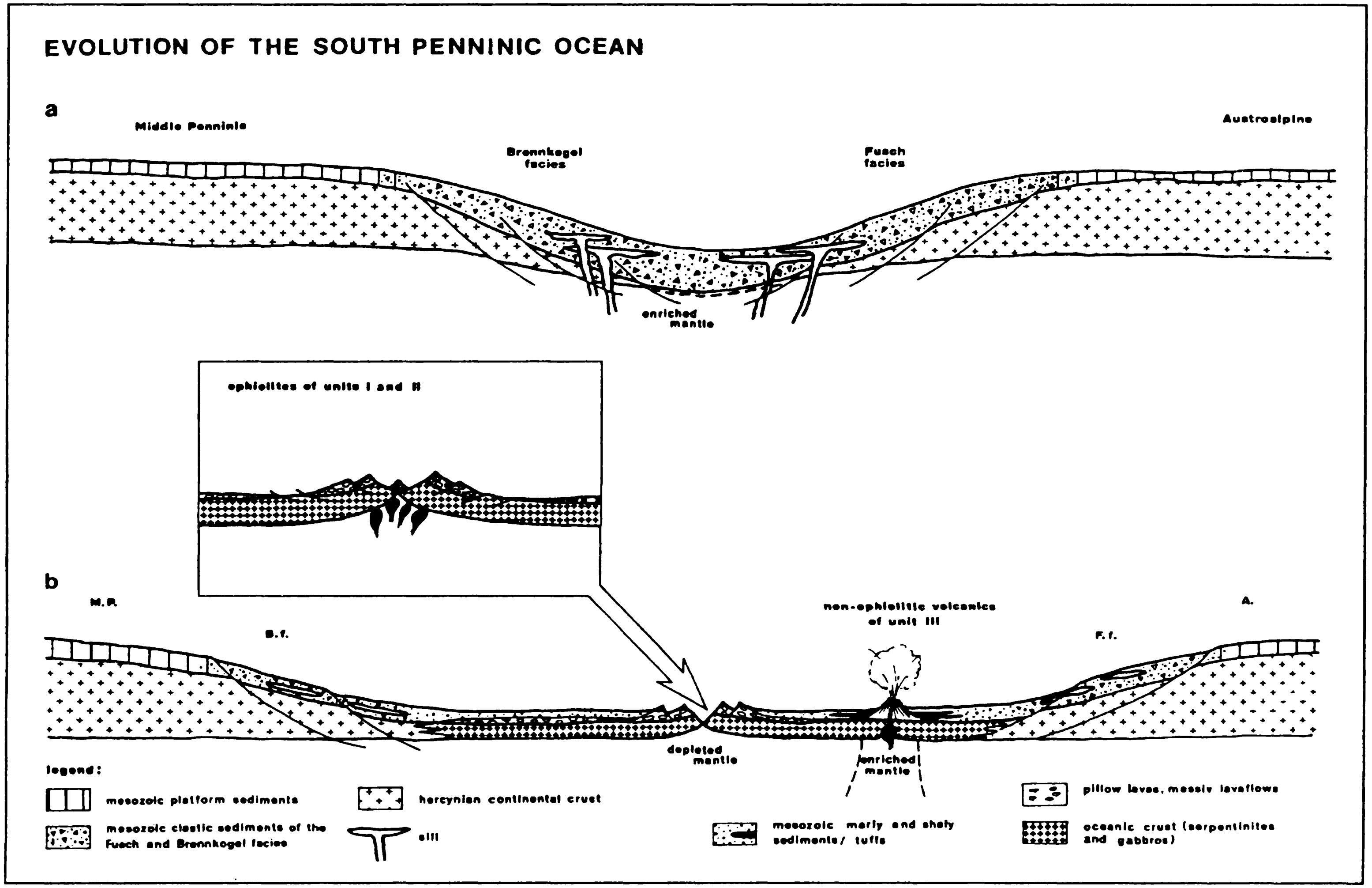

Fig.4: Tentative cross-sections showing the possible evolution of the South-Penninic ocean (The profiles are not in scale and not orientated.) 4a) depicts the early stage of rifting with the deposition of clastic sediments and the intrusion of sills. 4b) shows an oceanic stage with thinned crust near fracture zones and off-axis volcanism.

The following scenario for the evolution of the South-Penninic ocean (Fig. 4) is proposed. It should be noted however, that our model is based on information gleaned from the Tauern window, which provided the most complete sections.

The initiation of the Penninic ocean probably took place in the Early to Middle Jurassic with the rifting of the Hercynian continental crust and its post-Hercynian sedimentary cover forming a continental margin (Fig. 4a). The continental crust became thinner along normal (listric) faults and was covered with clastic sediments, shales, sandstones and breccias forming along fault scarps. During the last stages of thinning or the early stages of opening of the ocean basin, basaltic magmas derived from a relative enriched mantle were generated and injected into the clastic (still wet?) sediments of the Fusch and Brennkogel facies where they formed thick coarse-grained sills.

Subsequently a basin formed (Fig. 4b), floored by oceanic crust, probably segmented by closely spaced fracture zones (Abbate et al., 1984; Boccaletti et al., 1984; Lemoine, 1983; Weissert & Bernoulli, 1985). In the vicinity of the fracture zones the oceanic crust of the ridge area was stretched and eroded so that the gabbros and the ultramafics reached the ocean floor forming a rugged morphology (see insert in Fig. 4b). Such a scenario would be consistent with the tectonic models developed by Fox & Gallo (1984) for slow spreading ridge - transform - ridge plate boundaries or with the situation in the vicinity of the Kane fracture zone (Karson & Dick, 1984). An alternative model presented by Lemoine et al. (1987) postulating a Penninic ocean completely floored by ultramafics with small pods of gabbros and little extrusives seems not to fit the situation in the Eastern Alps, where coherent extrusive bodies are prevailing. The stage of stretching and erosion was accompanied by a slight hydrothermal oceanic metamorphism recorded mainly in the gabbros with the formation of pargasite and magnesio-hornblende. Further magmatic episodes generated the basalts on top of the gabbros and serpentinites. Their petrographical and geochemical variability reflects a depleted but slightly variable mantle composition and a slow spreading rate. The latter is postulated for the sinistral movement between Europe and Africa in the Jurassic by Savostin et al. (1986), Dercourt et al. (1986) and Ricou et al. (1986). A large influx of sediments sealed the basalts and prevented seawater from percolating through the lavas resulting in their minor hydrothermal alteration.

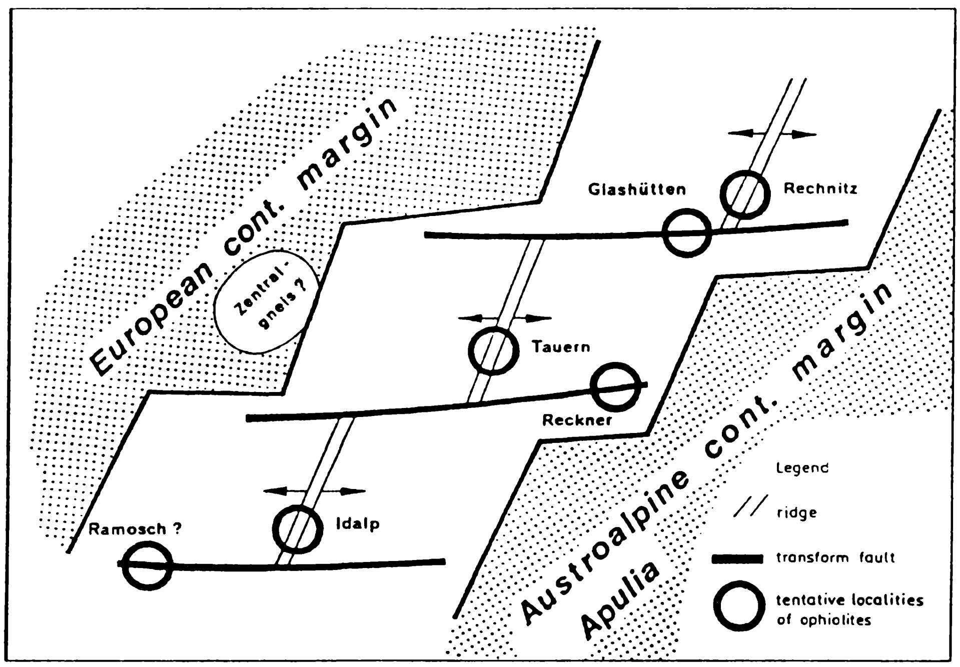

Fig.5: Tentative paleogeographic sketch map of the Penninic ocean in the Eastern Alps. The ophiolites from the Idalp, the Tauern Window and the Rechnitz Window Group are generated on ridge segments close to a ridge transform intersections. The ophiolites of Glashütten (Rechnitz Window) and Ramosch (Lower Engadin Window) as well as the Reckner complex (Lower Austroalpine unit) have possibly formed in a fracture zone environment.

Summarizing, the ophiolites in the Tauern window, in the Arosa zone (Lower Engadin window) and certain bodies in the Rechnitz window group were probably generated near a ridge-transform intersection in a slow-spreading ocean (Fig. 5). On the other hand, the ophiolites from Eastern Liguria, the Cottian Alps and the Arosa zone W of the Lower Engadin window (Abbate et al., 1980, 1984; Lemoine, 1980; Tricart & Lemoine, 1983; Weissert & Bernoulli, 1985), the Ramosch ophiolite (Vuichard, 1984a, b), smaller parts from the Rechnitz ophiolites (Koller, 1985) and also the Reckner complex in the Lower Austroalpine unit (Dingeldey, 1990; Dingeldey & Koller, 1991) are more likely to have formed in a fracture zone environment (Fig. 5).

Approximately coeval with the ophiolites were volcanic eruptions off the ridge axis (Fig. 4b). Several sequences consisting mainly of very fine grained and thin banded tuffs and lava flows were interbedded with the sediments. These different off-axis magmas have originated from relatively enriched mantle sources reflecting an inhomogeneous mantle beneath the south Penninic ocean.

The period and duration of the volcanic activity - ophiolitic or non-ophiolitic - is not well known. The evolution of the oceanic crust in the Penninic realm, however, had finished when subduction started to close the ocean sometime in the Cretaceous giving rise to the high pressure metamorphic assemblages in the ophiolites. Northward directed nappe movement accompanied by a greenschist to amphibolite facies metamorphism caused by the overthrusting of the Austro-alpine nappes (Frank et al., 1987), uplifting brought the ophiolites and associated rocks into their present position.

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ALPINE KINEMATICS OF THE EASTERN CENTRAL ALPS

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Introduction

The Eastern Alps are considered to result from the collision of the Austro-Alpine microplate with the European continent after consumption of the South Penninic oceanic realm (e.g., Ratschbacher et al., 1989 and references cited therein). However, the application of new methods in structural analysis significantly changed notions about Alpine kinematics in the Central Alps during the last decade. The major progresses were the interpretation of Mid Cretaceous structures due to dextral transpressive convergence (Ratschbacher, 1986), the recognition of Late Cretaceous extension and their relation with ductile sinistral strike slip zones (Neubauer, 1988; Ratschbacher et al., 1989) and of the Neogene setup as escape tectonics (Neubauer, 1988; Ratschbacher et al., 1989, 1991) related to the uplift of Penninic metamorphic domes (Genser and Neubauer, 1989; Ratschbacher et al., 1990). Compilations of these structural data are given in Behrmann, 1990, Neubauer and Genser, 1990; Platt et al., 1989, Ratschbacher et al., 1989. In this contribution we add new data which change the previous models significantly.

The thrust surfaces propagated in space and time both from intra-Austro-Alpine thrusting to overriding of the Penninic units and afterwards to intra-Penninic thrusting (e.g., Ring et al., 1990). In this contribution we shortly review kinematic paths and timing of Alpine structures which are responsible for the Alpine architecture of the eastern Central Alps.

Succession of deformation events

All data clearly suggest a changing displacement path for each unit. The displacement paths of thrusts show changing directions of displacement deduced from overprinting relations in mylonite zones (Krohe, 1987; Ratschbacher, 1986), from incremental strain analyses (Fritz, 1988; Fritz et al., 1991), from the relation to the growth of metamorphic minerals and from the general evolution from early penetrative ductile structures to late cool brittle structures.

Early Alpine nappe stacking in Austro-Alpine units

The onset of compression after a period of Permian to Mesozoic crustal extension in both Austro-Alpine and Penninic domains is not very well constrained by geochronological data. Sedimentological analyses of the Northern Calcareous Alps and the Flysch zone proof an Early Cretaceous flysch deposition which corresponds to ductile thrusting within the Austro-Alpine units which is responsible for intra-Austro-Alpine nappe stacking (e.g., Decker et al., 1987). Thrusting commenced with stacking of the Upper Austro-Alpine unit onto the Middle Austro-Alpine units (Tollmann, 1959, 1987), and continued with emplacement of the Middle Austro-Alpine eclogite-bearing nappes onto weakly metamorphosed Lower Austro-Alpine units (Dallmeyer et al., this volume). Evidence of general amphibolite facies conditions (Frank, 1987), and especially of high pressures in the southern Middle Austro-Alpine units (Thöni and Jagoutz, 1991; Miller, 1990), suggest deep burial of these units during continent-continent collision (Fig. 1) rather in a lower plate than in an upper plate position. General characteristics of intra-Austro-Alpine thrusting are:

1) Thrust geometries with ramps which climb from the basement to the cover towards North, respectively Northwest (Ratschbacher and Neubauer, 1989). Large portions of cover sequences are therefore missing in the Austro-Alpine units. These are probably accumulated in the northern Calcareous Alps (Neubauer and Genser, 1990).

2) A nearly complete decollement of cover units in large portions of the Central Alps. Relatively complete sections are only preserved in some limited Lower Austro-Alpine areas.

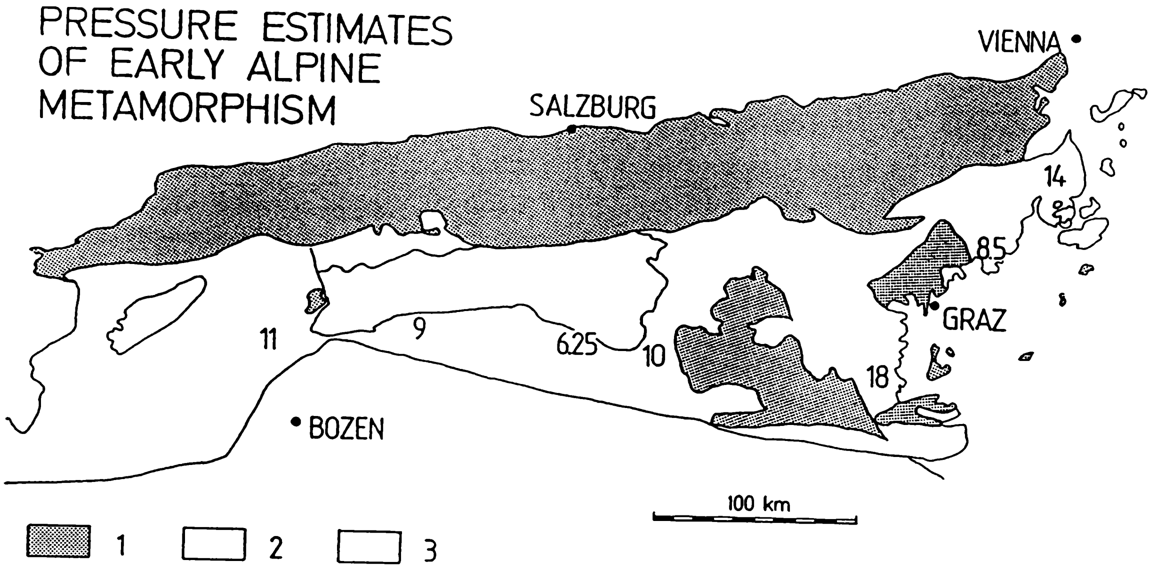

Fig. 1: Pressure estimates of the Early Alpine metamorphism within the Middle Austro-Alpine unit. Legend: 1 - Upper Austro-Alpine units, 2 - Middle and Lower Austro-Alpine units; 3 - Penninic units.

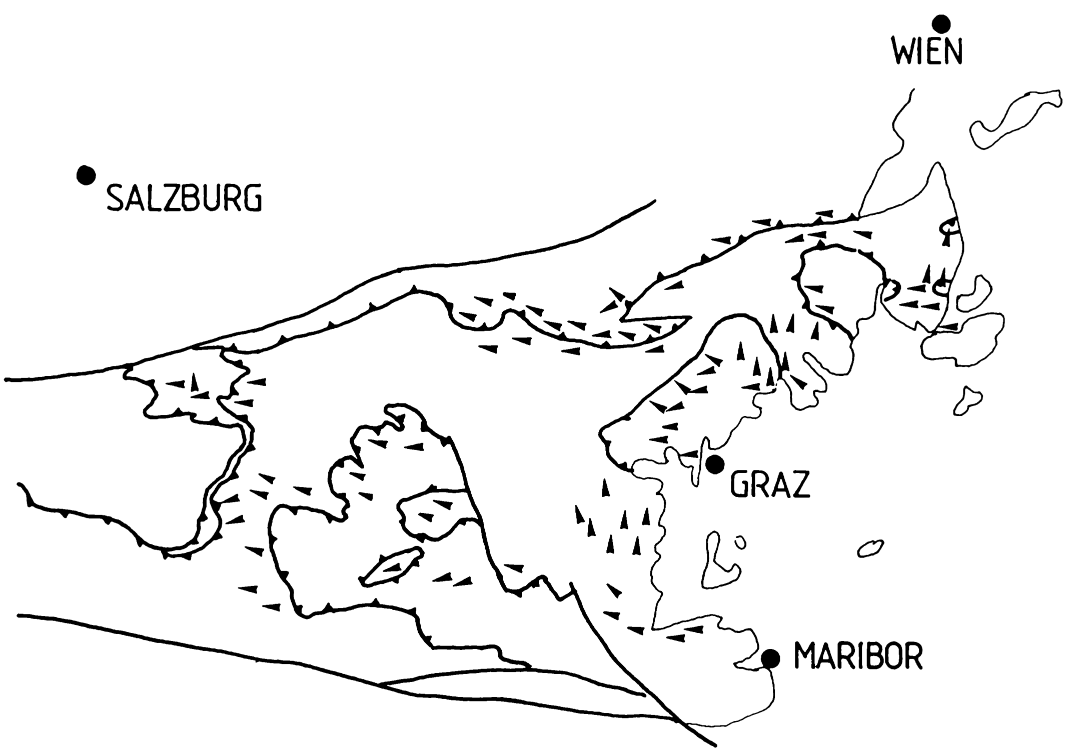

Fig. 2: Early to Mid-Cretaceous motion in the eastern Central Alps. Data base, see text.

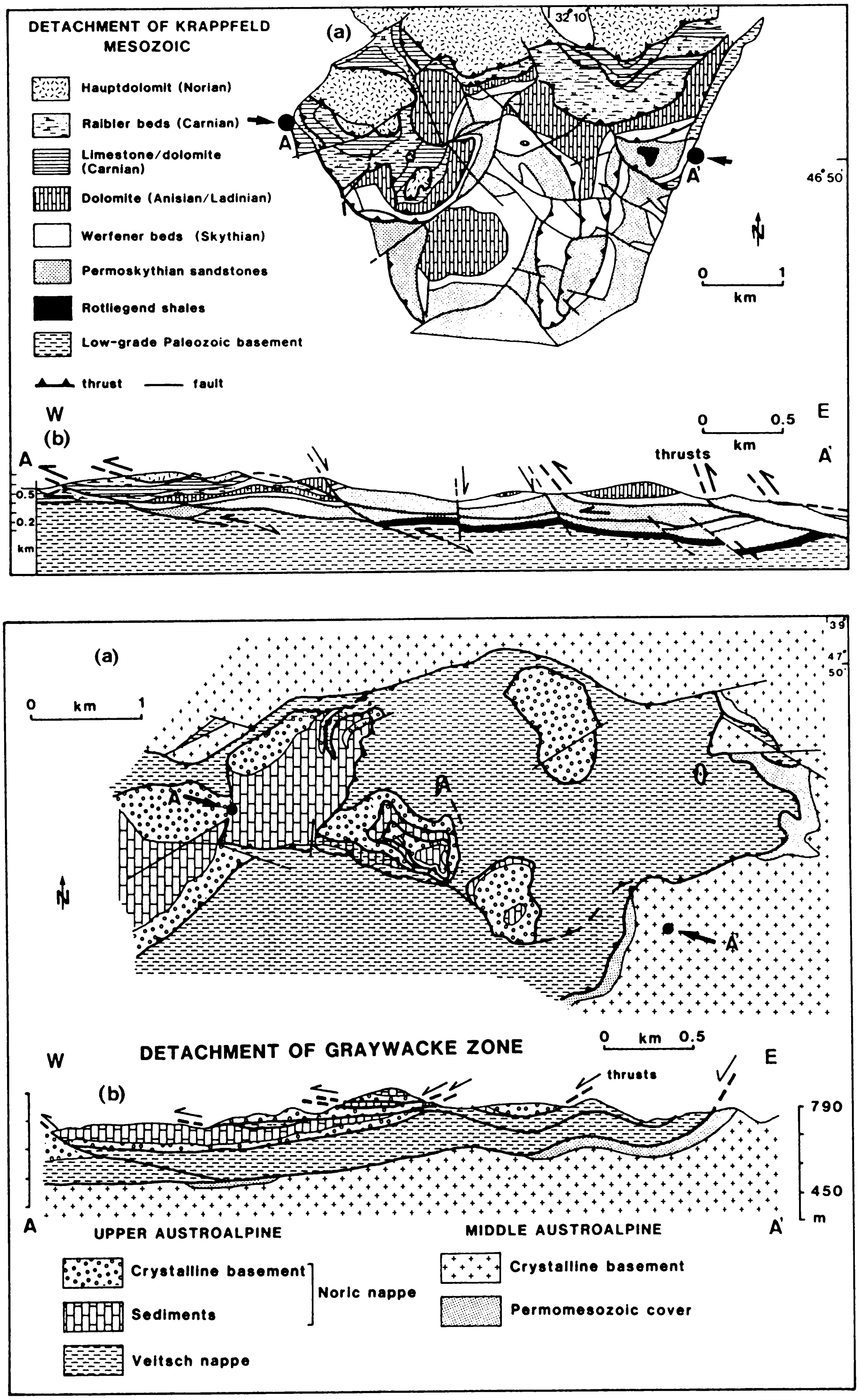

Fig. 3: Geometry of thrust and extensional faults a) in the Krappfeld Permomesozoic unit (cover of the Gurktal Thrust Complex) b) eastern Graywacke Zone (from Ratschbacher and Neubauer, 1989).

3) There is a break in metamorphic conditions due to the emplacement of eclogite-bearing Middle Austro-Alpine nappes onto weakly metamorphic Lower Austro-Alpine units (Dallmeyer et al., this volume).

3) Fabrics of ductile thrusting are often connected with decreasing P-T conditions of Cretaceous metamorphism.

4) Late Cretaceous marine basins overstep Alpine thrust surfaces of the Upper Austro-Alpine units; therefore, such thrust surfaces must predate deposition of these basins.

In the present-day geographic frame, displacement started with top to the NW displacement (Fig. 2), especially in northern portions of the Austro-Alpine units; whereas in more southern ones a top to the W to WSW displacement is common (Fritz, 1988; Genser, 1992; Neubauer, 1987, 1990). Examples of map-scale geometries which proof displacement to the NW are given in Fig. 3. The eastern portion of the Middle Austro-Alpine units is dominated by N to NNE trending stretching lineations which show a general top to the N displacement which is interpreted to be younger than the WNW-directed displacement of other areas (Reindl, 1990; own unpubl. data). These fabrics may be related to the emplacement of the eclogite-bearing units.

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Late Cretaceous extension and strike-slip in the Austro-Alpine units

The period of pre-Gosauian nappe stacking was followed by crustal extension combined with strike-slip displacement in a sinistral wrench corridor (Fig. 4). Some of the resulting shear zones

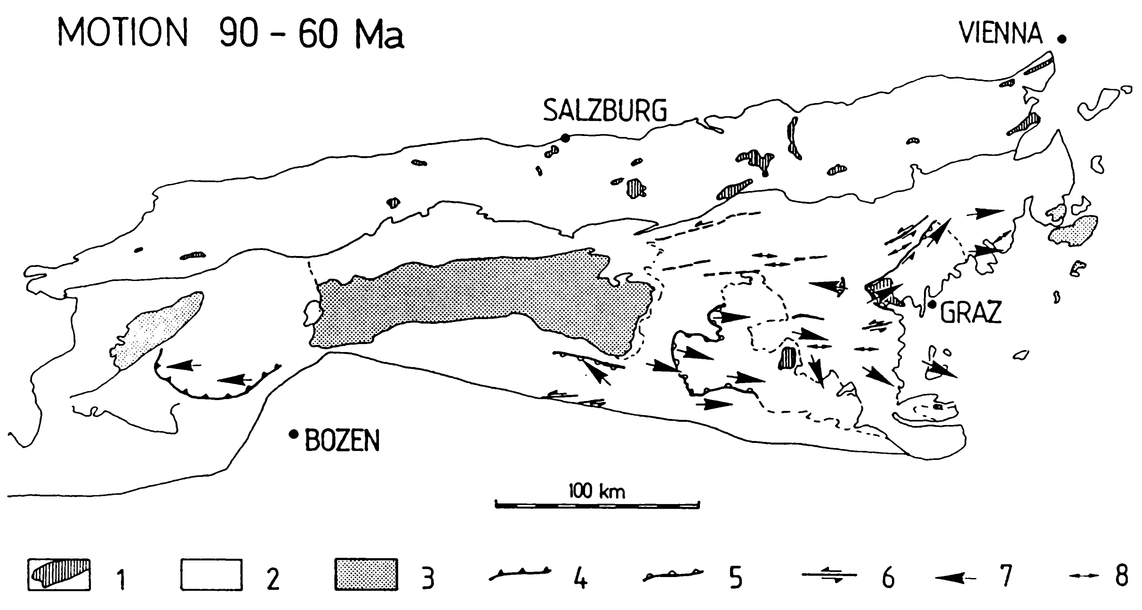


Fig. 4: Late Cretaceous motion in the eastern Austro-Alpine units. Legend: 1 - Gosau basins; 2 - Austro-Alpine Nappe Complex; 3 - Penninic units. Late Cretaceous ductile/brittle fault zones: 4 - thrust; 5 - low-angle normal fault; 6 - strike slip fault; 7 - sense of shear; 8 - coaxial deformation .

reactivated previous ductile thrust faults along nappe boundaries. The general displacement is directed to E, NE and SE. General features of these faults are: 1) The break of metamorphic isogrades along such fault zones with the superposition of amphibolite areas by low to very low grade areas; 2) distinction in cooling age provinces between ca. 120 Ma in hangingwall units and ca. 90 - 75 Ma cooling ages in footwall units; 3) fabrics which show a sequence from ductile to brittle behaviour reflecting motion during cooling from peak metamorphic conditions.

Therefore, these shear zones operated as low-angle normal faults leading to extension of higher intra-Austro-Alpine nappes and subsidence of late Cretaceous Gosau basins.

A detailed study done in the Gleinalm area displays a clear relationship between NE-trending sinistral strike-slip faults and low-angle normal faults, linking segments of the strike-slip faults (Fig. 5). Therefore, we think that extension is related to a major sinistral wrench corridor.

The decompression and unroofing of possible Cretaceous eclogites in the Koralm/Saualm area started during this time. All resulting structures indicate motion of hangingwall units towards the southeastern sector (Neubauer, 1991).

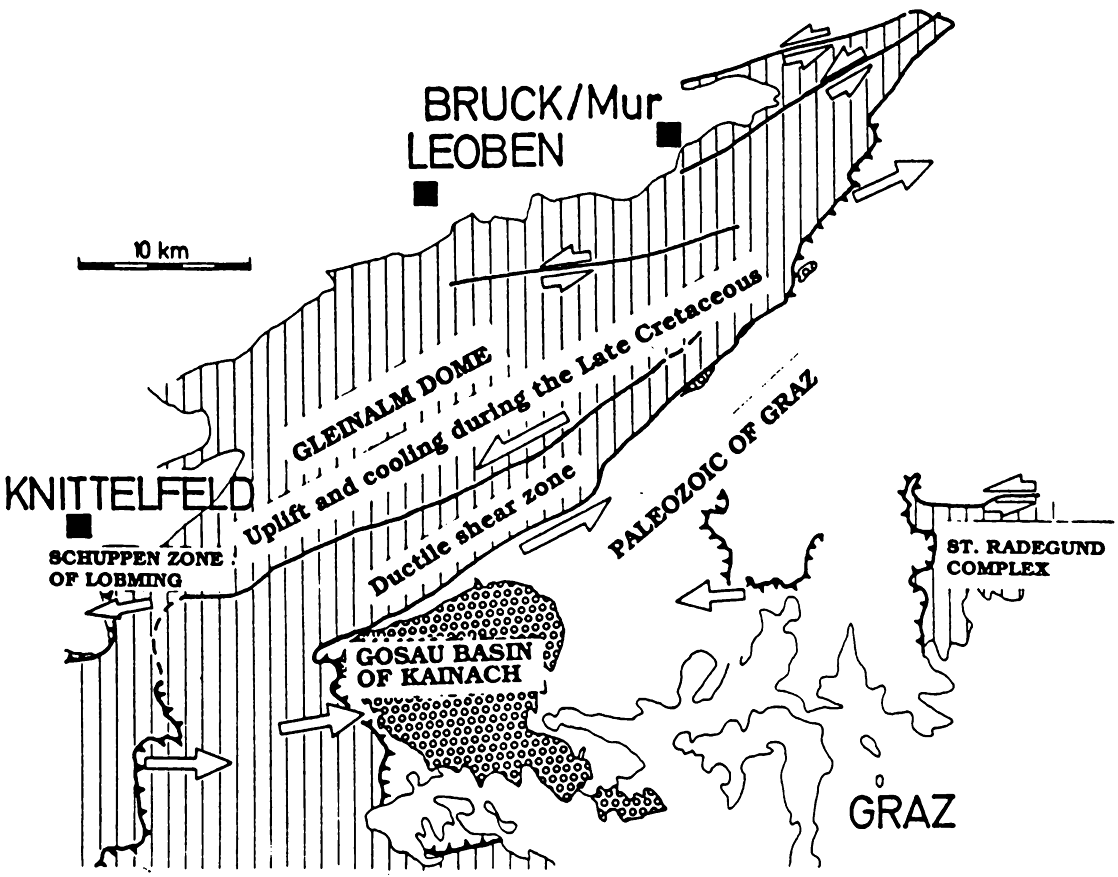


Fig. 5: Structures related to the uplift of the Gleinalm metamorphic dome.

Nappe stacking in the Penninic units

The timing of eclogite formation due to burial in the Penninic zone is controversial. Generally, a cretacous age of eclogite formation is assumed (Fig. 6) (Behrmann and Ratschbacher 1989).

At the eastern margin of the Tauern Window two main deformation events can be distinguished. The older one is expressed in the formation of a mylonitic foliation with a N-S-trending stretching lineation (Fig 7). Shear criteria indicate a noncoaxial displacement path with a motion of top to the N. This deformation affects the higher parts of the Penninic domain and is related to an internal stacking of Penninic units (Storz complex onto Central gneiss units). The deformation is

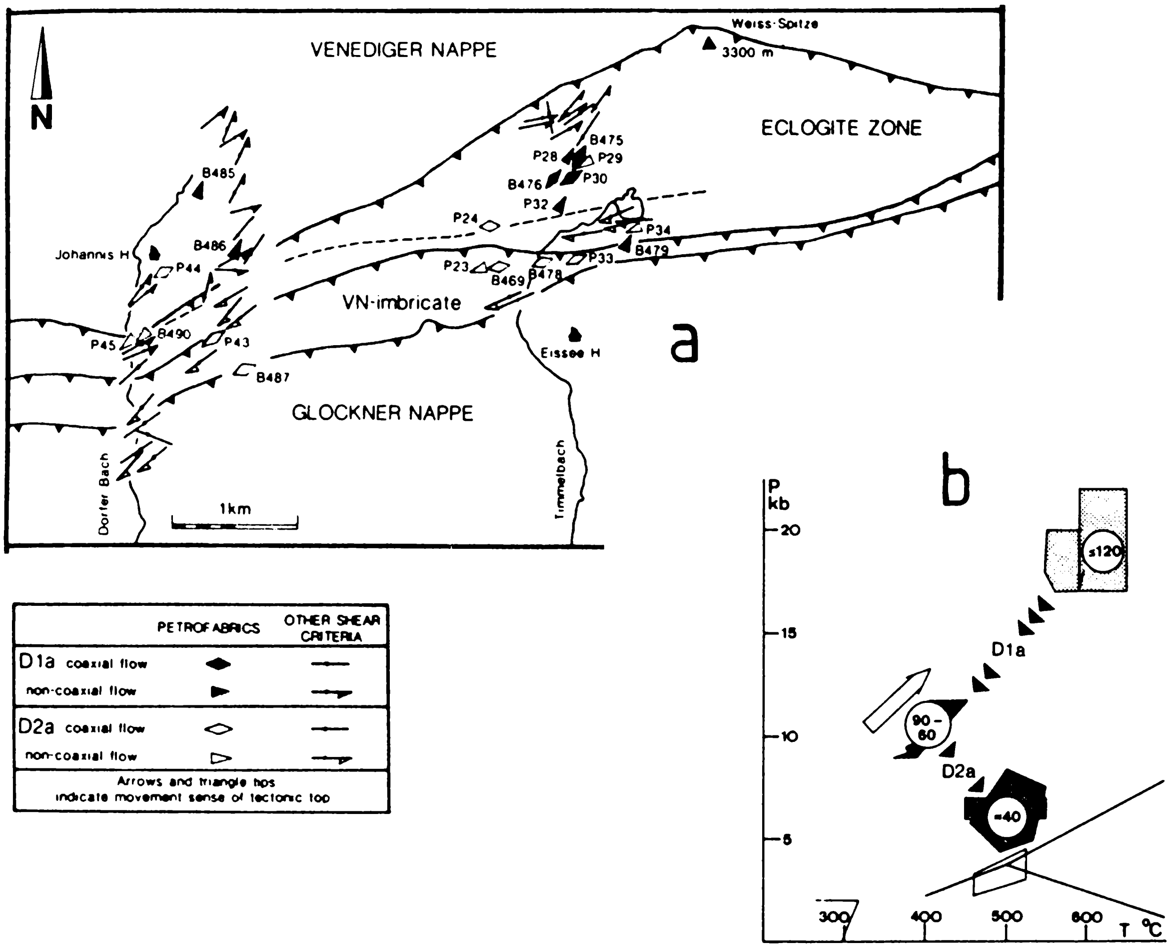


Fig. 6: Displacement path (a) and suggested P-T path and time of deformation events in the Penninic eclogite zone of the southern Tauern Window (from Behrmann and Ratschbacher, 1989).

contemporaneous with peak metamorphic conditions in higher parts of the Penninic realm and can thus be dated at about 40 Ma (timing of metamorphic peak according to Hawkesworth, 1976).

These structures are overprinted by a WNW-directed shearing in deeper parts. Most of the Zentral gneiss units, down to the deepest exposed levels, are first deformed by this shearing. The mylonitic foliation belonging to this deformation generally dips to the E(SE); areas with steeply dipping foliations (e.g. around Koschach) show a constrictional strain with a component of dextral shearing. This deformation is synmetamorphic in these levels, the timing must hence be Oligocene (metamorphic climax in deep levels at about 25 Ma according to Cliff et al., 1985). This WNW-directed motion can be related to an ongoing stacking of continental crust by subduction of the European foreland. For other Penninic windows see Fig. 8.

Oligocene and Neogene extension and strike-slip in the Central Alps

The eastern portion of the Central Alps shows a pattern of brittle ductile faults which are related to a sinistral wrench corridor along the northern margin of the Central Alps, and a dextral wrench corridor along the Periadriatic Lineament (Neubauer, 1988; Ratschbacher et al., 1989, 1991). In detail, motion along the sinistral zone often predates dextral displacement along the Periadriatic Lineament. Therefore, detailed structural studies record differing displacement paths from place to place within the orogen. In any case, the result is an extrusion of the eastern Central Alps towards east, crustal extension of the intermediate portion between the two wrench corridors, and exhumation of

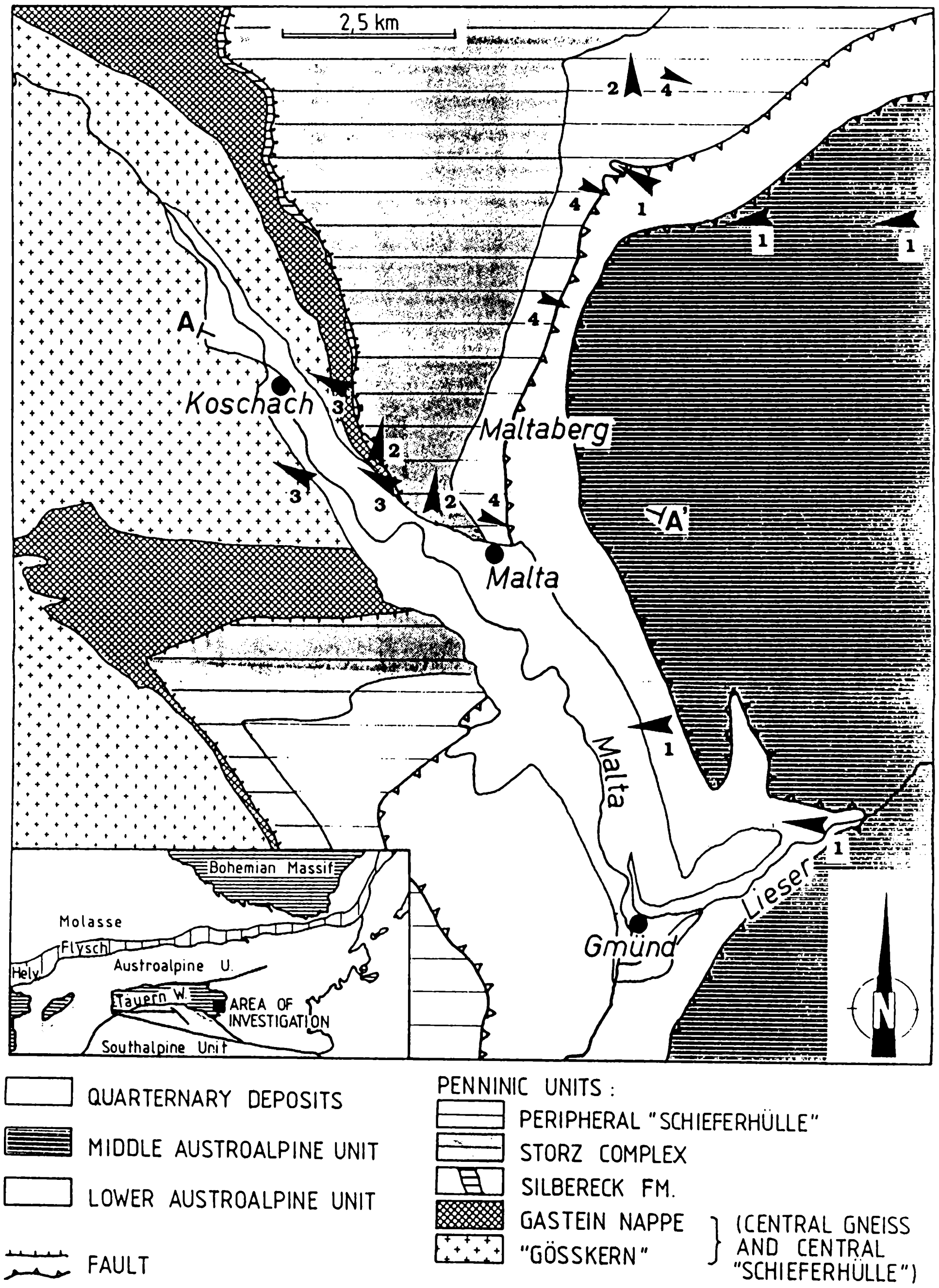


Fig. 7: Displacement path at the eastern margin of the Tauern Window (Genser, 1992). Suggested timing of displacement: 1 - Cretaceous thrusting; 2 - Paleogene thrusting; 3 - Oligocene thrusting; 4 - Neogene extension.

Penninic metamorphic domes by the same process. For the Penninic Tauern Window two models have been postulated: 1) A pull-apart dome mechanism which is related to a step of sinistral strike slip faults (Genser and Neubauer, 1989); 2) brachyanticline (Laubscher, 1988; Ratschbacher et al., 1991). It should be noted that this pattern of large-scale faults is also supported by paleogeographic data (Kazmer and Kovacs, 1985). These authors first proposed a sort of escape model to explain paleogeographic data of the Alpine/Carpathian system. But the northern sinistral margin of the escaped block is, however, after our structural and paleogeographic data much more farther to the North, ca. 100 km, than suggested by these authors.

The recent seismic pattern of the region suggests a similar escape mechanism like that one which operated during the Neogene (Fig. 10; from Gutdeutsch and Aric, 1987).

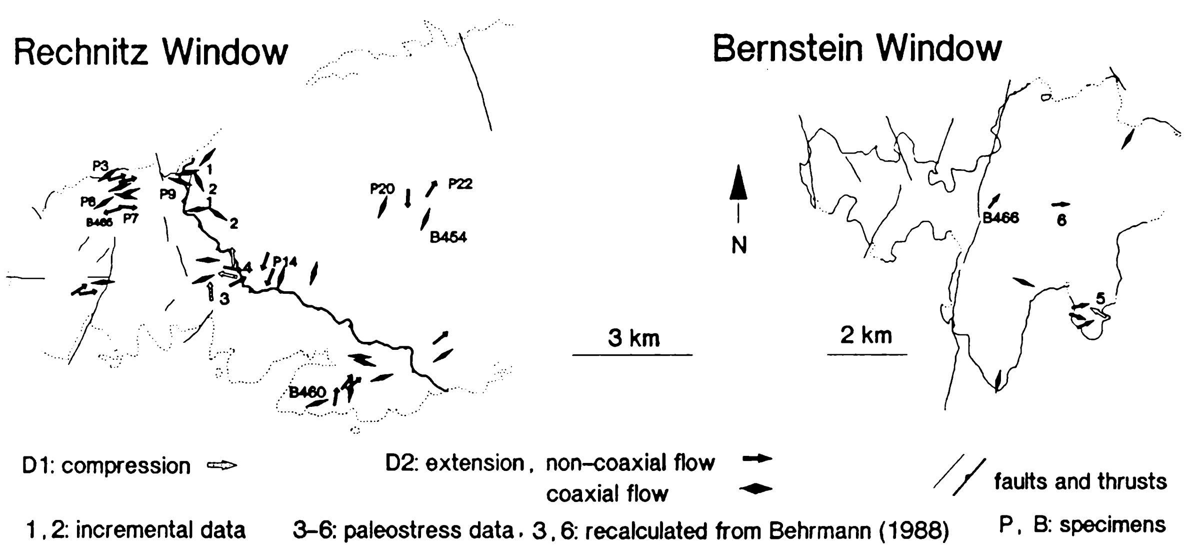
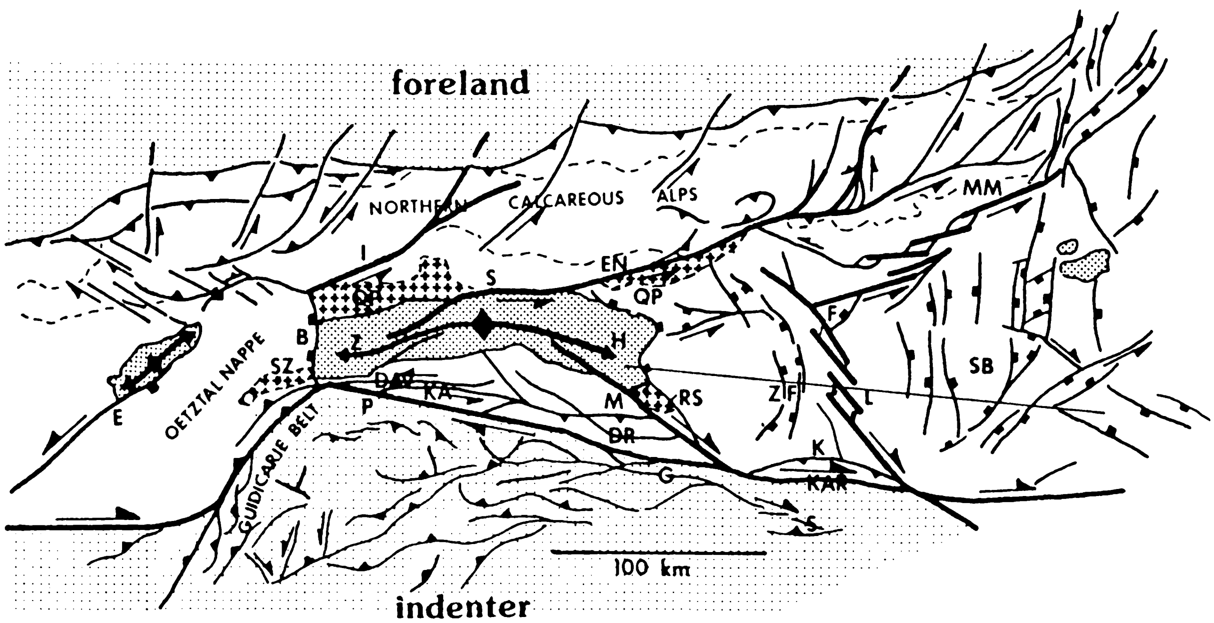


Fig. 8: Ductile and brittle structures in the Penninic Rechnitz and Bernstein Windows at the eastern margin of the Alps (from Ratschbacher et al., 1990).



Strike-slip faults:
B Brenner, DAV Defereggen-Antholz-Vals, E Engadine, EN Ennstal
G Gailtal, I Inntal, KA Kalkstein, L Lavanttal, M Mölltal
MM Mur-Mürz, P Pustertal, S Salzachtal
Basins: F Fohnsdorf, K Klagenfurt, S Save
Grabens: SB Styrian, Z Zollfeld
Domes: H Hochalm, Z Zillertal
Lithological units:
DR Drauzug, KAR Karawanken, QP Quartzphyllite
RS Radenthein series, SZ Schneeberg Zug

Fig. 9: (Oligocene and) Neogene fault pattern of the Eastern Alps (from Ratschbacher et al., 1991).

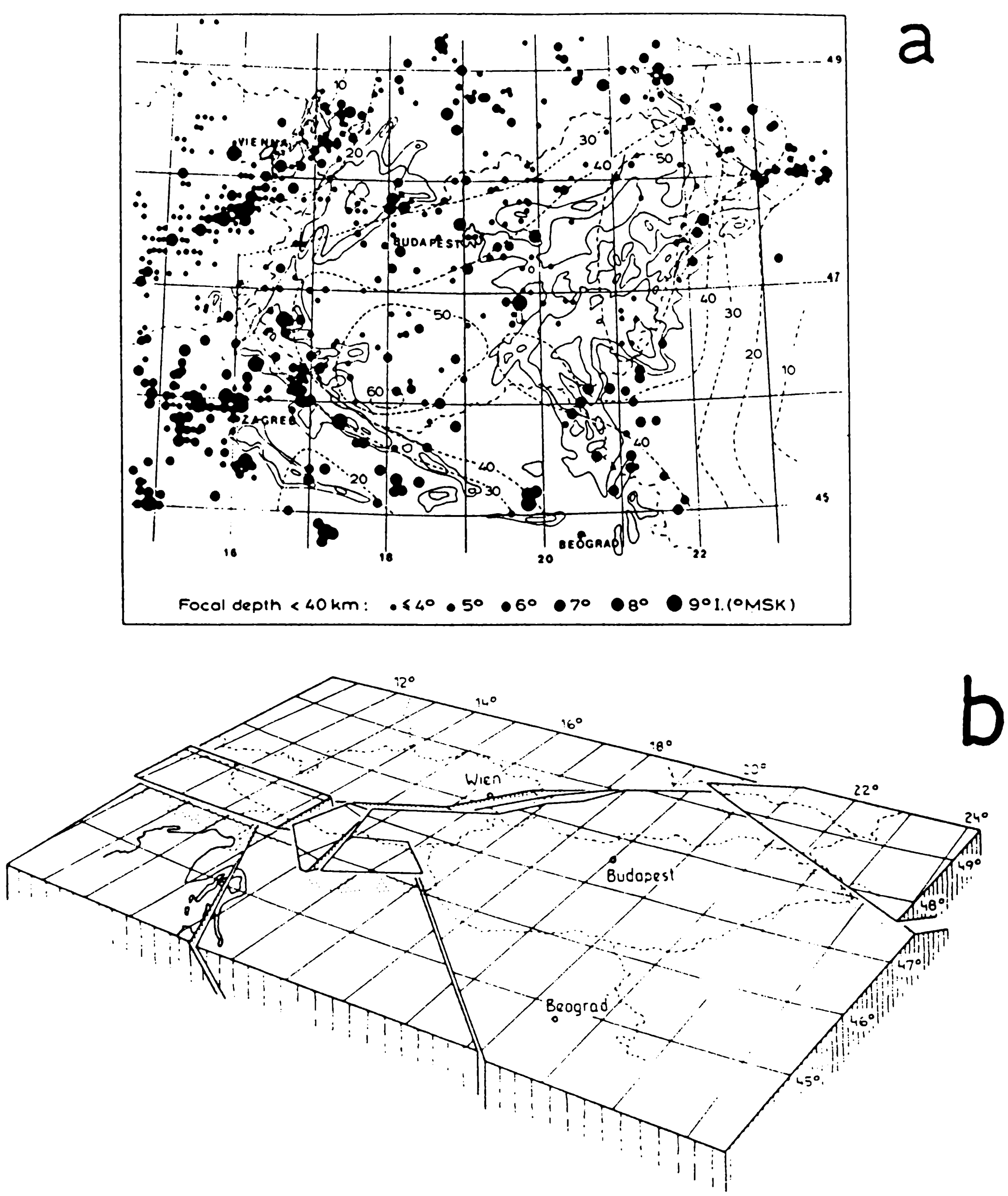


Fig. 10: Neogene motion of crustal blocks in the ALCAPA region.

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FINAL EPISODES OF THE COOLING HISTORY OF EASTERN TERMINATION OF THE ALPS

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The formation and metamorphic ages of the major alpine units are known for decades, however on the last interval of the t/T stories only very limited pieces of information exist (Frank et al., 1987). The most promising techniques to date the <200°C events is the fission track method. The investigated formations in the most cases contain both apatite and zircon, which enable to identify two points or intervals on the cooling pathes. The interpretation of apatite and zircon results possible only in the simplest way, as cooling ages. A minority of samples were suitable for the AFTA method, to estimate the duration spent in the 70-120°C temperature range in course of cooling. The considered blocking temperatures for the minerals are: 100 20°C for apatite, and 200 30°C for zircon.

The four investigated tectonic units and their lithofacieses are the following (starting with the highest one, see Fig. 1):

(1) Neogene intramontane sediments (sandstone, conglomerate, fanglomerate),
(2) Sieggraben unit (gneisses of MAA),
(3) "Grobgneis" unit (orthogneiss and micaschist members of the LAA),
(4) Wechsel/Waldbach unit (gneiss, schists, Permomesozoic metasediments of LAA),
(5) Penninic unit (quarz phyllite, greenschist, metagabbro).

In some cases the FT results are in harmony with the structural position of the terrains, the upper ones served older ages. Such type of results could determined in several orthogneiss samples of the LAA unit; they show late Cretaceous-Paleocene apatite ages. These results are accounted rather old in the crystalline domains of the Eastern Alps and express that the exhumation of LAA unit happened soon after its Cretaceous metamorphism (see Dallmeyer et al. in this vol.). Moreover zircon data are very close to the apatite cooling ages which proves that the uplift was very rapid in the Cretaceous and the eastern termination of this terrain was in a cool, near-surface position in the last 60-70 Ma (Dunkl, 1991).

There is a characteristic difference between the apatite results of the orthogneisses and the micaschist members of LAA unit. The schists show Middle Eocene-Early Oligocene ages, which are younger than the apatite data measured in the gneisses by 23-29 Ma. Three possible interpretations are on these discrepancies, namely:

- the schists were the most mobile bodies in the "Grobgneis" unit in course of Tertiary tectonics, and this Tertiary event was recorded only locally in the apatites of the schists at the northeastern part of the LAA unit,
- the Tertiary data are mixed ages produced by the partial rejuvenation of the significant Neogene tectonics,
- some traces of hydrothermal events were found in these formations, maybe the rejuvenation linked to an enhanced fluid activity in course of Eocene-Oligocene.

We may reject the fourth (the simplest) explanation, to interpret the Cretaceous and Tertiary ages as signs of different uplift episodes. It is not realistic, because two pairs of the sites sampled with different ages are very close to each other.

The Wechsel unit cropped out in some windows from below the "Grobgneis" unit show a Neogene cooling event by the apatite FT ages with a weighted average of 10.4 Ma. The range of 6 to

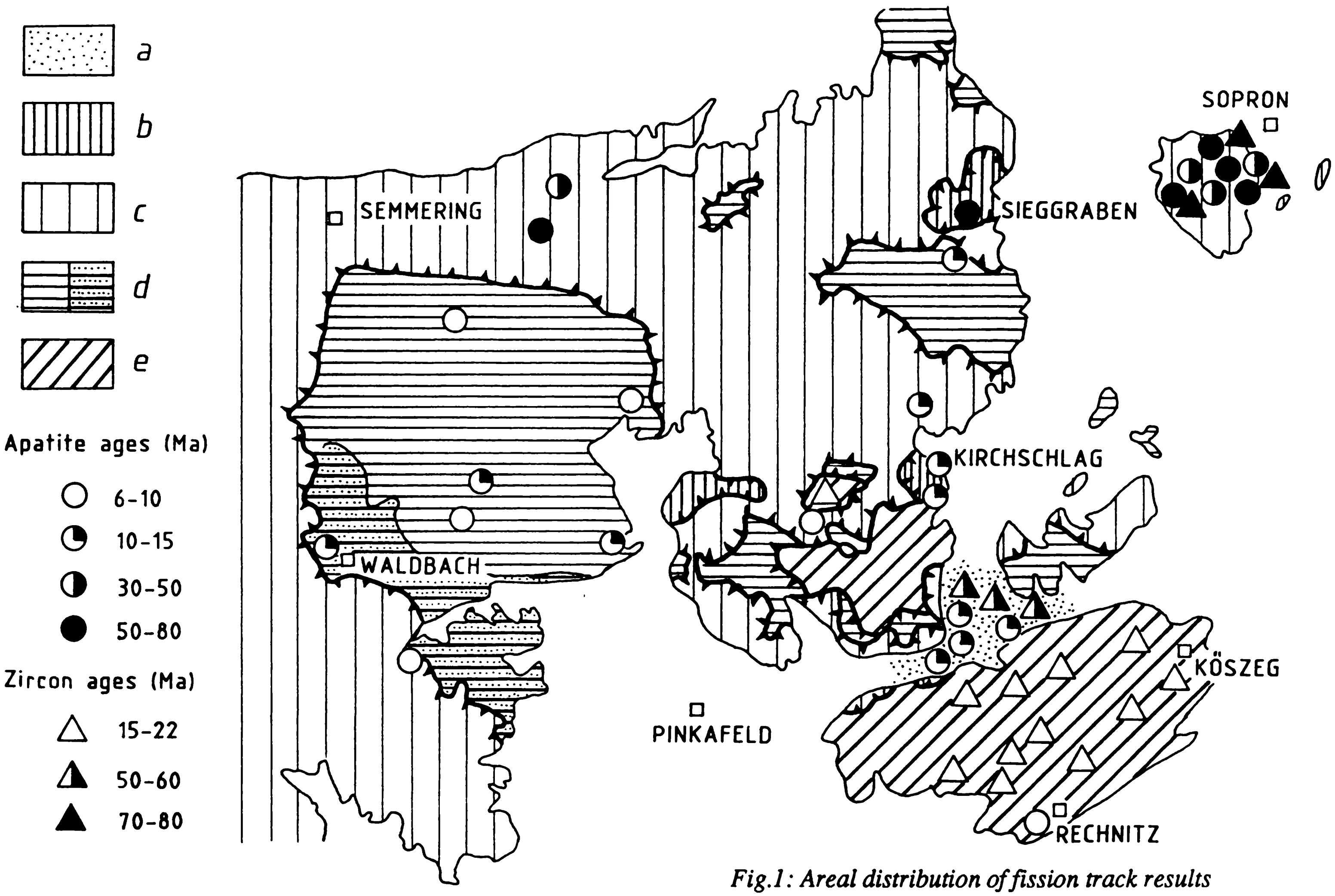

Fig.1: Areal distribution of fission track results
a: Neogen sediments, b: Sieggraben unit,
c: "Grobgneis" unit, d: Wechsel/Waldbach unit,
e: Penninic unit
(geology after Neubauer and Frisch, 1992)

15 Ma ages were recorded not only in the Wechsel rocks but the covering "Grobgneis" formations served similar ages south and east of the Wechsel window. Two ways of explanation are possible on these young ages: (a): The samples situated in the lower part of "Grobgneis" unit, and their cooling happened simultaneously with the uplift of the Wechsel dome. (b): The Neogene ages are not connected to the position of the samples within the LAA unit, rather to the warming up in course of Neogene extensional tectonics. So these rejuvenated ages are produced by the increased heat-flow.

Similar Neogene ages were determined in a greenschist and in a metagabbro sample of the Rechnitz-Köszeg window. The Penninic apatite ages somewhat younger than the Wechsel apatite samples, may express the later uplift of the Rechnitz window. (However it is noteworthy that the difference is not significant, a great part of the apatite ages have extremely large uncertainity due to the low uranium concentration.) The petty difference between the FT ages of the Wechsel and the Penninic apatites indicates that the formation of these two structures is connected to the same extension stage.

Zircon ages between 15 and 22 Ma from the Penninic rocks express the date of passing through the 200°C isotherm surface. Apatite and zircon cooling data make possible to calculate the cooling rate for the Neogene uplift. It is derived 10°C/Ma, close to the published results of other Penninic terrains of the Central and Western Alps.

The Sinnersdorf beds consist of silty sandstone, conglomerate, and fanglomerate. Their deposition was connected to intramontane basin formation in Miocene time. The petrography of the pebbles proves that at the time of the erosion/deposition the Penninic rocks had not reached the surface. The FT ages of detrital apatite and zircon grains of the conglomerate reflect that the cooling of the formations were exposed in course of the Neogene tectonics and basin formation. Strong difference were found between the ages of the apatite and zircon grains. The apatites form a population with a mean of 13-14 Ma; the zircon group is significantly older, it can characterized by a 51-58 Ma peak. Both of the two groups are very compact, sharp, the peak/with ratios of the two populations are nearly identical. In the apatite group the number of grains older than 25 Ma are negligible (the age distribution is symmetric with a tiny tail). At the evaluation of the apatite results we have to take into consideration that the Neogene sediments of the extensional basins were affected by the increased heat-flow during the opening of the basins. The measured apatite ages may reduced by a post-depositional reheating recorded by the maturation of the organic matter (Sachsenhofer, 1991). Because there are no evident results about the possible reheating of the dated outcrops now the apatite FT data are considered as cooling ages of the source terrains. What kinds of considerations can we drown from these facts?

- The sample sites contain debris only from rock bodies which reached the surface just before the erosion.
- No grains of units cooled under 100°C before the Miocene uplift were deposited into the samples beds.
- The zircon grains cooled under their blocking temperature in course of a Paleocene-Eocene uplift stage.
- The contribution of the zircons older than late Cretaceous is insignificant.
- The missing of the Neogene zircon grains proves that the early Miocene tectonics unroofed maximum the upper 4-6 km thick layer.

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EVOLUTION OF THE NEOGENE STYRIAN BASIN

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Regional setting

The Styrian Basin is the westernmost embayment of the Central Paratethys. Its northern and western margins as well as its pre-Tertiary basement are formed by the Penninic tectonic unit, Lower and Middle Austroalpine tectonic units and the Upper Austroalpine Paleozoic of Graz (Fig. 1). To the east the Styrian Basin is separated from the Pannonian Basin by a NNE-trending basement high, the Südburgenländische Schwelle. The Mittelsteirische Schwelle, a N-S oriented morphological basement high, separates the up to 1000 m deep Western Styrian Basin from the more than 3000 m deep Eastern Styrian Basin which is segregated into several subbasins. The relief of the basement is strongly controlled by fault tectonics. Its structure, lithologies and geophysical peculiarities are well documented in a set of maps at the scale of 1:200.000 (Kröll et al., 1988). Comprehensive geological information is provided by Kollmann, 1965; Flügel and Heritsch, 1969; Flügel and Neubauer, 1984, and Ebner and Sachsenhofer, 1991.

Stratigraphy, facies and paleogeographic evolution

A major part of our knowledge about the Styrian Basin is based on the studies of Arthur Winkler-Hermaden, carried out in the first half of this century (see for summary Winkler-Hermaden, 1951, and references cited therein). Hydrocarbon exploration in the Eastern Styrian Basin provided additional (subsurface) data (Kollmann, 1965). As detailed biostratigraphic and sedimentologic studies are still lacking for large parts of the basin (especially for younger drill holes, see Friebe and Poltnig, 1991) and seismic data are not released by the oil companies, this paper can give only our preliminary view of the evolution of the Styrian Basin.

Due to the complex tectonic evolution of the Styrian Basin individual subbasins (Fig. 1) show a quite different stratigraphic and paleogeographic evolution.

Sedimentation started probably in the Ottnangian (for correlation of the regional stages of the Central Paratethys with the Mediterranean standard stages see Rögl and Steininger, 1983; Steininger et al., 1990). The southwestern part of the Eastern Styrian Basin was characterized by fluviatil-lacustrine deposition whereas fan-delta sedimentation in a fault-controlled setting (K. Stingl, pers. comm.) prevailed in the southernmost subbasin of the Western Styrian Basin (Fig. 2).

During the Karpatian a transgression flooded the central part of the Eastern Styrian Basin (Gnas Basin) resulting in a thick succession of marine siltstones (Steirischer Schlier). Its foraminiferal fauna indicates water depths of at least 100 meters (Friebe, 1990, 1991b). Marine conglomerates (fan delta deposits ?) record the initiation of the halfgraben of Fürstenfeld at the same time (Fig. 3). Cyclic fluvial and paralic (?) sediments with major coal seams were deposited in the Western Styrian Basin (Eibiswald formation). In the south braiddelta deposits (Arnfels conglomerate) link the paralic (?) sediments of the Western with deposits of deeper water of the Eastern Styrian Basin.

In the uppermost Karpatian a tectonic event lead to a re-organisation of the basins. Block-tilting caused an uplift of the hinterland (Koralm) as well as the Sausal Mountains. This coincided with an eustatic sea-level lowstand thus forming a tectonically enhanced sequence boundary (Styrian Unconformity; Friebe, 1991b; Friebe submitted).

The Lower Badenian sea-level rise lead to (shallow) marine conditions throughout a major part of the Styrian Basin (Fig. 4). Fluvial sedimentation was restricted to the western margin of the basin. The opening of a marine seaway between Paratethys and Indo-Pacific and the re-establishment

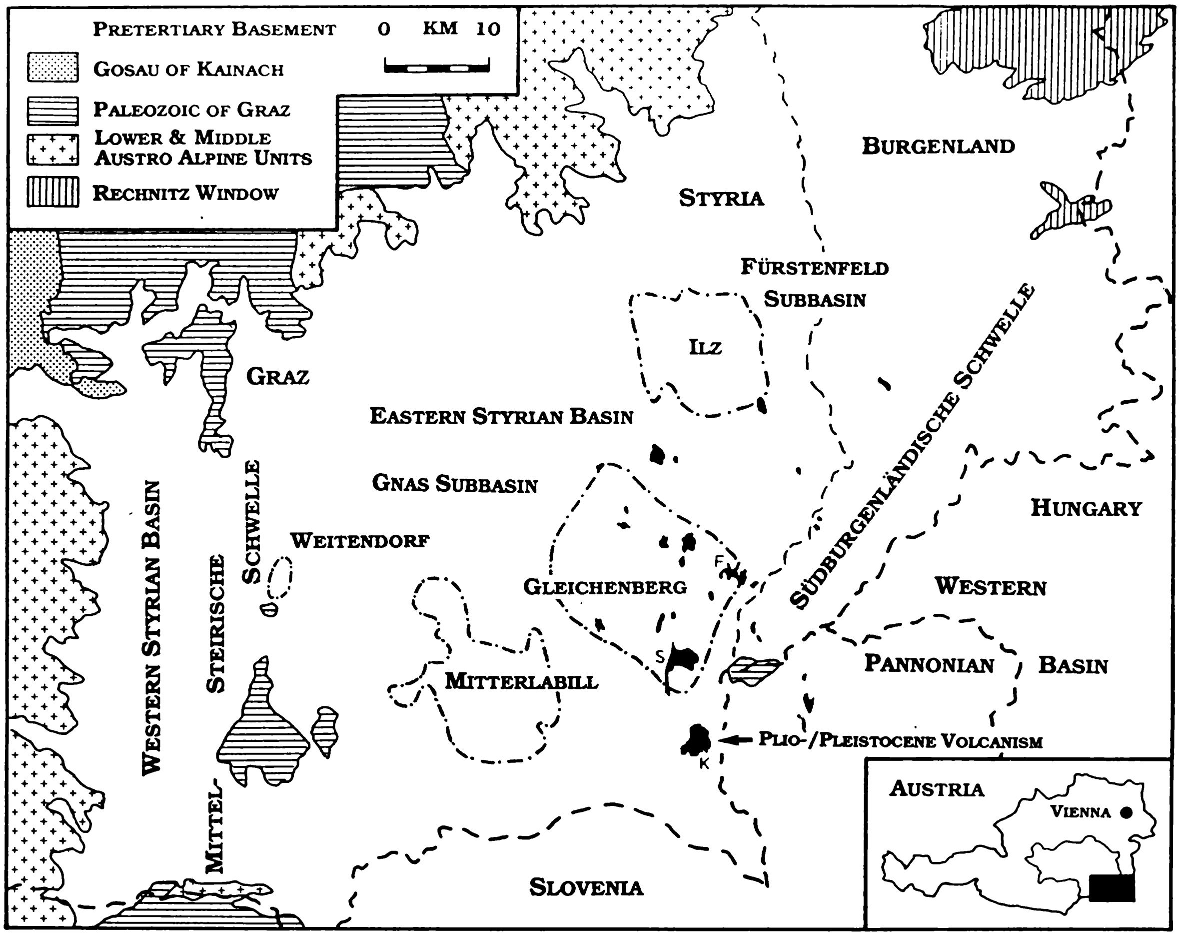

Fig.1: Location and major features of the Styrian Basin. Plio-/Pleistocene volcanism: F = Feldbach-Steinberg, S = Straden, K = Klöch.

of a circum-equatorial warm-water circulation system allowed the development of a strongly diversified marine fauna in the entire Central Paratethys (Rögl and Steininger, 1984). In the Styrian Basin coral reefs and rhodolith platforms (coralline algal limestone: Leithakalk) which were separated by siliciclastics developed on shoals both in the vicinity of the Mittelsteirische Schwelle (Weißenegg Formation) and fringing the volcanoes of the Eastern Styrian Basin (Friebe, 1990, 1991a). Within the Weißenegg Formation three depositional sequences, recording eustatic sea-level cycles, can be distinguished (Friebe, submitted).

A major sea-level drop at the end of the Badenian caused the progradation of a (braid-) delta into the Western Styrian Basin (Eckwirt gravel and Dillach Member). In the Eastern Styrian Basin this event is recorded by a (local) hiatus and unconformity, respectively.

The Sarmatian started with a new transgression. In the vicinity of Graz shallow marine sediments interfinger with fluvial deposits (Waldhof formation , Riepler, 1988). Fine-grained siliciclastics with intercalations of limestones of various microfacies are also found at the northern margin of the Eastern Styrian Basin (Rollsdorf formation). Salinity was probably slightly reduced (Krainer, 1984, 1987b). In the Western Styrian Basin Sarmatian sediments are not preserved. Shallow marine conditions prevailed throughout the Eastern Styrian Basin (Fig. 5). The Middle Sarmatian is characterized by an intercalation of fluvial conglomerates prograding from the Southwest (Kollmann, 1965). In the Upper Sarmatian a shallow marine realm was re-established (Fig. 6). In marginal areas siliciclastic shallowing-upward cycles, each terminated by a bed of ooid grainstone, reflect minor sea-level fluctuations (Friebe, in prep.). Foraminifera and mollusc associations indicate reduced salinity. Similar deposits are found at the northern margin of the basin.

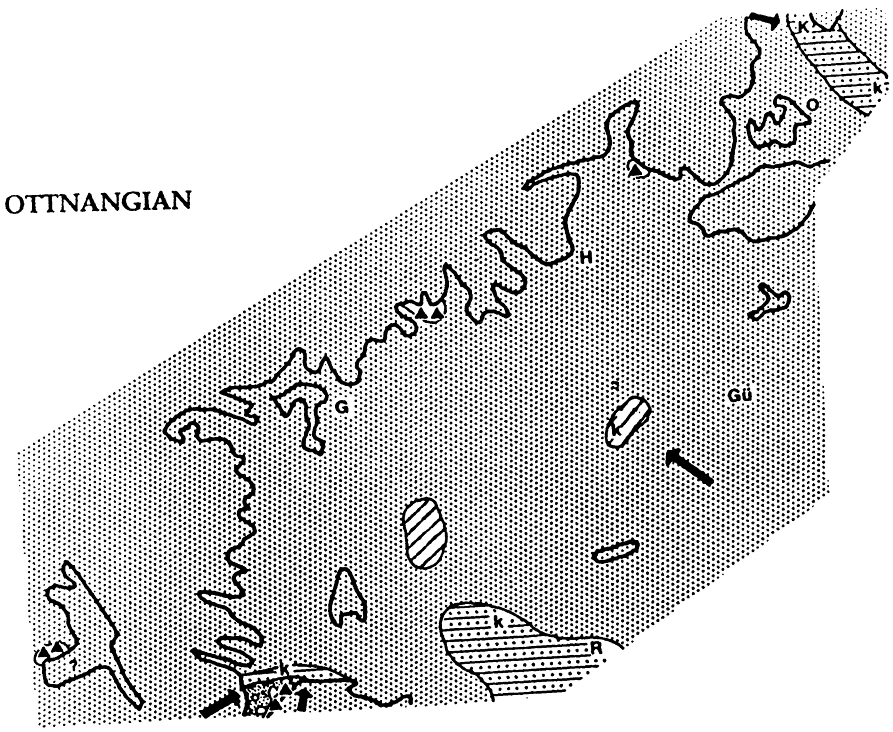

Fig. 2: Paleogeographic sketch of the Styrian Basin during the Ottnangian (Ebner & Sachsenhofer, 1991). For legend see Fig.4.

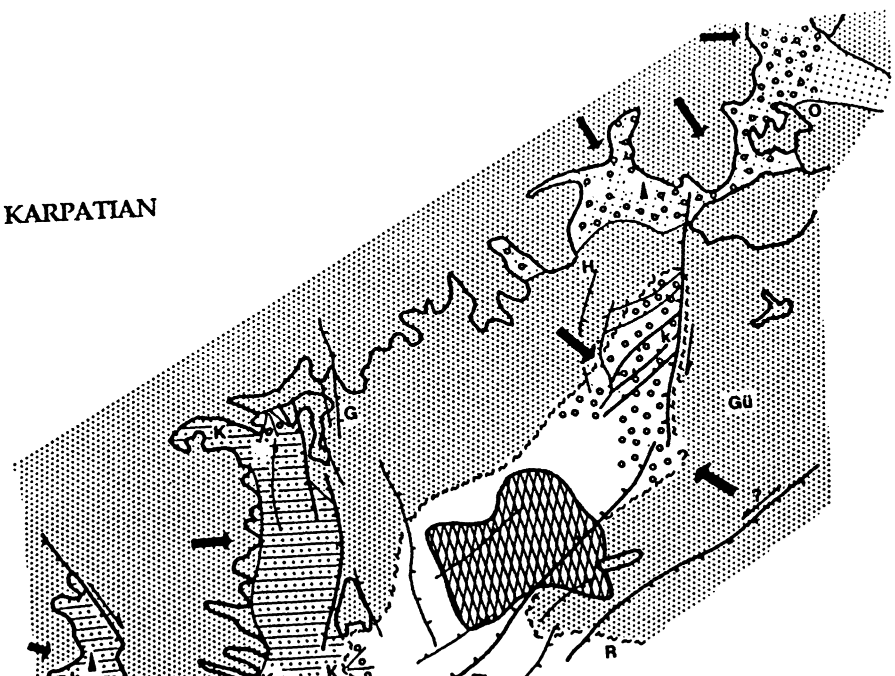

Fig. 3: Paleogeographic sketch of the Styrian Basin during the Karpatian (Ebner & Sachsenhofer, 1991). For legend see Fig. 4.

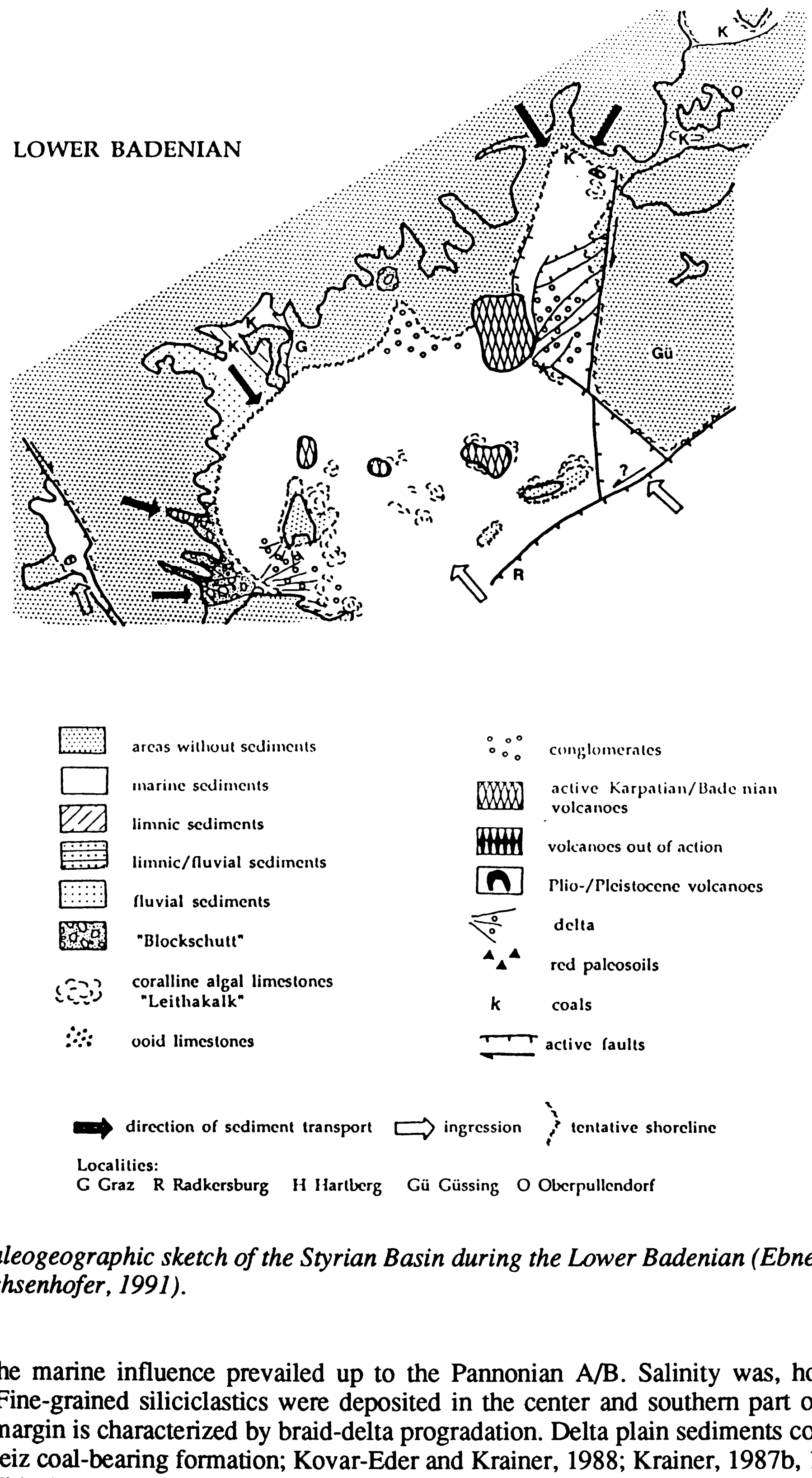

Fig. 4: Paleogeographic sketch of the Styrian Basin during the Lower Badenian (Ebner & Sachsenhofer, 1991).

The marine influence prevailed up to the Pannonian A/B. Salinity was, however, strongly reduced. Fine-grained siliciclastics were deposited in the center and southern part of the basin. The northern margin is characterized by braid-delta progradation. Delta plain sediments contain major coal seams (Weiz coal-bearing formation; Kovar-Eder and Krainer, 1988; Krainer, 1987b, 1988).

With the beginning of the Pannonian C the marine influence ceased. Coarse-grained fluvial sediments were then deposited in the northern to southeastern part of the Eastern Styrian Basin (Fig. 7). At the northern margin alluvial fans shed terrigenous siliciclastics into the Basin (Puch gravel Krainer, 1987b). They were transported southwards by maeandering streams (Kapfenstein/Kirchberg gravel). Active channels were separated by wide alluvial plains with abundant vegetation (Kovar-Eder and Krainer, 1989, 1990; Krainer, 1987a, 1987b, 1990).

Pontian fluvial sediments are restricted to the immediate vicinity of the Südburgenländische Schwelle (Fig. 8).

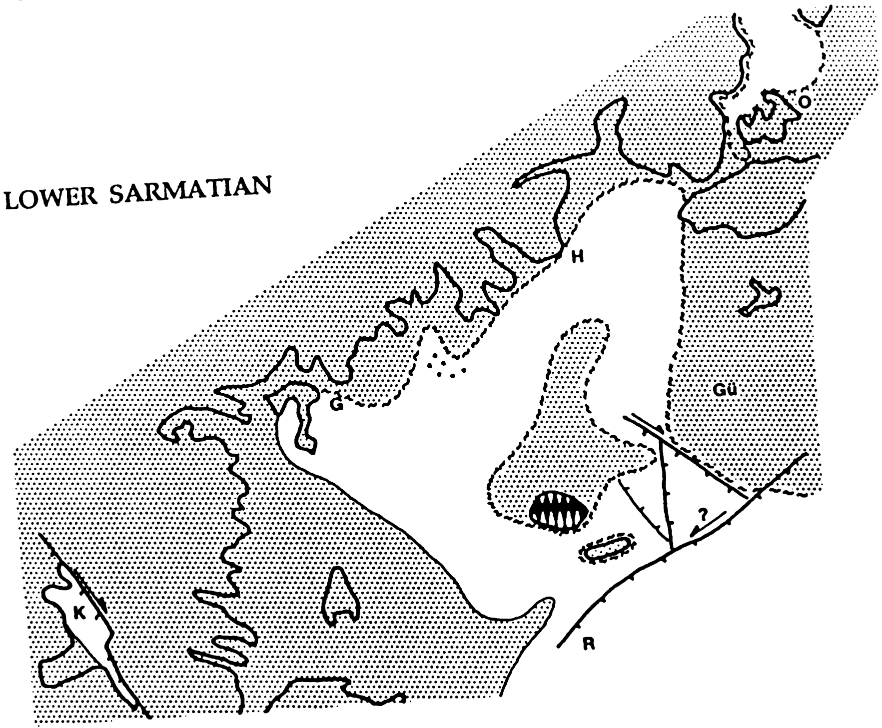

Fig. 5: Paleogeographic sketch of the Styrian Basin during the Lower Sarmatian (Ebner & Sachsenhofer, 1991). For legend see Fig. 4.

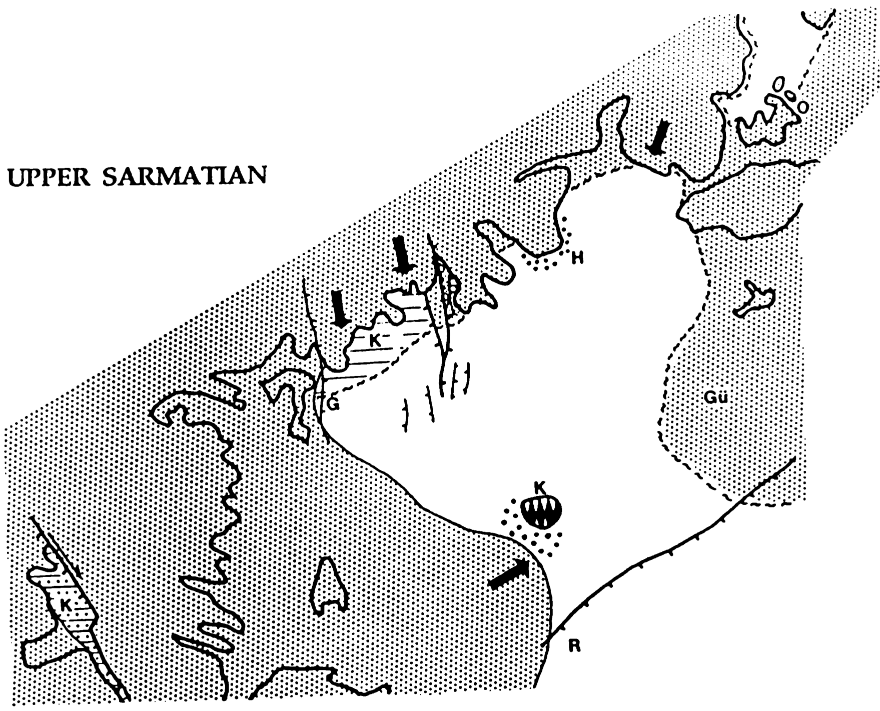

Fig. 6: Paleogeographic sketch of the Styrian Basin during the Upper Sarmatian (Ebner & Sachsenhofer, 1991). For legend see Fig. 2.

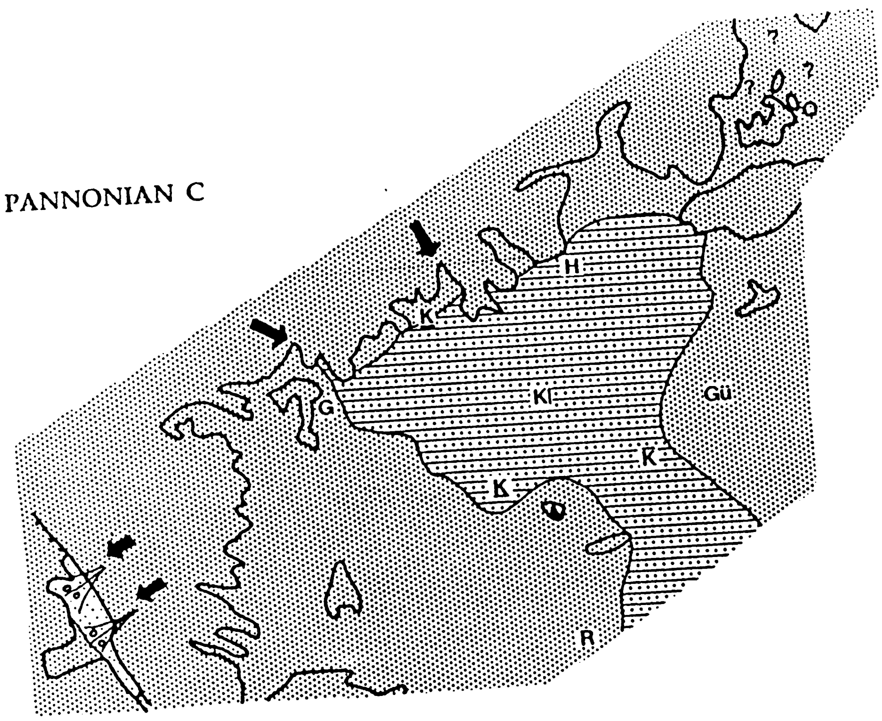

Fig. 7: Paleogeographic sketch of the Styrian Basin during the Pannonian C (Ebner & Sachsenhofer, 1991). For legend see Fig. 2.

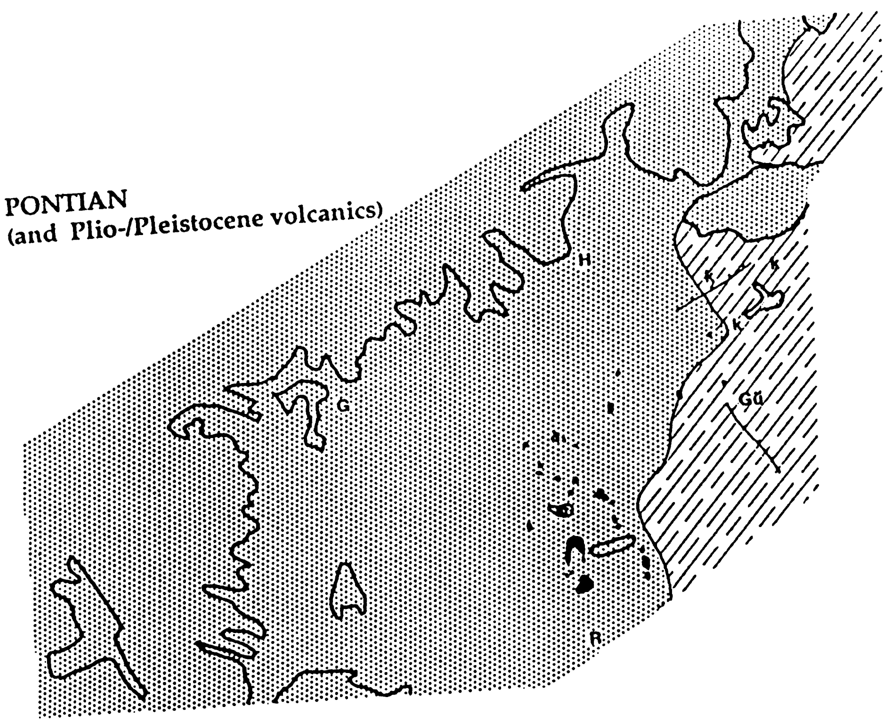

Fig. 8: Paleogeographic sketch of the Styrian Basin during the Pontian (Ebner & Sachsenhofer, 1991). For legend see Fig. 2.

Volcanism

The volcanic events in the Styrian Basin are related to the magmatic activities of the intra-Carpathian region. Two distinct volcanic episodes of different magmatic character can be distiguished.

Karpatian to Lower Badenian acid to intermediate volcanics are concentrated to the areas of 1) Mitterlabill 2) Gleichenberg, 3) Ilz-Walkersdorf and 4) Weitendorf (Fig. 1). Further terminal apophyses of a subvolcanic intrusion cut Lower Badenian sediments at Retznei. Vitric tuffs, sometimes altered to bentonites, are widely spread throughout the subbasins. Although most of the volcanoes are buried by younger sediments they can be mapped excellently by geophysics. Radiometric K/Ar ages ranging from 15.2 0.9 to 16.8 0.75 Ma were determined by Lippolt et al. (1975) and Steininger and Bagdasaryan (1977), the biostratigraphy of associated sediments was determined by Kollmann (1965) and Krainer (1987c).

During this volcanic episode magmatic activities probably shifted northward (Karpatian: Slovenia, southern part of Mitterlabill-Gleichenberg; Lower Badenian: northern part of Gleichenberg, Ilz/Walkersdorf, Weitendorf). In some of the southern localities Lower Badenian sediments cover the Karpatian volcanics.

Together with this regional trend a change in magma character from the subalkaline towards the boundary of the subalkaline/alkaline field occurred (Fig. 9). The generally calc-alkaline character suggests a subduction-related genesis. However, a modern genetic interpretation related to plate tectonic concepts is still missing especially in account of lacking trace element investigations. All available main element analysis of Miocene volcanics of Slovenia and Styria are shown in Fig. 9.

A second major volcanic episode of Pliocene to Pleistocene age resulted in approximately 30 to 40 occurrences of nephelinitic/basanitic lava flows and a wide variety of pyroclastic rocks related to pipes, calderas and maar structures in the Eastern Styrian Basin (e.g. Steinberg/ Feldbach,

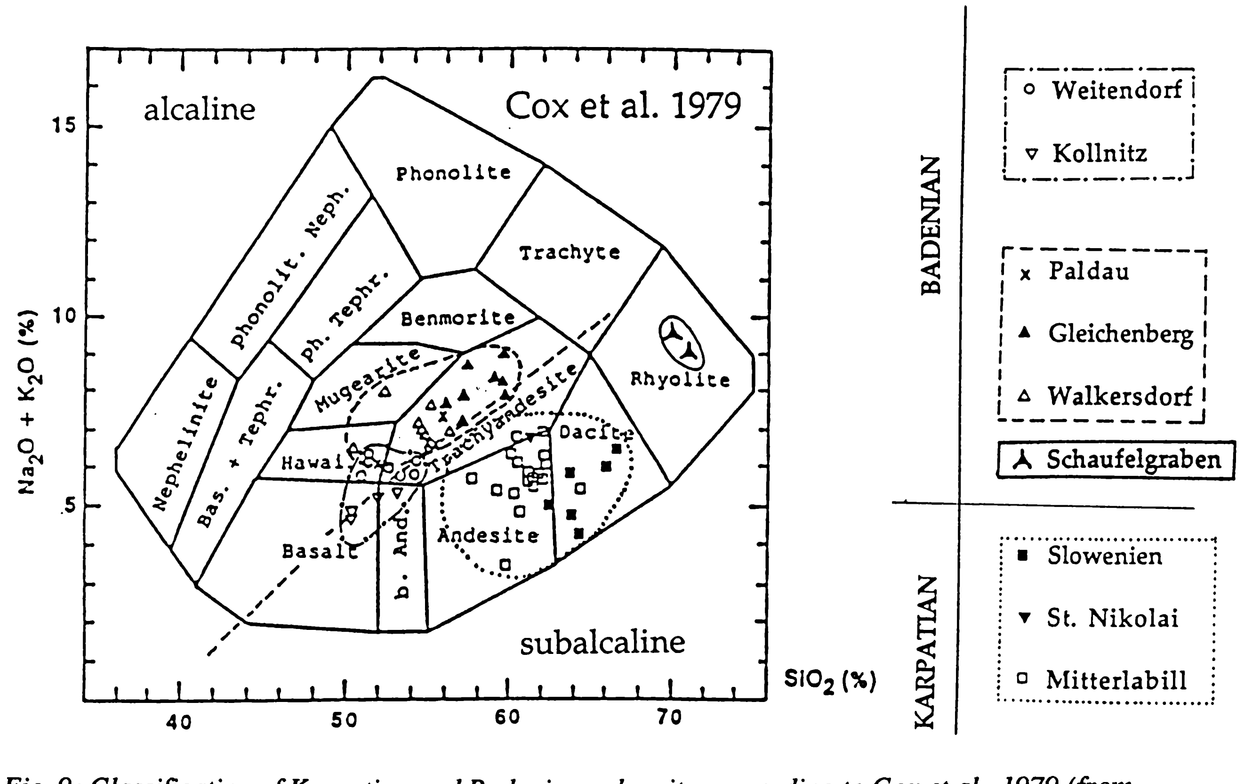

Fig. 9: Classification of Karpatian and Badenian volcanites according to Cox et al., 1979 (from published data; see Ebner & Sachsenhofer, 1991). Obviously altered samples were not plotted.

Klöch, Stradner Kogel, see Fig.1 for location) can be related to this younger volcanic period. Radiometric K/Ar ages range from 1.7 0.7 to 3.8 0.4 Ma (Balogh et al., 1989). The petrology of xenoliths suggests a source situated 50 - 80 km deep within the mantle (Kurat et al., 1980). All available analysis are plotted in Fig. 10.

Subsidence

Decompacted subsidence profiles of the Styrian Basin have been studied by Ebner and Sachsenhofer, 1991.

Subsidence in the Western Styrian, Mureck, and Gnas subbasins started in the Ottnangian and accelerated during the Karpatian, when maximum subsidence rates reached > 20 cm/100 a. This corresponds with intense normal faulting along the basin margins. An important factor for rapid subsidence in the oval shaped Gnas basin, which is characterized only by minor faults, is the load of the thick and relatively dense Miocene volcanic rocks and probably the emptying of the magma chamber underneath. Consequently in this basin the tectonic subsidence is less pronounced.

In some parts of the basin a hiatus occurred in the uppermost Karpatian. In Badenian times the area of subsidence widened, but velocity decreased (< 5 cm/ 100 a). The Badenian depocenter is located in the Halfgraben of Fürstenfeld.

In the Sarmatian the Eastern Styrian Basin subsided relatively uniformly and rapidly (up to 10 cm/100 a). Sarmatian subsidence is independent of the internal structure of the Eastern Styrian Basin, which originated in Ottnangian to Badenian times. The Western Styrian Basin and the Mureck area stayed relatively stable during this time.

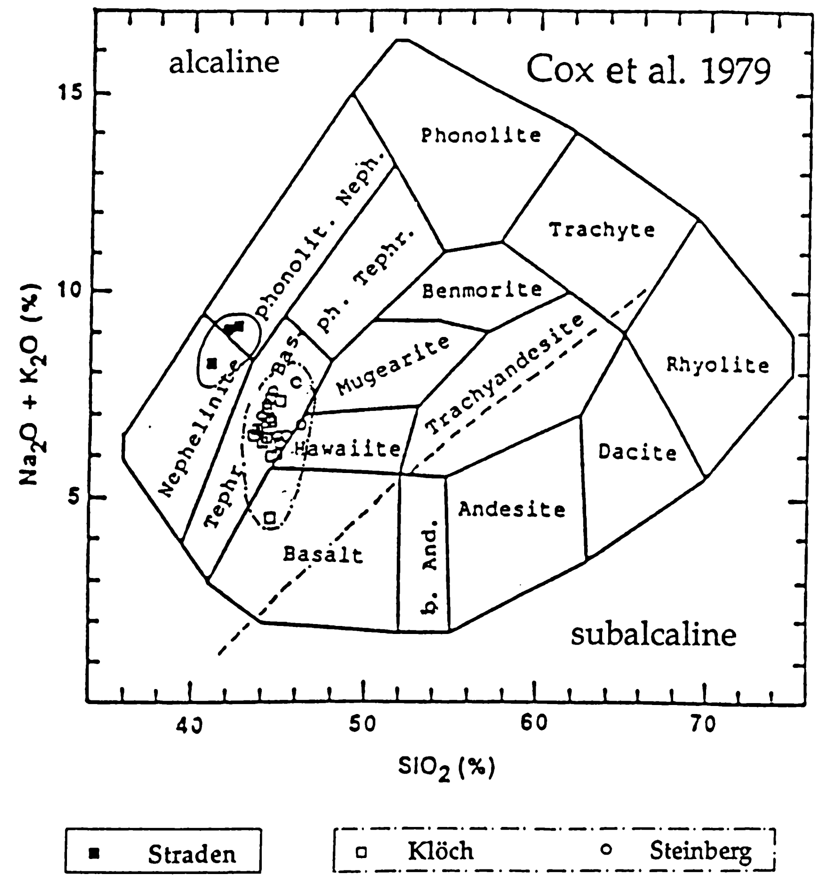

Fig.10: Classification of Plio-/pleistocene volcanites according to Cox Et Al., 1979 (from published data; see Ebner & Sachsenhofer, 1991).

Pannonian subsidence is relatively slow (< 1 cm/100 a). The depocenter shifted to the east. Therefore, subsidence also affected the northern part of the Südburgenländische Schwelle. On the other hand the Western Styrian Basin and the Mureck area were already uplifting. In Pliocene times subsidence was replaced by uplift in the whole basin. Minor sedimentation occured only in regions near the Pannonian realm.

Thermal history

The thermal history of the Styrian Basin can be deduced using vitrinite reflectance data from 150 outcrop samples and 25 drill holes (Fig. 11; Ebner and Sachsenhofer, 1991; Sachsenhofer 1990, 1991, submitted).

Vitrinite reflectance of outcrop samples is generally in the range of 0.2 %Rr to 0.4 %Rr. Local coalification maxima occur in the southwestern and northeastern basin. Some wells are characterized by a linear to sublinear increase in reflectance (e.g. Jennersdorf 1, Übersbach 1, Litzelsdorf 1). Reflectance gradients at a maturity level above 0.5 %Rr range from 0.22 to 0.37 %Rr/km. Reflectance curves of wells, located in the vicinity of Miocene volcanoes are characterized by a succession of two different gradients (e.g. Mitterlabill 1, Pichla 1, Blumau 1a). The slope-break of these curves corresponds to Karpatian (southern basin) or Lower Badenian (northeastern basin) levels. Coalification gradients of the lower segments increase towards the volcanic vents. The highest reflectance gradient (3.6 %Rr/km) can be observed in the Mitterlabill 1 well. This well is situated only 2 km west of a volcanic vent and drilled sediments above and underneath several hundred meters of volcanic rocks. Here vitrinite reflectance reaches 4 %Rr at a depth of only 1700 meters. The coalification pattern of the Eastern Styrian Basin is summarized in a schematic SW-NE trending maturation profile (Figs. 12, 13).

The one dimensional PC-version of the "Pre Drilling Intelligence" (PDI) software package of IES was used to simulate the temperature history. Calculation of vitrinite reflectance data follows a kinetic approach by Sweeney and Burnham (1990).

A good fit between measured and calculated vitrinite reflectance data from 20 boreholes is obtained with the following heat flow model (Sachsenhofer et al., 1992).

The regional, undisturbed heat flow during Karpatian and Badenian times (17.2 - 12.8 Ma) was 90 to 120 mW/m^2. Heat flow increased toward the volcanoes and locally reached 300 mW/m^2. In the southern Styrian Basin (Pichla area) this high heat flow related to volcanism already ended during the Karpatian, whereas it remained high until the Badenian in the northern and northeastern part of the basin. This is a consequence of a northeastward shift of the magmatic activity (Ebner and Sachsenhofer, 1991).

Sarmatian to Pliocene (12.8 - 1.8 Ma) heat flow is generally in the range of 65 - 100 mW/m^2. Relatively high heat flow is probably due to thinned crust beneath the Styrian Basin.

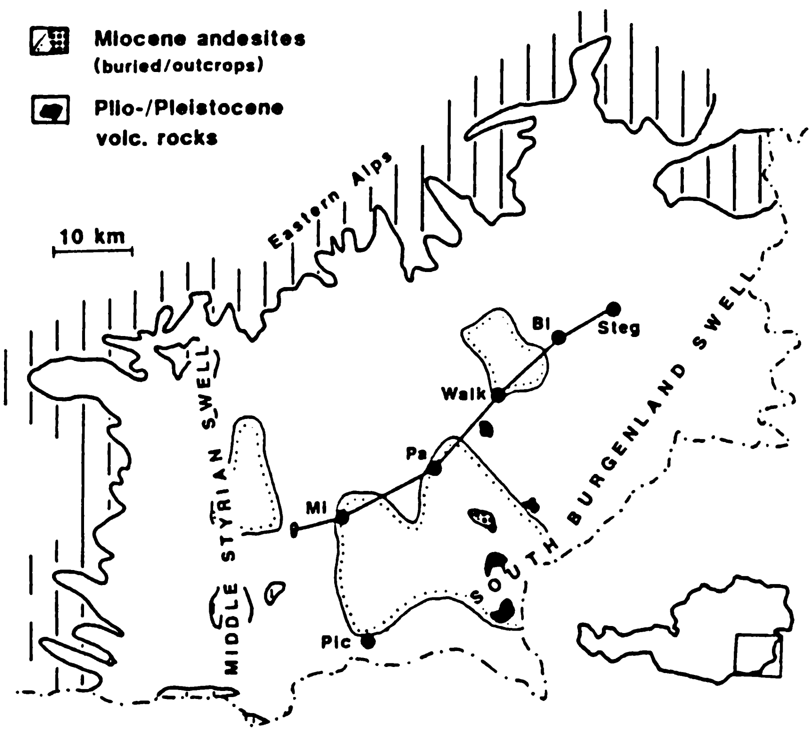

Fig. 12: Sketch map of the Styrian Basin and Location of Fig. 13 cross section. Pic = Pichla; Mi = Mitterlabill; Pa = Paldau; Walk = Walkersdorf; Bl = Blumau; Steg = Stegersbach.

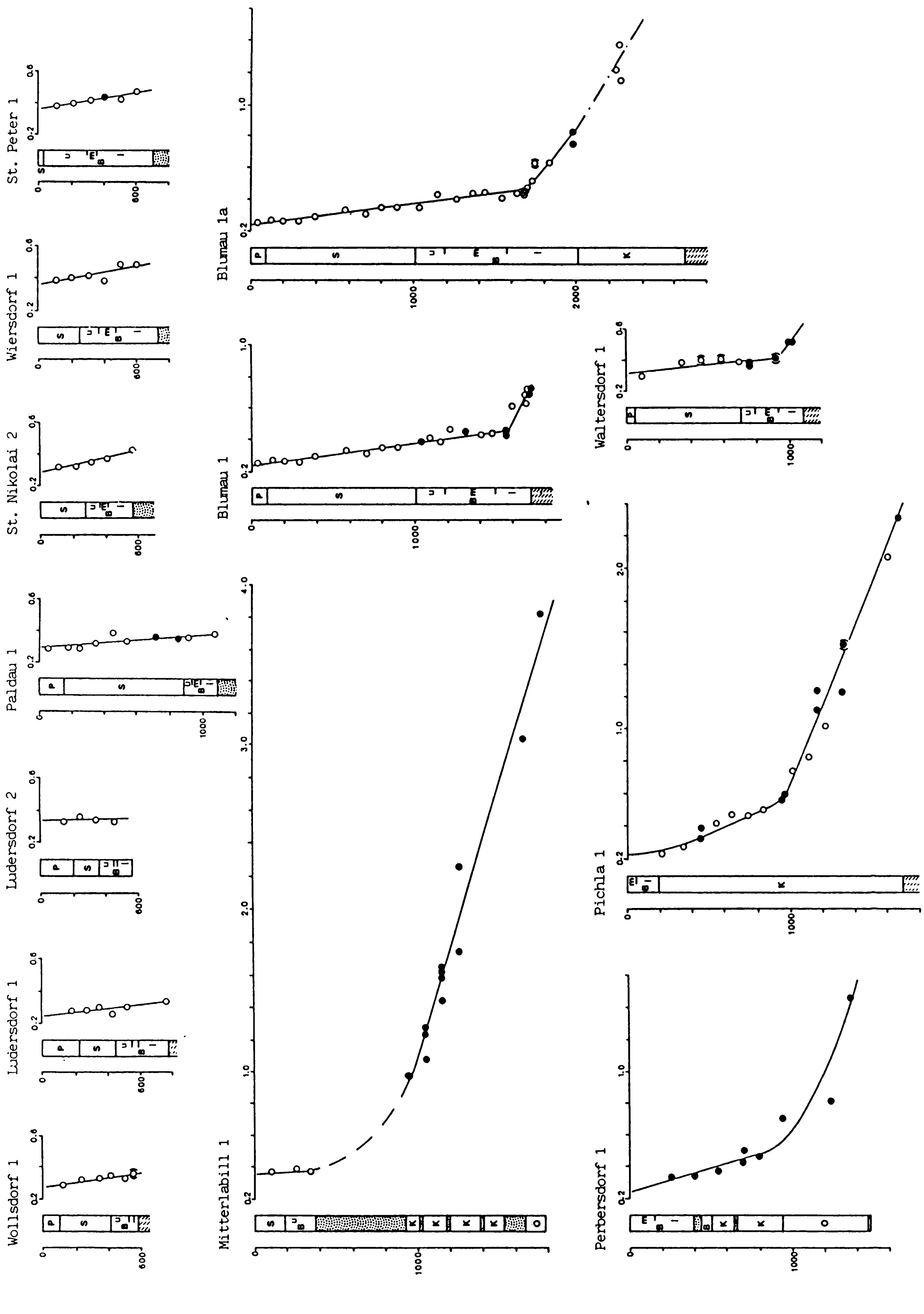

Fig. 11: Vitrinite refectance profiles from wells in the Styrian Basin (Sachsenhofer, 1991).

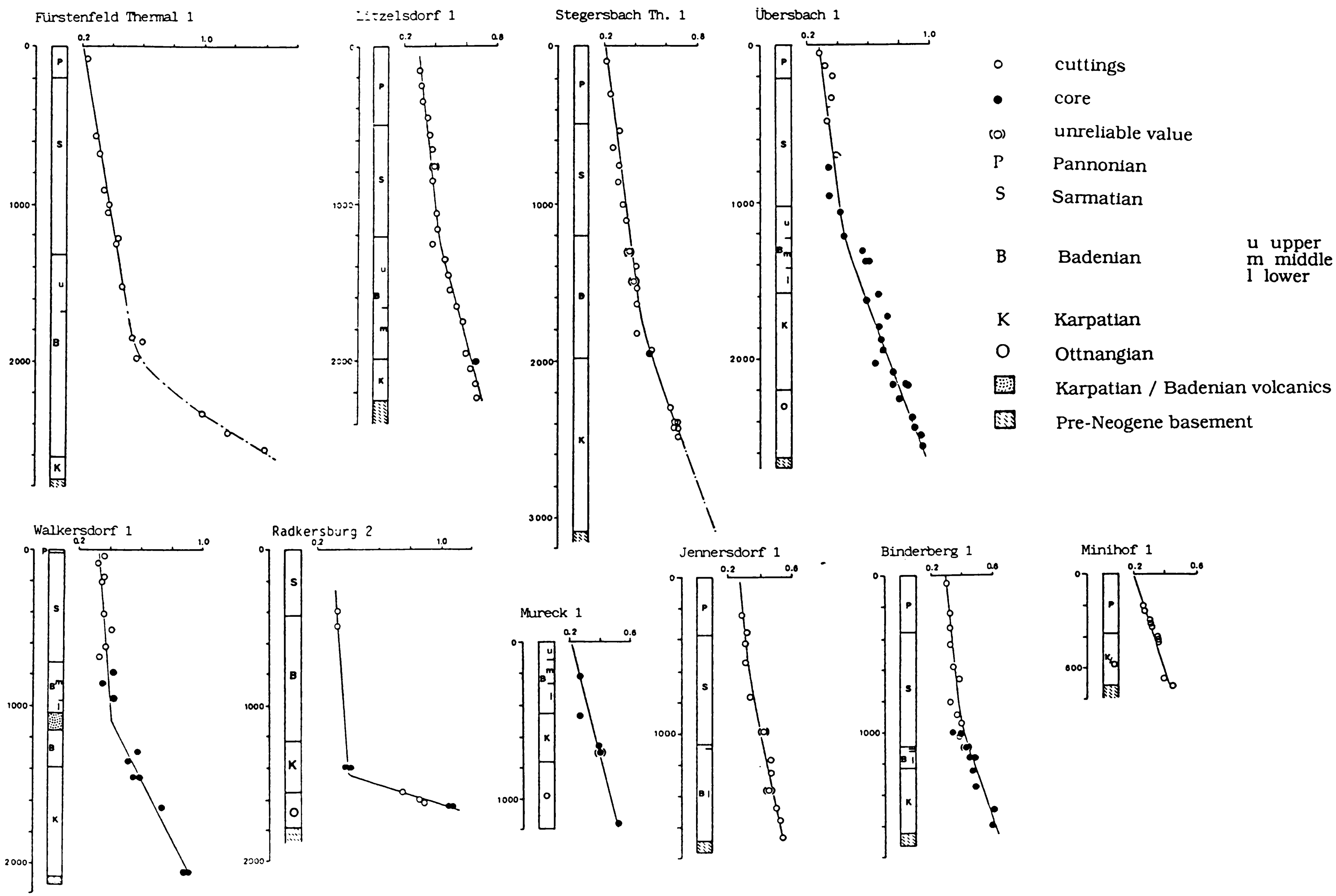

Fig.11 continued.

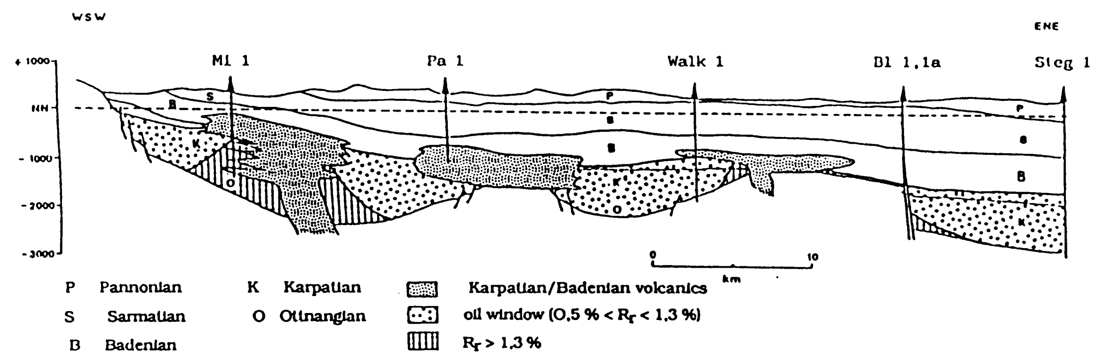

Fig. 13: Cross section through the Eastern Styrian Basin showing coalification trends. For location and abbreviations see Fig. 12.

In some areas, heat flow increased slightly during the Pleistocene. At least partly, this is a consequence of ascending hot waters flowing from deep into shallow parts of the basin (Goldbrunner, 1988). Perhaps, Plio-/Pleistocene volcanism also contributed to this heat flow increase.

Tectonic evolution

The tectonic evolution of the Styrian Basin is closely related to extensional tectonics and block tilting in connection to the east-directed continental escape of the Eastern Alps during the last stage of the alpine orogeny (Neubauer, 1988; Neubauer and Genser, 1991; Ratschbacher et al., 1991). The escaping block is bordered by the dextral Periadriatic and Vardar Lineaments to the south and a system of sinistral shear zones to the north (Defreggen-Antholz Fault, Salzachtal-Ennstal Fault, Mur-Mürz Fault).

The basement structures of the Styrian Basin are controlled by normal faults, block tilting and pull-apart processes inside the crustal wedge moved to the east. These structures were predominantly active during the Karpatian (west) to Lower Badenian (east) and formed the Mittelsteirische Schwelle as well as the synsedimentary halfgraben of the Fürstenfeld Basin. Intra-Sarmatian normal faults are known especially from the northern margin of the basin (Gleisdorf, Weiz; Krainer, 1984). Block tilting resulting in an angular unconformity (Styrian Unconformity), the development of fault-bounded swells (Mittelsteirische Schwelle, Südburgenländische Schwelle), major facies differentiations, and the Miocene volcanic activity are related to these processes (Ebner and Sachsenhofer, 1991; Friebe, 1991b).

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EXCURSION TO THE PENNINIC TAUERN WINDOW AND TO THE AUSTRO-ALPINE NAPPE COMPLEX: DESCRIPTIONS OF STOPS

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Introduction

This excursion provides an overview about the Penninic basement and cover units of the eastern Tauern Window and of all major basement units in a West-East section through the Austro-Alpine Nappe Complex and its post-orogenic cover between Tauern Window and Graz. The excursion includes two mountain roads which are only accessible with fees. Please, note that the access to quarries is only allowed with (written) permission of the owner after a new law for mines and quarries.

The pre-Permian basement of the eastern Tauern Window

R. MARSCHALLINGER

In the area of the eastern Tauern Window, a medium to high grade pre-Permian basement complex is exposed below the peripheral, Permo-Mesozoic cover. Principally, the basement complex can be subdivided into (Fig.1):
a) a pre-Variscan country rock formation comprising migmatic clastic and volcaniclastic series
b) pre-Permian intrusives ranging in composition from syenites and tonalites to granodiorites and granites, summarized in the term "Zentralgneis". (Cliff et al., 1971; Cliff, 1981; Exner, 1979).

Until recent times the internal structures of the pre-Permian basement were interpreted mainly in the light of Alpine tectonics (Exner, 1982; Tollmann, 1977), yielding a merely descriptive concept of huge, Alpine "Zentralgneis" nappes separated by metasediment zones, the pre-Alpine genetic relationships being obscured for the most part. Partly based on the work of Cliff et al. (1971), a different view of the internal structure and genesis of the basement complex was developed: detailed field studies proved that pre-Permian intrusive relations between granitoids and country rocks have been almost perfectly preserved in many locations, unraveling a consistent intrusive series among the "Zentralgneis" types. Thus, in combination with geochemistry and zircon typology investigations, a model of Eastern Tauern Window basement complex genesis along a Variscan, destructive continental margin could be established (Marschallinger 1987, Holub 1988) - a view shared by Finger and Steyrer (1988) for the majority of Tauern Window Zentralgneis types.

Among the pre-Variscan country rocks of the Zentralgneis series, two formations in different structural levels are recognized:
a) at a lower level, best exposed in the Malta valley, the so called "Altkristalline Migmatit Formation",
b) in a higher structural position, predominantly in the area of the Ankogel peak, the Habach Formation.

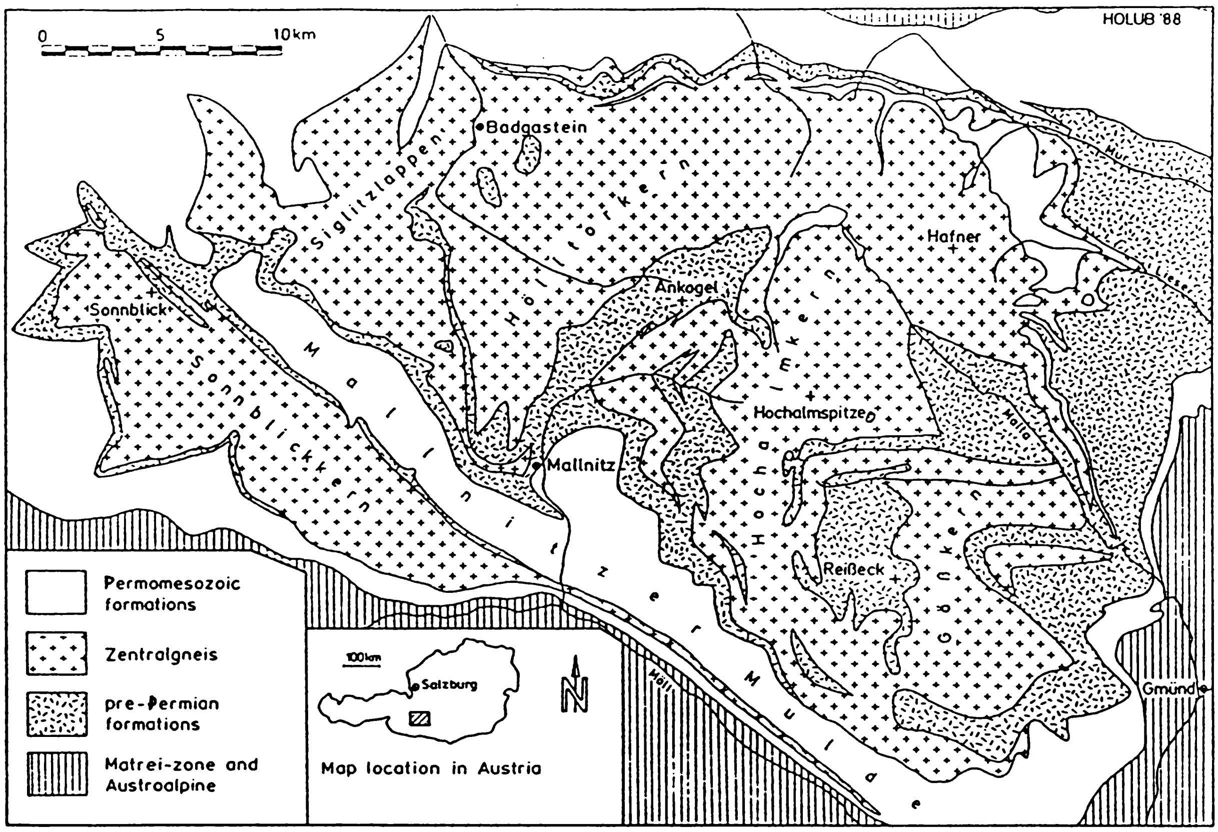


Fig.1: Geological sketch map of the pre-Permian, Penninic basement of the eastern Tauern Window (from Holub and Marschallinger, 1989).

The Altkristalline Migmatite Formation is dominated by banded lithologies (Angel and Staber, 1952) originating from paragneisses subject to pre-Alpine, high grade metamorphic to anatectic conditions. In the Malta valley, two clastic series can be distinguished (Marschallinger, 1987): (1) the so called "migmatitic plagioclase gneiss" (modal composition approx. quartz 20%, plagioclase 50%, biotite 20%, hornblende + epidote 10%). Petrographic and geochemical evidence suggest immature greywackes as source rocks; the series is widespread in the eastern Tauern Window (Vavra, 1989). Towards higher structural levels, the migmatitic plagioclas gneisses grade into the (2) "migmatitic two mica gneisses" (modal composition approx. quartz 30%, plagioclase 35%, K-feldspar 10%, biotite 15%, white mica 10%); source rocks are thought to be shales or K-Al rich greywackes. Besides a small amount of garnet mica schists, the Habach formation comprises fine to coarse grained, massive amphibolites and banded amphibolites originating from bimodal volcanism (Holub, 1988; Stadlmann, 1990).

For the different "Zentralgneis" types, a consistent intrusive sequence can be deduced in the Eastern Tauern Window; at least two major cycles of high K calcalkaline I-type intrusions, developing from basic to acid compositions, can be distinguished (Holub and Marschallinger, 1989; see Fig.2 and 3): an older cycle is represented by calcalkaline syenites and small, isolated granite bodies ("Grosselend flaser granite", modal comp. approx. quartz 25%, plagioclase 30%, K-feldspar 40%, biotite 5%). A younger cycle, preserved more completely, starts with a syntectonic, flat-lying tonalite ("Malta tonalite", approx. quartz 30%, plagioclase 50%, K-feldspar 0-5%, biotite 15-20%) followed by a huge granodiorite body ("Hochalm porhyric granite", approx. quartz 25%, plagioclase 40%, K-feldspar 25%, biotite + white mica 10%), a leuco- granodiorite to granite ("Kölnbrein leucogranite", approx. quartz 30%. plag. 40%, K-feldspar 23%, biotite + white mica 7%), small granite stocks ("younger flaser granite", modal comparable with the Grosselend flaser granite) and ending with a fine-grained two mica I-type granite intrusion (Holub and Marschallinger 1990). At the moment, the

"Göss granitoids" (Na-rich (leuco-) granodiorites to granites) cannot be definitely merged to the intrusive scheme.

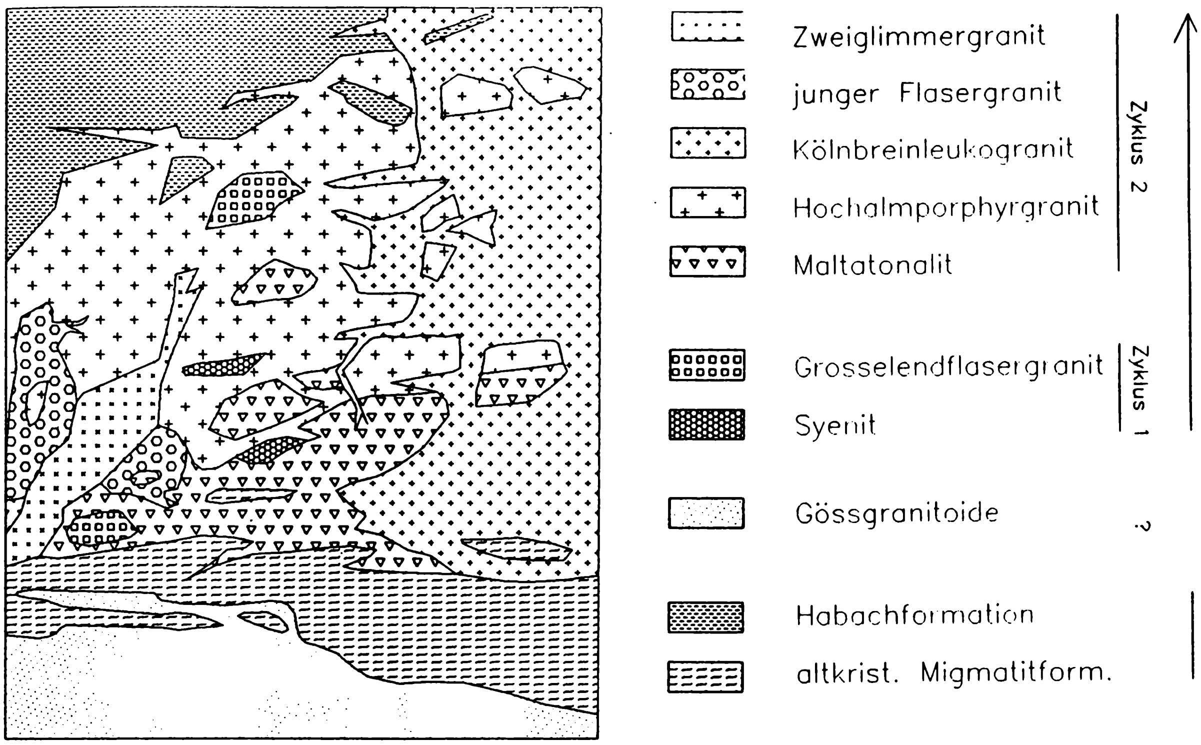


Fig.2: Schematic model of intrusive relations in the southeastern Tauern Window (from Marschallinger and Holub, 1990).

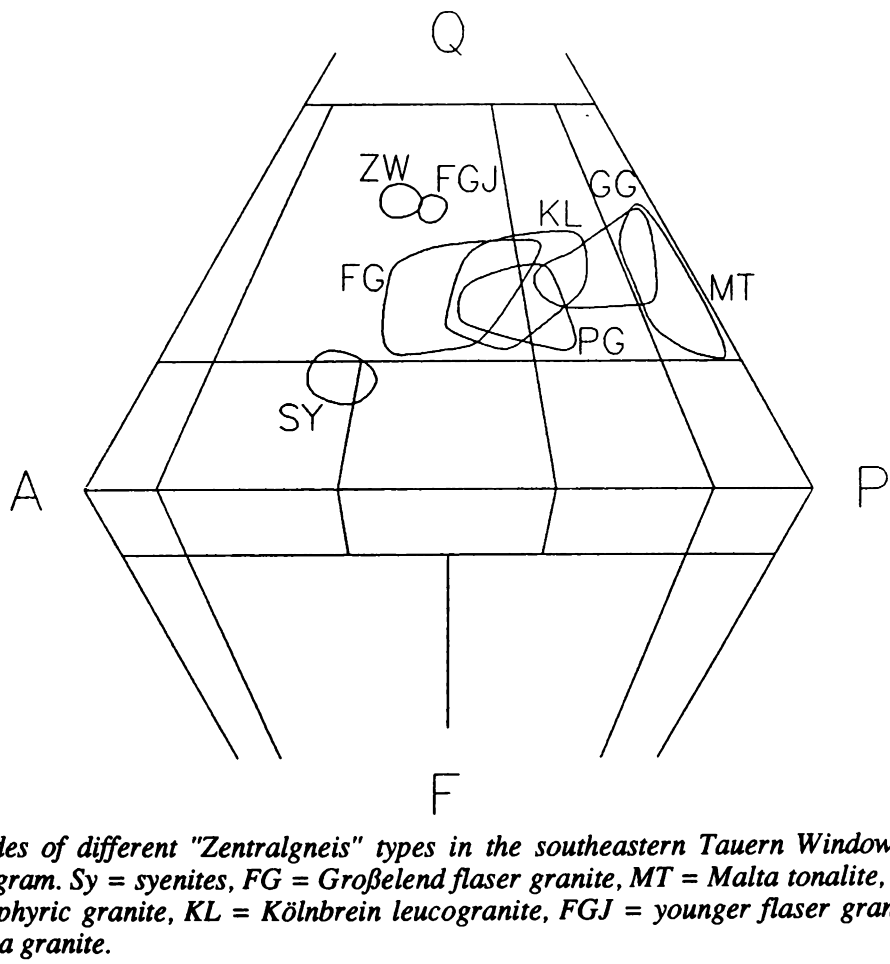


Fig.3: Modes of different "Zentralgneis" types in the southeastern Tauern Window in Streckeisen diagram. Sy = syenites, FG = Großelend flaser granite, MT = Malta tonalite, PG = Hochalm porphyric granite, KL = Kölnbrein leucogranite, FGJ = younger flaser granite, ZW = Two mica granite.

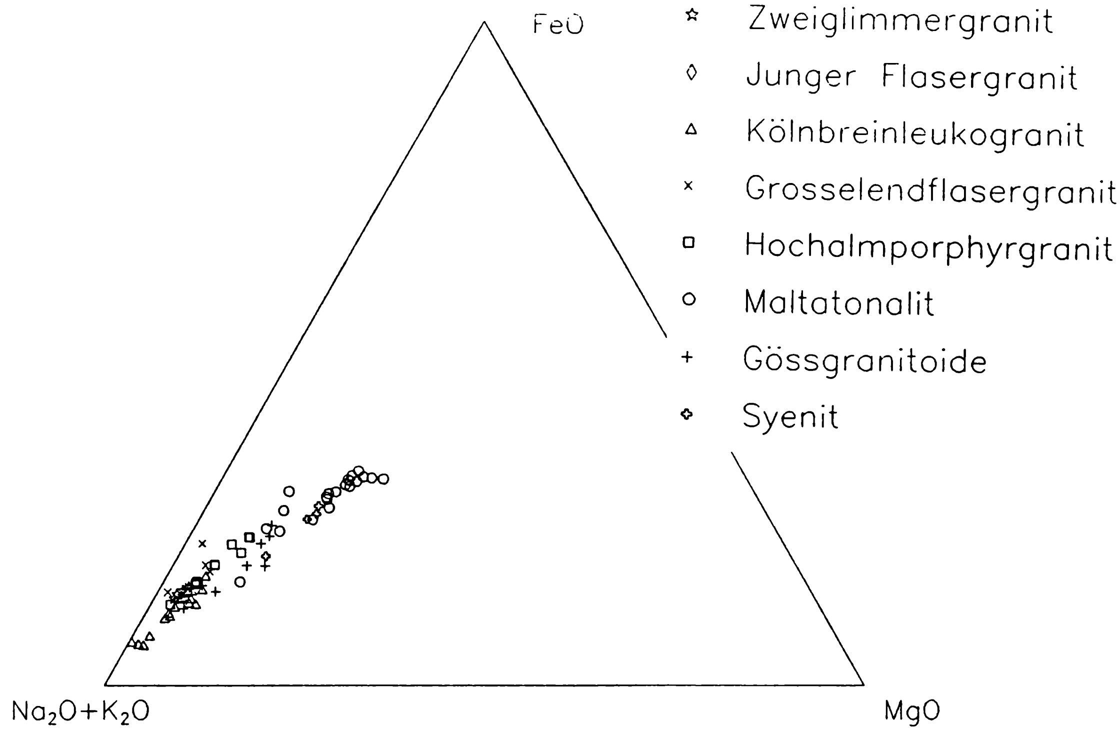


***Fig.4:** AFM diagram: "Zentralgneis" types are plotting along calkalkaline trend with position in evolutionary trend corresponding to relative age mapped in field. Symbols of "Zentralgneis" types used in Fig. 4 - 7.*

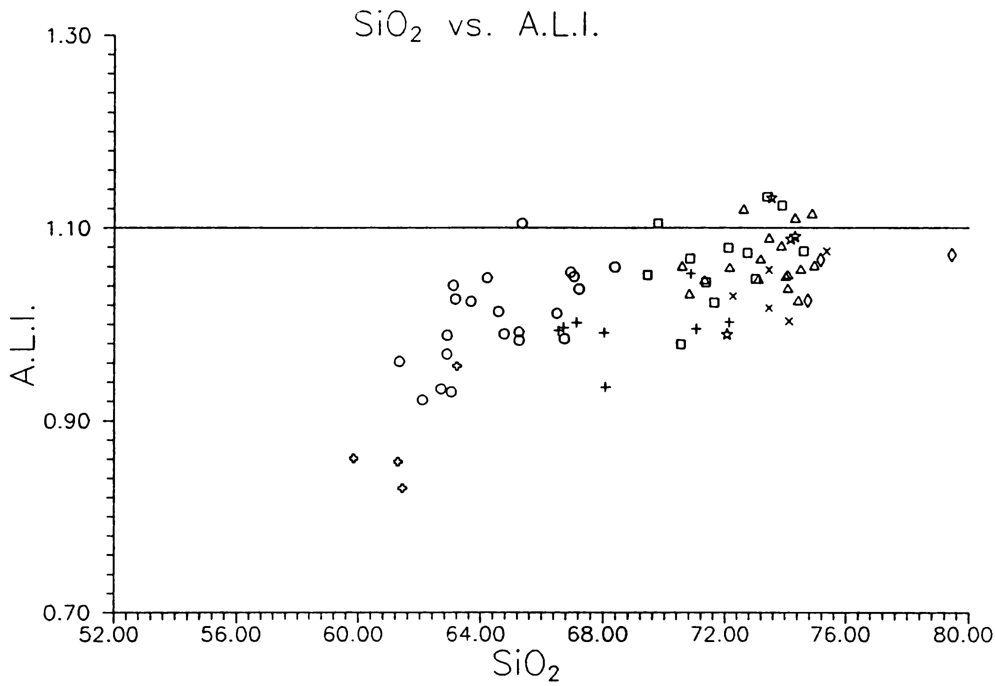


***Fig.5:** ALI (alkali lime index) diagram (after Chappell and White, 1974) classifies most Zentralgneis samples as I-type (igneous source rock derived); ALI gently rising with SiO2 as typical of most orogenic intrusive suites with latest stages overlapping S type field. Symbols of "Zentralgneis" types, see Fig. 4.*

Although the complete series of Zentralgneis types encounters a wide spread in SiO2, the overall geochemical fingerprints are quite similar: all types described above can be classified as normal to high-K calcalkaline (after Peccerillo and Taylor, 1976), I-type (after Chappell and White,

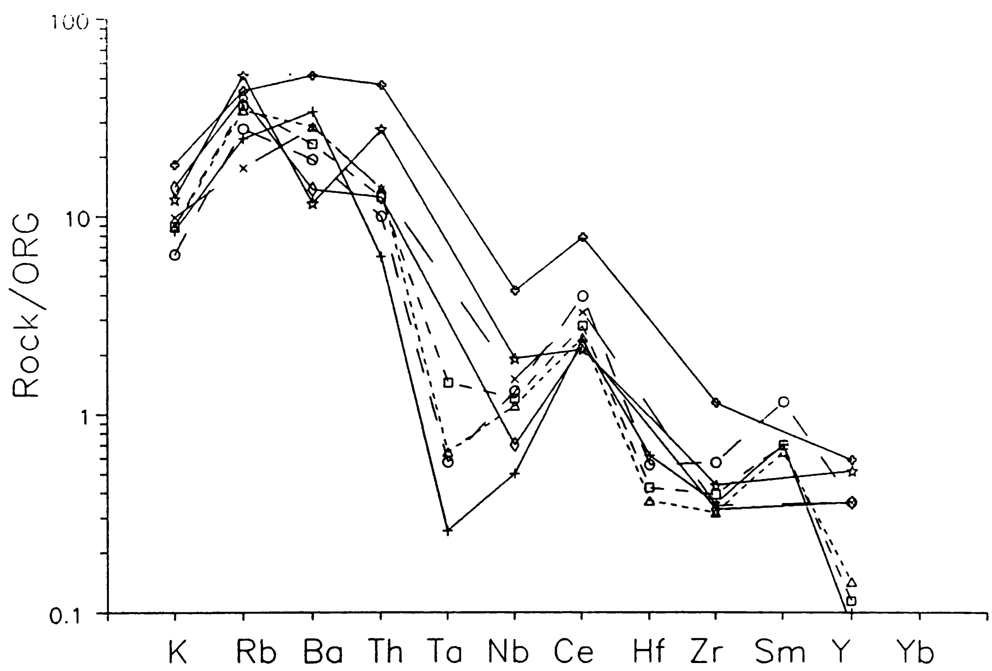


Fig.6: Rock/ORG patterns (after Pearce et al., 1984), despite different absolute concentrations, show similar fingerprints for all "Zentralgneis" types: enriched LIL, low Ta, Nb, high Ce, low Zr, Y. Symbols of "Zentralgneis" types, see Fig. 4.

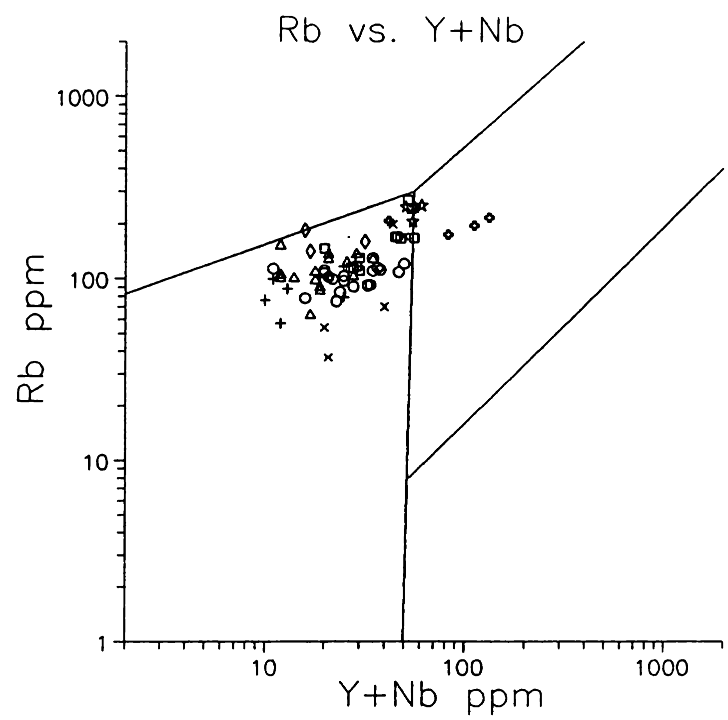


Fig.7: Rb vs. Y + Nb diagram (Pearce et al., 1984) classifies Zentralgneis types (with exception of syenitic types) as volcanic arc granites. Symbols of Zentralgneiss types, see Fig. 4.

1974) granitoids (see Figs. 4, 5) rich in Na2O. Trace element spectra show remarkable enrichments of Rb, Sr, Ba, Th and Ce while Nb and Y, Yb, Ta are low (see Fig.6), consistent with a genesis in a volcanic arc area (Pearce et al., 1984; Harris et al., 1984; see Fig. 7). Systematic studies in zircontypology are in accordance with field observations and geochemical evolution of the intrusive series: in the typological diagram after Pupin (1985), zircon populations develop along a trend typical of calcalkaline, crust contaminated I-type granitoid sequences (see Fig. 8). The role of crust contamination processes upon intrusion into the migmatic paragneiss series is highlighted by an ncreased amount of detrital zircons in samples from border zones of "Zentralgneis" bodies accompanied by a concurrent adulteration of primary I-type to S-type geochemistry (Marschallinger and Holub, 1991).

Summarizing the results of field work, petrography, geochemsitry and zircon morphology investigations, the "Zentralgneis" series is interpreted as cycles of intrusions into a mature, Variscan continental margin closely resembling areas like the Andes, where major rhythms of granitoid intrusions, each developing from basic to acid but of the same overall characteristics, were emplaced into continental crust (e.g., Pitcher, 1982).

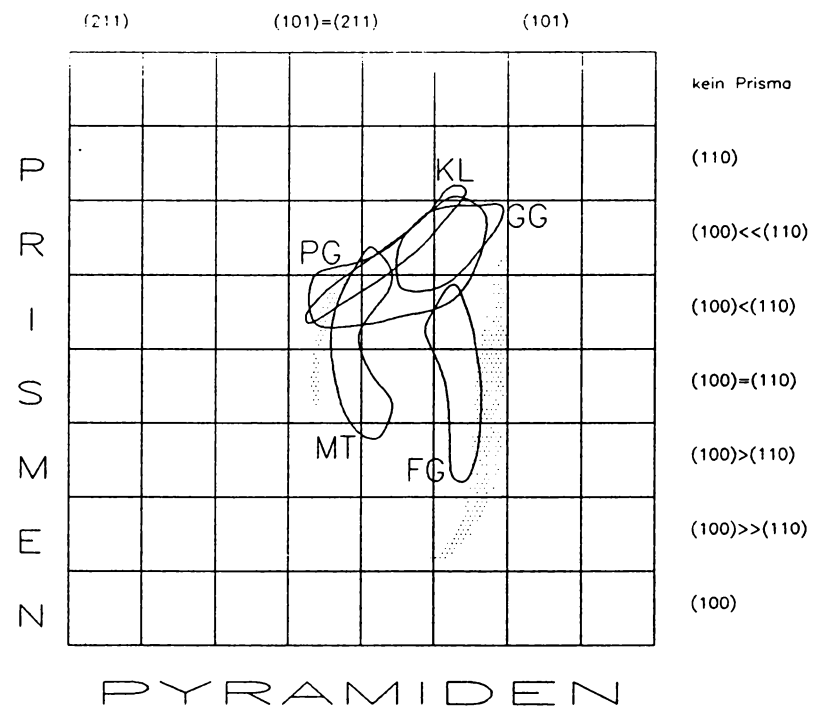


Fig.8: Zircon typological diagram with I-type granite field after Pupin (1985); younger cycle (see text) evolves along trend for calc-alkaline I-type suites subject to crustal contamination. Abbreviations see Fig. 3.

Stop No. 1: Granodiorite orthogneisses of the Gößgraben intrusive complex ("Central gneiss"). Alpine structural and metamorphic evolution of the "Central gneiss".

R. MARSCHALLINGER, J. GENSER

Location: OEK 50, sheet 182, Spittal an der Drau. Koschach Quarry. 13°27'45" E/46°58'15" N. Gmünd - Malta - Koschach (bridge across the river Malta).

In the area of the Göß valley the structurally lowest rocks of the Penninic basement complex of the eastern Tauern Window are exposed (Fig. 9). Exner (1979) described them as "orthogneisses of the Göß-Kern". The quarries in and around Koschach give a survey over the petrographic variability (tonalites to granites) of granitoid gneisses of the Göß-Kern (intrusive age ca. 320 Ma: Cliff and Cohen, 1980). In the Koschach quarry, a strongly lineated, light grey granodiorite Augengneiss is exposed. Orthogneisses are cross-cut by some generations of pegmatites deformed in the same way.

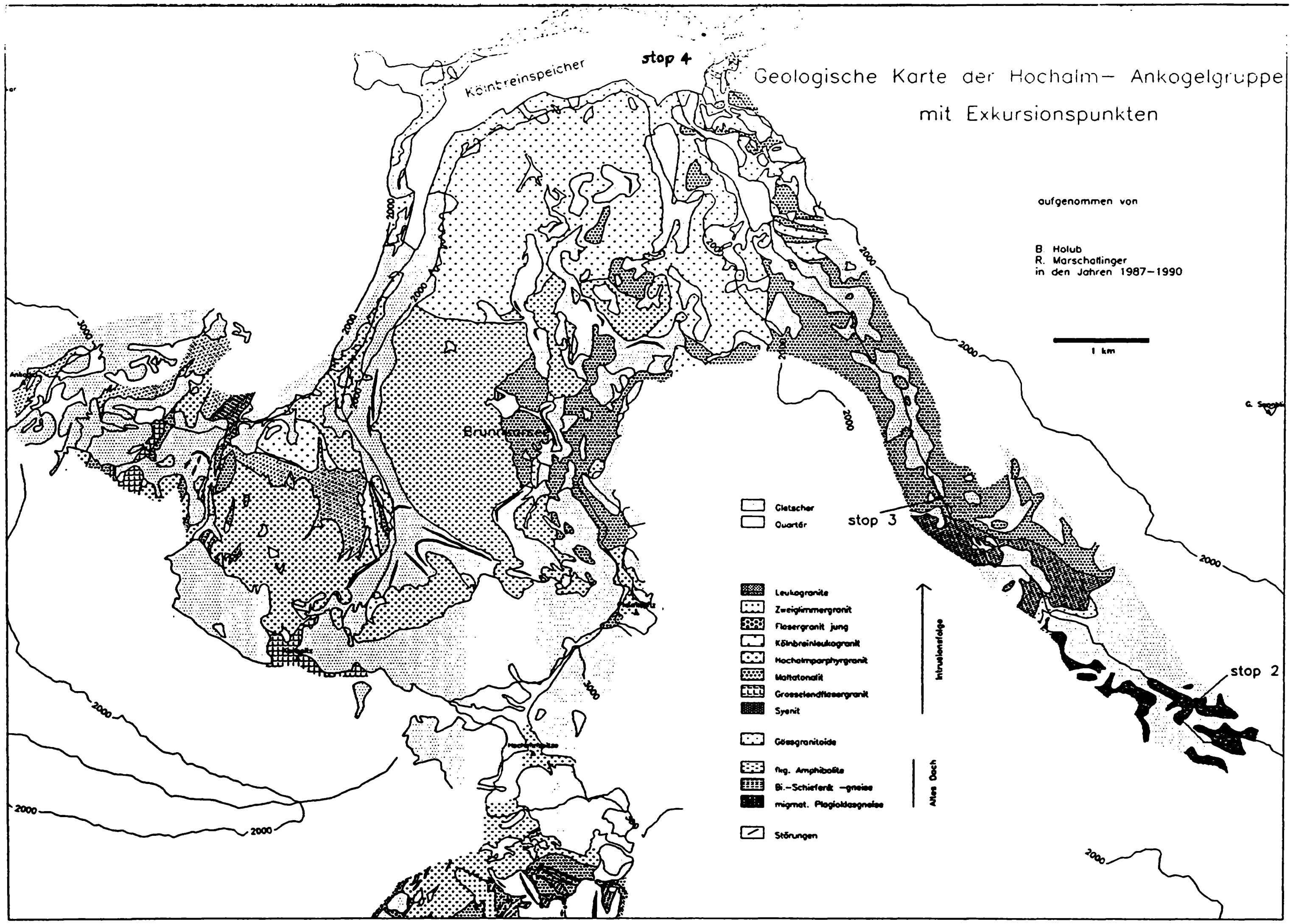


Fig.9: Geological map of southeastern Tauern Window according to detailed mapping by Holub and Marschallinger (carried out between 1987 and 1990), including locations of stops 2-4.

Petrography: K-feldspar crystal interiors still are transparent, featuring twinning after Karlsbad law. Plag (oligoclase) usually is more strongly recrystallized. Mafics comprise biotite, sphene, allanite and epidote. Zircons show strong zonations and I-type morphology (after Pupin 1985). Geochemistry: Göß granitoid rocks resemble Na-rich high K calcalkaline I-type granitoids, in part featuring almost trondhjemitic affinity. Trace element patterns show VAG characteristics (class. Pearce et al. 1984) with selective enrichment of LIL elements and low Rb/Zr. Genesis in an active continental margin regime seems most probable.

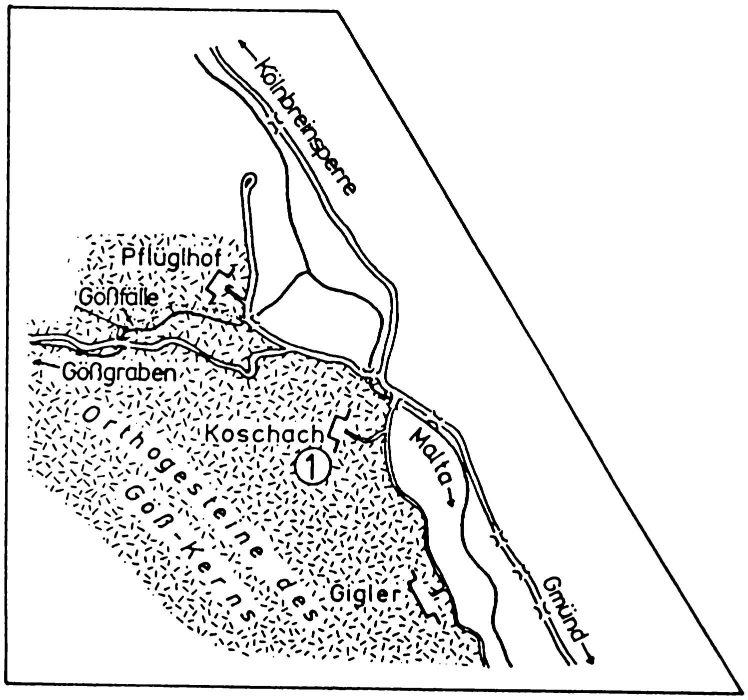


Fig.10: Sketch of Koschach quarry location (Göß granitoids).

The Alpine metamorphic paragenesis of the granodiorites is

Olig-Qtz-Kfs-Bt-Ep-Grt-Mag-Ttn

Oligoclase shows an inverse zoning (appr. 15 - 25 % An), K-feldspar is strongly replaced by myrmekite. Garnet is formed due to the breakdown of epidote by the general reaction

$$Ep + Qtz = Grs + An + Mag + H_2O$$

In this quarry three main structural events can be distinguished:

1) The main deformation led to the penetrative foliation and the prominent stretching lineation of the orthogneiss (Fig. 10). Pegmatites were folded by this deformation, older aplites mostly not, owing to a missing viscosity contrast to the country rock at the conditions of the deformation. The strong lineation indicates deformation in the constrictional field, which is also corroborated by quartz-c-axes distributions (type I crossed girdles). In the Koschach quarry the foliation dips steeply to the NNE (30/70), south of the Malta valley to the S (180/40), north of the valley to the E, forming a great circle distribution around the uniformly oriented stretching lineation (120/20). This distribution is due to the constrictional strain field (not due to a later folding). Weakly developed shear criteria and quartz textures indicate a noncoaxial strain path with a component of dextral shearing. This deformation worked near and up to peak metamorphic conditions, indicated by dynamic recrystallization of plagioclase, K-feldspars and quartz.
The deformation can be placed in Oligocene times based on the dating of the metamorphic climax in deeper levels of the Tauern Window (Cliff et al., 1985).

2) Conjugate ductile shear zones, which are several mm to cm wide, cut discordantly across the main foliation. They dip mainly gently to the ESE and WNW and show a sense of movement of top to the ESE and WNW respectively, leading to an ESE-WNW-directed extension and subvertical thinning.

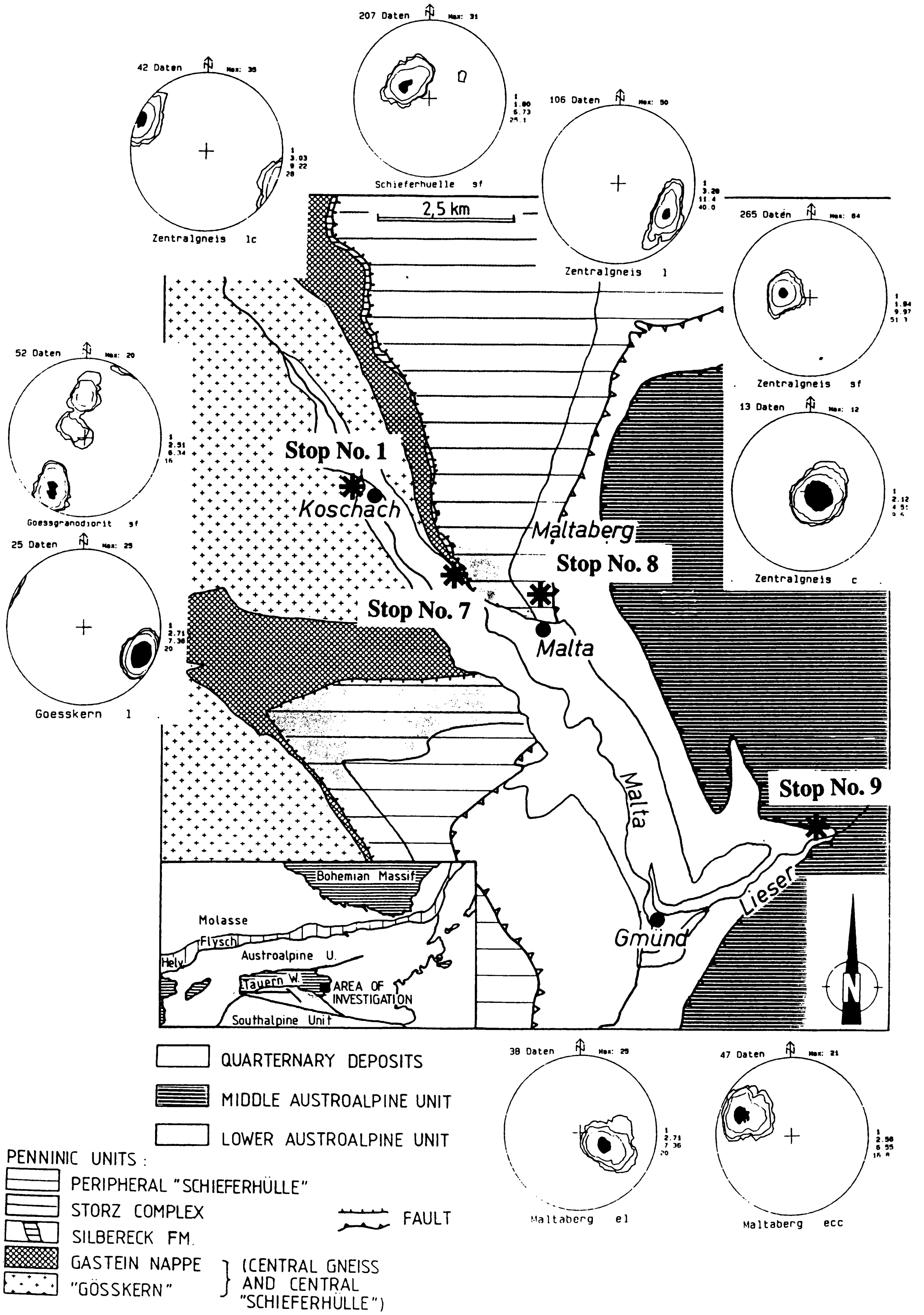


Fig. 11: Schematic geological map of the eastern margin of the Tauern Window (after Exner, 1980) and location of stops and orientation data of main structural elements of the Goesskern granitoids (sf - penetrative foliation; l - stretching lineation), the Central Gneiss (sf - penetrative foliation; l - stretching lineation; c - shear band foliation; ec - striae on shear bands), and the Peripheral Schieferhuelle at the Maltaberg (sf - penetrative foliation; ecc - extensional crenulation cleavage; el - striae on ecc).

In the shear zones plagioclase and quartz recrystallize, biotite and green amphiboles are formed. This indicates an activity of this structures at still elevated temperatures (upper greenschist to lower amphibolite facies). This ESE-WNW-extension is related to the uplift of the Penninic Units.

3) Steeply dipping, ESE-WNW-trending faults (parallel to the main foliation), which show a normal movement of the northern hangingwall, indicating an extension in NNE-SSW, too. They were active from near peak metamorphic conditions (asymmetric folding of biotite schists and aplites, with static recrystallization of biotite after the deformation) down to cool conditions (striae, fault gouges).

This sequence can best be seen in the NW-corner of the quarry.

Stop No. 2: Migmatitic country rocks of the Gößgraben intrusive complex.

R. MARSCHALLINGER

Location: OEK 50, sheet 156, Muhr. Parking Hochbrücke / Maltatalstraße.

Moving towards NW, sucessively higher structural positions within the pre-Permian basement are cut by the Malta Valley. Variscan intrusive relationships of Göß orthogneisses and their country rocks have been preserved. Country rocks are made up of a series of high grade (i.e. migmatized) greywackes and shales. Since the perfect preservation of Variscan intrusive contacts (see also stop no. 3), the migmatite event cannot be younger than the Late Variscan intrusions of granitoids. A fine outcrop of greywacke derived migmatites is located directly along the Malta valley road at the parking area of the Hochbrücke inn.

Here, the habit of the paragneiss derived migmatites is nebulitic, rafts with old sedimentary structures being incorporated in more homogenized, granitoid-looking areas with schlieren structures. Some rafts exhibit "Titanitfleckendiorit" textures with sphene speckles.

Petrography: fine - to medium grained rocks, consisting predominantly of xenomorphous oligoclase, some quartz in small aggregates, and mafics: biotite, sphene, epidote, hornblende; mode after Streckeisen is tonalite. Within zircon spectrum, sediment derived, rounded types may be distinguished from sharp-edged types ascribed to anatectic stadium.

Geochemistry: overall I-type calk-alcaline, tonalitic composition. Trace elements significantly enriched in LIL and Ce. Genetically, pre-migmatic material could have been immature greywackes.

Stop No. 3: Intrusive contact of the Malta tonalite with country rocks.

R. MARSCHALLINGER

Location: OEK 50, sheet 156, Muhr. Bed of Malta creek.

Towards higher structural levels, the greywacke derived migmatites discussed below grade into another migmatic paragneiss series, the so called "Migmatische Zweiglimmergneise" (migmatitic two mica gneisses). These are thought to be derived from shales; petrographically they differ from the former series in containing significant amounts of white mica and K-feldspar, sometimes garnet. Due to their bulk chemistry closer resembling the granite minimum melt composition, they show a higher degree of anatectic mobilization than the greywacke derived series. This series was intruded by a Variscan (ca. 320 Ma; Cliff and Cohen, 1980) Malta tonalite. Original intrusive relations have been perfectly preserved (Marschallinger, 1987), the contact being exposed in the bed of the Malta creek; therefore, hypotheses considering the Malta tonalite as a huge Alpine nappe (Exner, 1982; Tollmann, 1977) cannot be verified in the field.

Petrography: the Malta tonalite is a medium grained, massive rock unit - the term "gneiss" is misleading in most locations. In places, elliptically shaped diorite inclusions occur as swarms. Oligoclase in the tonalite still features original magmatic complex twinning, the inclusion trails of epidote minerals tracing the old magmatic Ca/Na zoning. Quartz is aggregated in lenses as are mafic minerals such as biotite, allanite, sphene and epidote; this tonalite variety misses hornblende - a mineral usually common in tonalites. The zircon spectrum may be split in an acuate population originating from growth in Malta tonalite magma and a well-rounded population inherited from clastic country rocks upon intrusion; ratio of tonalite derived / sediment derived zircons closely resembles location in the tonalite pluton, i.e. nebulitic tonalite parts with sediment rafts show larger portion of detrital, inherited clastic zircons. Magma derived population may be classified as I-type according to Pupin (1985).

Geochemistry: high K calcalkaline I-type granitoid characteristics, strongly enriched in Na. Trace element spectrum typical of VAG intrusions, enriched in Ce. S-type characteristics in places of pronounced country rock resorption. Genesis: the Maltatonalite is interpreted as a lenticular intrusion into an already mature, Variscan active continental margin (Marschallinger, 1987); it is the oldest, most basic member of a younger cycle of calcalkaline intrusions ranging in composition from tonalitic to granitic (Marschallinger and Holub, 1991).

Stop No. 4: Leucocratic granitoid gneisses ("Kölnbrein leucogranite").

R. MARSCHALLINGER

Location: OEK 50, sheet 156, Muhr. Kölnbrein quarry.

The huge quarry area near the hydroelectric dam of the Kölnbreinsperre enables studies concerning the variability of the latest large area Variscan intrusion, the so called "Kölnbrein leucogranite" (Holub 1988); the Kölnbrein leucogranite intruded in serveral phases which may be distinguished mainly on the basis of mafic minerals amounts. The fine to medium grained leucocratic granite gneisses incorporate a consistent population of country rocks, ranging from migmatic paragneisses to older intrusives like the Malta tonalite or the Hochalm porphyric granite. Places of incomplete resorption of country rocks are characterized by schlieren textures.

Petrography: rock compositions range from leucocratic granodiorites to granites, original intrusive textures being preserved in part (epidote trails tracing old chemical zonation in oligoclase, oligoclase trails in K-feldspar). Some muscovite and biotite present, in places garnet. Zircon population: I-type granitoids, locating at the low temperature end of calc-alkaline I-type trend in typological diagram after Pupin (1985).

Geochemistry: high-K calkalcaline I-type, enriched in Na, trace elements showing characteristics like majority of intrusives in the Eastern Tauern Window: strongly enriched in LIL and Ce, VAG type pattern according to Pearce et al. (1984). Genesis: Kölnbrein leucogranites are interpreted as the youngest, large volume member in a cycle of high K calc-alkaline intrusions located in a Variscan, active continental margin (Holub 1988).

Further reading for stops No. 1-4: Marschallinger, 1987; Holub, 1988; Holub and Marschallinger, 1989; Marschallinger and Holub, 1991.

The following two stops in the Gastein valley show important non - calc-alkaline variants of granitoids of the Hohe Tauern Batholith. The first one (Prossau augen gneiss) is an example of a late stage A-type granite intrusion, the second one (Romate gneiss) is a typical member of the early stage high-K_2O I-type granitoid group (see contribution of Finger et al., this volume).

The **next two stops** provide evidence for A-type granitoids within the Tauern batholith. These stops are accessible from the Salzach valley north of the Tauern Window.

Stop No. 5: The Prossau Augengneis, a strongly deformed A-type granite.

B. HAUNSCHMID

Location: OEK 50, sheet 155, Bad Hofgastein. At the northern entrance to the village of Böckstein, on the eastern side of the road, the Prossau Augengneis (Haunschmid, 1992) crops out.

A distinctly deformed porphyric granite is visible at the excursion stop. It contains porphyric K-feldspar "augen" up to 10 cm and was therefore termed "Riesenaugengneis" by Exner 1951. The Prossau Augengneis type occurs several times in the eastern Tauern Window. One large body extends from this excursion stop several km towards the south and east (Mindener Hütte, Kl. Tauernsee, Graukogel). A second important body is in the area of Hölltorkogel - Tischlerkar - Prossau. There, the Prossau metagranite is less deformed and its original magmatic fabric is well preserved.

Generally, the Prossau metagranite to augengneiss is very leucocratic and contains ca. 40% K-feldspar, 30% quartz and 20% plagioclase (An_{20}). Mafic minerals are brown biotite (3%), secondary white mica (2%) and small amouts of chlorite, epidote and garnet.

A chemical analysis of the rock (sample F20B) is:
SiO_2 72.54, TiO_2 0.30, Al_2O_3 13.98, FeO_{tot} 1.92, MnO 0.07, MgO 0.47, CaO 1.49, Na_2O 3.43, K_2O 4.53, P_2O_5 0.08, LOI 0.60 (wt.%), Cr 6, Ni 18, Co 4, Rb 240, Ba 431, Sr 168, Ta 2,5, Nb 16.3, Zr 162, Y 49, Th 30, U 15, La 33, Ce 63, Nd 32, Sm 9.2, Eu 0.75, Tb 1.08, Yb 4.31, Lu 0.65 (ppm)

Compared with the most felsic end members of the calc-alkaline Hochalm suite of the eastern Tauern Window (e.g. the Kölnbrein leucogranite, see stop no. 4) the Prossau Augengneis is markedly enriched in HREE (see Fig. 12) and Y, but depleted in Ba and Eu (see Finger et al., this vol.).

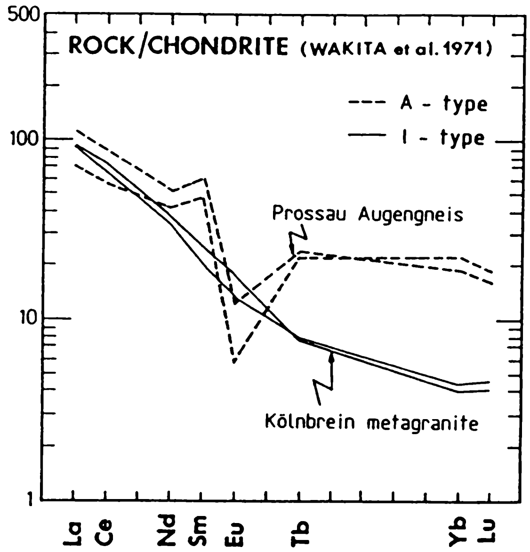


Fig. 12: Chondrite normalized REE patterns for A-type granites and felsic calc-alkaline granites of the Hochalm suite of the eastern Tauern Window (Finger et.al., this vol.).

Stop No. 6: Romate gneiss with younger granitic to aplitic dikes.

B. HAUNSCHMID

Location: OEK 50, sheet 155, Bad Hofgastein. Kesselfall bridge. From Böckstein we drive up to Naßfeld (Sportgastein) and stop at the hydroelectric building at Bärenfall. We walk the path down the Naßfelder Ache valley until we cross the river at the cascade "Kesselfall" (approximately 1,5 km foot walk). Just below the bridge the "granosyenitic Romategneis" (Exner 1957) is exposed.

The rock is coarse-grained, quartz-syenitic to monzonitic in composition, and extends as a narrow N-S trending lamella from Badgastein to Mallnitz. Very typical is the contrasting white-black speckled appearance. The mafic components of the Romategneis are mainly biotite and epidote, which often form together dark green aggregates, which are commonly interpreted as pseudomorphoses after hornblende (see Exner 1957 and references therein). In low strain samples relics of hornblende are preserved in these aggregates and sometimes also some clinopyroxene. Droop (1982) concludes that this coexisting mineral assemlage (hbl + cpx + bt + ep + ab) formed during Alpine time under metamorphic conditions close to 500°C and around 6kb.

The felsic components of the Romate gneiss are K-feldspar (ca. 40%), plagioclase (ca. 30%) and quartz (ca. 10%). The K-feldspars are characterized by strong perthitic zoning (Exner, 1949). The plagioclase is albite, but contains many microlitic exsolutions of epidote which indicate a much higher primary An content.

The Romate gneiss contains numerous more basic inclusions (Exner, 1957; Droop, 1982) and also inherited paragneisses (Winkler, 1926).

A chemical analysis of the Romate gneiss (sample HA3/88, location: road tunnel just above this excursion stop) is:

SiO_2 60.10, TiO_2 0.79, Al_2O_3 14.90, FeO_{tot} 3.59, MnO 0.08, MgO 2.40, CaO 3.88, Na_2O 3.42, K_2O 6.80, P_2O_5 0.62, LOI 1.00 (wt.%), Cr 69, Ni 37, Cu 25, Zn 74, Rb 391, Ba 2339, Sr 960, Nb 15, Zr 357, Y 14, Th 77(ppm)

It can be seen below the bridge, that several fine-grained granodioritic to granitic dikes and aplites crosscut the Romate gneiss. These dikes trend preferably in NW-SE and NE-SW directions. Due to their composition (Haunschmid, 1992), the first mentioned dikes are believed to be related to the calc-alkaline I-type granitoids of the Hochalm suite. An Alpine quartz vein crosscuts all the granitoids in N-S direction.

Further reading: Finger et al., 1992; Marschallinger and Holub, 1990.

Stop No. 7: Shearing top to the WNW in tonalite at the margin of the "Zentralgneis" Unit.

J. GENSER

Location: OEK 182, Spittal an der Drau, 13°29'02" E/46°58'05"N. Rockface on the NW-flank of the Malta valley (Rödern). Malta - bridge across the Feistritz brook (first brook to the NW of Malta village) - 500 m along path to the N up to the rock ledge.

The tonalite (Malta tonalite, compare stop No. 3) reaches the valley floor as strongly thinned lamella (appr. 200 m thick) here.

The Alpine metamorphic paragenesis of the orthogneiss is

Olig-Qtz-Bt-Kfs-Czo-Ttn-Ms(Phen).

Oligoclase is again inversely zoned (An 15 - 25), white mica is present in minor amounts only, concentrated in strongly deformed rocks.

The tonalite shows a strong, homogenous, penetrative foliation and a well developed stretching lineation. Aplites are folded due to this deformation, the foliation is parallel to the axial surfaces of the folds. The foliation dips gently to the E (90/30), the stretching lineation to the ESE (120/25). An abundance of shear criteria, as shear bands, s-porphyroclasts and also quartz textures indicate shearing top to the WNW. See Fig. 10 for orientation of foliation, stretching lineation, ecc's.

The deformation occurred up to peak metamorphic conditions, indicated by the dynamic recrystallization of plagioclase, quartz and biotite. It must be placed in Oligocene times, too.

Further reading: Exner, 1980, 1982.

Stop No. 8: Ductile to brittle low-angle normal faulting to the ESE in the Peripheral Schieferhülle.

J. GENSER

Location: OEK 182, Spittal an der Drau, 13°30'25-30" E/46°57'35" N. Roadcut on the road to Maltaberg. The road is accessible for big busses. Ca. 25 minutes to walk from the village Malta. Malta, road to Maltaberg, after second corner closing to the W (1010 m NN).

This roadcut exposes a succession from the uppermost part of the Storz Group (Vavra and Frisch, 1989), a pre-Variscan basement unit, here mainly amphibolites and plagioclase-gneisses, overlain by the post-Variscan sequence of the Peripheral Schieferhülle. This sequence starts, appr. 70 m after the crossing path, with black albite porphyroblast schists. Then quartzites follow, which are believed to be Permo-Triassic in age and finally intercalated greenschists, metapelites and calcschists, the so called Bündner Schiefer, Jurassic-Cretaceous metasediments and -volcanics. A detailed description of this section can be found in Exner (1980).

Alpine metamorphic paragenesis are

Ab-Qtz-Ms-Bt-Chl-Cal-Ilm (semipelites)
Cc-Qtz-Ab-Ms-Rt-Chl (calcschists)
Amph-Chl-Ab-Ep-Qtz-Ttn-Bt-Cal (greenschists)

Two structural events can be recognized in these outcrops:

1) A penetrative foliation with a mostly weakly developed stretching lineation. The foliation dips moderatly to the ESE, the lineation trends NNE-SSW. These structures can best be seen in the rocks of the Storz Group, in the higher sequences they are strongly overprinted by the second deformation. In deeper parts of the Storz Group and in more northerly parts of the Peripheral Schieferhülle, where this structures are not overprinted by the later deformation, a transport of top to the N can be derived.

2) The second deformation leads to a further flattening of the older foliation and an extension in an ESE-WNW-direction. The deformation is noncoaxial, expressed in ESE-dipping shear bands, which often occur in multiple sets. A conjugate set of WNW-dipping shear bands is only weakly developed in very strongly deformed rocks. In calcschists a new mylonitic foliation with an ESE-plunging stretching lineation is developed (Fig. 10). All this asymmetrical structures indicate a shearing top to the ESE. Further expressions of this extension are extension veins and boudins, especially in the quartzites of the Peripheral Schieferhülle. Small-scale folds, which are overturned to the ESE, can be related to this shearing of top to the ESE, too.

This deformation commenced after peak metamorphic conditions, expressed in the formation of greenschist facies minerals (chlorite, epidote) in the shear zones in the basal amphibolites and continued to cool conditions with the formation of brittle normal faults. The main deformation is ductile, however.

This deformation, a low-angle normal faulting, led to the unroofing of the Penninic by displacing the Austroalpine Unit to the ESE. The timing of this event is Lowermost Miocene, based on the rapid, nearly isothermal uplift of the Penninic Unit, dated by Cliff et al. (1985).

Further reading: Cliff et al., 1985; Exner, 1971, 1980; Genser and Neubauer, 1989.

Stop No. 9: Boundary between Lower and Middle Austroalpine units.

J. GENSER

Location: OEK 182, Spittal an der Drau, 13°34'13" E/46°55'22" N (LAA); 13°34'16" E/46°55'28" N (MAA). Roadcut along the road Eisentratten - Heitzelsberg. Turn-off from main road immediately E of new church, until first corner (920 m NN). Park the car here! You must go back about 200 m, then take the road to the W. The outcrop of the Lower Austroalpine (LAA) is about 250 m from the turn-off. The outcrop of the MAA is at the corner, where you park the car.

The upper parts of the Lower Austroalpine Unit consist mainly of retrogressed (diaphthoritic) quartz-phyllites to quartzites, which bear relicts of biotite and garnet, most probably of pre-Alpine age. In this outcrop biotite is more abundant than on the average. It occurs as only tiny plates (about 0,1 mm), however and exhibits a bronze colour. The stable mineral assemblage during the Alpine metamorphism is quartz, sericite, chlorite and pyrite.

The rocks show a well developed foliation and a weak stretching lineation, which trends E-W to NE-SW. Quartz-c-axes show oblique girdles, which indicate shearing top to the W to SW. This foliation is folded around NE-SW-trending axes with the development of a crenulation lineation. The last deformation is a brittle normal faulting, forming cataclastic zones with rock fragments from dm-size to fault gouge. One of this brittle faults can be seen in the outcrop. The activity of this faulting is contemporaneous with the ductile low-angle normal faulting in the Peripheral Schieferhülle (see stop No. 7).

Going back to the cars notice the depression and the lack of outcrops, which must be due to an increase in brittle faulting up to the base of the MAA.

The garnet-micaschists of the outcrop at the road corner are typical for this part of the MAA. In higher parts they contain pre-Alpine staurolite, too. The Alpine mineral assemblage is muscovite, biotite, quartz and in higher parts garnet, which overgrows pre-Alpine garnets. At the base of the MAA Priedröf Nappe (further to the N the LAA is overlain by the Aineck Nappe) no Alpine garnet rims could be recognized. In contrast to the LAA the minerals form grains mm across, in an assemblage typical for higher metamorphic conditions.

The micaschists exhibit a well developed foliation with isoclinally folded quartz veins and boudinaged garnets. The main deformation is prior to the metamorphic climax, as mica and quartz show static recrystallization after the the formation of the foliation. Quartz-c-axes exhibit a random distribution.

The last structures are slickensides, between which blocks shows a slight rotation. They point to an E-W-extension.

The Alpine metamorphism is Cretaceous in age, with the climax at about 100 Ma (Hawkesworth, 1976; Schimana, 1986).

The present contact between the LAA and the MAA is a normal fault, which was active due to an ESE-WNW-directed extension, related to the uplift of the Penninic Tauern Window.

Further reading: Genser and Neubauer, 1989; Neubauer and Genser, 1990; Genser, 1992.

Stop No. 10: Middle Austro-Alpine basement with Priedröf micaschist/paragneiss and Bundschuh orthogneiss; Alpine metamorphic overprint.

W. FRANK, F. NEUBAUER

Location: OEK 50, sheet 183, Radenthein. Road exposure along the Nockalm road in the Heiligenbach valley, ca. 400 metres South to the custom-house at Innerkrems.

Both the Priedröf micaschist/quartzitic paragneisses (footwall) and the Bundschuh orthogneisses (hangingwall) are exposed along the Nockalm road and along the opposite wall of the valley. The Priedröf micaschist/paragneiss essentially contains quartz, feldspar, biotite, muscovite, garnet and rare pseudomorphs after staurolite. The Bundschuh orthogneiss is composed of K-feldspar porphyroclasts, quartz, plagiocalse and light-greenish white mica.
Theiner (1987) found a polymetamorphic evolution with a Variscan metamorphic overprint in nearby localities with ca. 600 - 640°C and Alpine temperatures ranging from 500 to 520°C based on garnet-biotite geothermometry. The age of the Bundschuh orthogneiss is uncertain. Rb-Sr whole rock investigations resulted in sets of subparallel isochrons with model ages between 371 and 397 Ma and high Sro ratios between 0.721 and 0.739 (Frimmel, 1988). White mica of the Bundschuh orthogneiss from the Innerkrems area range between 305 ± 12 and 119 ± 1 Ma (Theiner, 1987). Geochemical and petrography indicate a syn-collisional granites (Frimmel, 1988). The first age is interpreted to be close to the time of Variscan metamorphism, the second age as result of Cretaceous resetting of the Rb-Sr isotopic system.

Both lithologies contain a ESE plunging stretching lineation. Shear criteria suggest both a first top WNW shear and a later, semiductile ESE displacement.

Further reading: Frimmel, 1988; Pistotnik, 1974; Theiner, 1987.

Stop No. 11: Ductile low angle normal fault at the tectonic boundary between the Stangalm and Pfannock Permo-Mesozoic sequences and the Gurktal thrust system.

F. NEUBAUER

Location: OEK 50, sheet 183, Radenthein. Nockalm road. Park your car at the Eisentalhöhe parking place. Follow the path to the Eisentalhöhe (exposure of Haupt dolomite and Kössen Formation of the Pfannock slice of the Gurktal Nappe Complex). Follow ridge from the Eisentalhöhe to the West which exposes the phyllonite zone and the underlying dolomite marble of the Stangalm unit.

The dolomite marbles of the Stangalm Mesozoic sequence are in part strongly foliated and lineated. The lineation plunges E and ESE. The marbles are overlain by a ca. 10 metres thick phyllonite which exhibit a clearly visible ecc fabrics. Sense of displacement is top to the E/ESE. The phyllonite was interpreted as Carnian Raibl Formation. But the inclusion of chlorite schists exclude this stratigraphic interpretation. This level is now interpreted as part of the Murau Nappe of the Gurktal Nappe Complex because lithological composition and continuous exposure to true Murau Nappe along the structural base of the Gurktal Nappe Complex. In the hangingwall, dark Late Triassic limestones which belong to the cover of the Pfannock Nappe of the Gurktal Nappe Complex are exposed. These limestones include in part rich faunas (Thamnasteria rectilamellosa, Isocrinus bavaricus, Cardita austriaca). A detailed structural section is given in Fig. 13 (modified from Gosen, 1989).

Further reading: Gosen, 1989; Pistotnik, 197 ; Ratschbacher et al., 1990; Tollmann, 1975.

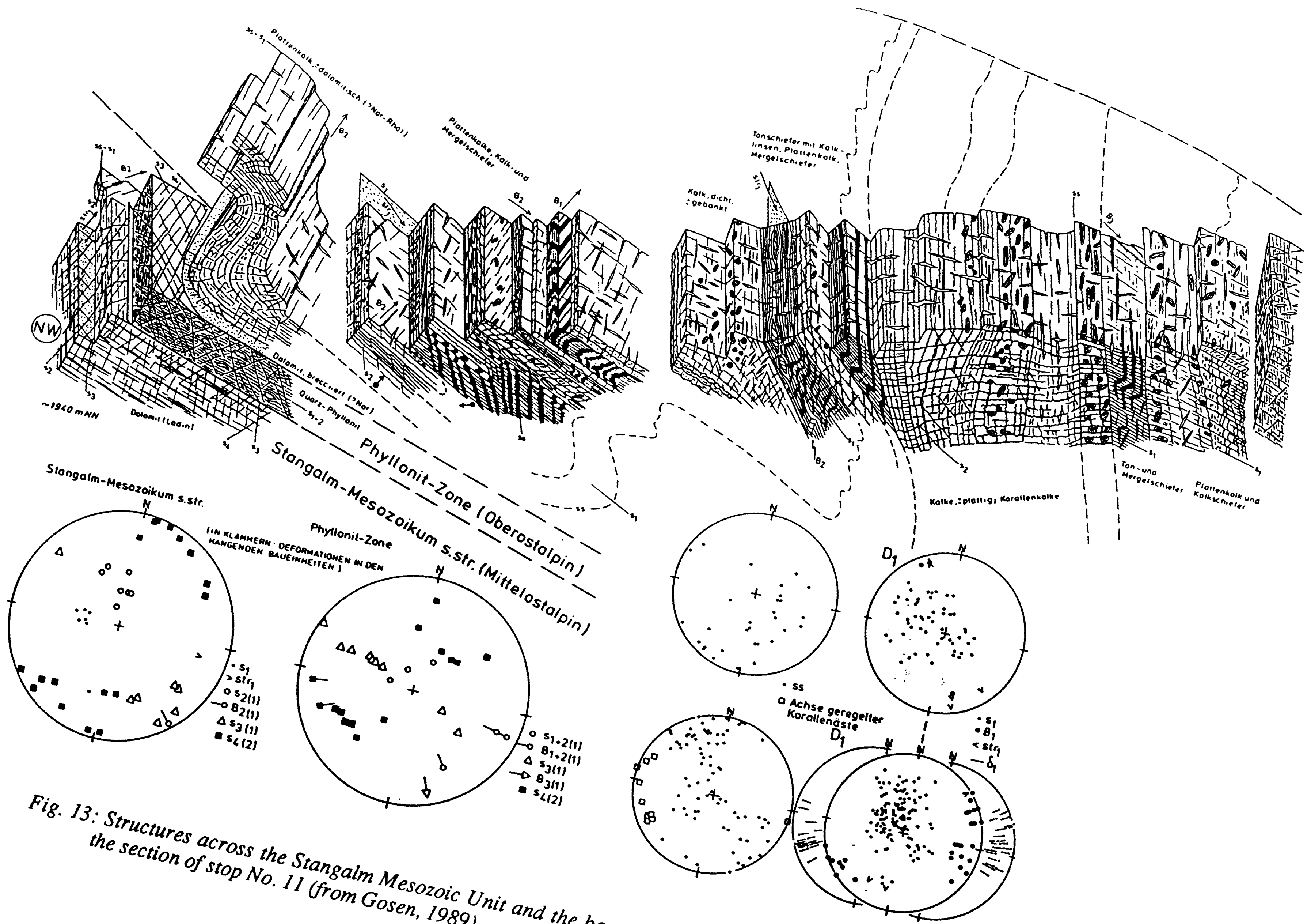
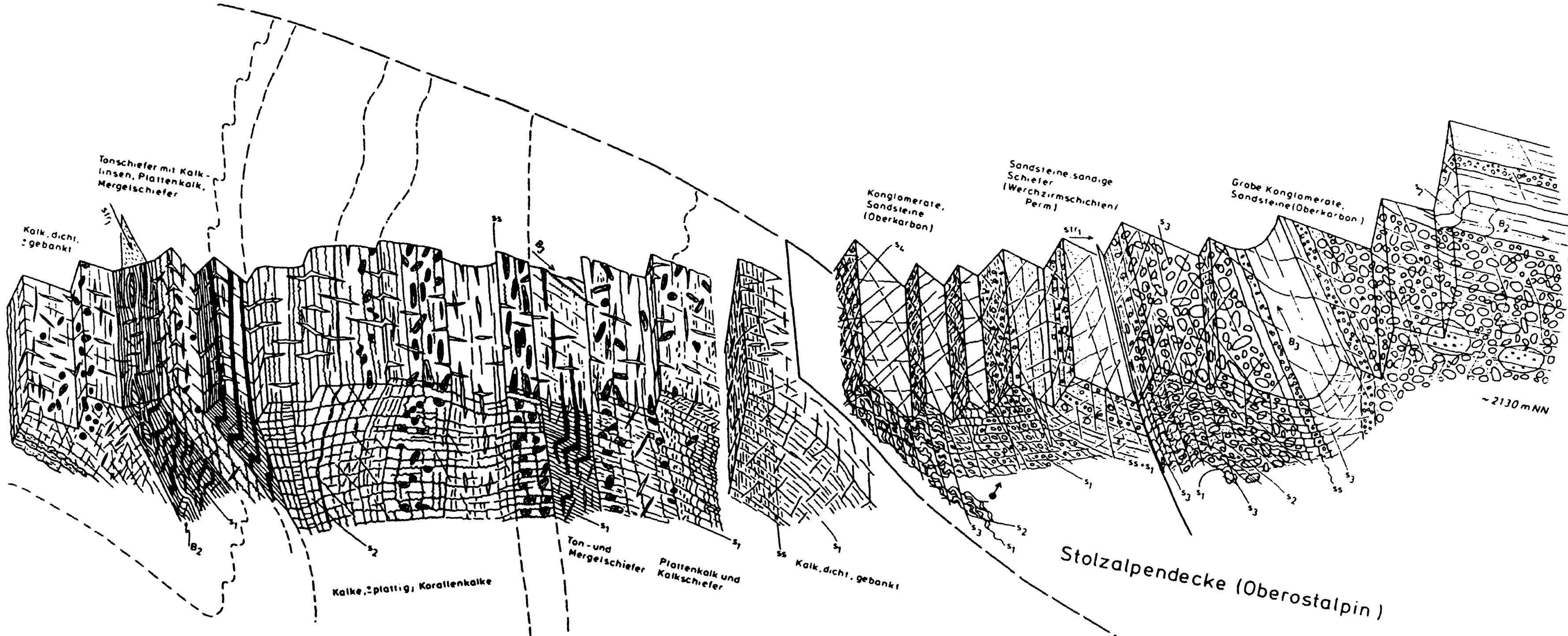


Fig. 13: Structures across the Stangalm Mesozoic Unit and the basal Gurktal Nappe Complex ca. at the section of stop No. 11 (from Gosen, 1989).



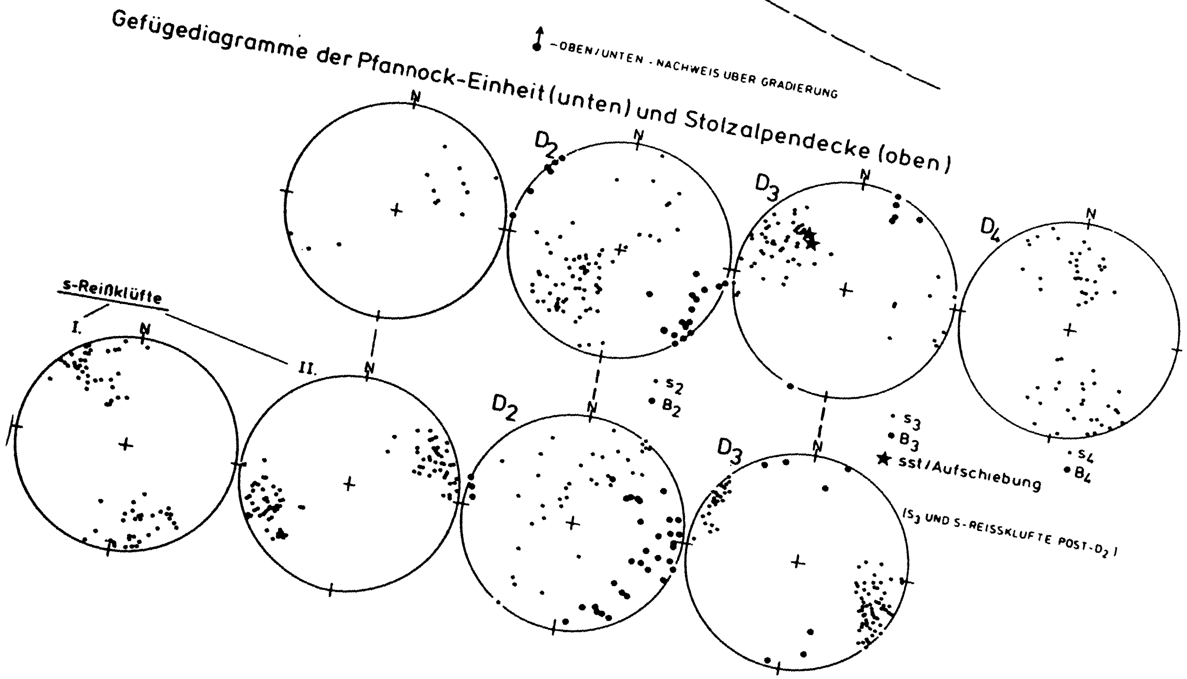


Fig. 13, continued.

Stop No. 12: Late Carboniferous molasse sediments (Stangnock Formation) of the Gurktal Nappe Complex.

K. KRAINER

Location: OEK 50, sheet 183, Radenthein. Walking tour to the western flank of Königstuhl. From the parking place "Eisentalhöhe" (2,100m) of the Nockalmstraße (National Park "Nockberge") footpath to the Königstuhl (2,336m) (about 1 hour) and Stangnock (2,316m).

The best outcrops of the Stangnock Formation are situated at the northern flanks of the Königstuhl and Stangnock mountains (Fig. 14).

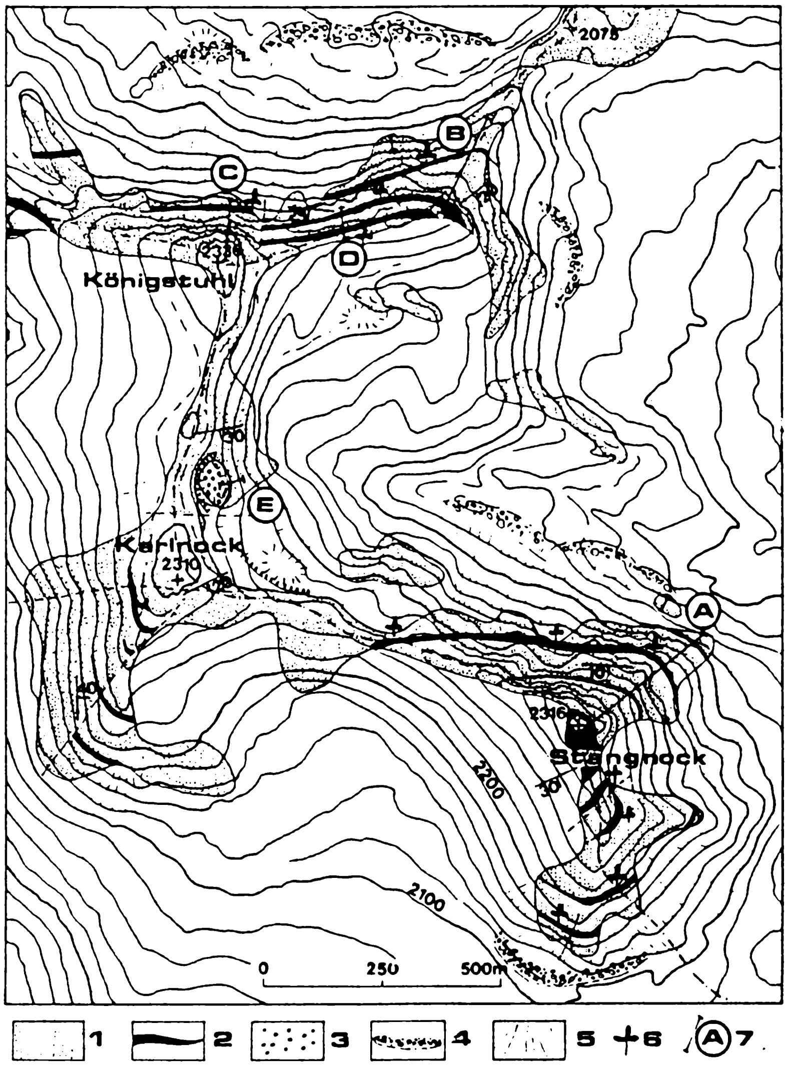


Fig. 14: Geologic map of the Stangnock-Königstuhl area with position of investigated sections and some important plant fossil localities. 1 Conglomerates and sandstones of the Stangnock Fm., 2 shales of the Stangnock Fm., 3 sediments of the Lower Permian Werchzirm Fm., 4 boulder walls, 5 talus cones, 6 plant fossil localities, 7 investigated sections (from Krainer, 1989b).

The Stangnock Fm., exposed at the NW-margin of the Gurktal thrust system (Upper Austroalpine), represents a more than 400m thick sequence of intermontane molasse fillings, which accumulated under humid climatic conditions.The sequence starts with polymict conglomerates and intercalated immature, coarse-grained sandstones (poorly sorted, angular-subangular, feldspathic lithic arenites) at the base, deposited on the proximal part of a fluvial system (?alluvial fan). The main series is built up by a few, indistinctly developed megasequences, beginning at the base above a sharp,

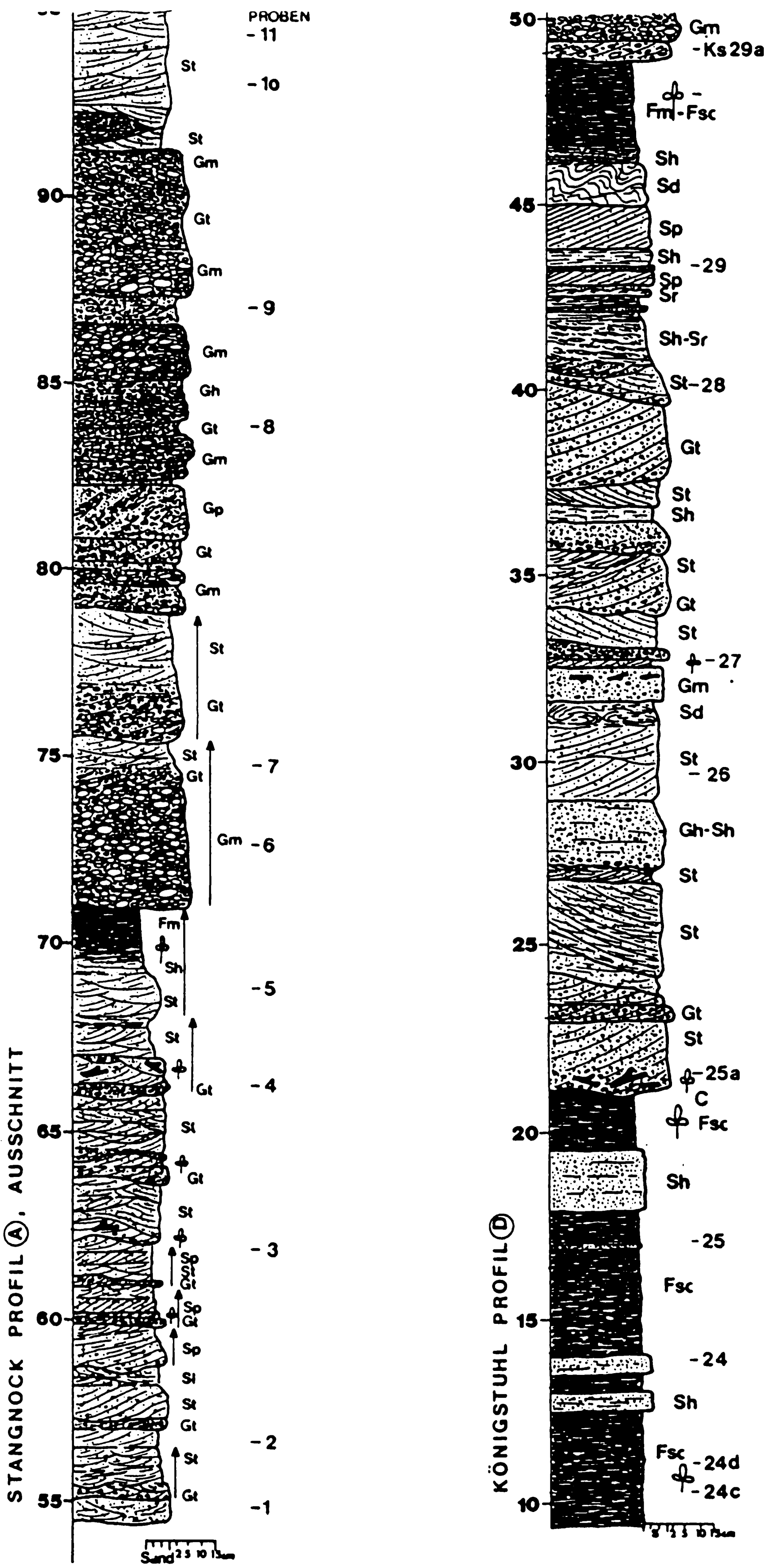


Fig. 15: Columnar sections through parts of the Stangnock Formation (main series) at the Königstuhl (section D) and Stangnock (part of section A) (from Krainer, 1989b).

erosive boundary with sediments of a gravelly, braided river system, grading upward into a gravel-sandstone facies, sometimes showing characteristic features of a meandering river system.

At the top of this sequences usually shales are developed, containing abundant plant fossils. At some places the shales, which are interpreted as overbank fines deposited on flood plains and in oxbow lakes, are overlain by thin anthracite seams (see Fig. 15). Conglomerates of the main series are very rich in quartz (>90%), sandstones are classified as moderately sorted, subangular lithic arenites - sublitharenites, in part lithic wackes, with high amounts of polycrystalline quartz (Fig. 16).

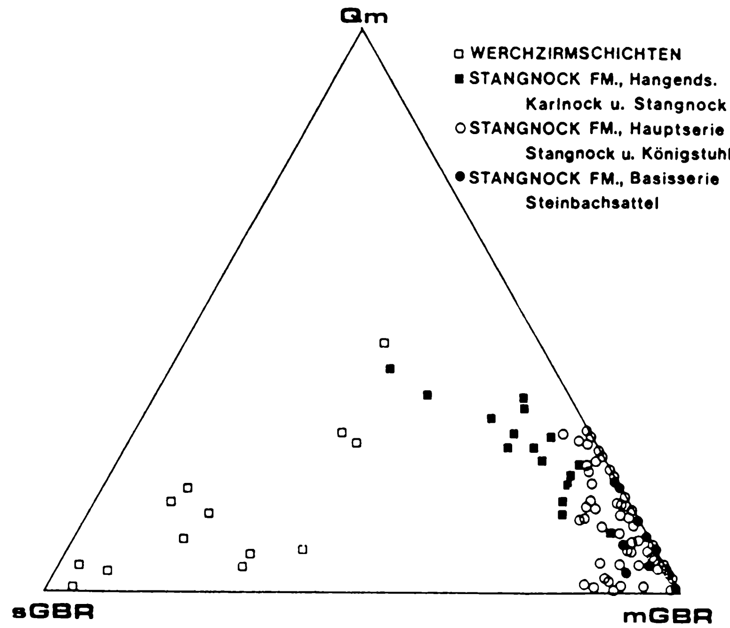


Fig. 16: Sandstones of the Stangnock Formation and overlying Lower Permian Werchzirm Formation plotted in the Qm (total quartz) - sGBR (sedimentary rock fragments) - mGBR (metamorphic rock fragments) compositional diagram. Sandstones of the top series (Hangendserie) are characterized by higher amounts of monocrystalline quartz and sedimentary rock fragments, sandstones of the Werchzirm Formation are mainly composed of sedimentary rock fragments (from Krainer, 1989 b).

The top series does not show significant differencies in facies compared to the main series, slight differences exist concerning the composition of the sediments. Volcanic rock fragments, especially volcanic quartz, are a characteristic feature of the sandstones, referring to first volcanic activity during the uppermost Carboniferous in the studied area.

The sharp, erosional appearance of the megasequences and the top series, starting with coarse-grained accretions, is referred to synsedimentary fracture tectonics. From current directions which show a significant eastward trend, it is concluded that the intermontane basin developed in an approximately east-west-direction.

Well preserved plant fossils from dark shales of the Stangnock Fm. are known from several localities for more than 200 years. The complete fossil list contains 72 taxa (see Fritz, Boersma and Krainer, 1990). A flora rich in Linopteris neuropteroides and Lycophyta, containing Neuropteris scheuchzeri and Sphenophyllum oblongifolium but without Pecopteris feminaeformis in the lower part of the Stangnock Formation (localities Brunnachhöhe and Turrach 1) indicates Cantabrian age (Odontopteris cantabrica Zone). The flora from the horizon Königstuhl 31a (lower part of the Stangnock Formation) with Sphenophyllum oblongifolium, Callipteridium pteridium, Odontopteris and Pecopteris feminaeformis points to Barruelian age (Lobatopteris lamuriana Zone). The Alethopteris zeilleri Zone (Stephanian B) with the significant species Sphenophyllum thonii var. minor is represented by the flora Turrach 5 (lower part of the Stangnock Formation). The Sphenophyllum angustifolium Zone (Stephanian C) is indicated by the flora from the localities

Königstuhl 25a and Reißeck (middle part of the Stangnock Formation) containing the species Sphenophyllum angustifolium.

The uppermost part of the Stangnock Formation is characterized by the first appearance of Callipteris cf. conferta (locality Stangnock Südostgrat 1), indicating uppermost Stephanian C/Autunian age (Callipteris conferta Zone).

Further Reading: Frimmel, 1986, 1988. Fritz et al., 1990; Krainer, 1989a, b.

The Lower Paleozoic sequences at the northwestern border of the Gurktal Nappe

U. GIESE

At the NW-border of the Gurktal nappe the Lower Paleozoic is composed of monotonous alternations of phyllites and meta-volcanics, which are unconformably overlain by Upper Carboniferous molasse sediments. The Lower Paleozoic has been divided by lithological, structural and petrological-geochemical means into two different lithostratigraphic sequences, the Nock sequence and the Eisenhutschiefer sequence (Fig.17, 18; Giese, 1987,1988).

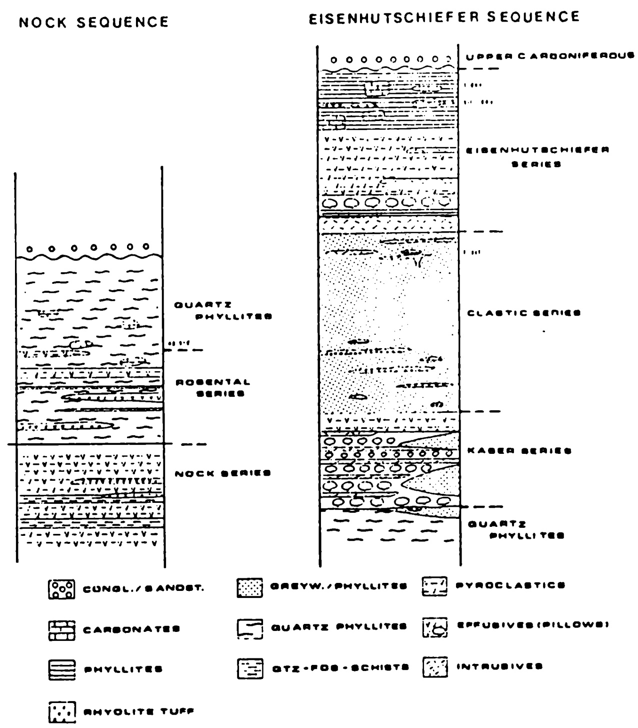


Fig. 17: Simplified stratigraphic sections of the Nock sequence and the Eisenhutschiefer sequence (no scale).

The Nock sequence crops out only along the NW border of the Gurktal nappe in a sickle-shape form and disappears rapidly to the NE and SW. The whole structure is interpreted as an antiformal stack of tectonic slices. Due to the lack of marker horizons both, structure and stratigraphic section is difficult to unravel in detail. The sequence is composed of various mafic schists, phyllites and carbonates; the later have yielded Upper Ordovician conodonts (Neubauer and Pistotnik, 1984).

To the east the Nock sequence is tectonically overlain by the Eisenhutschiefer sequence (Fig. 19), in which a stratigraphic section has been established by Silurian to Lower Devonian conodont findings (Höll, 1970, Neubauer and Pistotnik, 1984). Two volcanic stages, the basal Kaser series and the Eisenhutschiefer series, are separated by fine-grained clastic sediments, in part turbidites, with

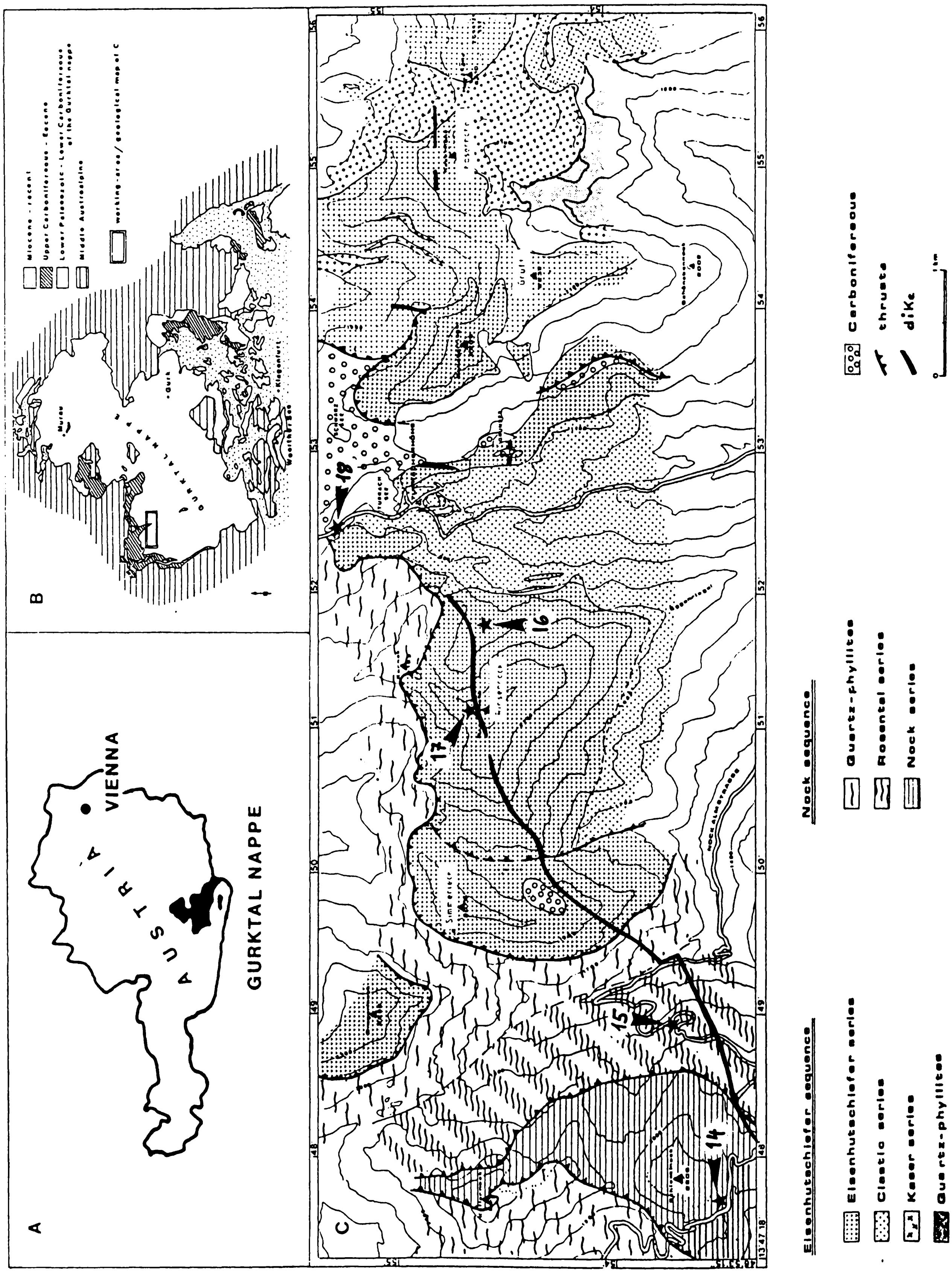


Fig. 18:Geological map of the NW part of the Gurktal nappe (C) with described outcrop localities, A & B - location of Gurktal nappe and geological map of C.

intercalations of basic volcanics and black cherts. The hanging-wall is represented by slates with interstratified massive Fe-dolomites and locally occuring rhyolite tuffs.

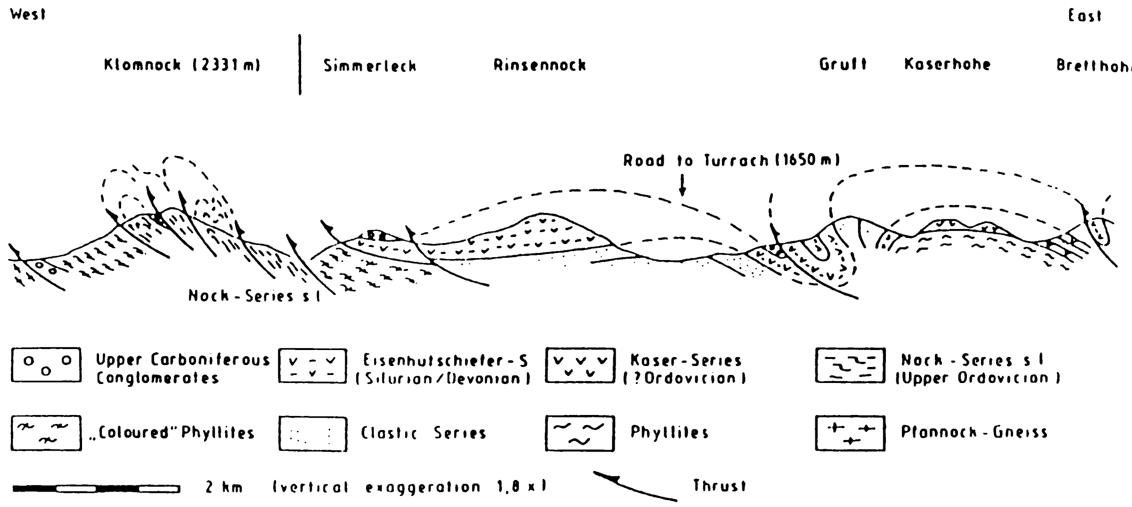


Fig. 19: Schematic geological cross-section through the northwestern part of the Gurktal nappe (Loeschke, 1989).

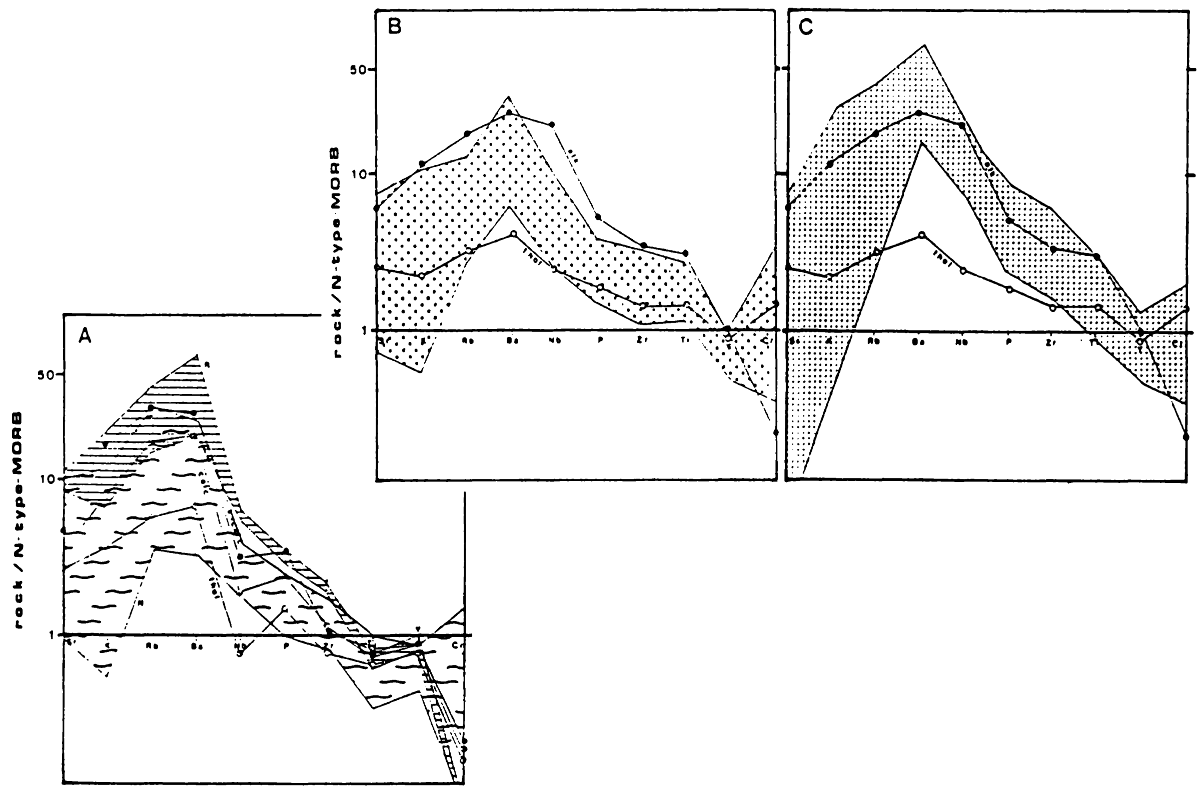


Fig. 20:MORB-normalised element distribution patterns after Pearce (1983). A. Basalts of the Nock series and the Rosental series in comparision with average compositions of tholeiitic, calc-alkaline and high-K calc-alkaline basalts from Java and Bali (Whitford et al., 1979). B. Basalts of the Kaser series in comparision with a tholeiite and an alkalibasalt from Hawaii (Pearce, 1983). C. Basalts of the Eisenhutschiefer series in comparision with a tholeiite and an alkali basalt from Hawaii (Pearce, 1983).

Both sequences contain several volcanic units, which display due to their compositional differences an Ordovician-Silurian igneous evolution, which is marked by the transition from calc-alkaline to alkaline magmatism (Fig. 20). This has been interpreted as a back-arc setting or the change from a post-collisional stage to an extensional stage (Giese, 1988, Loeschke, 1989).

The sequences are unconformably overlain by Upper Carboniferous (Westphalian/Stephanian - Tenchov, 1978, Fritz & Boersma, 1984) and Permian clastic sediments.

Late tonalitic dikes of assumed Tertiary age cross cut all Lower Paleozoic units.

All units have experienced low-grade to very low-grade metamorphism. While the Nock sequence has been affected by greenschist-facies conditions, the Eisenhutschiefer sequence indicates upper anchizonal conditions. A metamorphic gap between the Lower Paleozoic and the Upper Carboniferous proves that the peak of metamorphism is of Variscan age, while Alpine metamorphism has only reached lower anchizonal conditions (Mulfinger, 1986, Giese, 1987).

As both sequences have experienced a comparable alpine deformation history, the juxtaposition of both sequences must have occured during variscan defomation. However, assumed variscan structures can only be recognized in the Nock sequence, where small-scale E-verging isoclinal folds mark a first deformation phase. The main structures are generated during Alpine emplacement of the Gurktal nappe (Fig.5). W to NW-directed transport is indicated by W-verging, small and large-scale, in part recumbent folds, by thrusting and increasing imbrication towards the NW and by W-NW trending stretching lineations. This phase is overprinted by open to tight folds with W-E or NW-SE trending fold-axes. Several younger structural phases are of minor regional significance.

Stop No. 13: Contact of Lower Paleozoic phyllites and Upper Carboniferous molasse sediments (Fig. 21).

U. GIESE

Location: OEK 50, sheet 183, Radenthein. Western slope of the Mallnock (WSW of peak at 2080m - 2100m)

In the overturned section the contact is marked by a massive Fe-dolomite which is overlain by sandy shales, coarse-grained sandstones and conglomerates of Westphalian age (plant fossils indicate Westphalian C/D - Tenchov, 1978). No tectonic contact can be recognized. On the basis of sedimentological investigations Liegler (1970) has argued for a normal transgressive contact.

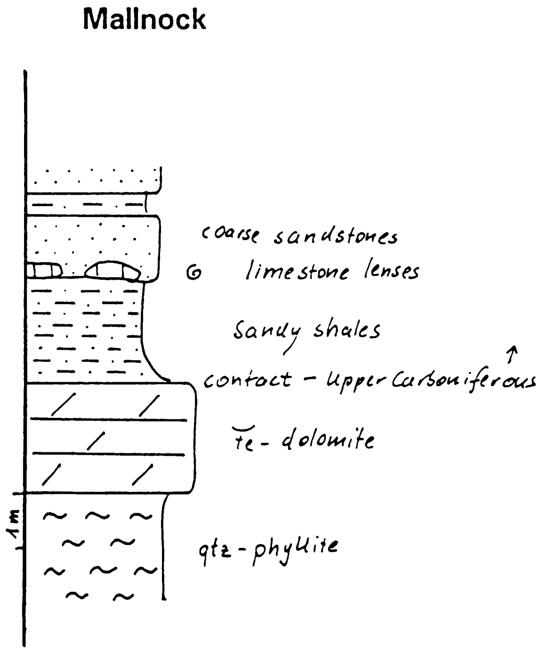


Fig. 21: Contact of Lower Paleozoic phyllites and Upper Carboniferous sediments of the Mallnock.

At the base of the first sandstone horizon dark limestone lenses (up to 0,5m of size) have been discovered, which are rich in fossiliferous debris. The lenses have yielded brachiopods, lamellibranchiata, crinoid stems and corals. One coral has been described by Schlöser et al. (1990) as Hexaphyllia cf. mirabilis, which indicates a Visean/Namurian age. The finding indicates that a Visean-Namurian carbonate plattform might have existed comparable to the Veitsch nappe of the Greywacke zone, which has been reworked in Westphalian time.

Stop No. 14: Lower Paleozoic phyllites and dolomites of the Nock sequence, to the north intercalated quartzites. Mafic schists are exposed along the path to the Klomnock or Schiestelnock.

U. GIESE, F. NEUBAUER

Location: OEK 50, sheet 183, Radenthein. Schiestelscharte at the Nockalm Road.

The exposed rocks belong to the undated, basal part of the Nock sequence which is composed of mafic schists, quartz-feldspar-schists and phyllites. Quartzites, white marbles and Fe-dolomites are sometimes intercalated. Due to the lack of marker horizons and intense imbrication with overlying phyllites, a detailed lithostratigraphic section has not been established.

Mafic schists are often laminated. The layers are mm to cm thick and are composed of chlorite-epidote, chlorite-actinolite-epidote and quartz-albite-epidote. In these layers phenocrysts of plagioclase and brown basaltic hornblende occur which are regarded as primary volcanic constituents. The lamination refers to different tuff, ash-tuff, crystal tuff and tuffite layers. Therefore, most of the mafic schists are pyroclastic in origin. Massive, partly feldspar porphyritic rocks which represent effusives are rare.

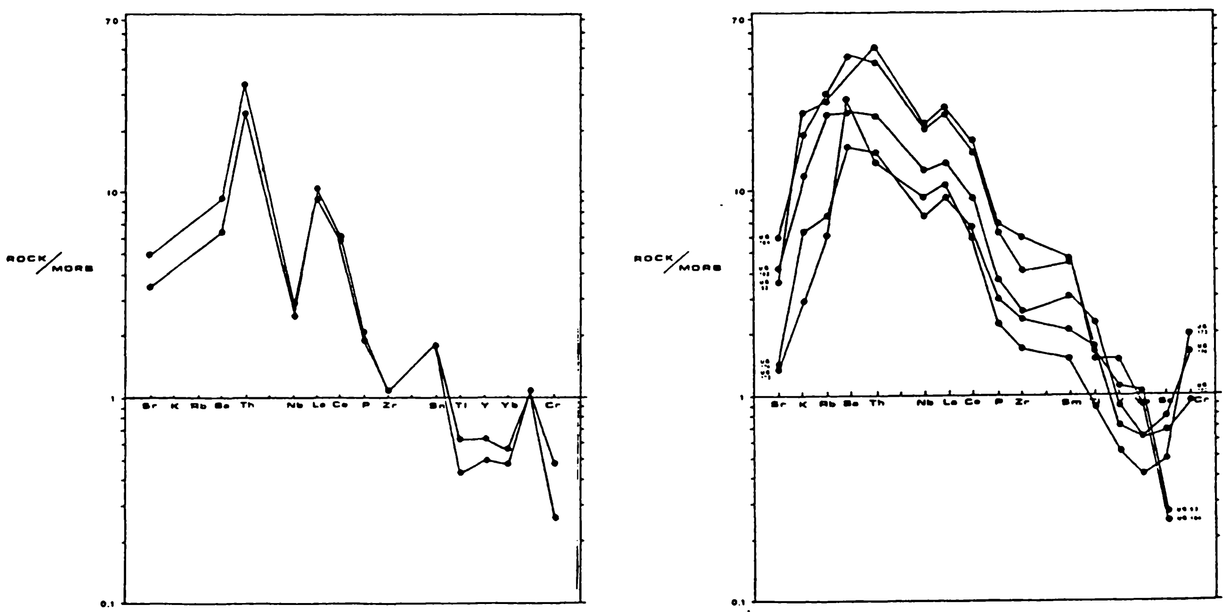


Fig. 22: MORB-normalised element distribution patterns after Pearce (1983). A. Basalts of the Nock series. B. Basalts of the Eisenhutschiefer series.

Intercalated plagioclase-rich schists are composed of various muscovite-albite, epidote-albite, calcite-chlorite-albite and muscovite-chlorite-calcite-albite assemblages. They might represent intermediate volcanics and pyroclastics in part, but on the whole petrographic features favour a sedimentary origin. This is in accordance with the occurrence of several mature quartzite horizons. According to chemical analyses the mafic schists refer to basalts, basaltic andesites and andesites. The mayor element chemistry is characterised by relative high Al2O3 contents (14%-18%) and low TiO2 (<1,36%) and P2O5 (<0,43%) contents. The FeOtot/MgO ratio shows constant values and no iron-enrichment trend can be observed. MORB-normalised distribution patterns of least enriched basalts shows a humped pattern with strong enrichment of LIL element and depletion of HFS elements. However, the pattern is distinctly spiked with peaks at Th, La, Ce and Sm and marked troughs at Nb, Zr, Ti, Y and Yb, which is typical of high-K calc-alkaline of continental margins or continental island arcs (Fig. 20, 22).

Stop No. 15: Upper Ordovician dolomites and mafic schists of the Nock sequence

U. GIESE, F. NEUBAUER

Location: OEK 50, sheet 183, Radenthein. Nockalm road near Rosentaler Alm, elevation ca. 1,800 to 1740 m.

The exposed rocks belong to the upper part of the Nock sequence, which is in tectonic contact to the previously described lower part. A lithostratigraphic section of this series (from the Steinnock) is given in Fig.24. Alternating phyllites and mafic schists occur at the base, while towards the top monotoneous phyllites predominate with interstratified various carbonates. Light-colored dolomites have yielded Upper Ordovician conodonts (Caradoc/Ashgill), dark dolomites, impure marbles and limy phyllites occur as well.

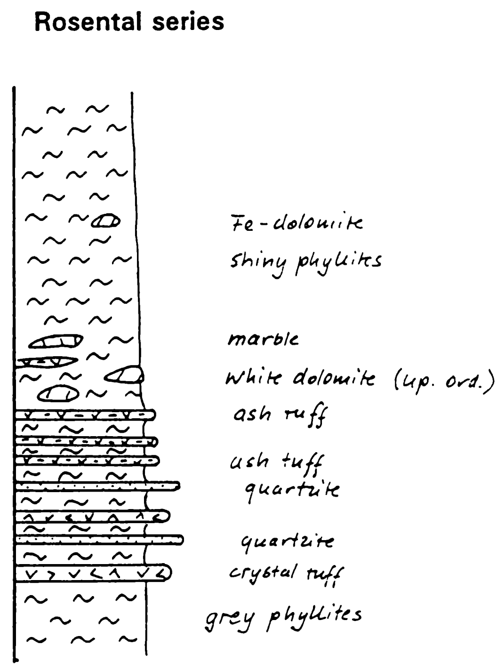


Fig. 23:Schematic stratigraphic section of the Rosental series (no scale), upper part of the Nock sequence.

The mafic schists are predominantly fine-grained ash-tuffs, rare crystal tuffs have been found. Chemical analyses show calc-alkaline affinities. However, in comparison to the basal part of the Nock sequence, these meta-volcanics are more enriched and indicate a transition to alkalic compositions (Fig. 20).

Stop No. 16: Volcanics of the Eisenhutschiefer series, old cinnabar mine at the Korhütte.

U. GIESE

Location: OEK 50, sheet 189, Ebene Reichenau. Eastern slope of the Rinsennock, Korhütte.

Volcanism of the Eisenhutschiefer series consists predominantly of pyroclastic rocks which usually make up more than 50% of the whole volcanic series. At the Rinsennock vesicular pillow basalts and intrusive sills form the basal part of the series, while pyroclastics dominate towards the top (Fig. 24). Small dikes and stocks of intermediate composition cut across the volcanics.

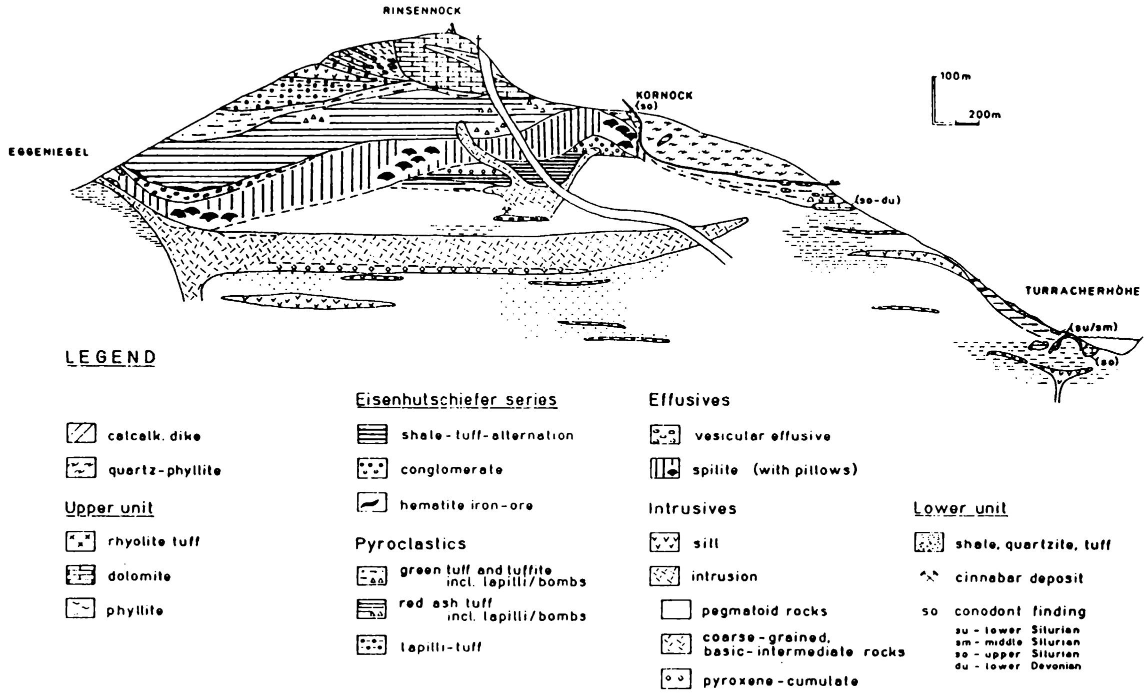


Fig. 24: Schematic sketch of the Eisenhutschiefer series at the eastern and northeastern side of the Rinsennock.

Pyroclastics are dominated by fine-grained ash tuffs and tuffites, in part reworked with turbiditic features. Coarse lapilli tuffs, volcanic breccias and agglomerates indicate proximal, shallow marine deposition close to a former eruption center. Basaltic conglomerates and 'tailed bombs' in volcanic breccias argue for temporarily subareal conditions of a volcanic island.

Pillow basalts have aphyric, vesicular and porphyritic textures with phenocrysts of Ti-rich clinopyroxene and plagioclase. Intrusives show intersertal and intergranular textures and consist of Ti-augite, plagioclase, kaersutite and red- to brown-colored biotite.

Chemical compositions clearly reveal an alkaline character. Pillow basalts classify mainly as alkali basalts and hawaiites. Intrusives are more evolved and have compositions of hawaiites and mugearites. Intermediate rocks show strong enrichment of incompatible elements and are phonolytic trachytes. MORB normalised distribution patterns are in excellent accordance with alkali basalts of oceanic islands (Figs. 20, 22).

In conclusion, the Eisenhutschiefer series at the Rinsennock represents an alkali basalt - hawaiite - mugearite - trachyte suite of an oceanic island volcano.

Cinnabar deposits (Höll, 1970), which have been worked untill the 40th in a small mine at the Korhütte, and submarine hydrothermal iron-ore deposits are associated with the volcanism.

Stop No. 17: Dolomites of Silurian age and volcanics and pyroclastics of the Eisenhutschiefer series. Towards the north in tectonic contact Lower Paleozoic phyllites are exposed and on the eastern side of the road Upper Carboniferous conglomerates and sandstones crop out.

U. GIESE

Location: OEK 50, sheet 184, Ebene Reichenau. Turracher Höhe, along the road at the Steiermark-Carinthian boundary.

The dark dolomite has yielded Lower Silurian conodonts (Llandovery/Wenlock boundary, Höll, 1970; Neubauer and Pistotnik, 1984). Its position is close the base of the Eisenhutschiefer series and marks the onset of the volcanism. Light-colored dolomites which have yielded Upper Silurian to Lower Devonian conodonts overlie the Eisenhutschiefer series at several localities (some are exposed at the southern end of the Turrach lake). From this the age of the volcanism can be deduced as Lower to Middle Silurian.

At the Turracher Höhe the Upper Carboniferous contains several anthracite coal horizons which have been worked until the 60th.

Stop No. 18: Calc-alkaline tonalitic dike of assumed Tertiary age.

U. GIESE

Location: OEK 50, sheet 184, Ebene Reicehnau. Rinsennock, on the path from the Kornok to the Rinsennock at 2,280m.

Here a 20m thick, undeformed tonalitic dike with chilled margins is exposed, which cut the volcanic rocks of the Eisenhutschiefer series. The dike strikes W-E and can be traced over almost 10km from the Klomnock at the western border of the Gurktal nappe to the Turracher Höhe. Similar dikes are also found to the east, for example at the Lattersteig and the Haidner Höhe. The dike is not dated.

The mineralogical and chemical composition of the dike is very homogeneous. It is composed of plagioclase (An38), ilmenite, quartz and +/-augite, +/-basaltic hornblende and +/-biotite. Inclusions of veins-quartz and quartz-feldspar enclaves indicate some degree of crustal contamination. The chemical composition corresponds to a tonalite with high-K calc-alkaline affinity. It is very similar to

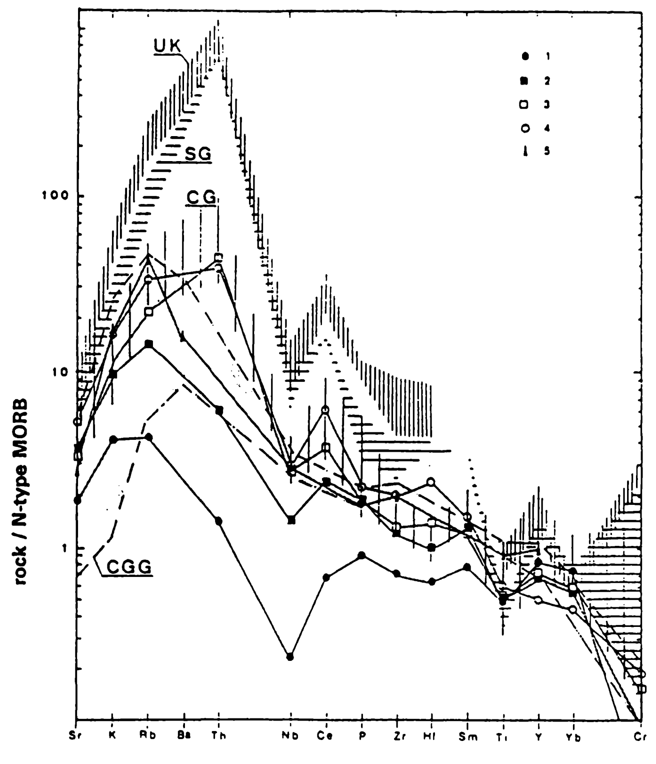


Fig. 25: MORB-normalised element distribution patterns of calc-alkaline Tertiary dikes of the Alps (after Pearce, 1983 and Venturelli et al., 1984). UK - Lamprophyres, SG - Shoshonites, CG - Calc-alkaline dikes, CGG - Calc-alkaline dikes of the Gurktal nappe. Andesites of different geotectonic position for comparision (after Bailey, 1981): 1 - low-K andesite of island-arc, 2 - andesite of island-arc, 3 - andesite of continental island-arc, 4 - andesite of active continental margin, 5 - sample of calc-alkaline dikes of the Gurktal nappe (UG 6).

Oligocene dikes of other part of the western and eastern alps (Fig. 25; Venturelli et al., 1984, Deutsch, 1984). If isotope dating would confirmed this age, the dikes might help to unravel the late alpine history of the Gurktal nappe.

Stop No. 19: Late Triassic sequences (Pölling Limestone/Dolomite and Raibl Fm.) of the Eberstein Permo-Triassic Group, Gurktal Nappe Complex; thrust flats along the Raibl Formation.

(by F. NEUBAUER after T. Appold, 1989)

Location: OEK 50, sheet 186, St. Veit an der Glan. Old quarry NW of Launsdorf. Follow road by foot from western exit of Launsdorf (not for big busses !).

The quarry exposes a major internal thrust zone at the level of the Pölling Limestone/Dolomite and Raibl Fm. within the Eberstein Permo-Triassic Group of the Gurktal Nappe Complex (Fig. 26). The base is composed of Pölling Limestone/Dolomite which is overlain by an oolitic limestone, brownish marls and slates of the Raibl Formation (Fig. 27). The marls are overlain and cut by Pölling Dolomite and Late Triassic Haupt Dolomite (outside of the quarry).

The thick Haupt Dolomite forms a major thrust sheet over a thrust flat inside of the Raibl Formation.

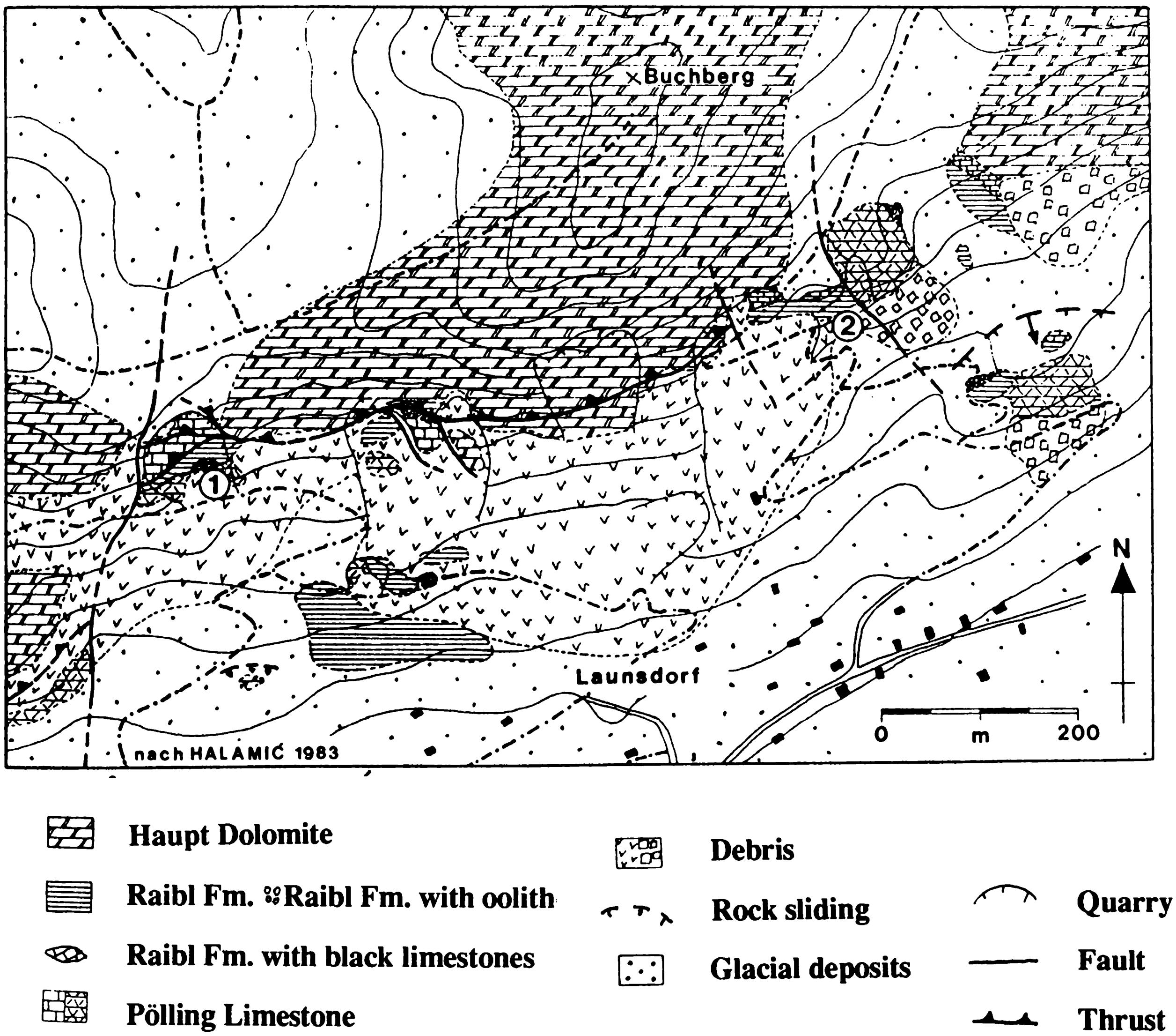


Fig. 26: Map of the Launsdorf area of the Eberstein Permo-Triassic Group (after Appold in Appold and Thiedig, 1989, p. 151).

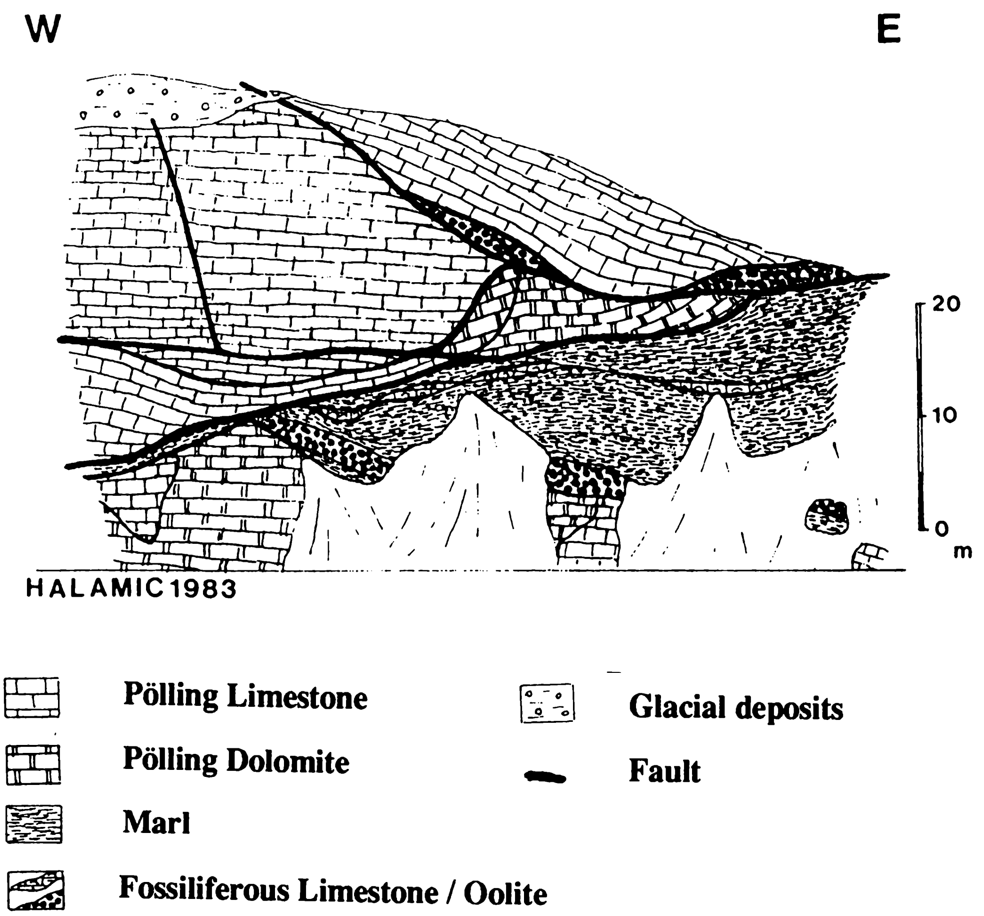


Fig. 27: Northern wall of the Launsdorf quarry (after Appold and Thiedig, 1989, p. 152).

Stop No. 20: Late Cretaceous turbidites and debris flows.

After Neumann in Appold and Pesch, 1989).

Location: OEK 50, sheet 186, St. Veit a.d. Glan. northern part of the quarry of the Wietersdorfer Zementwerke AG.

The quarry exposes basal turbidites and a thick megaturbidite bed. The turbidites of the basal, northern part are ca. decimeter thick limestones (calcarenites) which separated by marl layers of the normal basina sediments. The debris flow contain up the meter-sized reef limestones with rudists (Fig. 28).

Further reading: Neumann, 1989; Thiedig, 1975.

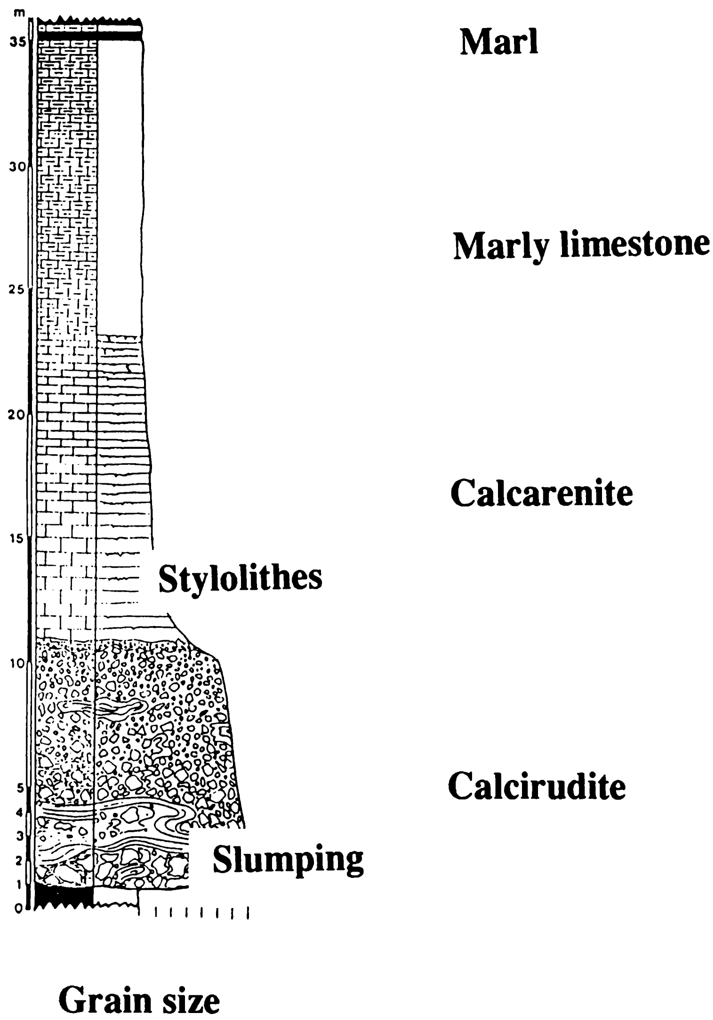


Fig. 28: Section of the debris flow with rudist clast from the Wietersdorf quarry (from Neumann, 1989).

Stop No. 21: Eocene nummulite limestones.

(After WILKENS in Appold and Thiedig, 1989).

Location: OEK 50, sheet 186, St. Veit a.d. Glan. Quarry at the Fuchsofen east of Kl. St. Paul.

The quarry exposes nummulite limestone of Paleogene age. The limestones are subdivided into several, internally massive beds with ca. 140 m thickness. Three members have been distinguished by Wilkens (1989):

1) The limestones are very pure and lack terrigenous detritus. They contain large foraminifera.

2) In contrast to the first member,the second member contains quartz together with associations of large foraminifera and incrustend foraminifera and red algae.

3) The third member is another very pure nummulite limestone with extreme dimorphism of nummulites.

The limestones are cut by karst and overlain by the Waitschach gravels of supposed Miocene age.

Numerous N-S trending faults are ca. parallel to the large Görtschitztal fault which separates the Krappfeld graben from the Saualm metamorphic horst. The striae on most faults within the quarry are subhorizontal suggesting predominant dextral strike-slip displacement along the Görtschitztal fault zone.

Further reading: Wilkens, 1989.

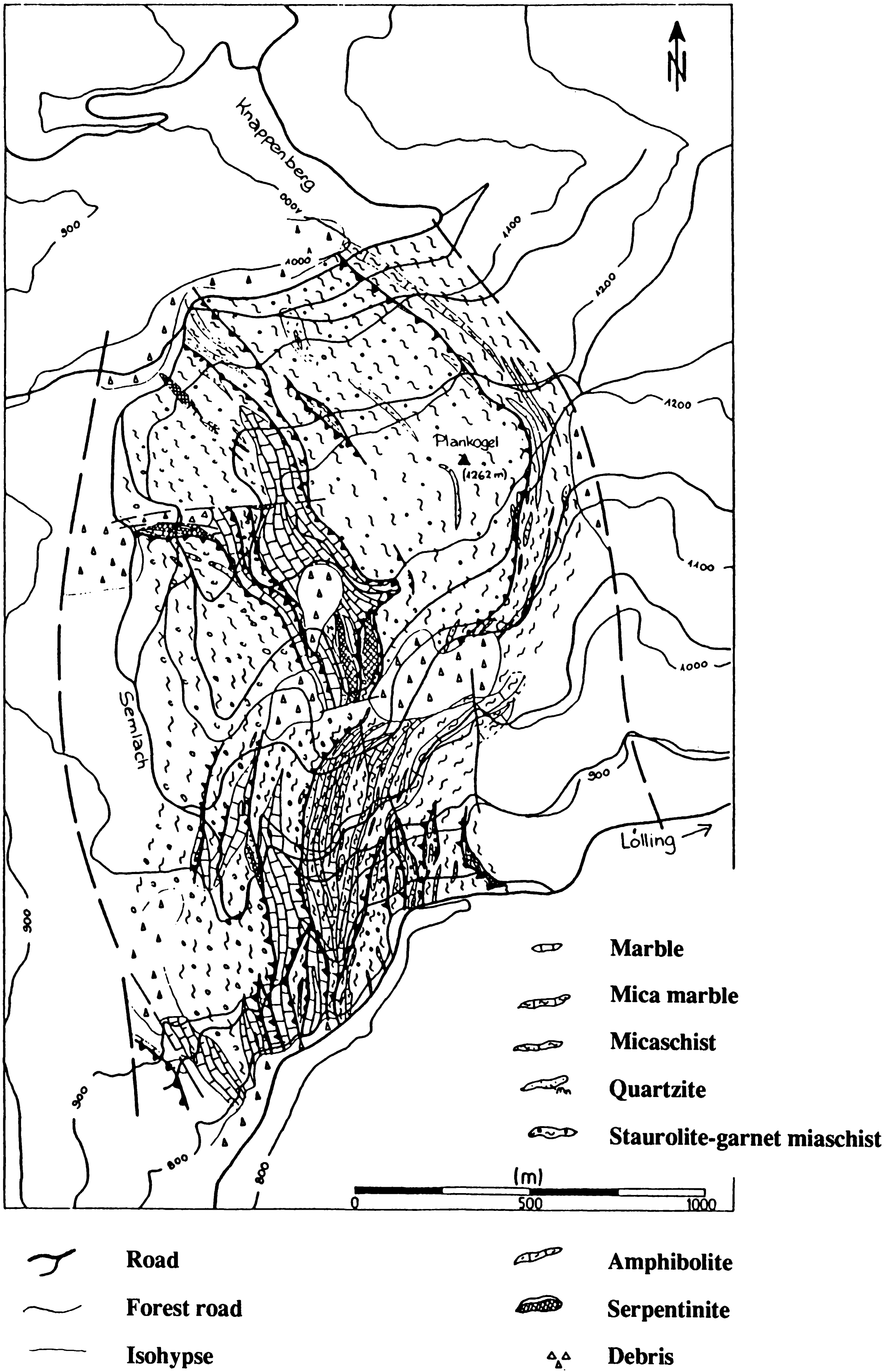


Fig. 29: Map of the Plankogel area with exposures along forest roads (from Schmerold, 1989).

Stop No. 22: Plankogel complex, Middle Austro-Alpine unit, at the type locality.

F. NEUBAUER (after Schmerold, 1989)

Location: OEK 50, sheet 186, St. Veit an der Glan. Follow road from Knappenberg in direction to (Ober-)Semlach. After leaving the woods walk along forest road to the eastern slope of the Plankogel (see Fig. 29).

The forest roads on the eastern slope of the Plankogel expose the Plankogel complex at the type locality. Schmerold (1988) here distinguished between (1) manganese quartzite-bearing sequence and (2) and serpentinite-bearing sequence (Fig. 29).

The manganese quartzite-bearing sequence is composed of biotite- and plagioclase-rich micaschists which contain lenses of manganese quartzite, amphibolite (with alkali basaltic WPB chemistry) and impure marbles. The serpentinite-bearing sequence is formed by coarse-grained micaschist, garnet amphibolites (with tholeiitic MORB chemistry) and pure marbles.

The magmatic rocks of the serpentinite-bearing sequence are interpreted as part of an ophiolithic melange. The manganese quartzite-bearing sequence as part of a seamount.

The detailed structure is complicate. From the map, imbrication between both sequences is obvious. All rocks have a flatlying foliation and a ca. WNW trending stretching lineation. Quartz textures favour a top ESE shear which is probably related to final, Late Cretaceous uplift of the Saualm metamorphic complex.

Further reading: Appold, 1989; Schmerold, 1988; Neubauer et al., 1989.

Stop No. 23: Garnet-two mica gneiss close to the structural base of the Koralm Gneiss Group.

W. FRANK, F. NEUBAUER

Location: OEK 50, sheet 188, Wolfsberg. The road exposure is in the Lavant valley amidst between the village Twimberg and St. Gertraud North to the town Wolfsberg, ca. 1,7 km South to Twimberg, West to the confluent Jovenbach to the Lavant. Dangerous outcrop because of traffic !

The outcrop exposes micaschist and gneisses from the structural base of the Koralm Gneiss Group with well-preserved, only weakly deformed mineral parageneses which have been formed during Cretaceous metamorphism. Essential constituents are white mica, quartz, feldspar and minor garnet and biotite. Two thin slab isochrones from two nearby located sites gave ages of 81 2 and 107 3 Ma (Fig. 30; Frank et al., 1983; Jung, 1982). These ages are interpreted to date the peak metamorphic conditions at the structural base of the Koralm Gneiss Group with complete Sr isotopic exchange over distances of 20 to 30 centimetres (Frank et al., 1983; Jung, 1982).

A widely spaced post-metamorphic foliation is probably related to Late Cretaceous uplift and exhumation of the Koralm Gneiss Group.

Further reading: Frank et al., 1983.

Stop No. 23: Paragneiss with pseudomorphs of kyanite after andalusite, and Platten gneiss of the Koralm Gneiss Group.

W. FRANK, F. NEUBAUER

Location: OEK 50, sheet 188, Wolfsberg. Follow from St. Gertraud the road to the Weinebene, a saddle in the Koralm. From the Weinebene follow the footpath to the South resp. Southwest along the ridge, resp. east of it.

Along the path there are some exposures with well-recrystallized paragneisses, some retrogressed eclogites, and of a paragneiss with pseudomorphs of kyanite after andalusite. These pseudomorphs reach sizes of several centimetres and are nearly undeformed.

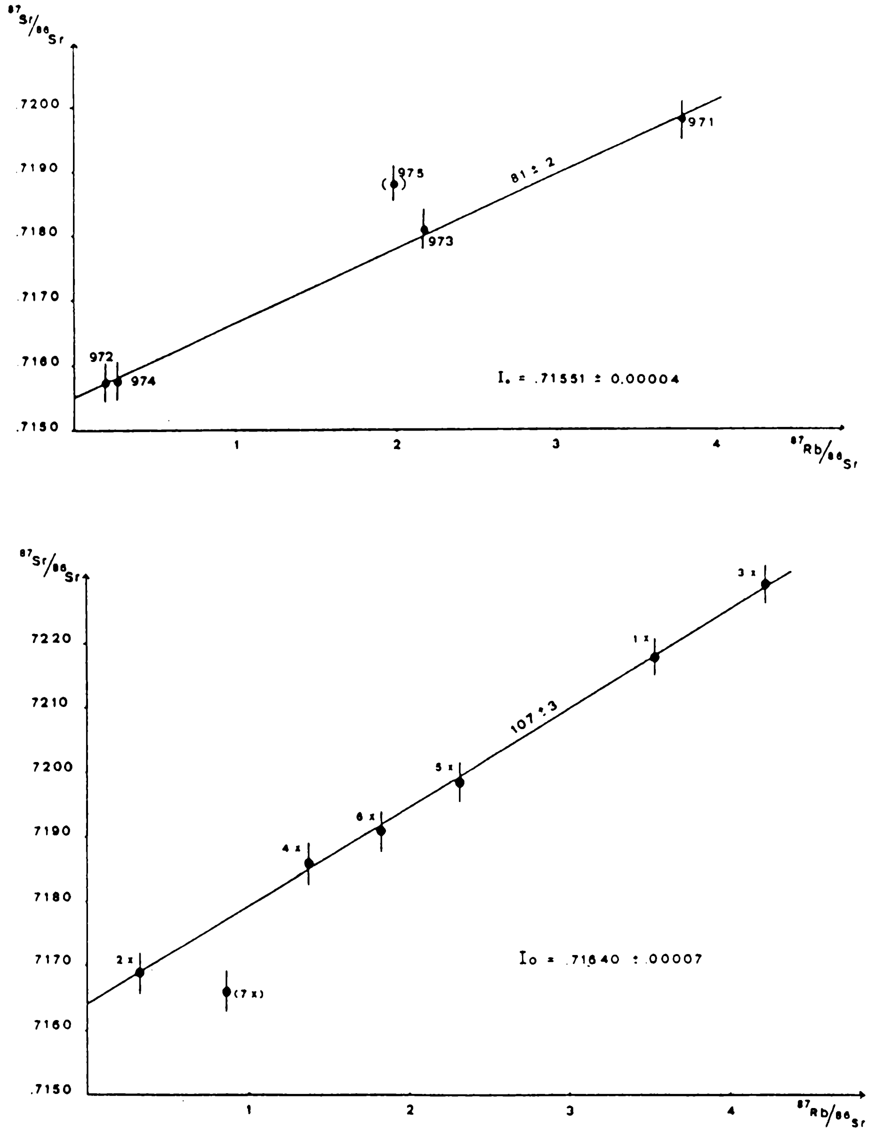


Fig. 30: Rb-Sr thin slab isochrons of basal gneisses of the Koralm Gneiss Complex (from Frank et al., 1983).

Another possible walking tour is from the Weinebene saddle to the North, in direction to the Handalpe. Along this path which is upsection in direction to the Platten gneiss you may observe continuous increasing deformation of gneisses and micaschist.

The gneisses grade into mylonites with a close spacing of schistosity, a N trending stretching lineation and secondary grain size reduction (Fig. 31, 32 from de Roo, 1983).

Further reading: Frank et al., 1983; de Roo, 1983;

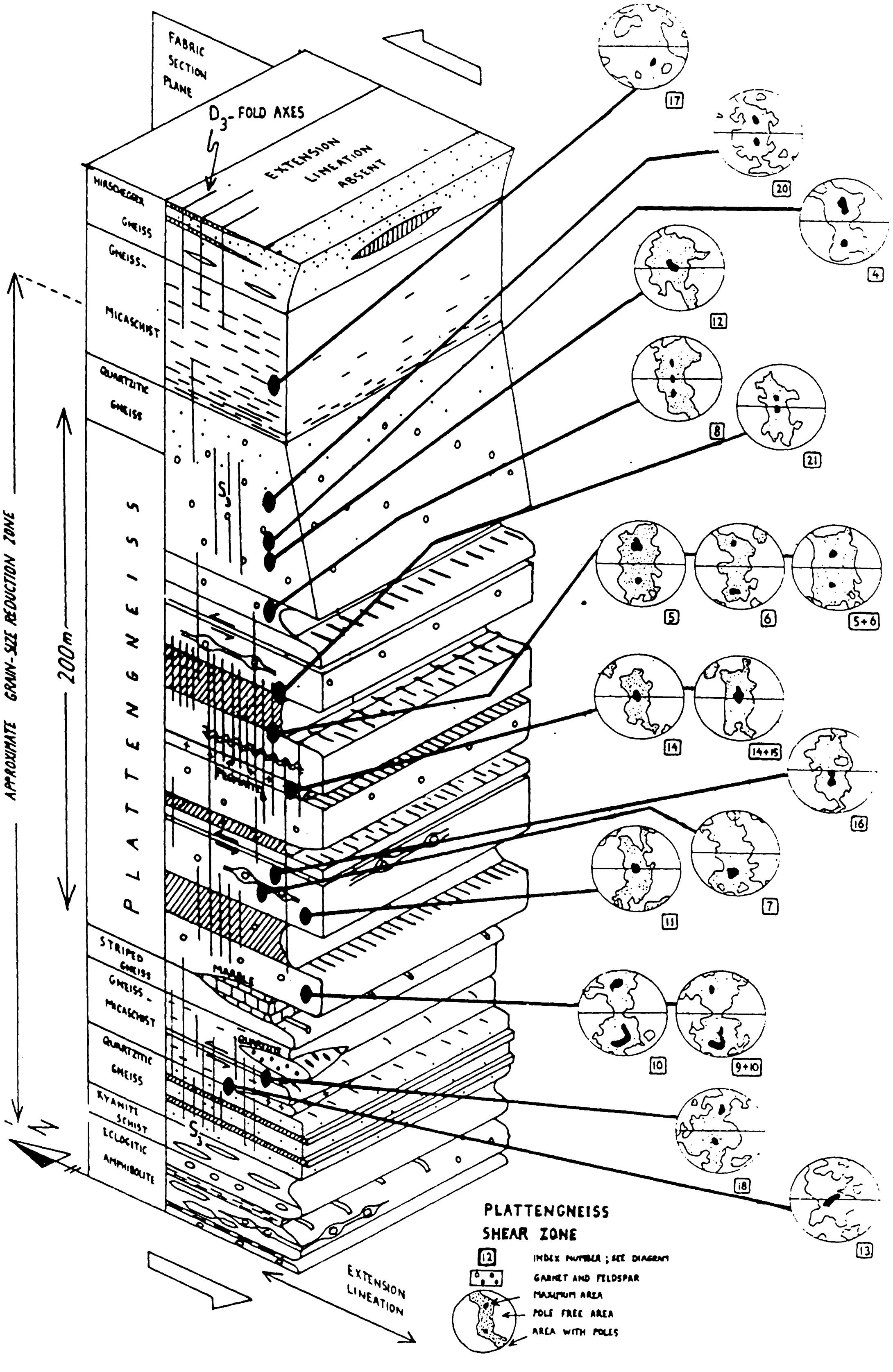


Fig. 31: Schematic structural section through the Platten gneiss of the Handalpe area (from de Roo, 1983).

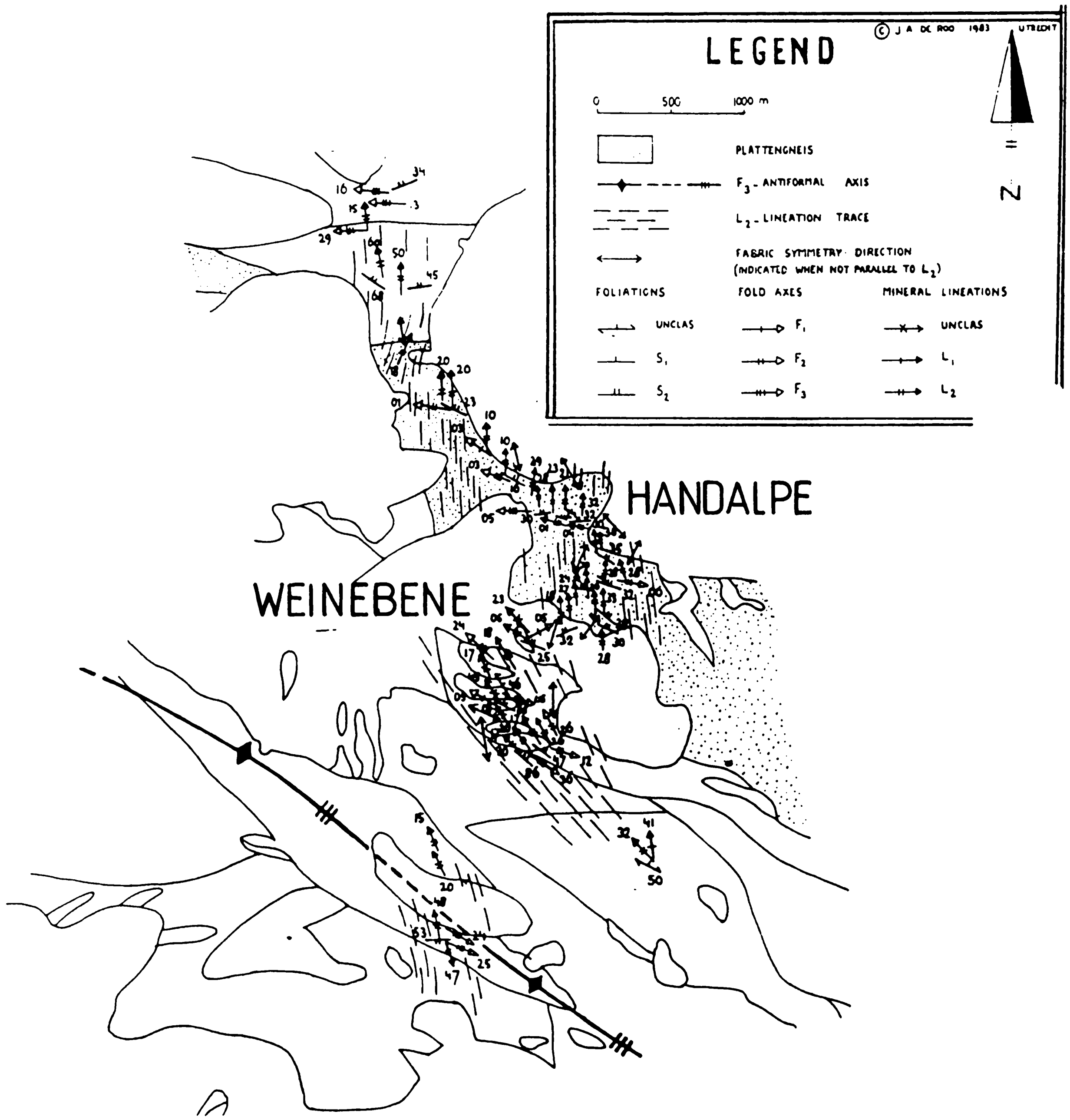


Fig. 32: Map of the Weinebene - Handalpe area with structural data (from de Roo, 1983).

Stop No. 25: Permian metagabbro and Alpine eclogites of the Koralm Gneiss Group.

M. THÖNI, F. NEUBAUER

Location: OEK 50, sheet 189, Deutschlandsberg. Follow from Schwanberg, central place to the left, the so-called Kalbenwaldstraße (Kalbenwald road) in direction to the Gregormichlalm up to the cross-road in the Goslitzgraben (already on OEK 50, sheet 188, Wolfsberg). Follow to the foot path to the South (five minutes to walk) which starts from the first forest road east of the Goslitzgraben. The Bärofen is a big exposure in an elevation of ca. 1170 m.

The outcrop exposes the largest metagabbro body in the Koralpe. The petrographic description follows a field guide of Miller (1985): The magmatic mineral assemblage is composed of plagioclase (An65), clinopyroxene (Wo45 En47 Fs8) with deformation- and orthopyroxene exsolution lamellae and of minor orthopyroxene (En77) (Miller 1985). At the pyroxene/plagioclase grain boundaries coronas consisting of pleonaste, orthopyroxene, clinopyroxene, cyanite have developed. In a later stage the plagioclase is replaced by a fine-grained aggregate of zoisite, kyanite, quartz and jadeite.

Pyroxene is pseudomorphed by rutile, omphacite and/or magnesiohornblende. Garnet (Pyr42Alm36Gross21Spess1) coronas develop between pyroxene and plagioclase. At the temperature o 630°C, the presence of jadeite would indicate a minimum pressure of 17 kb (Miller, 1985; 1990).

A Sm-Nd whole rock-plagioclase-pryoxene isochron gave an age of 275 +/- 18 Ma (Fig. 33) which is interpreted as the age of protolith formation (Thöni, 1990; Thöni and Jagoutz, 1991).

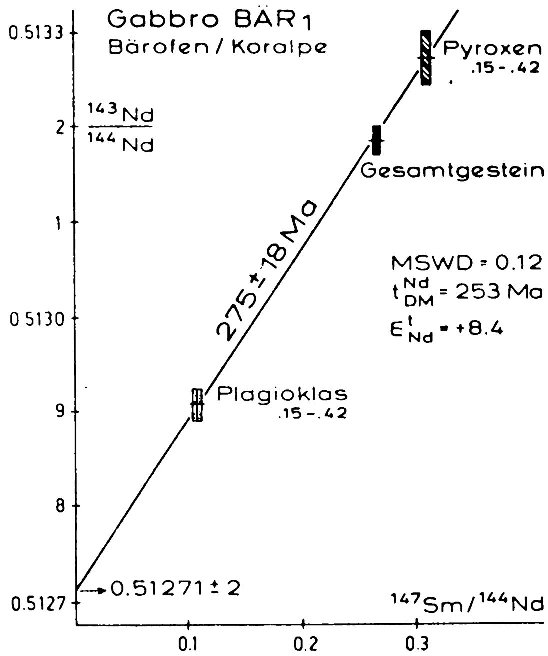


Fig. 33: Sm-Nd mineral isochron of the Bärofen metagabbro (Thöni, 1990).

Structural studies reveal a polyphase deformation history within eclogite stage of metamorphism. A first folation formed a boudin-like structure with metagabbro lenses which are surrounded by eclogite mylonites. These sometimes extremely fine-grained mylonites include a WNW trending mineral lineation with omphacitic clinopyroxenes. Local extensional crenulation cleavages (ecc) argue for a top to the ESE-shear. The eclogitic foliation is sometimes folded in recumbent, WNW-vergented folds which also include a c. two cm-spaced axial surface foliation.

Further reading: Miller, 1985; 1990; Neubauer, 1991; Thöni, 1990; Thöni and Jagoutz, 1991.

Stop No. 26: Platten gneiss (Stainz gneiss) of the Koralm Gneiss Group.

W. FRANK, F. NEUBAUER

Location: OEK 50, sheet 189, Deutschlandsberg. From the town Stainz follow the road in direction to Wald (in the Stainzbach valley). In the village Wald turn to the S in direction Angenofen, follow always right-hand roads, finally the "Buchwald road" (not accessible to big busses. The quarry is at the termination of this road along the Rainbach in an elevation of 540 m.

The quarry exposes the typical, fine-grained mylonitic Platten gneiss with a flat-lying lineation and a N-trending stretching lineation. The Platten gneiss is composed of quartz, feldspar (K-feldspar and plagioclase, muscovite, biotite and kyanite. Feldspar is completely recrystallized during deformation, quartz displays momomineralic layers with quartz shapes similar to those of granulites. Quartz textures the Platten gneiss are dominated by oblique girdles with preferred rhomb planes (Frank et al., 1983). L.P.O. suggest top N displacement (Fig. 34). Wimmer-Frey (1984) found uniform metamorphic equilibrium conditions of ca. 600°C and 10 - 14 kb.

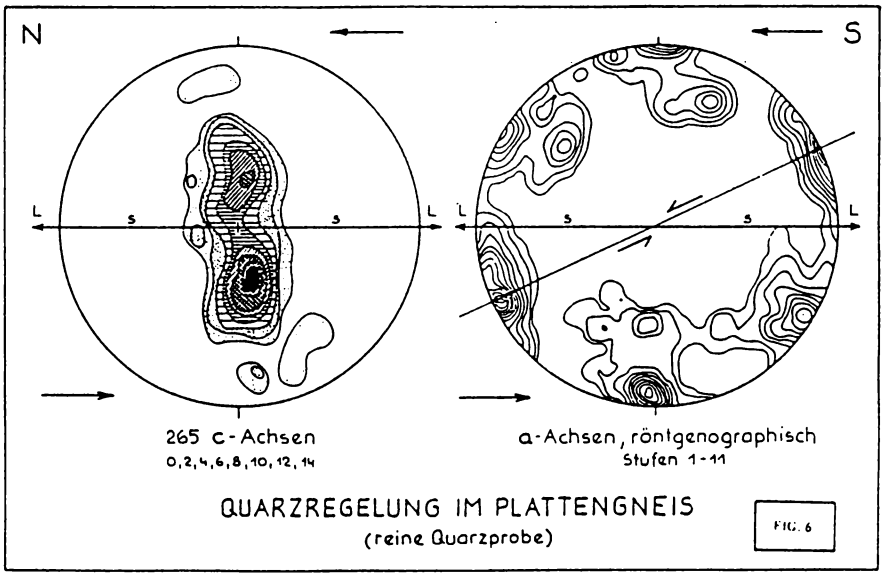


Fig. 34: Typical quartz c-axis pattern and X-ray a-axis pattern of the Platten gneiss (from Frank et al., 1983).

A Rb-Sr thin-slab isochron yielded an errorchrone with 249 6 Ma (Fig. 35). The errorchrone is interpreted to result from incomplete isotopic homogenization during Alpine deformation due to lack of fluids (Frank et al., 1983).

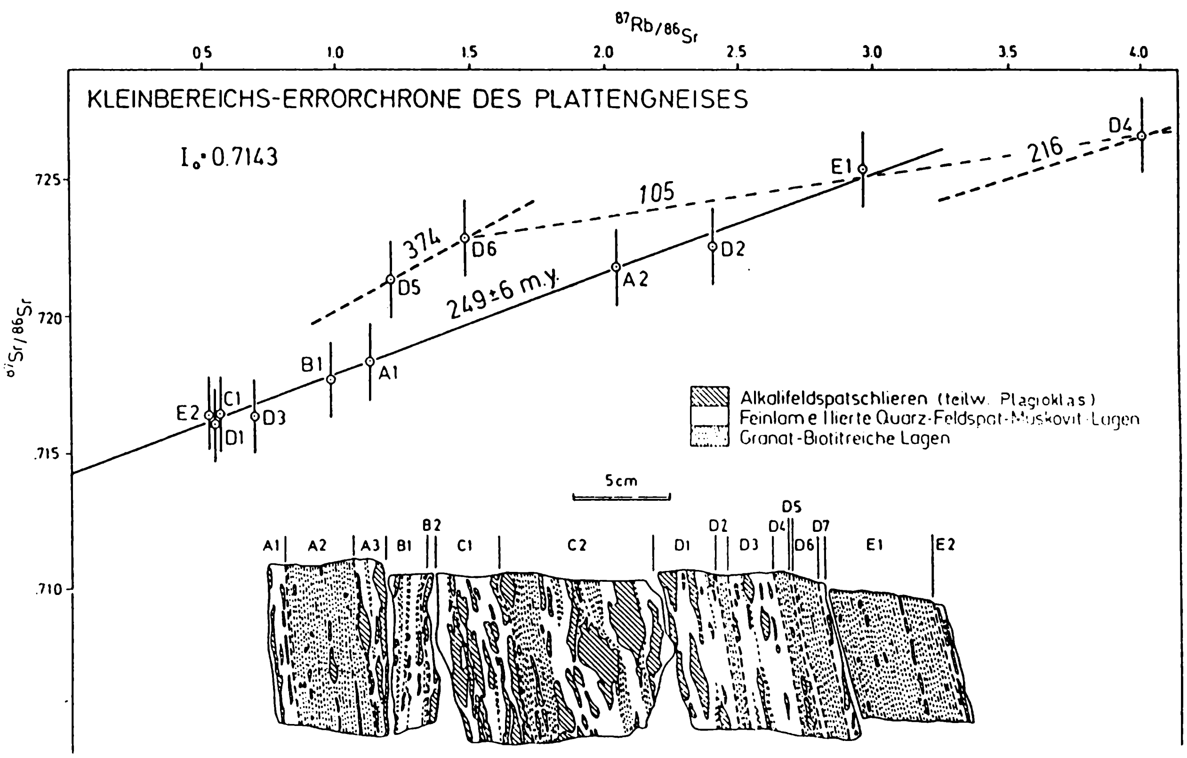


Fig. 35: Rb-Sr errorchron of the Stainz Platten gneiss of the Wald quarry.

Further reading: Frank et al., 1983, Krohe, 1986; Wimmer-Frey, 1984.

Stop No. 27: Middle Miocene shoshonite and sedimentary cover.

F. EBNER, J. FRIEBE

Location: OEK 50, sheet 190, Leibnitz. "Basalt"(= shoshonite) quarry Weitendorf (Fig. 36, 37).

Stratigraphic units: Shoshonite of Weitendorf/Wundschuh, Weißenegg Formation (both Lower Badenian: Upper Lagenid Zone)

The quarry of Weitendorf is located on the southern margin of the volcanic area of Weitendorf/Wundschuh. There an appr. 50 meter thick lava flow overlays sandy marls of Lower Badenian age (Upper Lagenid Zone) with an abundant mollusc fauna. A slab of these basal sediments (1 - 2 m x 25 - 30 m) was sheared off and incorporated into the lava flow. The margins of the slab, which is internally deformed, are altered thermally.

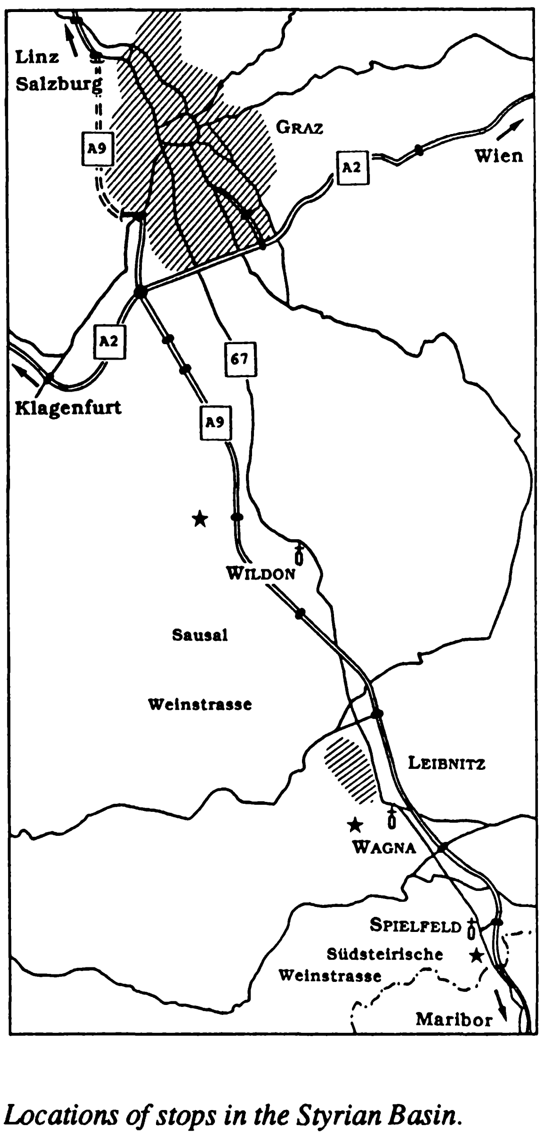


Fig. 36: Locations of stops in the Styrian Basin.

The shoshonite was dated with 16.0 +/- 0.3 Ma (upper level) to 16.8 +/- 0.75 Ma (base of the quarry) by Steininger and Badgasarjan (1977) and 15.2 +/- 0.8 Ma by Lippolt et al. (1975), respectively (K/Ar whole rock). As the first occurrence of the foraminifer *Orbulina suturalis* BROENNIMANN (= base of plankton zone N9), which is found in the sediments beneath the lava flow, was dated with approximately 15.2 Ma in the Mediterranean, the latter analysis seems more reliable.

The shoshonite shows a trachytic or prismatic - granular matrix with a main mineral component of plagioclase - labrador, olivine, augit, hypersthene, and accessoric magnetite. Olivine displays indications of alterations to iddingsite. The chemical characteristics of the Shoshonite are listed in Tab. 1.

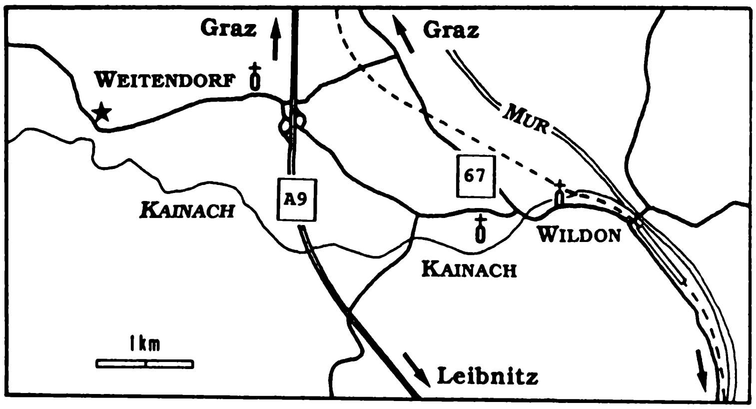


Fig. 37: Location of Weitendorf Quarry.

Gew.-%		Norm				
SiO_2	54,1	qz	5,2			
TiO_2	0,8	or	16,6	Sanidin	26,9	(40% ab)
Al_2O_3	19,5	ab	25,4			
Fe_2O_3	0,56	an	19,4	Plagioklas	34,5	(55% an)
FeO	4,8	hy	22,6			
MnO	0,16	il	1,5			
MgO	6,1	mt	0,8			
CaO	6,2	ap	0,9			
Na_2O	3,0	cc	3,2			
K_2O	2,8	c	4,4			
P_2O_5	0,38					
CO_2	1,4					
H_2O+	0,5					
	100,3					

Tab. 1: Chemical characteristics of the Weitendorf Shoshonite (from Heritsch, 1967).

The lava flow is covered by Tertiary siliciclastics of unknown age. The coarsening- and shallowing-upward profile (Fig. 38) reflects the transition from an open marine environment to shallow sand bars and a sheltered bay or lagoon.

Further reading: Krainer, 1987 (and references cited therein)

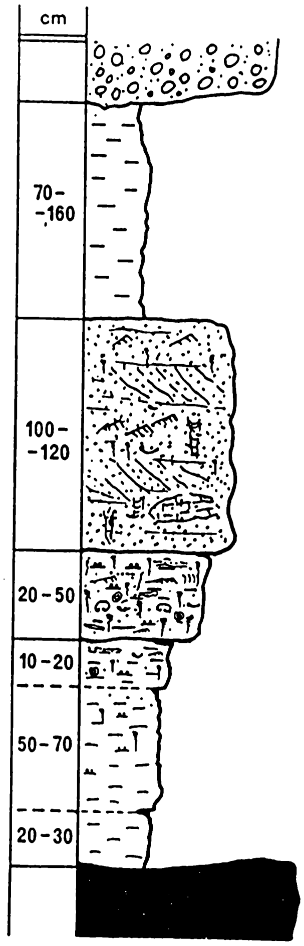


Fig. 38: Stratal characteristics of the Badenian sedimentary cover of the Weitendorf Quarry (from Krainer, 1987).

Stop No. 28: The Styrian angular unconformity.

J. FRIEBE

Location: OEK 50, sheet 190, Leibnitz. Abandoned clay pit, Wagna near Leibnitz (Fig. 39).

Stratigraphic units: Steirischer Schlier (Karpatian), Weißenegg Formation (Uppermost Karpatian, Badenian)

The abandoned clay pit of Wagna is nowadays considered the type locality of the Styrian unconformity. The Karpatian "Steirische Schlier" forms the main portion of the outcrop. It consists of thinly bedded siltstones to fine-grained sandstones with rarely turbiditic layers. Macrofossils (e.g. sea-urchins) are scarce. The locally abundant Karpatian foraminiferal fauna (e.g. *Pullenia bulloides* (d'ORBIGNY), *Gyroidinoides soldanii* (d'ORBIGNY), *Uvigerina graciliformis* PAPP and TURNOVSKY, and others) suggests a water depth of at least 100 meters. Dip of strata is 20° to 25° to the southeast (azimuth 115° to 125°).

The "Steirische Schlier" is overlain unconformably by massive to laminated (marly) siltstones which were deposited in a subtidal to intertidal environment. The shallow dip towards the south is caused by an erosional relief. Nannoplankton biostratigraphy and magnetostratigraphy date these sediments as uppermost Karpatian (nannoplankton zone NN4; J. Auer, Vienna, pers. comm. 1990). With the beginning of the Badenian a small carbonate platform (coralline algal limestone: Leithakalk) developed north of the patch reef of Retznei (Piller et al., 1991). At that time water depth was less than 10 meters.

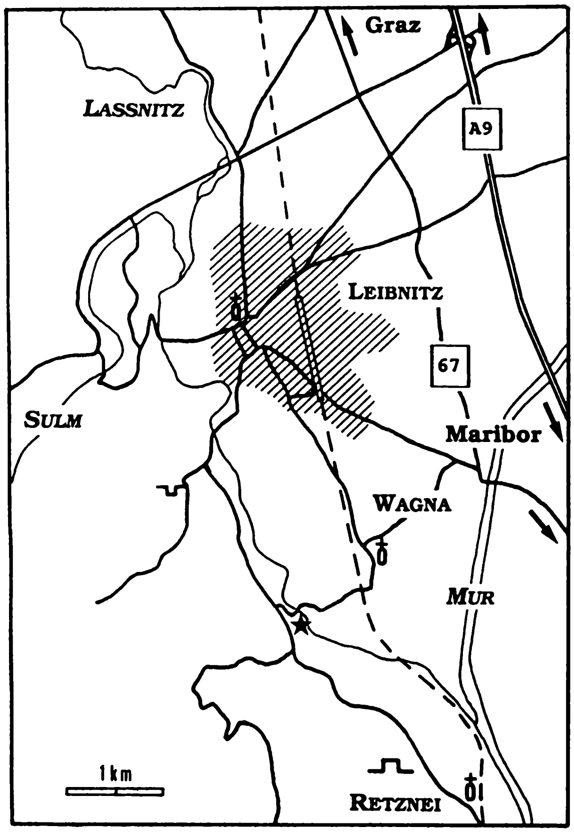


Fig. 39: Location of the clay pit of Wagna. The locations of the Retznei Quarry and the abandoned Tittenbacher Quarry (see Piller et al., 1991) are also indicated.

Block tilting within the escaping crustal wedge in the upper Karpatian caused the rapid uplift, tilting, and subsequent erosion of the "Steirische Schlier" as well as the Sausal mountains (which formed islands during the Badenian). Thus the "Mittelsteirische Schwelle" became a major morphological element in the Styrian Basin which controlled Badenian sedimentation. These tectonic processes coincided with an eustatic sea-level lowstand. The Lower Badenian transgression provided the environment for rhodolith growth and patch reef development. In terms of sequence stratigraphy (van Wagoner et al., 1988) the Styrian unconformity resembles a tectonically enhanced sequence boundary.

Further reading: Friebe, 1991 (and references cited therein).

Stop No. 29: The Styrian angular unconformity.

J. FRIEBE

Location: OEK 50, sheet 208, Mureck. Katzengraben near Spielfeld (Fig. 40).

Stratigraphic units: Steirischer Schlier (Karpatian), Weißenegg Formation (Uppermost Karpatian, Badenian)

The Styrian unconformity is excellently exposed in an artificial outcrop. Together with the foraminiferal fauna turbiditic layers within the "Steirische Schlier" indicate a depositional water depth beneath storm wave base. Small normal faults within these deposits (offset: a few centimeters), which are sealed by younger sediments, indicate east-west-extension. The "Steirische Schlier", which dips

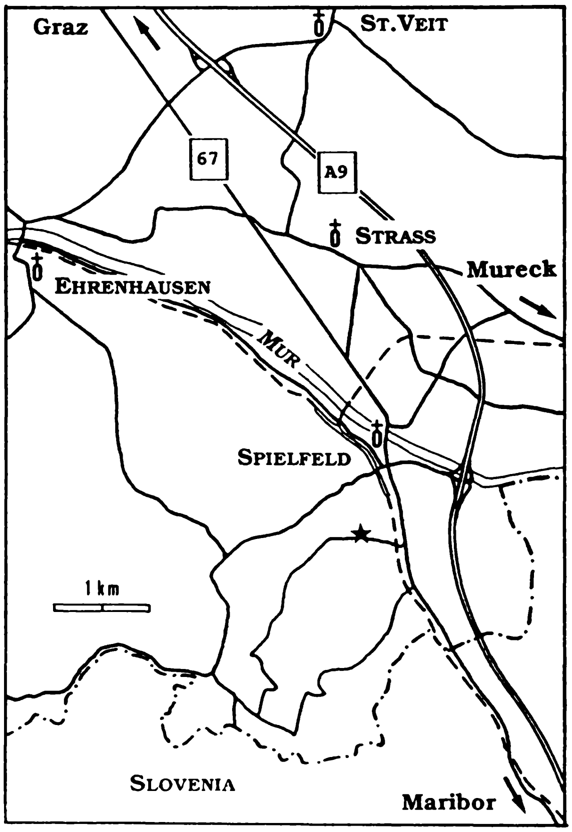


Fig. 40: Location of the Katzengraben outcrop.

approxumately 20° to the NNE (azimuth: 10° to 20°), is unconformably overlain by a thin reworking horizon. Pebbles of reworked Schlier are often bored. This horizon contains scarce fossil debris and (macro-) fossils (e.g. oysters, sea-urchins, etc.). Accumulations of coarse gravel on top of the bed are interpreted as transgressive lag. High terrigenous input inhibited the development of a carbonate platform during the Lower Badenian. Instead massive, medium to coarse-grained sand bars of shoreface origin were deposited. Distinct layers with well cemented nodules, which probably represent the first stage in hardground formation, record minor transgressive pulses.

Further reading: Friebe, 1991 (and references cited therein).

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EXCURSION TO THE EASTERN CENTRAL ALPS: DESCRIPTIONS OF STOPS

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Introduction

The excursion provides an overview about lithologies of various units of the Austro-Alpine basement as well as of its Permo-Mesozoic cover sequences. Most introductory notes are given in separate contributions within this volume (Dallmeyer et al., Dunkl, Fritz et al., Hubmann, Neubauer and Frisch, Neubauer et al.). The excursion starts with the Graz Nappe Complex looking for Silurian/Carboniferous geodynamics and Cretaceous imbrication. It continues with pre-Variscan, Variscan and Alpine geodynamic aspects of the Gleinalm area. Next stops provide an overview about recent results of the Greywacke zone, especially concerning contrasting Silurian/Devonian geodynamic histories of the Kaintaleck Complex. Then excursion turns to the Variscan plutonic/migmatitic area of the Raabalpen Unit, continues with the very recent results of the Wechsel Unit (evidence of Late Devonian cooling after a major tectonothermal event). Climbing higher in the Austro-Alpine nappe pile the Sieggraben Unit will be discussed with results which apparently proof Alpine eclogite metamorphism. Finally, the excursion visit the Penninic Windows at the eastern margin of the Eastern Alps with the Tertiary metamorphism and cooling including ductile normal faulting during exhumation of these units.

Stop No. 1: Upper part of the Barrandei Limestone Formation, Graz Thrust Complex.

B. HUBMANN

Location: OEK 50, sheet 163, Voitsberg. Section along the forest road "Attems" (Frauenkogel NW Graz). See Fig. 1.

The "Barrandei Limestone Formation" represents a highly fossiliferous sequence whose boundaries are not clearly identificable till now. Locally the sequence may range from Upper Emsian to Lower Givetian. Generally, four types of microfacies and thirteen types of submicrofacies have

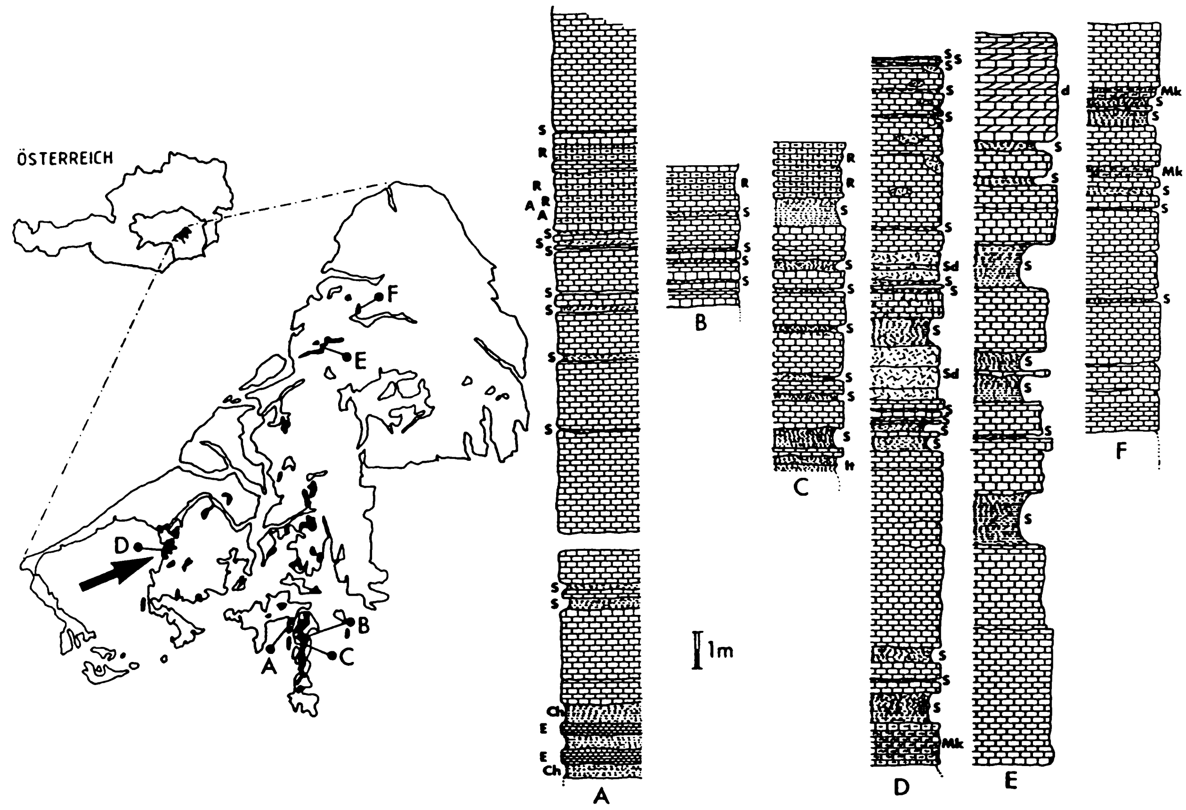


Fig.1: Outcrops of Barrandei Limestones (black coloured) in the Palaeozoic of Graz and sections of this formation. Note the location of the stop no. 1, road Attems (A), and of stop no. 2, St. Pankrazen Road Section (arrow, D).

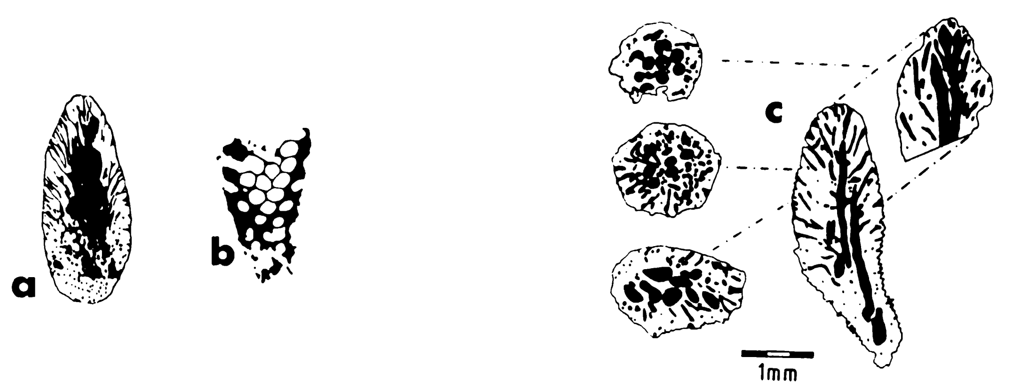


Fig. 2: Udoteaceae from the Stop No. 1.

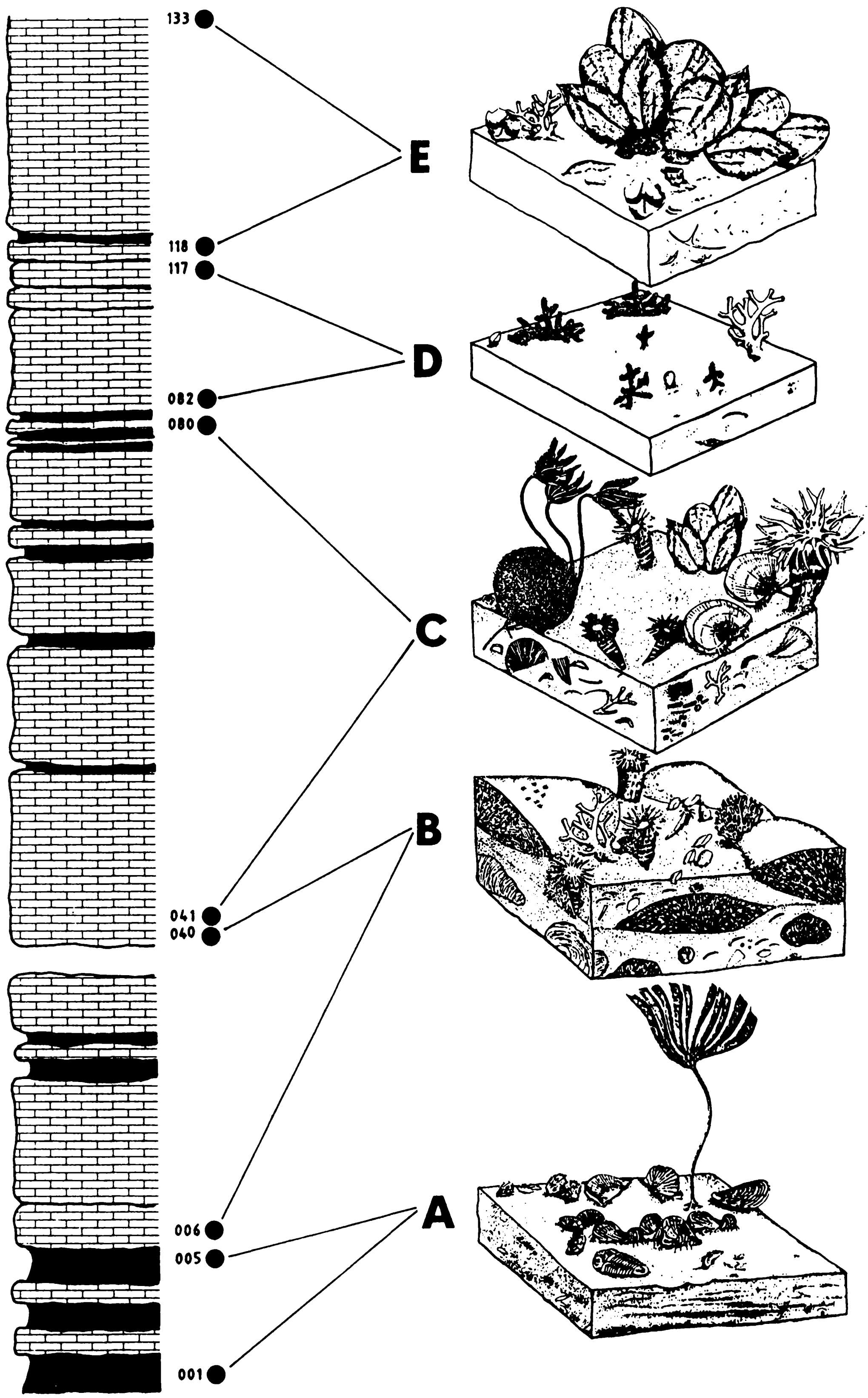


Fig. 3: Biofacies types from the Barrandei Limestone.

been recognized. The comparison of Wilson`s types of microfacies with the Barrandei Limestone sequence suggests that this limestone was deposited in restricted (lagoonal), semirestricted and open platform environments and on the platform margin and foreslope.

The exposure contains the oldest representatives of Udoteacean Green Algae known from the Eastern Alps which were recently described from this outcrop (Hubmann, 1990b): *Litanaia graecensis* and *Pseudopalaeoporella lummatonensis* (Fig.2). The occurrence of calcified green algae in the Middle Devonian of Graz is of major importance, because they allow a more accurate analysis of the depositional environment than the (partially endemic) fauna.

Special data: The whole section may be roughly subdivided into 5 biofacial parts (Fig.3):
a) Siliciclastic Brachiopod-Trilobite-Biofacies ("Chonetenschiefer") with: *Chonetes sp., Maladaia sp.,* and *Crinoids*;
b) Coral-Stromatoporoid-Biofacies with: *Actinostroma sp., Thamnophyllum stachei, Thamnophyllum murchisoni, Favosites styriacus, Thamnopora sp., Striatopora sp., Heliolites cf. barrandei, Heliolites cf. peneckei, Crinoids*;
c) Coral-Brachiopod-Biofacies with *Thamnophyllum stachei, Thamnophyllum murchisoni, Thamnopora reticulata ?, Thamnopora sp., Striatopora (?) suessi, Favosites sp., Chonetes sp., "Spiriferids", Crinoids*;
d) Algae-Biofacies with *Pseudopalaeoporella lummatonensis, Litanaia graecensis*;
e) Brachiopod-Coral-Biofacies with: *Zdimir cf. hercynicus, Thamnopora cf. reticulata, Striatopora (?) suessi.*

As the intensity of the light which is necessary for photosynthesis decreases with increasing water depth, green algae are almost all restricted to the uppermost 40 to 0 meters. Also distribution is determined by physical and chemical factors, that is to say water temperature, hydrodynamical conditions, geometrical shape of the niche, salinity, etc. Recent benthonic calcareous green algae usually display their greatest diversity of individuals in shallow water of a few meters and are regarded as facies indicators of warm water regions proximity to the coast.

Taking into account these ecological factors, beds of this section containing autochthonous green algae represent environmental conditions mentioned above. The interesting fact of the occurrences of algae is that they are intercalated in some more or less isolated patches (niches) within slates or marly limestones, suggestive calmy conditions of sedimentary patterns of the siliciclasic-rich beds. Layers of slates are no products of a short-term sediment accumulation, e.g. caused by current events but they represent the hydrodynamic "low energy (background-) sedimentation".

Stop No. 2: Platform carbonates of the Rannach Group: Dolomitsandstein Fm., Barrandei Limestone and Platzkogel Limestone.

B. HUBMANN

Location: OEK 50, sheet 163, Voitsberg. Road section south to St. St. Pankrazen (Fig. 4).

In this section the following types of microfacies can be recognized (Fig. 5):
a) Low energy mudfacies, subdevided into the following types of submicrofacies:
(1) Mudstone-subfacies
(2) Calcispheres-wackestone-subfacies
(3) Gastropodes-pellet-wacke-to grainstone-subfacies
b) Higher energy mudfacies, subdivided into
(4) Crinoidal-Brachiopodes-wacke-to grainstone subfacies
(5) Amphipora-Thamnopora-floatstone subfacies
(6) Coral-Stromatoporoid-subfacies
(7) Brachiopod-coral-subfacies
c) High energy detrital facies, with the subfacies types
(8) Silty pellet-subfacies
(9) Eventstone (Tempestite)-subfacies

These types of microfacies (submicrofacies, respectively) and their connections to Wilsons`s standard microfacies types are demonstrated in Figure 5.

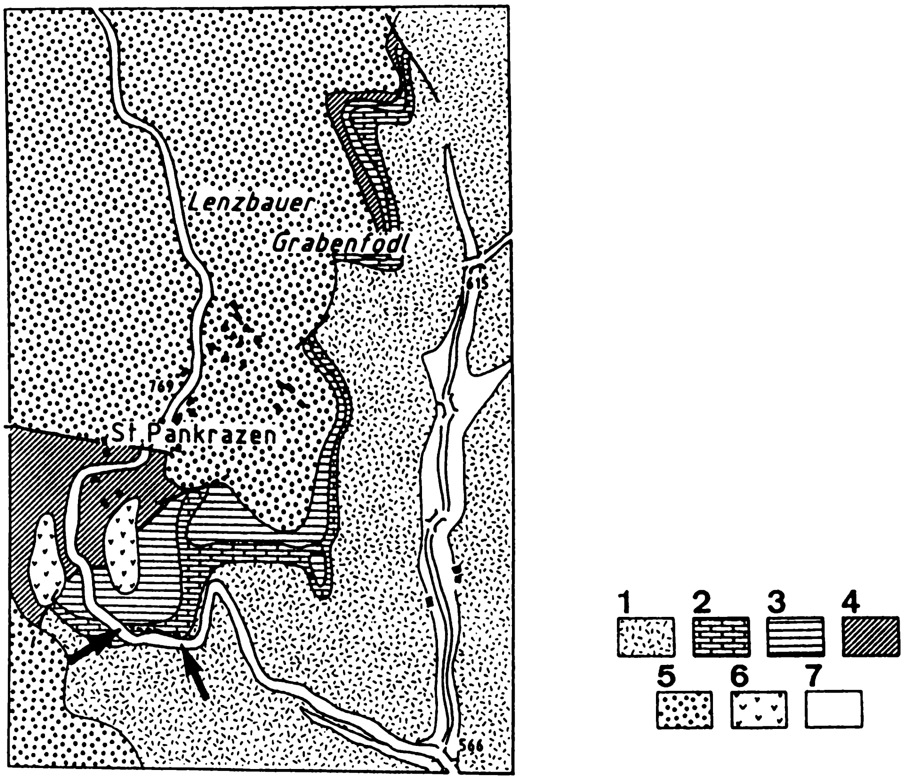


Fig. 4: Geological map of the St. Pankrazen area. 1 - Dolomitsandstein Fm.; 2 - Barrandei Limestone; 3 - "Middle Devonian Dolomite"; 4 - Platzlkogel Limestone; 5 - Gosau of Kainach; 6 - Debris; 7 - Alluvions.

Paleontological survey: Exept of crinoidal ossicles the majority of the fossil content is composed of Brachiopodes (*Zdimir cf. hercynicus* and others), tabulate and rugose corals (*Thamnopora retic ulata, Striatopora suessi, Favosites styriacus, Favosites cf. radiciformis, Thamnophyllum stachei*) and Stromatoporoids (*Actinostroma sp.,. Amphipora sp. and Stachyodes sp.*). For distributional patterns of the biota, see Fig. 7.

Paleoecological characteristics: Distributional patterns and growth habits that is to say skeletal morphology and shape of colonies, especially of stromatoporoids and tabulate corals (favositids), and special compositions of the faunal content (e.g. Thamnopora-Amphipora-associations) indicate typical back reef biocoenoses.

Geochemical data: Geochemical trace element concentrations (Fig. 8) support the sedimentological and paleoecological evidence of the depositional environment. Especially the low content of Manganese may be interpreted as a reference to shallow water environments relatively near the coast. High concentrations of Strontium in the lower part of the section indicate rapid deposition and diagenesis in a closed system afterwards.

Sedimentological features: Deposition of higher energy mud facies is predominant. There are also characteristic sequences with a "muddying-upward-trend" which indicates storm-generated sedimentation ("tempestites"). The introduction of large amounts of fine grained siliciclastic material into the system is a cyclic event that accounts for the alternating deposition of limestones, marls and shales and for the highly variable amounts of acid-insoluble residue in the limestone sequence itself. This fact is clearly demonstrated in a diagram, which shows the absolute insoluble residue content versus the thickness of the bedding (Fig. 8). It is open to question that the cycles with higher absolute contents of acid-insoluble residues (A to E) are related to contemporaneous ("sequence stratigraphical") eustatic fluctuations (transgressions and regressions)known from the Rhenish Slate Mountains.

Further reading: Hubmann 1990a,b, 1991.

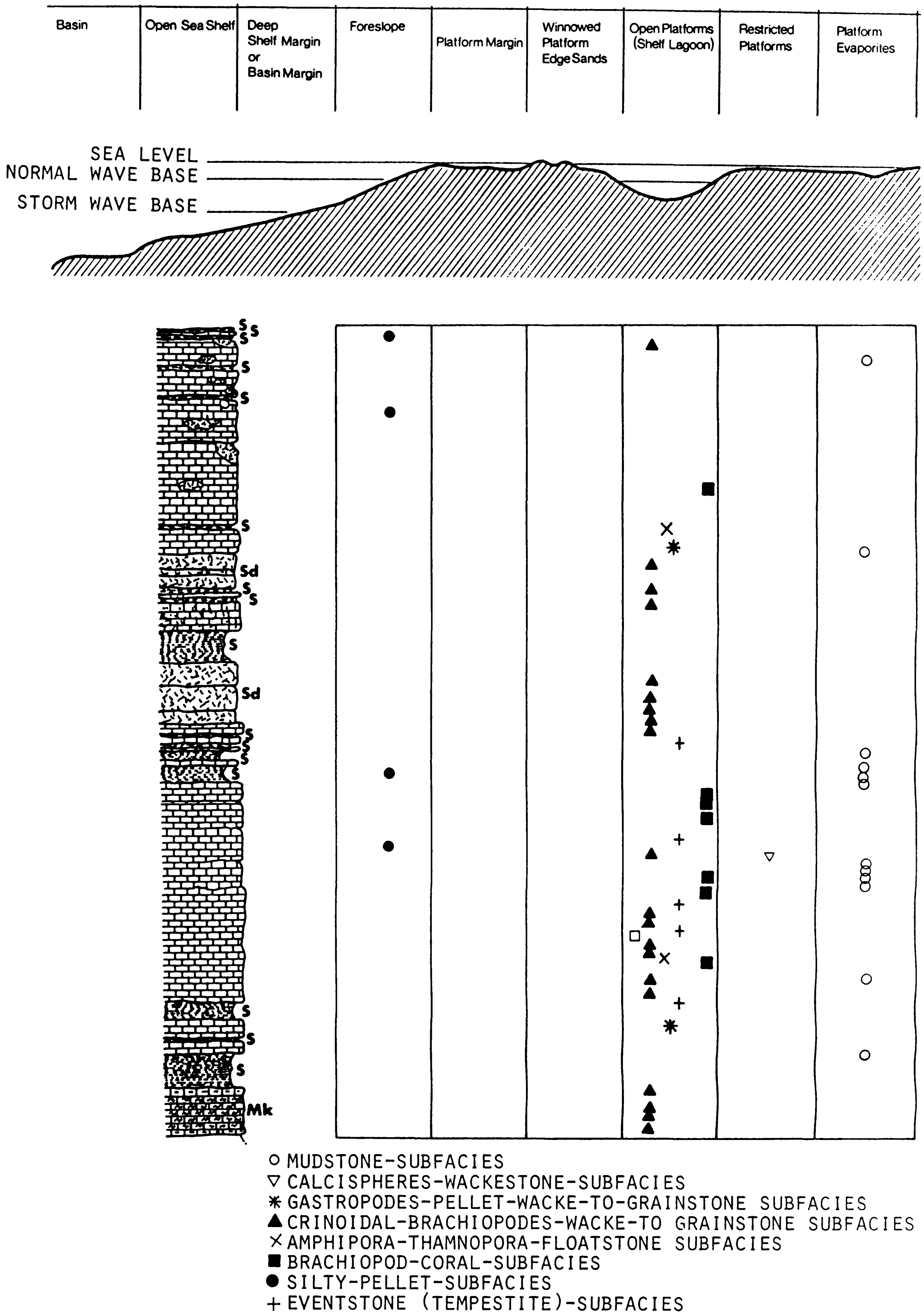


Fig. 5: Microfacies types of the St. Pankrazen section.

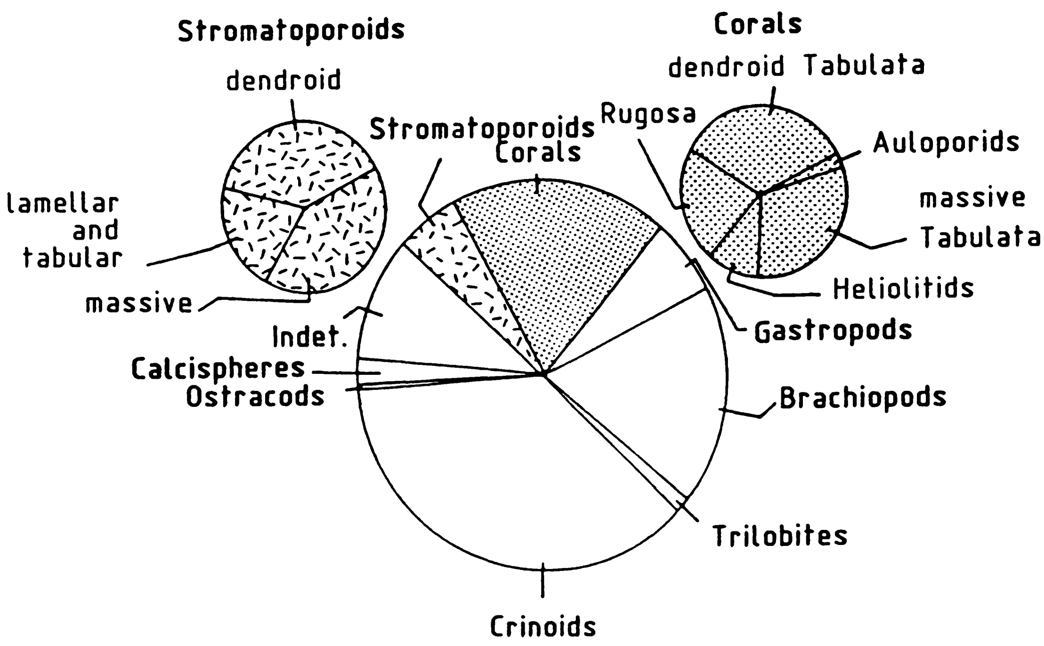


Fig. 6: Distributional patterns of fossils.

A															
B	2														
C	-	1													
D	1	2	2												
E	1	6	2	1											
F	2	7	3	2	15										
G	2	3	1	1	4	6									
H	1	2	2	4	2	5	1								
I	1	1	-	1	-	1	1	2							
J	4	8	4	2	11	14	4	3	2						
K	2	8	5	2	17	21	5	3	-	23					
L	-	-	1	-	1	1	1	-	-	2	2				
M	4	11	6	5	17	24	6	9	3	29	37	6			
N	-	-	-	-	-	1	-	-	-	1	2	-	1		
O	-	3	-	-	4	7	1	1	-	8	8	1	12	1	
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O

A...ALGAE
B...DENDROID STROMATOPOROIDS
C...LAMELLAR AND TABULAR STROMATOPOROIDS
D...MASSIVE STROMATOPOROIDS
E...RUGOSE CORALS
F...DENDROID TABULATE CORALS
G...AULOPORIDS
H...MASSIVE TABULATE CORALS
I...HELIOLITIDS
J...GASTROPODS
K...BRACHIOPODS
L...TRILOBITES
M...CRINOIDS
N...OSTRACODS
O...CALCISPHERES

Fig. 7: Frequency of common faunal elements.

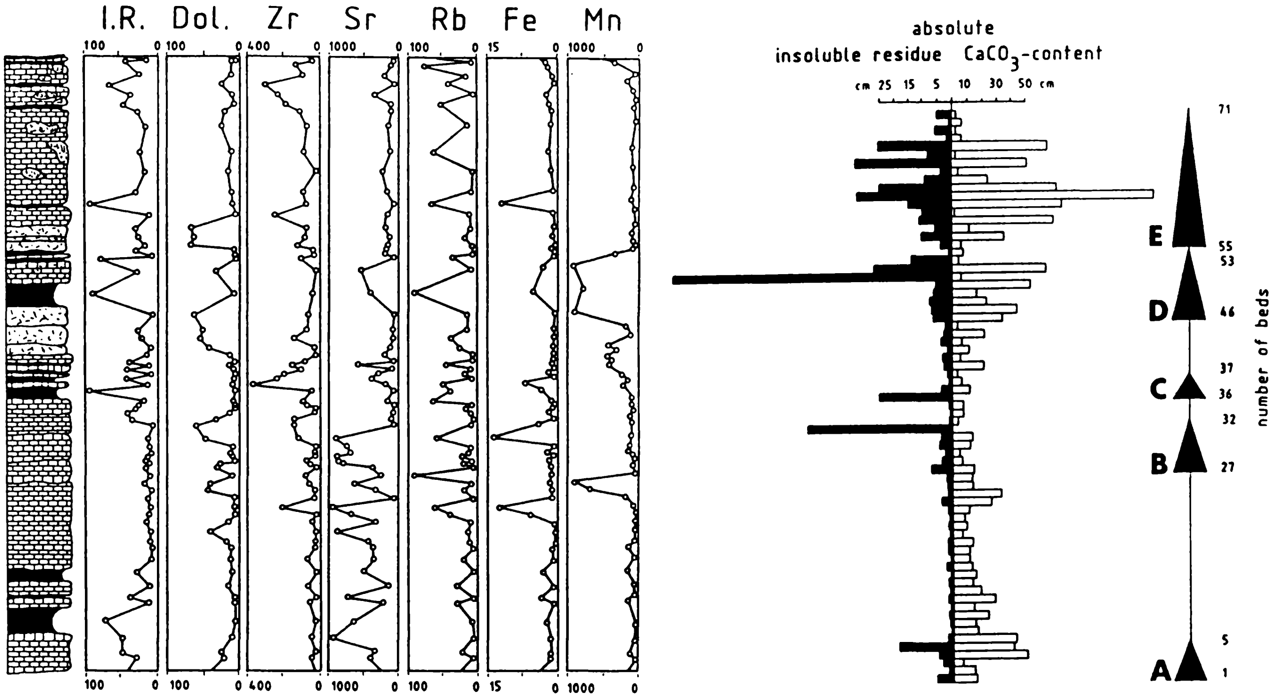


Fig .8: Distribution of geochemical trace elements. Concentrations in ppm; Fe-content (Fe2O3) in %; I.R. - insoluble residue in %; Dol. - portion of dolomite. Absolute contents of insoluble residues and absolute CaCO3-content of the section.

Stop No. 3: Middle Devonian to Late Carboniferous succession of the Rannach Group.

F. EBNER

Location: OEK 50, sheet 164, Graz. Follow the road from Graz, east of the Mur river, in direction to Gratkorn. Ca. 300 m after passing the bridge of the highway road in direction to Hartbauer. Parking place at the beginning of the road.

The Late Devonian to Late Carboniferous evolution of the Rannach Group is demonstrated in the Hartbauer section in an impressive way. The small thickness of ca. 45 - 50 m ranging from the top of the Kanzel Limestone (boundary from Middle to Late Devonian) to the Dult Fm. (Namurian B to ?Westfalian A) is the product of both very low pelagic sedimentation rate (micritic limestones rich in conodonts and cephalopodes) and stratigraphic gaps. The gaps are located between the Late Devonian *Marginifera* zone of the Steinberg Limestone and the Upper Sanzenkogel Formation starting within the *Scaliognathus anchoralis* zone (uppermost Tournaisean). A second gap is situated between the top of the Sanzenkogel Fm. and the Dult Fm.

Fillings of karst fissures with conodont mixed faunas (stratigraphic leaks) are going down to the Middle/Upper Devonian boundary (lithological boundary between the massive, grey shallow water Kanzel Limestone and the yellowish/brownish pelagic Steinberg Limestone). Unfortunately, the fillings are hardly to recognize in the field in account of vegetation and Quaternary cover. As the composition of the mixed faunas of the karst fissures and of a few cm thick level at the base of the Sanzelkogen Formation is the same and conodonts representing the time span of the gap are missing, the sedimentary break can be interpreted as follows:

* After pelagic sedimentation of the Steinberg Limestone the environment became terrestrial by synsedimentary tectonics and/or sea level fluctuations within the Famennian.

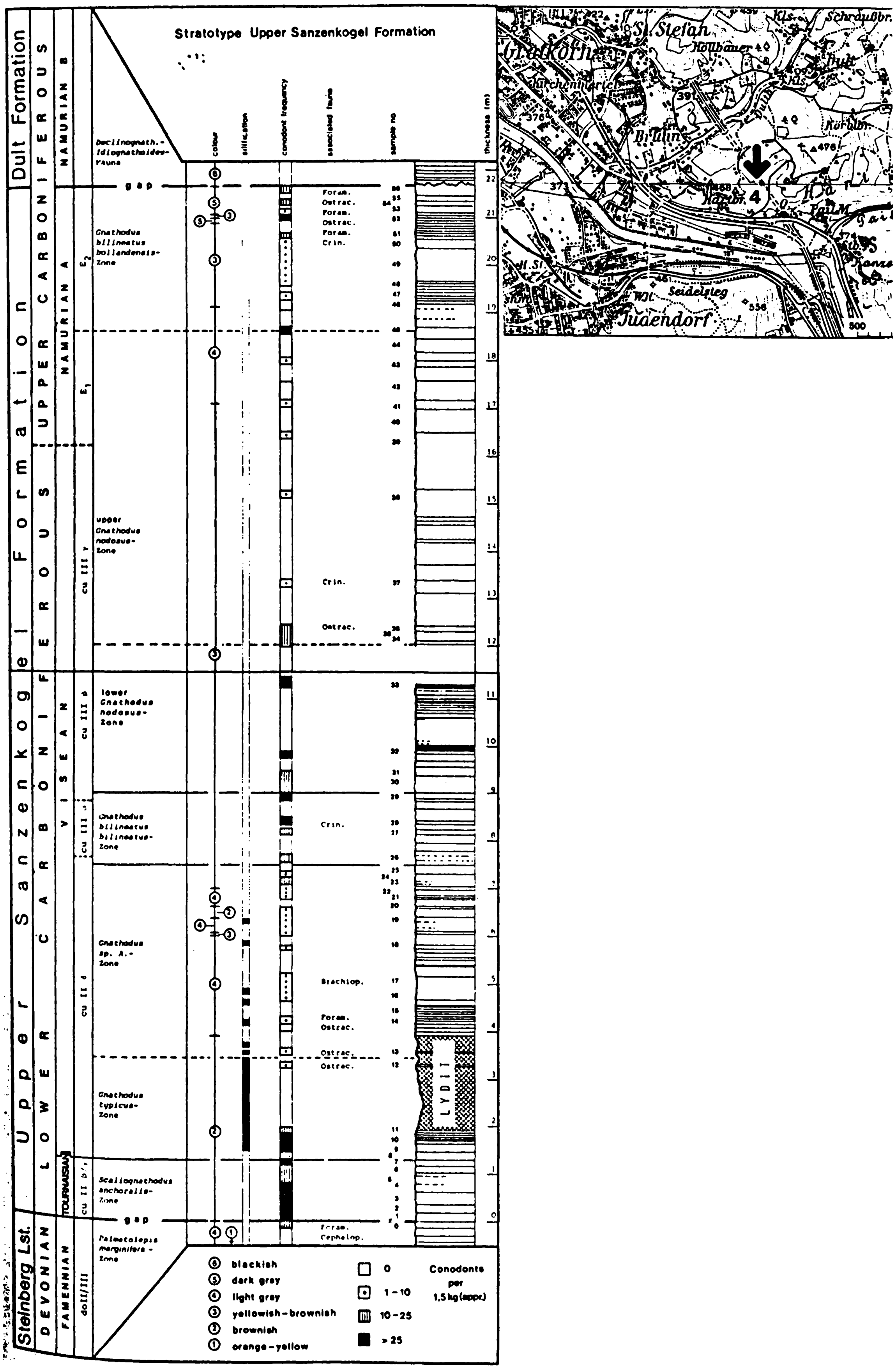


Fig. 9: Hartbauer section (modified from Ebner, 1980).

* Famennian - Tournaisean karstification produced karst fissures and residual sediments with isolated conodonts.
* In the uppermost Tournaisean a marine transgression closed the gap by the formation of conodont mixed faunas. These ones occur in a few cm thick microbreccia and fillings of the karst relief.

The sedimentary environment of the Upper Sanzenkogel-Fm. was similar to that of the Steinberg-Lmst. as demonstrated by microfacies and geochemical data. Intercalations of 200 cm thick bedded brown lydites within the *Scaliognathus anchoralis*-zone are the only break of the pelagic carbonatic sedimentation of the Upper Sanzenkogel-Fm. reaching up to *Gnathodus bilineatus bollandenis*-zone (Namurian A).

Together with continuous sections across the Devonian-Carboniferous boundary in the western parts of the Rannach group the Paleozoic of Graz offers an unique situation in the Eastern Alps to proof all conodont zones from Middle/Upper Devonian boundary to Namurian A (Ebner 1978, 1980).

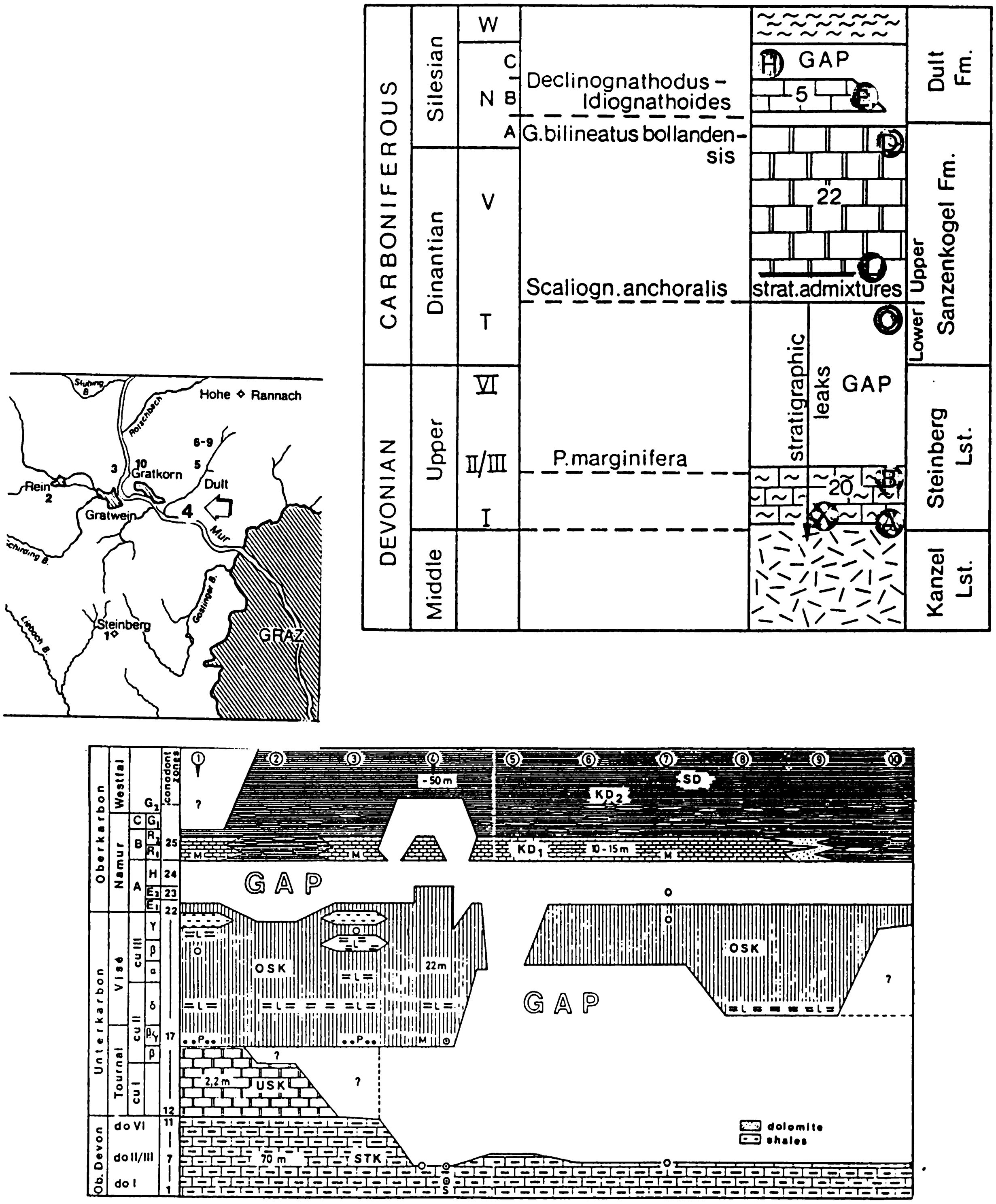
After a further erosional gap within the *Homoceras*-stage of Namurian A sedimentation started again with the Dult-Fm. (Namurian B; *Idiognathoides*-fauna; Ebner 1978). Dark limestones with conodont mixed faunas (stratigraphic admixtures) form the base. Following a few metres thick carbonate sedimentation is covered by hematitic crusts which point to a further intraformational erosional plane before sedimentation of the dark Dult Shales began.

Description of the outcrops: Red marks of capital letters indicate important positions of the section:
A: Boundary horizon Kanzel-Lmst./Steinberg-Lmst. Kanzel Lmst.: Grey massive shallow water limestones
X: Fillings of karst fissures with yellow-brownish reworked carbonatic materials or dark brown crinoidal limestones with upper Devonian/Lower Carboniferous conodont mixed faunas.
B: Top of Steinberg-Lmst. (*Marginifera*-zone).
C: Base of Sanzenkogel-Fm. (*Scaliognathus anchoralis*-zone) Sanzenkogel-Fm.: Different coloured and well bedded micritic limestones.
L: Lydites within the *Scaliognathus anchoralis*-zone.
D: Top of Sanzenkogel-Fm. (*Gnathodus bilineatus bollandensis*-zone, Namurian A).
E: Base of Dult-Fm. (*Idiognathoides* fauna, Namurian B) Dult-Lmst: Dark, ? shallow water limestones.
H: Pocket with hematitic crusts at the top of Dult-Lmst. followed by Dult-Shale.

1. Road section:
a) Kanzel-Lmst.
b) fissure fillings (X) with conodont mixed faunas
c) Steinberg-Lmst.
d) Gap between top of Steinberg-Lmst. (B) and Upper Sanzenkogelformation (C) with lyditic intercalations (L).

The contact between Steinberg-Lmst. and Sanzenkogel-Fm. is slightly tectonically disturbed. The hanging wall parts of the Sanzenkogel-Fm. are covered by Quarternary along the road section.

2. In the slope above A of the road section:
a) Top of Kanzel-Lmst.
b) Steinberg-Lmst.
c) fissure fillings with conodont mixed faunas (X)
d) boundary situation between top (B) of Steinberg-Lmst. (MARGINIFERA-zone) and base of Sanzenkogel-Fm. (C). The boundary plane was the erosional surface from which the karst-fissures went down to position A of the section.
e) above B/C type section of Upper Sanzenkogel-Fm. (Fig. 9): note the lydite intercalation approx. 2 m above B/C).
f) Top of Sanzenkogel-Fm. (D; Gnathodus *Bilineatus bollandensis*-zone (Namurian A), is formed by an erosional unconformity at the base of Dult-Fm.
g) Dark and sometimes laminated (recrystallized algal laminites) Dult Lmst. (Namurian B) with reworked limestone materials of the Sanzenkogel-Fm.
h) Top of the Dult-Lmst. with red, carbonatic-hematitic crusts at the base of the Dult-Shales.
i) Dark Dult-Shales.



Name of sections:

1 Steinberg area = type section of the Lower Sanzenkogel-Fm. (USK)
2 Eichkogel
3 Gratwein / Au
4 Hartboden = type section of the Upper Sanzenkogel-Fm. (OSK)
5 Dult monastery
6-9 Hahngraben area, Schraussberg
10 Hofgraben

Dult-Fm.: SD Dult shales
KD_1, KD_2 Dult limestones
Upper Sanzenkogel-Fm.: OSK, L lydites, P phosphoritic nodules
Lower Sanzenkogel-Fm.: USK
M formation age of conodont mixed faunas or fissure fillings
O components of conodont mixed fauna
. components of fissure fillings

Fig. 10: Stratigraphic scheme of the Late Devonian and Carboniferous of the Rannach facies.

Further reading: Ebner 1976, 1978.

Stop No. 4: Devonian sedimentation of the Schöckl Group and Early Alpine thrusting in the Graz Thrust Complex.

H. FRITZ

Location: ÖK 50, sheet 164, Graz. Artifical outcrop close to the south portal of the railway tunnel at the western flank of the Mur canyon north of Peggau (Fig. 11; 20 kilometer north of Graz). To reach the outcrop by car a bridge must be crossed which is limited to the weight of 10^4 kilogram.

A vertical section of about 80 meters shows a repetition of probable Middle Devonian limestones (Schöckl-Lmst.) on top of the section with Lower Devonian siliciclastics of the Arzberg-Fm. Drillings in the Mur valley penetrated again Schöckl-Lmst. and Arzberg-Fm. and proved tectonic stacking (Fig. 12). Vertical faults offset this section on northern and southern margins.

The Arzberg-Fm. exhibits sediments of anoxoic environment with episodical clastic input from a continental source. Typical are laminated black shales and phyllites accompanied by plenty of sulfide mineralisation, mostly pyrite and locally lead-zinc. The amount of graded silt- and sandstones as well as lenses of limestones and dolomites increases towards the top of the sequence. Rare occurrences of chlorite bearing phyllites point to weak volcanoclastic influence. Conodont findings in limestone lenses west of the described outcrop gave Lower Devonian age.

The Schöckl-Lmst. on top of the black shales and, with a tectonic contact, at their base is a very uniform rock type. Characteristic are mm-spaced banded limestones with dark silicate-rich layer and pure calcite layer.

Penetrative structures (D1) are a gently W-dipping mylonitic foliation and a very pronounced E-W oriented stretching lineation. Shear senses deduced from asymmetric pressure shadows around rigid objects and S-C fabrics gave uniform top-to-the W transport. Strain calculated from pressure shadows around pyrite varies from 200% to 1000% stretching, whereas maximum strain intensity has been found at the tectonic base of the Arzberg Fm.

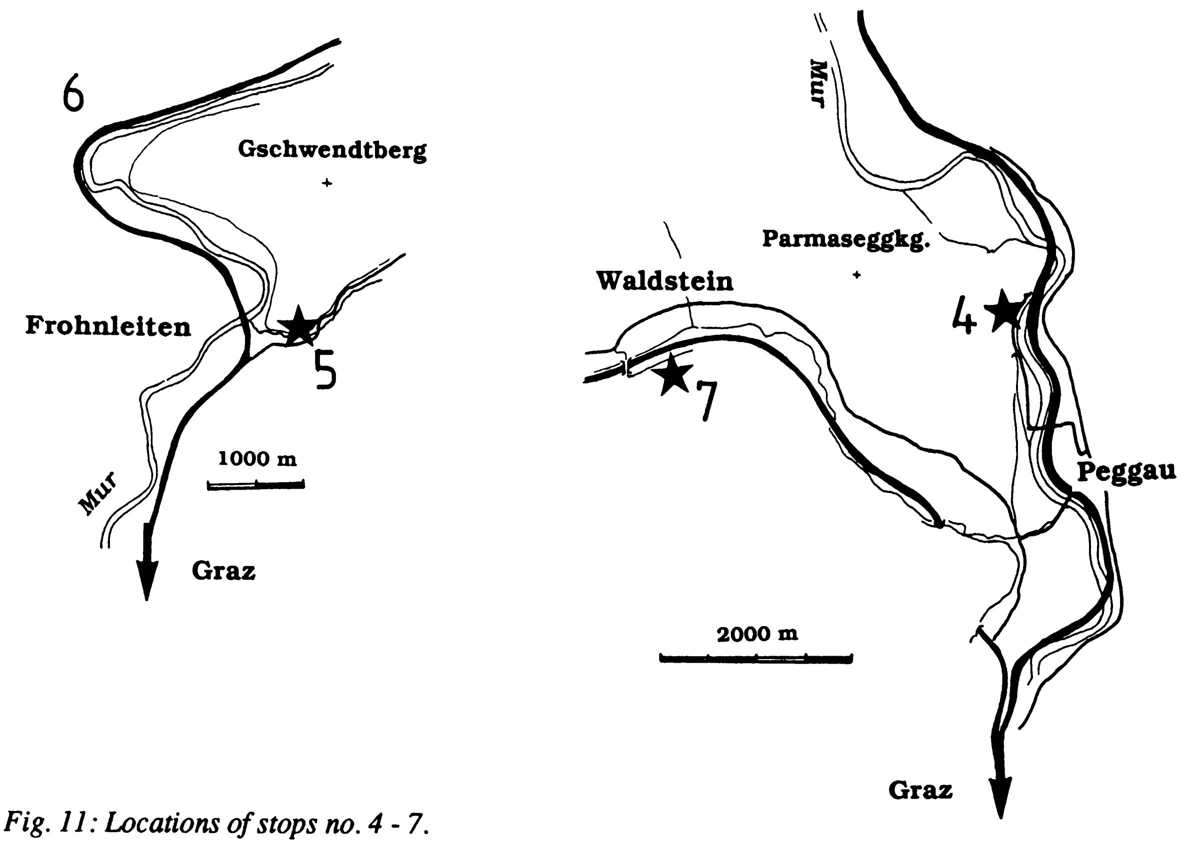


Fig. 11: Locations of stops no. 4 - 7.

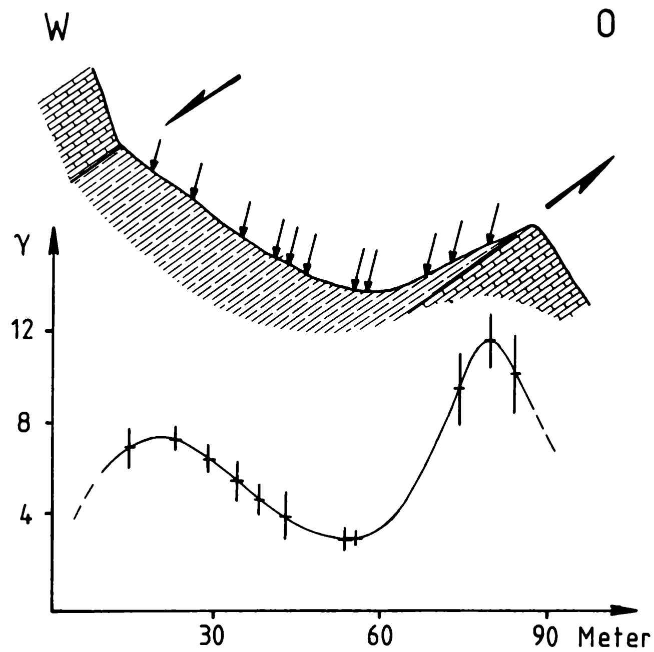


Fig. 12: Strain profile across the outcrop section, stop no. 4. Shear strains are plotted on vertical bars, analyzed locations (black arrows) on horizontal bars.

Recumbent similar folds with fold axes parallel to the stretching lineation refold D1. These folds are rarely seen in carbonate-rich rocks. In the anisotropic phyllites developed highly irregular folds with very variable fold axes.

Viscosity contrasts on a bigger scale between easily deformable limestones and phyllites and stiff dolomites caused shear localisation with lense shaped bodies in the central parts of the outcrop.

Geochronological data favour an Early Alpine age of the penetrative deformation (D1). White mica with grain sizes up to 400 m have grown synkinematically in pressure shadows behind rigid objects. This mica are contrasted by very finegrained mica in the matrix. K/Ar ages of the mica in pressure shadows gave approximately 130 Ma which is in good concordance with the 125 Ma Rb/Sr ages of the small mica. However, unrealistic ages resulted from K/Ar datings of the matrix mica due to excess argon (approximately 500 Ma).

The structural setting of this outcrop is a result of Early Alpine thrusting. The deformable phyllites of the Arzberg-Fm. represent a major shear zone within the lower nappe system of the Graz Thrust Complex. Thrust geometry is interpreted as foreland dipping duplex during top-to-the W displacement. Enhanced flattening strain caused local recumbent folds.

Further reading: Tschelaut, 1985; Fritz and Neubauer, 1988; Fritz, 1988, 1991.

Stop No. 5: Devonian sedimentation in the Kalkschiefer Group; Early Alpine fold-and-thrust structures.

H. FRITZ, F. NEUBAUER, E. WALLBRECHER

Location: OEK 50, sheet 133, Leoben. Outcrop 500 meters NE of Frohnleiten, approximately 30 kilometers north of Graz. At the roadcross Frohnleiten - Rechberg follow the road to Rechberg (Fig. 11). The outcrop is on the NW bank of the little creek opposite to a sawmill.

Bedded limestones with variable amount of siliciclastic material as seen in this outcrop are the typical sediments of the Kalkschiefer Group. With the exception of some crinoids, biodetritus and few conodonts there could not be found any fossils in this group. Conodonts suggest Lower to Middle Devonian age of the sedimentation.

Oldest deformation (D1) is a system of steeply SE dipping foliation planes which cut a flatlying bedding. Relationships between bedding and axial plane foliation point to NW-vergent folding. Stretching on the foliation planes is evident from stretched crinoid ossils and pressure shadows around pyrit, sense of shear is top-to-the NW. This deformation corresponds with a macroscale fold which is best seen from the town Frohnleiten at NE view direction.

D1 is overprinted by kink folds and coeval reverse faults with nicely developed slickenside striations. A complete set of thrust faults following a ramp-and-flat geometry, back faults, tear faults and associated fault-bend-folds is visile in the NE part of the outcrop. Paleostress analyses from fault planes and slickenside striations gave NW-SE horizontal compressive stresses and subvertical minimum stresses.

All structures are interpreted to reflect Early Alpine stacking at progressively cooling temperature conditions and hence increasing brittle material behaviour.

Further reading: Tschelaut, 1984a, b; Fritz et al., 1991.

Stop No. 6: Gams conglomerate.

H. FRITZ, F. NEUBAUER, E. WALLBRECHER

Location: OEK 50, sheet 133, Leoben. Outcrop along road immediately North of the village Röthelstein in the Mur valley (Fig. 11).

The outcrop along the road exposes a reddish, polymict terrestrial conglomerate which is correlated with the basal conglomerate (Late Cretaceous) of the Gosau sequence of the nearby Kainach basin. The grain size ranges from sand-sized grains up to several tens of decimetres. The composition is dominated by red Werfen clasts (Scythian), Triassic and Jurassic limestones and dolomites, and some material of the Paleozoic of Graz. The composition of the conglomerate evidences a completely eroded Mesozoic cover sequence of the Paleozoic of Graz. The structure is dominated by NE and N trending strike slip faults and ca. NNE trending extension gashes which resulted from the nearby sinistral tear fault of the metamorphic Gleinalm dome.

Further reading: Gollner et al., 1987.

Stop No. 7: Late Silurian to Early Devonian sedimentation of the Rannach Group and Early Alpine deformation.

H. FRITZ

Location: OEK 50, sheet 163, Voitsberg. Section along a small road parallel (south) to the highway Graz - Übelbach - St.Michael. 1 km west of the small village Waldstein in the Übelbach valley (25 km north of Graz) take the first bridge to cross the highway (Fig. 11). The section described below follows the track to the east to a restplace along the highway.

The section starts with Silurian volcanoclastic sediments at the base and shows a complete section to the Early Devonian carbonatic/clastic sediments of the Rannach Group. Bedding planes generally dip SE, so the section is decribed from stratigraphic bottom to top. A macroscale fold is exposed in eastern portions of the section.

(1) Greenschist metamorphic conditions transposed the finegrained volcanoclastic sediments to chloriteschists. Primary lamination is rarely preserved and argue for mafic tuffs as source. Small limestone layers which bear conodonts of Upper Silurian age are intercalated within the upper portion of the volcanosedimentary sequence.

(2) The carbonatic evolution starts with a 40m thick sequence of somtimes Fe-rich dolomites and siltstones of the Late Silurian to Early Devonian.

(3) This sequence is followed by finegrained marly limestones with plenty of sulfide mineralisation, mostly pyrite. Towards the hangingwall the amount of siliciclastic material decreases and the grainsize increases, limestones and dolomites are intercalated by siltstones.

(4) Crinoid rich limestones with sand- and siltlayers occur on top of the section. Biodetritus and sedimentary structures point to higher water energy.

Progressive carbonate production and input of coarse material are interpreted to reflect decreasing water depth and increasing influence of a continental hinterland.

Change of the stretching directions from E-W to NW-SE stretching may be observed in single layers, especially the marly limestones. NW stretching is correlated with outcrop-scale thrusting which is seen in the stiff dolomites and with asymmetric recumbent folds in the limestones in the estern section of the profile. NW stretching overprints an earlier W-E increment which is associated with top-to-the W displacement.

Further reading: Fritz and Neubauer, 1988; Fritz, 1988, 1991.

Stop No. 8: Lithologies of the Gleinalm "Core complex" (pre-Alpine basement), Variscan and Alpine structures.

F. NEUBAUER, R.D. DALLMEYER, I. DUNKL

Location: ÖK 50, sheet 133, Leoben. Abandoned quarry in the Kumpelgraben, Gleinalm (southern margin of the sheet 133), Fig. 13.

The quarry exposes the Humpelgraben granite gneiss and its country rocks, especially amphibolite, banded amphibolite (cm to dm thick amphibolite layers alternating with fine-grained orthogneisses), and biotite plagioclase gneiss. All lithologies are strongly foliated and fine-grained which feature underlines the mylonitic aspect. The age of country rocks of the Humpelgraben granite gneiss is not well constrained. Similar fine-grained orthogneisses (plagioclase orthogneiss) have been dated by Frank et al. (1976) with 518 +/- 50 Ma (Rb-Sr whole rock errorchrone).

The Humpelgraben granite gneiss, exposed in the lower central part of the quarry, is a two mica granite of supposed Early Carboniferous age. It shows relation to nearby, well-dated, sheet-like augen gneisses along the hangingwall edge of the Gleinalm "Core" complex. The outcrop exposes

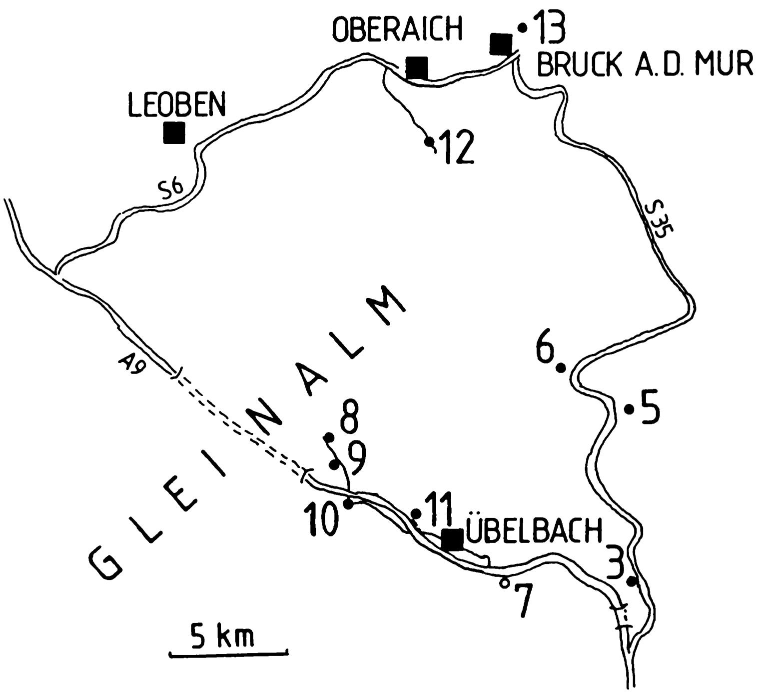


Fig. 13: Locations of Gleinalm stops (stop nos. 8-11).

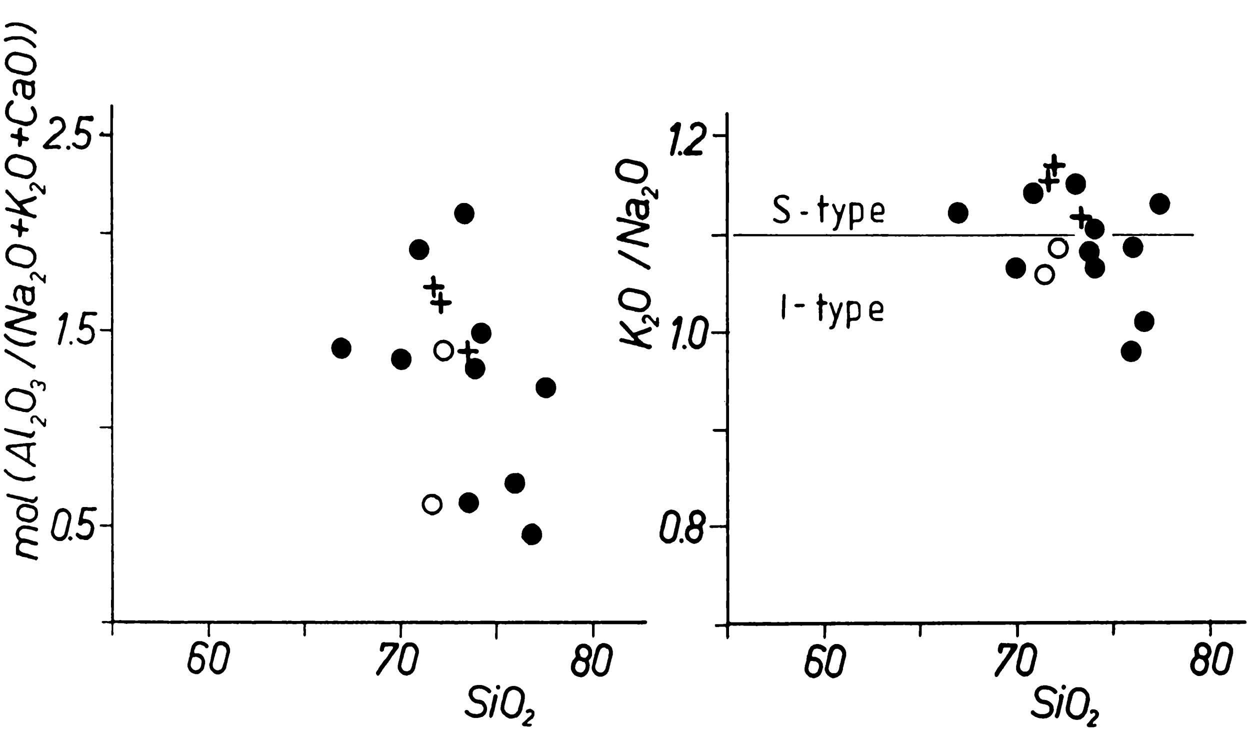


Fig. 14: Major element discrimination of the Humpelgraben granite gneiss (crosses), the Gleinalm augengneisses (filled circles) and augen gneisses of the Speik Complex (open circles) from samples of the central Gleinalm area.

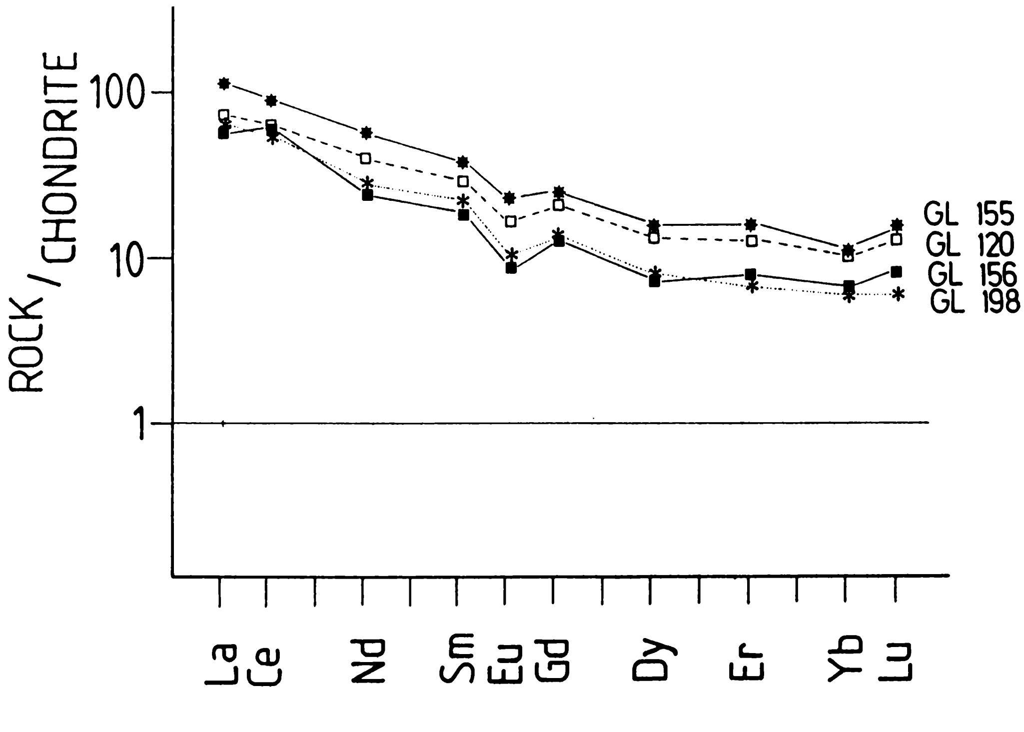


Fig. 15: REE patterns of a biotite plagioclase gneiss (GL 155) and of the Humpelgraben granite gneisses (GL 156, GL 198) from the Humpelgraben quarry. Sample GL 120 is an augengneiss from a site close to stop n. 9.

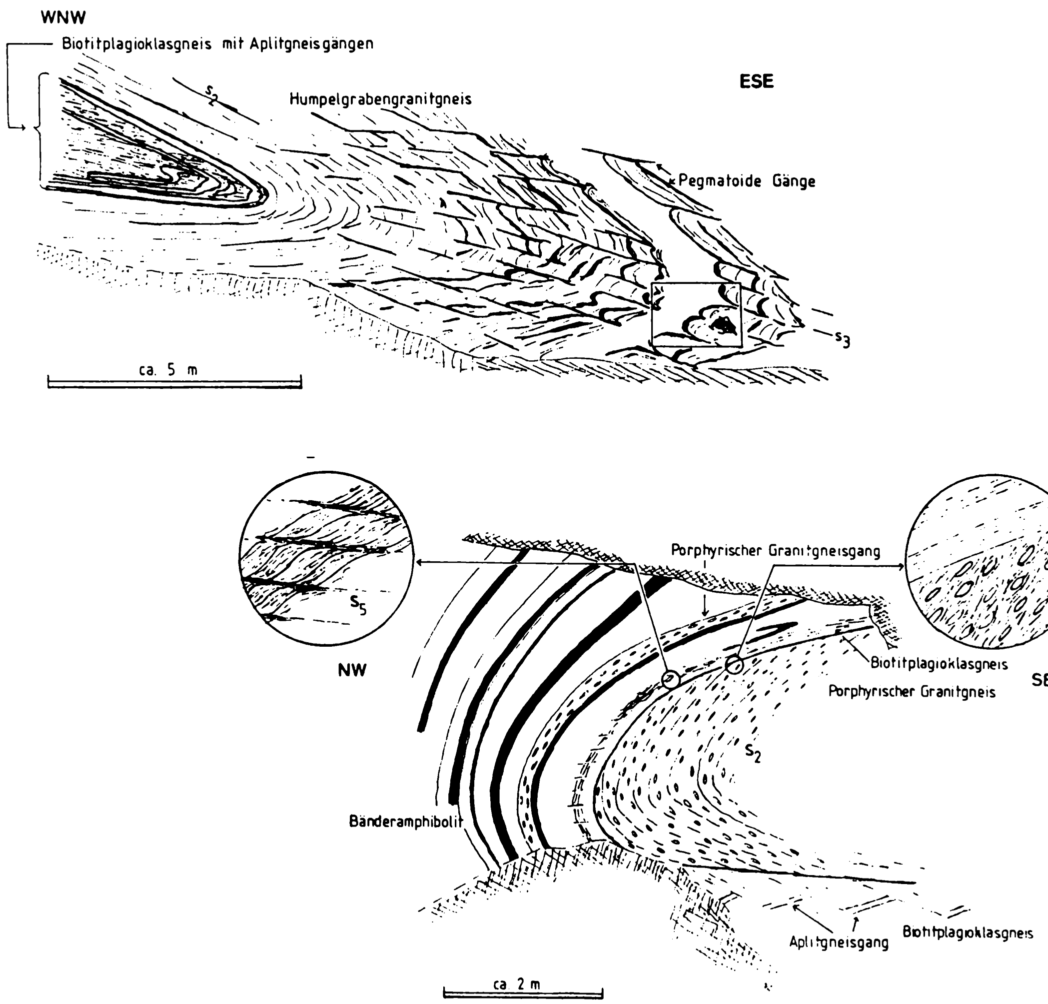


Fig. 16: Two fold generations from the Humpelgraben quarry.

largely veined porphyric orthogneisses with K-feldspar megacrysts. The Humpelgraben granite gneiss have the geochemical characteristics transitional between I-type and syn-collisional S-type granite (Fig. 14). REE patterns of rocks exposed in this outcrop, see Fig. 15.

The granite gneiss exhibits a foliation with a banding of alternating mica layers and quartz/feldspar layers. The foliation is folded in a recumbend isoclinal fold. A related axial surface foliation forms mullions composed of pegmatoids and thin pegmatitic veins parallel to the axial surface foliation of the fold (Fig. 16a). The formation of these isoclinal folds is, therefore, apparently related to the intrusion of the Humpelgraben granite gneiss.

Others folds with similar orientation of fold axes and axial surface foliation only show minor recrystallization, and postdate the first fold generation (Fig. 16b).

Further structures are semiductile conjugate low angle normal faults which indicate ca. E-W stretching of the Gleinalm "Core" complex.

Recent 40Ar/39Ar dating of a hornblende and a muscovite concentrate combined with previous Rb-Sr muscovite and biotite data and a zircon fission track date monitor cooling after early Alpine metamorphism between 95 to 65 from 500°C to ca. 225°C. The second fold generation as well as the E-W stretching on conjugate semiductile normal faults are obviously related to the uplift of the Gleinalm "Core" complex.

Further reading: Neubauer 1988, Dallmeyer et al., this vol..

Stop No. 9: Gleinalm augengneiss (hangingwall unit of the Gleinalm "Core Complex").

F. NEUBAUER

Location: OEK 50, sheet 163, Voitsberg, Kumpelgraben, ca. 700 m N of the Gh. Triebl.

The outcrop on the road exposure exposes the strongly foliated augen gneiss which forms a sheetlike body along the hangingwall edge of the Gleinalm Core complex.

The augen gneiss is composed of K-feldpar porphyroclasts with a fine-grained matrix of K-feldspar, plagioclase, large muscovite fishes, biotite and recrystallized sericite, quartz and accessories (apatite, zircon). The modal composition of the augen gneiss ranges from granite to granodiorite. The augen gneiss have the geochemical characterics transitional between I-type and syn-collisional granites (Fig. 14).

The foliation dips to the SE and contains a subhorizontal stretching lineation. The mylonitic appearance is the expression of a two-step deformation of the augen gneiss. An older fabric is combined with recrystallisation of K-feldspar within amphibolite facies conditions. The younger fabric overprinted the older one and include recrystallized quartz, feldspar and some transformation of feldspar into sericite.

Further reading: Angel, 1923; Neubauer, 1988, 1989; Teich, 1979.

Stop No. 10: Neuhof Micaschist and garnet amphibolite of the Speik Complex.

F. NEUBAUER

Location: Kleintal valley, road exposure immediately S of the Gh. Triebl (Fig. 13).

The outcrop exposes garnet-bearing micaschist of a tectonic slice between the Gleinalm Core Complex and the Speik Complex and the basal portion of the Speik Complex. The amphibolite is mainly composed of garnet and amphibole and part of the Speik complex which is interpreted as pre-Alpine ophiolite. In general, the garnet amphibolite have a N-MOR basaltic geochemical characteristics but no data are available from this outcrop. The micaschist often contains semiductile S-C fabrics which are related to a wide sinistral shear zone between the Gleinalm Core Complex and the Graz Nappe Complex.

Further reading: Neubauer, 1988; Neubauer et al., 1989;

Stop No. 11: Lithologies of the Micaschist-Marble Complex, Gleinalm dome.

F. NEUBAUER

Location: OEK 50, sheet 133, Voitsberg. Forest road east of the highway. The Forest road starts below the highway bridge ca. at the confluence of the Übelbach and Kleintal valleys (Fig. 13).

The Micaschist-Marble Complex is a tectonic unit with a structural thickness of ca. 1,500 metres. The road exposes light-cloured quartzites, marbles, dolomite marbles, calcsilicate marbles, black micaschist and pegmatites (after the second, northern gorge from the eastern side of the Kleintaltal valley.

Like other complexes of the Gleinalm dome metamorphism is of polymetamorphic character with a first, Variscan metamorphism and an Alpine (Cretaceous) also within amphibolite facies. The pegmatite is probaly related to the intrusion of the Gleinalm augengneiss.

Further reading: Neubauer, 1988, 1989.

Stop No. 12: Layered intrusion of the Rennfeld igneous complex.

F. NEUBAUER

Location: OEK 50, sheet 133, Leoben. The exposures are along forest roads near to the Gh. Tischler (see Fig. 13, 17).

Here in the Utschgraben, an Early Carboniferous pluton is very well exposed with a large variety of rocks which range from ultramafic rocks (metapyroxenite, hornblendefels, metaperidotite), metagabbros and amphibolite, metatonalite (now "metablastic amphibolite) and porphyric granites. The pluton is part of the major Rennfeld igneous complex. On a forest road ca. 500 m N of the Gh. Tischler, cumulate sequences and intrusional breccias along the contact with country rocks (biotite plagioclase gneiss) are exposed.

Further reading: Herrmann, 1972; Neubauer, 1988.

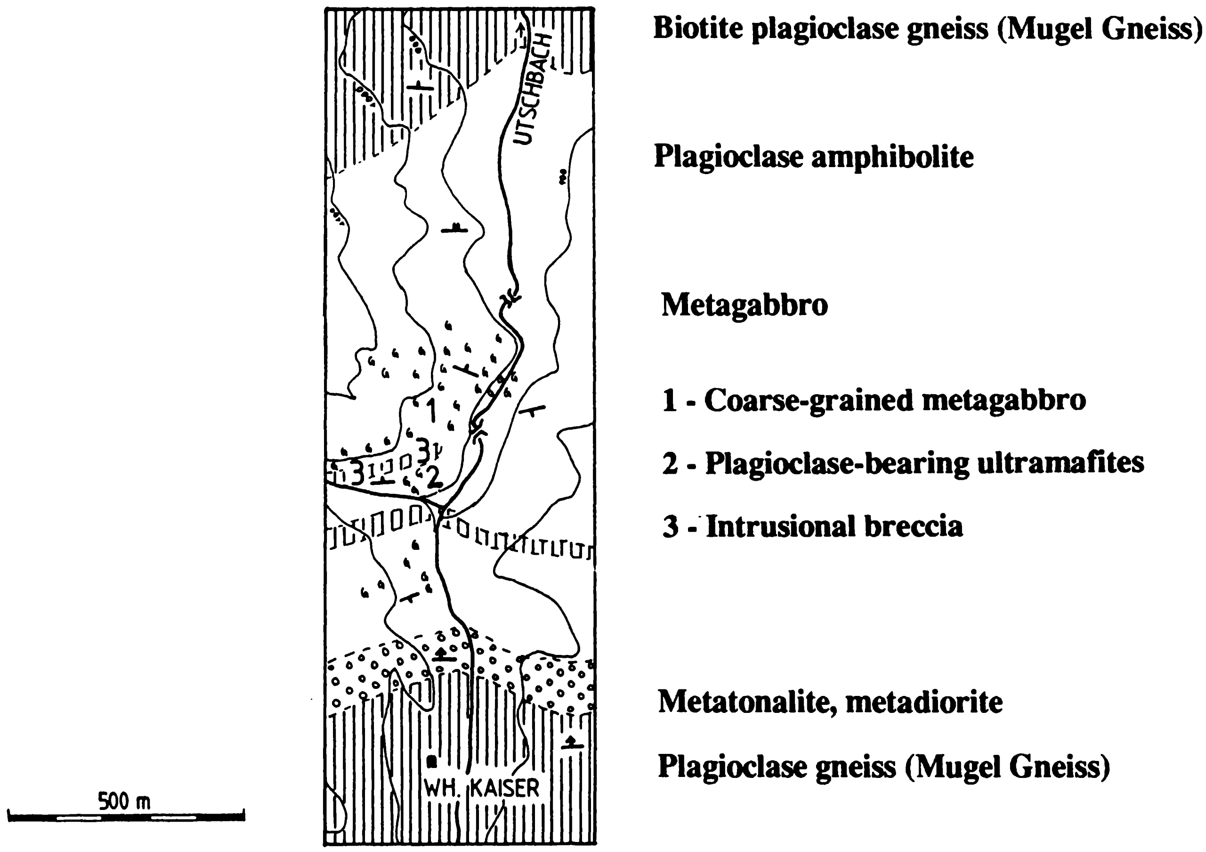


Fig. 17: Section along the Utschgraben with exposures of the Rennfeld igneous complex.

Stop No. 13: Steilbachgraben and Triebenstein Fms. of the Veitsch Group, eastern Greywacke Zone.

R. HANDLER, F. NEUBAUER

Location: OEK 50, sheet 133, Leoben. Quarry "Gloriette" NE of Bruck/Mur. The quarry can be reached by car on the road which leads from the railroad station Bruck/Mur into the "Kaltbachgraben". Approximately 500 m after the road passes under the railroad track, the "Steinbruchweg", on the north side of the Kaltbachgraben, leads to the quarries on both, the NW and the SE, sides of the hill (Fig. 18).

The Veitsch Nappe is the lowermost unit of the Upper Austroalpine nappe complex and directly overthrusts the Middle Austroalpine unit. It also forms the basal part of the Greywacke Zone. It consists of clastic to calcareous sediments of Carboniferous age. Following Ratschbacher (1987), this nappe is devided into three major units:

1) The uppermost Sunk Fm. consists of a generally coarsening upward sequence from limestone-shale intercalations to conglomerates. It is interpreted to originate from a regressive shore line, the conglomerates are interpreted as channel filling.

2) The intermediate Triebenstein Fm. is build up by massive, pure carbonates, which display a subtidal carbonate facies with scattered bioherms.

3) The lowermost Steilbachgraben Fm. consists of fine-grained, laminated clastic sediments, which may contain dolomite and magnesite lenses. They are interpreted as the result of episodic sedimentation below the range of wave action.

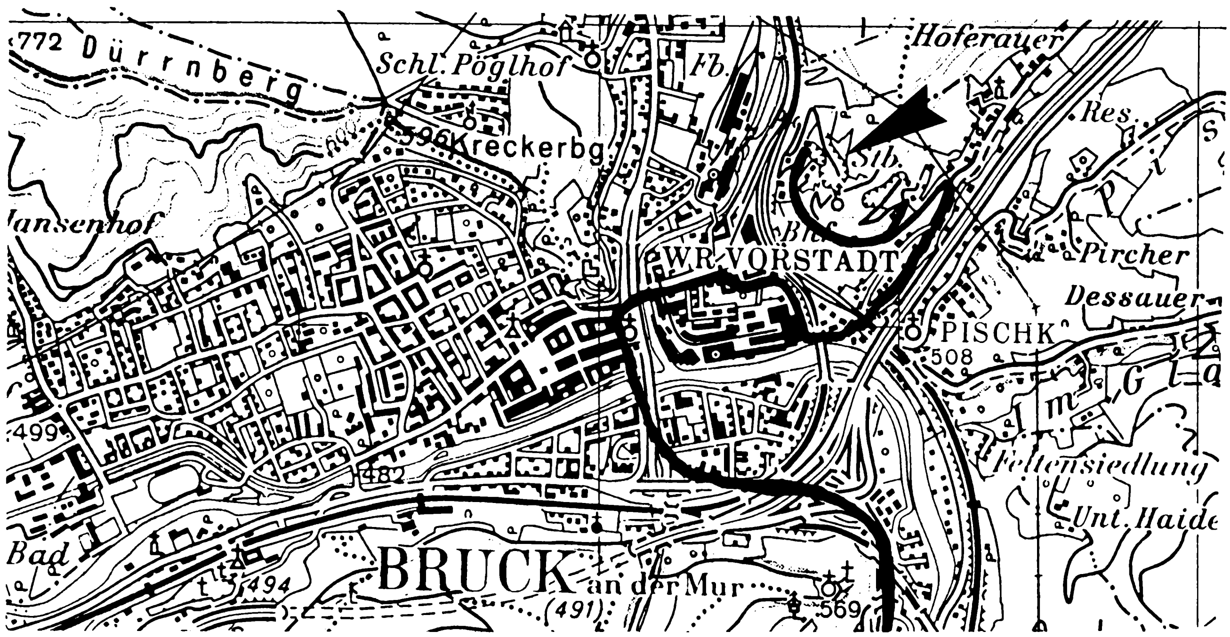


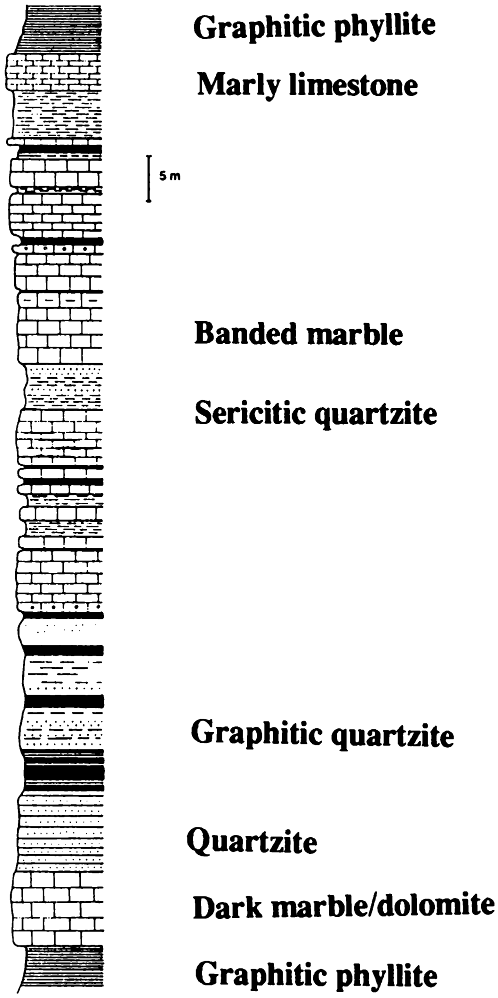
Fig. 18: Location of the Gloriette quarry near Bruck/Mur.

For both siliciclastic formations, morphometric investigations on zircons indicate a uniform source area.

During Early Alpine (Cretaceous) metamorphism the Veitsch Nappe suffered penetrative ductile deformation within greenschist facies conditions.

A section through the quarry is shown in Fig. 19.

Further reading: Ratschbacher, 1987.



(from Schönlaub, 1979)

Fig. 19: Section of the Gloriette quarry.

Stop No. 14: Sequences of the Silbersberg nappe (especially Silbersberg Conglomerate) and the Pre-Variscan Kaintaleck Complex.

R. HANDLER

Locality: OEK 50, sheet 133, Leoben. Oberdorf in the Laming valley ca. 15 km NW of Bruck/Mur; roadcut along the forest road east of the Obertaler creek, 850-880 m NN.

The Greywacke Zone builds up the base of the Upper Austroalpine (UAA) nappe complex and consists of several nappes. The different nappes can be traced along the whole strike of this zone, but are sometimes missing as a consequence of Late Alpine deformation. From bottom to the top these nappes are: (1) the Carboniferous Veitsch Nappe (directly overthrusting the Permomesozoic cover sequences of the Middle Austroalpine crystalline unit), (2) the Silbersberg Nappe, which consists of (?) Paleozoic carbonate phyllites and a Permian Verrucano-type sequence, (3) the medium- to high-grade metamorphic rocks of the Kaintaleck Complex, and (4) the Noric Nappe, which consists of a clastic sequence reaching from Ordovician to Permian, and builds up the basement of the Permo-Mesozoic sequence of the Northern Calcareous Alps.

In this section a more or less complete profile of the intermediate part of this Upper Austroalpine nappe can be observed. The profile ranges from the upper part of the Veitsch Nappe to the Kaintaleck Complex. All units are in an upright position and dip with intermediate dipangles of 35-50° to the NW to N (Figs. 20, 21).

The road starts in the **Sunk Fm.** of the **Veitsch nappe**, which is the highest part of the Veitsch Nappe. Typical are dark gray phyllites, in some places detrital white micas can be found.

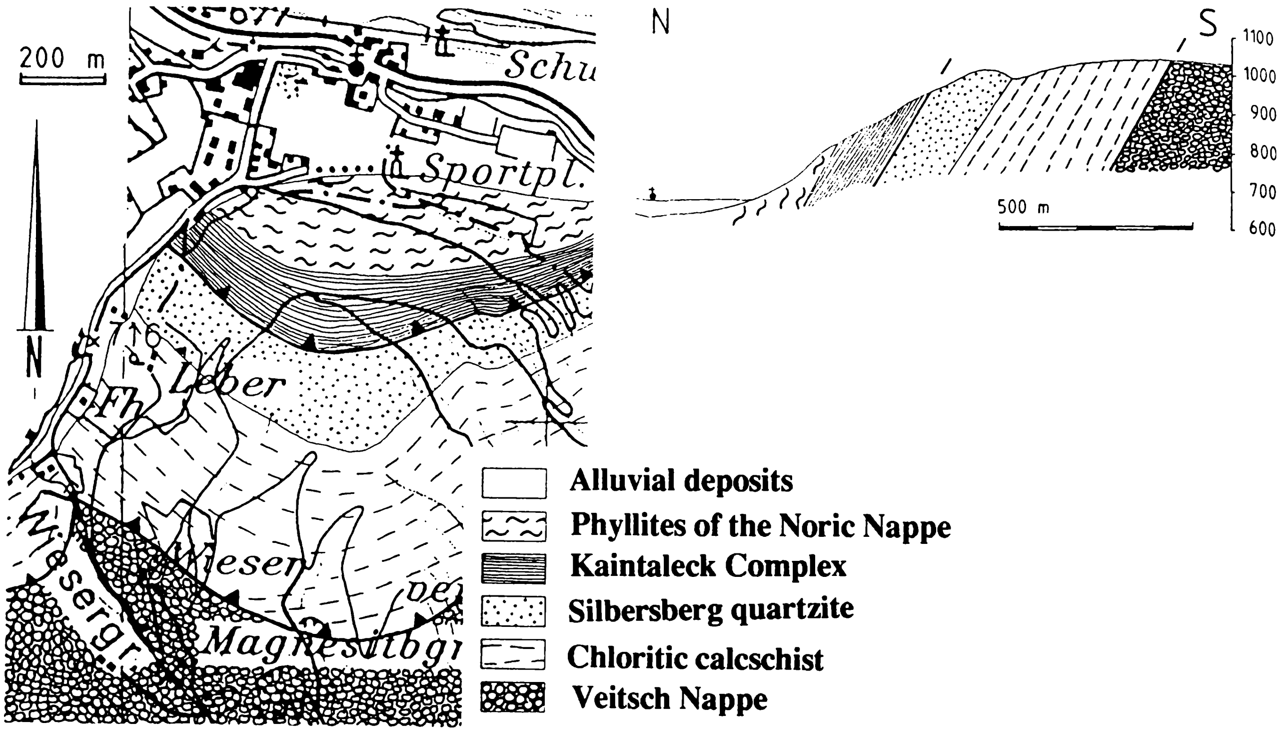


Fig. 20: Location of the stop no. 14 (a), south of Oberdorf in the Laming valley near Bruck/Mur, and geological sketch map.

Rb-Sr ages of two size fractions from these micas gave ages of ca. 418 Ma (500-355 µm) and 406 Ma (250-125 µm; both calculated with a theoretical initial Sr of 0.706), which is interpreted to date post-Caledonian cooling of the source area.

The **Silbersberg Nappe** consists of a monotonous sequence of green calcareous schists of supposed Early Paleozoic age, covered by a conglomerate sequence. The conglomerate consists of metaconglomerates to metapelites. Boulders of this conglomerate vary from a few millimeters to more decimeters in size. They typically consist of large gneiss-boulders, quartzites, and red quartz grains of a few centimeters in size. The conglomerates lead gradually to fine grained brown phyllites. The asymmetric size of the boulders point to a top to N movement during greenschist-facies metamorphism.

Two different size fractions of detrital white micas from the metapelitic sequence yielded Rb-Sr two point isochron ages of 349 +/-1 (500-355 µm) and 333 +/-4 Ma (355-250 µm), which is interpreted to date Post-Variscan cooling of the source area of these micas.

The **Kaintaleck Complex** includes a variety of medium-grade metamorphic rocks. The total thickness of the complex in this region reaches 140 m. The sequence starts with garnet and tourmaline bearing micaschists, which are followed by a thick sequence of amphibolites, which are intercalated by micaschists and marbles. Although a strong greenschist facies metamorphic overprint due to Alpine orogenesis can be recognized, dating of the white micas yielded Pre-Variscan mineral ages:

Two different size fractions of a micaschist yielded Rb-Sr two point isochrone ages for phengitic muscovites of 401 +/-3 Ma (500-355 µm) and 472 +/-6 Ma (355-250 µm). $^{40}Ar/^{39}Ar$ analysis of the size fraction 250-200 µm of the same sample yielded a highly discordant age spectrum with a total gas age of 350 +/-2 Ma, starting at ca. 290 Ma in the low temperature portions and reaching to ca. 375 Ma in the high temperature steps of the experiment.

The age of 472 +/-Ma is supposed to be some kind of a "Cadomian Sr-memory" of the white micas. The younger age of the coarser size fraction can be explained by an extremely high phengitic rim of the micas (Si [iv] = 6.9), which indicates the polymetamorphic evolution of these minerals. We suppose, that during "Caledonian" metamorphism the Cadomian white micas suffered partly resetting of the Rb-Sr isotopic system, as well as the growth of a phengitic rim, and a complete resetting of the Ar-system. After post-Caledonian closure of the micas (375 Ma intercept of the Ar-profile) partial diffusional overprint of the Ar-system took place due to Variscan and/or Alpine reheating (290 Ma intercept at the low-temperature portion of the Ar-spectrum).

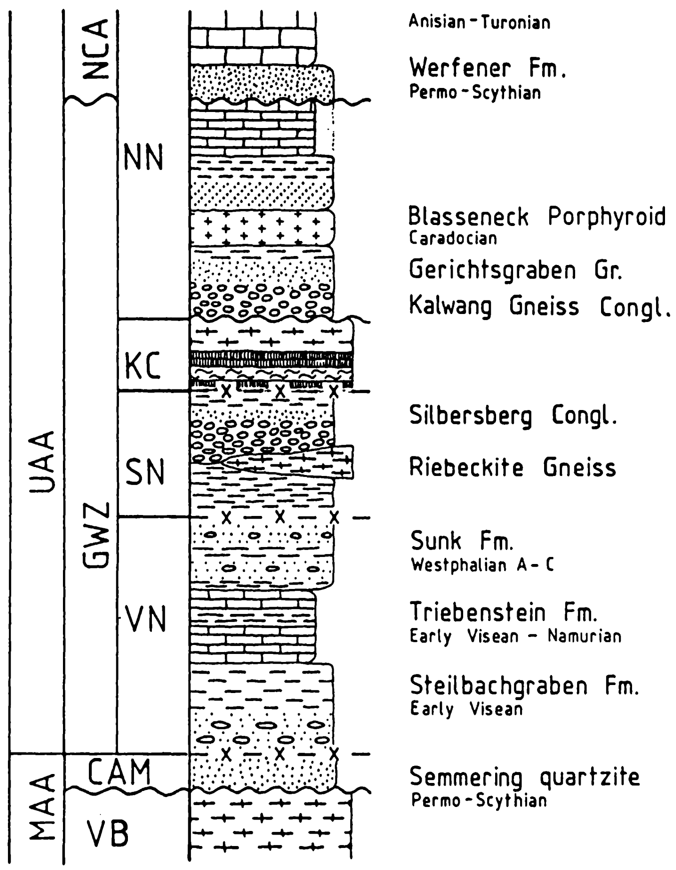


Fig. 21: Section through the basal portion of the Upper Austro-Alpine nappe complex in the area close to Oberdorf in the Laming valley. Idealized profile through the upper part of the Austroalpine nappe pile, from the Variscan metamorphic basement of the Middle Austroalpine to the Northern Calcareous Alps.
MAA - Middle Austroalpine: VB - Variscan Basement, CAM - Central Alpine Mesozoic; UAA - Upper Austroalpine: GWZ - Graywacke Zone, NCA - Northern Calcareous Alps, VN - Veitsch Nappe, SN - Silbersberg Nappe, KC - Kaintaleck Complex, NN - Noric Nappe.

Stop No. 15: Grobgneiss of the Lower Austro-Alpine Unit (LAA).

F. NEUBAUER

Location: OEK 50, sheet 135, Birkfeld (Fig. 22). Quarry 700 metres south to Miesenbach.

The outcrop exposes the "Grobgneis", an augengneiss of the "Raabalpen unit" (LAA). The Grobgneis is composed of porphyroclasts of K-feldspar, plagioclase, quartz, white mica and accessories. The outcrop exhibit a flat-lying foliation, and NNE trending stretching lineation which suggest top NNE displacement.

Further reading: Kiesl et al., 1983, Reindl, 1990.

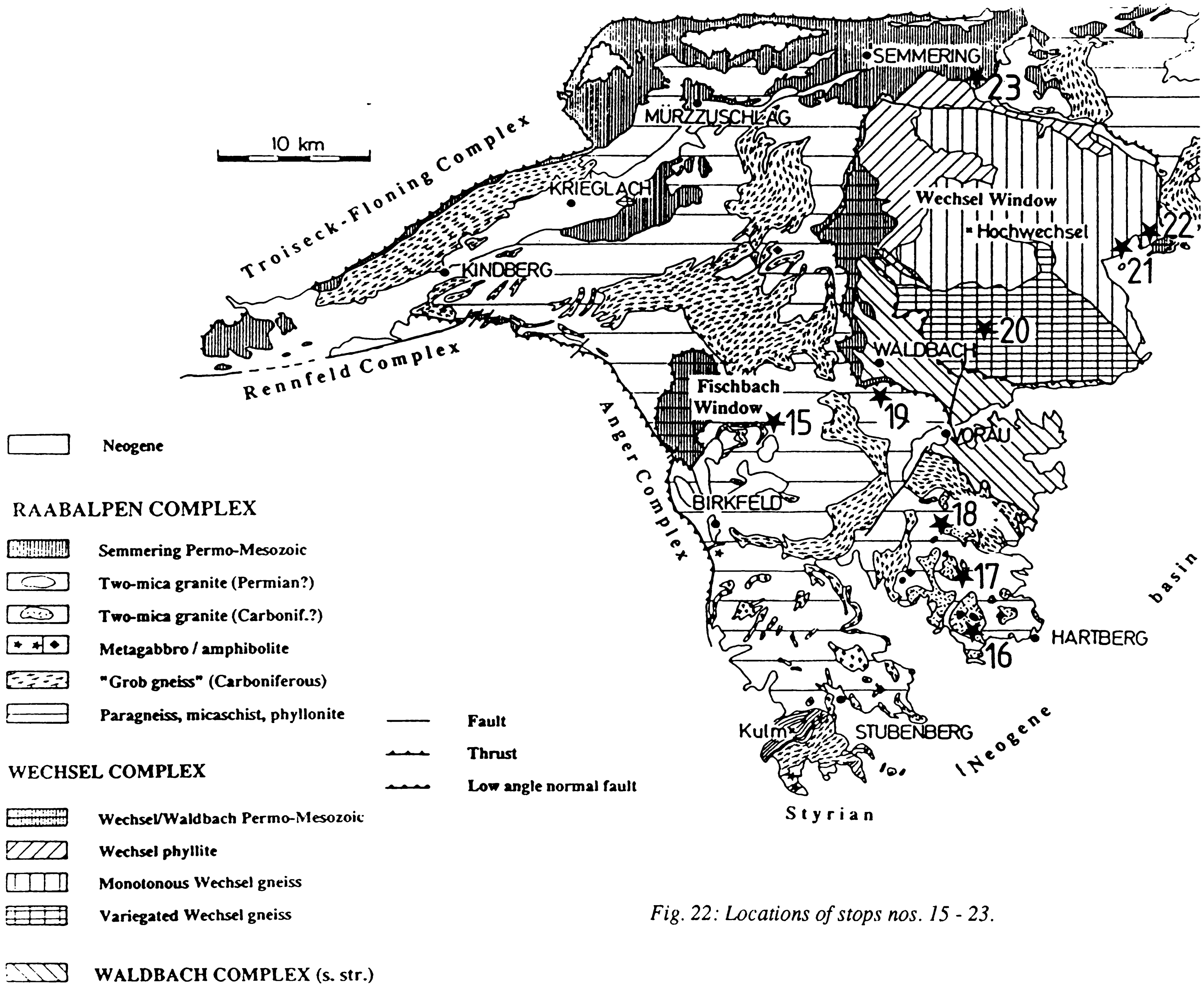


Fig. 22: Locations of stops nos. 15 - 23.

Stop No. 16: Carboniferous two-mica granite and clinopyroxene-bearing amphibolite.

P. PEINDL

Location: OEK 50, sheet 136, Hartberg. The outcrop is situated at the road 500 m NNW castle Neuberg (E of the town Hartberg; Fig. 22).

At the western part of this outcrop, there occurs a slightly foliated two-mica-granite showing very clearly (in thin section) the progressive replacement of magmatic muscovite by fibrolitic sillimanite + K-feldspar + quartz.

Geochemistry, Rb-Sr data and metamorphic evolution see introductory chapter of this volume.

Modal composition:

Quartz	37 %
Alkali feldspar	44 %
Plagioclase	7 %
Muscovite	2 %
Biotite	9 %
Accessories	1 %

In the central part of the outcrop, an clinopyroxene-bearing amphibolite can be seen.The clinopyroxenes occur in the central part of the amphibolite only. In the direction to the granite, the clinopyroxenes disappear obviously beeing replaced by brown hornblende.

Small extension veins in the amphibolite are filled with plagioclasite (95 % plagioclase, 1 % quartz, 4 % hornblende).

The eastern part of the outcrop shows ductile low angle normal faults in the amphibolite. The mineralogy of the mylonites with light green hornblende, relicts of garnet, epidote, zoisite, klinozoisite, sphene with cores of rutile and some quartz suggests a formation within epidote and amphibolite facies conditions. Contrary to the amphibolite above, plagioclase is missing. Biotite is grown postkinematically. A few meters further to the east, in the wood: Some unspectacular shear zones in orthogneiss.

Further reading: Peindl, 1990.

Stop No. 17: Contact of a Carboniferous two-mica granite with migmatitic paragneiss and amphibolite.

P. PEINDL

Location: OEK 50, sheet 136, Hartberg. Waldbach-valley, N of mount Ringkogel situated N of village Hartberg (Fig. 22). Small clearing 605 m above sea-level on the northern slope of the valley.

Geochemistry, Rb-Sr data and metamorphic evolution see introductory contribution.

Modal composition of the granite:

Quartz	46 %
Alkalifeldspar	40 %
Plagioclase	8 %
Muscovite	2 %
Biotite	3 %
Accessories	1 %

The prograde decomposition of the muscovite can not be seen as clearly as at the stop before (stop no. 16). Green flakes of biotite grow in the muscovite. Garnet grows in biotite and plagioclase.

Up to several centimeters large pseudomorphs of kyanite after andalusite often occur. The kyanite itself is very often altered to sericite. The growth of andalusite and the occurence of magmatic muscovite indicate a pressure of about 4 kb for the time of intrusion (Hyndman, 1985).

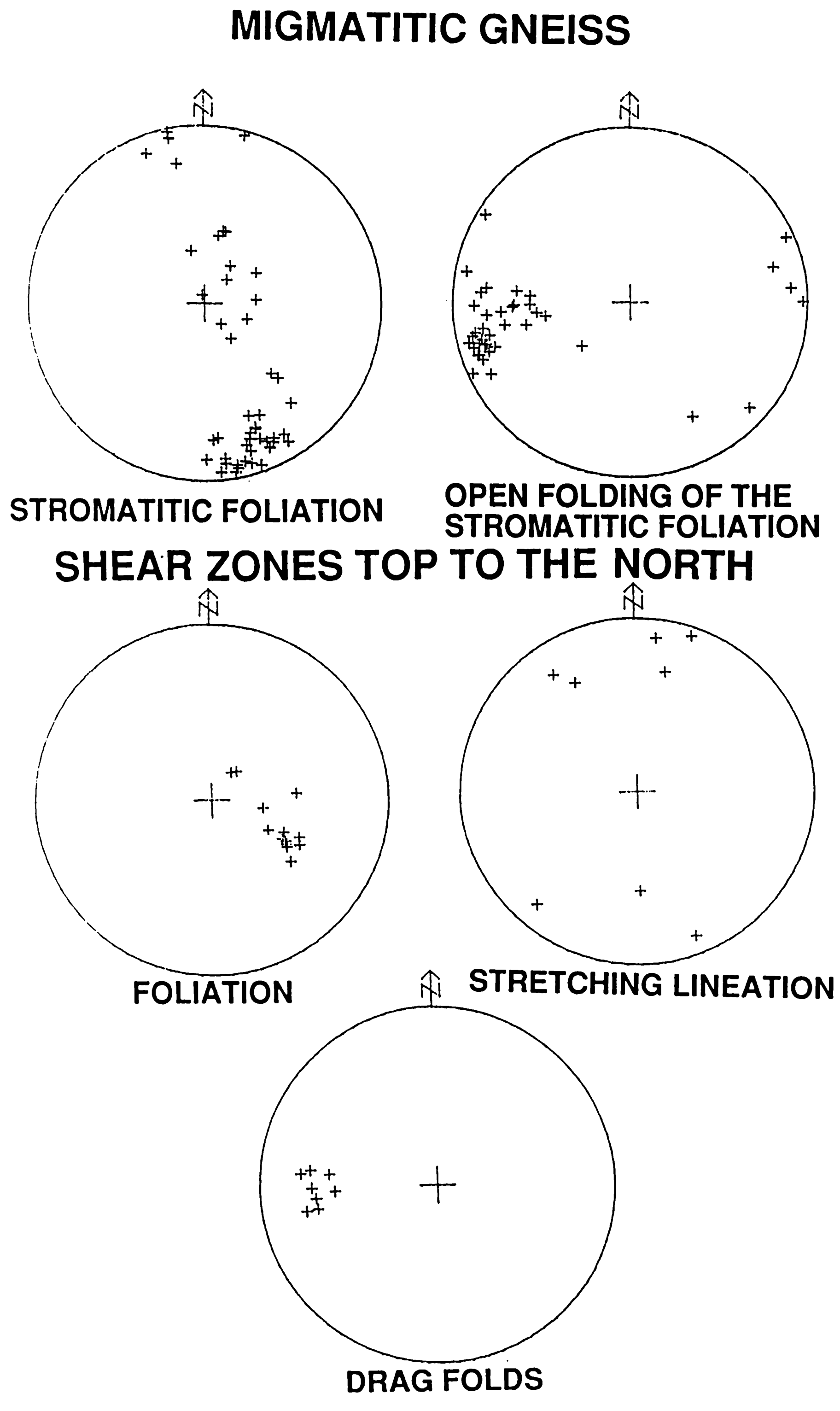


Fig. 23.: Structural elements of stop 18.

Amphibolite xenoliths of all sizes, showing reaction rims consisting of biotite, can be seen everywhere in this outcrop, but the best specimens are found in big isolated block being almost at the foot of the slope (do not hammer, please).

Rare spherical ore-aggregates with a diameter up to two cm can be found. The core consists of rutile, the rim of Ti-magnetite. Probably, these spheres are the assimilation product derived from the amphibolite.

Further reading: Hyndman 1985, Peindl 1990.

Stop No. 18: Conjugate low angle normal faults in migmatitic paragneiss.

P. PEINDL

Location: OEK 50, sheet 136, Hartberg. This outcrop is situated in the wood above the road between Wiesberg and Waldkrausler. You can find this location on the map NW of the church of the town Hartberg, 6.5 km as the crow flies.

The migmatite in this outcrop shows an occasionally open folded stromatitic foliation. Arranged parallel to the foliation, there are boudinaged isoclinal folds consisting of quartz. Most of the biotite from the melanosome is changed to sericite (much higher Alpine than Variscan pressure).

The granite dykes in this outcrop are not investigated by geochemical methods, but petrographically they correspond to the Carboniferous granites (see introductory chapter).

In the shear zones, the core of garnet II grows syn-, the rim late-kinematically. The occurrence of garnet, newly grown, very small grains of staurolite and of kyanite indicates the formation of these shear zones at the time of the Alpine temperature peak (amphibolite facies). Conjugate low angle normal faults (dipping to the N and to the SSE) show the Alpine shear deformation. The orientation of the open folds of the stromatitic foliation is the same as the orientation of the drag folds from the stromatitic foliation into the shear zones. So, the reason for the open folding of the stromatitic foliation is the Alpine shear deformation too. The additional fact, that the mylonitic foliation and stretching lineation lie on a great circle (Fig. 23) allows the interpretation of these structures as the result of the thinning and N-S-stretching of this rock complex during the Alpine uplift.

Further reading: Peindl 1990.

Stop No. 19: Alpine "whiteschists" and Variscan "Grobgneiss" at structural base of the "Grobgneis" unit.

R.D. DALLMEYER, I. DUNKL, H. FRITZ, F. NEUBAUER

Location: ÖK 50, sheet 136, Hartberg. Outcrop in a right-side confluent of the Wießenbach ca. 250 m S of the farm "Franzl in der Mühl" (S of Vorau).

The gorge exposes extremely thin layered "whiteschists" which include lenses of foliated "Grobgneiss". The term "whiteschists" is an old term used by Alpine geologists for orthogneiss mylonites. These white schists consist only of white mica and quartz. All gradual transitions to foliated Grobgneiss may be observed in this outcrop which underline the derivation of the white schists from orthogneisses by transformation of K-feldspars into muscovite.

The foliation plunges to the SW, the stretching lineation to the SSW. Macroscopic structures are related to the overthrusting of the Grobgneis unit over the Wechsel/Waldbach units.

A 40Ar/39Ar muscovite concentrate yielded a plateau of ca. 74 Ma (Dallmeyer et al., this volume). A fission track apatite age with ca. 10 Ma monitors a very young ccoling through ca. 100°C.

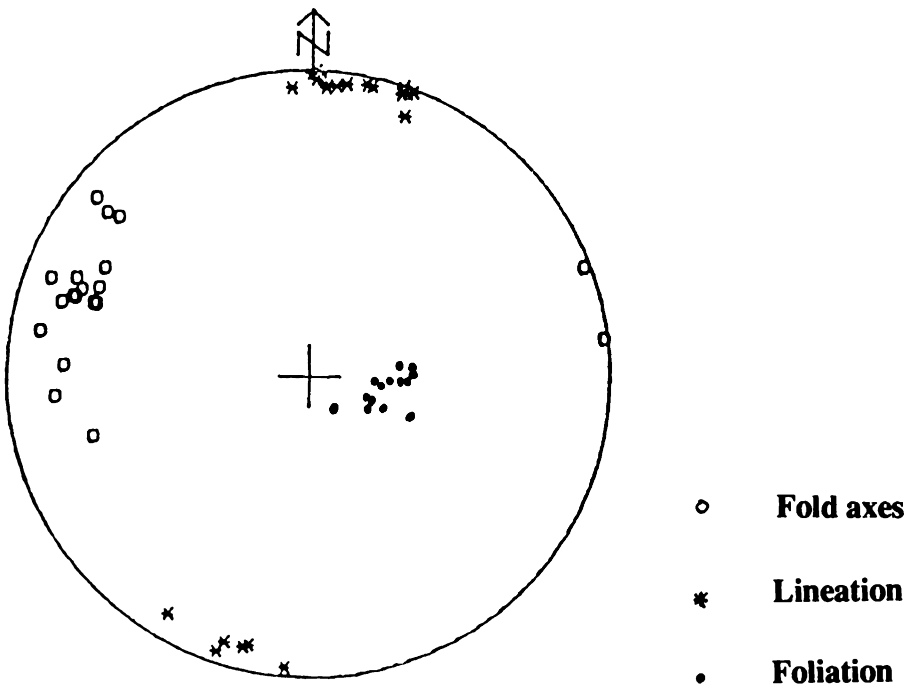


Fig. 24: Structures in the Lambert projection.

Stop No. 20: Lithologies and normal faulting in the southern Wechsel gneiss complex.

F. NEUBAUER

Location: OEK 50, sheet 136, Hartberg. Abandoned quarry and surroundings at the third bridge after Demmeldorf in the Vd. Waldbach valley.

The abandoned quarry exposes lithologies of the "Variegated Wechsel Gneiss Complex". These include light-coloured, massive quartzite in an isoclinal fold with east trending fold axis, epidote amphibolite and some Wechsel gneiss. The epidote amphibolite is composed of actinolite, chlorite, epidote and albite porphyroblasts. The quartzite is interpreted as orthoquartzite which is derived from quartz arenite because heavy mineral contents like zircon. The epidote amphibolite have a calc-alkaline chemistry (Neubauer et al., this vol.).

Along the road, Wechsel gneiss is exposed which displays steep semiductile normal faults due to uplift of the Wechsel dome.

Stop No. 21: Ductile deformed Wechselgneiss, Wechsel window.

W. MÜLLER

Location: OEK 50, sheet 105, Neunkirchen. From the village Mönichkirchen road B54 with direction Hartberg and Graz, approx. 100m before (SE) 1st serpentine turn to the right (NE), narrow street, after 20m: quarry.

The quarry exposes Wechsel gneiss which suffered with strong ductile deformed (top-to-WNW-shear sense) characteristic albite blastesis.

Mineralogical composition: quartz; albite (with inclusions of white mica, chlorite, epidote); white mica; chlorite; epidote + klinozoisite; ore minerals; accessory: tourmaline, rutile, apatite.

Age and mechanism for the characteristic albite blastesis remain unknown; however, an Alpine age as suggested by previous workers seems to be unlikely.

Structures: dip direction and dip angle: S 230/38 + l_s 290/20

Sense of shear: Because of the occurrence of parallel to lineation stretched 2.5 cm long tourmaline the lineation is assumed to be a stretching lineation; sense of shear deduced from shearbands is top-to-WNW.

Geochronological data: Rb/Sr: white mica - whole rock: 375 +/- 5 Ma

$^{40}Ar/^{39}Ar$: white mica: low-temperature-increments indicate a rejuvenation at approx. 250 +/- 10 Ma; high-temperature-increments: around 320 Ma.

Stop No. 22: Wechsel gneiss with greenschist intercalations. Ductile deformation with top WNW sense of shear.

W. MÜLLER

Location: OEK 50, sheet 105, Neunkirchen, and sheet 106, Aspang. Quarry 2 km SW Aspang/Wechsel. From the village Aspang road B54 with direction Moenichkirchen and Graz, after 2^{nd} serpentine and 500m straight - turn right (W/NW) on a dirty road, after 300m large abandoned quarry.

Mineralogical composition of the Wechsel Gneiss: quartz; albite (with inclusions of white mica, chlorite); white mica (2 different phengites and paragonite); chlorite; epidote + klinozoisite; ore minerals; accessory: garnet, apatite, rutile.

Greenschist: mineralogical composition: albite (with inclusions of chlorite, titanite, epidote + klinozoisite, quarz); chlorite; epidote + klinozoisite; calcite; quarz; amphibole.

In the northern part, on the upper dirty road, the transition of Wechsel gneiss into greenschist can be observed, in the middle portion a massive, non-foliated greenschist is exposed, and in the southeastern part Wechsel gneiss with shear sense shows indicating a top-to-WNW shear sense (large shear bands (ecc), rotated porphyroclasts, S-C fabrics) can be seen. Mineral age data: Rb/Sr: phengite1-phengite2-whole rock: 375 +/- 8 Ma; paragonite-whole rock: 270 +/- 4 Ma; $^{40}Ar/^{39}Ar$: phengite1: low-temperature-increments indicate a rejuvenation at appr. 250 +/- 10 Ma; high-temperature-increments: ca. at 350 Ma.

Stop No. 23: Semmering quartzite (Permo-Scythian): weak Cretaceous metamorphic overprint with new white mica.

W. MÜLLER

Location: Quarry 1km W Otterthal. OEK 50, sheet 105, Neunkirchen. From Kirchberg or Otterthal road with direction Trattenbach; approx. 1.2 km WSW crossing in Otterthal, between 2 houses turn right (NE) on a steep road, after 300m: quarry.

The quarry exposes the cover sequence deposited on Variscan metamorphosed basement rocks (here in particular: Raabalpen Unit), Lower Austroalpine Unit.

The Semmering quartzite generally is a very mature sediment, and contains, therefore, only quartz and some metamorphic phengitic mica (sometimes with characteristic greenish colour).

A fine-grained, dark dolomitic marble (Middle Triassic ?) is only exposed in the very front of the quarry.

Both lithologies contain only a very weak foliation (S 174/24). Dominant structures are brittle faults with associated cataclasites. Estimations of the principal paleostress axes orientations yield a NE-SW direction of σ_1 in a strike-slip-regime, which is consistent with many other paleostress-investigations in this area. We suppose, therefore, a link between the strongly brittle strike-slip deformation and the formation of the small Miocene basin between Kirchberg and Otterthal (?pull-apart-basin). Miocene deposits can be observed best at Alpltal (SSE Otterthal).

Geochronologic data: Rb/Sr phengitic white mica: 84 +/- 1 Ma; $^{40}Ar/^{39}Ar$ phengitic white mica: 81 Ma (plateau age).

Stop No. 24: Eclogite, eclogite amphibolite, marble and biotite gneiss of the Sieggraben Unit.

R.D. DALLMEYER, F. KOLLER, F. NEUBAUER, W. KIESL, A. TAKASU, WEINKE

Location: ÖK 50, sheet 137, Oberwart. Abandoned quarry immediately north of the village Zöbersdorf (Fig. 25).

The Sieggraben Unit (klippen of the Middle Austro-Alpine Thrust Complex at the eastern margin of the Alps) is a tectonic melange which includes eclogite-bearing metamorphic units which contain both ophiolite-like fragments (retrogressed N-MORB type eclogites and serpentinites) and supracrustal, probably Pre-Alpine continental rocks. In this outcrop carbonate eclogites, eclogites, and nearly completely retrogressed eclogite amphibolites are exposed as well as hornblende gneiss as country rocks are exposed.

A well defined cross section through the Upper Austroalpine "Sieggraben Serie" (Tollmann, 1977) is exposed in a shut-down quarry north of the village Zöbersdorf. Apart from metamorphic ultramafic rocks, all rock types representative of the metamorphic unit are present. The latter include laminated garnet-bearing biotite gneisses, partly amphibolitized eclogites, and marbles. Eclogites and marbles show evidence of a common primary contact and they are deformed together. The eclogite amphibolite consists of cataclastic deformed garnets of up to 1 cm in diameter and relictic omphacites. The old omphacites are replaced by a relative coarse-grained symplectite consisting of diopsid-rich pyroxene and plagioclase. The symplectitic pyroxene is partly replaced by green hornblende forming large porphyroclastic grains. Rutile is the predominant TiO2-phase. The symplectite is absent around omphacite inclusions in garnet. In the vicinity of the marble/eclogite contact, the degree of amphibolitization decreases indicated by the color of the rocks which ranges from black in the amphibolites to green in the eclogites. Near the contact between the eclogite and the marble the grain size of the symplectite increases and the degree of amphibolitization decreases. Further a replacement of rutile by idiomorphic sphene and of garnet mainly by epidote is observable in this area. In the common eclogite-amphibolite epidote occurs predominantly in veins.

The garnet in the eclogites contains approximately 20 mol% pyrope. Towards the contact with the marble, the pyrope component decreases to 10 mol%, while the grossular and andradite content increases, documented by higher Ca contents (Tab. 1). The omphacite contains about 15 mol% jadeite and acmite respectively. In the vicinity of the contact to the marble the diopside and hedenbergite abundance increases. The amphibole is a pargasitic hornblende which becomes K-poor near the contact with the marble. Oligoclase is the most abundant plagioclase, while the white mica is a phengite with a Si content in the structural formula of around 3.32 and with approximately 10 mol% paragonite component. The epidotes within the eclogites in the vicinity of the marble has a XFe ~ 0.20. Using the garnet-clinopyroxene geothermometer of Ellis and Green (1971) temperatures about 630°C were calculated by Pahr et al. (1990). Formation pressure of around 10 kbar have been determined for the eclogites by using the jadeite content in the pyroxenes (Holland, 1983) and the phengite content of the white micas (Masonne, 1991).

The eclogite-amphibolites have a composition similar to MORB. The chondrite-normalized rare earth element (REE) patterns of both eclogite samples are relatively flat with a slight heavy REE enrichment (Fig. 26). Garnet and epidote in both samples are depleted in light REE and show some similarities in their patterns (Fig. 26). This may be indicative for the replacement of garnet by epidote near the contact to the marble due to high Ca contents as well as an increase in XCO2 according to Allen and Fawcett (1982) and Taylor and Liou (1978). Both, the Ca content and the XCO2 value is controlled by metasomatic infiltration from the adjacent marble into the eclogite.

Mineral chemical characteristics of eclogites/eclogite amphibolite indicate a P-T evolution illustrated in Figure 27. Inclusions of hornblende and epidote in eclogite-facies garnets suggest that an initial epidote amphibolite facies assemblage dehydrated to eclogite. P-T conditions maintained during eclogite formation were c. 670-750° C and 14-16 kbar (based on garnet-clinopyroxene and jadeite-bearing assemblages). Retrogression of eclogite included: 1) replacement of eclogitic omphacite by sodic augite; 2) development of sodic plagioclase symplectite; and, 3) formation of epidote-horblende bearing assemblages. The symplectite formed at c. 500-600° C and c. 6-9 kbar.

The retrogressive transformation of the eclogite to eclogite amphibolite is combined by a mylonitic foliation and stretching lineation (D1). The foliation dips to the SSW, the stretching lineation is marked by stretched garnet aggregates and an hornblende mineral lineation which dips ca. to the S (Fig. 28). E-dipping extension fissures which are partly infilled by amphibole, epidote and chlorite are apparently related to WNW dipping, cm-wide, local shear zones (D2). These ductile shear

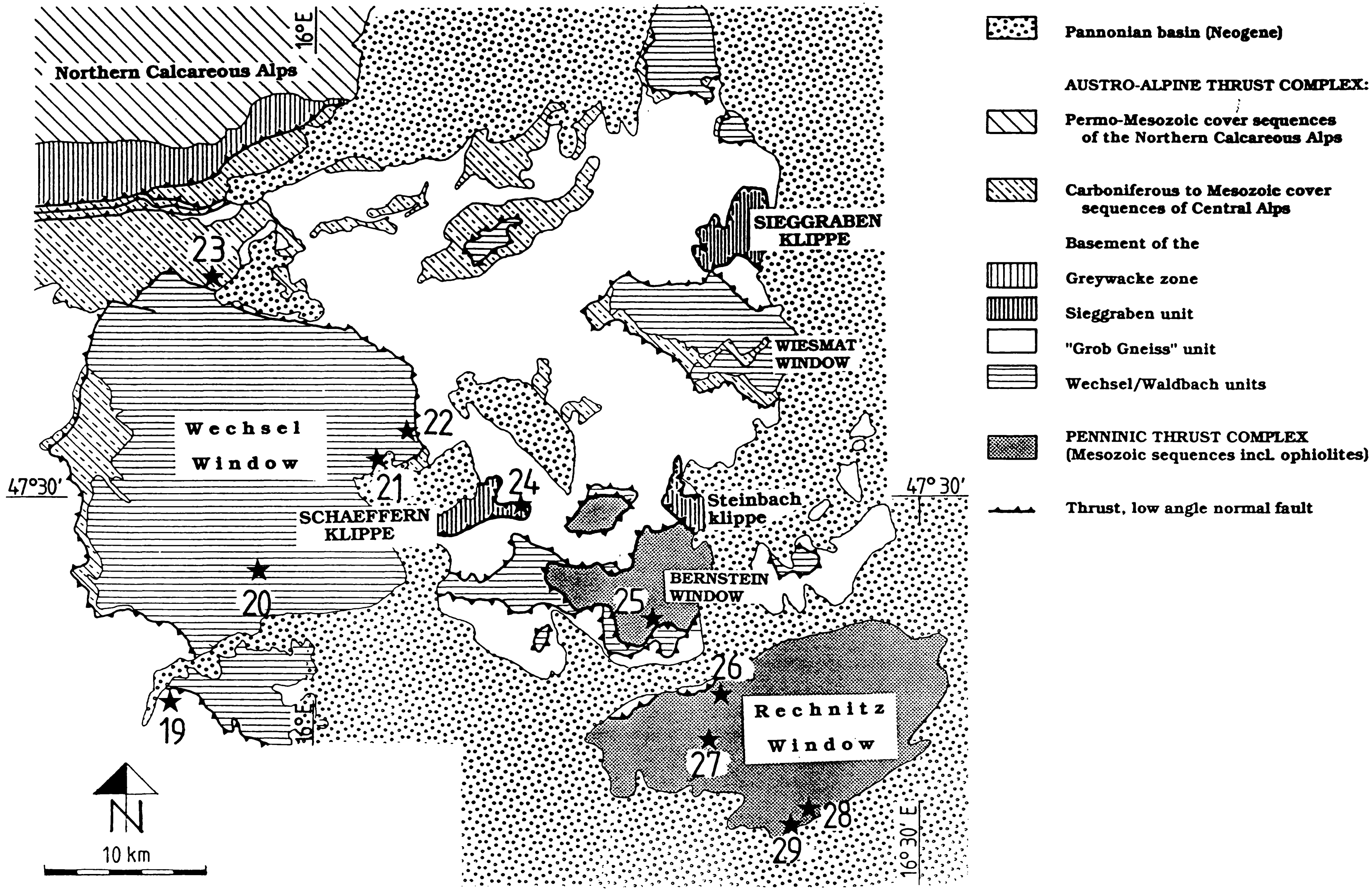


Fig. 25: Locations of stops at the eastern margin of the Alps.

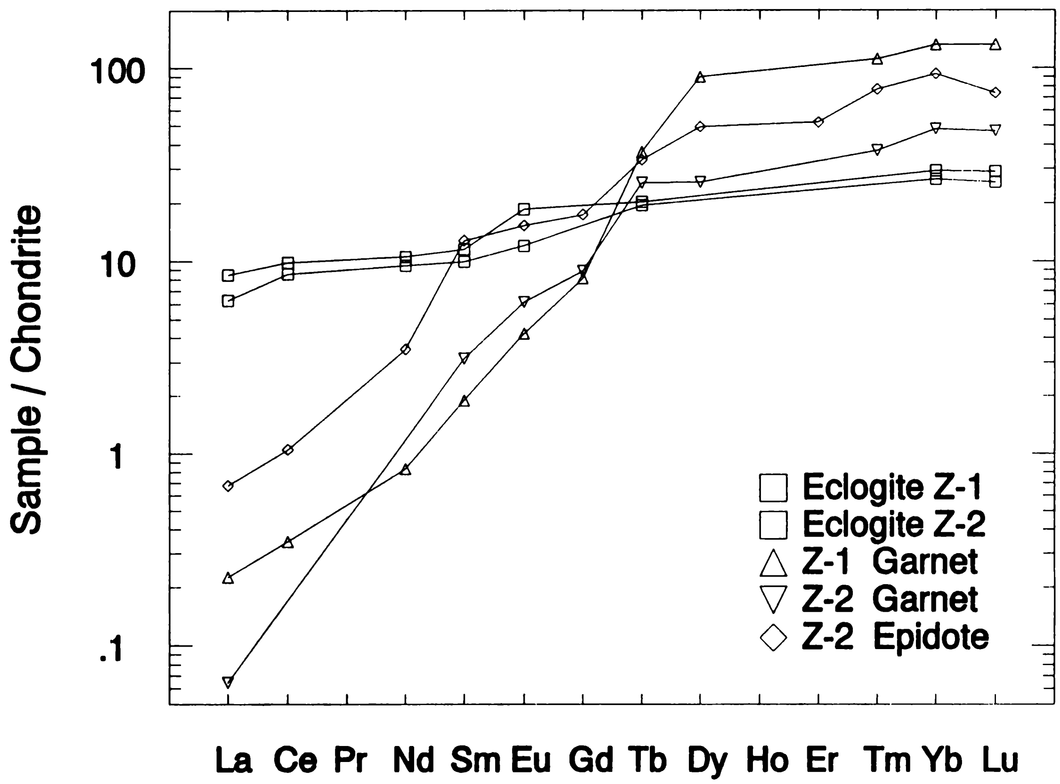


Fig. 26: Chondrite normalized REE patterns for normal eclogite-amphibolite (sample Z-1) and for coarse grained eclogite at the contact towards the marble (sample Z-2). Additional garnets from both samples and one epidote from the marble contact are included. Normalizing values used after Boynton (1984).

Sample	Z1-Gt	Z1-PX	Z1-Amp	Z1-Mu	Z1-Plag	Z2-Gt	Z2-PX	Z2-PX	Z2-Amp	Z2-Ep
SiO_2	38.34	52.59	42.85	49.29	66.44	37.87	51.20	51.83	39.96	39.18
TiO_2	0.18	0.21	0.92	1.02	0.00	0.04	0.27	0.20	0.18	0.21
Al_2O_3	21.66	5.66	12.58	29.14	21.38	21.66	4.81	6.58	15.87	24.98
Cr_2O_3	0.04	0.03	0.10	0.01	0.00	0.02	0.00	0.00	0.04	0.02
FeO	24.05	7.95	13.19	2.26	0.33	23.88	11.71	10.66	21.41	9.03
MnO	0.77	0.06	0.06	0.01	0.00	0.75	0.09	0.03	0.32	0.06
MgO	5.02	10.44	12.23	2.24	0.00	2.72	9.37	8.62	5.86	0.09
CaO	9.69	18.60	10.40	0.05	2.90	13.10	19.50	17.49	11.11	23.89
K_2O	0.00	0.00	0.76	9.17	0.12	0.00	0.00	0.00	0.00	0.00
Na_2O	0.00	3.55	2.87	0.69	9.32	0.00	2.58	3.94	3.24	0.00
Total	99.75	99.09	95.96	93.88	100.49	100.04	99.53	99.35	97.99	97.46

Tab. 1: Representative microprobe data for garnet (Gt), omphacite (PX), amphibole (Amph), plagioclase (Plag), and epidote (Ep) from normal eclogite amphibolite (sample Z-1) and coarse grained eclogite at the contact towards the marble (sample Z-2).

zones show a clear WNW down-dip displacement. Both structures (D1 and D2) are related to the decompression and subhorizontal extension of the Sieggraben Unit.

40Ar/39Ar analyses of two concentrates of hornblende within retrograde assemblages yield similar, internally-discordant age spectra (see Dallmeyer et al., this volume). Most intermediate-temperature increments record similar apparent ages. Isotope-correlation of these date yield plateau isotope correlation ages of 136.1 +/- 0.5 Ma and 108.2 +/- 0.3 Ma. These date the last cooling through c. 500° C.

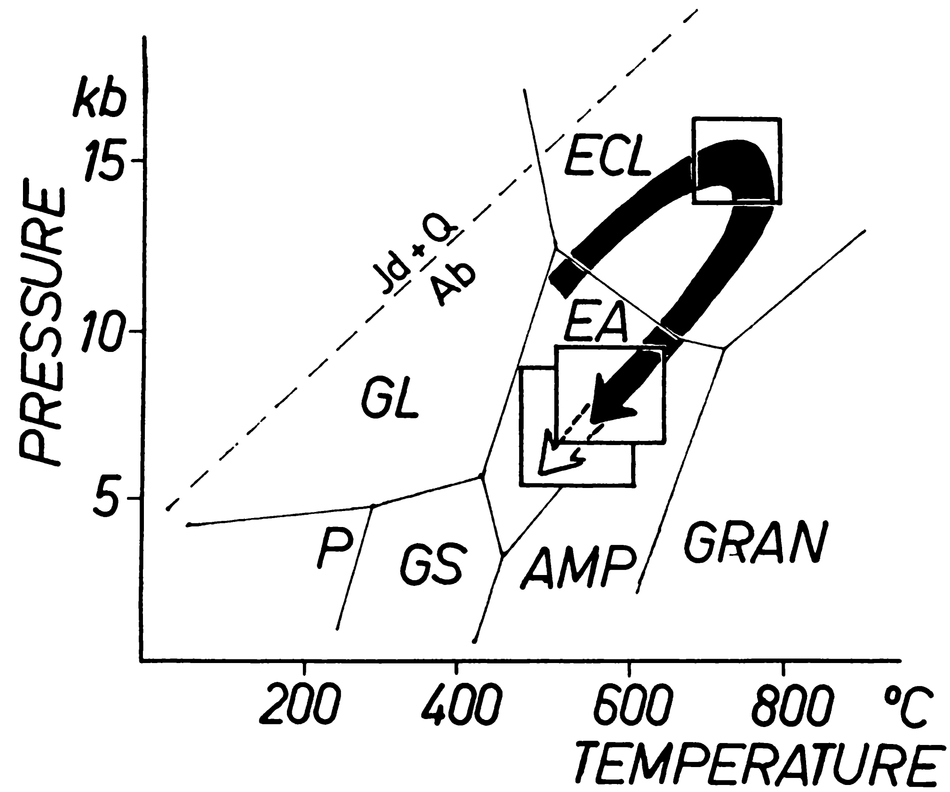


Fig. 27: P-T path of retrogressed ecologites from the Zöbersdorf quarry.

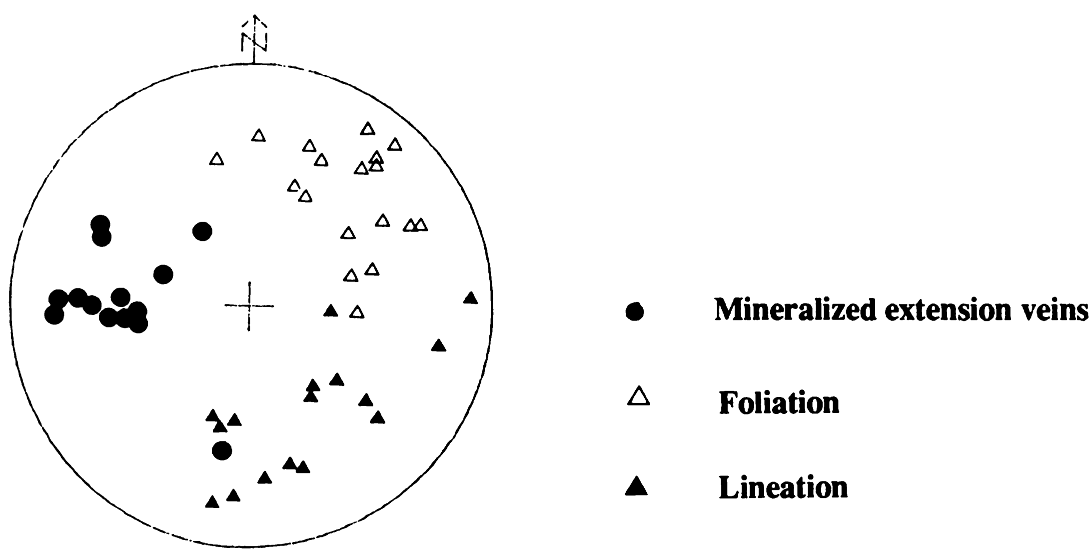


Fig. 28: Structures of Sieggraben eclogites in the Lambert projection.

Alternative models to explain the similar late Jurassic - Cretaceous mineral ages which are recorded throughout the Austro-Alpine Thrust Complex include: 1) The Sieggraben Unit to represent a basement nappe which was buried and remetamorphosed during Cretaceous A-subduction and associated imbrication within the Austro-Alpine Thrust Complex; or, 2) The Sieggraben Unit initiated within a Permo-Mesozoic ophiolitic suture zone during Mesozoic plate collision. The record of Cretaceous ages and high-pressure assemblages argue for development of the Sieggraben Unit within a Jurassic-Cretaceous subduction zone which likely entrained significant portions of Austro-Alpine crust.

Further reading: Dallmeyer et al. in prep.;

The Evolution Of The Rechnitz Window Group

F. KOLLER

The Penninic Unit within the Eastern Alps occurs in different windows. From the West to the East these are the Lower Engadin Window, the Tauern Window and the Rechnitz Window Group. The latter was named by earlier authors "Rechnitzer Schiefer" or "Rechnitzer Serie". From the North to the South four small windows can be determind and they are named: window of Möltern, Bernstein, Rechnitz, and Eisenberg (Fig. 29). Schmidt (1951) was the first assigning the "Rechnitz Serie" to the Penninic Unit. The Mesozoic age of the metasediments was proved by Schönlaub (1973) and the nappe system was documented by drilling (Pahr, 1960). A complete documentation of the metamorphic evolution and the geochemistry of the ophiolites were presented by Koller (1985) The Rechnitz Window Group consists of a tectonically reduced ophiolite, interpretated as fragment of the South Penninic ocean and of a thick metasedimentary sequence. General descriptions are reported by Koller (1985, 1990), Koller and Pahr (1980, 1990), Pahr (1975, 1977, 1980, 1990), Pahr et al. (1990). The metasediments with a thickness of more than 2000 m are formed dominantly by calcareous micaschists ("Bündnerschiefer equivalent") and quartz phyllites, minor by graphite phyllites, marbles, conglomerates, and rauhwackes. The ophiolite sequence, rarely covered by radiolarites up to 10 m thickness, consists of fine laminated greenschists up to 200 m thickness. Primary textures are missing. The plutonic section with clear magmatic relicts and partly preserved primary textures is formed by plagiogranites, ferrodiorites, common ferrogabbros, and Mg rich Cpx-gabbros. The ultramafic rocks are built up by harzburgites and completely serpentinized. A thickness up to 260 m for the serpentinites was proved by drilling. In the Rechnitz Window some of the ultramafic bodies are surrounded by ophicarbonates with a thickness of several meters. Apart for rare magmatic relicts a complex metamorphic evolution is recorded in the mineral assemblages (Koller, 1985). Critical mineral phases are listed in Tab. 1. The following three different metamorphic events have been distinguished by Koller (1985):

1) An oceanic metamorphism restricted to the ophiolites, forms high temperature amphiboles common in gabbros and rare in the metabasalts. Besides an intensive oxidation additional metasomatic changes are observed locally. Even in the ophicarbonates relicts of the oceanic event are present.

2) A low T/high P Cretaceous metamorphic event in the pumpellyite-actinolite facies is proven for the ophiolites and few parts of the metasediments. In the greenschists and adjacent metasediments remnants of the high pressure metamorphism are rare.
Typical mineral phases are alkalipyroxene, ferroglaucophane and Mg-rich pumpellyite, substituted by lawsonite or epidote in Fe-rich parageneses.

3) The last event is documented for all rock types in greenschist facies. White micas show K/Ar ages around 19-22 Ma. From the North to the South a slight increase of temperature is documented by the biotite isograde for metabasic rocks in the northern part of the Rechnitz series and by the first appearance of garnet in metapelites in the Eisenberg Region in the South.

The geodynamic evolution (Koller, 1985, 1990; Koller and Höck, 1987, 1990; Höck and Koller, 1989) starts in the Penninic ocean with a midocean ridge system forming typical N-type MORB. The Penninic ocean seems to be a small basin controlled by transform faults with rapid sedimentation on the oceanic crust. No age values for the initial rifting phase are available for the Rechnitz Window Group so far. A general feature for all ophiolite in the Eastern Alps are the missing sheeted dyke complex. The relatively wide variability in magma composition and the numerous

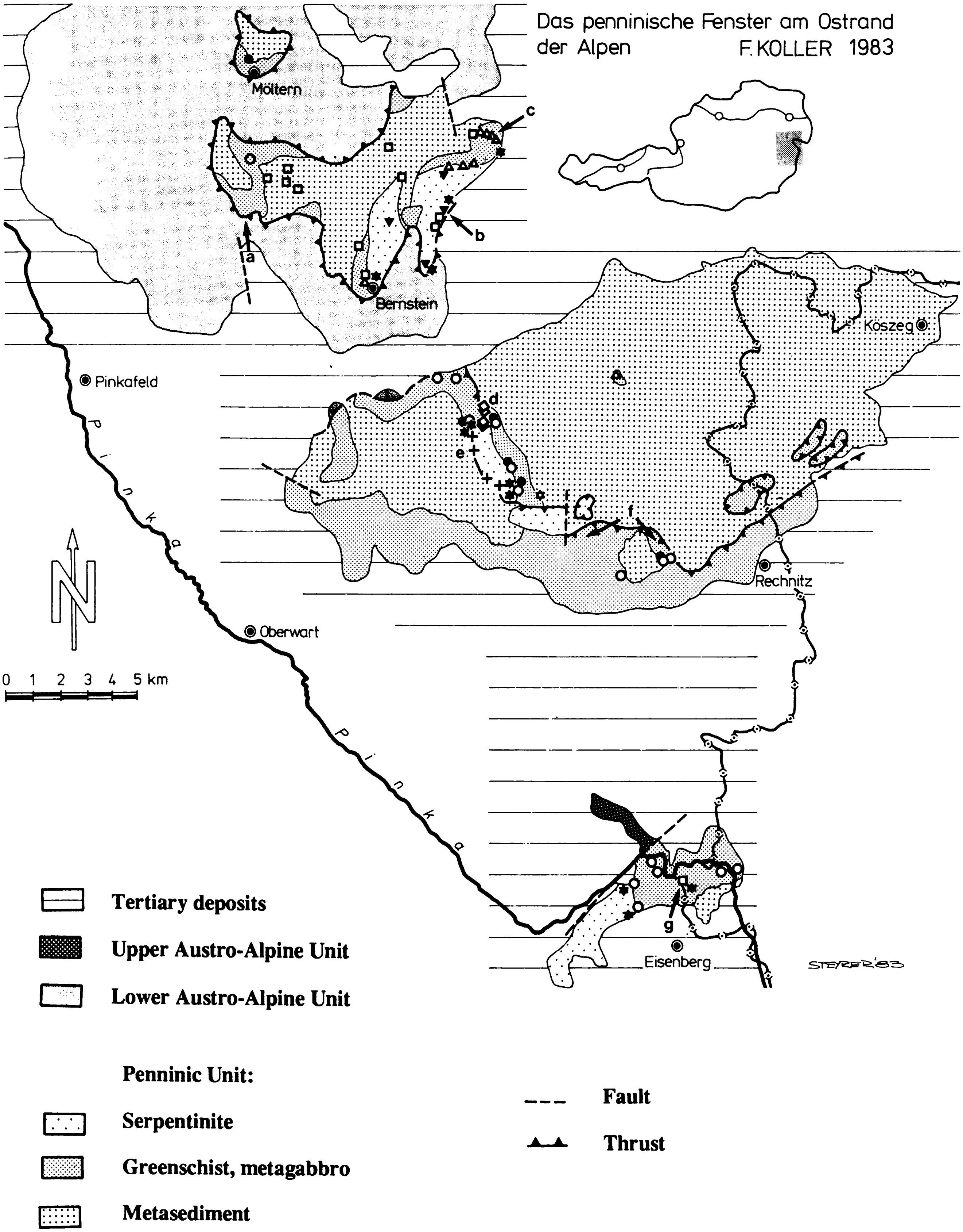


Fig. 29: Geological map of the Penninic Window at the eastern end of the Alps after Koller and Pahr (1980). Symbol legend: Ultramafic rocks, normal Cpx-gabbros, rodingites, ferrogabbos, blueschist (former plagiogranites and diorites), greenschists, albite and epidote rich mobilisations within the greenschists, — non ophiolitic greenschists, + ophicarbonates.

distinct magma groups, especially the widespread plagioclase cumulate basalts (Höck and Koller, 1989; Koller and Höck, 1990) may have formed in small separated magma chambers typical for slow spreading oceans. In few areas small complexes of within plate alkalibasalt, strongly spilitized volcanism, is reported by Koller (1985). The common occurrence of ophicarbonate rocks close to the ultramafics is interpretated as a formation of the ophiolites in the vicinity of a transform fault (Koller, 1985; Koller and Höck, 1990; Höck and Koller, 1989). During a subduction process fragments of the Penninic oceanic crust were metamorphosed in Cretaceous time in a high pressure regime at a depth of about 25-30 km, followed by a rapid uplift and a regional metamorphism under greenschist facies conditions.

This Late Tertiary event took place in a depth of about 10 km. The Penninic rocks were then covered by the Austroalpine nappes. After an uplift and an erosion phase the first unmetamorphosed sediments deposited on Rechnitz series are of Sarmatian age.

Stop No. 25: Penninic Bernstein Window with serpentinite, rodingite, and "Edelserpentin"; ductile low angle normal faulting at the hangingwall boundary of the Bernstein Window.

F. KOLLER, H. FRITZ, F. NEUBAUER

Location: OEK 50, sheet 137, Oberwart. Large quarry ca. 2 km east of Bernstein ("Bienenhütte quarry").

The quarry is situated in the Penninic Window of Bernstein close to the tectonic border of the overlying Lower Austroalpine Wechsel Unit and consists of strongly tectonized serpentinite, rodingitized gabbroic dykes and pure chlorite schists. The latter are locally mined for art crafts and named "Edelserpentin".

The serpentinite contains mainly chrysotile and lizardite, no primary mineral phase has survived. The formation of tremolite, talc or fibrous asbest minerals is related to the last Tertiary metamorphic event. All serpentinites derive, according to their geochemistry, from a harzburgitic source. The metamorphic recrystalization of the Mg-rich Cpx-gabbros can be characterized by the formation of chlorite, actinolite, albite, and Mg-pumpellyite during the high pressure event. Later the pumpellyite is replaced by clinozoisite or at the contact to the serpentinite or within ultramafic bodies by hydrogrossular. Metagabbros with pumpellyite breakdown to clinozoisite show normal Ca composition. In case of a Ca-metasomatism combined with a depletion in Na hydrogrossular is formed. The following reactions have been reported by Koller (1985) and have been used to calculate the metamorphic evolution according to the experimental results by Schiffmann and Liou (1980):

(1) Mg-Al-pumpellyite + chlorite + quartz clinozoisite + actinolite + H2O (2) Mg-Al-pumpellyite + Ca2+ grossulare + chlorite + H2O. The rodingites exhibited in the quarry are boudinated dykes with a thickness up to 2 meter. They show a relative white color and consist of hydrogrossular with up to 1.5 wt% H2O content. According to microprobe analyses the grossular contents range between 75-92 mol%, the other components are andradite and spessartite (up to 3mol%). Almandine and pyrope contents are generally low. The clinopyroxene, locally replaced by chlorite and grossular, is a diopside with typical Cr and Na contents of an ophiolitic gabbro. The chlorite is a Fe-poor clinochlore.

The bulk geochemistry shows high Ca concentrations between 19 - 25 wt.% CaO and a complete removement of Na. All immobile major and trace elements such as Al, Ti, Zr, Y, Cr, and the REE are at the same level as in an equivalent metagabbro without metasomatic effects. These dykes are surrounded by a metasomatic blackwall consisting of pure clinochlore. This reaction zone is equivalent to the monomineralic chlorite lenses common for the serpentinite bodies in this area. The are called "Edelserpentin" and used in local manifactures for art crafts. Koller (1985) has demonstrated by geochemical investigations, that chlorite lenses and blackwall zones around rodingite have a similar composition and origin. They derive from a former gabbro. Some type of chlorite schists have idiomorphic magnetite crystals and resemble some Fe-richer gabbro types.

The outcrop exposes a flatlying, semiductile fault zone a few decameters below the hangingwall boundary of the Penninic Units within the Bernstein Window. The flatlying semiductile fault zone includes semiductile fault surfaces which display the gradual transformation of massive serpentinite into wellfoliated serpentinites (Fig. 30). Shear sense indicators as ESE trending drag folds and S-C fabrics indicate top to the SW shear of hangingwall units. A paleostress analysis yielded a subvertical orientation of the σ_1 principal stress axis (Fig. 30).

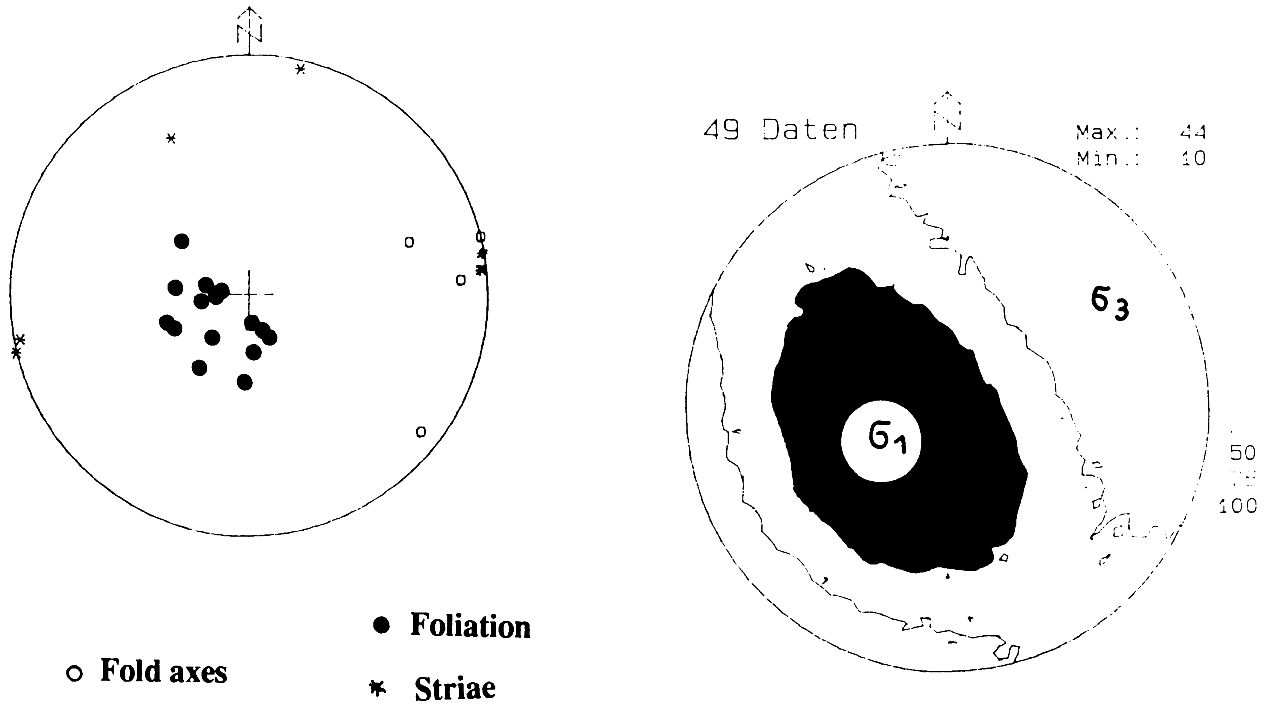


Fig. 30: Structures of the serpentinites.

The fault zone is interpreted as being formed during the uplift of Penninic Units. It apparently separates the Penninic Units with Neogene post-cooling from the Austro-Alpine Units.

Stop No. 26: Quarry near Unterkohlstätten, Window of Rechnitz

F. KOLLER

Additional coments in the eastern part of the Rechnitz Window calcareous phyllites or silicate marbles are the dominant metasediments. They resemble the typical "Bündnerschiefer" and are formed in a marine sedimentation environment.

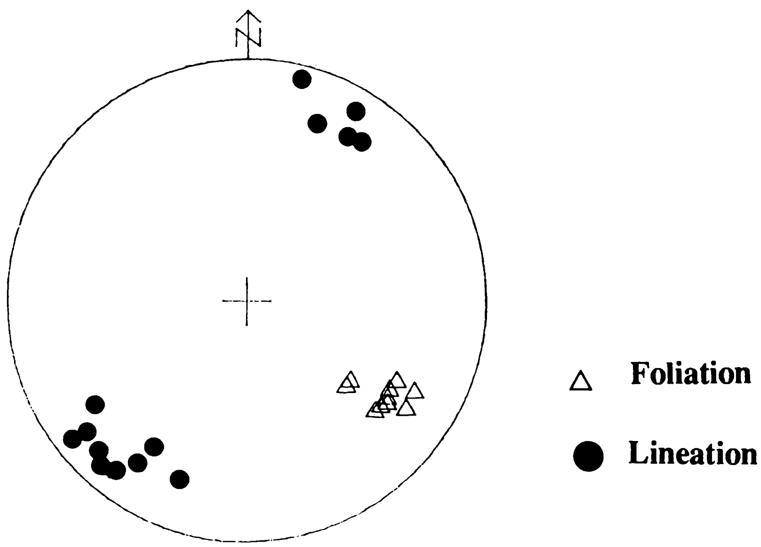


Fig. 31: Structures.

The essential minerals are calcite, smaller amounts of graphite, quartz, phengite, paragonite and chlorit. As accessory phases epidote, tourmaline, sphene and pyrite are common. Analytical results prove the high calcite content up to 90 wt.%. Furthermore high Sr (~ 600 ppm) and S (~ 900 ppm) contents are typical. According to Grum et al. (1992) all of the investigated marbles and calcite sample from the Rechnitz Window have 87Sr/86Sr ratios typical for Lower Cretaceous seawater Sr-isotope composition.

Stop No. 27: Ophicarbonate rocks and other blue amphibole bearing rocks.

F. KOLLER, H. FRITZ, F. NEUBAUER

Location: Glashütten, near Schlaining.

The serpentinite complex south of the Glasbach valley is urrounded by ophicarbonate rocks. These rocks are characterized by coarse grained calcite (ranging from 60-90 wt.%) which is red colored by a fine hematite pigmentation. The following three main types can be distinquished:

1) Ophicarbonate type 1: This type is less common and shows dominant silicate phases such as epidote/clinozoisite, phengite, sphene and rare albite. The geochemistry is characterized by higher Al, Ti and lower Fe, Cr, and Ni contents compared with the other groups. According to Koller (1985) this type is interpretated as mechanical mixture of a gabbroic and sedimentary source rocks.

2) Ophicarbonate type 2: Besides calcite the main mineral phases are alkalipyroxene, alkaliamphibole, Cr-rich epidote, phengite, fine grained and disperse distributed hematite and idiomophic magnetite. Chemically, type 2 is characterized with high Fe, Cr and Ni contents combined with low Al-content. Ti is almost missing. In the silicate portion the Cr values are as high as 1.2 wt.% Cr2O3. The origin of the type is related to mechanical mixture of a chromite rich ultramafic source and the calcarous metasediment.

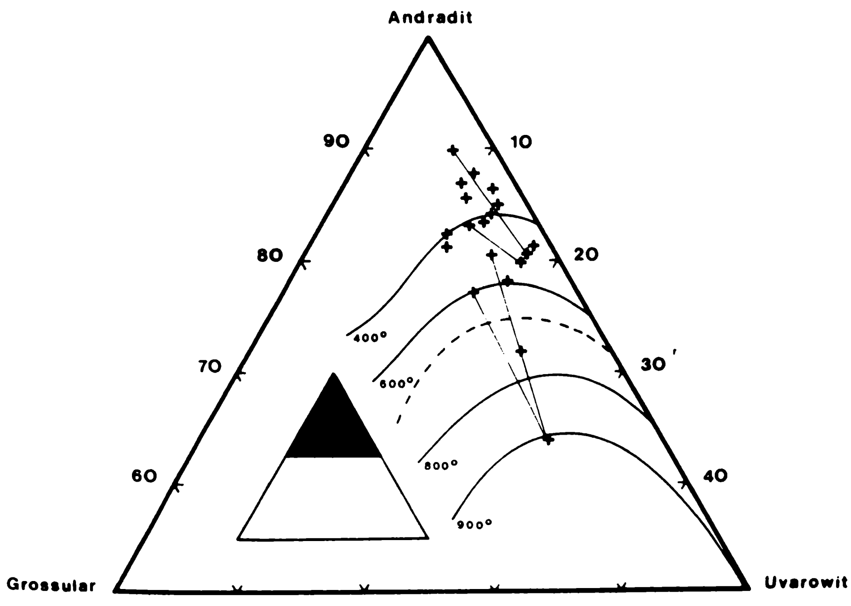


Fig. 32: Plot of the Cr-andradite of the ophicarbonate samples from the Rechnitz Window in the triangle andradite-grossular-uvarovite after Koller (1985). Stability curves for a spinoidale mixing model after Ganguly (1976), broken line for solvus at 800 °C, straight lines connect cores-rim.

3) Ophicarbonate type 3: This lesser deformed type can be characterized by brecciated serpentinite fragments in a carbonate matrix. Typical mineral phases are serpentinite, tremolite and chlorite. According to Koller (1985) this type seems to be a tectonic breccia formed during Alpidic metamorphic events. Chromite has been found as the oldest mineral in all ophicarbonate type 2 and 3 samples. Sometimes this chromite is surrounded by a yellow garnet with high andradite (88-60 mol%) and uvarovite (7-25 mol%) contents (Fig. 32) combined with low grossular and spessartitecomponents. After Ganguly (1976) the formation of these garnets needs relative high temperatures. During the Cretaceous high pressure event the andradite is unstable and is replaced by other minerals. These facts combined with the high grade of oxidation, documented by the hematite pigmentation, are the evidences for a transform fault related origin of this ophicarbonate rocks (Koller, 1985; Koller and Höck, 1990; Höck and Koller, 1989). Recent examples have been reported oceanic fracture zones (White, 1991).

The high pressure paragenesis consists of alkali pyroxene (Fig. 3), Cr-phengite und Cr-epidote and hematite, sometimes chlorite. The alkali pyroxene is replaced during the Tertiary event by a blue amphibole with riebeckitic or magnesioriebecktic composition (Fig. 4) coexisting with idomorphic magnetite octaeders up to a size of 5 mm. The alkalipyroxene is zoned with a core containing 12 mol % jadeite and 60 mol% acmite (Fig. 3). The rim shows a decrease of jadeite and acmite component. The Si values of the phengite range around 3.4 with up to 7 wt. % Cr2O3 contents.

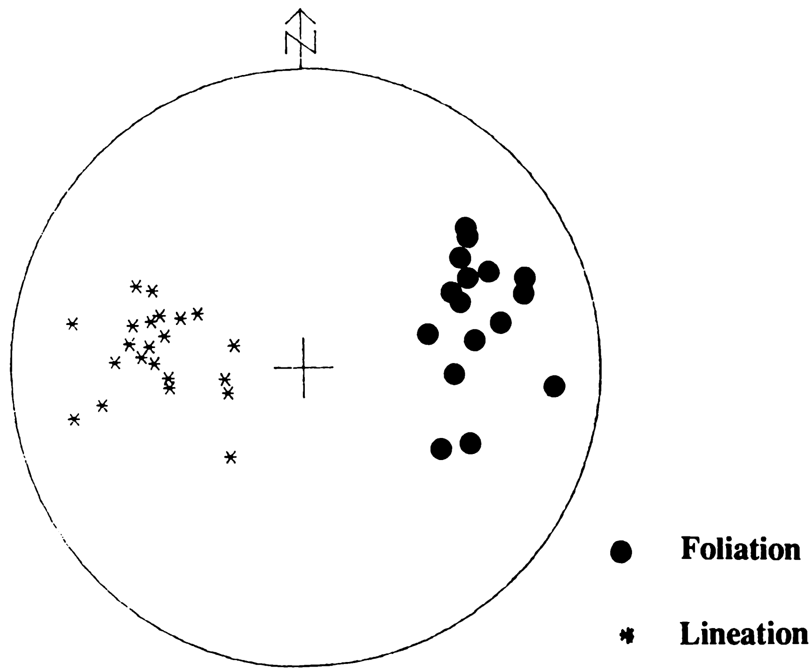


Fig. 33: Structures.

From the villages Oberkohlstätten to Glashütten several small lenses of alkaliamphibole and albite-rich rocks have been mapped by Herrmann et al. (1988). Koller (1985) interpretated these rocks as highly fractionated magmas, strongly enriched in incompatible elements with a ferrodioritic or plagiogranitic composition. High Na2O (6-9 wt%), P2O5 (0.4-1.2 wt%), Zr (700-1440 ppm, Y (200-400 ppm), and REE contents are typical. A flat REE chondritic pattern around 100-200 combined with a CeN/LuN value 1.03 are typical for recent plagiogranites (Coleman and Donato, 1979). Besides large zircon crystals and form relicts after plagioclase no magmatic phase has been found. During the high pressure metamorphism a brown colored acmite (Fig. 34) core (Jd0.22 Ac0.63 Di0.09 He0.06) has formed together with albite, phengite, stilpnomelane, rutile and Ti-bearing hematite. Accessory phases are apatite, epidote, chlorite and pyrite. In few cases the brown alkalipyroxene is overgrown by a green acmit (Jd0.02 Ac0.88 Di0.08 He0.02) coexisting with a blue amphibole. Normally all alkalipyroxenes have been replaced by a crossite or a riebeckite (Fig. 4) coexisting with newly formed idiomorphic magnetite. Stilpnomelane can be partly replaced by green biotite. These reactions are related to the Tertiary event. The amphibole bearing process can be described by the following reaction:

3) 4 acmite + 3 hematite + 8 quartz + H+ = riebeckite

The structure of this outcrop is related to D2-folding of an earlier D1 foliation. The measured foliation is the D2 foliation which surfaces exhibit cm-spacing (Fig. 33). The Cr phengite forms rods parallel to the D2 fold axes.

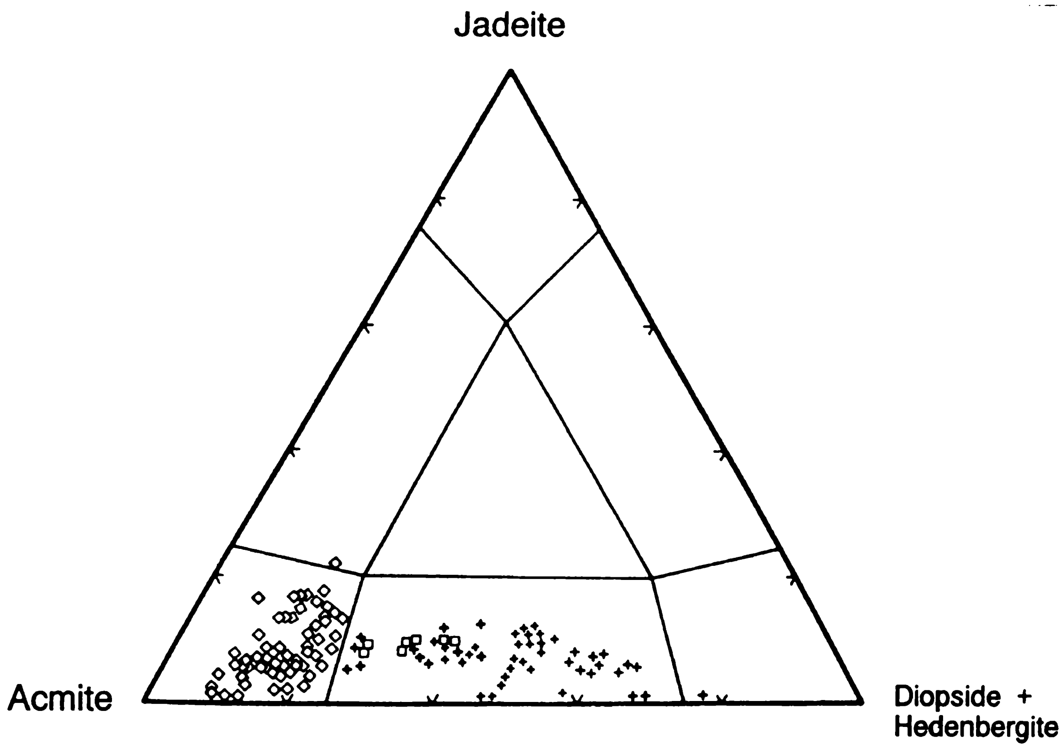


Fig. 34: Jadeite-acmite-(diopsid+hedenbergite)-plot for alkali pyroxenes after Koller (1985), fields in the triangle after Black (1974). Symbol legend: ferrogabbro, blueschist and + ophicarbonate samples

Stop No. 28: Penninic calcschists and greenschists of the Rechnitz Window.

F. KOLLER, H. FRITZ, F. NEUBAUER, E. WALLBRECHER

Location: OEK 50, sheet 138, Rechnitz. Freingruber quarry which is located ca. 2 km NW of the town Rechnitz.

In this quarry greenschists and calcareous micaschists are exhibited, both dipping slightly towards to the north below the serpentinite of Rumpersdorf and "Kleine Plischa". The calcareous micaschists are dark grey colored by graphitic pigmentation and are veined by white recristallized calcite. The total calcite content ranges from 70 - >90 %. Besides calcite variable amounts of quartz, phengite, chlorite, albite, and epidote are present. 10-20 % of the white mica may be paragonite. As accessory phases tourmaline, pyrite and dispers distributed graphite are present. High Sr and S contents are typical (Koller, 1985). Demeny and Kreulen (1989) determined for calcite a δ 18O values ranging form -6.6 to -9.7 and for the graphites of the carbonate rich samples a δ13CGr > -13.0 . This is in accordance with the metamorphic conditions derived from the metabasic rocks and consistent with the Bündner schists of the Penninic Tauern Window (Demeny, 1987, 1989).

The greenschists are massive, sometimes laminated on a fine scale or strongly folded. All primary magmatic textures are extinct. Locally coarse grained mobilisations of albite or calcite exist. Besides rare high pressure relicts only the parageneses of the Tertiary event can be found in the coarse grained mobilisations. The typical mineral assamblage is actinolite-chlorite-epidote-albite-sphene corresponding to greenschist facies.

As very rare older relicts brown or dark green colored hornblende as alteration product of a former clinopyroxene can be mentioned. In few samples complex zoned epidote occurs as a remnant of an older event. In the coarse grained mobilisations locally a winchitic amphibole is present.

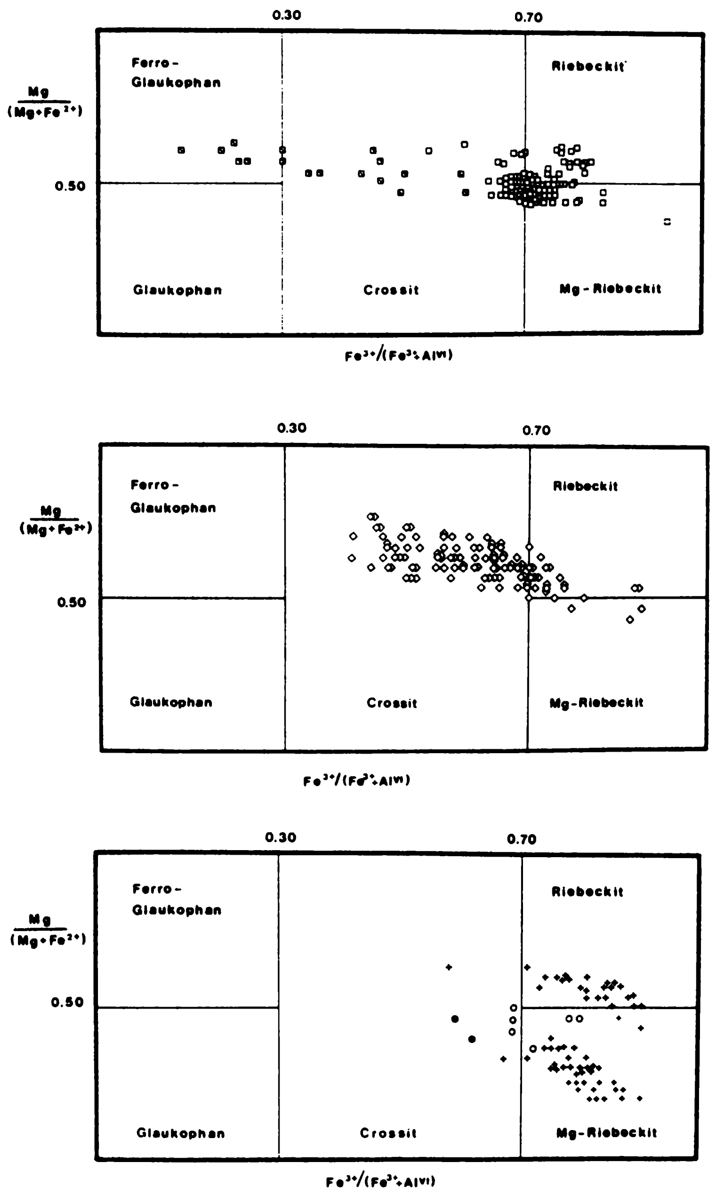


Fig. 35: Alkali amphibole-plot for blue amphiboles of the Rechnitz Window Group after Koller (1985). Symbol legend: ferrogabbro, blueschist and + ophicarbonate samples

All geochemical investigations show a clear N-type MORB composition (Koller, 1985). The distribution of immobile elements including the REE's support this interpretation. Based an the data of Koller (1985) and in comparison with the ophiolites from the other Penninic Windows Höck and Koller (1989) and Koller and Höck (1990) have found the following different fractionation and accumulation processes for the metabasalt genesis:

a) plagioclase accumulation
b) olivine accumulation
c) ilmenite + Ti-magnetite accumulation
d) olivine + plagioclase (+ clinopyroxen) fractionation
e) clinopyroxene + olivine + plagioclase fractinotion

In the metabasalts of the Rechnitz Window Group all five evolution trends exist and support a complex magma evolution model for the South Penninic ocean. The wide spread similar evolution in all Mesozoic ophiolites of the Eastern Alps is caused by effects such as different partial melting degrees of a heterogeneous mantle (Höck and Koller, 1987, 1989; Koller and Höck, 1990). In general comparable features may be found in the evolution of the Atlantic ocean.

The quarry exposes the contact of schistose marbles of the footwall and greenschists in the hangingwall.

The structure is dominated by a flatlying foliation (D1) which also contains a WSW trending stretching lineation. The lower level of the quarry exposes a structural assemblage which overprints the D1 structures. This structural association is dominated by widely spaced semiductile normal faults which also contain a WSW trending stretching lineation resp. striae, N-S oriented, open folds with a westerly dipping axial surface foliation s2 (Fig. 36). Sense of displacement on both normal faults and axial surface foliation is opposite suggesting subvertical contraction (Fig. 36). We interpret the structural association D2 as normal fault with a general top to the ENE sense of displacement of hangingwall Units during the uplift and cooling of the Penninic Units of the Rechnitz Window.

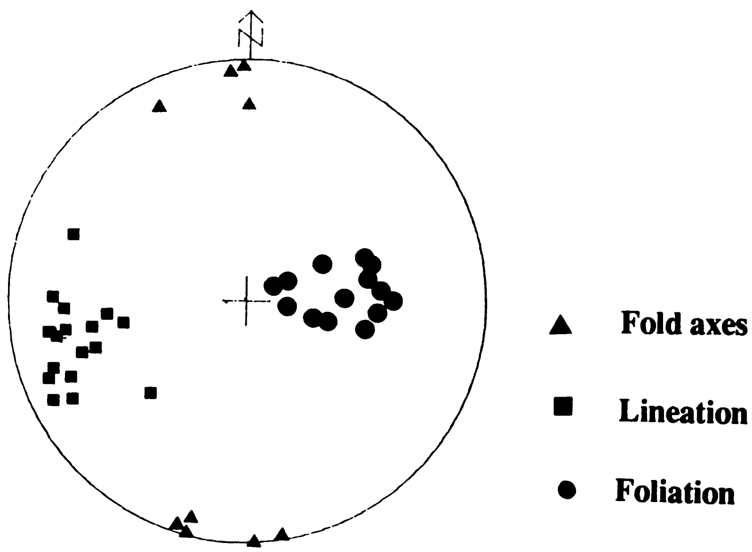


Fig. 36: Extensional structures in stop no. 28.

Stop No. 29: Markt Hodis, Rechnitz Window - Albite porphyroblast bearing calcareous micaschist

F. KOLLER

Location: OEK 50, sheet 138, Rechnitz. From the Freingruber quarry following a forest the excursion reaches an old mining area near the village Markt Hodis.

The route follows a section through the metasediment sequence. Near an old tunnel graphite-coated, albite-bearing calcareous micaschists are exposed. In the fine grained metasediments black albite porphyroblasts up to two cm in diameter occur. This albites show a clear two stage crystallisation with an inclusion rich core and a clear, inclusion free outer rim. The texture of the core inclusions and the grain size of graphite is different from the matrix. In these metasediments evidence for a clear polyphase metamorphic evolution is observable.

Rock type	Magmatic relics	Oceanic metamorphism	High pressure metamorphism	Tertiary event
		< 750-?°C, ≤1 kbar, oxidation and locally metasomatism (Na or Ca)	330-370°C, 6-8 kbar	390-430°C, ≤3 kbar
Ultramafic rocks (normaly Harzburgites)	form relics of Opx, Cpx and spinell	1. serpentinization	2. serpentinization	chrysotile and lizardite/antigorite, locally talc, tremolite and magnetite
Leucogabbro	Diopside	Magnesio hornblende	Mg-pumpellyite (±actinolite-chlorite-albite)	Actinolite-clinozoisite/hydrogrossular-chlorite-albite
Ferrogabbro	Augite, form relics after ilmenite and titanomagnetite	Magnesio hornblende, barroisite and pargasite	Aegirine-augite-stilpnomelane-hematite-rutile-epidotel or ferroglaucophane/crossite-magnetite (±chlorite-albite)	alkali amphibole2-actino^lite-epidote2-chlorite±biotite-albite-magnetite-sphene
Blueschists (former ferro-diorites and plagiogranites)	Zircone, form relics after Cpx and plagioclase	High grade of oxidation	Acmite/crossite-stilpnomelane-hematite-rutile-albite (locally talc+phengite)	jadeite free acmite/alkali amphibole2±biotite±chlorite±epidote-albite-magnetite-sphene
Greenschists (former MOR-basalts)	only rare form relics of Cpx and plagioclase	Magnesio hornblende, rare barroisite	epidote1, rare crossite, stilpnomelane, hematite and lawsonite	actinolite-chlorite-epidote2-albite-sphene
Ophikarbonates	chromite	Cr-andradite, ferrichromite and serpentinization of ultramafic fragments	Aegirine-augite/crossite-tawmawite-Cr-phengite-hematite-stilpnomelane	jadeite free alkali pyroxene/alkali amphibole2/actinolite-calcite-chlorite-magnetite±serpentine±epidote

Tab. 1: Correlation between metamorphic events and critical mineral phases for the typical ophiolite rocks from the Rechnitz Window Group after Koller (1985)

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