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Outline of the Geology of Austria

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With 20 figures, 14 tables and a coloured Geological Map of Austria 1 : 1,500.000

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Foreword

This Outline of the Geology of Austria was produced on the occasion of the 26th International Geological Congress in Paris 1980. It is provided with a coloured Geological Map of Austria in a scale of 1 : 1,500.000. Previously published modern reviews of the geology of Austrian regions available in English are either brief (CH. EXNER, 1966) or dealing only with the Eastern Alps (E. CLAR, 1973) or with their central part (E. R. OXBURGH, 1968).

The chapters dealing with the Molasse Zone, Tertiary Basins, Helvetic Zone, Flysch Zone, Northern Calcareous Alps, Southern Alps, Pleistocene, and the Mineral Deposits have been written by W. JANOSCHEK. A. MATURA has prepared the General Remarks and the Introduction as well as the chapters on the Bohemian Massif, on the Penninic Windows, and on the Central Zone of the Eastern Alps.

The authors express their gratitude to I. DRAXLER, G. FUCHS, R. GRILL, M. HEINRICH, H. HOLZER, A. KRÖLL, G. MALECKI, R. OBERHAUSER, A. PAHR, B. PLÖCHINGER, S. SCHARBERT, W. SCHNABEL, H. P. SCHÖNLAUB, and F. STEININGER, for their valuable comments, respectively for their permission to use not-yet published manuscripts. The English manuscripts has been read by Mrs. A. PÄRTAN to whom we must give special thanks. The figures and tables have mainly been drawn by O. BINDER, S. LASCHENKO, K. UHER and I. ZACK, to all of whom we are grateful for their careful work.

General Remarks

Austria covers an area of about 84 000 km² in the centre of Europe. It has an extension of about 550 km in east-west direction and of about 300 km in north-south direction. The Eastern Alps and the Danube are the most prominent features of the Austrian landscape.

The Eastern Alps are part of a Tertiary mountain belt, passing in a twisted course through the southern part of Europe and continuing both into Africa and Asia. The major part of the Austrian territory is dominated by the mountainous character of the Eastern Alps. They extend in a generally east-west direction and represent the eastward continuation of the Swiss Alps. At their eastern end near Vienna the Eastern Alps swing north-eastwards and pass into the Carpathians. The highest regions in the central part of the Eastern Alps, in the Hohen Tauern, as well as in the western part are glaciated and the summits exceed an altitude of 3000 m. Eastwards the average height of mountains is gradually decreasing.

Near Vienna the Danube cuts across the smooth spur of the mountain chain. Apart from small regions at the western and the northern border, the Austrian territory is entirely drained by the Danube and its tributaries. Upstream, west of Vienna, the Danube valley takes its course along wide low-lands between the smooth northern outliers of the Alps in the south and the well-wooded, moderate mountainous region in the north (Mühlviertel, Waldviertel). In this section the Danube is mainly supplied by the rivers Inn, Salzach and Enns from the northern flank of the Eastern Alps. Not far east of Vienna the Danube leaves Austrian territory. Along its further course towards the Black Sea it is apart from other tributaries supplied by the Drau river which together with the Mur river draines the major part of the southern flank of the Eastern Alps.

The eastern and south-easternmost parts of Austria are occupied by wide low-lands which continue eastwards into the Pannonian plain.

Geological research in Austria has been carried out since the early nineteenth century and has developed particularly in the second half, notably by A. BOUÉ, F. v. HAUER, D. STUR, E. SUESS, M. HOERNESS, and E. v. MOJSISOVICS. Systematic geological mapping of wide areas of the former Austrian-Hungarian monarchy on a scale of 1 : 75 000 was initiated by the Geological Survey in Vienna, which was founded in 1849 as one of the first geological surveys in the world. Among the most well known contributors to classical Austrian geology in the twentieth century F. BECKE, F. E. SUESS, A. WEGENER, O. AMPFERER, B. SANDER, and L. KOBER should be mentioned.

At present research in geology and related sciences is carried out by the Geological Survey in Vienna and by several geological departments at the universities in Vienna, Graz, Innsbruck, Salzburg, and Leoben. Remarkable collections and libraries exist at museums in Vienna, Linz, Graz, Innsbruck, Salzburg, and Klagenfurt.

General geological maps of Austria are available on a scale of 1 : 1,500 000, 1 : 1,000 000, and 1 : 500 000, special geological maps essentially on scales of 1 : 50 000 and 1 : 25 000. A list of periodicals dealing with the geology and related sciences in Austria and of the most important books about the regional geology of Austria are to be found at the end of the paper.

Introduction

Austria is subdivided into following units, arranged from north to south, according to their paleogeographical position:

Bohemian Massif	
Molasse Zone	
Helvetic Zone	
Penninic Zone	Flysch Zone
	Penninic Windows
Austro-Alpine Unit *)	Central Zone of the Eastern Alps
	Northern Calcareous Alps
Southern-Alpine Unit	

The northern part of Austria is occupied by the southern margin of the *Bohemian Massif*. This unit exhibits a deeply eroded remnant of the middle-European branch of the Variscan orogenic system with older structural elements. It is built up in Austria essentially by medium-grade metamorphic rocks of Precambrian to Palaeozoic age and extensive granite plutons of Variscan age. The major part in the center is considered as the Moldanubian Zone with a regional strike of abouth north-north-east—south-south-west. A deeper monotonous group of paragneisses can be very well distinguished from a higher variegated series with more or less graphitic marbles as typical intercalations. The highest tectonic position is occupied by relatively extensive masses of Ordovician granulite and orthogneiss. This tectonic position is probably the result of Caledonian or early Variscan movements.

*) Denotes a tectonic unit; used here synonymously to the German term "Ostalpin" and should be carefully distinguished from the geographic term „Eastern Alps".

According to F. E. SUESS the external zone in the eastern part of the Bohemian Massif is called Moravian Zone. It chiefly consists of the pre-Devonian Thaya pluton and a series of low to medium-grade metamorphic ortho- and pararocks. During the Variscan period the Moravian Zone probably had been overthrust by the Moldanubian Zone from west. This assumption, however, is not unanimously accepted.

In the western part of the Bohemian Massif in Austria extensive migmatisation, metablastesis and locally anatexis was caused by the emplacement of an earlier generation of granitic masses of the Variscan Moldanubian pluton. This event was accompanied by synintrusive tectonic movements; the older Moldanubian structures vanished in this area and were replaced by new structures with a strict regional strike in northwest-southeast direction (Bavarian Zone). Subsequent granitic intrusions were unaffected by these tectonic movements.

Two main sets of late to post-Variscan faults cut across the Bohemian Massif in north-east and north-west direction, controlling narrow furrows and basins in which a thin post-Variscan sedimentary cover (Permian to Tertiary) is preserved.

The Bohemian Massif with its locally developed post-Variscan sedimentary cover dips southwards and eastwards below the Molasse basin and further continues below the Alps where it has been recorded by some drillings.

The *Molasse Zone* comprises a sequence of detrital sediments of Late Eocene to Middle Miocene age, overlying unconformably the foreland basement. The succession is up to 4000 m thick and was deposited both under marine and brackish-water conditions. Two structurally different parts can be distinguished. The major part has only been affected by steep faulting (Foreland Molasse). In the south, however, the Molasse sediments are more severely deformed (Sub-Alpine Molasse), namely by the nordward moving thrust-sheets of Flysch and Helvetic Zone during later orogenic phases. Its continuation north of the Danube is known as Waschberg Zone. Molasse sediments continue far beneath the Alps.

The *Helvetic Zone* represents the narrowed eastern continuation of the Swiss Helvetic Zone. This stratigraphic-tectonic unit has fairly prominent outcrops near the Austrian-Swiss border south of Bregenz. East from there, however, it is restricted to narrow southward dipping thrustslices along the junction between the Molasse Zone to the north and the Flysch Zone to the south. East of the Enns river the tectonically corresponding unit is called Gresten Klippen Zone. It is only exposed in tectonic windows within the Flysch Zone, and locally along the boundary between the Flysch Zone and the Northern Calcareous Alps. Both, Helvetic Zone and Gresten Klippen Zone comprise a series of limestones, marls and rare sandstones, ranging in age from lower Jurassic to Eocene. These intensively deformed rock successions have been sheared off from their basement and transported northward.

The *Flysch Zone* which is the northern part of the *Penninic Zone,* is a tectono-stratigraphic unit which forms an east-west trending belt of Cretaceous and Palaeogene sediments. It extends westwards into the Western Alps and eastwards into the Carpathians. This zone is the surface outcrop of a southward dipping thrust-sheet which has overridden the Helvetic Zone to the north and itself is overridden from the south by the Northern Calcareous Alps. The Flysch Zone has a complex internal structure. The rock series consist predominantly of marls and sandstones with graded bedding. The original site of this complex is assumed to be south of the Helvetic Zone and is generally considered as the youngest and northermost part of the Penninic Zone.

The other part of the *Penninic Zone* in Austria appears in a number of tectonic *windows* below the Austro-Alpine Unit along an axial culmination in the central part of the Eastern Alps. At the western margin of the Eastern Alps the tectonic superposition of the Austro-Alpine Unit upon the eastward plunging Penninic system of the Western Alps is impressively exposed. The *Tauern Window* in the district of the Hohe

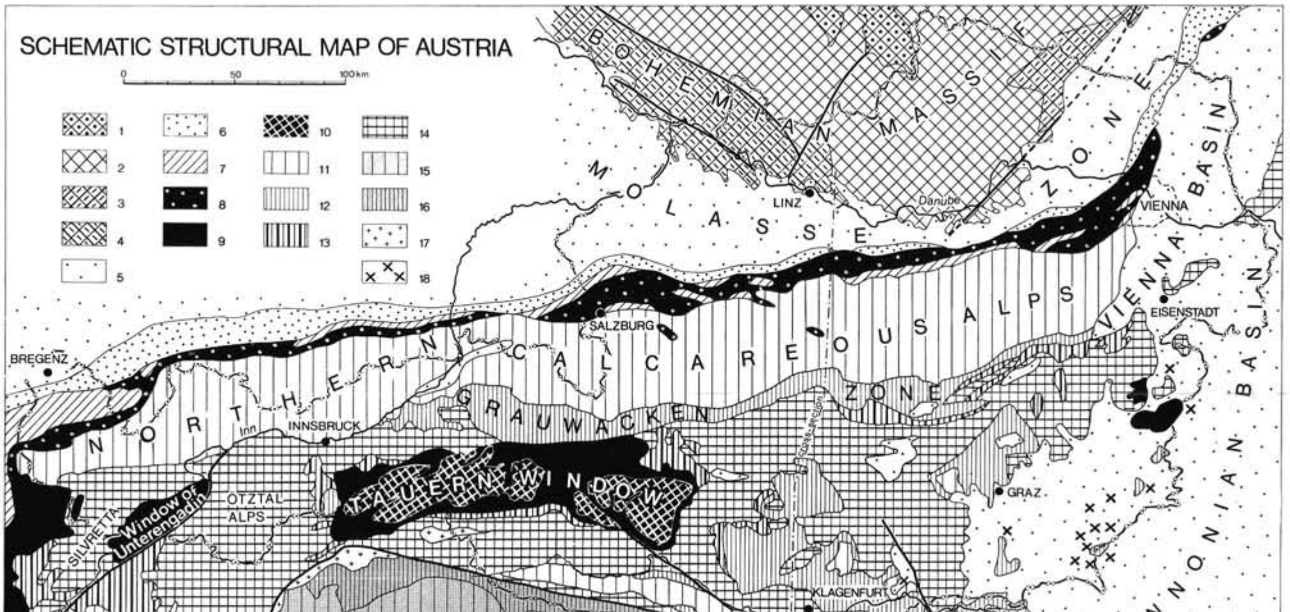


Fig. 1: Schematic structural map of Austria (after P. Beck-Mannagetta & A. Matura, 1980). 1—4 = Bohemian Massif: 1 = Post-Variscan sedimentary cover; 2 = Moldanubian Zone; 3 = Moravian Zone; 4 = Bavarian Zone; 5 = Tertiary basins; 6 = Subalpine Molasse; 7 = Helvetic and Klippen Zone; 8 = Flysch Zone; 9 = Metasedimentary rocks of the Penninic Zone; 10 = Crystalline basement of the Penninic Zone; 11—14 = Austro-Alpine Unit; 11 = Permomesozoic in North-Alpine facies; 12 = Palaeozoic; 13 = Permomesozoic in Central Alpine facies; 14 = Crystalline basement ("Altkristallin"); 15 = Permomesozoic of the Southern Alps; 16 = Palaeozoic of the Southern Alps; 17 = Periadriatic intrusive masses; 18 = Neogene andesites and basalts. Cross-section see fig. 2.

Tauern is the most prominent occurrence of Penninic rocks within the Eastern Alps. The whole complex comprises a crystalline basement (chiefly Hercynian granites and migmatites) and Palaeozoic and Mesozoic metasedimentary series. The major part is occupied by the Jurassic portion of the succession which is represented by eugeosynclinal, more or less calcareous phyllites and notable ophiolitic intercalations. The complicated tectonic structure of the Penninic system and the epi- to meso-zonal metamorphism of the Penninic rocks is a consequence of the Alpine orogenic events.

The *Austro-Alpine Unit* occupies the highest tectonic position in the Eastern Alps. This huge allochthonous thrust-sheet exhibits an extreme complex internal structure. In vertical direction it can be subdivided into two (Upper and Lower Austro-Alpine) or three (Upper, Middle and Lower Austro-Alpine) subunits, each of which comprises a pre-Alpine crystalline basement with its Palaeozoic and Mesozoic sedimentary cover. The *Northern Calcareous Alps* occupy the highest position and form a wide belt of Mesozoic rocks in the north. They extend more than 500 km in east-west direction and about 50 km in north-south direction. The underlying series with prevailing crystalline rocks are exposed in the Central Zone of the Eastern Alps. The Northern Calcareous Alps rest in a zone of net basement depression, the Central Zone or axial zone is a zone of net basement elevation. The west-end of the Austro-Alpine Unit at the Rhine valley impressively exhibits the superposition upon the deeper tectonic units. At the eastern end, apart from small somewhat questionable joints towards the Carpathians, the Austro-Alpine Unit is buried by Neogene sediments. On the northern flank of the Northern Calcareous Alps the thrust-faults are dipping southwards and the sheets have moved northwards over the Flysch Zone. These extensive horizontal movements are proved by a certain number of small tectonic windows (up to 20 km south of the northern front of the Calcareous Alps) where the Flysch Zone appears. South of the Northern Calcareous Alps there is a belt of Palaeozoic rocks dipping northward under the Northern Calcareous Alps. This zone is called *Grauwackenzone* and is considered to be the sedimentary base of the Permo-Mesozoic succession of the Northern Calcareous Alps. The broad area south of the Grauwackenzone in our scheme of description forms together with the latter the *Central Zone of the Eastern Alps*. In this zone igneous and metamorphic rocks are prevailing. In some places it is interrupted by those already mentioned tectonic windows which expose the underlying Penninic system. Parts of this crystalline complex are covered by Palaeozoic and by Permomesozoic meta-sedimentary series. The nature of the contact is partly a tectonic one and partly a sedimentary one.

The Austro-Alpine Unit is bounded in the south by the *Periadriatic Lineament* which is an important

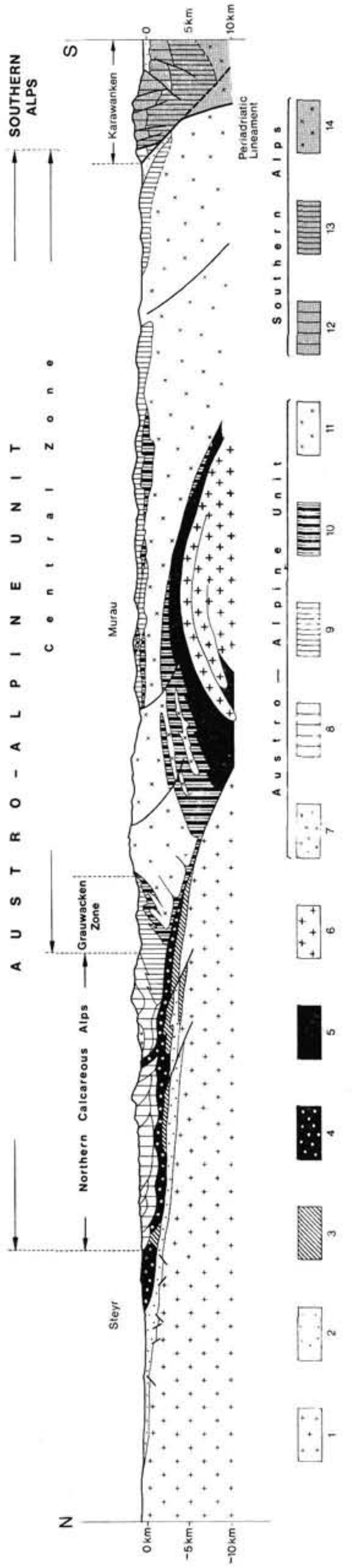


Fig. 2: Schematic cross-section of the Eastern Alps along the line Linz — Klagenfurt (modified after S. Prey, 1976; for exact position of the cross-section see fig. 1). 1 = Extra-Alpine basement of the Bohemian Massif; 2 = Molasse Zone and intra-Alpine Tertiary (post-upper-Eocene); 3 = Helvetic Zone 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.

fault system. The adjoining zones are intruded by several minor, granitic to tonalitic masses of probably Alpine age.

South of the Periadriatic Lineament follows the *Southern-Alpine Unit* that continues towards east into the Dinarides. Only a narrow section of this extensive unit occurs in the southernmost part of Austria. It comprises a sequence of Palaeozoic and Mesozoic rocks.

Near Vienna the main Alpine belt is cut across by the *Vienna Basin,* a fault-bounded zone of thick Neogene sediments. Further occurrences of Tertiary sedimentary rocks within the Eastern Alps are confined to several small fault-bounded intramontaneous basins. The lowlands in the eastern and southeastern part of Austria are occupied by Neogene sediments. Neogene volcanic activity is evident by local occurrences of andesites and basalts.

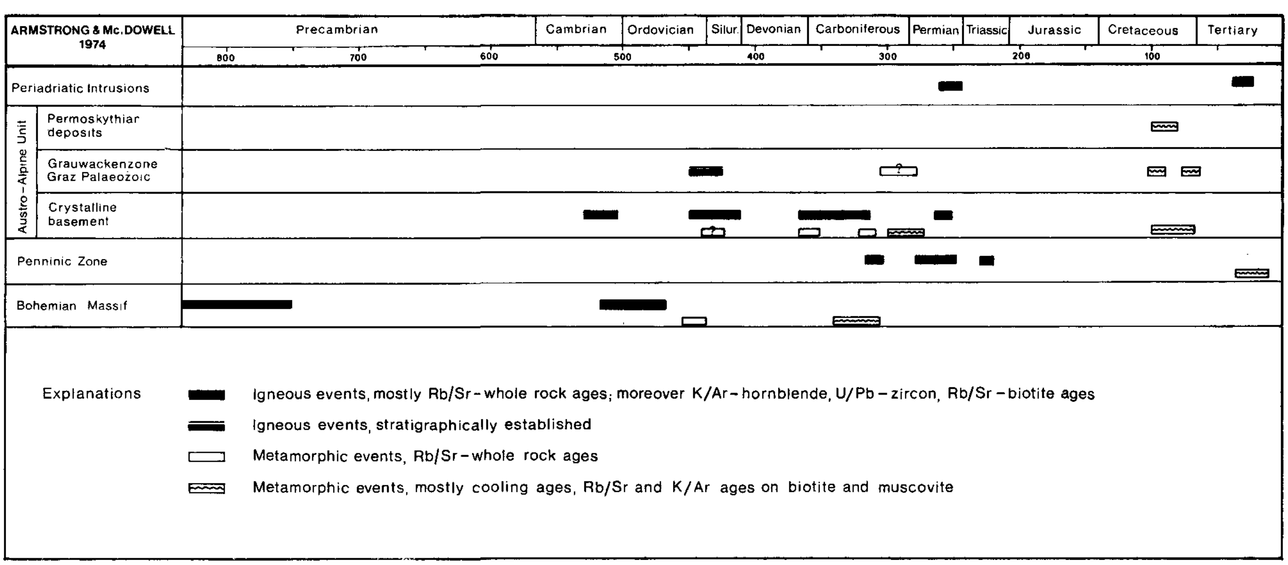
The glacial epoch during the Pleistocene had an important influence on todays landscape. Proofs of glacial erosion and deposition are widespread and allow to distinguish at least four phases of glaciation.

The Geological History of Austria

The geological history of Austria is dominated by the Variscan and Alpine orogenic events. The knowledge about the preceding history of the non-metamorphic or low-grade metamorphic Early Palaeozoic series of the Eastern Alps is rather well established but still contains considerable hypothetical elements. The conceptions about the developments of the crystalline complexes of the Eastern Alps and the Bohemian Massif, however, are more hypothetical and mainly based on some radiometric dates. The portions of Pre-Cambrian rocks are practically unknown.

Within the Austrian part of the Bohemian Massif the oldest rock type so far detected by radiometric dating is the Bittesch Gneiss which yielded an age of 800 m.y. The intrusion of the Thaya Batholith is probably of Cadomian age. The educt age of the Moldanubian and Moravian para-series of the Waldviertel is considered to be partly Pre-Cambrian partly Early Palaeozoic. Whether their medium to high-grade metamorphism and strong deformation — including the eastwards Moldanubian overthrust — has been caused by Caledonian and/or Variscan events is a matter of controversy. However, the age of 430 m.y. of the granulite metamorphism is a strong evidence of a Caledonian event. From the uppermost Devonian to upper Carboniferous the Variscan plutonites intruded the Moldanubian metamorphic series in several phases. In the area of the Mühlviertel the early stages of these magmatic events were associated with strong deformation.

During the late Carboniferous, uplift and erosion began. Subsequently the consolidated basement was broken by two major sets of fault-systems, striking



Tab. 1: Igneous and metamorphic events, based on geochronological studies (compiled by S. SCHARBERT).

north-east or north-west. Relics of a late Palaeozoic terrestrial sedimentary cover were preserved in narrow basins that subsided along prominent faults.

In the area of the Eastern Alps monotonous pelitic to psammitic sediments associated with episodic basic igneous rocks and tuffs have been accumulated in pre-Silurian times. From about 500 to 430 m.y. an extensive acid igneous activity is evident. Various granites and the significant upper-Ordovician quartz-porphyry of the Grauwackenzone are allocated to this event. There are some radiometric indications for metamorphism and associated deformation during the time interval between 440 and 410 m.y. These deep-seated events are supposed to be reflected at the surface by widespread stratigraphic gaps at the Ordovician-Silurian boundary and by the facial differentiation of the succeeding Silurian deposits (mainly pelitic and carbonate rocks, interbedded by volcanic rocks). During the Devonian mainly carbonate rocks were formed. During the Carboniferous the Variscan movements caused strong folding and thrusting accompanied by regional metamorphism ranging up to amphibolite facies conditions. The associated magmatic activity continued into the Permian.

After an erosional phase the Alpine cycle began with the sedimentation of clastic material in the uppermost Carboniferous and Permian. Subsequently the sedimentary conditions were passing over into a marine regime. During the Permian evaporites were formed in extensive areas of lagoonal-salinar environment. During the Triassic a number of distinct east-west trending facies belts became established. Whether or not these belts were controlled by elongated ridges or island arcs is in discussion.

The subsidence during the Triassic appears to have been greatest in the south, an area which was going to become the Northern Calcareous Alps and the Southern Alps (North-Alpine and South-Alpine facies belt). Sporadic volcanic activity during the Permian and early Triassic indicates rifting of the continental lithosphere. The thickness of the very differentiated and extensive carbonate platform of the middle to late Triassic section exceeds 3000 m in the area of the North-Alpine facies belt. The Central Alpine facies belt next to the north exhibits a smaller thickness of the Permo-Triassic succession with special lithofacial and biofacial features indicating a certain foreland influence. In the northward joining Penninic realm this trend continued and resulted in a thin Permo-Triassic sequence with a more pronounced episodic "Germanic" (epicontinental) influence.

During Jurassic times the axis of maximum subsidence began to shift from the Austro-Alpine facies belt towards north. There is much evidence of contemporaneous movements, local elevations, olisthostromes, and subareal erosion in the area of the Northern Calcareous Alps.

In the Penninic realm the opening to a wide ocean occurred. A minimum width of 250 to 400 km is suggested by some authors. The facies of the thick Jurassic and Early Cretaceous rock sequence (Bündnerschiefer) suggests eugeosynclinal conditions. Ophiolitic intercalations within the Bündnerschiefer indicate a deposition upon an oceanic crust. In the southern part of the Penninic trough the Bündnerschiefer deposition was continuing into the Cretaceous, but it is uncertain how

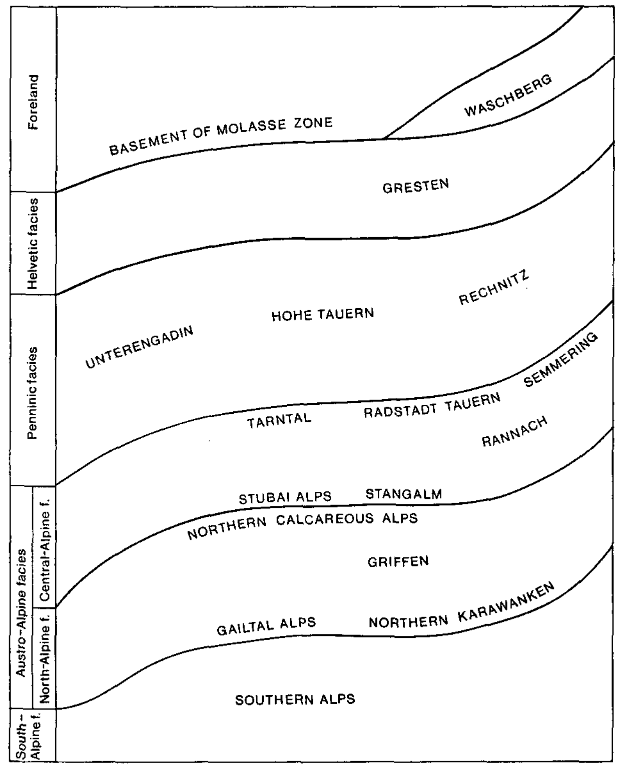


Fig. 3: Paleogeographic scheme of the Eastern Alps before the Alpine orogeny.

long this has taken. In the northern part of the trough, however, where the rocks of the Flysch Zone were formed, deposition locally continued into the Eocene. North of the Penninic trough, in the Helvetic Zone and its northward continuation on to the gently sloping flanks of the Bohemian Massif very slow discontinuous deposition had been going on throughout the Jurassic and Cretaceous. The influence of the northern epicontinental facies is prevailing.

In the late Early Cretaceous major movements (Old-Alpine orogenic events) began in the realm of the Austro-Alpine facies belt and the closing of the Penninic ocean started by subduction of the Penninic oceanic crust under the Austro-Alpine and South-Alpine sialic crust. As a result of compressional deformation the Austro-Alpine realm was dissected into a number of nappes, each thrusting and gliding northward on top of the respective neighbouring unit. Thus, a pile of extensive but comparatively thin superjacent sheets was formed (the Austro-Alpine Unit). Within the area of the Northern Calcareous Alps more or less east-west trending parts were elevated and became detached from their basement to slide as thin sheets over other Calc-Alpine rocks. Two main phases can be distinguished: the Austric (pre-Cenomanian) phase and the pre-Gosau phase. Between the two phases marine clastic sediments were deposited along the northern margin of the Northern Calcareous Alps. After the pre-Gosau phase from Coniacian to Eocene a sedimentary sequence (the Gosau Formation) was deposited unconformably upon the deformed Calc-Alpine basement. The sequence, which is highly variable both in thickness and in facies (reefs, marls, turbidites, clastics, conglomerates), itself provides evidence of continuing Late Cretaceous movements.

During the Campanian a marked change in the heavy mineral assemblage of the Gosau Formation by disappearing of chromite in favour of garnet took place. That indicates at least that the Penninic ophiolites were buried by the northward advance of the Austro-Alpine Unit. Some authors think that during this intra-Gosau phase together with the elimination of the Penninic ophiolites, the entire Penninic trough in the area of the later Eastern Alps was subduced. The objections to that hypothesis of complete subduction of the Penninic trough, however, are the evidence of sedimentation continuing into the Early Tertiary in the Penninic Engadine and Rätikon areas, as well as difficulties which arise from the general continuity of sedimentation in the Gosau region, the Flysch Zone and Helvetic Zone from late Cretaceous into the Tertiary.

The main Alpine movements (Young-Alpine orogenic events) began in the Eocene. According to some authors these events are connected with the collision of continental plates at the end of the continuous southward subduction of the Penninic oceanic lithosphere during Late Cretaceous and early Palaeogene. At first the Penninic realm was buried by the main pile of the Austro-Alpine nappes. Differential movements affected both the Penninic basement and its sedimentary cover and produced thrusting and folding with a variety of axial directions. Subsequently the Northern Calcareous Alps, which at that time already formed the front of the Austro-Alpine Unit, were moved northwards upon the Flysch Zone and the Helvetic Zone, pushing up sheets of these units which were completely detached from their basement.

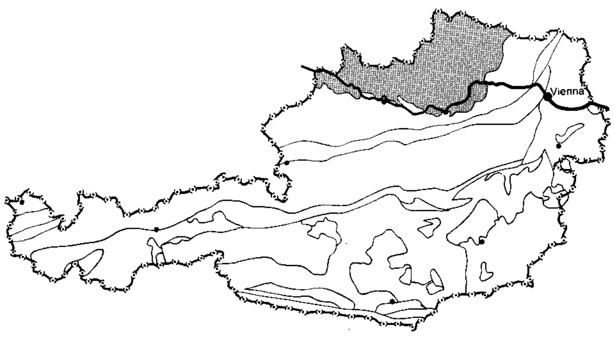
On the base of radiometric age determinations the development of the Alpine regional metamorphism can be correlated with the main orogenic events. Low to medium-grade regional metamorphism of old-Alpine age affected major parts of the Austro-Alpine Unit. Even parts of the Northern Calcareous Alps were slightly influenced. Blueschist and eclogite facies minerals in the Penninic rocks of the Tauern Window are probably of the same age. Young-Alpine regional metamorphism of low to medium grade is restricted to the Penninic Zone of the Tauern Window. The Alpine magmatism is evident both by a series of Late Eocene to Oligocene tonalite and granodiorite bodies (the Periadriatic Intrusions), which are closely following the southern margin of the Austro-Alpine Unit, and by a generation of various dykes.

Finally, caused by isostatic movements and under persistent compression, a net regional elevation of the central zone of the Austro-Alpine Unit happened. Not only did this axial zone begin to undergo rapid subaerial erosion, supplying clastic debris northwards over peneplains of what was going to become the Northern Calcareous Alps into the Molasse basin, but also a further northward movement by gravitational gliding off the rising axial zone, connected with episodic advance of the nappe pile over the Molasse basin occurred as well as southward overthrusting upon the central arching zone. At about mid-Miocene times the Penninic system became exposed in the Tauern Window. Final northward overthrust movements at the margin of the Molasse Zone became younger towards the east and ceased before the Middle Miocene near Vienna. During the late Palaeogene an anticlockwise rotation of the Southern-Alpine Unit is assumed to have been connected both with strikeslip faulting along the Periadriatic Lineament and probably with the westward thrusting of the Ötztal mass.

During Neogene times locally intramontaneous fault-bounded basins developed and were filled up with marine and lacustrine sediments. The most important is the fault-bounded Vienna basin which cuts across the Alps near Vienna and buries their continuation into the Carpathians under several thousand metres of Neogene beds. Evidence of Neogene volcanic activity exists at the eastern end of the Eastern Alps in the Styrian Neogene basin. In Pliocene times the mountainous character of the Alps developed. The net regional elevation has been persistent until present time. Seismic activity is still going on, chiefly confined to a north-east—south-west trending zone between Vienna and Villach.

During the Pleistocene the Eastern Alps underwent several phases of glaciation and glacial and interglacial deposits are widespread.

The Austrian Part of the Bohemian Massif



The crystalline rocks of the Bohemian Massif extend from Bavaria and Czechoslovakia to the northern part of the Austrian territory and in the south are roughly bounded by the Danube. The western part of this region is known as Mühlviertel, the eastern part is called Waldviertel. In some places the outcrops of this crystalline basement extend up to 20 km south of the Danube, for example in the Sauwald westnorthwest of Linz, the region west of Ybbs and in the area of Melk and Krems (e. g. Dunkelsteinerwald, Hiesberg).

This crystalline basement represents the consolidated and deeply eroded part of the Middle-European Variscan orogenic system. These truncated uplands with mean elevations of 500 to 700 m, locally up to 1300 m, have undergone denudation since Variscan times. Usually the rocks are deeply weathered and crumbled. The detrital material accumulated in flat depressions. In the south and east the crystalline basement dips under the sediments of the Molasse Zone and further continues below the Eastern Alps where it has been recorded by drillings.

The crystalline basement is divided into three units. The major part in the center is made up by the Moldanubian Zone. The external region in the east is called Moravian Zone after F. E. Suess 1903. Southwest of the Moldanubian Zone extends the external region of the Bavarian Zone according to G. Fuchs 1976. The following account begins with the Moravian Zone in the east, followed by the Moldanubian Zone and by the Bavarian Zone.

The Moravian Zone

The Moravian Zone forms an external belt at the southeastern margin of the Bohemian Massif. Its southwestern end is exposed in the Waldviertel.

The *Thaya Batholith* has the deepest and easternmost position in this rock complex. It is of granitic to granodioritic composition and is generally foliated. Massive structure does not occur frequently. By comparison with the analogous Bruenn Massif in Czechoslovakia which is unconformably overlain by Devonian sediments, and where K/Ar ages of biotite and hornblende of 555 m.y. were reported (A. Dudek & V. Smejkal, 1968) a pre-Devonian origin can be postulated for the Thaya Batholith.

An assemblage of basal quartzite, conglomeratic and more or less carbonaceous phyllites, meta-volcanites and very low-grade metamorphic limestones occurring at the southern end of the Thaya Batholith and named the "Series of Olbersdorf" by G. Frasl 1974 was interpreted by the same author as an early Palaeozoic (? Devonian) transgression series.

The contact metamorphic country rocks of the Thaya Batholith form a very narrow and discontinuous zone around the intrusive body.

A series of paragneiss and mica-schists follows westwards upon the Thaya Batholith with a general medium dip westwards and north-westwards. The principal rock types of the deeper division are quartzites and orthogneisses with rodding texture ("Weitersfelder Stengelgneis") forming long narrow zones. The upper section consists of marbles and carbonate bearing mica-schists.

The highest position of the Moravian Zone is occupied by the *Bittesch Gneiss.* This very typical and persistent Moravian unit dips westwards under the Moldanubian Zone. The Bittesch Gneiss is of granitic to granodioritic composition. Frequently porphyritic structure with augen of alkali-feldspar can be observed. The upper portion of the gneiss is concordantly interbedded with amphibolite layers. By radiometric age determinations (whole rock, Rb/Sr; S. Scharbert, 1977) an age of about 800 m. y. is suggested for the Bittesch Gneiss. An axial culmination running transversely to the regional NNE-SSW-strike caused the arch structure of the Bittesch Gneiss near Messern.

In general the rocks of the Moravian Zone underwent progressive metamorphism. In the northern, eastern and southern part greenschist facies is developed; the western part near the Messern arch shows amphibolite facies. The metamorphic zoning is not controlled by the regional strike.

F. E. Suess (1903) was the first who distinguished between the Moldanubian and the Moravian Zone because of their distinct differences regarding structure, metamorphic degree, and rock assemblage. He suggested the boundary plane to be an important thrust plane on which the Moldanubian Zone was moved eastwards upon the Moravian Zone during the Variscan orogeny. G. Frasl (1970), however, recognized the widespread correspondence of metamorphic grade on both sides of the "*Moldanubian Line*" and the lithological similarity between both the Bittesch Gneiss and the Moldanubian Dobra Gneiss.

Following the ideas of F. E. SUESS the Moravian Zone was subdivided by K. PRECLIK (1924, 1926) and L. WALDMANN (1924) into two sub-nappes. Both, the higher Bittesch Gneiss Nappe and the lower Pleißing Nappe are thought to have been dragged by the Moldanubian thrust-sheet upon the Thaya Batholith.

According to the ideas of F. E. SUESS, L. WALDMANN and K. PRECLIK the following model of the geological development of the Moravian Zone can be suggested. The Thaya Batholith intruded during the "early Moravian phase" (pre-Devonian). The principal events of the "middle Moravian phase" (? Bretonian) were the formation of folds and thrust-sheets and syn- to post-tectonic regional metamorphism in greenschist to amphibolite facies. During the "late Moravian phase" only shearing connected with retrograde metamorphism occurred.

The Moldanubian Zone

The Moldanubian Metamorphic Rocks in the Waldviertel

This region is bounded in the west by the Moldanubian Pluton and in the east by the Moravian Zone. A wide assymetrical syncline is developed with a shorter eastern limb and an axis which corresponds to the regional NNE-SSW-strike.

The following account essentially refers to the succession of the western limb of the synclinorium. The eastern limb is a subject of controversy and not univocally understood as the reduced pendant of the western limb.

A *Monotonous Series* of paragneisses has the deepest position and extends into the western part. The schistosity shows a more or less high angle eastward dip. Principal rock-types are biotite-plagioclase-gneisses with frequent garnet and sillimanite and cordierite-gneisses. Occasionally amphibolites, calc-silicate-gneisses, quartzites and smaller bodies of granite-gneiss are intercalated.

Eastwards follows the *Dobra Gneiss* with a sharp tectonic contact. This orthogneiss of granitic to granodioritic composition follows the regional strike along a great distance. Frequently augen structure is developed. Concordant interbedding with layers of amphibolite, biotite-amphibolite or biotite schists are characteristic; discordant contacts are rare exceptions. The lithological similarity with the Moravian Bittesch Gneiss was already pointed out above. A direct connection between the Dobra Gneiss and the Bittesch Gneiss in the depth is quite possible. Along the western boundary a thin (few meters), discontinuous lamella of granulite underlies the Dobra Gneiss (G. FUCHS, 1976). It indicates an important, generally eastward dipping tectonic plane.

In the east the Dobra Gneiss is overlain by a *Variegated Series.* Both are intensely folded together. The contact is probably of sedimentary origin. The major part of the Variegated Series is formed by inhomogeneous biotite-plagioclase-gneisses with garnet and sillimanite. In the deeper section quartzites, arkose-gneisses, more or less graphitic marbles, amphibolites, and the *Granodiorite-gneiss of Spitz* are intercalated. The latter has a complexly folded internal structure and is probably genetically related to the Dobra Gneiss. Above this deeper section there follows eastwards a horizon rich in thin-banded amphibolites (*Rehberg Amphibolites*), associated with ultrabasic rocks, granite-gneisses, and sporadic marbles. The paragneisses of the upper section exhibit a more migmatitic character. They are intercalated by diorite-gneisses, granitoid gneisses, aplite- and pegmatite-gneisses.

The highest unit in the center of the syncline consists of granulite, Gföhl Orthogneiss and associated rocks such as amphibolites and paragneisses. Locally this tectonic unit rests discordantly upon the deeper complexes.

Apart from smaller occurrences the *granulites* form three major masses (Blumau, St. Leonhard, Pöchlarn-Wieselburg/Dunkelsteinerwald). Light-coloured, acid varieties are prevailing. Several smaller inclusions of basic granulites and few, more or less serpentinized pyrope-olivine rocks and garnet-pyroxenites are especially known from the largest granulite occurrence in the south. A rather uniform east-west striking internal structure is developed in the granulite bodies and thus runs across the regional strike. On the base of radiometric age determinations (whole rock; Rb/Sr) A. ARNOLD & H. G. SCHARBERT (1973) reported an Ordovician age for the granulite formation and metamorphism. Usually the granulite bodies are surrounded by a narrow zone of ultramafic rocks and (pyroxene-) amphibolites. Regarding the texture and minerals the adjoining paragneisses occasionally resemble the granulites.

The *Gföhl Orthogneiss* forms extensive, monotonous bodies of granitic composition (Gföhl—Horn, Waidhofen/Thaya). The predominance of alkalifeldspar over oligoclase is typical. Garnet, sillimanite and kyanite are the principal accessories. Locally transitions to granulites occur. Moreover, after unpublished measurements of A. ARNOLD the age of the Gföhl Orthogneiss corresponds with that of the granulite. Like the granulites also the Gföhl Orthogneiss bodies are surrounded by a narrow zone of basic rocks, chiefly migmatitic garnet-biotite-amphibolites, locally anorthosite-amphibolites.

A migmatitic complex of biotite-gneiss, amphibolite, and pyroxene-gneiss near Raabs and the Syenite-gneiss of Wolfshof are closely associated with both granulite and Gföhl Orthogneiss.

The gneiss complex of the Waldviertel Moldanubian Zone close to the eastern boundary comprises a variety

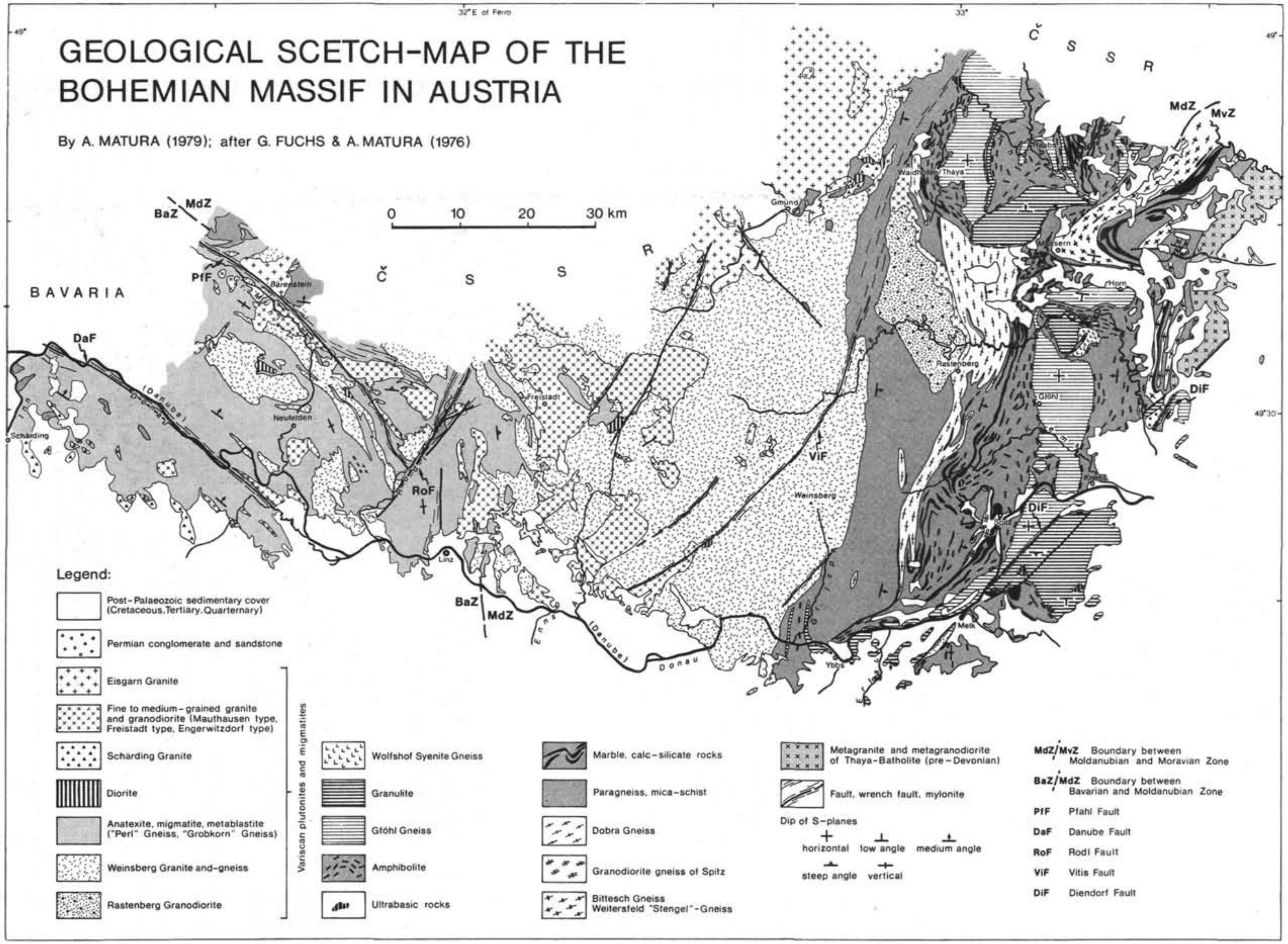


Fig. 4: Geological sketch-map of the Bohemian Massif in Austria.

of rock types similar to the Variegated Series but generally dipping towards west. The tectonic correspondence of this eastern limb with the Variegated Series of the western limb of the Waldviertel synclinorium, however, is, as already mentioned, a matter of controversy.

Apart from the granulites amphibolite facies rocks are developed in the Moldanubian series of the Waldviertel. Frequently the mobilisation of the light coloured minerals gave rise to migmatitic appearance.

The *Diendorf Fault* dissects the southeasternmost part of the Moldanubian basement. It belongs to a set of NE-SW-striking sinistral wrench-faults. The adjoining blocks were displaced up to 25 km. The age of the fault is thought to be post-Lower-Permian.

A uniform tectonic interpretation of this region is not yet achieved. As already mentioned, F. E. SUESS adopted the hypothesis according to which the Moldanubian Zone was thrust eastwards upon the Moravian Zone by the Variscan orogeny. More recent interpretations by G. FUCHS (1971) and O. THIELE (1976) support this tectonic model, but differ among each other concerning the internal tectonics of the Waldviertel Moldanubian Zone. G. FUCHS assumes Caledonian westward nappe movements before the Variscan eastward thrusting of the Moldanubian Zone. O. THIELE supports the idea of an exclusively Variscan and eastward directed nappe movement. A. MATURA (1976) rejects the concept of a separation of the Moldanubian and Moravian Zones and suggests a Caledonian age for the main orogenic phase during which the tectonic emplacement of the Gföhl-Orthogneiss-granulite thrust-sheet occurred; the Variscan tectonic activity in this area was restricted chiefly to faulting.

The Moldanubian Pluton

This extensive Variscan intrusive mass occupies the center of the Austrian part of the Bohemian Massif. L. WALDMANN (1951) distinguished three principal generations of granites, which is a generally accepted model.

The *Weinsberg Granite* is the oldest and most extensive type. It is rather poor in quartz and has a coarse-porphyritic texture. In general the very coarse alkalifeldspar phenocrysts show preferred orientation. By E. JAEGER & al. (1965) Devonian zircon ages (about 400 m. y.) and upper Carboniferous cooling ages were reported.

The *Rastenberg Granodiorite* is related to the Weinsberg Granite and is probably of the same age. It forms an isolated synclinal body within the Waldviertel Moldanubian gneiss zone. Its texture is coarse-porphyritic. Dioritic to gabbroic inclusions of dm to km sizes are very typical and are distributed over the whole area. The texture of the Rastenberg Granodiorite is partly massive, partly a parallel texture is developed which is adjusted to the synclinal shape of the body.

Several local varieties (Mauthausen, Altenberg, Freistadt) are grouped together as *Feinkorn* (fine-grained) *Granites.* Their common features are the massive and fine to medium-grained texture and sharp, discordant intrusive contacts against the older Weinsberg Granite. The composition varies from granitic to granodioritic, and is locally tonalitic. Marginally the Feinkorn Granite bodies split up into swarms of dykes. O. THIELE (1970) reported about orbicules around country-rock inclusions within such a dyke.

The *Eisgarn Granite* represents the youngest generation of the Moldanubian Pluton. It mainly occurs in the north-eastern part of the Waldviertel and extends NNE-wards into Czechoslovakia. This two-mica-granite has the highest quartz-content of the Moldanubian Pluton assemblage. Frequent preferred orientation of the slim, idiomorphic alkalifeldspars probably indicates fluidal texture of this coarse-grained granite type.

Diorites and *gabbros* are of minor importance.

There is a broad variety of *dykes* related to the Moldanubian Pluton. They are rather rare in the center of the pluton, however, numerous in the adjoining country rock (Persenbeug, Waidhofen/Thaya, Raabs). Dykes of granite and granite-porphyry are considered to belong to the Feinkorn Granite and Eisgarn Granite generation. Dykes of aplite, pegmatite, diorite-porphyrite and lamprophyres can not definitely be associated with one of the above mentioned granite generations.

Regional heating especially connected with the emplacement of the Weinsberg Granite gave rise to migmatisation and metablastesis. These effects are less evident in the country rocks east of the big batholith, but the intrusion of the Weinsberg Granites may have some genetic bearing on the crystallisation of the cordierite gneisses in the Monotonous Series. Westwards, however, the heating effects by far are more pronounced ones. This will be subject of the next chapter.

A group of wrench-faults with NNE- to NE-direction cuts across the granite massif, namely the *Vitis Fault* in the east, but also several faults east of Freistadt. They caused mylonitization and silicification as well as sinistral displacements up to 20 km in the case of the *Rodl Fault.* The already mentioned Diendorf Fault is also considered to be associated to this fault system.

The Bavarian Zone

The term Bavarian Zone was introduced by G. FUCHS (1976) and denominates the south-western marginal part of the Bohemian Massif. It occupies the western part of the Bohemian Massif in Austria. It is characterized by the strictly NW-SE-striking of chiefly migmatitic gneisses cut by numerous granite bodies. Two marked NW-SE-striking faults, the Pfahl Fault and the Danube Fault, dissect this zone. The pronounced individual structure of this region — different from the Moldanubian Zone in the north — was pointed out by G. FUCHS & O. THIELE (1968) and interpreted as the result of magmatotectonic events of Variscan age which intensively affected the southwestern portion of the Moldanubian Zone.

Paragneisses with cordierite, sillimanite, and garnet are considered to be remnants of the former Moldanubian rock complex, which is preserved at some places. Associations of paragneisses, graphite-schists, calc-silicate rocks, amphibolites, and marbles at Herzogsdorf (Mühlviertel) and Kropfmühl (Bayerischer Wald) resemble the Variegated Series.

Several, irregular-shaped bodies of Weinsberg Granite occur in the Bavarian Zone. Their emplacement caused anatexis and meta-blastesis and extensive transition zones between the granite and the country rock. Next to the granites a zone of *Grobkorn* (coarse-grained) *Gneisses* is developed with alkalifeldspar-phenocrysts which are less frequent and smaller than in the Weinsberg Granite. The major part, however, is occupied by Perl Gneisses („pearl gneisses") homogenous, nebulitic metablastites. The Weinsberg Granite, its associated migmatites and the preexisting gneiss-complex underwent intensive synintrusive deformation in the region of the Bavarian Zone.

The intrusive masses of Feinkorn Granite and Eisgarn Granite, however, were not affected by these tectonic movements.

The *Schärding Granite* is restricted to the southwestern part of the Bavarian Zone. It also shows transitions to the surrounding metablastites. As this complex has not been as much affected by tectonic deformations, the Schärding Granite is considered to be somewhat younger than the Weinsberg Granite. The associated metablastites of the Schärding Granites contain cordierite, and as accessories sillimante, herzynite, and garnet. The Peuerbach Granite is a special variety of the Schärding Granite.

Rare diorite and gabbro bodies were formed between the instrusions of the Weinsberg Granite and Feinkorn Granite according to G. Fuchs & O. Thiele (1968).

The *Pfahl Fault* in the north along the upper Mühl valley and the *Danube Fault* in the south are parallel and dip with medium-angle towards north-east. They are associated with mylonites and silicificated hartschiefer of considerable width (up to 2 km and more). Their origin is probably of late Variscan age. By these faults the Bavarian Zone can be subdivided into following zones: The *Böhmerwald Zone* northeast of the Pfahl Fault is a transition zone. It shows the structural change from the older Moldanubian NE-SW-direction into the Variscan WNW-ESE-direction. Locally already Weinsberg Granite, Grobkorn Gneiss and Perl Gneiss occur. The Eisgarn Granites of the Böhmerwald Zone are considered to be the western continuation of the main Eisgarn Granite body of the northwestern Waldviertel displaced from each other by the sinistral Rodel Fault.

The *Mühl Zone* between the Pfahl Fault in the northeast and the Danube Fault in the southwest are structurally dominated by a strict northwest strike and a medium angle northeastward dip of schistosity. There are folds overturned towards southwest which developed particulary in the region next to the Danube Fault. The principal rock-types are Grobkorn Gneiss and Weinsberg Granite. The southeastern continuation of the Mühl Zone has been displaced for about 20 km along the sinistral Rodel Fault. In this district of the Mühl Zone the strike turns towards south.

The *Sauwald Zone* southwest of the Danube Fault is mainly composed of Perl Gneiss and Schärding Granite. The structural adjustment to the regional northwest-southeast strike is not as well developed as in the other zones.

The Post-Variscan Sedimentary Cover

An occurrence of Lower Permian northeast of Zöbing (Waldviertel) represents the subsided remnant of a Lower Permian sedimentary cover. The beds show high to medium angle southward dip. In the northwest the sequence overlies the granulite with transgressive somewhat tectonized contact. In the southeast the occurrence is bounded by the Diendorf Fault. The sequence mainly comprises conglomerates, sandstones, and arkoses. They have yielded remnants of plants, insects and freshwater bivalves. The poorly assorted components, mainly granulite fragments differ in size (up to meter-dimension) and are more or less well-rounded. These phenomena allow to deduce continental accumulation.

Near Gmünd part of the Trebon basin extends into Austria. It is filled with limno-fluviatile upper Cretaceous and Tertiary sediments. Another basin occurs at Kefermarkt and Freistadt with probably Tertiary fillings. Tertiary age is also considered for isolated pebbles, boulders and windkanters. The crystalline basement itself became deeply weathered and crumbled, locally kaolinized. From the south and east marine Tertiary series transgressed upon the marginal parts of the Bohemian Massif.

The Pliocene to Quaternary epigenitic development of the Danube and some of its northern tributaries is evident in several terraces. Remains of Pleistocene loess accumulations are well preserved in many places.

The Molasse Zone

The Molasse Zone is a more or less wide belt forming the outer border of the Alpine-Carpathian mountain range.

A considerable part of the Molasse Zone is tectonically superimposed by the various Alpine tectonic units. There is no doubt, that the whole Flysch Zone and the Helvetic Zone rest tectonically upon Molasse beds. It has also been proved by deep drilling that the Molasse Zone extends southwards far beneath the Northern Calcareous Alps. Generally it can be assumed that the Molasse Zone in the subsurface of the body of the Eastern Alps extends at least as far as the southern rim of the Northern Calcareous Alps; in other words, it

MILLION YEARS	EPOCHE		MEDITERRANEAN EUROPEAN STAGES	CENTRAL PARATETHYS REGIONAL STAGES	FORMERLY USED PARATETHYS STAGES
	PLIOCENE	LATE	PIACENZIAN-ASTIAN	ROMANIAN	LEVANTIN
5	PLIOCENE	EARLY	ZANCLIAN-TABIANIAN	DACIAN	DAZ
	MIOCENE	LATE	MESSINIAN	PONTIAN	PONT
10	MIOCENE	LATE	TORTONIAN	PANNONIAN (H, F, E, A)	PANNON
	MIOCENE	MIDDLE	SERRAVALLIAN	SARMATIAN s.str.	SARMAT
15	MIOCENE	MIDDLE	SERRAVALLIAN	BADENIAN	TORTON
	MIOCENE	MIDDLE	LANGHIAN	BADENIAN	TORTON
	MIOCENE	EARLY	BURDIGALIAN	KARPATIAN	"HELVET"
	MIOCENE	EARLY	BURDIGALIAN	OTTNANGIAN	"HELVET"
20	MIOCENE	EARLY	BURDIGALIAN	EGGENBURGIAN	BURDIGAL
	MIOCENE	EARLY	AQUITANIAN	EGERIAN	CHATT AQUITAN
25	OLIGOCENE	LATE	CHATTIAN	EGERIAN	CHATT AQUITAN
30	OLIGOCENE	MIDDLE	RUPELIAN	RUPELIAN	RUPEL
35	OLIGOCENE	EARLY	LATDORFIAN	LATDORFIAN	LATDORF
37,5					

Tab. 2: Correlation of Oligocene and Miocene stages in Central Europe (after F. STEININGER et al., 1976, and F. RÖGL et al., 1978).

extends southwards to the younger (northern) subduction zone, which formely was assumed by O. AMPFERER (1906) and by E. KRAUS and has been recently discussed again by S. PREY (1978), A. TOLLMANN (1978) and others (see figures 2 and 15).

According to the intensity of influence by Alpine tectonic movements, the Molasse Zone can be divided in

Foreland Molasse (undisturbed Molasse)

Disturbed Molasse (folded, erected on the southern rim) and

Sub-Alpine Molasse (strongly folded, imbricated and thrust-faulted, parautochthonous to allochthonous).

A very comprehensive and well-reasoned discussion on the tectogenesis of the Alpine Molasse Zone was given by W. FUCHS (1976), comparing and paralleling the various „disturbed" and „subalpine" Molasse units. The results of biostratigraphic investigations are presented in F. STEININGER et. al (1976) and F. RÖGL et al. (1978).

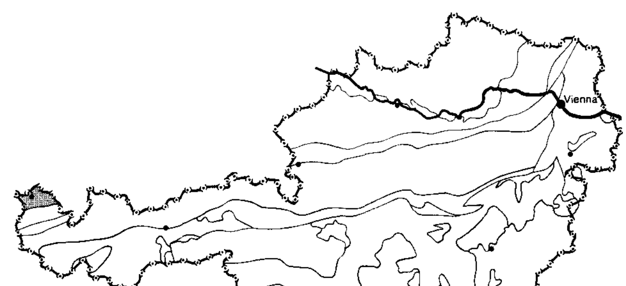
The normal section of the Molasse beds extends from the Upper Eocene to the Neogene, in some regions up to and including the Lower Pannonian (Late Miocene). This succession comprises different facies, e. g. freshwater facies with coal or lignite, marine algal limestones and bituminous marls and shales as well as conglomerates, sandstones, marls and siltstones (the actual Molasse facies), which are defined as products of erosion from the arising Alps in the south.

Most of the knowledge of the stratigraphy and the structure of the Molasse Zone and its basement in Austria is a result of detailed paleontological and facies studies, geophysical work and drilling in the search for crude oil and natural gas, which has been considerably successful during the past 25 years. Two productive areas exist in the Austrian Molasse Zone: the region of Upper Austria and the region north of the river Danube. The oil is connected mainly to Malm, Upper Cretaceous and Upper Eocene reservoir rocks, in the east also to the Gresten Formation (Lias); gas deposits are mainly found in the Upper Eocene, in the Puchkirchen Formation (Oligocene), the Hall Formation and the Oncophora Formation (early Miocene).

The Molasse Zone of Austria can be divided into main regional parts as follows:

- the Molasse Zone of Vorarlberg,
- the Tertiary beds of the Inn valley,
- the Molasse Zone between the rivers Salzach and Inn in the west and the area of Amstetten in the east,
- the Molasse Zone of the area of St. Pölten and Tulln and
- the Molasse Zone north of the river Danube.

The Molasse Zone of Vorarlberg



The stratigraphy and the structure are closely related to the Swiss and the Bavarian Molasse Zone (U. P. BÜCHI & S. SCHLANKE 1977). Two units are being distinguished: the Sub-Alpine Molasse and the Foreland Molasse. In both units the section consists of a reiterated alternation of both, freshwater and marine facies. The validity of the classification in the Lower Marine

Molasse *(Untere Meeresmolasse, UMM),* the Lower Freshwater Molasse *(Untere Süßwassermolasse,* USM), the Upper Marine Molasse (*Obere Meeresmolasse,* OMM) and the Upper Freshwater Molasse (*Obere Süßwassermolasse, OSM*) is limited, as different from the meaning of these terms partly marine ingressions or freshening took place.

In the *Sub-Alpine Molasse* only the older part of the sequence is existing. The Lower Marine Molasse is represented by marine siltstones and marls ("Tonmergelschichten") of the Lower Rupelian and mainly sandstones of the brackish Baustein Beds (Upper Rupelian to Lower Chattian). The Lower Freshwater Molasse of Chattian and Aquitanian age consists of variegated marls and sandstones and thick layers of Nagelfluh (Weissach Beds, Steigbach Beds, Kojen Beds). The sediments of the freshwater beds mainly come from the south, out of the rising Alps.

It can be assumed that the beginning of the Alpine tectonic movements in the Sub-Alpine Molasse of Vorarlberg occurred during the Chattian. At the end of the Aquitanian it has been completely overridden by the Alpine nappes.

The Sub-Alpine Molasse complex is strongly folded and thrust-faulted. So the well Dornbirn 1 drilled underneath a 340 metres thick Quaternary filling of the Rhine valley to the final depth of 2.920,6 m, at first steeply dipping, then lowly dipping beds of the Lower Marine Molasse; it can be taken for granted that imbrication has taken place.

The oldest beds of the *Foreland Molasse* are freshwater sandstones and marls of the Egerian (Aquitan), the so-called „Granitische Molasse". They are superimposed by various marine sandstones, shales and conglomerates of the Eggenburgian to Karpatian (Burdigal and Helvet), including a small lignite-bearing freshwater intercalation. The youngest beds belong to the Upper Freshwater Molasse of the Badenian and Sarmatian (Torton/Sarmat), like the Nagelfluh of the Pfänder mountain.

In the southern part, at the border to the Sub-Alpine Molasse, the beds are steeply erected; in the north they are generally slightly dipping northwards.

The pre-Tertiary basement of the Molasse Zone in Vorarlberg is not known. It most likely consists of Mesozoic limestones (Malm) in the Helvetic facies, as it is known from the neighbouring Swiss and Bavarian Molasse.

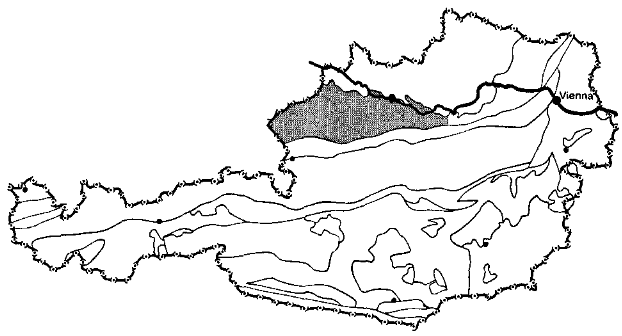
Tertiary Beds of the Inn Valley in the Area of Kufstein — Wörgl

In this paper we include the Upper Eocene and Oligocene beds of the Inn valley into the Molasse Zone.

Southward subduction of the European under the African plate (according to A. Tollmann, 1978, under the intra-tethyal „Kreios" plate) took place and the Flysch Zone as well as the Penninic Zone were eliminated during the Palaeogene. The partly thrust-faulted and imbricated Northern Calcareous Alps were brought into direct contact with the Priabone marine basin of the Helvetic Zone (according to W. Fuchs, 1976, there is no difference between the Helvetic and the Molasse trough in this time). As a consequence southward marine ingressions could enter depression zones of the Northern Calcareous Alps and deposit sediments in the facies of the Molasse Zone. Subduction movements continued and therefore we find older Molasse sediments both beneath and above the Northern Calcareous Alps (especially in the Inn valley, but also in Reichenhall near Salzburg).

In the Inn valley the section begins with Priabonian to Lower Oligocene *Häring Beds,* an alternation of freshwater and marine conglomerates, breccias, sandstones, marls and clays, partly coal-bearing and bituminous (e. g. in Häring in Tyrol). The standard section is continued by the Upper Oligocene *Angerberg Beds,* freshwater conglomerates, sandstones and marls. Lower Miocene age (Aquitan) has sometimes been assumed, but not been proved until now.

The Molasse Zone between the Rivers Salzach and Inn and the Area of Amstetten



Crystalline rocks of the Bohemian Massif are forming the northern border of this part of the Molasse basin. They slightly dip southwards beneath the sedimentary filling of the basin, respectively beneath the Alpine body. The southward dipping is locally strengthened by synthetic or antithetic faults, which, however, are not younger than Oligocene.

On the surface the southern border is formed by the Alpine nappes of the Helvetic Zone and the Flysch Zone. Therefore in the south the boundary on the surface is a tectonic line, whereas the sinuous northern boundary is marked by the stratigraphic contact between the Molasse sediments and their crystalline basement.

Today the Molasse basin displays strong asymmetry, as the original southern border during the time of sedimentation is not known and buried far beneath the Alpine body.

The biggest thickness of about 4.000 metres of the Molasse sediments is found near the Alpine nappe front in the region of Salzburg. To some extent imbricate structures within the Sub-Alpine Molasse like the Perwang structure must be considered to explain this thickness.

The Pre-Tertiary Basement

The deepest part is formed by crystalline rocks of the Bohemian Massif, which continues under the Alps. In the northern and eastern parts of the region discussed, granites and gneisses are found immediately beneath the Tertiary sediments. Upper Carboniferous sandstones and conglomerates occur mainly along the continuation of the Landshut-Neuötting Ridge Zone and in the southern part right under Molasse sediments.

Unconformably overlying the crystalline basement and the younger Palaeozoic rocks, we can find an incomplete succession of Mesozoic beds in the facies of the European shelf („Germanic facies"). From the west to the east the thickness is decreasing and the sequence becomes more incomplete. Sediments in various facies of the Keuper, Lias and Dogger occur within isolated areas (K. Kollmann, 1977). The Malm is represented by limestones and dolomites, partly with chert. As for long time exposed on the surface carstification took place often.

A big gap in the sedimentation separates up to 1.000 metres thick marine sediments of the Cenomanian to the Lower Campanian (marls, sandstones, stilstones, shales) from the underlying beds.

The *Central Ridge Zone,* the continuation of the *Landshut-Neuötting ridge* and some NNW-SSE striking pre-Tertiary faults with throws up to 900 metres, created an area with moderately dipping block-faults and separated some Cretaceous sedimentary basins.

The Tertiary Basin Filling

A considerable erosion-phase in the early Palaeogene has formed a peneplain, on which the sea advanced northwards from the (former) Helvetic sedimentation area in the south (fig. 5).

According to the facies of the Molasse beds three phases of deposition are recognized in this area (R. Janoschek, 1964).

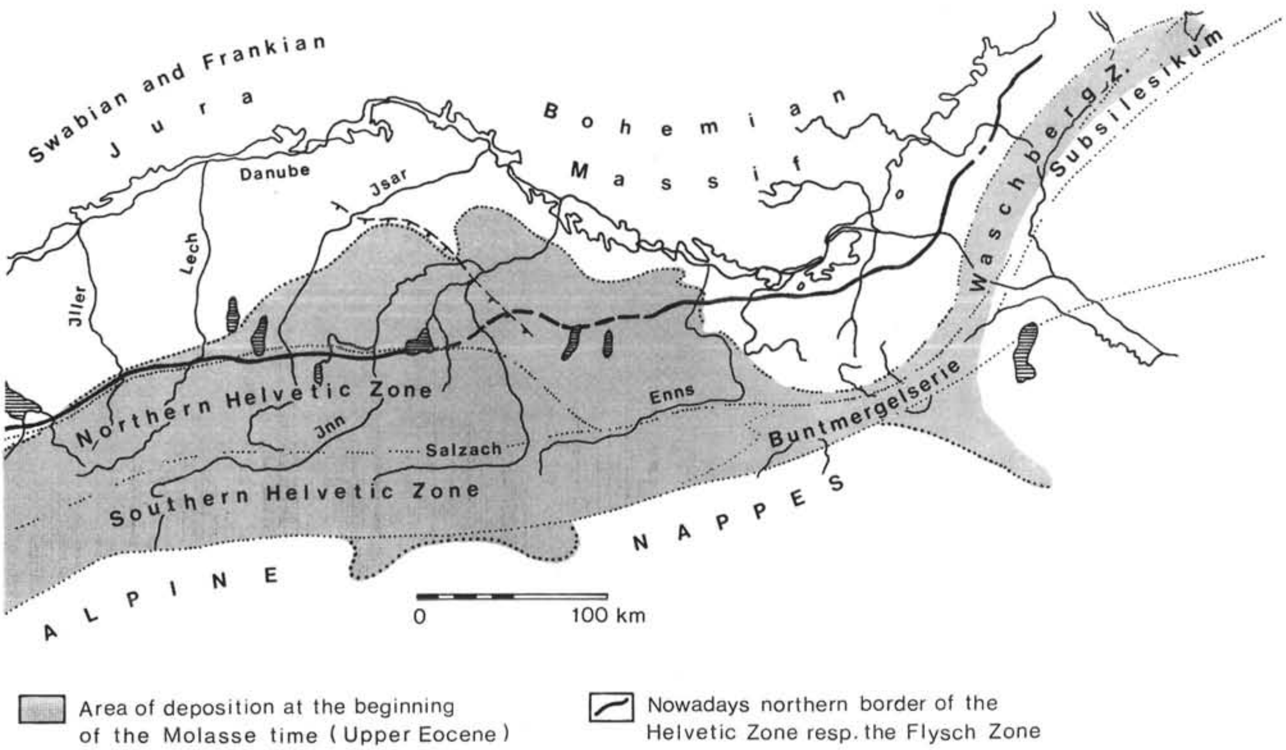


Fig. 5: Attempt of reconstruction of the depositional situation of the Helvetic Zone and the Molasse Zone at the beginning of the Upper Eocene. It is shown that the area of deposition at the beginning of the Molasse time (toned field) is identical with the Helvetic Zone. Note the northward bulge between the rivers Lech and Enns (i. e. the Upper Eocene sediments at the basis of the Foreland Molasse in Bavaria and Upper Austria) and the two small southward bulges (Tertiary of the Inn valley and of Reichenhall) (after W. Fuchs, 1976, fig. 3).

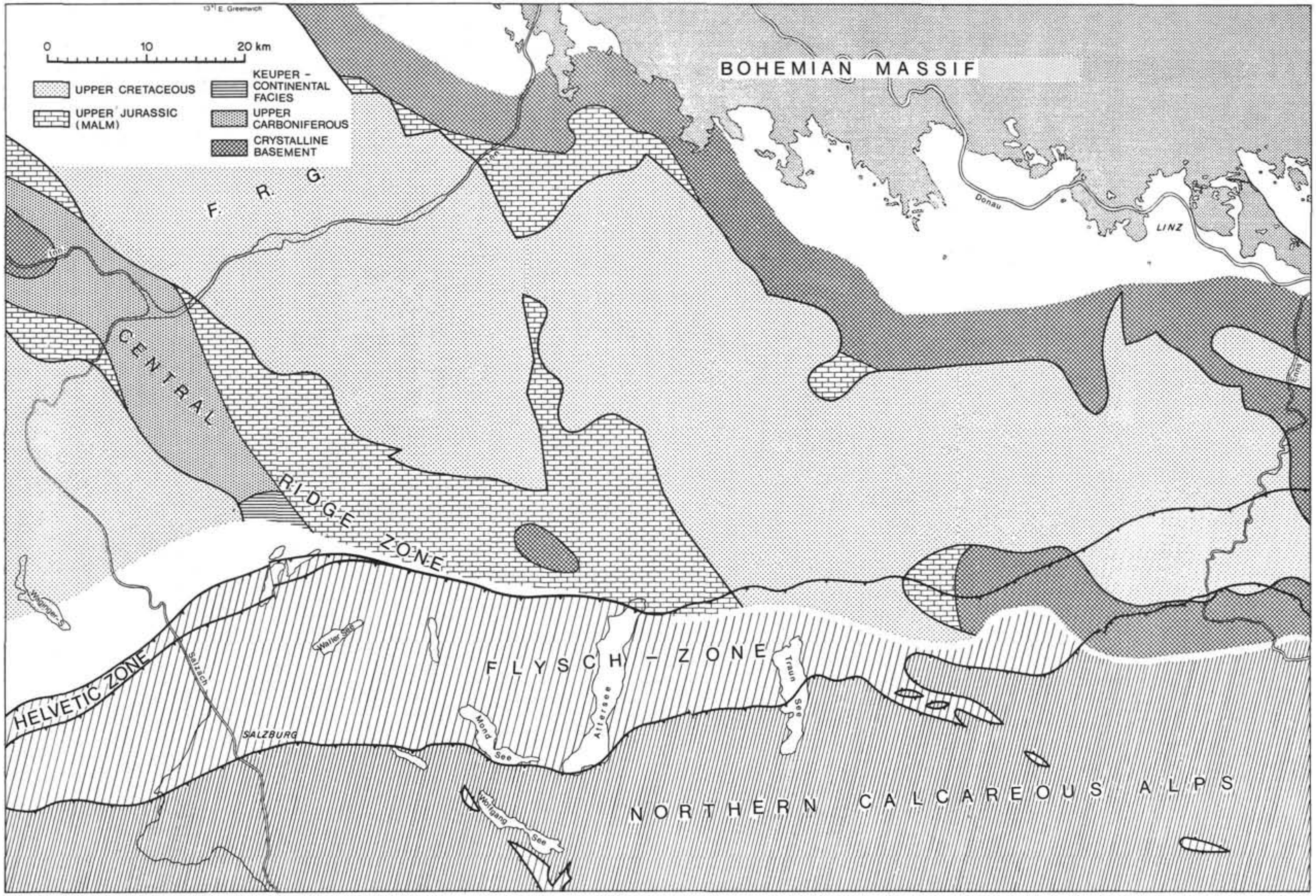
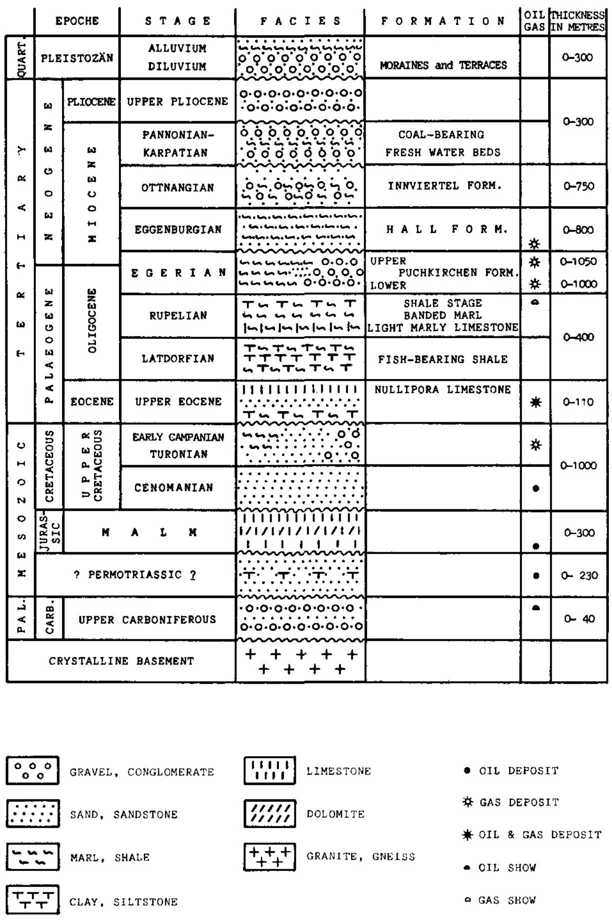


Fig. 6: Subsurface map of the pre-Tertiary basement of the Molasse Zone between the rivers Salzach and Enns. The basement is subdivided into various Cretaceous basins by the Central Ridge Zone (the continuation of the Landshut-Neuötting Ridge) and by pre-Tertiary block-faulting (after K. KOLLMANN, 1977, fig. 6; modified).

1. Late Eocene to mid-Oligocene (lowest Rupelian)

Thin lacustrine, lagoonal and neritic sediments of the Upper Eocene mark the beginning of the Molasse epoche. The lacustrine series with variegated clays and intercalations of sandstones and coal is limited to the southern and middle regions, while marine facies, e. g. *Nullipora-limestone,* is becoming more prominent towards the north. The *Fischschiefer* (fish-bearing shale)



Tab. 3: Stratigraphic diagram of the Molasse Zone between the rivers Salzach and Inn and the area of Amstetten (after K. KOLLMANN, 1977; modified).

of the Latdorfian, the *Heller Mergelkalk* (light marly limestone) and the *Bändermergel* (banded marl) of the Rupelian show conditions of a sedimentation in deeper water (200 metres and more).

It has been proved by studies on heavy minerals (G. WOLETZ, 1963, H. KURZWEIL, 1973), that the sediments can be derived mainly from the crystalline rocks of the Bohemian Massif.

2. Mid-Oligocene (late Rupelian) to mid-Miocene (Ottnangian)

During this phase the bulk of the Molasse beds has been deposited, mainly derived from the rising Alps in the south. The sequence consists up to 3.000 metres of marine streaky marls *(Schliermergel).* Mainly in the south considerable intercalations of sand and sandstones as well as gravels and conglomerates occur. Their pebbles consist of quartz, crystalline rocks, dark dolomite and chert; the younger part contains additionally debris from the Northern Calcareous Alps and the Flysch Zone. The heavy mineral assemblage also indicates Alpine crystalline source rocks (H. KURZWEIL, 1973).

Four main formations form the typical Molasse sediments (from the top to the bottom):

Innviertel Formation (Ottnangian)
Hall Formation (Eggenburgian)
Puchkirchen Formation (Egerian)
„Tonmergelstufe" (Shale Stage, Upper Rupelian)

Tonmergelstufe (Shale Stage): Thin alternating shales and fine sands (the so-called „Schlier"), deposited in the relative quickly subsiding Alpine fore-deep, represent the oldest sediments in Molasse facies in the area discussed. From the south intercalations of coarse material are common.

Puchkirchen Formation: In the Lower and Upper Puchkirchen Formation (Egerian) pelitic beds prevail in the north, besides a more or less wide belt of Linz Sand, a light quartz-sand, which represents a basal transgression bed of the northwards advancing Molasse sea.

In the south the pelites interfinger with coarse-grained sediments: quartz-pebbles are predominant; carbonate pebbles from the Central Alps and the Northern Calcareous Alps occur; pebbles from the Flysch Zone are rare (K. KOLLMANN, 1977). These sediments are derived from big rivers coming from the rising Alps and mouthing into the Molasse sea. The material became distributed by mud streams and turbidity currents along the axis of the basin.

In some cases also in the south exists an interfingering with pelitic sediments, but in most cases a tectonical truncation of the coarse-grained beds took place by the overriding Alpine nappes (thrust-slices of the Sub-Alpine Molasse, the Helvetic Zone and the Flysch Zone).

The subsidence of the floor of the Molasse basin was now accompanied by faults, swinging around the west-east direction. The main activity of faulting happened during the sedimentation of the „Tonmergelstufe" and the Lower Puchkirchen Formation. All faults are tension faults.

In this region of the Molasse Zone a last climax of Alpine subduction movements took place during the late Oligocene. These southward movements of the basement caused northward imbrication and nappe-structures in the sedimentary cover. In the area discussed it lead to the development of the *Perwang* and the *Bad Hall imbrication* structure. They comprise elements of the Mesozoic basement, of the Helvetic Zone and of the Molasse beds up to the Upper Puchkirchen Formation.

The movements were ebbing down by the end of the Oligocene. The southern rim of the Molasse basin became stabilized. The further subsidence of the Molasse basin took place without major faulting.

Hall Formation: The Hall formation (Eggenburgian) spreads unconformably over the Foreland Molasse. It consists of streaky marls with intercalations of sands and sandstones, originating from the south.

Innviertel Formation: The Hall Formation is conformably overlain by the Innviertel Formation (Ottnangian). In the western part sands and gravels predominate, while in the east the occurrence of „Schlier" is common.

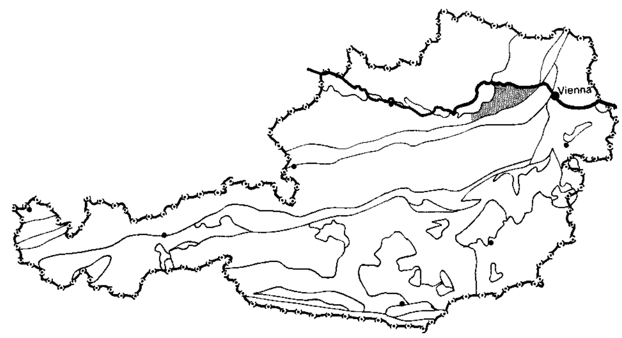
The marine history of the Molasse Zone in the area discussed ends with the Innviertel Formation. The partly developed and up to 25 metres thick Oncophora Beds of the late Ottnangian show brackish to lacustrine environment.

3. Late Miocene to Early Pliocene

The late Miocene to early Pliocene comprises fluviatile and lacustrine sediments, in general resting unconformably upon the earlier Tertiary beds. At the basis lignite-bearing clays are being found, overlain by gravels and conglomerates. A fauna of mammals and terrestrial gastropods were recorded. This series is an equivalent of the Upper Freshwater Molasse in the west.

Pleistocene moraines and fluvioglacial terraces of the various glacial periods cover wide areas of the Molasse basin and can reach a considerable thickness of a few hundred metres.

The Molasse Zone of the Area of St. Pölten and Tulln



The stratigraphic sequence in this region is reduced and incomplete. There are mainly beds of Egerian and Eggenburgian age, directly overlying the crystalline basement. In this district (Lower Austria) the Melk Sand is an equivalent formation to the Linz Sand. On the surface the western region is the most narrow part of the entire Alpine Molasse Zone.

Within the southward bordering Flysch Zone remarkable tectonic windows occur exposing imbricated Molasse beds together with units of the Helvetic Zone (window of Rogatsboden—Scheibbs, window of Texing). Moreover, the results of the well Urmannsau 1 obviously show the tectonic position of the Molasse Zone. In these windows older Molasse beds of Lower Oligocene age, imbricated with the „Buntmer-

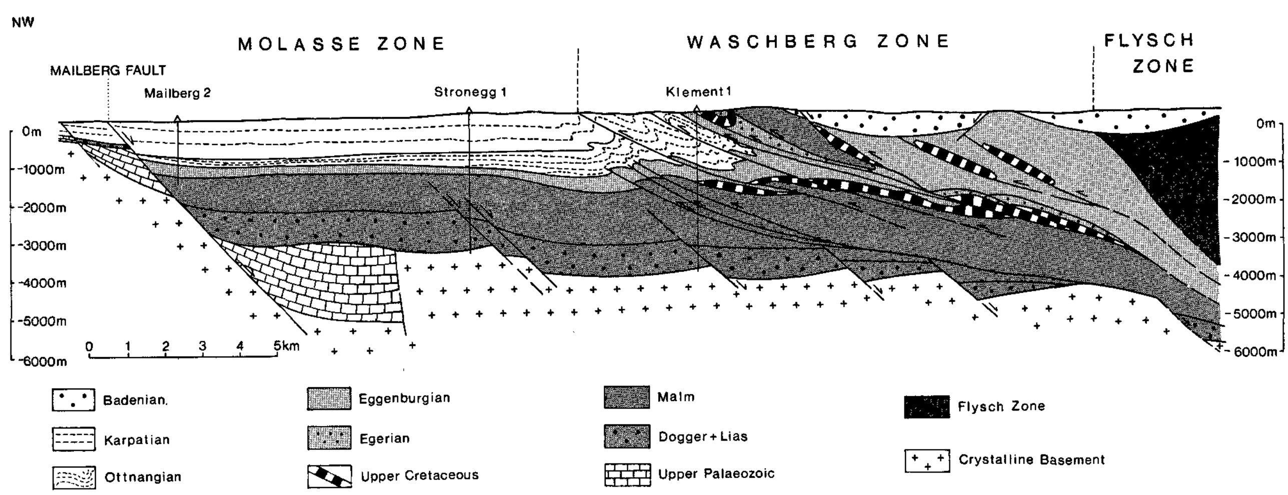
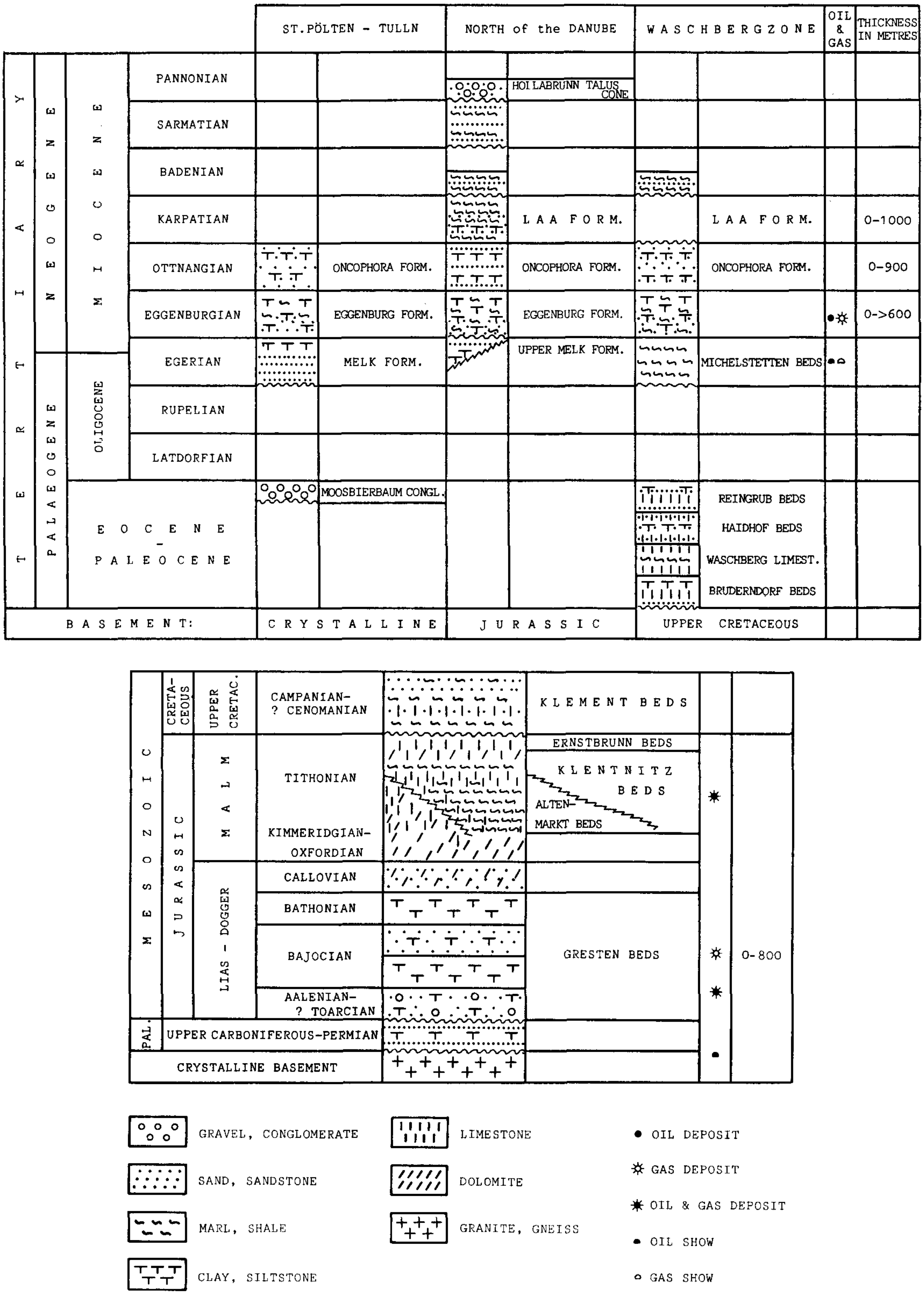


Fig. 7: Cross-section of the Molasse Zone, the Waschberg Zone, and the Vienna basin in Lower Austria north of the Danube (after F. Brix & A. Kröll in F. Brix, A. Kröll & G. Wessely, 1977; simplified).



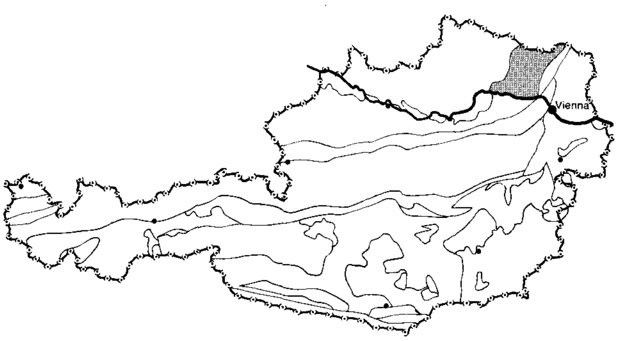
Tab. 4: Stratigraphic diagram of the Molasse Zone and its basement in Lower Austria east of Amstetten (after F. Brix, A. Kröll & G. Wessely, 1977; simplified).

gelserie" of the Helvetic Zone are occurring. The well *Urmannsau 1,* located about 15 kilometres south of the southern border of the Molasse Zone on the surface, met under different units of the Northern Calcareous Alps a) in a depth of 1.990 to 2.925 metres imbricated Helvetic Zone (Buntmergelserie and Klippen Zone) together with older beds of the Sub-Alpine Molasse (Upper Eocene to Lower Oligocene, 2.363—2.600 m); b) undisturbed autochthonous Egerian Molasse sediments (formerly Chatt to Aquitan) in 2.925 to 3.015 metres; there the well finally penetrated crystalline rocks of the Bohemian Massif (A. Kröll & G. Wessely, 1967).

In the eastern part of the area discussed, the Molasse Zone becomes wider again and the sediments as well as the tectonic movements become younger.

Apart from the locally developed Moosbierbaum Conglomerate (Upper Eocene in freshwater facies) the section starts with the *Melk Formation* (equivalent of the Puchkirchen Formation) with coal-bearing clays and Melk Sand. It is overlain by the *Eggenburg Formation* (equivalent to the Hall Formation), mainly siltstones and sandy shales („Schlier"). The Molasse sedimentation ends with the neritic *Oncophora Formation* of the Ottnangian; sometimes brackish and freshwater elements are occurring.

The Molasse Zone North of the River Danube



This part of the Molasse trough stretches along the Carpathian southwest—northeast direction. Two parts can be discussed separately:

a) The Undisturbed Molasse Zone in the northwest, the main part of the formerly so-called Extra-Alpine Vienna Basin
b) The Sub-Alpine Molasse Zone in the southeast, the so called Waschberg Zone.

The Undisturbed Molasse Zone

Rocks of the Moravian Zone of the Bohemian Massif form the crystalline basement.

West of the northeast—southwest striking *Mailberg Fault* the Tertiary beds are mainly resting upon the crystalline rocks, or locally on a few hundred metres thick Palaeozoic to Mesozoic cover. Mainly shallow water facies is common; on the Bohemian Massif occur wide onlaps of the sea (e. g. the Tertiary *Horn Basin*), partly with deposition of littoral and neritic sediments rich in fossils.

East of the Mailberg Fault the Palaeozoic to Mesozoic autochthonous sedimentary cover becomes more prominent; the thickness increases up to 2.000 metres or more. Younger Palaeozoic rocks are mainly occurring within the continuation of the Boskovice Furrow.

The unconformably overlying Mesozoic sequence comprises sediments from the Lias up to the Upper Cretaceous in various facies, varying within time and space.

Lias and Dogger are represented by the *Gresten Beds,* which have been deposited near the continent. In the area discussed they reach a thickness up to 800 metres and a twice alternation of quartz-arenites and siltstones, partly coal-bearing can be observed. In the uppermost Dogger biogenic limestone-sedimentation is increasing.

Conformably superimposed are more or less biogenic carbonatic beds of the Malm; reef limestones interfinger laterally with banked marly limestones and marls, overlain by calc-arenites. The Malm succession ends with the Upper Malm *Ernstbrunn Beds,* which mainly consist of white pelitic limestones. The reef and banked limestones together are named *Altenmarkt Beds,* the marly and arenitic beds are named *Klentnitz Beds.*

The Upper Cretaceous (?Cenomanian to Campanian) *Klement Beds* lie transgressively upon the Malm beds. Basal coarse-grained, glauconite-bearing quartz-arenites are superimposed by medium to fine sandstones and marls; carbonatic intercalations are to be found.

After a gap in the sedimentation and a phase of erosion, in eastern direction the onlap of the Tertiary Molasse beds became younger. Shales with fine-sand intercalations of the *Upper Melk Formation* only occur isolated.

Transgressively superimposed is the *Eggenburg Formation,* containing various sandstones, shales and siltstones, sometimes terrigenous influenced (coal fragments); the maximum thickness drilled is more than 600 metres.

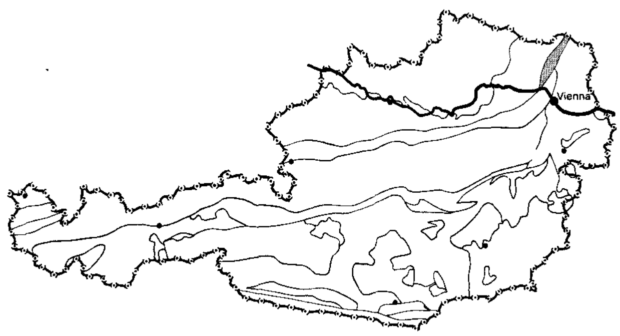
The *Oncophora Formation* of the Ottnangian is similar like in the western parts of the Molasse region, but becomes thicker eastwards (about 900 metres); the marine influence is increasing in northeastern direction. Locally diatomites are occurring.

The *Laa Formation* of the Karpatian is a new element in the Austrian Molasse section and it mainly occurs in the area north of the river Danube. The bulk of the maximal approximately 1.000 metres thick marine Laa Beds consists of shales with intercalations of sandstone. North- and westwards the Laa Formation lies transgressively upon various older beds. In the area discussed the Molasse basin has now its widest extension.

During the Badenian wide westward ingressions as far as the Wachau region (W. FUCHS, 1977) from the subsiding Vienna Basin (formerly Intra-Alpine Vienna Basin) took place. Marine shales, sandstones and lithothamnion limestones have been deposited.

In the Upper Badenian, the Sarmatian and the Lower Pannonian brackish finegrained sediments or gravels and conglomerates of mouthing rivers alternate locally (e. g. *Hollenburg-Karlstetten Conglomerate, Hollabrunn-Mistelbach Talus Cone*).

The Waschberg Zone



This complicated and more seperated unit has various names and became allocated to different Alpine units (e. g. Sub-Alpine Molasse, Sub-Carpathian Molasse, Sub-Beskidian Flysch, External Klippen). Its continuation to Czechoslovakia is named Steinitz Unit. According to W. FUCHS (1976) its tectonical position differs moderately from the Perwang structure: in the original deposition area it was situated further in the south, but due to its eastern position, the sedimentation went on for a longer time and the dislocation started later.

The Waschberg Zone (R. GRILL, 1953) is strongly folded, imbricated and thrust-faulted (see fig. 7 and tab. 4). The involved beds comprise Mesozoic rocks from the basement, outcropping in the so-called *"Klippen"* of Staatz, Ernstbrunn and others; there mainly occur Malm and Upper Cretaceous beds in various facies (Ernstbrunn Limestone, Klentnitz Beds, Klement Beds). The Palaeogene is represented by *Bruderndorf Beds* (Paleocene), *Waschberg Limestone, Haidhof Beds* and *Reingrub Beds* (Eocene), unconformably overlain by *Michelstetten Beds* (Egerian). The bulk of the sediments of the Waschberg Zone is the *Schiefrige Tonmergel* or the Ernstbrunn Tonmergel of the Eggenburgian. It has been proved by drill-holes, that the Schiefrige Tonmergel are some hundred metres thick, while in the same well the thickness of the Eggenburg Formation of the autochthonous Molasse, which is of the same age, is less than hundred metres.

The few hundred metres thick *Oncophora Beds* (Ottnangian) are completely involved in the imbrication structure of the Waschberg Zone, the *Laa Beds* (Karpatian) lie transgressively on these structures, but are still moderately imbricated (F. BRIX, A. KRÖLL & G. WESSELY, 1977). Herewith the independant history of the Waschberg Zone is finished.

Locally Lower Badenian beds overlie unconformably and transgressively the Waschberg Zone and the overthrust Flysch Zone.

Different gravels of the Lower Sarmatian as well as the *Hollabrunn-Mistelbach Talus Cone* of Lower Pannonian age show the precursor of the river Danube, crossing the Molasse Zone north of the two-day's Danube valley, the Waschberg Zone and the western part of the Vienna basin (R. GRILL, 1968).

The Helvetic Zone (Helvetikum)

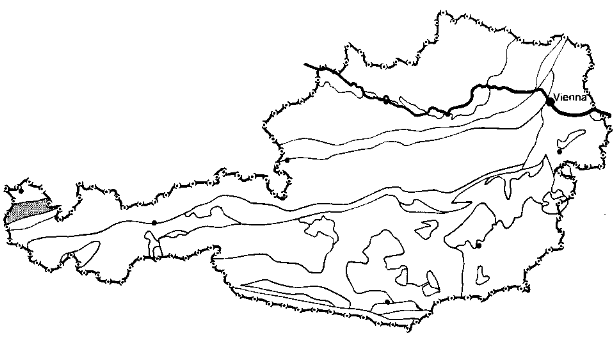
The Helvetic Zone is an external unit of the Alps, typically developed in the Western Alps and extending eastwards in a narrow belt forming the northernmost part of the Eastern Alps.

The external zones have been situated — in a paleogeographical point of view — for a long time outside or on the margin of the Alpine geosyncline being a part of the epicontinental European platform. Therefore minor tectonic movements, fluctuations of the sea level, or alternating of the climate brought considerable unconformities, transgressions, regressions, changes in facies, stratigraphic gaps and so on. It was only at the end of the Cretaceous and during the Palaeogene, when the northward moving Alpine geosyncline reached the external area and brought Flysch facies (M. P. GWINNER, 1978, p. 343).

In the Eastern Alps the external Zone has a deep structural position and is extensively tectonically superimposed by the (Penninic) Flysch Zone and the Austro-Alpine nappes. Therefore the very differentiated Helvetic Zone of the Western Alps is only very fragmentarily preserved or even poorly developed in the Eastern Alps. It comprises mainly a series of limestones, marls and sandstones, ranging in age from the Lower Jurassic to the Eocene, tectonically always strongly thrust-faulted or imbricated and in par-autochthonous or allochthonous position.

A part of the area showing "Helvetic facies", however, remained outside of the Alpine tectonic body, as sediments in Helvetic facies are the basement of the undisturbed Foreland Molasse (for instance Lower Cretaceous in the basement of the Bavarian Molasse, as well as probably Jurassic and Cretaceous beds in Vorarlberg).

In *Vorarlberg* the outcropping Helvetic Zone is of considerable extension and with a complete stratigraphic succession, comparable to the Helvetikum in the eastern part of the Western Alps. In the Bregenzer Wald



area the main Helvetic nappe, the *Säntis Nappe,* shows folded and shearfolded Jurassic and Cretaceous beds. The neritic, bioclastic to zoogenous limestones of the Lower Cretaceous can be designated as *Urgon Facies* (e. g. *Schratten Limestone*). Eastwards in the Bregenzer Wald, sandy and marly beds, containing glauconite, respectively limestone with chert are increasing (e. g. *Drusberg Beds*).

Various, partly variegated marls (*Leist Marls, Wang Beds*), intercalated by greensands (e. g. *Fraxen Greensand*) represent the Upper Cretaceous, conformly overlain by Paleocene to Eocene sandstones and marls. Stratigraphy has mainly been established by foraminifers.

The southern margin of the Helvetic realm was originally occupied by the *Ultrahelvetic Zone* bordering the Penninic sedimentation area and showing moderate, southwards increasing analogies to it.

In Vorarlberg the Ultrahelvetic Zone is represented by two tectonic units (S. Prey, 1968): The northern, respectively the deeper *Liebenstein Zone* or Liebenstein nappe is related by some authors to a South Helvetic Zone.

The southern, respectively the higher *Feuerstatt Zone* or Feuerstatt nappe was originally situated in the area bordering to the Penninic Zone to which it is added by some authors (A. Tollmann, 1978). Characteristic for the Feuerstatt Zone are *Wildflysch* beds, polymict coarse-grained breccias and boulder beds, originating from the northern slope of the Flysch basin.

East of the river Iller the Helvetic and the Ultrahelvetic nappes submerge eastwards under the Flysch Zone and the Northern Calcareous Alps and become restricted to a narrow, only a few kilometres wide thrust-slice between the Molasse Zone and the Flysch Zone.

The classification of the various small Helvetic and Ultrahelvetic thrustslices and windows in Austria east of the river Salzach varies among the different authors. According to S. Prey (1974) the Upper Cretaceous and Lower Tertiary sandstones, marls and limestones bearing nummulites and discocyclines north of Salzburg (St. Pankraz, Mattsee) belong to the Helvetikum (i. e. the South Helvetic Zone in Bavaria), while the outcropping small thrust-slices in the east belong to the Ultrahelvetikum (according to the increase of flyshoide influences, especially agglutinating foraminifers).

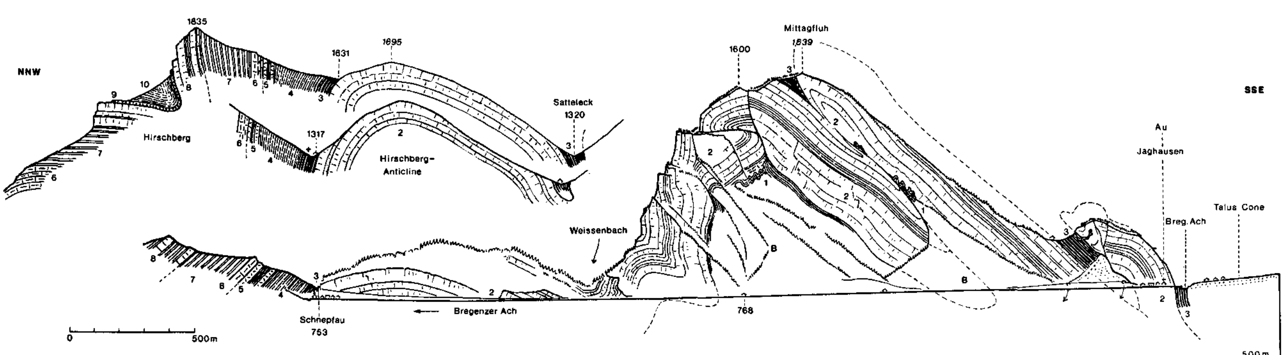


Fig. 8: Cross-section through the Säntis nappe (Helvetikum) in the Bregenzer Wald district along the Bregenzer Ache river (after A. Heim, 1933). 1 = Schilt Beds; 2 = Quinten Limestone; 3 = Zementstein Beds; 4 = Marls of the Valanginian; 5 = Limestone of the Valanginian; 6 = Kieselkalk of the Hauterivian; 7 = Drusberg Beds; 8 = Schratten Limestone; 9 = Brisi Sandstone; 10 = Leist Marls; B = landslide.

In *Upper Austria* mainly the *Northern Ultrahelvetic Zone* occurs, consisting chiefly of red and variegated marls with intercalations of spotted limestones, ranging from the Lower Cretaceous to the Eocene; in the Tertiary also limestone with lithothamnions and nummulites as well as sandstones are occurring.

The *Southern Ultrahelvetic Zone* is also named *Buntmergelserie* (Mottled Marl Series) and is including the *Gresten Klippen Zone.* The main extension of the Gresten Klippen Zone lies north of the Northern Calcareous Alps between the rivers Enns and Traisen. The actual Klippen series is represented by the Liassic *Gresten Beds* (arkose with siltstone, intercalated by coal beds), *Posidonia Marls,* sandy to brecciated limestones (*Neuhaus Beds*) and siliceous clays of the Dogger as well as radiolarites, cephalopoda limestones and aptychus limestones of the Malm and the deeper part of the Lower Cretaceous.

The Klippen beds are surrounded by Cretaceous (upper part of the Lower Cretaceous) to Eocene variegated to spotted marls, intercalated by thin sandstones of the Buntmergelserie, here named *Klippenhülle* (i. e. Klippen cover).

The original basement of the Klippen Zone can be assumed to consist of crystalline rocks from the or comparable with the Bohemian Massif, as shown by dislodged slices of granite near Waidhofen/Ybbs; one of these outcrops became a monument for the famous geologist Leopold von Buch (1774—1852; *Leopold von Buch Granite*).

The Gresten Klippen Zone and the Buntmergelserie continue beneath the Northern Calcareous Alps (well Urmannsau 1, see fig. 9) and occur in the *Flysch and Klippen window of the Lake of St. Wolfgang,* here also containing Jurassic diabase, gabbro and serpentinite.

Eastwards the Klippen Zone continues as an imbricated Zone within the Flysch Zone, the *Hauptklippenzone* of the Wienerwald. The normal succession is closely related to the Gresten Klippen Zone, covered by Buntmergelserie.

In many cases it is evident that the narrow windows of the Ultrahelvetic Zone within the Flysch Zone originate from sheared anticlines of the overlying Flysch nappe.

The entire Klippen Zone is highly deformed, faulted and imbricated and has fault contacts with all adjacent units. Therefore the original position in the sedimentation area has not always been clear: Some former authors imagined a close depositional relationship of the Mesozoic Klippen rocks and the Northern Calcareous Alps (F. Trauth, L. Kober). Later, however, lithological and faunal investigations have confirmed the Gresten Klippen Zone and its cover as a part of the Helvetikum, which had a somewhat different depositional or deformational history from the rest of the unit. Both Helvetikum and Klippen Zone are thus parautochthonous to allochthonous and had an original site of deposition immediately north of the Flysch Zone.

Concerning the continuation of the Helvetic Zone into the Carpathian mountains, the Subsilesikum (with the Wadowice Klippen) in the north occupies an analogous position to that of the Helvetikum (S. Prey, 1974).

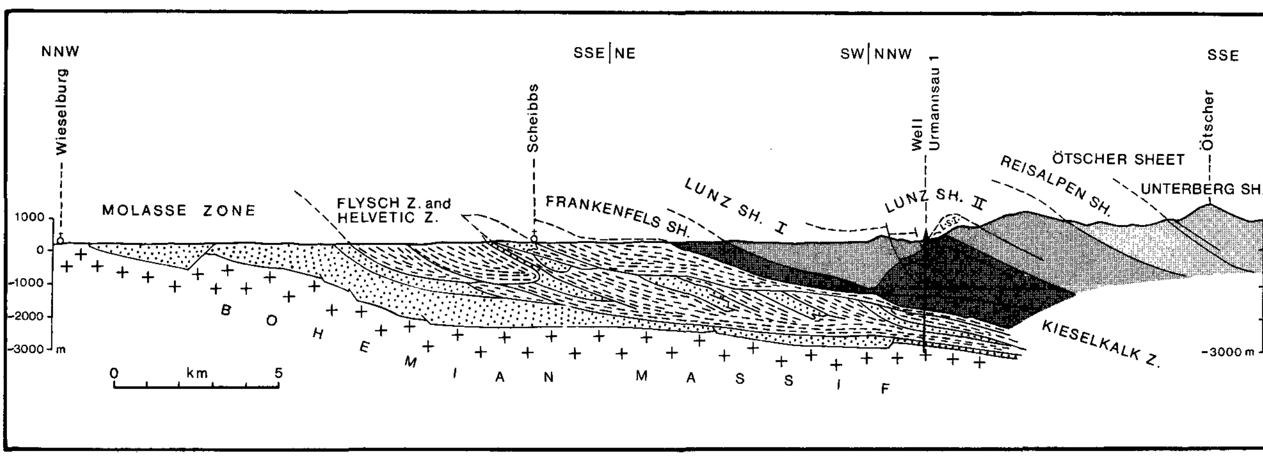
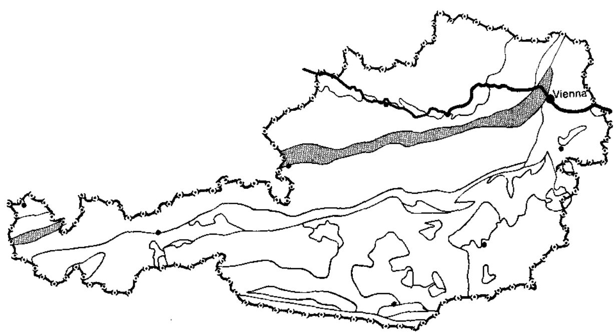


Fig. 9: Cross-section through the Molasse Zone, the Ultrahelvetic Zone, the Flysch Zone, and the Northern Calcareous Alps in the area of the window of Rogatsboden and the well Urmannsau 1. Demonstrated are the submerging Foreland Molasse, the thrustslices of the Sub-Alpine Molasse within the Ultrahelvetic Zone, the Flysch Zone, the internal structures of the Northern Calcareous Alps, and the location of the well Urmannsau 1 (after A. Kröll & G. Wessely, 1967).

The Penninic Zone

At the western end of the Eastern Alps the major part of the Penninic complex of the Western Alps dips eastwards under the Austro-Alpine Unit. The eastern continuation of a minor part (Flysch Zone) crops out along the northern margin of the Austro-Alpine Unit. The eastern continuation of the main complex, however, reappears in several tectonic windows below the Austro-Alpine Unit in the central zone of the Eastern Alps.

The Flysch Zone



The Flysch Zone is a belt of mainly Cretaceous, partly Tertiary sediments which is more or less continuous along the entire length of the Eastern Alps. Generally it is supposed to be an analogous unit of the Western Alpine *Prätigau Flysch* of the Northern Penninic Zone, but probably became deposited in a southernmore sedimentation area of the Northern Penninikum. Eastwards it extends into the Carpathians, remaining an important tectonic unit.

The term "Flysch" originates from the Swiss Simmental, characterizing shaly rocks inclining to land-slides.

In the Eastern Alps it is important to distinguish between the Flysch facies and the Flysch Zone. The Flysch Zone is a tectono-stratigraphic unit, most of the rocks exhibiting Flysch facies, but also containing rock types in other facies.

Following Ph. KUENEN we understand Flysch facies sediments to be originated in a deep sea basin, probably a trench, by turbidity currents: turbidite sandstones with graded bedding, sharp bottoms, load and flow casts, traces etc., and intercalated argillaceous and calcareous layers. In case of submarine sliding also fluxo-turbidites are occurring; fossils, particularly macrofossils are rare. According to this, sediments in Flysch facies can be observed in various tectonic and stratigraphic units of the Eastern Alps, e. g. "Flysch-Molasse", flyshoid Gosau beds, Palaeozoic Flysch of the Carnic Alps, etc.

As a result of uniform tectonic position in the Eastern Alps, but somewhat different from the position of the Flysch in the Western Alps and in the Carpathians, the *Eastern Alpine Flysch Zone* is also named *Rheno-Danubian-Flysch* (R. OBERHAUSER, 1968), in consequence of its extension between the rivers Rhine and Danube. Contrary to this, A. TOLLMANN (1963, 1978) supposes, that the Flysch trough was trending obliquely to the older facies regions. In the west it is connected to the Middle Penninic Zone, in the Vienna district it lies transgressively upon Gresten Beds of the Helvetic Zone and eastwards it is continuing in an area north of the Pieniny Zone.

In Vorarlberg, at the western end of the Rheno-Danubian Flysch, the tectonic position of the Flysch Zone is between the underlying Ultrahelvetic Liebenstein nappe and Feuerstatt nappe and the overlying Penninic Arosa Zone.

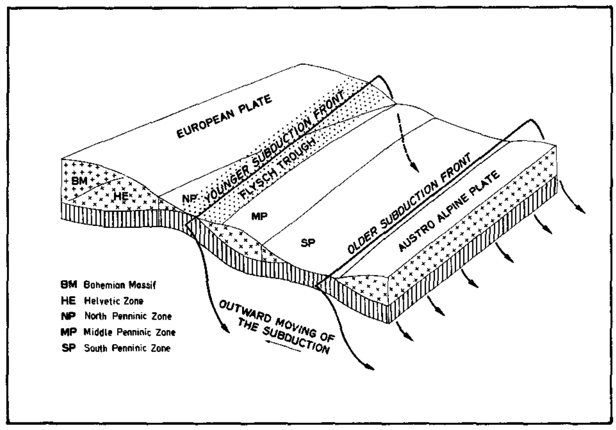


Fig. 10: The oblique trending of the Flysch trough in the Eastern Alps. It is caused by a parallel northward moving of the subduction front and the eastward wedging out of the North Penninic Zone (after A. TOLLMANN, 1978, fig. 5).

The Flysch Zone of Vorarlberg mainly comprises a limestone series (*Tristel Beds*) and a quartzite series ("*Gault-Flysch*") of the lower Cretaceous, overlain by the *Schwabbrünnen Series* ("Hauptflyschsandstein" in the west, Reiselsberg Sandstone in the east), up to 600 metres thick graded sandstones of the Cenomanian to the Turonian. It is superimposed by the *Plankner Series* (siliceous limestones) of the Coniacian to Santonian, the *Planknerbrücken Series* of the Campanian and the *Fanola Series* of the Maastrichtian; the latter two developed in typical Flysch facies. Till now an extension into the Paleocene has not been proved.

Here and in the adjacent Allgäu area three nappes (or subordinate nappes) can be distinguished: the *Üntschen Nappe* or the actual Vorarlberg Flysch Zone and the *Sigiswang Nappe,* which both belong to a northern facies region, as well as the *Oberstdorf Nappe*, belonging to a southern facies region and showing more prominently marly facies ("Zementmergel"). From here as far as the Vienna region the Flysch Zone is not divided into different tectonic sub-units.

East of the river Salzach the Flysch Zone comprises Neocomian to Paleocene age (S. PREY since 1950, W. JANOSCHEK 1964). Calc-sandstones, shales, detrital and spotted *limestones* with aptychi and *breccias* of the *Neocomian* are overlain by black and dark-green shales, sandstones and quartzites, often glauconite-bearing (*"Gault-Flysch"*). The Upper Cretaceous begins with variegated shales (*Untere Bunte Mergel*) and the *Reiselsberg Sandstone* of the Cenomanian and Turonian, in most cases overlain by another variegated shales-stratum (*Obere Bunte Mergel*). A prominent bed is the several hundred metres thick *Zementmergelserie* ("Cement Marl Series") reaching from the Coniacian to the Campanian. Most frequent are marls and marly shales with rare thin calc-sandstone intercalations, fucoides, chondrites as well as helminthoides. The *Mürbsandsteinserie* ("friable sandstone series"), also several hundred even up to 1.000 metres thick, comprises alternating layers of calc-sandstones, shales, marls and coarser friable sandstones. Fucoides, chondrites and helminthoides occur frequently in the shales. The age is Maastrichtian and Paleocene. In some areas, but mostly lacking in the south, the Zementmergelserie and the Mürbsandsteinserie are seperated by a third variegated shale intercalation (*Oberste Bunte Schiefer*).

As the Zementmergelserie is normally thicker in the south and the Mürbsandsteinserie is thicker in the north, a slow northward movement of the axis of the Flysch trough can be assumed.

In the Vienna district three subsidiary nappes show slightly different successions and facies (K. FRIEDL 1921, B. PLÖCHINGER & S. PREY 1974). In the northern *Greifenstein subsidiary nappe* there is a gap between the Lower Cretaceous Flysch and the Campanian *Kahlenberg Beds*, which are comparable with the Zementmergelserie in the west. Locally also vestiges of variegated shales of Campanian age are occurring. In the normal section follow Maastrichtian to Paleocene *Altlengbach Beds*, comparable with the Mürbsandsteinserie in the west. They are overlain by the Paleocene to mid-Eocene *Greifenstein Beds*, which consist of thick layers of partly glauconitic sandstone and sandy shales.

The central *Kahlenberg subsidiary nappe* has a complete sequence: *"Gault-Flysch"* of the lower Cretaceous, variegated shales with intercalations of *Reiselsberg Sandstone* of the mid-Cretaceous, *Kahlenberg Beds* and *Sievering Beds* (analogous to the Altlengbach Beds respectively to the Mürbsandsteinserie).

The section of the southern *Laab subsidiary nappe* begins with *Kaumberg Beds* of the Coniacian to Campanian: variegated shales and marls with layers of calc-sandstones. Thin-bedded quartzites and shales are of Maastrichtian age, while at the border to the Tertiary black shales and glauconitic quartzites are dominating. The superimposed *Laab Beds* of the Paleocene to the Middle Eocene are composed of thick-bedded sandstones (Hois Beds) and shales with sandstone-layers (Aggsbach Beds).

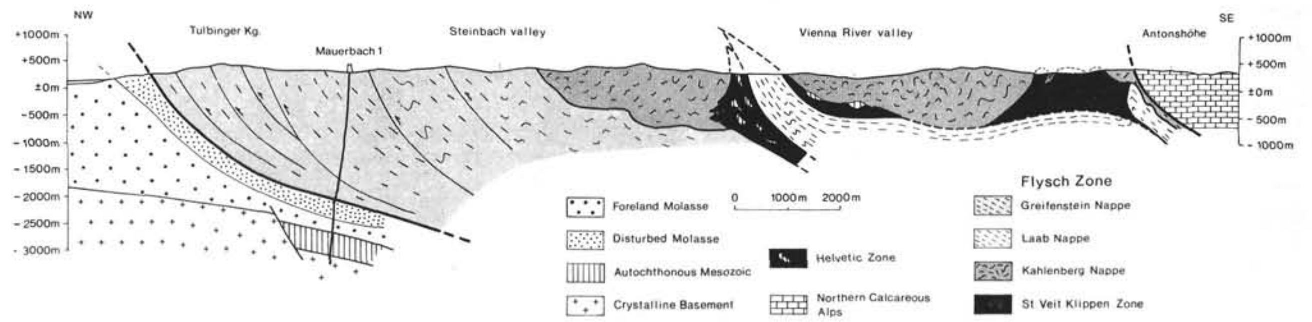


Fig. 11: Cross-section of the Flysch Zone of the Wienerwald. Demonstrated are the three subsidiary nappes of the Flysch Zone as well as the Helvetic Hauptklippenzone and the St. Veit Klippen Zone (after S. PREY in W. DEL NEGRO 1977).

An old problem of the geology of the Vienna district is the stratigraphy, the facies and the structural position of the *St. Veit Klippen Zone*. The similarities of the sections of the Hauptklippen Zone (see chapter "The Helvetic Zone") and the St. Veit Klippen Zone are well known: While lacking in the Hauptklippen Zone, in the St. Veit Klippen Zone the uppermost Triassic (Rhaetian) is represented by *Keuper quartzites* as well as marls and limestones (*"Kössen Beds"*). The Jurassic and the Lower Cretaceos beds are similar to the sequence of the Gresten Klippen Zone. This may suggest a close spatial relationship of the two units at the time of deposition.

But there exist considerable differences in the Klippenhülle (Klippen cover): The Klippen cover of the

Hauptklippen Zone in the facies of the Helvetic Buntmergelserie has been discussed in the chapter "The Helvetic Zone". The *sedimentary cover* of the Klippen of St. Veit mainly consists of red shales with faunulas of agglutinating foraminifers and intercalations of Reiselsberg Sandstone of Cenomanian to Turonian age. This series is doubtless part of the section of the Flysch Zone. Therefore F. BRIX (1970) and S. PREY (since 1973) are of the opinion that the St. Veit Klippen Zone is the original depositional basement of the Flysch Zone or at least of a part of the Flysch Zone. Nothing, however, is known about the basement of the other parts of the Rheno-Danubian Flysch zone.

In southern direction the Flysch Zone extends far beneath the Northern Calcareous Alps, as shown in the sections fig. 2 and 15.

Forming small outcrops in the Waschberg Zone and being present in the basement of the Intra-Alpine Vienna Basin, in north-eastern direction the Flysch Zone continues into the Carpathians. The northern (outer) Flysch subsidiary nappes (Greifenstein and Kahlenberg unit) can be roughly compared with the Silesian units, the Laab subsidiary nappe with the Magura unit of the Carpathians. The Pieniny Klippen can be seen as an equivalent, however, not as a direct continuation of the St. Veit Klippen Zone (S. PREY, 1974).

The Penninic Windows

The sedimentary rocks occurring in these windows are usually slightly metamorphic and mostly unfossiliferous. Parts of this assemblage have been compared on lithological grounds with the Jurassic-Cretaceous Bündnerschiefer of the Penninic Zone in the Western Alps. The interpretation of reappearing Penninic realms gave rise to important ideas about the tectonic history of the Eastern Alps. Moreover, although the fossils found within the Penninic Windows of the Eastern Alps are sporadic and questionable, as a whole, however, they support Mesozoic age of major parts.

The Arosa Zone and the Falknis-Sulzfluh-Nappe which directly underlie the Austro-Alpine Unit at its western margin are allocated with some reservation by R. TRÜMPY 1972 to the Penninic system. This concept is applied in the following account.

The Window of Gargellen

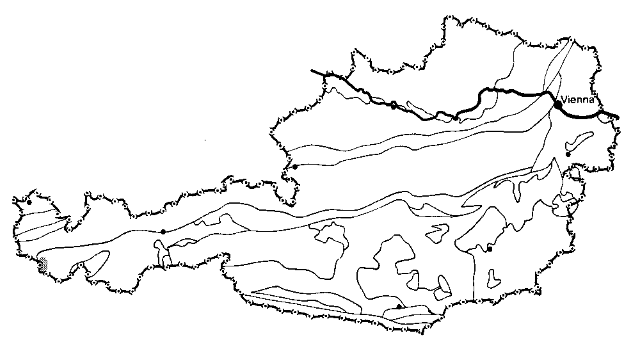
The Window of Gargellen, 7 km long and 1 to 2 km wide, exposes the Penninic system only 3 km east of the western end of the Austro-Alpine Unit. It stretches in NNE-SSW-direction. According to a recent review by H. BERTLE 1974 the rock assemblage of this window is grouped into following tectonic units:

The *Prätigauflysch* at the basis forms the major part of the complex. It consists of slates and marly slates, calc-sandstones with glauconite, siliceous and marly limestones, quartzitic sandstones and fine-breccias. The series yielded fossils of Campanian to lower Eocene age.

The *Falknis Nappe* directly overlies the Prätigauflysch as a thin (few meters) tectonic unit, consisting of pale limestones ("Couches Rouges") and containing a rich microfauna of upper Campanian (to ? Maastrichtian) age.

The *Sulzfluh Nappe* follows above. The base is formed by the green, sometimes reddish Sulzfluh Granite with a maximum thickness of 3,5 m. It is overlain by the pale, late Jurassic (Malm) Sulzfluh Limestone attaining a thickness of 70 m near Gargellen. Locally the sedimentary character of the boundary between the granite and the limestone is tectonized.

At the top the sequence is closed by the *Arosa Zone.* It comprises a strongly deformed, unfossiliferous suc-



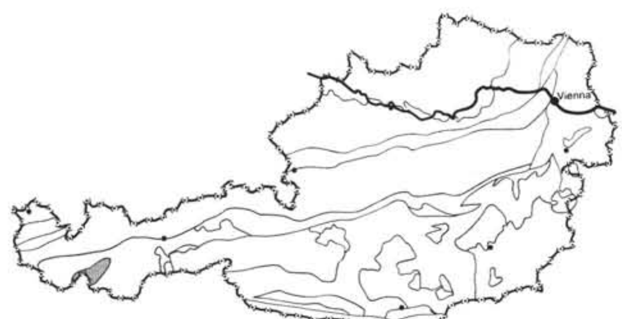
cession of shales and calc-shales with transitions to radiolarian cherts, siliceous limestones and breccias. Jurassic to Cretaceous age is assumed. Frequently blocks of different size are tectonically included. They might represent Permomesozoic strata. In general the Arosa Zone is understood as a highly disturbed tectonic horizon marking the basal thrust-plane of the Austro-Alpine Unit.

The frame of the Gargellen window is formed by the Silvretta crystalline complex representing here the Austro-Alpine Unit.

The fold-axes show a general low angle dip towards east. The folds are distinctly overturned towards the north which can be obviously attributed to the northward movement of the overriding Austro-Alpine Unit. The window of Gargellen is situated along an important fault line in NNE-SSW direction. Sinistral displacements along this fault with a certain uplift of the western part are younger than the main nappe movements.

The Window of Unterengadin

The window of Unterengadin lies in the area of the upper Inn valley between Ardez in the southwest and Prutz in the northeast. In NE-SW-direction it is about 55 km long and 17 km wide. The southwestern half is



situated on the territory of Switzerland, the northwestern half in Austria. Interaction of probably Miocene arching along the longitudinal axis as well as erosion exposed the underlying Penninic series. Their complex tectonic structure makes correlation between the Swiss and Austrian part of the window very difficult. The following account is based on A. TOLLMANN 1977 and H. UCIK 1977 and describes a pile of tectonic sheets beginning with the bottom part.

The *Pfunds Series:* The basal 2000 to 3000 m are formed by the "Grey Bündnerschiefer", a monotonous sequence of more or less sandy and calcareous slates and sporadic breccias. In their uppermost part the "Saderer Joch Series" is intercalated consisting of phyllites, quartzites, and micro-carbonate-breccias which yielded a Campanian-Maastrichtian fauna. The "Grey Bündnerschiefer" are overlain by the "Coloured Bündnerschiefer". They attain a thickness of about 100 m and consist of more or less brownish quartz-carbonate-sandstones and greenish chlorite-sericite-phyllites with interbedded conglomerates and breccias. In different levels of the Pfunds Series ophiolite layers of variable thickness are intercalated.

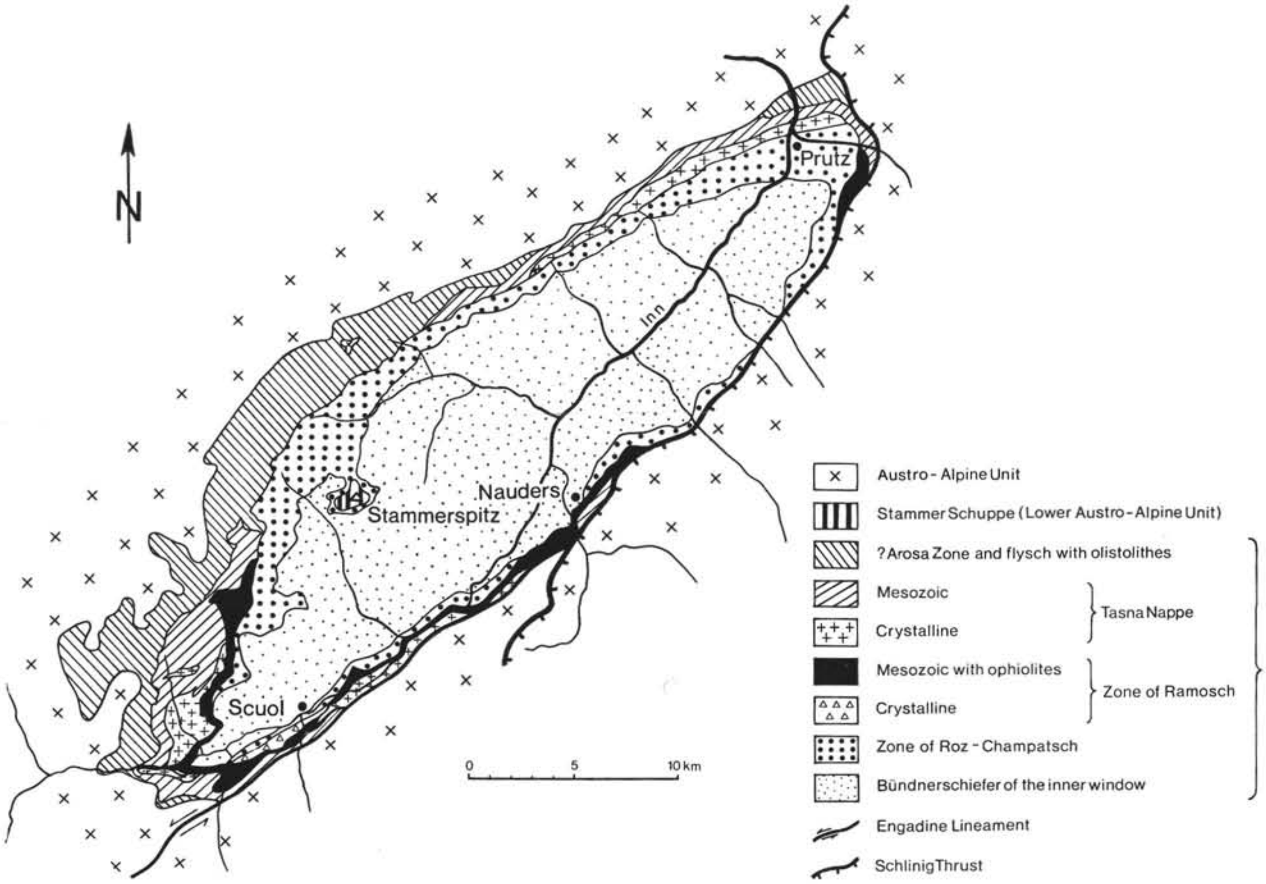


Fig. 12: Tectonic sketch-map of the window of Unterengadin (modified after J. CADISCH, and R. TRÜMPY, 1972).

The *Pezid Series:* At the base layers or isolated blocks of Permotriassic rocks (quartzite, dolomite, limestone) occur. The overlying sequence corresponds lithologically to the Pfunds Series but is of minor thickness. The primary thickness of the Pezid Series was about 200 to 300 m. By folding it became approximately 1000 m thick. The tectonic contact against the underlying and the overlying units is disturbed by folding and slicing. In the Swiss part of the Window of Unterengadin the Pezid Series may correspond with the "Schuppenzone of Roz-Campatsch".

The *Ramosch Schuppe* is mainly confined to the southwestern half of the Window of Unterengadin and consists of phyllonitic crystalline rocks, Triassic dolomite and gypsum, Bündnerschiefer and ophiolites. Some occurrences of diabase show pillow-like structure.

The *Prutz Series* is almost unfossiliferous and shows strong tectonic disturbance. Palaeozoic quartz-phyllites (max. thickness 50 m) with pieces of ankeritic dolomite are overlain by the Permoskythian Ladis Quartzite (max. thickness 100 m) and pieces of Triassic limestone (max. thickness 150 m). Grey Neocomian shales of 10 to 30 m and a "Clastic Series" of about 100 m which lithologically correspond to the "Coloured Bündnerschiefer" close the sequence at the top.

The *Tasna Series or Nappe* in the Austrian district resembles lithologically as well as in the order of the sequence the Prutz Series. In the Swiss part the Tasna Series exhibits a broader succession. Upon a crystalline basement of green granites, granite-gneisses, and mica-schists a sedimentary sequence is developed comprising Permian to fossiliferous Lower Senonian strata.

The *Fimber Unit:* This term was proposed by A. Tollmann 1977 in order to denominate a questionable equivalent of the Arosa Zone. The Fimber Unit mainly consists of "Tasnaflysch" with olistolithes. The youngest strata so far examined are of Cenomanian-Turonian age (R. Oberhauser, 1976).

The frame of the Window of Unterengadin in the north, west and south is formed by the Silvretta crystalline complex, in the east by the Ötztal crystalline complex, representing the Austro-Alpine Unit.

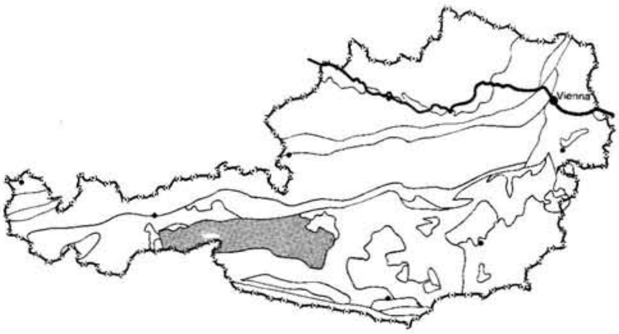
The *Outlier of the Stammerspitz* within the window area is a peculiar problem. It rests upon Bündnerschiefer of the deepest unit and is made up chiefly by fossiliferous, carbonatic upper Triassic and Jurassic strata. It is generally considered as an Austro-Alpine element and is allocated by A. Tollmann to the Central-Alpine facies.

As mentioned before the axes of the generally updomed Penninic series of the Window of Unterengadin runs NE-SW. The majority of fold-axes and lineations, however, has E-W-orientation and reachs into the crystalline complexes of the Austro-Alpine frame of the window. Only low-grade Alpine metamorphism affected the Penninic series of the Window of Unterengadin and was slightly stronger in the northeastern part.

According to the youngest strata involved the main Alpine thrusting must be dated post-Maastrichtian.

The *Engadin Lineament* striking NE-SW is an important fault which bounds the Window of Unterengadin in the southeast. Southwestwards it can be traced beyond the Majola Pass and northeastwards after A. Tollmann 1977 as far as to the Northern Calcareous Alps. In Miocene times probably sinistral movements began and subsequently changed into northeastward upthrusting. On Austrian territory the Engadin Lineament joins with the Schlinig Thrust plane.

The Tauern Window



The Tauern Window is a magnificent example of Alpine tectonics. It was recognized in 1903 by P. Termier and in the subsequent 50 years it has been subject of passionate controversies. Today its window nature is generally accepted.

This major tectonic window in the area of the Hohe Tauern mountains is about 160 km in an east-west direction and about 30 km from north to south. It is situated in the central part of an axial culmination where the deepest tectonic units of the Eastern Alps are exposed.

The series can be divided into two main lithological suites. One is formed by the cores of "Zentralgneis" (Central Gneiss), the other one by their "Schieferhülle" which literally means "schist mantle" or "schist cover" composed of Palaeozoic and Mesozoic rocks. This strongly deformed rock assemblage exhibits a very complex internal structure.

Lithology and Stratigraphy

1. The *Altkristallin Series:* This term is used to designate the pre-Mesozoic metamorphic basement of probably Precambrian to early Palaeozoic metasedimentary and metavolcanic rocks, such as paragneiss, garnet-mica-schist, amphibolite, migmatite, plagioclase-gneiss, and locally serpentinite and marble. The pre-Mesozoic progressive metamorphism happened under amphibolite facies conditions. The Alpine metamorphism, however,

had a retrograde effect on the rocks of the Altkristallin Series.

2. The *(Early) Palaeozoic Series (Habach Series):* The main rock types are black, almost carbonate-free phyllites (Habach Phyllites) besides minor amounts of graphitic quartzite, sericite-phyllite and kyanite-quartzite. Igneous rocks are abundant and comprise metakeratophyrs, porphyroids, greenschists, amphibolites; ultramafic rocks are represented by peridotites, pyroxenites, and hornblendites, all of which tend to be serpentinized. Widespread greenschist facies metamorphism which attained mesozonal intensity in the central parts only *(Greiner Schiefer Series)* is mainly attributed to Alpine events. Lithological analogies exist between the unfossiliferous Palaeozoic rocks of the Schieferhülle and the fossiliferous Palaeozoic rocks of the Austro-Alpine Unit. G. Frasl 1958 identified this older Schieferhülle in the northern part of the middle Hohe Tauern mountains.

3. The *Zentralgneis* can be divided into different generations of late Variscan granitoids which intruded into the Altkristallin and Habach Series. The more or less well-developed foliation and metamorphism of the Zentralgneis is of Alpine age. Orthogneisses of granodioritic to granitic composition and coarse porphyritic texture (coarse alkalifeldspar augengneiss) represent the oldest generation. Tonalites belong to a subsequent generation. Finally the intrusion of leucocratic fine-grained granites and various groups of dykes (aplites, pegmatites, and kersantites) terminate the magmatic activity. A number of radiometric determinations mainly yielded middle Permian ages for the Zentralgneis.

4. The *Permotriassic Series* in general is a thin series. It has a relatively thick development (max. 300 m) in the middle part of the Tauern Window. There are lithological similarities to the Central Alpine facies of the Austro-Alpine Unit. Foliated quartzites, arkose-gneisses with cobbles of quartz-porphyry, and greenish-white phengite-quartzites are believed to represent Permoskythian in transgressive facies. This series was called *Wustkogel Series* by G. Frasl 1958. The middle and upper Triassic succession (*Seidlwinkltrias*) is composed

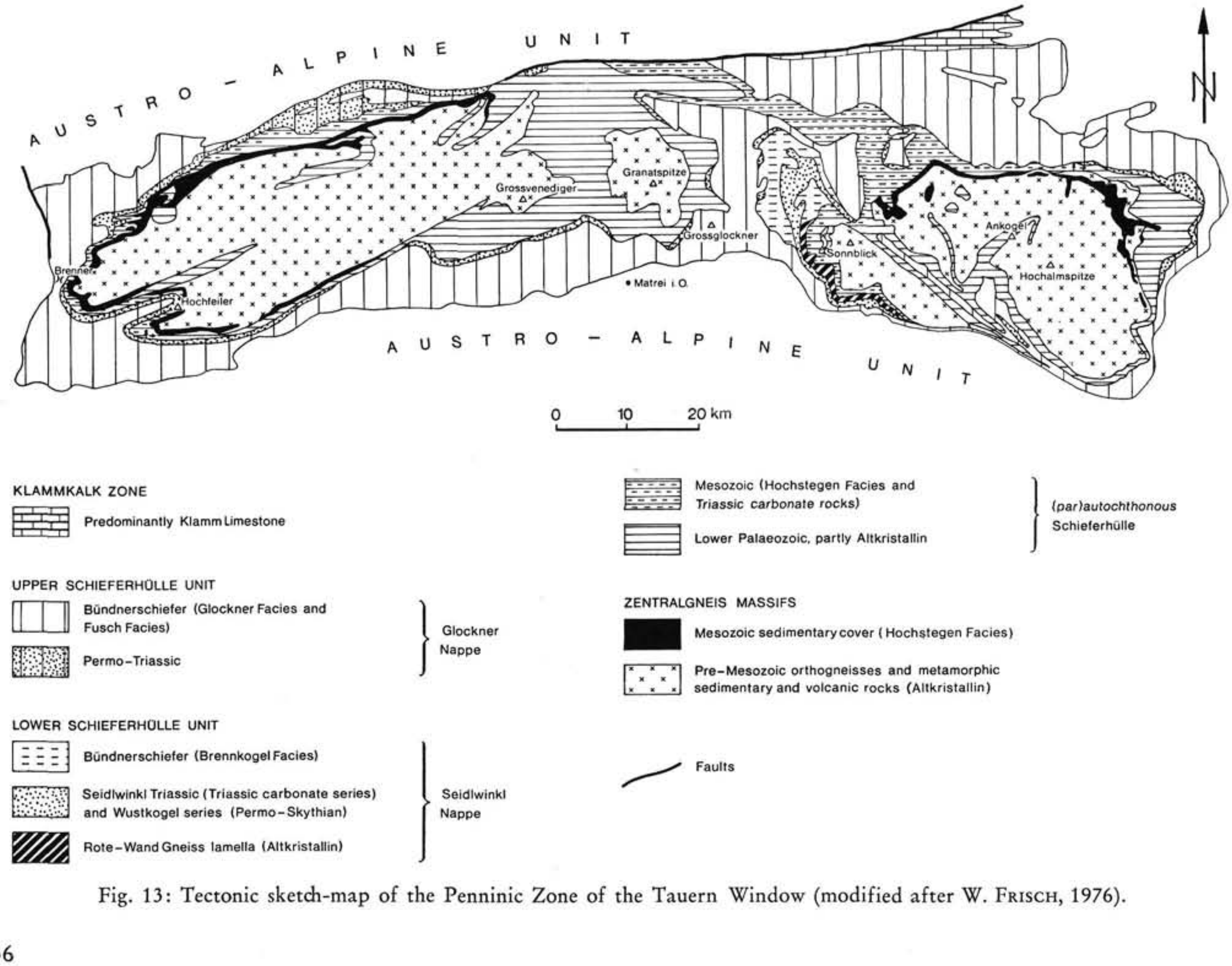


Fig. 13: Tectonic sketch-map of the Penninic Zone of the Tauern Window (modified after W. Frisch, 1976).

of rauhwacke, banded limestone, cherty limestones, pale or gypsiferous dolomite, overlain by chloritoid-phyllites and quartzite-phyllites (both equivalent to the Swiss Quartenschiefer or to the Bunter Keuper in Central Alpine facies as it occurs in the Semmering area).

5. The *Jurassic-Cretaceous Series (Bündnerschiefer)* is believed to be lithologically equivalent to the series of Bündnerschiefer in the Western Alps. Four facies types could be distinguished. Their original arrangement from north to south is believed to be as follows (G. Frasl & W. Frank, 1966):

The *Hochstegen Facies:* Lithology and minor thickness indicate deposition on an elevated area in the north. The sequence begins with a thin layer of quartzite, arkose and phyllite, resting directly on the Zentralgneis. W. Frisch (1968) supports Liassic age for this layer. It is succeeded by Malmian Hochstegen Limestone, which yielded the famous specimen of Perisphinctes (Oxfordian). The sequence is topped by more or less calcareous phyllites interbedded with quartzites and breccias ("Kaserer Series") which is believed to range up into Lower Cretaceous. In the eastern part of the Tauern Window quartzites (partly conglomeratic, with kyanite and chloritoid) and the Angertal Marble resting upon the Zentralgneis are allocated also to the Hochstegen Facies by Ch. Exner. O. Thiele (1970) and W. Frisch (1975) do not want to assign the Hochstegen Facies to the Penninic, but to the Helvetic Facies realm.

The *Brennkogel Facies:* Occurrences of considerable thickness are exposed in the central part of the Tauern Window (northwest of Hochtor at the Glocknerstraße). The sequence is resting with sedimentary contact upon the Seidlwinkl Triassic. Principial rock types are dark graphitic phyllites with variable proportions of carbonate. White, yellow and grey quartzites are interbedded more often in the deeper section. Moreover frequently breccias with carbonate and quartzite fragments are intercalated. Basic metavolcanic rocks are of minor importance.

The *Glockner Facies* is dominated by thick micaceous marbles and ophiolites. Intercalations of phyllites, garnet-mica-schists, dolomite breccias, and quartzites are of surbordinate importance. The micaceous marbles can be derived from somewhat bituminous marls and limestones, the huge quantities of greenschists (partly eclogitic) from basic tuffs and submarine basalts. Occasionally serpentinites are associated with the greenschists. Apart from isolated ?Triassic slices at the basis the basement of the Glockner Facies series is nowhere exposed. Petrological studies on ophiolites of the Glockner Facies, carried out by V. Höck (1976), yielded a petrological affinity to oceanic basalts. This supports deposition on ocean-floor for the Glockner Facies series, which subsequently became detached during Alpine movements.

The *Fusch Facies:* It is mainly confined to the northern part of the eastern Tauern Window. Carbonate-poor black phyllites are prevailing. Locally micaceous marbles, meta-basites, greenish-grey thinly stratified quartzites and frequent breccias are interbedded. Because of the low-grade metamorphism in this part of the Tauern Window ophitic and amygdaloidal texture of volcanic rocks is locally well preserved. The above mentioned greenish-grey, thinly stratified quartzites probably represent metamorphic radiolarian cherts which are of stratigraphic significance indicating upper Jurassic. Occasionally detritic episodes exhibit flysch-like character.

Whether the *Klammkalk Zone* — confined to a wedge-shaped area in the northeastern part of the Tauern Window — must be considered or not as another Bündnerschiefer facies type or even as part of the Lower Austro-Alpine Unit of the Radstadt Tauern mountains is still a matter of controversy. The principal rock-types are the typical light-coloured or grey Klamm Limestones; additionally there are calcareous phyllites and quartzites, greenish-white phyllites and subordinate dolomite and rauhwacke.

Metamorphism

All units exhibit almost entirely Alpine, syn- to post-tectonic regional greenschist facies metamorphism. The Permomesozoic portion underwent progressive alteration, whereas the pre-Permomesozoic assemblage was partly affected by retrograde alteration. The grade of metamorphism increases towards the central parts (V. Höck, 1976), where locally mesozonal parageneses (staurolithe, biotite, garnet, oligoclase-andesine) can be observed. Regarding this "young-Alpine" metamorphism an age of about 40 m.y. is supported on the base of radiometric age determinations (R. Cliff & al, 1971). Relictic high-pressure mineral assemblages in eclogites are believed to indicate an "old-Alpine" metamorphic event of probably Cretaceous age. Cooling ages are spread about a time interval between 12 to 20 m.y. (middle-Miocene) indicating subsequent uplift which began in the eastern part of the Tauern Window and later affected the western part.

Structure

Crustal shortening by southward subduction during Alpine events piled up a series of regional thrust-sheets each of which was transported relatively northwards upon their adjacent units. This is also reflected by the principal features of the internal structure of the Penninic Series in the Tauern Window. It is expressed in numerous geometric (attitude of folds) and litho-facial data of both local and regional proportions. Multiphase deformation (including pre-Mesozoic phases) and lithological irregularities caused very complex structures which are difficult to understand because of paucity in fossils due to the influence of metamorphism. All this lead to a diversity of interpretations, which, however, coincide in a number of fundamental aspects.

1. The *basement complex* comprises the cores of Zentralgneis and their thin Mesozoic cover, mainly preserved along their northern margins. The basement complex is either regarded as autochthonous (Ch. EXNER, 1957, 1964) or as parautochthonous (A. TOLLMANN). It occupies major parts of the Tauern Window area and can be divided from west to east into following four occurrences:

The *Zillertal-Venediger Core* occupies the central western Tauern Window. Enormous Alpine compression caused steeply inclined ENE-striking structures, the formation of elongated, more or less symmetrical ridges, and recumbent anticlinal folds with northward diving crests.

The dome-shaped *Granatspitz Core* in the center of the Tauern Window is without any Mesozoic cover. According to A. TOLLMANN it represents the deepest complex, but in spite of that he regards it as parautochthonous as well.

The *Sonnblick Core* in the eastern part of the Tauern Window forms a ridge trending NW-SE and is divided into several anticlines and synclines. The Zentralgneis is covered by Altkristallin Series, but, apart from small, questionable occurrences the Mesozoic cover is lacking.

The *Hochalm-Ankogel Massif* in the central part of the eastern Tauern Window extends northeast of the Sonnblick Core from which it is separated by the Mallnitz Syncline. At the northern margin of the massif a

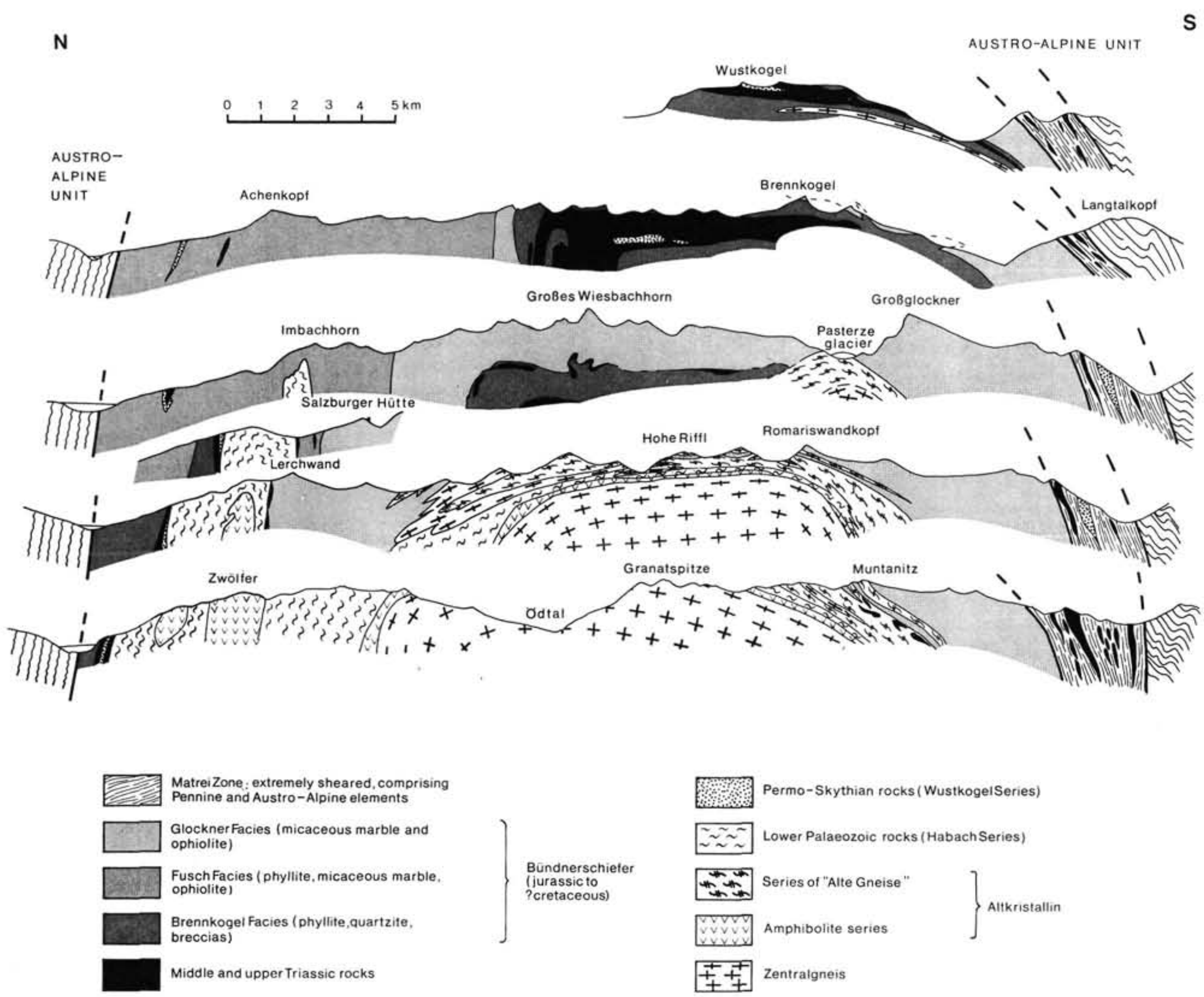


Fig. 14: Sections across the central part of the Tauern Window (modified after W. FRANK, 1965).

thin cover of quartzite and marble is developed, which Ch. Exner allocates to the Hochstegen Facies series. The Hochalm-Ankogel Massif can be divided by north-south or NE-SW trending depressions into the Hochalm Core, the Hölltor-Rotgülden Core and the Sieglitz Complex ordered from east to west.

2. The *Lower Schieferhülle Unit* mantles the basement cores and comprises a number of local thrust-sheets which can be hardly correlated over the whole area of the Tauern Window. It mainly consists of Palaeozoic Schieferhülle series and intercalations of Altkristallin lamellae and Mesozoic rocks (Triassic dolomites, Bündnerschiefer in Hochstegen Facies). The Porphyrmaterial-schiefer-Schuppe in the northern part of the western Tauern Window, the Riffl Nappes which overlie the Granatspitz Core, as well as the Storz Nappe upon the Hochalm-Ankogel Massif belong to this nappe system.

The *Seidlwinkl Nappe* (according to W. Frank, 1969 and W. Frisch, 1976) is confined to the central part of the Tauern Window and is also allocated to the Lower Schieferhülle Unit. It is a recumbent thrust-fold composed of rocks of the Rote-Wand Gneiss Lamella, the Wustkogel Series, the Seidlwinkl Triassic and of Bündnerschiefer in Brennkogel Facies.

3. The *Upper Schieferhülle Unit* represents the highest tectonic unit within the Tauern Window. It consists of Bündnerschiefer in Fusch Facies and in Glockner Facies, regarded as a sedimentary cover which became completely detached from its basement during the northward Alpine movements. At several places the basis of the Nappe-System is marked by strongly deformed pieces of its questionable Triassic basement. Along the middle part of the northern margin of the Tauern Window along the Salzach Valley the Upper Schieferhülle Unit dies out, but elsewhere throughout the whole Tauern Window it mantles the updomed deeper units.

The above mentioned questionable facial relationship of the wedge-shaped *Klammkalk Zone* at the northeastern margin of the Tauern Window is reflected in its tectonic interpretation. A. Tollmann, for example, considers the *Klammkalk Schuppe* as the highest tectonic subunit of the Penninic complex.

4. Distribution and diversity of *fold axes directions* reflect a complicated and multi-phase tectonic history. In general the B-axes direction is parallel to the east-west elongation of the Tauern Window and its slight northward convex bend. In the easternmost part of the Tauern Window these axes plunge eastwards, elsewhere they show a low-angle westward plunge. Crossfolds are developed in the central part of the eastern Tauern Window. The north-south trending *Glockner Direction* predominates in a huge depression of the Upper Schieferhülle. Southeastwards it gradually turns into the NW-SE trending *Sonnblick Direction* developed in the area of the Sonnblick Core and the Mallnitz Syncline. Finally the major part of the Hochalm-Ankogel Massif and its Lower Schieferhülle mantle show well-preserved NE-SW trending fold axes of the *Ankogel Direction.* The knowledge on the distribution of B-axes in the eastern Tauern Window is mainly based on the studies of Ch. Exner (1957). He further discovered a *Zone of Axial Discordance* which bounds the area of cross-axes to the north against the area of the longitudinal E-W trending B-axes. On the ground of the structural relations to each other the Ankogel Direction can be regarded as the oldest, followed by the Sonnblick and Glockner Direction and finally by the longitudinal direction. This very hypothetical model implies the possibility of very small time intervals between the different deformational phases. The attitude of the majority of the longitudinal folds indicates the general northward direction of tectonic transport. At the northern margin of the Tauern Window, however, southward overturned folds were recorded (A. Matura, 1967; W. Frisch, 1976).

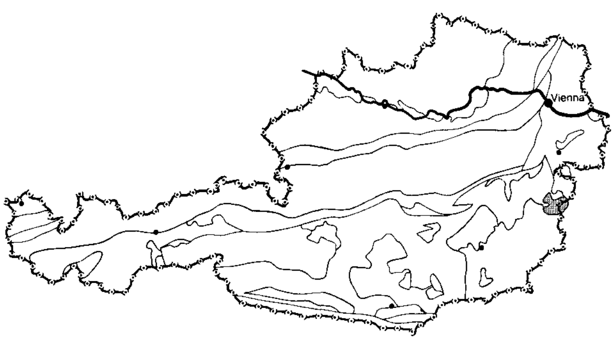
5. Regarding the general medium to high angle outward dip of the Penninic series of the Tauern Window beneath the superincumbent Austro-Alpine Unit there are some exceptions. An important vertical east-west trending post-Miocene fault (*Tauernnordrand Fault* or *Salzach Longitudinal Fault*) connected with the development of broad mylonite zones marks part of the northern boundary of the Tauern Window. The adjoining Penninic series show almost vertical position too. The western part of the southern boundary plane is partly vertical partly overturned dipping northwards.

Alpine History

The multi-phase Alpine movements began during mid-Cretaceous times and finally ceased in Oligocene times having crucial points during upper Cretaceous and the late Paleogene. It is a subject of controversy whether the Penninic series were buried by the overriding Austro-Alpine Unit during upper Cretaceous or in Paleogene times. In any case until Campanian the Northern Calcareous Alps were still resting south of the Penninic realm. This can be deduced from detrital chromite identified in Cenomanian beds at the northern margin of the Northern Calcareous Alps as well as ophiolithe fragments and again chromite found in upper-Santonian to lower-Campanian Gosau Beds of the Northern Calcareous Alps. Chromite and ophiolithe fragments are believed to be debris coming from uplifted oceanic crust in the north. Disregarding the question whether the Penninic series of the Tauern Window were buried or not during the subsequent upper-Cretaceous movements, the importance of this tectonic phase is emphasized both by corresponding radiometric ages from the crystalline basement of the overlying Austro-Alpine Unit and the probably related highpressure mineral assemblages in the Penninic complex. The dimension of the Paleogene movements, however, are impressively exposed at the western end of the Austro-Alpine Unit south of Bregenz, where lower-Eocene Ruchberg Beds of the Prätigauflysch are represented as the youngest strata in the underlying Penninic complex. This is one of the principal arguments of R. OBERHAUSER (1964) who supports the assumption of complete tectonic subdual of the Tauern Window area since the Eocene. According to A. TOLLMANN, however, subsequently to the ceasing chromite supply, the Tauern Window area was already completely buried in the upper-Cretaceous.

Late-Alpine updoming in the region of the Tauern Window continues until recent times. Elevation rates of about 1 mm per year were measured (E. SENFTL & Ch. EXNER, 1973).

The Windows of Rechnitz, Bernstein and Meltern



This group of windows, close to each other, is situated at the eastern end of the Eastern Alps, where the basement rocks disappear under Neogene sediments. About 200 km east of the eastern end of the Tauern Window Penninic Series are exposed again. Their partly Mesozoic age is proved by fossils. Each of these three windows mentioned in the title is either framed by a higher tectonic unit or by Neogene sediments. In general the rock assemblage consists of low-grade metamorphic meta-sediments and meta-volcanic rocks.

According to A. PAHR (1977) the Penninic series of the *Rechnitz Window,* which is the southernmost and largest among the mentioned three occurrences, can be divided into two tectonic units. The bottom part of the deeper unit is formed by about 2000 m of phyllites and quartz-phyllites with rather low but homogeneously distributed carbonate content. They are overlain by greenschists. The higher unit with complex internal structure comprises phyllites, calc-phyllites, platy limestones, greenschists, and serpentinites and overlies the deeper unit in the southwestern and southern part of the Rechnitz Window. Layers of Jurassic *Cák Conglomerate* are interbedded in basal phyllites. The conglomerate consists almost entirely of dolomite pebbles and occasional gneiss pebbles within a detritic calcareous groundmass. The platy limestones yielded Cretaceous sponge spicules (H. P. SCHÖNLAUB, 1973). It is uncertain whether some (? Triassic) intercalations of serizite-quartzites, rauhwackes, dolomite- and calcite-marble are of sedimentary or of tectonic nature. The top-most member of the higher unit are again greenschists associated with big serpentinite bodies. There are striking structural differences between both units: The orientation of B-axes in the deeper unit is north-south, in the higher unit the B-axes are scattered around the east-west direction.

The Penninic occurrences of *Bernstein* and *Meltern* consist of more pure, partly coloured and streaky foliated limestones with occasional cobbles of quartz, of graphitic phyllites, quartzites and on top again of greenschists. At Bernstein an extensive serpentinite body occurs in this highest level. Such serpentinite bodies are believed to give rise to a westward dipping row of magnetic anomalies (G. WALACH, 1977), which could be traced from the surface in the area around Rechnitz and Bernstein to as far as 40 km west of it in the depth beneath the Austro-Alpine Unit. It is thought to mark the westward dipping upper surface of the Penninic series of the Rechnitz area.

An isolated basement exposure about 12 km south of Rechnitz shows greenschists and serpentinites allocated to the Penninic series. At that place the Penninic rocks are bounded by faults against the adjoining Austro-Alpine lower Palaeozoic rocks.

The Austro-Alpine Unit

The Austro-Alpine Unit forms a large regional nappe of complex internal structure and occupies the major part of the Eastern Alps. In the course of Alpine movements the Austro-Alpine Unit split up into separate sheets during northward transport and now forms a pile of thrust-sheets resting with low-angle tectonic contact upon the overridden foreland. The prevailing relative northward direction of transport is generally accepted and postulated on account of a large number of structural and lithofacial facts, such as attitude of folds and the paleogeographic arrangement of the Permomesozoic facies belts. In individual cases minimum distance of northward tectonic transport is proved by natural (tectonic windows) or artificial (drillings) exposures. The internal tectonic subdivision of the Austro-Alpine Unit in vertical direction, however, is still a subject of controversy, which is reflected in alternative application of particular terms. It is virtually impossible in a few lines to do more than to mention only the principal features of the main alternative interpretations still under discussion.

According to A. TOLLMANN (since 1960) the Austro-

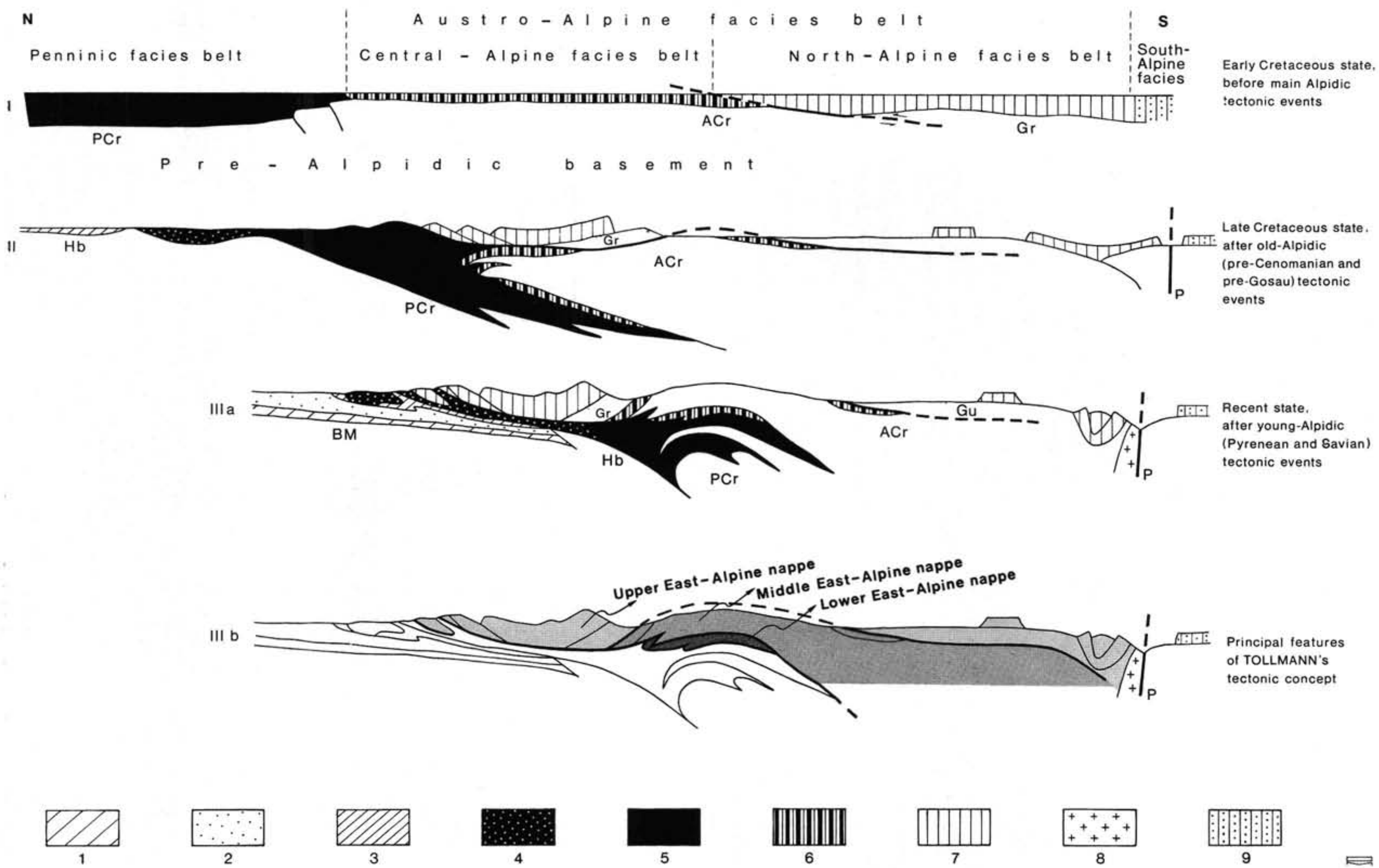


Fig. 15: Hypotheses of the tectonic evolution of the Eastern Alps (sections I, II, and III a; modified after E. Clar, 1973) and a schematic section (III b) showing the subdivision of the "East-Alpine" (= Austro-Alpine) Unit supported by A. Tollmann (1963).

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.

Alpine Unit can be divided into three superimposed units (fig. 15). The "Oberostalpin" (Upper East-Alpine *) Nappe) is a thick sedimentary sequence of Palaeozoic and Mesozoic rocks in North-Alpine facies, detached from its original basement and mainly represented by the Northern Calcareous Alps and the Grauwackenzone. The "Mittelostalpin" (Middle East-Alpine Nappe) comprises the major part of the Austro-Alpine crystalline complex and its specific low-grade metamorphic Permomesozoic cover in Central-Alpine facies. The "Unterostalpin" (Lower East-Alpine Nappe) consists of Austro-Alpine crystalline basement and its associated low-grade metamorphic Permomesozoic cover in Central-Alpine facies. It is mainly represented in the Tarntal mountains, in the Radstadt Tauern mountains, and in the Semmering-Wechsel area. TOLLMANN's concept requires a relatively considerable expanse of the Austro-Alpine facies belt (about 450 km in north-south direction) and, as a consequence, adequate dimension of the subsequent thrust movements.

According to a previous tectonic model, however, which distinguished between two Austro-Alpine subunits, the term "Oberostalpin" (Upper East-Alpine Nappe) is still used by some authors in the original meaning, comprising what later was separated by A. TOLLMANN into "Oberostalpin" and "Mittelostalpin."

The tectonic concept of E. CLAR (1973) demands relatively modest expanse of the pre-tectonic Austro-Alpine facies belt. He considers the mechanical and physical problems of the Alpine nappe movements and supposes gravitational sliding of considerable extent. During an initial period (mid-Cretaceous) the main structures in the sedimentary cover of the Austro-Alpine units were shaped as a result of compressional deformation: To the north the Austro-Alpine crystalline basement and its Central-Alpine Permomesozoic cover formed a huge recumbent nappe-fold; in addition, on a low-angle basal thrust-fault the Palaeozoic and Mesozoic sedimentary cover of a more southerly region of the Austro-Alpine facies belt became detached and started sliding northward. During subsequent phases (late Cretaceous and Tertiary) the major part of this detachment nappe continued its northward advance mainly by gravitational sliding on a gentle northward slope and finally became the Northern Calcareous Alps and the Grauwackenzone.

In the following account the Austro-Alpine Unit is described in two parts, one is dealing with the Northern Calcareous Alps the other with the Central Zone of the Eastern Alps.

*) A. TOLLMANN prefers the term "East-Alpine" instead of the synonymous "Austro-Alpine".

The Northern Calcareous Alps

One of the most prominent units of the Eastern Alps are the Northern Calcareous Alps, which extend uninterrupted for about 500 kilometres from the Rhine to Vienna, forming a 20 to 50 kilometres wide belt. At its eastern end it is bounded by the Vienna basin, which subsided during the Neogene; in the basement of the Vienna basin, however, the Northern Calcareous Alps continue into equivalent units of the Western Carpathians. Apart from small "Klippen", the Northern Calcareous Alps do not have a comparable continuation into the Western Alps.

The Northern Calcareous Alps consist of mountain ranges with considerable plateau mountains, the latter being a remnant of the older Tertiary peneplain, faulted and partly up-lifted in the (late) Miocene. In the western and middle part the highest peaks reach elevations of up to 3.000 metres above sea level and are locally glaciated. In the eastern part elevations are up to 2.000 metres.

As the name suggests, carbonate lithologies are predominating, but also clastic sediments are frequent. They comprise all Mesozoic periods, of which the Triassic is the most prevailing one. The section, however, begins in the Permian (e. g. Haselgebirge) and locally extends into the Palaeogene (Gosau formation).

Apart from slightly metamorphosed beds at the basis, the Northern Calcareous Alps do not exhibit any metamorphism.

The original region of deposition has to be located south of the Penninic trough, being the southernmost part of the Austro-Alpine sedimentation area and neighbouring directly the sedimentation area of the Southern Alps. This altogether was part of the *Tethyan Sea* and during Mesozoic times became the Alpine geosyncline. The part where the Northern Calcareous Alps have been deposited, is considered to be of miogeosyncline type (according to A. TOLLMANN 1968 it is an aristogeosyncline). The Penninic sedimentary realm became the eugeosyncline part of the Tethys.

The Northern Calcareous Alps have been the subject of controversy for many years and they still are at the time being. Major disagreement arises by the discussion of

the relationships of facies within the Northern Calcareous Alps,

the internal structure of the Northern Calcareous Alps,

the structural relationship of the Northern Calcareous Alps within the Eastern Alps and their original site of deposition.

For the authors of this paper and for most of the Alpine geologists there is no doubt nowadays, that the Northern Calcareous Alps have originally been the southernmost part of the Austro-Alpine Unit which subsequently overrode the Penninic Zone and now are the uppermost part of the large Austro-Alpine thrustsheet.

By further movements the Northern Calcareous Alps were detached from their original basement and finally slided upon younger beds of the Molasse Zone, the Helvetic Zone or the Flysch Zone. The allochthonous position is proved by some tectonic windows (e. g. Windischgarsten) and by wells (e. g. Urmannsau 1).

Comprehensive investigations on stratigraphy, facies and tectonics of the Northern Calcareous Alps have recently been published by A. Tollmann (1973, 1976 a, 1976 b) and by B. Plöchinger (1980) *).

Stratigraphy and Facies

Permian

The original depositional basement of the Northern Calcareous Alps has been the Grauwackenzone. The contact is exposed at the southern border of the Northern Calcareous Alps; in most cases it is a tectonic one, but the original transgressive superposition is preserved only very locally.

The succession of the Northern Calcareous Alps in general either begins with coarse to medium grained sediments of the Upper Permian (e. g. *Alpiner Verrucano* or *Präbichl Beds*) or with an Upper Permian evaporitic series, which comprises rock salt, anhydrite, gypsum, clay and thin layers of dolomite; volcanic rocks occur (diabase, melaphyre, tuffite). By diapiric and tectonic movements this series became a clay-salt-gypsum-breccia, the so-called *Haselgebirge* (an old mining term). According to its facies it is one of the most important sliding horizons in the Northern Calcareous Alps, both concerning tectonic movements as well as big land slides; but it can also be seen as an important generator of structural movements by salt tectonics and diapirism (G. Schäffer 1976).

Triassic

A big number of various beds and formations has been distinguished during the more than 100 years old history of research within the Northern Calcareous Alps. Basic investigations have been carried out in order to distinguish different facies and different biozones by studies on cephalopods. The relationship of lagoonal, reef and basin realms can be studied in many places. The typical Hallstatt facies of the Middle and Upper Triassic, variegated limestones, rich in cephalopods, continues into the Himalayas and to the Far East. It derived its name from the small village Hallstatt in the central part of the Northern Calcareous Alps. The terms "Dachstein Limestone", "Hauptdolomit", "Werfen Beds" etc. are used in many other countries.

The broad variety of lithologies within the Calcareous Alps reflects marine depositional conditions changing in both time and space. In the large area, in which the Northern Calcareous Alps have been deposited — it must be assumed to be 1,5 up to 5 times wider than nowadays — the rate of subsidence and of sedimentation was not the same in every place. Therefore considerable differences of thickness of the Triassic succession are recognized. On the whole the thickness of the Triassic beds varies between some hundred up to several thousand metres. It is a traditional question of the calc-alpine geology and still in discussion, whether the depositional zoning was arranged more or less strictly east-west trending or not. Consequently the interpretation of the internal structures differs very much.

Somewhat but not too much simplified three main facies groups can be distinguished: the Hauptdolomit facies, the Dachstein Limestone facies, and the Hallstatt facies.

The Hauptdolomit Facies. The existence of the Hauptdolomit in the Norian is significant for the Hauptdolomit facies. The *Hauptdolomit* is an up to 2.000 metres thick brownish-greyish, bedded to laminated, bituminous dolomite, fractured and cleavaged and therefore wheathering into characteristic detrital material. In the western areas intercalations of bituminous shales (*Ichthyolschiefer*) occur in the upper parts. According to the depositional scheme basin—reef—lagoon (A. G. Fischer 1964), the Hauptdolomit was deposited in a very shallow lagoon, far in the north of the reef belt. The environment was slightly hyper-saline and influenced by the tides. The dolomitization took place during an early-diagenetic phase.

In its uppermost parts the Hauptdolomit grades into the *Plattenkalk* by increased limestone layers; also lateral interfingering is occurring. The Plattenkalk ranges from the Norian to the Rhaetian and was also deposited in a lagoonal environment. The water-depth, however, was increasing gradually. There also exist transitions to the lagoonal Dachstein Limestone.

The Rhaetian *Kössen Beds*, marly limestones and marls, are generally very rich in fossils and overlie the Hauptdolomit and the Plattenkalk as well as the Dachstein Limestone. In some places the Triassic section ends with an *oolithic* or a *reef limestone* of the uppermost Rhaetian (probably extending into the lowest Jurassic).

The Carnian stage below the Hauptdolomit exhibits a lot of different facies, but always indicating more terrestric influence. In the west (Vorarlberg and Tyrol) the *Raibl Beds* are occurring, which consist of shales, sandstones and evaporites (gypsum and "Rauhwacke") with intercalations of limestone, but also with coal seams. In the eastern parts of the Northern Calcareous Alps the *Lunz Beds* are developed, which are an alternation of shales, marls, sandstones and arkoses with coal seams and oolithic limestones; in the upper part

*) The authors like to express their gratitude to Dr. B. Plöchinger for his permission to use the unpublished manuscript of the mentioned paper.

of the Carnian the *Opponitz Beds* (limestones of various types) are common. The incompetent, not so hard Lunz Beds and Raibl Beds exhibit a characteristic morphologic horizon within the rocky scenery of the Northern Calcareous Alps.

The Middle Triassic in the Hauptdolomit facies is mainly represented by the Ladinian *Wetterstein Limestone* and *Dolomite,* which comprise reef to lagoonal limestone and dolomite types. Their thickness can reach up to 1.700 metres. In channels within the reef environment the marly and shaly *Partnach Beds* have been deposited. In the Vorarlberg and western Tyrol area are the several hundred metres thick *Arlberg Beds.* They consist of grey marly limestones and shaly marls and have been built in shallow water.

The *Reifling Limestones* or *Reifling Beds* of Upper Anisian to older Ladinian are well-bedded and show nodular grey limestones with chert and significant greyish-greenish clay intercalations of a few millimetres thickness. The main part of the Anisian is represented by the dark grey to black, thin-bedded *Gutenstein Limestones* and *Dolomites.* Volcanic activity is shown by locally occurring thin layers of tuffites, here as well as in the Reifling Beds and the Wetterstein Limestone.

During the Lower Triassic (Skythian) the lacustrine and shallow water environment, which also predominated during Permian age, continued and brought a succession of alternating quartzites, sandstones, shales and limestones, the *Werfen Beds;* reddish, violett and greenish colours are prevailing. During the Skythian the later distribution into the mentioned facies regions had not yet existed, therefore the Werfen Beds generally are of very similar facies within the whole Northern Calcareous Alps. Only in the western parts mainly quartz-sandstones and -conglomerates (*Alpiner Buntsandstein*) are occurring. They are overlain by the calcareous *Reichenhall Beds,* which continue into the lower Anisian.

Within the Hauptdolomit facies some varieties occur in the above described succession. Therefore, but also depending on its regional position, as well as according to the different interpretations by individual geologists, a *Vorarlberg Facies* (in the far west of the Northern Calcareous Alps), a *Tyrolian Facies,* a *Frankenfels Facies* (in the eastern parts), a *Lunz Facies* and some other subfacies can be distinguished.

The Dachstein Limestone Facies. The Dachstein Limestone facies is developed in large areas of the

	FACIES REGION / STAGE	HAUPTDOLOMIT FACIES IN THE WEST	DACHSTEIN LIMESTONE FACIES	HALLSTATT FACIES: SWELL FACIES	HALLSTATT FACIES: BASIN FACIES
TRIASSIC – LATE	RHAETIAN	"OBERRHÄTKALK" KÖSSEN BEDS	KÖSSEN BEDS	ZLAMBACH BEDS	
TRIASSIC – LATE	NORIAN	PLATTENKALK HAUPTDOLOMIT	DACHSTEIN LIMESTONE (reef or bedded limestone) DACHSTEIN DOLOMITE or HAUPTDOLOMIT	VARIEGATED HALLSTATT LIMESTONES	PEDATA BEDS PÖTSCHEN BEDS
TRIASSIC – LATE	CARNIAN	OPPONITZ BEDS RAIBL BEDS LUNZ BEDS	DOLOMITE CARDITA BEDS		HALOBIA SHALES
TRIASSIC – MIDDLE	LADINIAN	ARLBERG BEDS WETTERSTEIN LIMESTONE and DOLOMITE PARTNACH BEDS	RAMSAU DOLOMITE WETTERSTEIN LIMESTONE and DOLOMITE		
TRIASSIC – MIDDLE	ANISIAN	REIFLING LIMESTONE GUTENSTEIN LIMESTONE and DOLOMITE REICHENHALL BEDS	STEINALM LIMESTONE GUTENSTEIN LIMESTONE and DOLOMITE REICHENHALL BEDS		REIFLING LIMESTONE STEINALM LIMESTONE GUTENSTEIN LIMEST. and DOLOMITE
TRIASSIC – EARLY	SKYTHIAN	WERFEN BEDS BUNTSANDSTEIN	WERFEN BEDS	WERFEN BEDS	
	UPPER PERMIAN	H A S E L G E B I R G E			

Tab. 5: Simplified stratigraphic table of the main Triassic members of the Northern Calcareous Alps, arranged according to their position within the main facies regions (after W. DEL NEGRO, 1977, and B. PLÖCHINGER, 1980).

middle and eastern part in the Northern Calcareous Alps. The stratigraphic succession begins with the Upper Permian *Haselgebirge,* which is superimposed by the Skythian *Werfen Beds* and/or the lower part of the *Reichenhall Beds.*

The Anisian is represented by the upper part of the Reichenhall Beds, by the *Gutenstein Limestone* and *Dolomite,* and by the *Steinalm Limestone.* Up to there are no big differences in the sections of the Hauptdolomit facies and of the Dachstein Limestone facies.

In the Ladinian the *Wetterstein Limestone* and *Dolomite* and the *Ramsau Dolomite* are to be found. They close to the main reef. The typical rhythmic bedding of a few metres thick limestone layers with big shells (megalodonts) and a few millimetres thin intercalations of a limestone-dolomite rhythmite was called Lofer facies or *Loferite* (A. G. Fischer 1964); the limestone-dolomite layers indicate tidal influence and the big shells indicate calm shallow water; hypersalinity is suggested (H. Zapfe 1959). The bedded Dachstein Limestone can reach a total thickness of more than 1500 metres.

The unbedded or massive Dachstein Limestone or Dachstein Reef Limestone is more than 1000 metres

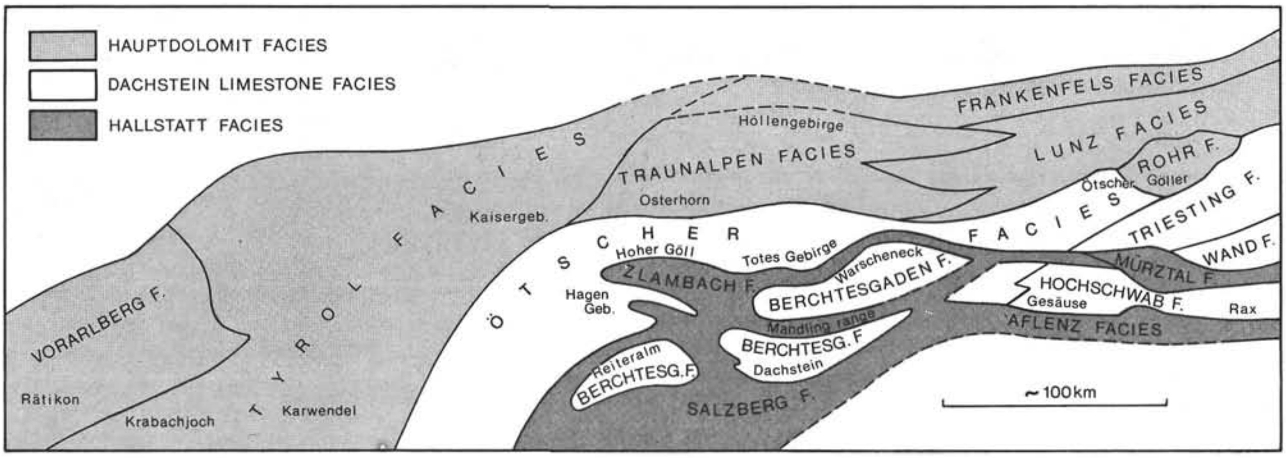


Fig. 16. Schematic palinspastic sketch of the original depositional area of the Northern Calcareous Alps, demonstrating the arrangement of the three main facies units and of some important facies sub-units. The relationship between the Dachstein Limestone facies and the Hallstatt facies in detail is under discussion. The scale is an approximative one (after A. Tollmann, 1976, fig. 14; simplified).

are developed in a similar way as they are in the Hauptdolomit facies. The facies of the Wetterstein Dolomite and of the Ramsau Dolomite is nearly identical, so that for some authors these names are of synonymous meaning. In contrary to the Hauptdolomit facies Reifling Beds and Partnach Beds, both indicating deeper water, are missing.

Sometimes between the thick layers of limestones or dolomites of the Ladinian (Wetterstein) and the Norian (Dachstein) a several tens of metres thick intercalation of marly and sandy limestones, partly rich in fossils, occur, the *Cardita Beds* of the Carnian epoch.

As the name suggests, the prevailing bed is the *Dachstein Limestone* of the Norian and the Rhaetian. There exist different facies of the Dachstein Limestone, depending on their depositional distribution in reef, back reef and lagoonal environment. The bedded Dachstein Limestone shows evidence of shallow water origin, cyclic sedimentation and has been formed in the lagoon thick and has been built in an outspread reef belt in front of the lagoon. It is abundantly fossiliferous; mainly calc-sponges, corals, algae, hydrozoans, and foraminifers are to be found.

At some places transitions of detrital back reef types to the lagoonal bedded limestone exist, but also an interfingering by reef slope types to the open sea facies (Hallstatt facies) can be observed.

Dolomitization mainly took place in the bedded limestone facies; where it is locally prevailing, the member is named *Dachstein Dolomite.* It is not easy to define the border to the Hauptdolomit, so that sometimes both names are of synonymous meaning.

As a result of the slightly modified composition of the succession of the Dachstein Limestone facies, the respective facies areas are being distinguished. The "*High-Alpine*" (hochalpin) facies area consists of the *Berchtesgaden subfacies* in the middle part and of the *Hochschwab subfacies* which is concentrated on the eastern part of the Northern Calcareous Alps. Some authors (B. PLÖCHINGER 1979) also distinguish a *"Fore-Alpine"* (voralpin) Dachstein Limestone facies, where the Hauptdolomit is thicker than the Dachstein Limestone; it occurs mainly in Lower Austria (*Triesting facies*).

The Hallstatt Facies. The third main facies unit is the Hallstatt facies. The deposits originated in deeper water of the open sea. Altogether they are of minor thickness than the reef and lagoonal facies; the entire Triassic may be up to 1000 metres thick.

The series of strata begins with the Upper Permian *Haselgebirge,* a (? tectonic) breccia being composed of clay, gypsum, anhydrite, rock salt, dolomite, and locally volcanic rocks (melaphyre, diabase). The rock salt has been mined since about 4000 years, but also gypsum and anhydrite are still mined nowadays. The Haselgebirge is overlain by the Skythian *Werfen Beds.*

The Middle and Upper Triassic section can be roughly divided into two facies complexes: a) The Hallstatt facies is a swell facies (within the basin), which mainly consists of variegated Hallstatt Limestones. The *Schreyeralm Limestone* is of Anisian and Lower Ladinian age, while the actual *Hallstatt Limestone* can be subdivided by detailed studies on sedimentology and ammonites stratigraphy into Upper Ladinian, Carnian and Norian parts. b) The *Zlambach Facies* is a basin facies, in which clayey deep water limestones with chert are common. In the Anisian *Gutenstein Limestones* and *Steinalm Limestones* (this is the Anisian part of the Wetterstein Limestone) are occurring. The Ladinian is represented by the *Reifling Limestone.* In the Norian marly-sandy, fossiliferous *Pedata Beds* and clayey, thin-bedded *Pötschen Limestones* are prevailing.

The Hallstatt facies and the Zlambach facies are closely related and lateral interfingering can be observed.

One may assume, that the occurrence of submarine ridge and basin areas within the Hallstatt facies realm is caused by salt tectonics and the beginning of a salt diapirism (salt-pilow-structure, G. SCHÄFFER 1976).

Both facies are covered by the Rhaetian *Zlambach Beds,* grey sandy marls, rich in fossils (ammonites, corals, foraminifers). In the Zlambach Beds locally layers with detritus of the Dachstein Reef Limestone can be found, indicating the close depositional relationship of Dachstein reef environment, fore-reef area and basin environment of the Zlambach Beds. On the other hand also debris of the Zlambach marls can be observed within some parts of the Dachstein Reef Limestone.

In the Styrian and Lower Austrian part of the Northern Calcareous Alps the somewhat varying developments of the Hallstatt Facies are called Mürzalpen Facies, Aflenz Facies, Hohe Wand Facies, Miesenbach Facies, and Hüpfling Facies (B. PLÖCHINGER 1979).

The original depositional relations of the three main facies areas of the Northern Calcareous Alps during the Upper Triassic are demonstrated by the models of A. G. FISCHER (1964) and H. ZANKL (1971). According to them the lagoonal Hauptdolomit and Kössen Beds (far from the reef) grade southwards into the lagoonal Loferite (bedded Dachstein Limestone), which in southern direction interfingers with the reef body. South of the reef the open sea spreads out, exhibiting the Hallstatt facies and being connected to the reef by detrital fore-reef limestones.

Nowadays it is not possible to establish an unanimously accepted theory concerning the original depositional relationships, as nearly all transitions between the three facies areas are to rather a great extent tectonically disturbed. Some authors believe in a more or less autochthonous position of the different Hallstatt facies areas within the Northern Calcareous Alps ("Hallstatt facies channels"), as primarily was discussed by E. v. MOJSISOVICS (1903). E. HAUG (since 1906), L. KOBER (since 1911) and their "school" considered only the existence of one Hallstatt facies belt, being originally situated north of the Dachstein Massif and south of the Totes Gebirge; J. NOWAK (since 1911), F. F. HAHN (since 1913) and E. SPENGLER (since 1919) believed in only one Hallstatt facies belt too, but they considered it to be situated south of the Dachstein Massif. Both "schools" developed structural models to explain the different present position of the Hallstatt Beds.

In the past years since about 1965 in general somewhat modified models of an autochthonous position of the Hallstatt facies zone between the carbonate platforms became more and more acknowledged (B. PLÖCHINGER since 1974, G. SCHÄFFER since 1971, W. SCHLAGER since 1967, A. TOLLMANN since 1976).

Jurassic

The axis of the Alpine geosyncline (eugeosyncline) moved northwards and became situated in the Penninic trough; within the area of the Northern Calcareous Alps the geosynclinal conditions continued, however. Tectonic movements like uplifts and subsidence increased, so that in the Jurassic rocks the facies zones correspond only partially to those, which have been established during the Triassic. But also considerable horizontal displacement by gravitational sliding began during the Jurassic epoch (B. PLÖCHINGER 1974, G. SCHÄFFER 1976). While the variety of facies increased considerably, the total thickness is smaller than in the Triassic. At places it can reach in total about 2000 metres (in the western parts of the Northern Calcareous Alps), but often it is only a few hundred metres or thinner and some beds are lacking. By tectonic movements as well as by erosion, a lot of the Jurassic series of strata is missing nowadays. Therefore it is very difficult to reconstruct the original depositional relationships.

Some authors suppose an emerging or a partially emerging of the big Dachstein Limestone platforms (older Kimmerian Phase), and carstification and a generation of cavities is considered to have taken place. The Liassic crinoid- and brachiopod-limestone (*Hirlatz Limestone*) filled up these fissures and cavities and rests unconformably upon the Dachstein Limestone.

At places the reef development continued without any interruption into the Liassic (*Rhaeto-Liassic Reef Limestone*).

In basin areas a sedimentation of dark-grey marly beds with various intercalations of limestone layers took place (*Allgäu Beds* in the west, *Fleckenmergel* = spotted marls in the east); intercalations of breccias can be observed, locally they grade laterally into olisthostroms (e. g. *Strubberg Beds*). At submarine ridges within the basins red cephalopod-limestones have been deposited, the most well-known of it is the *Adnet Limestone*. It comprehends the whole Liassic, proved by ammonite faunas. Its type-locality is situated in quarries south of Salzburg and the limestone is used as a decoration marble.

Also during the Dogger the three main facies types can be distinguished: In the basins the Fleckenmergel and Allgäu Beds sedimentation continues, red cephalopod-limestone (*Klaus Limestone*) is deposited at the sill areas, and on the top of the platforms a crinoid-brachiopod-limestone is occurring, the *Vils Limestone*.

A further differentiation of facies took place in the Malm, caused by movements of the younger Kimmerian Phase; at various localities the Malm beds overlie unconformably older Jurassic or Triassic beds. In general, however, basin, submarine ridge, and platform facies are to be distinguished.

The basin development is mainly represented by *radiolarites* and *siliceous shales* of the Lower Malm and by *Oberalm Beds* of the Upper Malm; the latter are thin-bedded light-grey limestones bearing characteristic chert nodules. Also *Aptychus Beds* are common, which continue, however, into the Neocomian.

Typical members of the submarine ridges are the *Agatha Limestone*, the Acanthicus Limestone, and the Mühlberg Limestone; in each of them ammonites are frequent.

On the platform areas the white, unbedded to massive *Plassen Limestone* was deposited, locally a growing of reef bodies can be observed. The detrital *Tressenstein Limestone* is a sediment of the slopes and interfingers laterally with both, Plassen Limestone and Oberalm Beds.

Cretaceous-Palaeogene

In the Lower Cretaceous marly and sandy sediments are prevailing. The Aptychus Beds of the Tithonian continue without any interruption into the Neocomian, while in other places an unconformity is recognized between the Malm and the Lower Cretaceous. The *Schrambach Beds* exhibit the fine-grained marly to limy member, while in the *Rossfeld Beds* sandy intercalations and quartzsandstones are also occurring; especially in the Upper Rossfeld Beds turbidites, olisthostroms and olistholites can be frequently observed (pre-Austric Phase).

At the northern border of the western and eastern part of the Northern Calcareous Alps a series of shales and marls with frequent intercalations of sandstones, conglomerates and breccias, composed by exotic gravels, occur. It is separated by a considerable unconformity (Austric Phase) of the underlying beds and is of Cenomanian age; locally an extension into the Lower Turonian has been proved (*"Randcenoman"*). The gravels originate from a ridge, the original location of which is a matter of discussion: it has serious consequences for the reconstruction and the classification of the tectonic movements of the Northern Calcareous Alps above the Penninic Zone.

The Gosau Formation. In the pre-Gosau Phase considerable tectonic movements took place in the Northern Calcareous Alps. Most of the internal nappe structures, thrust-sheets and imbricated structures became formed or at least set up. Upon this completely rebuilt and transformed unit a large marine ingression took place, beginning in the Coniacian and continuing until the Palaeogene, finally covering the whole Northern Calcareous Alps, but also other parts of the Austro-Alpine system. This heterogenous sedimentary series is known as the Gosau Formation.

In the type-locality of the Gosau basin in the Salzkammergut the total thickness of the Gosau Formation is recorded to be about 2500 metres, but elsewhere it is rather less.

A wide variety of rock types is found in the Gosau beds, depending mainly on the pre-existing relief, in which the ingression had taken place, and on continuing tectonic movements (intra-Gosau Phase).

Generally the Gosau sedimentation starts with coarse, variegated conglomerates and breccias of the Coniacian or the Santonian (*Basal Conglomerate*). The composition of the gravels can be derived either by the local surrounding (rocks of the Northern Calcareous Alps) or by exotic origin (crystalline or Palaeozoic rocks and quartz pebbles). This may indicate, that the ingression began in isolated bays.

The Gosau Formation includes deep-water shales, marls and intercalated turbidites, sands, conglomerates and breccias, rudist- and coral-reefs, bioclastic limestones and coal deposits.

During the Upper Campanian and the Maastrichtian the conditions of deposition seemed to be more uniform, as variegated pelagic marls and shales (*Nierental Beds*) occur in most of the nowadays preserved Gosau basins.

During the Maastrichtian and at the Cretaceous-Tertiary border tectonic activity increased (Laramic Phase); as a result conglomerates and breccias as well as turbidites were deposited (*Zwieselalm Beds*). The section of the Gosau Beds is terminated with marls or flyschoid sandstones of the Paleocene or the Lower Eocene. Stratigraphy mainly became established by pelagic foraminifers.

Heavy mineral studies in the Gosau Formation by G. Woletz (1967) show significant changes. All members older than Lower Campanian mainly contain chromite, zircon and subsidiary rutile and tourmaline; the younger beds are rich in garnet. This indicates considerable tectonic movements and a change in the source area.

Internal Structure

Nowadays the Northern Calcareous Alps are altogether in a complete allochthonous position. Their original sedimentation area was situated far in the south. The Northern Calcareous Alps and their original sedimentary basement (the Grauwackenzone) were brought on top of the Austro-Alpine thrust sheet and the whole pile of sheets was overriding the Penninic Zone in northern direction. As unanimously accepted by modern geologists, these considerable crustal movements are a result of plate and subduction tectonics. By continuing tectonic activities the Northern Calcareous Alps became detached from their basement and gravitationally slided further to the north; now they are resting as a big allochthonous mass upon the Flysch Zone, the Helvetic Zone and the Molasse Zone. The crystalline basement became completely subduced or at least a main part of it.

It is univocally accepted, that during the above mentioned history also remarkable internal movements must have taken place. No aggreement, however, exists about their intensity and their bearing upon the structural features of the Northern Calcareous Alps.

According to A. Tollmann (1976 b, p. 47) a primary nappe (*Stammdecke*) became developed during the northward transport of the Northern Calcareous Alps, which built the bulk of the mountain range. *Front parts* were cut off and overridden by the primary nappe, which continued moving to the north. Consequently the original northern parts became independent tectonic units (sheets), which are now in a lower tectonic position than the primary nappe.

Those other parts of the Northern Calcareous Alps, originally deposited in the south, were detached from their basement and carried on top of the primary nappe, now forming large and topping tectonic units (sheets), comparable to large *Deckschollen*.

In the western part of the Northern Calcareous Alps the Lechtal sheet can be seen as the primary nappe, while the Allgäu sheet and the "Cenoman-Randschuppe" are more or less continuous lower (= northern) tectonic units, while the Inntal sheet and the Krabachjoch sheet are higher (southern) units.

In the middle and eastern part of the Northern Calcareous Alps the primary nappe is represented by the so-called "Tirolikum" which is connected with the southeastern part of the Lechtal sheet. The northern and deeper units are here the Lunz sheet, the Frankenfels sheet and the "Kieselkalkschuppe", the higher and southern element is represented by the "Juvavikum".

That means — with other words: the terms "high", "higher", "upper", "hochalpin" a. s. o. are identical with "south" or "southern" in the original deposition area, while the northern regions of the original deposition area are described to be "low", "deep" or "fore-alpine" ("voralpin").

F. F. Hahn (1912) divided the Northern Calcareous Alps into the three main structural elements Bajuvarikum, Tirolikum and Juvavikum. This is a more general and comperatively neutral regulation principle, which is still very practicable and can be also applied, if considerable differences concerning more detailed problems are existing. (Note fig. 17.)

Bajuvarikum: It makes narrow strips at the northern margin of the Northern Calcareous Alps and it is developed in the Hauptdolomit facies. It can be subdivided into

the Lowest Bajuvarikum, comprising the "Cenoman-Randschuppe" and the "Kieselkalkschuppe"
the Lower Bajuvarikum, comprising the Allgäu sheet, the Ternberg sheet and the Frankenfels sheet and
the Upper Bajuvarikum, comprising the Lechtal sheet, the Reichraming sheet and the Lunz sheet.

Tirolikum: It is the main element of the Northern Calcareous Alps and comprises the Inntal sheet, the Staufen-Höllengebirge sheet, the Totes Gebirge sheet and the Ötscher sheet. In the north the Hauptdolomit facies is prevailing, grading southwards into the Dachstein Limestone facies.

Juvavikum: It is the uppermost (= southermost) structural element of the northern Calcareous Alps, but nowadays its continuous tectonic separation from the Tirolikum is in discussion. The Lower Juvavikum comprises all areas, which are predominantly developed in Hallstatt facies, and the Upper Juvavikum comprise those areas, where the Dachstein Limestone facies is prevailing.

Formerly one assumed a clearly defined separation of two sheets of the Lower Juvavikum (Lower Hallstatt sheet or Zlambach sheet and Upper Hallstatt sheet or Salzburg sheet) and one sheet of the Upper Juvavikum unit (Dachstein sheet and their equivalents in the west and the east, as Berchtesgaden sheet, Reiteralm sheet, Schneeberg sheet). This was caused by believing in separated sharply east-west trending facies belts of two Hallstatt Facies areas and the Dachstein Limestone

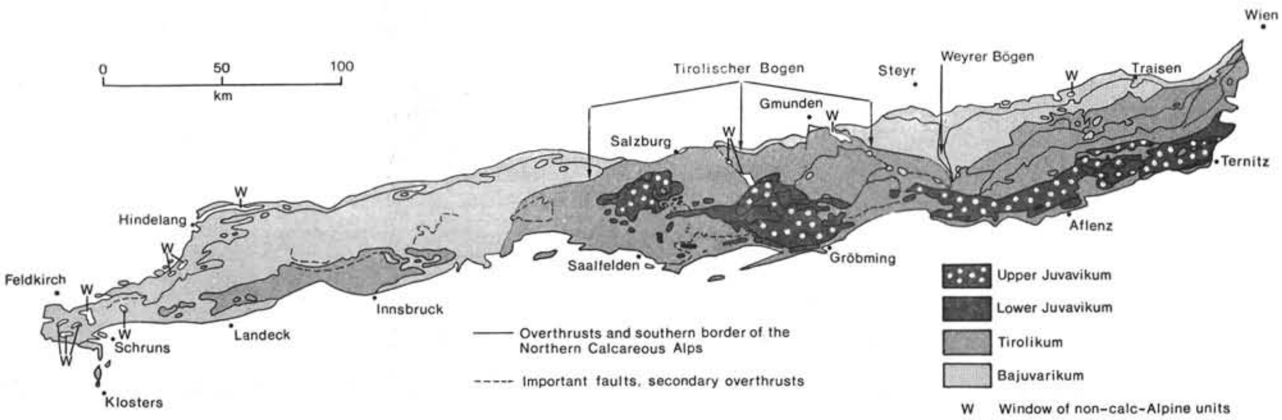
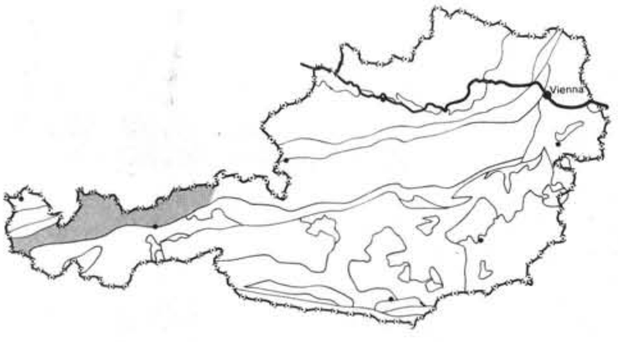


Fig. 17: Sketch-map of the main tectonic units of the Northern Calcareous Alps (after A. TOLLMANN, 1976, fig. 16; simplified).

Facies area. As mentioned above, recent investigations, however, showed, that the Hallstatt facies areas can easily be attributed to autochthonous to parautochthonous regions within the Dachstein Limestone area ("Hallstatt channels" within the Dachstein reef environment; see fig. 16). Consequently nowadays the term Juvavikum is of minor tectonic importance (A. TOLLMANN, 1976 b, p. 49).

Regional Description

The Area between the Rhine Valley in the West and the Cross Valley of the Inn in the East



At the western end the Northern Calcareous Alps are rising above surface and an impressive view into their tectonic basement can be obtained. The Arosa Zone, the tectonically much deformed South Penninic unit, used to be a lubricating layer for the Austro-Alpine Nappe, resp. for the Northern Calcareous Alps. It can be traced from the area south of the Rätikon, along the western border and to the northern border of the Northern Calcareous Alps as far as Hindelang. Below the Arosa Zone and the Falknis and Sulzfluh sheet the Penninic Flysch series surround the western end of the Northern Calcareous Alps. This is one of the facts showing thoroughly the allochthonous position of the Northern Calcareous Alps.

The westernmost part of the Northern Calcareous Alps is the *Rätikon.* It belongs in total to the Lechtal sheet. The area is cut by faults and thrust-faults (with only small distances of thrust) into a number of blocks or "Schuppen", which exhibit imbrication of the blocks. On the faults outcrops of the underlying Arosa Zone can be observed, but also on sliding planes within the gypsiferous Raibl Beds locally rocks of the Arosa Zone are occurring. The Triassic of the Rätikon is developed in the Vorarlberg facies of the Hauptdolomit facies. In the southernmost parts of the Rätikon a remarkable southward overturn of the folds is common (R. OBERHAUSER 1970).

Towards the east the *Lechtal sheet* becomes up to 40 kilometres wide. In the south it rests either upon the Phyllitgneiszone, or upon the Landeck Quarzphyllit or upon the Grauwackenzone; in most cases the contact plane is of tectonic nature, but sometimes the original depositional contact is preserved. The Triassic mainly is developed in the Tyrolian subfacies of the Hauptdolomit facies. Broadcrested folds prevail, which sometimes are cut by short-distance upthrows. Fold systems (synclinoria) with Jurassic and Lower Cretaceous beds can be observed, as for instance in the Rofan mountains east of Innsbruck.

Towards the north and tectonically below the Lechtal sheet follows the *Allgäu sheet,* which in its widest extension is preserved in the Bavarian Allgäu region. Narrow-crested folds and imbrication structures are predominating. The lowest distance of overthrust is shown by some windows and semi-windows ("Halbfenster"). So for instance in the valley of Hornbach, west of the Lech river, under the Hauptdolomit of the Lechtal sheet Allgäu Beds and Hauptdolomit of the Allgäu sheet are occurring in a big anticline (*Hornbach Halbfenster);* see fig. 18, section 1.

However, there existed attempts to develop structural models without more or less horizontal far-distance thrusts ("gebundene Tektonik"): Windows were ex-

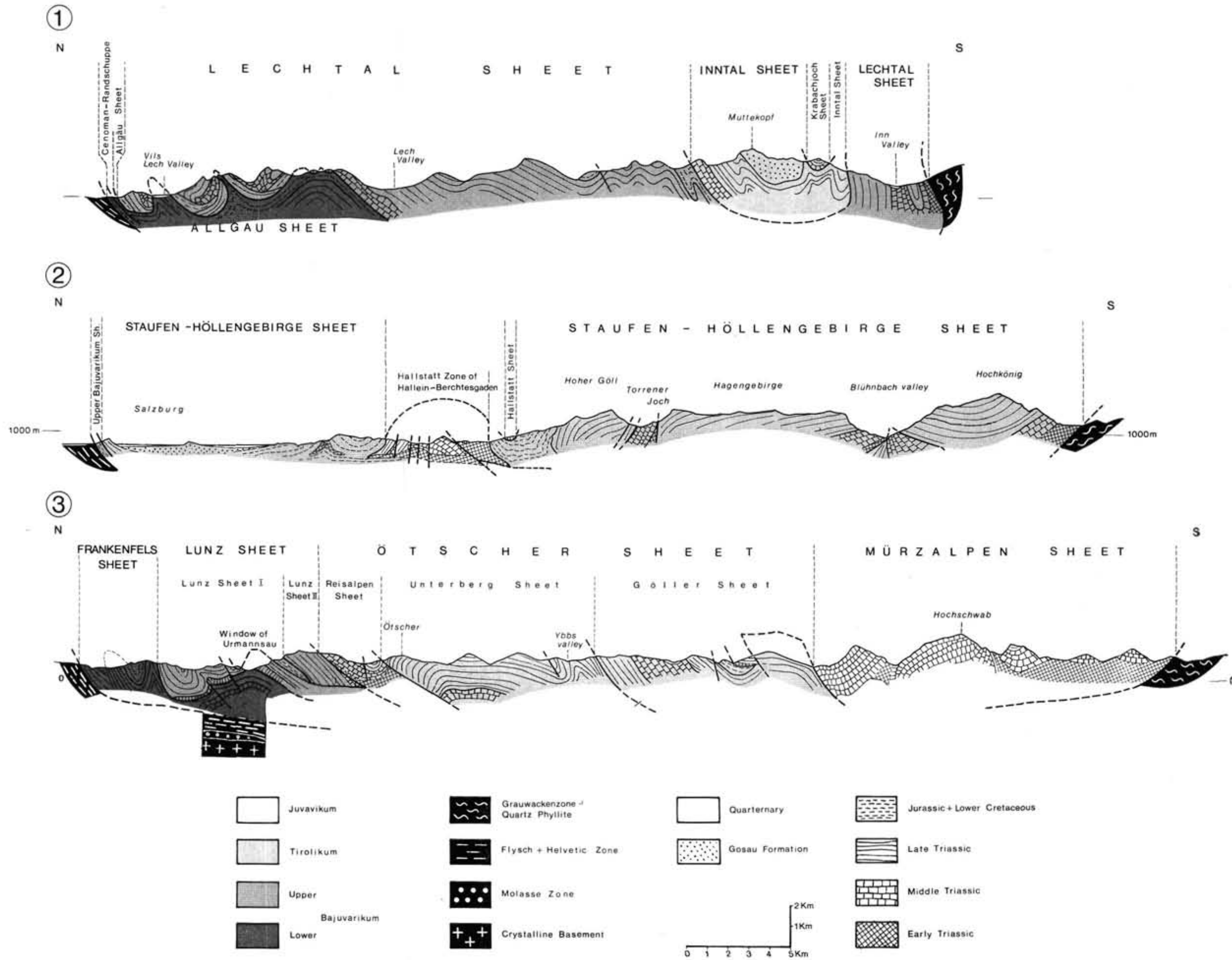


Fig. 18: Sections across the western (1), central (2), and eastern (3) part of the Northern Calcareous Alps (after A. TOLLMANN, 1976, pl. 6/8, and B. PLÖCHINGER, 1980, modified and simplified).

plained as "Beutelfalten" (synclines), "Deckenschollen" as box- or mushroomfolds (anticlines), both with somewhat sheared flanks (C. W. KOCKEL since 1956, V. JACOBSHAGEN 1975). Detailed studies, however, by H. BERTLE et al. (1970) und A. TOLLMANN (since 1970) proved the rootless nappe-structure of the Lechtal sheet upon the Allgäu sheet.

The northernmost and lowest tectonic part is represented by the *Cenoman-Randschuppe.* It can be understood as the frontal region of the entire Northern Calcareous Alps. Also its somewhat specific facies, containing Cenomanian with exotic pebbles is a proof for its independent position. Some authors consider close relationships with the Arosa Zone, but some other authors refuse this point of view by fundamental considerations concerning tectonic as well as facial relationships with the Northern Calcareous Alps.

According to its severe tectonic deformation it exhibits isolated thrust-slices and parts of sheared narrow folds. Nevertheless it is more or less continuous as far as the Vienna region, apart from an approximately 100 kilometres long area in the central parts of the Northern Calcareous Alps, where it is completely overridden by higher calc-Alpine tectonic units.

In the southern part the Lechtal sheet forms a wide syncline, in which the *Inntal sheet* is resting, comparable with a big "Deckscholle" of about 100 kilometres west-east and 10 to 20 kilometres north-south extension. Separated from it by erosion some isolated smaller Deckschollen are preserved in the Flexenpass—Arlberg area in the west and in the region south of the Achensee in the east. The Inntal sheet, which was established by O. AMPFERER (1911) is considered to be the westernmost part of the Tirolikum.

The internal structure of the Inntal sheet is comparatively simple in its western part and exhibits a broad fold-system in the east. The western and southwestern border, however, shows very complicated polyphase fold-structures, so that the boundary plane to the underlying Lechtal sheet is in discussion and some authors believe in a rooting of the Inntal sheet within the Lechtal sheet. Based on detailed studies A. TOLLMANN (since 1970) considered the allochthonous position of the Inntal sheet to be upon the Lechtal sheet (area around the Memminger Hütte).

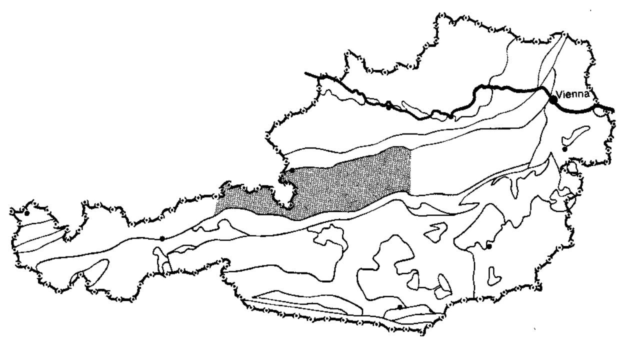
A remarkable element is the *Karwendel-Stirnschuppe* (A. TOLLMANN 1976 b), which exhibits a lower thrust-slice of the Inntal sheet and which can be observed for a long distance north of the actual Inntal sheet. At the overthrust plane between the "Stirnschuppe" and the Inntal sheet dislocated slices can be observed, derived from a southern part of the underlying Bajuvarikum.

Four Deckschollen of the Inntal sheet are being distinguished in the west, in the Flexenpass-Arlberg area. The most prominent one of it is the *Krabachjoch-Deckscholle,* which rests in a low-angle syncline of the Lechtal sheet with a core of Cretaceous marls. The Deckscholle consists of two tectonic units: a) a thin layer of Hauptdolomit, partly in the form of a mylonite, and Kössen Beds; this sequence represents the Inntal sheet. b) Hereupon tectonically a series of Middle to Upper Triassic with partly intensive folding is lying. It is the highest tectonic unit in the western part of the Northern Calcareous Alps and was named by O. AMPFERER (1915) *Krabachjoch sheet,* by other geologists *Ultradecke* according to its long-distance thrust. In this area also some other small Deckschollen of the Krabachjoch sheet are existing (fig. 18, section 1).

In its eastern part the Inntal sheet is typically developed in the Karwendel mountains, mainly exhibiting folded Hauptdolomit; here the Hauptdolomit reaches its maximum thickness of about 2200 metres.

In eastern direction the axis of the Inntal sheet rises and the younger beds of the Lechtal sheet appear below the basis of the Inntal sheet, such proving the allochthonous position of the Inntal sheet.

The Area from the Cross Valley of the Inn to the Weyrer Bögen



The central part of the Northern Calcareous Alps is characterized by the *Tirolischer Bogen* (F. F. HAHN 1913). This is a structural element which marks the northward advance of the Tirolikum, which in the area west and east of Salzburg reached the northern border of the Northern Calcareous Alps (fig. 17).

The *Bajuvarikum,* which is the main sheet in the west, is either completely overridden or only outcropping as a narrow belt in the north (Langbath sheet).

East of the Tirolischer Bogen the tectonic elements of the Bajuvarikum appear at the surface again but most of the corresponding units have different names. The "Cenoman Randschuppe" in the west corresponds with the "Cenoman Randschuppe" or „Kieselkalkschuppe" or "Kieselkalkzone" in the east; the Allgäu sheet in the west corresponds with the Ternberg sheet in the east; The Lechtal sheet in the west corresponds with the Reichraming sheet in the east. Both latter units are connected at the surface by a row of small overridden blocks, the biggest of which is the Langbath zone west of the Traunsee.

The main parts of the *Tirolikum* in the central part of the Northern Calcareous Alps are the Staufen-Höllengebirge sheet as well as the Totes Gebirge sheet and the Warscheneck sheet.

At the western end of the Tirolischer Bogen the distance of thrust becomes gradually smaller and finally the Tirolikum continues laterally into the Lechtal sheet. The Inntal sheet, which represents the Tirolikum in the western part of the Northern Calcareous Alps, is considered to originate from a more southerly area. In the east the Tirolischer Bogen spurs in the area of the Weyrer Bögen structure and the Tirolikum passes into the Reichraming sheet.

The Tirolikum in the central part of the Northern Calcareous Alps is developed in both, the Hauptdolomit facies and the Dachstein Limestone facies.

On top of the Tirolikum rests the *Juvavikum* unit, which consists of the lower Hallstatt unit and the higher Dachstein unit. The original depositional relationship of the southern part of the Tirolikum and both units of the Juvavikum is a matter of intensive discussions nowadays.

East of Kufstein and within the *Staufen-Höllengebirge sheet* the block of the *Kaisergebirge* is situated, which is built by a narrow syncline of Triassic beds. It is resting tectonically upon Palaeogene beds (Molasse of the Inn valley — Kössen basin) in the north and upon the Cretaceous *Gosau* Formation in the south. Some authors assumed an allochthonous position of the block of the Kaisergebirge with a far-distance thrust (e. g. O. AMPFERER 1921). Nowadays however, it is generally considered to be an autochthonous block upthrown and sheared on both sides (F. F. HAHN 1913, A. TOLLMANN 1976 b).

East of the block of the Kaisergebirge as far as the Berchtesgaden-Reiteralm unit extends the flat *Syncline of Unken* with a core of Jurassic to Lower Cretaceous. Upon it lies the *Berchtesgaden* or *Reiteralm sheet* of the Upper Juvavikum, being surrounded by a circle of outcrops of the Hallstatt unit. There exist a lot of different interpretations concerning this area, each of which is in discussion, but none being generally accepted.

A more or less allochthonous position of the Juvavikum is generally assumed; major differences exist however, about the mechanism and the age of the tectonic movements. A. TOLLMANN (e. g. 1976 b) and many other geologists are of the opinion, that the Hallstatt sheet as well as the Berchtesgaden-Reiteralm sheet of the Juvavikum are big allochthonous sheets having moved from a distant site; the main movements took place during post-Neocomian but pre-Gosau phases. B. PLÖCHINGER (1974, 1979), however, after detailed investigations assumed, that a) the Berchtesgaden-Reiteralm sheet could be eventually seen as a large olistolith, which during the Neocomian slided together with the blocks of the Hallstatt unit into its nowadays position, b) the Hallstatt zone of Hallein-Berchtesgaden (see fig. 18, section 2) at the eastern border of the Berchtesgaden-Reiteralm sheet was sliding during the Malm into the sedimentation area of the Oberalm Beds, which may have been caused by a diapiric uplift of the rock salt in the Permoskythian Haselgebirge formation. As this gravitational sliding of Hallstatt olistoliths also took place during the Neocomian, the origin of the Juvavikum is considered to have taken place during various phases of the (Upper) Jurassic up to the Neocomian, which then would always have been caused by diapirism.

Another unit of the Lower Juvavikum is the *Lammermasse* (Lammer unit, A. TOLLMANN 1968), which extends from the Königssee in the west until the Lammer valley northwest of the Dachstein region. H. ZANKL (1962) was the first, who assumed the more ore less autochthonous position of the Lammermasse within the Dachstein Limestone area („Hallstatt channel"), an assuption, which is now — apart from differences in details — accepted by the majority.

According to A. TOLLMANN (1976 b) the Lammermasse consists of the Torrener Joch zone west of the Salzach and of the Golling-Schwarzenberg, the Strubberg area, the Abtenau-Rigaus-Annaberg area (with Gosau Beds) and the Losegg-Hofpürgl thrust-slice south of the Dachstein sheet. The Lammermasse is situated fault-bounded between the Hoher Göll and the Osterhorn Tirolikum in the north and the Hagengebirge and the Tennengebirge Tirolikum in the south; in the east it is overlain by the Dachstein sheet. According to some other authors (B. PLÖCHINGER 1979) the Lammermasse is resticted to the actual area of the Lammer valley.

The *Staufen-Höllengebirge sheet* (E. SPENGLER 1928) is surrounding the different units of the Juvavikum (as Berchtesgaden-Reiteralm unit, Lammer unit and Dachstein unit) in the north, west and south. In consequence of its structural subdivision various subunits can be distinguished, the most important of which are:

The area of the Watzmann, Hoher Göll, Steinernes Meer and Hochkönig: for the most part it is built up by gently folded, but faulted plates of Dachstein Limestone. Sheared anticlines of Middle to Lower Triassic and sheared synclines of Jurassic and Cretaceous can be observed (fig. 18, section 2).

The block of the Hagengebirge and the Tennengebirge: situated on both sides of the river Salzach and south of the Torrener Joch zone, resp. the Lammermasse.

The "Werfener Schuppen Zone" on the southern border of the Northern Calcareous Alps. The facies slightly reminds of the Hallstatt facies, therefore it was recently assumed that it belongs to the Juvavikum (R. LEIN 1976), while L. KOBER considered it to be of the Bajuvarikum. Some authors assume a considerable southward imbrication (*"Hochgebirgsüberschiebung"* by F. TRAUTH 1916).

The Mandling Schuppe: it splits off south of the Dachstein sheet and is set like an isolated wedge in the Grauwackenzone. Concerning its tectonic position it is closely related to the Werfener Schuppen Zone, though it is developed in Hallstatt facies.

The Osterhorn block: it is bounded in the west by the Salzach river, marked by a young north-south striking fault, and in the east by the Wolfgangsee fault; in the north it extends as far as to the northern border of the Northern Calcareous Alps and in the south it is adjacent to the Lammermasse. In the Upper Triassic beds the facies passes from the Hauptdolomit facies in the north into Dachstein Limestone facies in the south, being covered by Jurassic beds. The Jurassic mainly comprises basin sediments, as Fleckenmergel (Allgäu Beds), Tauglboden Beds with radiolarites and Oberalm Beds with intercalations of Barmstein Limestone.

The Schafberg block: it is situated north-east of the Osterhorn block, separated from it by the Wolfgangsee Fault and exhibits more extensive folded and shear-folded structures. The facies of the Jurassic mainly shows shallow water rocks, like Hirlatz Limestone, sponge-limestone and Plassen Limestone.

The eastern parts of the Staufen-Höllengebirge sheet consist of the Höllengebirge, the Traunstein and the westernmost parts of the Totes Gebirge. Recently A. TOLLMANN (1976 b) included it into the Traunalpen block.

The easternmost parts of the Staufen-Höllengebirge sheet are the Kremsmauer and the Sengsengebirge range. North of it the Tirolischer Bogen gradually comes to an end.

The *Wolfgangsee Fault* (B. PLÖCHINGER 1961) is a considerable northwest-southeast striking wrench-fault, along which later on (post-Middle Eocene) the Osterhorn block was sligthly thrown upon the Schafberg block. Caused by this movement, dislodged slices of different tectonic units beneath the Northern Calcareous Alps became pushed to the surface: In the *window of St. Gilgen,* 5 kilometres off the northern border of the Northern Calcareous Alps and in the *window of Strobl,* additional 7 kilometres south, rocks of the Klippen Zone and the Buntmergelserie of the Helvetic Zone and rocks of the Flysch Zone as well as series from the basis of the Northern Calcareous Alps (Cenoman-Randschuppe) are appearing. Both windows, which probably continue under a Quaternary and Alluvial cover, have been discovered by B. PLÖCHINGER 1961 and studied in detail since 1964 (see fig. 17).

In the *Salzkammergut district,* which is mainly the area of the upper course of the Traun river and its tributaries and which got its name form the numerous mines of rock salt, both, the Lower and the Upper Juvavikum are developed.

The *Lower Juvavikum,* or the *Hallstatt zone,* resp. unit, is mainly developed in two large, but separated areas: (1) in the north in the area of Bad Ischl — Bad Aussee — Bad Mitterndorf; (2) in the south in the area of the Plassen mountain near Hallstatt (see fig. 17).

Upon the Hallstatt unit lies more or less continuously the Dachstein unit or sheet of the *Upper Juvavikum.* Until approximately 15 years ago it seemed to be proved, that long-distance thrusts have taken place: either the Dachstein sheet had overridden the entire Hallstatt sheet, whereby blocks of the Hallstatt sheet were brought on the top of the Dachstein sheet by diapirism (E. HAUG 1906, L. KOBER since 1911, W. MEDWENITSCH since 1949, A. TOLLMANN since 1958), or the Hallstatt sheet had overridden the entire Dachstein sheet and became wrapped at the northern border by continuous northward moving of the Dachstein sheet (J. NOWAK 1911, F. F. HAHN since 1913, E. SPENGLER since 1914).

W. SCHLAGER (1967) modified the old model of Hallstatt channels of E. v. MOJSISOVIC (1903) and demonstrated that the Hallstatt zones can be seen as autochthonous within the surrounding area of Dachstein Limestone (not necessarily belonging to the Dachstein sheet).

Concerning the original depositional situation, in general nowadays combinations of the three above mentioned ideas are existing. In detail, however, and concerning the various areas and the opinions of the different authors, no agreement has been achieved and a lot of concepts have been developed (U. PISTOTNIK 1975, B. PLÖCHINGER 1979, G. SCHÄFFER 1971, 1976, W. SCHÖLNBERGER 1974, A. TOLLMANN 1976 b).

No clearness exists, whether the *Hallstatt Zone* consists of one or two units (sheets). The lower unit (Nappe du Sel of E. HAUG, Lower Hallstatt sheet of L. KOBER, Zlambach unit of A. TOLLMANN 1976 b) mainly comprises Zlambach facies, the upper unit (Nappe du Hallstatt of E. HAUG, Upper Hallstatt sheet of L. KOBER, Sandling sheet of A. TOLLMANN 1976 b) is mainly developed in Hallstatt Limestone facies. On the one hand close relationships betweeen the Zlambach facies and the Hallstatt Limestone facies seem to prove that there exists only one Hallstatt unit with considerable variations in the facies (G. SCHÄFFER, U. PISTOTNIK); on the other hand A. TOLLMANN (1976 b) believes that the Sandling sheet has its root south of the Dachstein area, while the Zlambach unit has to be considered to be comparatively autochthounous betweeen the Tirolikum of the Totes Gebirge and of the Warscheneck (see fig. 16).

Another remarkable problem arises by the discussion of the *age of the tectonic movements.* In general a subdivision into pre-Gosau and post-Gosau phases was considered, the pre-Gosau movements being further subdivided into the pre-Cenomanian (Austrian) phase of the Albian and the actual pre-Gosau phase of the Turonian. The post-Gosau phases are the Palaeogene Illyrian resp. Pyrenean phase and the Styrian phases of the Middle Miocene. The latter, however, did not induce considerable horizontal movements in the Northern Calcareous Alps. Recent detailed investigations, however, also lead to the conception of important intra-Jurassic horizontal movements (G. SCHÄFFER 1976, B. PLÖCHINGER 1974). This gravitational sliding in the nature of olistostroms, caused by diapiric uplift of the basin floor, brought blocks of Dachstein Limestone facies in contact as well as on the top of areas which are developed in Hallstatt facies. The younger Jurassic beds are lying conformably upon both, Hallstatt and Dachstein Limestone facies. The later pre- and post-Gosau movements are partly cutting through these pre-existing units.

The *Dachstein sheet* comprises the Gamsfeld mountain range, the actual Dachstein mountain range, the Gosaukamm and the Grimming mountain. It is developed in the Dachstein Limestone facies, exhibiting both, lagoonal and reef development; mainly in the south transitions into the Hallstatt facies are occurring. The Jurassic Hirlatz and Klaus Limestone often is preserved in big syn-sedimentary fissures within the Dachstein Limestone.

The tectonic postion of the Dachstein unit seems to be identical with that of the Berchtesgaden-Reiteralm unit, but here too, like above, the structural position and the original depositional relationship with the Hallstatt units and with the Tirolikum is in discussion.

The type-locality of the Gosau Formation, the basin of Gosau, is mainly situated upon the Dachstein unit, but Gosau Beds are also lying transgressively upon the Juvavikum, thereby marking pre-Gosau movements. The Gosau Formation was folded and shear-folded by post-Gosau movements and locally it is overriden by Triassic beds.

East of the Dachstein unit the Tirolikum continues with the *Totes Gebirge sheet* and the *Warscheneck sheet,* both mainly flat-lying units composed of Dachstein Limestone with a considerable cover of Jurassic. The Totes Gebirge sheet is overthrust towards the north upon the Traunalpen sheet by forming a well-developed wrapped front.

The Warscheneck sheet exhibits also a typical involuted front south of the basin of Windischgarsten and in the Tauplitz Alm area. In the south the Wörschach block (A. TOLLMANN 1976 b) and the Admont Schuppen zone, an equivalent of the Werfener Schuppen zone, are situated, both separated from the Warscheneck sheet by considerable faults.

East of the Warscheck sheet and north of the Admont Schuppen zone the mountain range of the Haller Mauern is situated. According to B. PLÖCHINGER & S. PREY (1968) it belongs to the Tirolikum and continues into the Göller sheet east of the Weyrer Bögen. After A. TOLLMANN (1976 b) it is part of the Mürzalpen sheet, which is the Juvavikum of the eastern part of the Northern Calcareous Alps.

Between the Sengsengebirge and the Totes Gebirge one can observe the northwest-southeast striking *Windischgarsten-Treichl Fault.* It is well comparable with the Wolfgangsee Fault. 20 kilometres south of the northern border of the Northern Calcareous Alps the Flysch *window of Windischgarsten* is to be seen, exhibiting a Flysch series from the Lower Cretaceous up to the Upper Cretaceous Zementmergel series. Additionally rocks from the Lower Bajuvarikum are outcropping. The Flysch window was discovered in 1936 by R. BRINKMANN, but at that time it was so unimaginable (also by structural geologists like L. KOBER), that only detailed investigations by S. PREY, et al. (1959) proved the existence of the window.

Within the continuation of the Windischgarsten fault, at the northern border of the Northern Calcareous Alps, the Flysch *window of Grünau* (a "Halbfenster") is situated.

East of the Windischgarsten fault the Tirolischer Bogen is striking in east-southeast direction, indicating that the distance of the overthrust of the Tirolikum upon the Bajuvarikum becomes gradually smaller, finally ebbing completely east of the Krestenberg. Here an undisturbed continuation of the Tirolikum into the Reichraming sheet of the Upper Bajuvarikum is proved (fig. 17).

Caused by this retreat of the Tirolikum, the *Bajuvarikum* becomes wider again. The upper unit of the Bajuvarikum is the *Reichraming sheet* (F. TRAUTH 1922), well comparable with the Lechtal sheet in the west. It is characterized by continuous, partly northward overturned folds, locally cut by upthrow faults; the main rock on the surface is the Hauptdolomit. In the area of the Reichraming sheet the Nordtirol facies (with abundant Wetterstein Limestone) grades into the Lunz facies, both subfacies of the Hauptdolomit facies. The Reichraming sheet extends as far as the Weyrer Bögen, east of which it is replaced by the Lunz sheet.

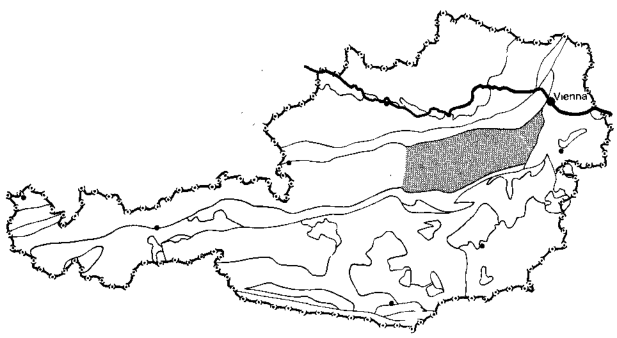
Along a steeply dipping overthrust the Reichraming sheet has overridden the Ternberg sheet (F. TRAUTH 1922) of Lower Bajuvarikum. It is a narrow zone, being composed of narrow folds, which are generally overturned northwards or recumbent. On the eastern side of the Weyrer Bögen this unit is called Frankenfels sheet.

The Area from the Weyrer Bögen to the Vienna Basin

One of the most interesting features of the Northern Calcareous Alps is the *Weyrer Bögen* structure, where the continuously east-west trending belts are obviously disturbed. The units of the Lower Bajuvarikum of the northern border of the Northern Calcareous Alps are distorted like an arc and extending in north-south direction as far as the border of the Juvavikum. Thereby the Upper Bajuvarikum and the Tirolikum sheets became interrupted and somewhat distorted, while the Juvavikum has overridden the southern end of the Weyrer Bögen without exhibiting any disturbance or influence caused by the Weyrer Bögen structure. In the area of this remarkable transverse disturbance the Gosau Formation is transgressing, but by post-Gosau movements it is also involved into this structure.

Numerous theories regarding the tectonic reconstruction of the Weyrer Bögen have been established: The imagination of the originally arched arrangement of the sedimentation areas is nowadays generally refused as well as the idea that the arc has been caused by a projecting hindrance of the Bohemian Massif during the northward transport of the Northern Calcareous Alps.

E. CLAR (1965) discussed the Weyrer Bögen in connection with comparable structures in the Grauwackenzone and in the Muralpen Crystalline, considering a joint origin of the arc structure during an early stage of the nappe movements when the sheets were resting one upon each other. Later on the Northern Calcareous Alps and the Grauwackenzone slided northwards, taking along the structure.



In contrary to that some other authors assumed that the arched structure was formed by transversal compression, caused by the bending of the Northern Calcareous Alps from the Alpine west-east trending into the Carpathian southwest-northeast trending during their sliding to the north (E. SPENGLER 1959, P. STEINER 1968, A. TOLLMANN 1976 b). The rotation, however, from the Alpine to the Carpathian striking can be observed at different locations in the various tectonic units and is depending on a change of the facies from a Carbonate platform facies to the Lunz and Triesting facies (G. HERTWECK 1961, A. TOLLMANN 1976 b).

The various tectonic units continue east of the Weyrer Bögen, well comparable with the sheets west of it, however have throughout different names. The *Frankenfels sheet* (L. KOBER 1911) represents the Lower Bajuvarikum and it continues as narrow belt as far as the faults, which are bounding the Vienna basin. It is composed of narrow overturned and recumbent folds and shearfolds. The Lower and Middle Triassic is not outcropping at the surface and it is considered, that it became rubbed off by structural movements and left under the Northern Calcareous Alps (fig. 18, section 3). An original missing of the older beds is also discussed. The Gosau formation is lacking, as probably at that time the Frankenfels sheet was completely covered by higher Calc-Alpine units. Locally dislodged slices of the *Cenoman-Randschuppe* resp. of the Kieselkalkzone occur north of the Frankenfels sheet.

The Upper Bajuvarikum generally is represented by the *Lunz sheet*, which assumption was originally established by L. KOBER (1912). In its widest extension it is developed closely east of the Weyrer Bögen, becoming smaller in eastern direction. It is composed of continuous folds of the Middle Triassic up to the Cenomanian, transgressively overlain by the Gosau formation. Several faults with short-distance throws cut the area of the Upper Bajuvarikum, giving different authors reason to border the Lunz sheet in widely differing ways. In the area of the village of Lunz and southwest of it a somewhat different element was distinguished, the so-called "Sulzbach Schuppe" (F. TRAUTH 1937, A. RUTTNER 1949, E. SPENGLER 1959), which further on lead to the terms "Lunz sheet I" and "Lunz sheet II" (= "Sulzbach Schuppe" by A. RUTTNER, 1963); P. STEINER (1968) called it Opponitz and Göstling subsidiary sheet. In contrary to that A. TOLLMANN (since 1966) distinguished a Lunz sheet and a Sulzbach sheet, classifying the latter to the Tirolikum. The Sulzbach sheet resp. the Lunz sheet II is developing from the reversed limb of a recumbent syncline, becoming a sheet in completely upside down position (fig. 9; fig. 15, section 3).

In the easternmost parts a distinction of the Frankenfels sheet and a Lunz sheet is not possible, so that A. KRÖLL & G. WESSELY (1973) are using the name *Frankenfels-Lunz system,* including a considerable, generally overturned Gosau syncline, the so-called *Gießhübl Syncline* (fig. 19 and 20).

In the area discussed the Tirolikum was previously named *Ötscher sheet* by L. KOBER (1912), but after additional investigations it became split up into various subsidiary sheets, which, however, differ concerning their definition as well as their classification from author to author. Also the facies of the Tirolikum is more differentiated than in the middle and western parts of the Northern Calcareous Alps, comprehending some subfacies of the Hauptdolomit facies and of the Dachstein Limestone facies (Lunz facies, Rohr facies; Ötscher facies, Triesting facies; fig. 16).

Apart from the above mentioned controversial classifications of the Sulzbach sheet commonly one can distinguish (from north to south; fig. 18, section 3).

The *Reisalpen sheet* (E. SPENGLER) which is developed only east of Lunz and is according to A. TOLLMANN (1973) a multi-facies sheet: the central part is developed in the Rohr facies; grading east- and westwards into the Lunz facies.

The *Unterberg sheet* (E. SPENGLER) or the entire Ötscher sheet exhibits predominantly Dachstein Limestone.

The *Göller sheet* (E. SPENGLER) is the most extensive sheet in the area discussed being continuous at a length of about 125 kilometres; at the border to the Vienna basin its north-south extension is more than 20 kilometres.

According to A. TOLLMANN (1976 b) a Peilstein sheet is classified between the Unterberg sheet and the Göller sheet, but most of the authors consider it to be a subsidiary wedge of the Göller sheet.

South of the tectonic line Pyhrn — Mariazell — Puchberg — Herrnstein the *Mürzalpen sheet* (E. KRISTAN-TOLLMANN & A. TOLLMANN 1962) ist situated, which is described to be a multi-facies sheet: In the middle and eastern part it exhibits the Mürztal facies (northern Hallstatt "channel"), a "hochalpin" limestone facies in the Gesäuse and Hochschwab mountains and the Aflenz facies (southern Hallstatt "channel") at the southern rim. Altogether it is comprehended in one tectonic unit, the Mürzalpen sheet, which rests in its entire extension upon the Tirolikum, comparable with a big Deckscholle, thus representing the Juvavikum. Only in the east a southern reef-limestone range became independent and was thrown as an additional sheet upon the Mürzalpen sheet; it is called *Schneeberg sheet* (L. KOBER 1909).

In comparsion with the Salzkammergut area L. KOBER (1912) originally considered two Hallstatt sheets (Lower Juvavikum) and one Schneeberg sheet (Upper Juvavikum). Other authors refused the existence of the Hallstatt sheets and acknowledged only a smaller Schneeberg sheet of the Juvavikum; in many details these models differ considerably (O. AMPFERER, E. SPENGLER, H. P. CORNELIUS). A lot of discussions exist, whether to classify different parts of the Mürzalpen sheet to other tectonic units, especially to the Tirolikum. So for instance some authors prefer to count the Hall Mauern or the Gesäuse mountains to the Tirolikum (B. PLÖCHINGER & S. PREY 1968). In the east B. PLÖCHINGER (1979) distinguishes an independent Hohe Wand sheet, while according to A. TOLLMANN (1976 b) it is a part of the Mürzalpen sheet. In some places the considered thrust plane of the Mürzalpen sheet is a matter of doubt.

A number of windows and "semi-windows" (Halbfenster) of the current lower unit is known in the area discussed and proves the complicated nappe tectonics of the Northern Calcareous Alps; the most well-known are:

The window of Brettl: The Flysch Zone and the Helvetic Zone is exposed within the Frankenfels sheet.

The window of Urmannsau: The Frankenfels sheet is exposed under the Lunz sheet. At the northern border of the window the well Urmannsau 1 was situated, which drilled 1900 metres rocks of the Frankenfels sheet, comprising also thick Middle Triassic dolomites before penetrating the Kieselkalkschuppe. Below it the well passed the Helvetic Zone with Klippen and the disturbed Molasse, altogether severly imbricated, then autochthonous Molasse and finally penetrated the crystalline basement (A. KRÖLL & G. WESSELY 1967; fig. 9; fig. 18, section 3).

The "semi-window" of the Traisen valley: The Frankenfels sheet can be observed for several kilometres southward within the area of the Lunz sheet.

The window of Annaberg and the window of the Schmelz: The Lunz sheet (Sulzbach sheet) is exposed under different subsidiary sheets of the Tirolikum (Reisealpen sheet, Ötscher sheet).

The window of the Schwechat valley (Schwechat Fenster): An overturned series of the Sulzbach sheet (?Bajuvarikum) is exposed under the Göller sheet (Tirolikum).

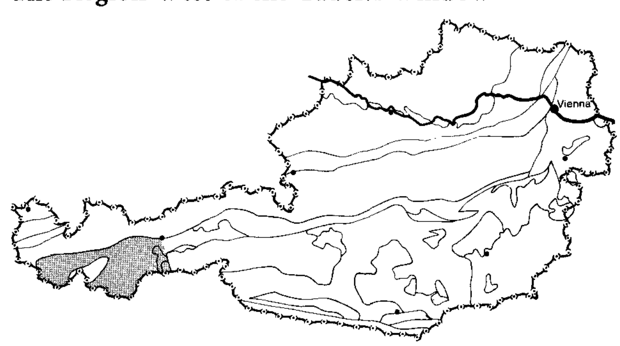
The window of the Ödenhof and the window of the Hengst: Rocks of the Tirolikum are outcropping under the Mürzalpen sheet and the Schneeberg sheet.

By a big Neogene fault system the Northern Calcareous Alps are cut in the east and have sunk several thousand metres, forming the basement of the southern part of the Vienna basin. Proved by many wells, the same units which are well-known at the surface are continuous on the subsurface in northeast direction (See the chapter "The Vienna basin").

The Central Zone of the Eastern Alps

This chapter concerns that part of the Austro-Alpine Unit which within Austria extends between the southern margin of the Northern Calcareous Alps to the north and the Periadriatic Lineament to the south.

The Region West of the Tauern Window



This region extends between the western end of the Austro-Alpine Unit and the western end of the Tauern Window. The Silvretta and Verwall Mountain Group and the Montafon valley occupy the western part, the Ötztal and Stubai Alps form the eastern part.

The Silvretta and Verwall Mountain Group and the Montafon. This region mainly consists of the Silvretta cristalline complex. At its western and southeastern margin it overlies the Penninic series with tectonic contact. The narrow "Phyllitgneiszone" in the north dips with medium to high angle southwards below the Silvretta crystalline complex. The Landeck Phyllite Zone succeeds north of the eastern part of the "Phyllitgneiszone". The boundary towards the Northern Calcareous Alps is steeply inclined partly overturned southwards dipping. West of Schruns the western end of the "Phyllitgneiszone" overlies parts of the Northern Calcareous Alps. In the east the above mentioned units are bounded by a thrust-fault with a high-angle eastward dip. This fault represents the northern continuation of the *Schlinig Thrust-Fault.*

1. The *Silvretta crystalline complex* mainly consists of paragneisses and mica-schists. Locally the content of aluminosilicates may rise considerably. In some places feldspar-metablastites are occurring. There is a broad variety of amphibolite types due to textural differences and to variable portions of plagioclase, garnet, biotite or epidote as minor constituents. They are derived from gabbros (relictic textures), volcanic rocks or pararocks. They mainly occur in the south of the Austrian part where they mark the *Schlingen* structure (regional folding about almost vertical axes). One occurrence of eclogite-amphibolite is known from the Jam valley. Granite gneisses show partly equigranular (fine- to coarse grained), partly porphyritic (augen-gneiss) texture. By radiometric age determinations two intrusive phases were distinguished (430 m.y., 350 m.y.). Various migmatites occur in the contact zone of the orthogneisses. Without any preferred orientation dykes of diabase and diabase-porphyrite cut across the crystalline basement. They are sheared within zones of pronounced Alpine deformation. Locally a network of *pseudotachylites* occurs close to the basal thrust-plane of the Silvretta crystalline complex in the south-east along the margin of the Window of Unterengadin. The pseudotachylites are interpreted as tectonic melting products.

The internal structure of the Austrian part of the Silvretta crystalline complex exhibits a fan-like order, a high-angle north-westward dip in the southeast, an almost vertical one in the central region, and a high- to medium-angle southward dip in the north. In addition, the rocks of the northern portion are strictly striking east-west, whereas in the southern part, in the area of the Samnaun mountain group, Schlingen structure (Vessel-Schlinge) is developed. These regional structures are the result of pre-Alpine tectonic movements to which two metamorphic events can be related. Eclogite facies conditions were achieved during the older metamorphic event which was accompanied by the intrusion of Caledonian granites. The later amphibolite-facies metamorphism produced metamorphic zoning which is unconform to the regional structure and is related with intrusions of early-Variscan granites. Widespread retrogressive metamorphism is mainly of Alpine age, partly of pre-Alpine age.

2. The *Phyllitgneiszone* north of the Silvretta crystalline complex shows a medium-angle southward dip. The phyllite-gneisses contain white mica and small garnets as typical minor constituents and alternate with mica-schists. Occasionally gneisses with porphyroblastic albite clots and leucogranitic to granitic orthogneisses are intercalated.

To the west there is almost no boundary to be recognized between the Phyllitgneiszone and the Silvretta crystalline complex. On this ground H. MOSTLER (1972) supports the existence of a primary connection of these units. However, in the eastern part south of Landeck a mylonite zone is developed, which has already been discovered by W. HAMMER 1918. It is connected with local (Thialspitze, Puschlin) intercalations of Permotriassic rocks, such as greenish-white sericite-schists with quartz-pebbles, calc-schists, thin-bedded limestone and black slates.

3. The *Landeck Phyllite Zone* succeeds north of the Phyllitegneiszone without any marked boundary. Lacking in the west, it crops out east of St. Anton gradually broadening towards east. Phyllites with frequent small garnets are predominating. Locally mica-schists, mica-quartzites, horn-blende-schists, albite-phyllites and muscovite-granite-gneisses are interbedded.

4. From the northwestern part (Montafon area) H. MOSTLER (1972) reported about an upper-Carboniferous succession of sandstones, slates, and laminated dolomites with transgressive, somewhat tectonized contact to its Phyllitgneis base. A detritic Permoskythian series forms the sedimentary connection between these upper-Carboniferous strata and the Triassic rocks of the Northern Calcareous Alps to the north. The beds are almost vertical, sometimes overturned dipping southward.

Conglomeratic sericite-schists and quartzites of probably Permoskythian age occurring at the northern margin of the Landeck Phyllite Zone are believed to be the original sedimentary cover of the Landeck Phyllites at the basis of the Northern Calcareous Alps.

According to A. TOLLMANN the Silvretta crystalline complex together with the Permotriassic rocks of Thialspitze and Puschlin belong to the "Middle East-Alpine". The Phyllitgneiszone and the Landeck Phyllite Zone represent the crystalline basement of the Northern Calcareous Alps and are considered as "Upper East-Alpine".

Stubai and Ötztal Alps. This area is mainly built up by the Stubai-Ötztal crystalline complex. In the west it is bounded by the Schlinig thrust-fault with a general high-angle southeastward dip bordering on the Penninic series of the window of Unterengadin, the Silvretta crystalline complex, the Phyllitgneiszone, and the Landeck Phyllite Zone. To the north the boundary against the Northern Calcareous Alps is buried beneath the Quaternary fillings of the Inn valley along which an important longitudinal fault (Inn valley line) is supposed. The eastern boundary is again marked by a fault (Sill valley fault) in the north and a thrust-plane against the

Penninic series of the Tauern Window in the south. Southwards this crystalline mass extends beyond the Austrian border. In the eastern part the crystalline complex is transgressively overlain by a slightly metamorphosed Permomesozoic succession (Brenner Mesozoic). Upon this an outlier of quartzphyllite with Carboniferous portions is resting (Steinach Nappe). Regional folding on horizontal east-west-trending axes is the main structural feature of the northern part, while folding in mm- to km-dimensions on axes with high-angle dip (e. g. *Venter Schlinge*) is developed in the southern part.

1. The *Stubai-Ötztal crystalline complex* is similar to the Silvretta crystalline complex regarding both its lithology and structure. The rock series have undergone mesozonal metamorphism. Metasedimentary rocks of variable composition are prevailing. Despite of metamorphism and deformation primary lithological alternations are preserved at many places. Principal rock types are biotite-plagioclase-gneisses, gneiss-mica-schists, and mineral-rich mica-schists. Marble, calc-silicate-rocks, quartzites, and para-amphibolites are of subordinate importance. Within these para-rocks ortho-rocks of considerable extent are intercalated. They can be grouped into basic rocks and into two generations of granitic to granodioritic gneisses. The older orthogneiss generation, partly with porphyritic texture (Augengneiss) forms concordant layers. Radiometric age determinations of whole-rock samples yielded Caledonian dates (about 415 to 500 m.y.). The younger orthogneiss generation forms discordant, rather massive intrusive bodies (Winnebach Granite) of anatectic character with numerous country rock inclusions. The basic rocks are concentrated in the central part of the crystalline complex. They consist of banded ampibolites, peridotites, eclogites, eclogite-amphibolites, and garnet-amphibolites. Diabase dykes roughly east-west oriented cut across the crystalline complex; they are lacking, however, in the overlying Permomesozoic.

2. The *Schneeberg Belt* south of the Stubai-Ötztal crystalline complex exhibits a conspicuous petrological difference with respect to its surrounding crystalline series. Only a very small part of this unit is exposed on Austrian territory. The northern marginal series comprises an alternating succession of coarse garnet-mica-schists, hornblende-schists, amphibolites, calcite-marbles, and quartzites and has undergone syn- to post-tectonic mesozonal metamorphism. The monotonous central series chiefly consists of garnet-mica-schists. Apart from some differences regarding the mineral assemblage the southern marginal series corresponds with the northern marginal series. The Schneeberg unit is considered to be the highest part of the crystalline complex. It forms an inclined syncline with northwestward dipping axial plane and is involved into pre-Alpine schlingen structures. By radiometric determinations the metamorphism is dated with about 110 to 120 m.y.; in addition, cooling ages of 75 to 80 m.y. were reported.

3. The *Brenner Mesozoic* rests upon the eastern part of the Stubai-Ötztal crystalline complex with unconform contact which was presumably of sedimentary nature and later on became tectonized. The series is regarded to be of Central-Alpine facies type. It underwent low-grade Alpine metamorphism. Originally this Permomesozoic cover may have had wider extent and in its present position may have been protected against erosion by eastward tilting of strata combined with step faults hading with the eastward dip. The areas of the Kalkkögeln, the Serles, and the Tribulaun are the three major occurrences arranged from north to south. The base is formed by clastic Permoskythian series such as quartz-conglomerates, sandstones, micaceous slates and phyllonites. It is succeeded by 30 to 50 m Anisian rocks, dark, grey limestones, marls, and slates. The overlying up to 400 m of pale, bedded dolomite extend from Anisian to Ladinian. The Carnian is represented by dark slates (Raibl Beds, to 10 m thick). It is overlain by thick-bedded Norian Hauptdolomit, locally 650 m thick. The Norian-Rhaetian boundary is marked by a polymict dolomite-breccia. The succeeding Jurassic limestones, dolomites, marls, slates, and radiolarian cherts exhibit very low-grade metamorphism but strong deformation.

4. The *Blaser Nappe* rests tectonically upon the Brenner Mesozoic. The rocks are also strongly deformed but hardly metamorphosed and comprise a fossiliferous sequence of Norian to Lias allocated to the North-Alpine facies.

In addition tectonic intercalations of middle-Triassic rocks within the Brenner Mesozoic, and upper-Jurassic rocks between Brenner Mesozoic and overlying Steinach Nappe were discovered recently and adopted as part of the Blaser Nappe. Thus an extremely complicated structure is exposed.

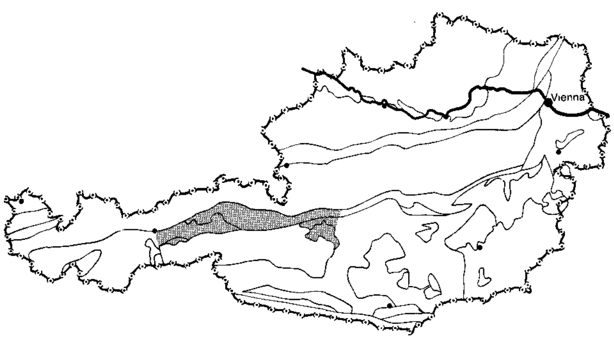
5. The *Steinach Nappe* overlies the southern part of the Brenner Mesozoic and comprises mainly quartz-phyllites the texture of which shows post-crystalline deformation. Locally considerable graphite-content occurs. Layers of ankeritic dolomite are interbedded occasionally in the upper part of the quartz-phyllites. Upper-Carboniferous quartz-conglomerates and sandstones rest transgressively upon the quartz-phyllites and gradually pass into graphite-schists. Within the fine clastic portions seams of anthracite occur which yielded Upper-Carboniferous plant-prints.

According to F. PURTSCHELLER (1971) the metamorphic zones caused by the main mesozonal phase of metamorphism — with an age of about 300 m.y. by radiometric dating — are unconform and therefore younger with respect to the internal structure of the crystalline complex. Further radiometric determinations concerning the southern part of the Stubai-Ötztal crystalline basement, the Schneeberg Belt, and the Brenner Mesozoic yielded old-Alpine ages of about 80 to 100 m.y. The according crystallisation is partly fixing the resulting structures of early Alpine movements.

6. The origin of the post-Pleistocene occurrence of *rock glass at Köfels* in the Ötz valley is still a subject of controversy. Most likely it was formed by meteor impact, but volcanic and frictional origin during mountain slide were also discussed.

According to the tectonic concept of A. TOLLMANN the Stubai-Ötztal crystalline complex, the Schneeberg Belt and the Brenner Mesozoic represent the "Middle East-Alpine" in this area, the Steinach Nappe and the Blaser Nappe, however, are considered as part of the "Upper East-Alpine".

The Region North of the Tauern Window



This region, described in the following account, extends about 170 km in an east-west direction between the Wipp valley near Innsbruck in the west and the area of Schladming to the east and attains a maximum width of 30 km. It represents part of the northern flank of the updomed central zone and can be roughly divided into two major tectonic units, the Lower Austro-Alpine Unit of the Tux Alps and Radstadt Tauern mountains and the western Grauwackenzone which is part of the Upper Austro-Alpine Unit.

1. *The Lower Austro-Alpine Unit of the Tux and Kitzbühel Alps.* The Lower Austro-Alpine series overlie the Penninic series of the Tauern Window along a thrust-plane of medium-angle — locally of low-angle — northward dip. To the west they are bounded by the Silltal Fault south of Innsbruck, to the north partly by the Inntal Line, partly by a thrust-plane dipping with low-angle below the adjoining Grauwackenzone. Eastwards the Lower Austro-Alpine series die out near Mittersill. The major part of this unit is occupied by a quartz-phyllite complex (Innsbruck Quartz-Phyllite), a narrow belt of Permomesozoic rocks of Central-Alpine facies type forms the southern marginal zone.

The *Innsbruck Quartz-Phyllite* represents an early Palaeozoic assemblage of low-grade metamorphic rocks with certain lithological analogies to the adjacent Grauwackenzone. According to H. MOSTLER (1978, lecture) the older part is formed by a succession of monotonous, light-coloured quartz-phyllites, closed on top by a prasinite horizon. In the younger portion of the quartz-phyllite, probably ranging upwards into the Devonian, layers of carbonate rocks, porphyroids, siliceous slates, graphite schists, and quartzites are interbedded. After H. MOSTLER (l. c.) within the Innsbruck Quartz-Phyllite complex a lower normal subunit and an upper invers subunit can be distinguished.

Malm	Serpentinite, laterally interfingered with radiolarian cherts (confined to Reckner Series) (- 160 m) Siliceous slates or radiolarian cherts, calcareous slates
Dogger + Lias	Calcareous slates, slates, siliceous limestone, breccias (- 100 m; confined to Reckner Series) Breccias with limestone-, dolomite-, and quartzite-components (Tarntal Breccia); Calcareous slates series } (- 600 m; confined to Hippold Series)
Rhaetian	Limestone, dolomite, slate (Kössen Beds; - 30 m)
Norian	Dolomite, massive to thick-bedded (Hauptdolomit; - 300 m)
Carnian	Dolomite, slate, limestone (Raibl Beds; - 150 m)
Ladinian	Dolomite, mainly massive (Wettersteindolomit; locally absent)
Anisian	Dolomite, banded limestone; Rauhwacke and gyprock } (- 160 m)
Permo-skythian	Sericite-quartzite-phyllite, quartzite (- 150 m)
Base	Quartz-phyllite

Tab. 6: Permomesozoic succession of the Tarntal mountains (after E. CLAR, M. ENZENBERG, and A. TOLLMANN).

The *Permomesozoic* section is mainly exposed in the *Tarntal mountains* and further occurs along the boundary to the underlying Penninic series. Isolated occurrences are pinched in this position at the western end of the Tauern Window. Two fossiliferous successions, both stratigraphically well-established, can be distinguished in the Tarntal mountains. They exhibit a pronounced lithofacial difference in the Jurassic section. The *Hippold Facies* is rich in breccias, the *Reckner Facies* is poor in breccias, but contains a remarkable serpentinite body (tab. 6). According to O. THIELE (1974) the *Richbergkogel Series* represents a tectonically mixed series comprising mainly post-Triassic rocks confined to the boundary between the Lower Austro-Alpine Unit and the Penninic series.

The northward transport of the Austro-Alpine Unit during the Alpine orogeny caused strong folding and thrusting. According to O. Thiele (1976) the Lower Austro-Alpine Unit of the Tux and Kitzbühel Alps is built up by three sheets. The lowest Hippold Nappe shows a normal succession of attenuated, locally lacking basal quartz-phyllite and breccia-rich Hippold Facies rocks. It is succeeded by the Reckner Nappe with Permomesozoic rocks of Reckner Facies. The overlying Quartz-Phyllite Nappe is inverse and chiefly comprises quartzphyllites and a reduced Permomesozoic proportion. This model corresponds with the previously mentioned subdivision of the Innsbruck Quartz-Phyllite by H. Mostler.

2. *The Lower Austro-Alpine Unit of the Radstadt Tauern Mountains.* There are conspicuous lithological and structural analogies between the Lower Austro-Alpine Unit in the Tux Alps and in the Radstadt Tauern mountains. However, practically no connection exists along the north side of the Tauern Window. To the north and east the series dip below the Grauwackenzone and the Schladming crystalline complex respectively. In the west and south they overlie the Penninic series. Along the eastern end of the Tauern Window the Lower Austro-Alpine series continue southwards in a very attenuated form. In the Radstadt Tauern mountains they build up a pile of sheets which have been sheared away from their crystalline basement and have split up during northward transport.

The *Tweng crystalline* rocks represent the basement and are mainly preserved at the base of the Lantschfeld Nappe. They comprise paragneisses, mica-schists, amphibolites and porphyritic granite-gneisses. The pre-Alpine mesozonal mineral assemblage underwent retrograde Alpine metamorphism under greenschist facies conditions. From studies on these Tweng crystalline rocks F. Becke (1909) introduced the term "Diaphthoresis".

The *Radstadt Quartz-Phyllites* achieve their greatest thickness in the north, but are almost lacking in the southerly, deeper sheets. They mainly consist of monotonous phyllites. Locally siliceous slates, diabases, greenschists, porphyroids, mica-quartzites, ankeritic dolomites, and banded limestones are intercalated. Carbonatic inclusions yielded an upper Silurian to lower Devonian micro fauna (H. P. Schönlaub, 1975). The quartz-phyllite complex is supposed to be of early Palaeozoic age which corresponds with the age of the Innsbruck Quartz-Phyllite.

The fossiliferous *Radstadt Permomesozoic* succession is allocated to the Central-Alpine facies type and shows two types of lithofacial developments. The Hochfeind facies sequence occurs in the deeper, southerly sheets and rests upon the Tweng crystalline rocks. The abundance of breccias in the Jurassic section is significant. The Pleisling facies sequence in the higher, northerly sheets is developed upon a base of either Tweng crystalline rocks or Radstadt Quartz-Phyllites and is characterized by a thick carbonatic Triassic section of variable lithology. Among the Jurassic strata breccias are of subordinate importance. The stratigraphy of the Radstadt Permomesozoic successions is mainly based on the studies by A. Tollmann (tab. 7). The Permomesozoic rocks were also affected by low-grade Alpine metamorphism which gave rise to the formation of quartzites, slates, and crystalline limestones. They also show evidence of very strong internal deformation (deformed belemnites).

Lower Cretaceous + Malm	Slate, sandstone, greywacke, breccia (Schwarzeck Breccia) (- 100 m; confined to Hochfeind Facies) Radiolarian chert, limestone (- 140 m; mainly confined to Hochfeind Facies)
Dogger + Lias	Violet crinoidal limestone (- 20 m confined to Pleißling Facies) Slate, carbonate-quartzite, dolomite breccia Türkenkogel Breccia; - 200 m; confined to Hochfeind Facies) Limestone, calc-slate, slate } (- 180 m) Breccia
Rhaetian	Limestone, thick-bedded to massive, partly dolomitic (- 20 m) Dark calc-slate and slate (Kössen Beds; - 30 m)
Norian	Succession of dolomite and limestone beds (Plattenkalk; - 20 m) Thick-bedded dolomite (Hauptdolomit: - 500 m)
Carnian	Layered dolomite, dolomite-slate, breccia, slate, Rauhwacke (- 170 m)
Ladinian	Pale dolomite, mainly massive (Wetterstein Dolomite; - 300 m)
Anisian	Dolomite, partly dark and thick-bedded Dark, banded marble } (- 200 m) Rauhwacke, slate, dolomite-slate
Skythian	Quartzite (Lantschfeld Quartzite: - 170 m)
Permian	Sericite- and phengite-phyllite, quartzite (- 130 m)
Base	Quartz-phyllite Tweng crystalline rocks

Tab. 7: Succession of Lower Austro-Alpine rocks of the Radstadt Tauern mountains (after E. Clar, and A. Tollmann).

According to A. Tollmann (1963) the structural subdivision is as follows:

Radstadt Quartz-Phyllite Nappe (inverted succession)

Kesselspitz Nappe Pleisling Nappe Lantschfeld Nappe	Pleisling facies
Hochfeind Nappe Speiereck Nappe	Hochfeind facies

The internal structure of the different nappes frequently exhibit recumbent, northwards overturned folds. These internal structures are unconformably cut by major thrust-planes, generally sloping northwards with a low to medium-angle dip. Besides the predominating east-west direction of fold-axes also westwards-facing cross-folds are developed.

The tectonic interpretation of the Radstadt Quartz-Phyllite has not yet achieved coincidence. A. TOLLMANN attributes the major part of the Radstadt Quartz-Phyllites to the uppermost inverted Quartz-Phyllite Nappe, which in the east is tectonically overlain by the Schladming crystalline complex. After E. CLAR, however, the Radstadt Quartz-Phyllites and the overlying Schladming crystalline complex are connected by primary contacts. This idea is supported by A. MATURA (1976) who found coarse-clastic metasedimentary rocks along the boundary between the two complexes. R. ROSSNER (1976) adopted the idea of a division into a deeper Quartz-Phyllite Fold-Nappe and a higher, inverted Quartz-Phyllite Nappe and refers to the analogous gross structures in the Innsbruck Quartz-Phyllite.

3. *Crystalline Rocks Overlying the Innsbruck Quartz-Phyllites.* In this tectonic position phyllite-gneisses, paragneisses, mica-schists with intercalations of amphibolites and marbles occur at the *Patscherkofel* and *Glungezer* mountains southeast of Innsbruck. According to H. MOSTLER (1978, lecture), however, the extension of these occurrences was previously underestimated, because considerable parts of the underlying quartz-phyllites are now recognized as a strongly deformed, diaphthoritic crystalline assemblage.

The *Schwaz Augengneiss* or *Kellerjoch Gneiss* appearing as foliated, diaphthoritic and prophyritic granite gneiss forms a row of isolated occurrences along the boundary against the overlying Grauwackenzone.

A sequence with a discontinuous basal layer of Schwaz Augengneiss and succeeding 500 m of garnetiferous albite-quartz-schists, garnet-mica-schists, and amphibolites occurs at the *Steinkogel* in the easternmost part of the Innsbruck Quartz-Phyllite area.

According to recent petrological and geochronological studies (M. SATIR & G. MORTEANI, 1979) the sedimentation age of the Steinkogel assemblage is about 540 m.y. and the intrusion of the Schwaz Augengneiss is believed to have occurred between 450 and 425 m.y. No evidence of Caledonian metamorphism could be found in both units. But they have been affected by amphibolite facies metamorphism during Variscan times. Finally, an early Alpine metamorphic event (90 m.y., Rb/Sr, biotite) could be detected. The same authors consider the movements which brought the Schwaz Augengneiss and the Steinkogel assemblage on top of the low-grade metamorphic Innsbruck Quartz-Phyllites to be of Variscan rather than of Alpine age, whereas A. TOLLMANN supports an Alpine overthrust of these "Middle East-Alpine" units upon the "Lower East Alpine" Innsbruck Quartz-Phyllite.

4. *The Western Grauwackenzone.* The Western Grauwackenzone is largely made up of early Palaeozoic rocks. It forms a continuous belt east of Schwaz. Its continuation east of Schladming is not dealt in this chapter. The contact between the Grauwackenzone and the Northern Calcareous Alps is of stratigraphic nature, although subsequently complicated by tectonic activity. The sinuous course of the southern boundary in the west is due to a generally low-angle northward slope of the undulated and locally folded basal thrust-surface which separates the Grauwackenzone from the underlying Innsbruck Quartz-Phyllites. Eastwards the Grauwackenzone is bounded to the south by a prominent fault zone (Salzach Longitudinal Fault) which can be traced from the upper Salzach valley eastwards into the Enns valley.

		Tyrol	Salzburg
Permian	Upper	Sandstone, slate	Sandstone, slate, gyprock and anhydrock Conglomerate
	Lower	Quartz conglomerate Basal breccia	Sandstone, slate, quartz porphyry tuff (Fellersbach Fm.) Conglomerate (Gainfeld C.)
Carboniferous			Sandstone, slate (Visé of Schwarzleo)
Devonian		Pale limestone	Nodular limestone Slate, siliceous slate
		Schwaz Dolomite (pale)	Spielberg Dolomite (nodular)
Silurian		Dark Orthoceras Limestone	complex of dark, layered dolomites and siliceous slates
		Phyllites with clastic intercalations (Upper Wildschönau Ph.)	Dark Orthoceras Limestone
		Conglomerate	
? Cambrian Ordovician		Porphyroid (- 350 m) Phyllites (Lower Wildschönau Ph.) with intercalations of basic volcanic rocks (diabase, locally with pillow-structure)	

Tab. 8: Stratigraphic succession of the Grauwackenzone of Tyrol and Salzburg (after H. MOSTLER).

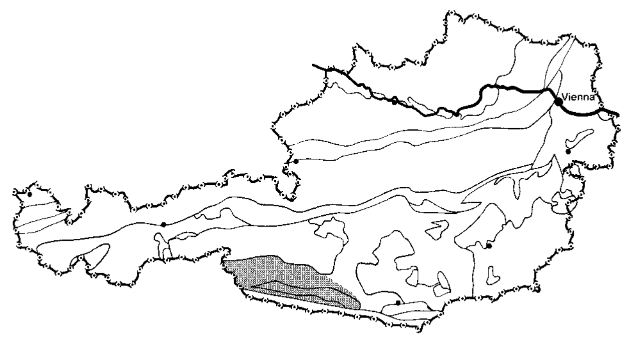
The stratigraphic succession of the Grauwackenzone (tab. 8) is partly fixed by fossils. Sedimentation probably began in (?Pre-)Cambrian times. Fragments of garnet-amphibolite, garnet-hornblende-gneiss, and paragneiss from volcanic breccias in basic volcanites are believed to represent the only remains of the crystalline basement (H. MOSTLER, 1970). The most significant and rather persistent horizon is an upper Ordovician *porphyroid* which lies on top of the monotonous sequence of the *Lower Wildschönau Phyllites.* During the early Silurian lithofacial differentiation into pelagic, swell and shallow-water facies occurred. Carbonate facies (mainly dolomites) predominates during upper Silurian and Devonian. After a stratigraphic gap a continental-detritic series follows which continues upwards into the Mesozoic of the Northern Calcareous Alps. At one place in the more easterly section (Schwarzleo) clastic Viséan is preserved.

The rock assemblage underwent progressive low-grade metamorphism which is partly of proven Alpine age because it also affected Mesozoic rocks of the overlying Northern Calcareous Alps (J.-M. SCHRAMM, 1977). The Alpine metamorphism is believed to mask a pre-Alpine metamorphism which is very difficult to identify because of its similar intensity.

The internal structure of the Grauwackenzone is the result of both Variscan and Alpine deformations which are difficult to distinguish at some places. After H. MOSTLER (1974) Variscan movements caused a pile of four superincumbent sheets. Broad folding mainly as well as faulting are attributed to Alpine movements. Besides the prevailing east-west direction of fold-axes also cross-folding is developed. Locally the basal thrust-plane is folded itself with northwards overturned attitude. Close to the Salzach Longitudinal Fault in the south which is thought to be of about Miocene age a steeply inclined, highly deformed *Schuppenzone* is developed. Further east-west trending faults occur within the Grauwackenzone generally displaying uplift of the southerly blocks. The Grauwackenzone dips northwards below the Northern Calcareous Alps. There the strata are frequently steepened and locally even overturned. At some places — mainly along the northern margin — late-Alpine southward thrusting occurred. The *Mandling Schuppe* represents the most prominent example of this structural peculiarity. It occurs in the area of Schladming where a wedge of Triassic rocks obliquely crosses almost the whole Grauwackenzone joining eastwards the basis of the Northern Calcareous Alps.

The Region South of the Tauern Window

This region is bordered in the north by the Tauern Window and the northwest-southeast trending Möll-Drau-Valley Fault, to the south by the Periadriatic Lineament along the Gail valley and extends from the Austrian border in the west as far as Villach in the east. Geographically the area is formed by the Deferegger Alps, the Schober Mountain Group, the Sadnig Mountain Group, the Kreuzeck Mountain Group, and — in the south — by the Lienzer Dolomiten Mountains and the Gailtal Alps. From the geological point of view this region is from north to south built up by the Matrei Schuppenzone, the Austro-Alpine crystalline complex, the Thurntal Quartz-Phyllite and equivalent early-Palaeozoic occurrences, the Permomesozoic of the western Drauzug, the Nötsch Carboniferous, and the Austro-Alpine Gailtal crystalline complex.



This section at the southern flank of the axial zone exhibits the effects of intensive Alpine compression in north-south direction which gave rise to steeply inclined or vertical structures particularly in the southern part.

1. *The Matrei Schuppenzone.* The Matrei Schuppenzone represents a highly deformed zone with high-angle southward dip comprising Penninic and Lower Austro-Alpine elements. It can be traced along the southern margin of the Tauern Window and continues eastwards into the Katschbergzone around the eastern end of the Tauern Window and further into the Lower Austro-Alpine of the Radstadt Tauern mountains. It consists of strongly deformed quartz-phyllites, Permoskythian quartzite-schists, Triassic carbonate rocks, and Bündnerschiefer comprising calc-phyllites, micaceous marbles, greenschists and certain serpentinite bodies. Thus the Matrei Schuppenzone displays the features of a very prominent movement interface in the Eastern Alps.

2. *The Crystalline Complex.* This complex is chiefly formed by mica-schists and various paragneisses of mesozonal metamorphic grade. Locally the rocks underwent retrograde metamorphism and post-crystalline deformation. Occasionally ortho-augen-gneisses, amphibolites, and, very sporadically marbles and calc-silicate-gneisses occur. At some places the crystalline complex is cut by stocks and dykes of granodioritic to tonalitic composition (Periadriatic Intrusions). They have been hardly affected by Alpine deformation and metamorphism.

In the central *Schober mountain group* and in the northern part of the *Kreuzeck mountain group* eclogite-amphibolites are to be found within an amphibolite-rich zone. They are considered as significant rocks types belonging to a higher, southerly unit of mica-schists and paragneisses. The deeper, northerly unit essentially consisting of quartzite-rich series of mica-schists and paragneisses forms major parts of the *Deferegger*

Alps and the Schober mountain group. The interface has been identified as a thrust-plane of about medium-angel southward dip along which pre-Alpine (?Variscan) movements have taken place.

Radiometric dating has established an age of about 440 m.y. for the formation of the augen-gneisses. Further radiometric dates derived from the northern marginal zone are attributed to an early-Alpine metamorphic event. Diaphthoresis is largely confined to zones of pronounced Alpine deformation.

Commonly the fold-axes trend east-west and the schistosity dips southwards. Pre-Alpine and Alpine axial directions can be distinguished. In the southern part of the Deferegger Alps and in the central Schober mountain group schlingen structure is developed. Locally the internal structure of the crystalline complex is cut unconformably by the thrust-plane to the north. Two diagonal sets of faults can be distinguished. Their pattern is followed by the main valleys. Dextral displacements occurred along the northwest-southeast trending faults.

According to S. Borsi & al (1978) the Austro-Alpine crystalline complex south of the Tauern Window is cut by two longitudinal zones of intensive post-crystalline deformation separating three main blocks significantly different regarding their macro- to mesoscopic structure. They have also undergone varying P-T-conditions during the main tectogenetic Alpine phases which is reflected by the regional distribution of biotite-ages. In the northernmost block neighbouring to the Tauern Window synmetamorphic folds, Alpine phyllonitisation and a later recrystallisation are developed. The two southern blocks only show post-crystalline effects of Alpine movements.

The *Rieserferner Tonalite* is exposed in the Deferegger Alps and is among the largest ones of the Periadriatic Intrusions. It occupies the core of an anticline of contactmetamorphic mica-schists. The age of intrusion is about 30 m.y. on the basis of radiometric measurements (S. Borsi et al, 1979). The tonalite and its country rocks are cut by garnetiferous porphyrite dykes. Another intrusive mass of smaller dimension and of granodioritic composition occurs in the Kreuzeck mountain group near Wöllatratten. Radiometric dating of biotites (K/Ar) yielded 31 to 44 m.y. ages. Also various dykes in the Schober and Kreuzeck mountain groups have been allocated to this intrusive generation.

A fault-bounded assemblage of quartzite-schists with quartz-pebbles, quartzites, rauhwackes, banded limestones, and dolomites occurring near *Kalkstein* is considered to be a remain of the Mesozoic cover in Central-Alpine facies.

3. *The Thurntal Quartz-Phyllite and Equivalents.* The predominating quartz-phyllites are interlayered by amphibolites, prasinites, porphyroides, and quartzites. The whole complex occurring west of Lienz exhibits a synclinal structure and underwent low-grade Variscan metamorphism. In the north it is separated from the crystalline complex of the Deferegger Alps by a mylonitic, up to 100 m wide zone. In this marginal zone occasionally pseudo-conglomerates are developed which previously were considered to be a transgressive assemblage.

A similar assemblage is exposed in the area of the *Goldeck mountain group* separated by a steeply southward dipping zone of strong deformation from the underlying diaphthoritic crystalline complex. The lower portion of the series is formed by low-grade metamorphic quartz-phyllites interlayered by graphite-schists, quartzites, calcite-marbles, greenschists, and diabases. The upper part consists of very low-grade metamorphic meta-volcanites and slates without any marble. Carbonate-layers from the quartz-phyllite complex yielded early-Palaeozoic conodonts.

Further sporadic occurrences of such rocks believed to be of early-Palaeozoic age are known from the area of the Kreuzeck mountain group.

4. *The Permomesozoic of the Western Drauzug.* The Permomesozoic rocks of the Western Drauzug rest in an elongate steep-limbed and fault-bounded synclinal depression upon the crystalline basement. At some places, however, the stratigraphic contact with the basement is still preserved, e. g. with the Gailtal crystalline basement and the Nötsch Carboniferous to the south and the quartz-phyllites of the Goldeck mountain group to the north. The terrestrial-fluviatile Permian occurring at Laas near Gailbergsattel represents the basal part of the succession (tab. 9). Marine conditions set in during the sedimentation of the Werfen Formation. The succeeding shallow-water deposition ranges up into Upper-Anisian. At that time this platform became broken by tectonic movements giving rise to lateral lithofacial differentiation of the succeeding carbonate-rock development. Locally layers of intermediate to basic pyroclastic rocks ranging from cm to some 120 m of thickness are interbedded. During the Carnian prevailed evaporitic conditions with episodes of drying up. That gave rise to the formation of the Bleiberg Facies which is connected with a considerable Pb-Zn mineralization. The lateral differentiation of the upper-Triassic sediments is less pronounced than of the middle-Triassic strata. The occurrence of Jurassic to lower-Cretaceous strata is restricted to the area south of Lienz. The lithofacial features of the whole succession are considered to be of an intermediate type between the north-Alpine and south-Alpine facies.

The internal structure of this unit exhibits steep-limbed folds, northward thrust slices, and several longitudinal and diagonal faults.

In the *Bleiberg district* on the northern side of the Drauzug extensive mineralization of the upper 120 m of the Wetterstein Limestone and of the lower parts of the overlying Raibl Beds has taken place. The mineralization follows both bedding and joint surface and apparently replaces the country rock. The main minerals are galena, sphalerite and marcasite in a calcite-dolomite-baryte-gangue with subsidiary anhydrite, flourite and quartz. The deposit is believed to be of sedimentary (epigenetic) origin with secondary hydrothermal remobilisation. The ore has been worked extensively at the famous Bleiberg mine.

L.Cretaceous	Bedded marls and turbidites (Lavant Flysch; - 370 m) Mottled marl (and limestone)	
Malm	Pale Calpionella Limestone	
Dogger	Red, marly limestone; red nodular limestone	
Lias	Red flaser limestone and marl (Adnet Limestone) Grey, mottled marl and bedded marl-limestone (Allgäu Beds)	
Rhaetian	Dark shales interbedded with marls and limestones (Kössen Beds; - 300 m)	
Norian	Thick-bedded, dark limestone (dolomite) (Plattenkalk; - 350 m)	
	Bedded, partly bituminous dolomite (Hauptdolomit; - 1200 m)	
Carnian	Limestone, dolomite and shales interbedded; locally oolithic layers and Rauhwacke	(Raibl Beds; - 260 m)
	Pb-Zn-mineralisation	
	Bedded Wetterstein Limestone and Dolomite; locally reef limestone (- 1700 m)	
Ladinian	Dark, bedded Partnach Limestone (- 500 m) with tuff layers	
Anisian	dm-bedded dolomite with tuff layers Nodular limestone, reef limestone	(- 180 m)
	Quartz sandstone with carbonate layers	
	Flaser limestone	Gypsiferous shales
Skythian	Grey shales, sandstone, Rauhwacke, gyprock Red sandstone and shales	(Werfen Beds; - 50 m)
	Fine-bedded sandstone (Alpine Buntsandstein; - 150 m)	
Permian	Sandstone, conglomerate (Gröden Beds; - 150 m) Quartz porphyry and -tuff (- 20 m) Conglomerate, sandstone, shale (Werchzirm Beds; - 150 m)	

Tab. 9: Permomesozoic succession of the Western Drauzug in the Lienzer Dolomiten mountains and Gailtal Alps (after A. Tollmann, 1977).

5. *The Nötsch Carboniferous.* This fault-bounded occurrence near Nötsch between the Permomesozoic rocks of the western Drauzug to the north and the Gailtal crystalline complex to the south can be divided into three groups of different ages. The *Nötschgraben Group* consists of slates intercalated by calcmarls. The major part is considered to be of Viséan age which is well established on the base of abundant fossils (e. g. productus, trilobites). The *Badstub Breccia* is a stratigraphic intercalation of volcanic type. The fine-grained, greenish, tough groundmass of plagioclase, quartz, hornblende, and chlorite contains mainly angular fragments of amphibolite, marble, quartzite, granite, gneiss, and mica-schists. The *Erlachgraben Sequence* of alternating coarse conglomerates, sandstones and slates yielded a Namurian flora. The *Pölland Sequence* of Westphalian age shows a thin-bedded alternation of conglomerates, sandstones, and shales severely disturbed by faulting and folding and in an almost vertical position.

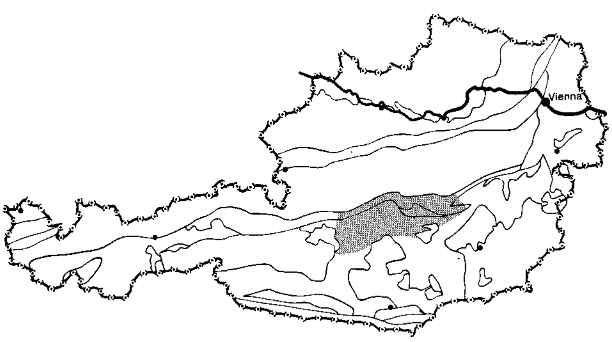
6. *The Gailtal Crystalline Complex.* The Gailtal crystalline complex forms a belt of 2 to 3 km of width between the Permomesozoic of the Drauzug to the north and the Periadriatic Lineament to the south. The western part consists of mica-schists and paragneisses with staurolite and garnet, granitic augengneisses, pegmatite-gneisses, and amphibolites. Parts of this rock assemblage underwent retrograde metamorphism. The eastern part is largely formed by low-grade metamorphic phyllites interlayered by diaphthoritic garnet-mica-schists, quartzites, graphite-phyllites, and marble. The latter yielded Silurian-Devonian conodonts. The northern margin in the easternmost part at Nötsch is occupied by a mylonitic, epimetamorphic granite *(Nötsch Granite)* and amphibolites. The Gailtal crystalline complex represents the basement of the transgressive Permomesozoic rocks of the western Drauzug. However, because of considerable subsequent faulting exposures of preserved stratigraphic contact are rare.

According to the tectonic concept of A. Tollmann the Matrei Schuppenzone is a zone of tectonic interlayering of Penninic and Lower East-Alpine elements, the crystalline complex and remains of Central Alpine Permomesozoic rocks such as those of Kalkstein belong to the "Middle East-Alpine", the Drauzug and the Gailtal crystalline complex are part of the "Upper East-Alpine".

The Region East of the Tauern Window

The Niedere Tauern Mountains and the Eisenerz Alps

This region extends between the Enns valley to the north and the Mur valley to the south and is occupied from west to east by the mountain groups of the Schladming Tauern, Wölz Tauern, Seckau Tauern, and the Eisenerz Alps. The major part is formed by crystalline basement rocks. Its northeastern flank in the area of the Liesing valley is covered by Permoskythian continental-detritic series (Rannach Series) of considerable thickness. Both, crystalline complex and Rannach Series, to the north are overlain by the Grauwackenzone which is relatively narrow in its western part along the Enns valley but attains a width of some 20 km in the area of the Eisenerz Alps.



1. The *Crystalline Complex of the Schladming Tauern mountains* occupies the western part and is mainly composed of orthogneisses and paragneisses. The orthogneisses are of granitic to granodioritic composition and locally show porphyritic texture (augen-gneiss). The granitic texture is only preserved in some places. Monotonous biotite- and garnet-bearing paragneisses show transitions to varieties with abundant quartz and hornblende. Migmatisation and metablastesis can be observed along the boundaries of the orthogneisses. A series of banded amphibolites and leucocratic gneisses are believed to be of volcanic origin. The amphibolite facies metamorphism of the rocks is of pre-Alpine age. They underwent retrograde metamorphism in zones which had suffered Alpine deformation, especially in the northern part. The internal structure exhibits several anticlines gently dipping eastwards with cores of orthogneisses. To the west the crystalline complex overlies the Lower Austro-Alpine series of the Radstadt Tauern mountains. The generally eastward dipping interface shows complex shape. In the area of the Seekarspitze-Gurpitscheck, for example, the westernmost part of the Schladming crystalline complex forms the core of a recumbent anticline. Eastwards it is overlain by a recumbent syncline made up of Radstadt Quartz-Phyllites and Permomesozoic rocks and finally by the main mass of the crystalline series. To the north a narrow wedge of crystalline rocks extends westwards as far as Radstadt separating the lower Radstadt Quartz-Phyllites from the higher Grauwackenzone. On the other hand narrow zones of Radstadt Quartz-Phyllites can be traced eastwards into the Schladming crystalline complex. These zones commonly have *sulfidic mineralization* which gave rise to the famous historic mining area south of Schladming.

2. The *Mica-schist of the Wölz Tauern mountains* overlie the crystalline complex of the Schladming Tauern mountains in the east. The prevailing mica-schists show local quartzitic, gneissose, or graphitic varieties. In the southerly regions the rocks become coarser grained, containing staurolite and kyanite. Diverse amphibolites and hornblende garbenschiefer are interlayered. Various crystalline carbonate rocks are concentrated mainly along the northern margin (Sölk-Gumpeneck) and in the southeastern part (Hohenwart—Bretstein—Oberzeiring) and are supposed to occupy a comparatively high (?stratigraphic) position. The carbonate rocks of the eastern part are associated with concordant, locally discordant, foliated pegmatite gneisses. They yielded an age of about 250 m.y. by radiometric dating (muscovite, Rb/Sr).

The internal structure shows broad folding on predominating WNW-ESE-trending axes. Southwards the mica-schists of the Wölz Tauern mountains continue beyond the arbitrary limits of this described region. In the area of Murau—Stolzalpe—Oberwölz they are overlain by low-grade metamorphic Palaeozoic rocks. Approaching the northern boundary the intensity of diaphthoresis gradually increases associated by a younger, northward dipping foliation. Thus lithological similarities with rocks of the adjacent series of the Grauwackenzone result. Vertical east-west faults partly associated by mylonites dissect the basement in the central and southern part. The pronounced straight parallel orientation of several valleys indicates probably another faulting in NNW-SSE-direction.

3. The *Gneiss complex of the Seckau and Rottenmann Tauern mountains* appears northeast of the mica-schist region of the Wölz Tauern mountains and occupies a deeper tectonic position. The core of the gneiss complex is formed by extensive masses of granitic to tonalitic composition and foliated, rarely massive texture. They are covered by a series of paragneisses with interlayered amphibolites, quartzites, granitic gneisses, and biotite-schists. Migmatites occur along the contact. A series of hornblende-gneisses and amphibolites occupies a higher position, but is only preserved at the southwestern flank of the gneiss-complex. The occurrences of ultrabasic rocks are also attributed to the latter series. The largest bodies are known from Oppenberg and Kraubath. The internal structure of the gneiss-complex exhibits broad gentle folding. To the southwest it is bounded by a steep, strongly deformed zone (Gaal Schuppenzone; K. Metz, 1971) comprising mica-schists, gneisses, amphibolites, schuppen of marble (Mölbegg Schuppen) and Rannach Series.

The *Pöls Line* striking north-south is part of an important regional fault-system and is connected in the SSW with the Lavant-Valley-Fault. The gneiss-complex of the Seckau Tauern is displaced by the Pöls Line in dextral sense to an extent of about 10 km.

4. The Permoskythian, continental-detritic *Rannach Series* overlies the northeastern flank of the Seckau crystalline complex with unconform, transgressive contact. The prevailing serizite-quartzite-schists are interlayered by rather extensive conglomerates, quartzite, and sporadic marbles. Narrow lateral continuations of

the main occurrence south of the Liesing valley are very persistent in this position on top of the crystalline basement. Further occurrences are known from within the area of the gneiss-complex. The Rannach Series is allocated to the Central-Alpine facies occurrences.

5. *The Grauwackenzone* of this area represents the eastern continuation of the previously described Western Grauwackenzone and is part of the so-called Eastern or *Styrian Grauwackenzone.* In the area of the Enns valley the thick sequence of phyllites with intercalated greenschists is known as *Ennstal Phyllites.* Upper Ordovician to Silurian strata were proved on the basis of a badly preserved fauna. The eastern section in the

Permian	Violet sandstones and slates interbedded Quartz conglomerate Basal conglomerate	(Präbichl Fm.)
Carbon.	Slate, sandstone, conglomerate with graphite deposits Slate, sandstone, limestone, dolomite, magnesite	
Devonian	Limestone, locally siderite-ankerite mineralized	
Silurian	Siliceous slates with black limestone interbedded	grey flaser limestone Orthoceras Limestone
	Greenschist, red spathic limestone	
Ordovician	Cystoidea Limestone Quartzite	Lydite, slate, arkose
	Porphyroid (Blasseneck P.; ~ 800 m)	
	Phyllites (Silbersberg Group) with quartzites Locally basal conglomerate (Kalwang C.)	
? Base	Schuppen of crystalline rocks (Vöstenhof, Stübming, Kaintaleck, Ritting)	

Tab. 10: Stratigraphic succession of the eastern Grauwackenzone (after H. P. SCHÖNLAUB).

Eisenerz Alps exhibits a broad and variable development of Palaeozoic strata (tab. 10).

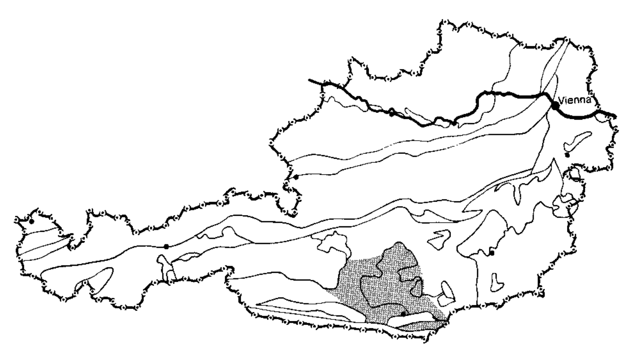
An Upper Ordovician porphyroid (*Blasseneck Porphyroid*) represents a very significant horizon. It is underlain by a series of phyllites with quartzites and greenschists. The sequence above the porphyroid locally begins with quartzites. A manyfold Silurian rock assemblage (carbonat-rocks, graptolite schists, volcanic rocks of different facies succeed. A uniform carbonate development predominates during Devonian times. Locally mineralization has occurred with the formation of *replacement carbonate deposits* (ankerite, siderite), for example at Eisenerz where this iron ore is still mined in an important open-pit mine. Among the various lower Carboniferous strata some of the carbonate rocks (magnesites) are of economic importance. The molasse-like upper Carboniferous sequence is free of any marine carbonatic episodes. Several graphite deposits of economic importance are known. The *Präbichl Beds* represent the Permoskythian base of the Northern Calcareous Alps and rest with unconform contact upon the rocks of the Grauwackenzone.

The Grauwackenzone of the Eisenerz Alps can be divided into two tectonic units. The deeper unit, called *Veitsch Nappe,* is made up exclusively by Carboniferous strata and forms a narrow belt along the southern margin of the Grauwackenzone. The higher unit, known as *Noric Nappe,* comprises an early Palaeozoic rock assemblage which locally ranges upwards into the lower Carboniferous. The internal structure shows intensive folding and faulting. Locally along the interface of these two tectonic sub-units (the Noric Line) slices of crystalline rocks occur which are believed to be the remains of the original crystalline basement.

The age of the internal structure of the Grauwackenzone is a subject of controversy. Because of the unconform transgressive contact of the Permoskythian Prebichl Formation upon the strongly deformed complex of the Grauwackenzone H. P. SCHÖNLAUB supports Variscan age for thrusting and folding and Alpine age for faulting. According to A. TOLLMANN the subdivision into two tectonic nappes and the major internal structures are the result of Alpine movements. Besides other arguments he refers to one occurrence of rauhwacke — which he believes to be of Triassic age — along the interface between the two nappes of the Grauwackenzone and to the pronounced tectonic slicing between the Carboniferous strata of the Veitsch Nappe and the underlying Permoskythian Rannach Series.

Regarding the tectonic concept of A. TOLLMANN the crystalline complex and the Rannach Series are parts of the "Middle East-Alpine", the Grauwackenzone belongs to the "Upper East-Alpine".

The Gurktal Alps, the Klagenfurt Basin, and the Northern Karawanken



This region extends east of the Tauern Window as far as to the western foot of the Saualpe and is marked there by a north-south trending fault system (Görtschitz-

Valley-Fault). To the north it borders the area of the Niedere Tauern without any pronounced geological contour. In the south the basement of the Klagenfurt Basin and the Austrian part of the Northern Karawanken will be dealt in this chapter. The area can be divided from west to east or from the bottom to the top into the Katschbergzone, the crystalline complex, the Permomesozoic of the Stangalm, the Palaeozoic of the Gurktal Alps, and the Permomesozoic of the Krappfeld. The southern part is occupied by the Permomesozoic of the Eastern Drauzug, which in the south is bounded by the Periadriatic Lineament.

1. The *Katschbergzone* forms a narrow zone along the eastern rim of the Tauern Window and overlies the eastward dipping Penninic series. This highly deformed unit is connected to the north with the Lower Austro-Alpine Unit of the Radstadt Tauern mountains and to the south with the Matrei Schuppenzone. The rock assemblage mainly consists of quartz-phyllite. Some carbonatic interlayers (banded marble, ankeritic dolomite) yielded an upper-Silurian fauna. In addition strongly deformed remains of Permomesozoic rocks (serizite-quartzite, dolomite- and calcite-marble) are intercalated. Most of the fold-axes are plunging eastwards with low to medium angle dip.

2. The *Austro-Alpine crystalline complex* overlies the Katschbergzone without any sharp contour. There is no pronounced metamorphic contrast at the contact-plane between the low-grade metamorphic quartz-phyllites of the Katschbergzone and the pre-Alpine mesozonal metamorphic crystalline complex. A. Tollmann explains that fact by important Alpine thrust movements along this interface which have caused shearing and associated retrograde metamorphism in the adjoining crystalline complex. It is chiefly made up of mica-schists and paragneisses with abundant quartz-content and rare intercalations of marble, amphibolite, and granitic augen-gneiss (*Bundschuh Orthogneiss*). Radiometric dating of the latter (whole rock, Rb/Sr) established a lower Devonian age of formation (370 m.y.). Parts of the crystalline complex, for example the meso- to katazonal metamorphic *Lieser-Gneiss-Series* in the southwest are rich in pegmatites. To the northeast the mica-schist-series continue into the area of the Wölz Tauern mountains. In the south, in the area of Klagenfurt, the mica-schists are overlain by a series of low-grade metamorphic phyllites. The progressive or retrogressive metamorphic origin of the latter is a matter of controversy. B. Schwaighofer supports the idea of progressive metamorphism on the basis of petrographic examinations whereas A. Tollmann considers this phyllite series to be part of a diaphthoritic zone indicating an important thrustplane on top of the crystalline complex. The northwest-southeast striking Möll-Drau-Valley Fault and the NNW-SSE striking Gegend Valley Fault are the most prominent faults in this area.

3. The strongly deformed and low-grade metamorphic *Permomesozoic of the Stangalm* rests transgressively upon the crystalline basement. It is regarded to be of Central-Alpine facies type and forms a narrow, sinuous and discontinuous belt which can be traced from the area of Murau in the north to the region east of Radenthein in the south. Because of subsequent faulting the transgressive contact at the base of the sequence is only preserved in some places. Permian serizite-quartzites and quartz-keratophyres form the bottom part of the sequence succeeded by Skythian quartzites, Anisian rauhwackes and dark, well-bedded limestones and dolomites, Ladinian thickly bedded Wetterstein Dolomite, and black Carnian slates on top. This succession appears to be rather poor in fossils.

4. In the north-south striking western part of the Stangalm Permomesozoic the succession is tectonically overlain by the *Pfannock-Schuppe* made up of Upper Carboniferous to Rhaetian strata which resemble the Mesozoic of the Northern Calcareous Alp as well as of the Drauzug and are locally inverted. A significant phyllonite horizon marks the interface. Isolated slices of siliceous calc-shales, calc-shales and red radiolarian cherts are thought to be of Jurassic age. In general the fold-axes show east-west direction.

5. A number of small, strongly deformed schuppen of Permotriassic rocks such as serizite-schists, quartzites, rauhwackes, dolomite breccias and dolomites, are known from the region between Villach and Klagenfurt in the south.

6. The *Palaeozoic of the Gurktal Alps* appears to be an extensive thrust-sheet known as *Gurktal Nappe*. The western and northern boundary of this nappe is very well defined by the tectonically underlying Stangalm Mesozoic. The eastern and southern boundary, however, is a subject of controversy because of the absence of any equivalents of the underlying Stangalm Permomesozoics. In addition, the low-grade metamorphic Palaeozoic rocks of the Gurktal Nappe are connected with the adjoining high-grade metamorphic rocks of the Saualpe in the east by gradual metamorphic transitions. This is believed to be the result of Variscan events. The major part of the rock assemblage is formed by anchi- to epimetamorphic early Palaeozoic strata. Quartz-phyllites, phyllites with occasional thick inclusions of metadiabase (*Magdalensberg, Murau*) are considered to be of Ordovician age. They are succeeded by Silurian phyllites with intercalated quartzites, siliceous slates, and carbonate layers. The Devonian is represented partly by carbonate rocks (limestones and dolomites in the area of *Oberwölz* and *Murau*), partly by phyllites with quartzitic and carbonatic layers. At the western margin of the Gurktal Nappe an occurrence of clastic upper Carboniferous — partly inverted — is pinched below the early Palaeozoic rocks of the Gurktal Nappe. It consists of conglomerates, sandstones, and shales with several plant-bearing strata. Locally the

sequence is ranging up into Permian with red clays, conglomerates and sandstones (*Werchzirm Beds*). Further small sporadic occurrences of upper Carboniferous rocks are known from the area northeast of Klagenfurt. The internal structure of the Gurktal Nappe shows broad folds. Their axes are mainly of east-west to WNW-ESE orientation.

7. The *Permomesozoic of the Krappfeld and Christofberg* northeast of Klagenfurt represents a major occurrence of North-Alpine facies rocks in the Central Zone of the Austro-Alpine Unit. The succession rests transgressively upon anchimetamorphic Palaeozoic rocks of the Gurktal Nappe and begins with dark-red shales and sandstones with interbedded acid tuffs. They are succeeded by upper Permian, reddish quartz-sandstones with several conglomeratic horizons, Skythian Buntsandstein and Werfen Beds, Anisian rauhwackes, dolomite breccias and dark dolomites, Ladinian Wetterstein Dolomite, platy limestones and dolomites with cherts and tuff interlayers, black Carnian shales alternating with well-bedded calc-marls, and finally Norian Hauptdolomit. After a stratigraphic gap up to 2000 m of upper Cretaceous (upper Santonian to lower Maastrichtian) limestones, sandstones and marls (*Gosau Formation of the Krappfeld*) have been deposited upon both the Triassic as well as the early Palaeozoic basement. The upper Cretaceous beds have been buried by an early Tertiary sequence of sandstones, conglomerates, clays, and limestones with episodic coal seams.

8. The *Eastern Drauzug* forms the *Northern Karawanken mountains* and appears south of the wide depression of the Drau valley. It extends from Feistritz in the west beyond the Austrian border towards east to Yugoslavia. To the south it is bounded by the Periadriatic Lineament. The connection with the Western Drauzug which has already been described above, is interrupted in the area of Villach. There is strong evidence of lithological and structural analogies between the two parts of the Drauzug. The rock assemblage is made up of crystalline rocks and Palaeozoic and Mesozoic strata. The southernmost position is occupied by the *diorite gneiss of Eisenkappel*. This mass contains numerous, small basic inclusions. Radiometric dating of the diorite gneiss (biotite, Rb/Sr) yielded approximately 29 m.y. A narrow zone of diaphthoritic paragneisses neighbouring to the north and interlayered by quartz-veins, amphibolite and orthogneiss shows contactmetamorphic phenomena. Further to the north a zone of coarse to medium grained *granites* follows containing basic early-magmatic differentiation products. It is dissected by various dykes of lamprophyric to aplitic-pegmatitic composition. Some of the dykes intruded into the southward neighbouring crystalline zone. Several radiometric determinations of the granite yielded ages varying between 225 to 245 m.y. (Permian-Triassic boundary). A narrow zone of early *Palaeozoic rocks* succeeding north of the granite underwent contact-metamorphism. A succession of various diabases predominates in this assemblage. Carboniferous strata could not doubtless be proved until now.

The *Permomesozoic* shows pronounced compressional folding and local thrusting and forms a zone up to 6 km wide along the northern margin of the Eastern Drauzug. The basal Permoskythian conglomerates and sandstones are succeeded by highly differenciated facies of the Anisian. Reef-debris and lagoonal facies can be distinguished within the Ladinian-Carnian Wetterstein Limestone Formation. Only partial sections of the Carnian Raibl Beds are preserved. They are considered as an important horizon along which movements

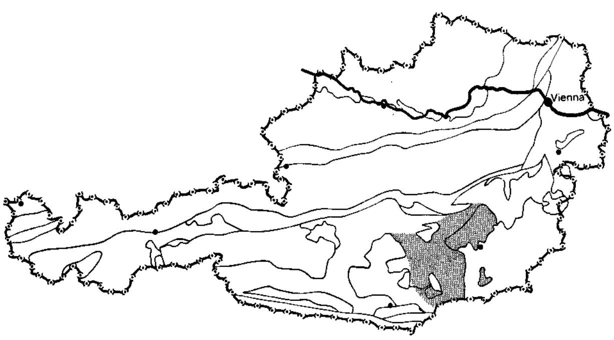
L.Cretac.-Jurassic	Red Aptychus Marls and flaser limestones Red crinoidal limestone
Rhaetian	Bedded, partly oolithic limestones and marls (Kössen Beds; - 100 m)
Norian	Bedded limestone and dolomite (Plattenkalk; - 400 m) Laminated dolomite, partly bituminous (Hauptdolomit; - 700 m)
Karnian	Limestones, dolomites and shales interbedded (Raibl Beds; - 300 m)
	Pb-Zn-mineralisation
Ladinian	Wetterstein Limestone (- 1400 m) Bedded marls and limestones (Partnach Beds; - 100 m)
Anisian	Limestone, partly nodular or cherty, with tuffs Dolomite Bedded limestone (- 400 m)
Skythian	Sandstone and shale interbedded (Werfen Beds)
Permian	Conglomerate, sandstone (Griffen Beds)
Carboniferous	?hiatus
Devonian	Series of limestones and shales, with lydite and breccias Flaser limestone Dark, well-bedded limestone
Silurian	Red and grey limestone, massive or nodular Series of slates and lydites (- 170 m)
? Ordovician	Slates with grauwacken beds Diabase series (tuffs, pillow-lavas, sills; - 350 m) Slates with conglomerates

Tab. 11: Palaeozoic and Mesozoic succession of rocks in the Northern Karawanken, Eastern Drauzug (after A. TOLLMANN, 1977).

occurred. Jurassic and lower Cretaceous strata tectonically underlie the Eastern Drauzug in the north. The upper Tertiary deposits of the Klagenfurt basin to the north were to some extent overthrusted by the Mesozoic rocks of the Eastern Drauzug.

According to the tectonic concept of A. TOLLMANN the Katschbergzone is attributed to the "Lower East-Alpine", the crystalline complex and the Stangalm Permomesozoic to the "Middle East-Alpine", the Gurktal Nappe, the Permomesozoic of Krappfeld and Christofberg and the Eastern Drauzug to the "Upper East-Alpine".

Eastern Carinthia and Central Styria



This region comprises the mountain groups of the Saualpe, the Koralpe, the Seetal Alps, the Packalpe, the Stubalpe, the Gleinalpe, the western Fischbach Alps and the mountains west and north of Graz. It is mainly made up of an extensive crystalline basement and the Graz Palaeozoic. The western boundary is marked by the already mentioned north-south trending Görtschitz Valley-Fault, the northern boundary by the Mur-Mürz valley. To the east both the crystalline basement and the Palaeozoic rocks are buried by late Tertiary sediments of the Styrian Basin.

In this region the Austro-Alpine crystalline complex shows a broad lithological variety and a complex structure. It can be divided into following units from north to south: the Mugel-Rennfeld crystalline basement, the Stubalpe-Gleinalpe crystalline basement, and the Saualpe-Koralpe crystalline basement.

1. The *Mugel-Rennfeld crystalline complex* is considered to be the eastern continuation of the Seckau Tauern crystalline complex. However, compared to this previously described area granitoid gneisses are less frequent. Mesozonal metamorphic paragneisses and amphibolites are prevailing. Parts of the assemblage underwent Alpine post-crystalline deformation and diaphthoresis. The structures are adjusted to the regional WSW-ENE strike.

2. The *Stubalpe-Gleinalpe crystalline complex* follows to the south. The boundary is marked by the Trasattel-Eyweg Fault. This complex shows a broad anticlinal structure trending southwest-northeast. The *gneiss-complex* in the core of the anticline is made up by banded plagioclase gneisses interbedded by augen- and granite gneisses. The banded plagioclase gneisses are believed to be derived from volcanic rocks (W. FRANK & al, 1976) which according to radiometric measurements were formed at the Cambrian-Ordovician boundary (520 m.y.). Locally, especially in the west, the mesozonal metamorphic assemblage underwent retrograde metamorphism. The basal gneiss complex is covered by a persistent horizon of *augen-gneiss* which achieves a maximum thickness of 500 m. It is overlain by an *amphibolite complex* comprising various amphibolites, ultrabasic rocks, and sporadic layers of marble and garnet-muscovite-schists. A large body of chromite-bearing serpentinite occurring at *Kraubath* is also attributed to this complex. The boundary to the overlying mica-schist-complex locally appears to be of tectonic character. The *mica-schists-complex* itself is preserved only at the southeastern flank and consists of kyanite and garnet-bearing mica-schists, and two-mica-gneisses interlayered by marble, quartzites and pegmatites. Tectonic position and lithology of the complex correspond to the mica-schists of the Wölz Tauern mountains. The sequence is closed on top by a series of marbles and pegmatites associated with kyanite-bearing-gneisses, staurolite-mica-schists, quartzites and amphibolites.

The *Anger Crystalline* which forms the eastern frame of the Graz Palaeozoic lithologically resembles the higher section of the Stubalpe-Gleinalpe crystalline complex with abundant mica-schists and marbles.

3. The *Saualpe-Koralpe crystalline complex* overlies the former in the south with unconform contact. Several thousand meters of kata- to anchizonal metamorphic rocks are interpreted to form a pile of thrust-sheets caused by synmetamorphic Variscan movements. The underlying complex is exposed in certain windows.

The deepest part consists of micaceous paragneisses and kyanite-flaser-gneisses with significant inclusions of eclogites and eclogite-amphibolites in higher and middle levels, and marbles in the lower level of the sequence. In the area of the Koralpe eclogite-gabbros and *Plattengneise* are further significant members of this deepest division.

The overlying succession begins with mesozonal metamorphic rocks which upwards pass into anchizonal metamorphic early Palaeozoic rocks of the Gurktal Nappe. Obvious lithological repetitions in vertical direction are therefore considered to be the result of synmetamorphic Variscan movements which concerned an early Palaeozoic sedimentary complex. Garnet-staurolite-mica-schists, marbles, quartzites, amphibolites and occasional ultrabasites form the deeper parts. Upwards their low-grade metamorphic equivalents appear. From the upper part of the mica-schist group a movement plane marked by a retrograde chloritoid-zone is recorded.

The important question, whether the crystalline complex of the Saualpe and the Palaeozoic rocks of the Gurktal Nappe are connected by pre-Alpine metamorphism or not is a subject of controversy. According to A. Tollmann the epi- to anchimetamorphic early-Palaeozoic series west and south of the Saualpe are separated from the underlying crystalline complex by an Alpine thrust plane marked by a metamorphic hiatus. These series form the "Upper East-Alpine" Gurktal Nappe. E. Clar, however, supports the idea that the crystalline complex of the Saualpe is connected with the early Palaeozoic series to the west and to the south by pre-Alpine, presumably Variscan, orogenic events.

The prevailing direction of fold axes is trending WNW-ESE. The Plattengneis complex in the Koralpe shows NNE-SSW trending lineations. They are interpreted either as b-axes caused by compression in an east-west direction (P. Beck-Managetta) or as a-striae genetically associated to the regional b-axes trending WNW-ESE (L. P. Becker).

Two prominent NNW-SSE trending fault systems are the result of late Tertiary movements which also caused the horst-like uplift of the Saualpe and the Koralpe. One is the *Görtschitz-Valley-Fault* at the western foot of the Saualpe where vertical displacements of several thousand meters are recorded by stepfaults. The other one is the *fault-system* of the *Lavant Valley* along which narrow fault-bounded occurrences of Neogene sediments have been subsided. It also separated the Saualpe from the Koralpe.

An isolated occurrence of the crystalline basement around *Radegund* northeast of Graz appears to be part of the Saualpe-Koralpe crystalline complex. It is overlain by Graz Palaeozoic rocks to the northwest and Neogene sediments to the southeast. The deeper parts are formed by thick-platy, kyanite, staurolite, and garnet-bearing paragneisses and pegmatites, the higher parts by mica-schists with amphibolites, calc-silicate-marbles, and quartzites. Eclogites are lacking. The zone close to the overlying Graz Palaeozoic complex is strongly deformed and shows mylonitisation.

4. The *Raasberg Sequence* consisting of limestones, dolomites, rauhwackes, serizite-phyllites, quartzites and dark slates very probably represents a Triassic assemblage. It crops out at the western, southern, and eastern margin of the Graz Palaeozoic tectonically intercalated between the crystalline basement and the Palaeozoic.

5. The *Graz Palaeozoic complex* occupies the area northeast of Graz. It extends about 50 km in northeast-southwest direction and is approximately 25 km wide. It rests tectonically upon the crystalline basement. Close to this thrust plane the crystalline basement shows retrograde metamorphism whereas the overlying

		Rannach Facies	Hochlantsch Facies	Slate Facies
Carbonif.		Shales and limestones (Dult Fm.)		
Devonian	Upper	Various limestones (- 500 m)		
Devonian	Middle		Massive, pale limestone (Hochlantsch Limestone; - 300 m) Platy limestone and dolomite Diabase	Platy limestone (Schöckel Limestone) Platy limestone, dark slate and quartzite
Devonian	Lower	Dolomite-sandstone-sequence (- 1000 m) Bedded limestones, calc-shales (- 100 m)	Thin-bedded limestone sequence (- 350 m)	Phyllites; marble, quartzite, greenschist, meta-diabas
Silurian		Sandy/calcareous shales (Upper Kher Fm.)	Slates and phyllites with sporadic limestones and quartzites	
? Ordovician		Shales, greenschists and meta-diabases (Lower Kher Fm.)		

Tab. 12: Facies subdivision and stratigraphy of the Graz Palaeozoic (after H. W. Flügel, 1975).

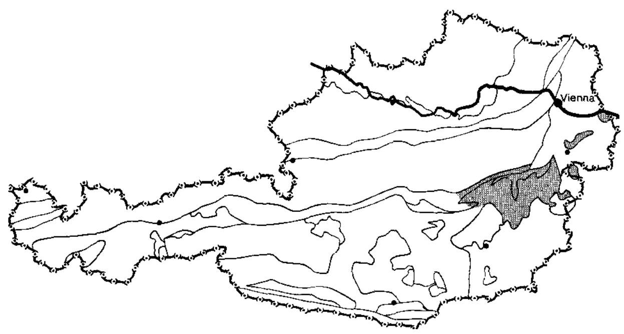
Palaeozoic complex underwent low-grade metamorphism. The whole assemblage can be divided into three different facies-domains: the *Rannach Facies,* the *Hochlantsch Facies,* and the *Slate Facies* (tab. 12). The stratigraphic succession generally comprises early Palaeozoic strata, in the Rannach Facies, however, it ranges up into Carboniferous. Three superincumbent nappes can be distinguished, the *Hochlantsch Nappe* at the bottom, followed by the *Schöckel Nappe,* and the *Rannach Nappe.* The internal structures indicate northwards thrusting. It is a matter of controversy whether these movements are of Alpine or Variscan age. In the southeast the Graz Palaeozoic complex is buried beneath the Neogene sediments of the Styrian Basin and only in some places appears at the surface. According to A. TOLLMANN the Graz Palaeozoic belongs to the "Upper East-Alpine" and occupies the same tectonic position as the Gurktal-Nappe and the Grauwackenzone.

6. Unmetamorphic *Permomesozoic* rocks occur southeast of the Saualpe between *Griffen* and *St. Paul.* They fairly correspond with the Permomesozoic of the Krappfeld. Continental-detrital Permian rests unconformably upon folded and very low-grade metamorphic early Palaeozoic rocks. The folded and eroded Triassic sequence is buried by Upper Cretaceous Gosau Formation, mainly marls (upper Coniacian to Campanian).

7. The *Gosau of Kainach* rests transgressively upon folded rocks of the Graz Palaeozoic complex and thus dates the pre-Gosau age of the internal structure of the Graz Palaeozoic complex. The upper Santonian basal conglomerate often reddish in colour achieves a thickness of up to 300 m. It mainly contains coarse pebbles the majority of which is derived from the Palaeozoic underground, few are from Mesozoic rocks. Crystalline components are lacking (!). The basal conglomerate is succeeded by approximately up to 100 m of upper Santonian to lower Campanian, dark bituminous marls with some small coal seams. An upper Campanian sandy-clayey sequence of flysch-like character and a thickness of up to 1200 m is overlying. It is almost calc-free and locally contains abundant pebbles. The succession is topped by up to 250 m of well-bedded marls and calc-arenites which range up into Maastrichtian. The internal folds show north-south trending axes. According to R. OBERHAUSER the Gosau of Kainach apparently indicates terrestrial influence. He underlines its close facial relations to easterly and southerly occurrences whereas the relations to the Gosau deposits within the Northern Calcareous Alps are less pronounced.

The Northeastern Part of the Central Zone of the Eastern Alps

The major part of this region is formed by the crystalline complex of the Semmering-Wechsel area and its associated Permomesozoic cover. This complex can be subdivided into several superincumbent sheets and shows the regional structure of a broad cupola. To the west it is overlain by the crystalline basement frame of the Graz Palaeozoic. Some schuppen of Permomesozoic rocks are arranged along this tectonic interface. The narrow belt of the easternmost part of the Grauwackenzone to the north is separated from the crystalline complex by an important northward dipping thrust-plane. The stratigraphic connection between the



Palaeozoic rocks of the Grauwackenzone and the Mesozoic development of the Northern Calcareous Alps is also evident in this region. In the northeast, east and south the basement is buried by Neogene sediments. The Leithagebirge and the Hainburg Mountains appear as isolated major basement exposures in the northeast thus representing the connection to the Carpathians just north of the Danube.

1. The *Wechsel Series* occupies the deepest tectonic position of the crystalline basement in this area and appears in the *Wechsel Window,* the center of a broad domal structure, and in several further small tectonic windows. The bottom part is formed by a series of gneisses (*Wechsel Gneisses*) mainly appearing as chlorite-bearing albite-gneisses interlayered by phyllites and greenschists. This assemblage is considered to be the Alpine retrograde metamorphic equivalent of a pre-Alpine mesozonal metamorphic assemblage of mica-schists, amphibolites, and granite-gneisses preserved in the southern part of the Wechsel Window. The basal series of gneisses is passing upwards into quartz-phyllites (*Lower Wechsel Schists*) with significant graphite-phyllites and graphite-quartzites. The succession is closed on top by phyllites (*Upper Wechsel Schists*) interbedded by thin layers of clastic feldspars and basic tuffaceous material.

2. The *Grobgneis Series* forms an extensive recumbent nappe-fold upon the underlying Wechsel Series. Monotonous phyllitic mica-schists predominate in the northern part, mica-schists with local abundance of quartz or pseudomorphs after staurolite as well as amphibolites in the southern part. Coarse-grained granite-gneisses appear as extensive bodies within the paraseries. Frequently an unfoliated texture is still preserved in the core of the orthogneiss bodies. Radiometric dating

(whole rock, Rb/Sr) established 340 m.y. for the age of their formation. Biotite-hornblende-metagabbro with irregular portions of *corundum-spinel-rocks* were recorded from the contact between the orthogneisses and their country-rock.

The Grobgneis Series is further exposed in the crystalline basement of the Leithagebirge. The crystalline basement of the Hainburg Mountains, however, by A. TOLLMANN is considered to be the southern end of a deeper tectonic unit, namely the Upper Tatricum, a Carpathian tectonic unit.

3. The *Floning-Troiseck crystalline complex* overlies the Grobgneis Series to the north. It consists of paragneisses and mica-schists frequently interbedded by amphibolites and pegmatites. Orthogneisses are rare. Widespread diaphthoresis as well as mylonitisation at the northern margin are being attributed to Alpine events. A certain lithological similarity can be recognized with the Stubalpe-Gleinalpe crystalline complex.

An assemblage of biotite-gneisses, platy microcline gneisses — resembling the Plattengneise of the Koralpe —, eclogite-amphibolites, eclogites, ultrabasites, amphibolites, kyanite-gneisses, marbles and calc-silicate-gneisses crops out in the east at *Sieggraben* overlying the surrounding Grobgneis Series. It is considered to be an outlier of the lithologically corresponding Saualpe-Koralpe crystalline complex. Further but smaller outliers of this type are known from this area.

4. A sequence of Permomesozoic rocks in Central-Alpine facies wraps round each major basement subunit like

Triassic	Upper	Slates with limestone and dolomite layers interbedded
		Variegated slates with quartzite, dolomite rauhwacke, anhydrock and gyprock (Variegated Keuper)
		Black slates with sandstones interbedded (Kapellen Beds)
	Middle	Pale, hardly bedded dolomite (Wetterstein D.)
		Thin-bedded black dolomite
		Banded limestone with cherts
		Variegated, streaky limestones and dolomites
		Series of slates interbedded with limestones, dolomites and breccias
		Rauhwacke
	Lower	Slate (Alpine Röt Beds)
		Quartzite with quartz conglomerates interbedded
	Permian	Phengite-phyllites, sericite-phyllites, arkosic phyllites, breccias, porphyroids (Alpine Verrucano)
	Base	Crystalline basement

Tab. 13: Permomesozoic succession of the Mürztal, Semmering and Wechsel area (after A. TOLLMANN).

the Wechsel Series, the Grobgneis Series, as well as the Floning-Troiseck crystalline complex and separates them from each other. The *Permomesozoic sequence* achieves maximum thickness and remarkable lithological variety in the area of the *Semmering*. The strongly deformed assemblage underwent low-grade metamorphism. The stratigraphic succession (tab. 13) begins at the base with continental-detritic Permian interlayered by *porphyroids*, which attain considerable thickness at the *Roßkogel*, west of the Semmering. Well-bedded, greenish-white lower Triassic quartzites or arkoses are succeeded by middle Triassic carbonate rocks. The upper Triassic division with prevailing shales apparently shows the influence of Germanotype facies (Keuper).

5. The Palaeozoic rocks of the *Grauwackenzone* overlie the crystalline complex and its Permomesozoic cover to the north. The boundary appears to be an important thrust-plane with high-angle northwards dip, locally overturned. To the east the Grauwackenzone disappears at the southern end of the Vienna Basin below Neogene sediments.

The tectonic subdivision of the Styrian Grauwackenzone into two nappes — already described from the Eisenerz Alps — can also be observed in this region. The deeper nappe (the Veitsch Nappe) made up of Carboniferous rocks accomodates an important *magnesite deposit* at *Veitsch*, which here appears to replace Carboniferous limestones. Apart from other early Palaeozoic members, mainly phyllites, the prevailing rock-type of the higher unit (the Noric Nappe) is the Ordovician *Blasseneck Porphyroid*. In the easternmost part of the Noric Nappe an occurrence of crystalline rocks crops out. Further occurrences of crystalline rocks appear as tectonic schuppen along the *Noric Line*. They are regarded to be remains of the crystalline basement of the Grauwackenzone. The Permomesozoic succession of the Northern Calcareous Alps overlies the strata of the Grauwackenzone with unconform transgressive contact.

The *Trofajach Line* is an east-west trending fault with a substantial vertical displacement. The subsidence of the southern part gave rise to the sinuous course of the subsurface of the Grauwackenzone in this area. The straight ENE-WSW trending course of the Mürz valley appears to be related to another set of faults, locally bounding subsided intramontane Tertiary basins.

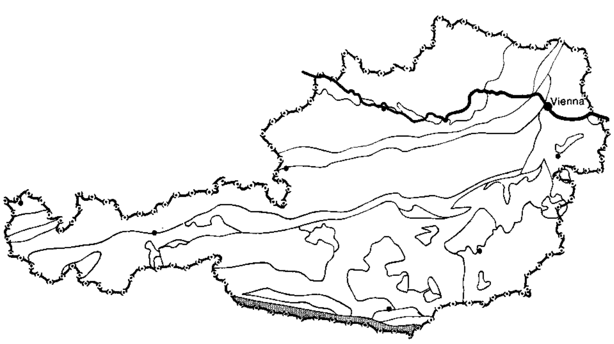
The principal structural features in this area support the assumption of relative northward transport of each tectonic unit during Alpine movements. However, the steeply inclined — partly vertical or even overturned — attitude of bedding planes or schistosity along the northern margin of the crystalline complex might have been caused by late Alpine compressional movements connected with considerable southward thrusting. Moreover, evidence of southward thrusting is recorded from the southern basis of the Northern Calcareous Alps in this region. In contrast, A. TOLLMANN explains the structural phenomena to be almost exclusively created by northward Alpine movements. According to him the Wechsel Series and the Grobgneis Series together with their Permomesozoic cover belong to the "Lower East-Alpine", the Floning-Troiseck crystalline complex and its own Permomesozoic cover, the Sieggraben outlier and equivalents are attributed to the "Middle East-Alpine", the Grauwackenzone to the "Upper East-Alpine".

The Periadriatic Lineament

This lineament makes a strong topographic feature and can be traced near the southern border of Austria along the Lesach and Gail valley as well as along the furrow which divides the Northern from the Southern Karawanken. In Austria it is marked by an east-west trending vertical mylonite zone of considerable width containing several thin lamellae of tonalitic and quartz-dioritic gneisses and — in the western part — of Drauzug Permotriassics. The orthogneisses are allocated to the suite of *Periadriatic Intrusions* which occur more or less close to the Periadriatic line. The majority of these intrusions is considered to be of Tertiary age. However, as previously mentioned, Permian-Triassic ages were recorded from the granite of Eisenkappel on the ground of radiometric measurements.

The Periadriatic Lineament is believed to have played an important role in the structural evolution of the southern part of the Alps. It separates regions of different depositional and tectonic history during the Palaeozoic and Mesozoic. Whether this fault became active in pre-Mesozoic times already, with Alpine reactivation, or only since Cretaceous times, is not yet certain. On account of facial differences of the Permomesozoic developments on both sides of the Periadriatic Lineament as well as structural observations and paleomagnetic surveys, considerable dextral but also vertical displacements are supposed to have occurred during late Alpine times.

The Southern Alps



Only very small parts of Austria are occupied by the Southern Alps, which are separated from the Eastern Alps by the Periadriatic Lineament. Two mountain ranges, both forming the border to Italy respectively to Yugoslavia exhibit rocks of the Southern Alps: The *Carnic Alps* and the southern part of the Karawanken (*Southern Karawanken*).

In Austria the Southern Alps comprise mainly Palaeozoic, less Mesozoic rocks, which are not or slightly metamorphosed. The crystalline basement is not exposed. Two sedimentary cycles, divided by the Variscan tectonic phase, are to be distinguished: The older Lower Palaeozoic or Variscan sedimentary cycle begins during the Ordovician and is terminated by the flyshoid Hochwipfel formation of the Upper Carboniferous. During the Variscan orogeny the beds became intensively folded and thrust-faulted, and in some parts metamorphosed. After a phase of erosion the second sedimentary cycle begins with the Auernig formation of the uppermost Upper Carboniferous and is continuous into the Mesozoic. Alpine tectonics occur only very slightly in the shape of fault tectonics; Alpine metamorphism is lacking completely.

The section begins during the Ordovician with slates, sandstones and quartzites of several hundred metres thickness, followed by a thin (approximately 5 to 15 metres thick) layer of limestone in the Early Ordovician (Wolayer Limestone, Uggwa Limestone). So far the oldest fossils have been found in beds of the lower Caradocian.

During the Silurian mainly two facies have been deposited. The richly subdivided limestone facies is in total up to 70 metres thick, the more uniform graptolite-bearing slates and siliceous slates are approximately 30 metres thick. In the Devonian exists a diversity of facies, which is represented by various limestones of lagoonal, reef, reef-slope and basin environment (*Rauchkofel Facies*) as well as slates, siliceous slates and lydites, which are continuous from the Siluran (*Bischofalm group;* H. P. SCHÖNLAUB, 1979). According to the various facies the thickness differs extremly: the massive reef limestone is more than thousand metres thick, while limestones of intra-basin ridges of the same age have a total thickness of less than hundred metres. Apart from small modifications (as for instance a decline of the reef growth) all facies are continuous during the Lower Carboniferous. But gradually the transformation of the discussed sedimentation area into a flysch trough took place and probably the deposition of the *Hochwipfel Flysch* began at the border Lower/Upper Carboniferous in the "Carnic Geosyncline" (H. P. Schönlaub 1979). It reaches a thickness of about 600 metres; the sedimentation is terminated by the main phase of the Variscan orogeny in the uppermost Upper Carboniferous.

The folded and thrust-sliced Variscan basement is transgressively overlain by the post-Variscan beds, which begin with the up to 700 metres thick *Auernig Formation* of the Stefanian. According to a repeated change of marine and freshwater influence, different members regarding their content of carbonate are distinguished.

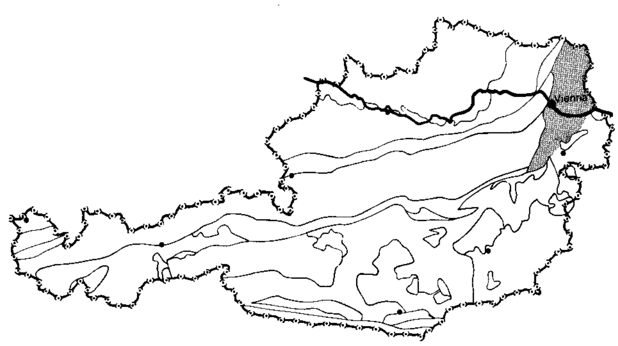
The Permian exhibits both calcareous and clastic facies. In the Lower Permian the limy Lower and Upper *Pseudoschwagerina Formations* are intercalated by the clastic *Grenzlandbänke*. By some authors the Lower and Upper Pseudoschwagerina Fm. and the Grenzlandbänke are included into the *Rattendorf Group*. The *Trogkofel Limestone* is an up to 400 metres thick reef-limestone and it is a particular part of the *Trogkofel Formation*, where marine clastic sediments are prevailing.

In the Middle Permian the sedimentation was interrupted by movements of the Saalian tectonic phase. The intensively red-coloured *Gröden Formation* of the Lower Zechstein lies unconformably upon both Lower Permian beds and older Variscan phyllites. The Upper Permian is represented by the *Bellerophon Formation*, a few hundred metres thick calcareous to dolomitic section which exhibits more or less marine influence.

The *Werfen Formation* of the Skythian is a continuing development from the Bellerophon Formation. Beds in the *facies of Sesio* and *Campil* as well as bedded dolomites occur at various places. The section is continued by Anisian limestone and dolomites (*Muschelkalk*), partly with tuffitic intercalations, and the several hundred metres thick *Schlern Dolomite* (reef-environment), laterally interfingering with bedded *Wengen Beds* of the Ladinian. In the Carnic Alps younger beds are not preserved. In the Southern Karawanken the succession is continued by the Carnian *Raibl Beds* (dolomites and limestones with three intercalations of shales) or the Carnian *Cardita Beds* (limestones, marls and sandstones). The Norian and the Rhaetian are represented by *Dachstein Limestone* and *Dachstein Dolomite*, which are together up to 1700 metres thick. On Austrian territory locally beds of the Lias and the Malm are occurring. In this part of the Southern Alps the Alpine tectonic movements are somewhat more intensive than in the Carnic Alps.

The Neogene Basins

The Vienna Basin



The Vienna basin is a typical fault-bounded "Graben", which is situated in the transition area between the Alps and the Carpathians. Formerly it was called "Inneralpine" Vienna basin in order to define the difference between the "Outeralpine" Vienna basin, as formerly the northeast striking part of the Molasse Zone in Lower Austria was called. But during past years both names became uncommon, and nowadays the latter one is called Molasse Zone, the other one Vienna basin.

The Vienna basin generally extends into that region, where the Alpine west-east direction of the striking is grading into the southwest-northeast direction of the Carpathians, considering, however, that the beginning of this change in striking can be observed west of the Vienna basin (see chapter: The Northern Calcareous Alps). In the underground of the Vienna basin the different Alpine geological units continue into the Carpathians.

It has the shape of an oblong rhomb with a north-northeast—south-southwest striking longitudinal axis of approximately 200 kilometres, and a maximum width of 60 kilometres; a considerable part in the north extends into Czechoslovakia.

The Vienna basin is all around bounded by a system of faults, which are sometimes morphologically recognizable by steep slopes. The most important faults are the *Schrattenberg Fault System* in the northwest, seperating the Waschberg Zone from the Neogene filling of the basin, and the so-called "*Thermenlinie*" south of Vienna, which seperates the Northern Calcareous Alps from the basin. Nowadays the Thermenlinie is proved to be a system of more or less parallel striking faults, which enabled moderate warm thermal waters to ascend (Spa of Baden, Bad Vöslau a. s. o.). Some fault

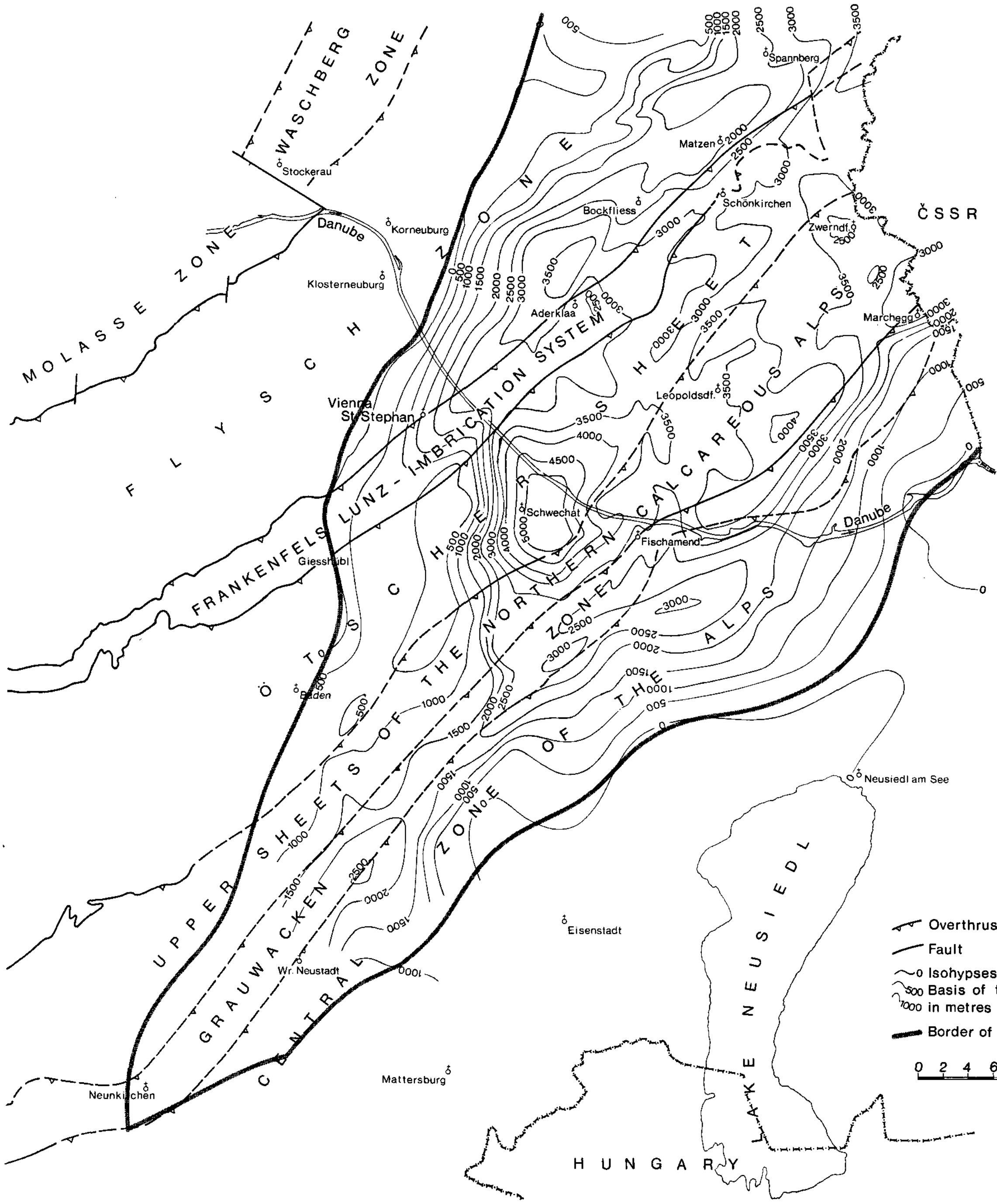


Fig. 19: Subsurface map of the Vienna basin (southern and central part) and adjacent areas (after A. Kröll & G. Wessely, 1973; modified and simplified).

systems within the Vienna basin subdivide the region into some blocks. Most of the geological information was obtained by the exploration on hydrocarbons.

Comprehensive studies on stratigraphy, facies, tectonics and hydrocarbons of the Vienna basin have been published by R. Grill *) & W. Janoschek (in press), R. Janoschek (1951, 1964), A. Kröll *) (in press), A. Kröll & G. Wessely (1973) and E. Thenius (1974).

*) The authors like to express their gratitude to Dr. R. Grill und Dr. A. Kröll for the permission to use not yet published manuscripts.

The Basement

As the pre-Neogene basement of the Vienna basin consists of Alpine structural elements, which are continuous into the Carpathians, it exhibits the same tectonic problems as the Alpine mountain range on the surface.

The basin floor shows a very strong relief, (1) caused by intra-basin faults, but (2) also by the fact, that for a long time (at least for a considerable part of the Palaeogene) this surface has been exposed to subaerial erosion.

Four Alpine tectonic units are forming the basement of the Vienna basin:

The Flysch Zone. The basement of the northwestern part of the basin is built up by the Flysch Zone, well known by oil drilling, especially in the region of

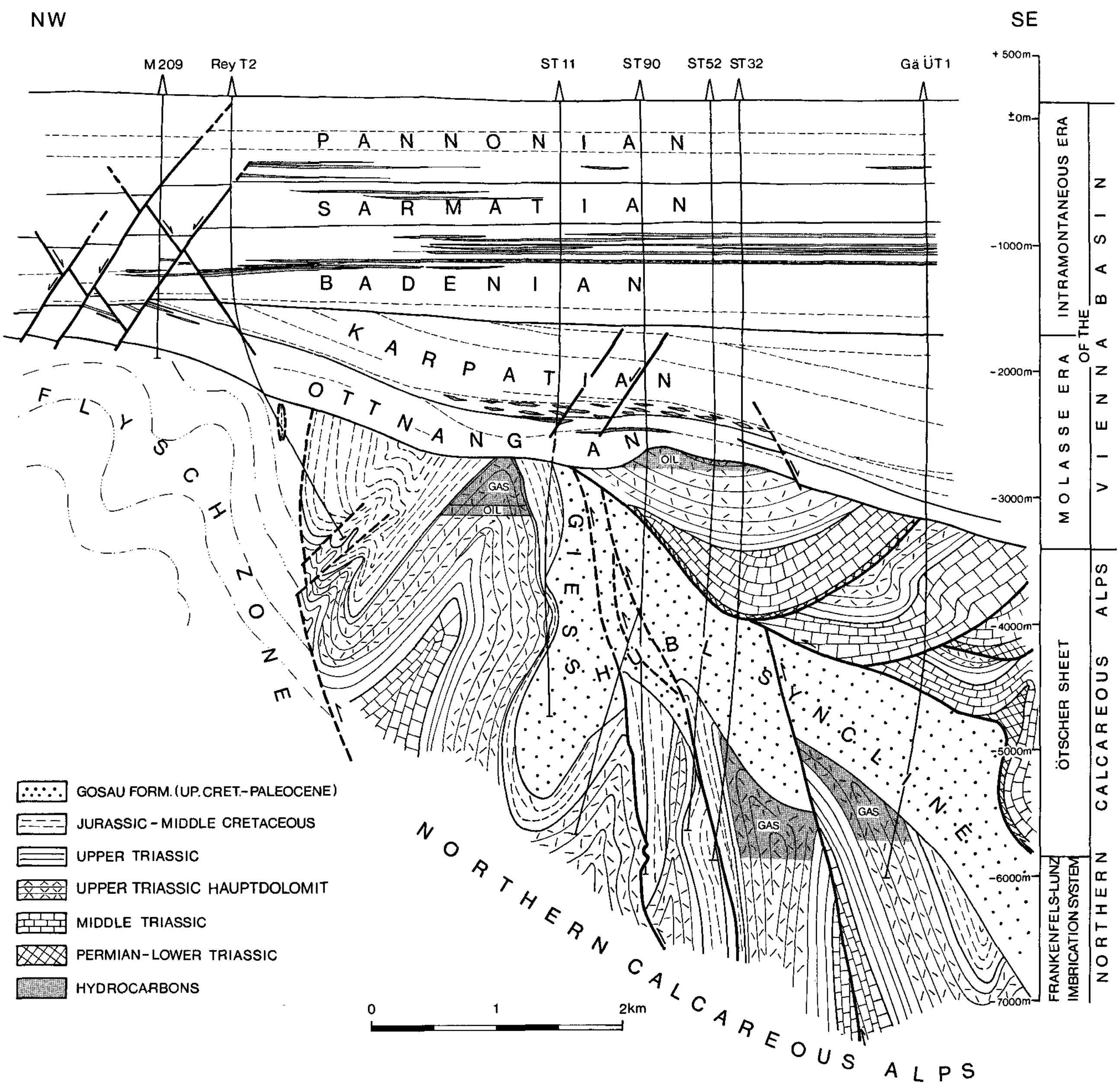


Fig. 19: Cross-section through the Vienna basin in the area of the oil- and gas-field of Matzen, Schönkirchen, and Reyersdorf (after A. Kröll, W. Krobot & G. Wessely in R. Grill & W. Janoschek, 1980; modified and simplified).

Matzen—Spannberg and along the *Steinberg Fault.* Rocks of the Upper Cretaceous are the most frequent ones, Lower Cretaceous and Paleocene strata occur locally.

Like on the surface, the Flysch Zone is composed by a pile of several thrust sheets or thrust slices of considerable total thickness: The well Linenberg 2 drilled to a depth of 4710 metres without leaving the Flysch Zone.

The Northern Calcareous Alps. Rocks of the Northern Calcareous Alps are forming the basement of a considerable part of the Vienna basin, trending obliquely to the basin axis in northeastern direction in an approximately 20 kilometres wide belt. In the Vienna basin the thrust plane between the Flysch Zone and the Northern Calcareous Alps is steeply overturned southwards, which was caused by later tectonic movements.

The lithological and structural arrangement at the basin floor and its correlation with the tectonic units at the surface has been comprehensively studied by A. Kröll & G. Wessely (1973) and G. Wessely (1975).

As according to these authors it is not possible to subdivide the Bajuvarikum into a Lower and an Upper unit, it is included into the *Frankenfels-Lunz imbrication system,* enclosing the *Gießhübl Syncline,* which is an overturned syncline of the Gosau Formation and comprises a section from the Upper Cretaceous up to and including the Palaeocene. Generally the overturned upper limb is cut by the overthrust of the Ötscher sheet.

In contrary to the narrow folded Frankenfels-Lunz imbrication system, the *Ötscher sheet* represents — as at the surface — a broad and weakly folded block of Hauptdolomit, but the complete stratigraphic section has been proved by wells (Skythian Werfen Beds up to the Norian—Rhaetian Dachstein Limestone; Jurassic beds and the Gosau Formation were drilled only in the south).

The southeastern part of the Northern Calcareous Alps in the Vienna basin is occupied by the "Higher Calc-Alpine Sheets" (*Juvavikum*), which have overridden the Ötscher sheet. Until now this unit is of minor economic interest concerning the oil and gas deposits and therefore only little information is available on the geology and the structure of this unit. The main beds are the Wetterstein Limestone and Dolomite and the Dachstein Limestone, well comparable with the Schneeberg area. Rocks which are developed in Hallstatt facies have not been drilled so far.

The subsided Northern Calcareous Alps in the Vienna basin include very important *oil* and *gas deposits,* as mentioned above mainly in the Bajuvarikum and the Tirolikum units. In any case the Hauptdolomit is the main storage rock. Generally two types of deposits can be distinguished: (1) buried hills of the Hauptdolomit, covered by the Neogene basin filling (e. g. the Schönkirchen Deep field) or (2) internal structures in the Frankenfels-Lunz imbrication system, sometimes overridden by the Ötscher sheet (e. g. the Schönkirchen—Gänserndorf Super-Deep structure). Here the produceable gas content was proved down to a depth of nearly 6000 metres (fig. 20).

The Grauwackenzone. The Grauwackenzone was drilled by a few wells, which met two types of rocks, dark slates and quartz-rich greywacke, which can be compared with the Carboniferous of the Veitsch nappe north of the Semmering region as well as calc-schists, probably comparable to the Palaeozoic of Graz (G. Wessely 1975).

The Central Zone. The southeastern-most area of the Vienna basin is occupied by rocks of the Central Zone of the Alps. Especially rocks of the Lower Austro Alpine *Semmering unit* are proved by a few wells. Middle Triassic limestones and dolomits, the characteristic Keuper series and probably Liassic are known. It must be considered, that the same crystalline rocks, which are outcropping in the Leithagebirge range, are also forming small parts of the basement in this region.

A few not yet verified considerations about deeper structural elements should be added to this chapter: Under the Flysch Zone the Molasse Zone is supposed to be situated, exhibiting a probably thin section of Palaeogene to Neogene beds and possibly subdivided into two units, which are the Disturbed and the Foreland Molasse. If lacking, autochthonous Mesozoic and Palaeozoic rocks of a considerable thickness, as having been drilled in the Molasse Zone, are supposed to form the basement of the Flysch Zone. The crystalline basement finally consists of rocks of the Bohemian Massif. As the Northern Calcareous Alps have overridden the Flysch Zone, no principal change of the underlying tectonic units should be considered, but it is not well imaginable, that the Tertiary Molasse beds in the south are reaching as far as the present position of the Northern Calcareous Alps.

As proven in the Foreland regions in Austria and Czechoslovakia, the Molasse beds as well as the autochthonous Mesozoic and Palaeozoic rocks are of considerable interest for exploration of hydrocarbons. In the Vienna basin therefore some exploration prospects exist on these units, what means drilling into depths of as much as 8000 metres and more. The surface of the autochthonous units is considered to be in a depth of about 10000 metres.

The Neogene Basin Filling

The filling of the basin consists of Neogene beds. According to the structural history of the basin two sedimentary cycles have to be distinguished (R. Janoschek, 1951). The main subsidence of the Vienna basin started during the Lower Badenian (Middle Miocene;

see tab. 2). All Neogene beds older than that are attributed to the older cycle (Eggenburgian to Karpatian, Early Miocene), thus representing the *Molasse era,* while all beds including the Lower Badenian and younger ones belong to the younger cycle, thus representing the *intramontaneous basin era* of the true Vienna basin.

In the northern part of the Vienna basin the sedimentation started transgressively with marine variegated shales or coarse-grained basal beds *(Schlierbasisschutt)* of the *Eggenburgian.* Whereas in Czechoslovakia beds of the Eggenburgian are outcropping at the surface, in the Austrian part the Eggenburgian has only been proved by wells.

A next transgression during the Upper Eggenburgian lead to the deposition of the *Schlier* (shales with thin sand intercalations), which continued into the Ottnangian. In regions, where the transgression spread out onto the older basement (esp. upon the Flysch Zone), "Schlierbasisschutt" was deposited. During that time the Vienna basin did not exist and it is supposed that there must have been marine connections towards the west (Waschberg Zone, Molasse Zone) and the east (basin of Trnava east of the Small Carpathians). The transgressive marine Karpatian is represented by up to 1000 metres thick beds of the *Laa Formation.* This sequence, however, was only deposited in the northern part of the Vienna basin, exhibiting the "Molasse-like" development. In the southern part limnic and lacustrine sediments are prevailing, e. g. the *Gänserndorf Beds* or the *Aderklaa Beds,* resp. older beds are lacking at all. Both parts have been divided at that time by the *Spannberg ridge,* which was an important

PLIO-CENE		DACIAN			VARIEGATED LOAM SERIES			INTRAMONTANEOUS BASIN ERA (VIENNA BASIN)
MIOCENE	LATE	PONTIAN	H		YELLOW SERIES	ROHRBACH CONGL. FRESHWATER LIMESTONE	CLAY, SAND AND GRAVEL	
			G		BLUE SERIES			
			F			LIGNITES		
		PANNONIAN	E D		CONGERIA BEDS	INZERSDORF TEGEL		
			C B A	FIRST OCCURENCE OF HIPPARION		MISTELBACH TALUS CONE		
						SANDS AND SHALES		
				"VERARMUNGSZONE"				
		SARMATIAN		NONIUM GRANOSUM ZONE	MACTRA BEDS (CERITHIA BEDS)	ATZGERSDORF SANDSTONE	SAND AND SHALE	
	MIDDLE			ELPHIDIUM HAUERINUM ZONE	ERVILIA BEDS (CERITHIA BEDS)			
				ELPHIDIUM REGINUM ZONE	RISSOA BEDS (CERITHIA BEDS)	HERNALS TEGEL		
		BADENIAN		ROTALIA ZONE				
				BULIMINA-BOLIVINA ZONE	LEITHA LIMESTONE			
				SPIROPLECTAMMINA ZONE				
				UPPER / LOWER LAGENIDA ZONE		BADEN TEGEL		
	EARLY	KARPATIAN		ZONE WITH GLOBIGERINOIDES BISPHERICUS	ADERKLAA CONGL. / ADERKLAA SCHLIER (ADERKLAA BEDS)	LAA FORMATION	SCHLIER	MOLASSE ERA
		OTTNANGIAN			FISHBEARING SHALES	ONCOPHORA FORMATION		
				CIBICIDES-ELPHIDIUM SCHLIER				
				CYCLAMMINA-BATHYSIPHON SCHLIER				
		EGGENBURGIAN			"SCHLIERBASISSCHUTT" MARINE VARIEGATED SHALES			

Tab. 14. Stratigraphic diagram of the Vienna basin (after R. Janoschek, 1964, E. Thenius, 1974, and A. Papp & F. Steininger, 1979).

structural element. During the Karpatian tectonic movements increased and locally caused gaps in the sedimentation as well as erosion (see fig. 20).

At the beginning of the Badenian the actual Vienna basin was created by the beginning of the subsidence along the rhombically arranged fault systems. Some areas, which have not been inundated before, became part of the Vienna basin and therefore the Badenian is resting unconformably not only upon the older Neogene beds, but also upon the Alpine-Carpathian basement. Also onlaps on adjacent areas are common (e. g. bay of Gainfarn, basin of Gaaden in the Northern Calcareous Alps south of Vienna, bay of Niederleis in the Waschberg Zone north of Vienna).

Apart from beds of varying facies at the transgression plane, the Badenian is mainly developed in two facies: The *Leitha Limestone* is a paralic facies, which is mainly composed of lithothamnions, corals and bryozoas. It is developed in large areas in the southeast, the Leitha mountain range, but it is common in many other parts of the Vienna basin too. The Leithagebirge range as well as the Spannberg ridge were islands. The latter, however, has lost its importance in being a facies divide and became inundated during the Badenian (*Spiroplectammina Zone*). The *Wiener Neustadt-Ödenburg Pforte* is the name of a wide marine connection which existed south of the Leitha mountain range between the Vienna basin and the basin of Eisenstadt.

The other facies type comprises fine-grained clayey marls, the so-called *Baden Tegel*, which was deposited in a water depth of about 100 to 200 metres (A. BACHMANN et al., 1963). Frequent intercalations of sands became the most important oil and gas reservoirs of the Vienna basin (e. g. the Matzen Sand of the Lower Badenian, with an average thickness of 30 metres over an area of 16 to 30 km^2). The total thickness of the Badenian in the central part of the basin can reach up to 1500 metres, on upthrown blocks, however, it is only 100 to 600 metres.

The Vienna basin is subdivided by numerous synsedimentary faults into different blocks, which exhibit a various thickness of the basin filling. The most prominent faults are the Steinberg fault north of the Danube and the Leopoldsdorf fault south of the Danube.

The *Steinberg Fault* separates the *Mistelbach upthrown block* in the west from the main part of the Vienna basin (*Eichhorn downthrown block*). The amount of throw is up to 2000 metres, concerning the Badenian. In the area of Zistersdorf the Steinberg fault is outcropping and was reason for the initial search for oil in the Vienna basin, which was successful at the beginning of the thirties.

The Vienna basin (especially the part northeast of Vienna) is considered to be the most important oil province of Middle Europe (cumulative production since 1930 approximately 80 million metric tons of oil and 38 billions cubic metres of natural gas); the production results from both, the Neogene basin filling and the older sedimentary basement.

The *Leopoldsdorf Fault System* south of Vienna separates the *Oberlaa-Achau upthrown block* from the *depression of Schwechat*, the deepest part of the Vienna basin, where a maximum thickness of the Neogene of up to 5.500 metres is considered. It is proved that movements along the Leopoldsdorf fault continued until the Quaternary.

In the uppermost Badenian the sea started to become brachyhyaline, which continued during the Sarmatian. Apart from some western spurs into the region of the Wachau, the Vienna basin became the westernmost bay of the Paratethys.

The Sarmatian (Middle Miocene) is up to 2000 metres thick and comprises various facies: In the central parts of the basin and in areas with stillwater, the Tegel (*Hernals Tegel*) prevails, in nearshore areas sands, conglomerates, sandstones (*Atzgersdorf Sandstone*) are common. A characteristic bed is the *Detrital Leitha Limestone*, which is derived from the debris of the Leitha Limestone of the Badenian.

The Pannonian (late Miocene) is subdivided by A. PAPP (1953) into eight biozones A to H, but by recent investigations one considers to restrict the Pannonian to the zones A to E only, whereas the zones F, G and H are allocated to the Pontian. The biozones have been established on molluscs, ostracods, and micromammals.

At the beginning of the Pannonian the water level increased again, but the freshening continued and gradually an inland lake developed.

In the central parts of the basin the Pannonian and Pontian is up to 1500 metres thick. Clayey marls (*Inzersdorf Tegel*), sands and sandstones are frequent. The influence of big rivers, coming from the Alps, increased noticeably (*Mistelbach—Hollabrunn Talus Cone* of the Pannonian, *Rohrbach Conglomerate* of the Pontian/Dazian). Lignites, which have been of considerable economic importance, were formed in swampy bays at the margin. During the Upper Pontian (uppermost late Miocene) the warping of the Vienna basin began. Variegated clays mark the end of the sedimentation in the inner parts of the Vienna basin; gravel, sands, freshwater limestones and variegated loams (*Red Loam Series*) mark it in the marginal areas.

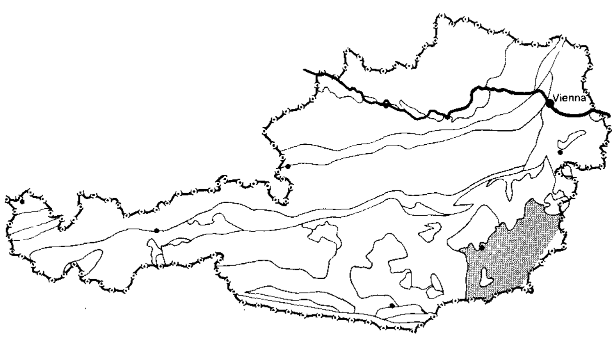
Upon these beds the various *Quaternary* accumulation terraces of the Danube and its tributaries have been deposited, which are corresponding to the at least four glaciation periods of the Alps. According to the alternation of erosion and accumulation, the older terraces are to be found in a higher level than the younger ones. Well developed steps of terraces can be observed in the Vienna district. The older terraces exhibit phenomena of cryoturbation.

In some inner parts of the Vienna basin subsidence continues in fault-bounded troughs during the Quaternary. South of the Danube the *Mitterndorf trough* is filled with up to 200 metres thick gravels; north of the Danube the *trough of Lassee* is showing youngest downthrow.

Neogene Basins within the Southern and Eastern Parts of the Central Alps

Various structural units of the Central Alps in the east and southeast are covered by Neogene sediments, which were deposited in different bays and basins. They are partly bounded by faults and flexures and exhibit commonly a similar, but in details varying geological history. In general they can be considered as marginal bays of the large marine or lacustrine areas situated in the south or southeast (Paratethys or subsequent inland lakes). The big Pannonian basin, however, which is nowadays the morphological continuation of the above mentioned Neogene basins, has a different geological history.

The Styrian Basin



The Styrian basin is an area of Neogene subsidence, which took place earlier than in the Pannonian basin. At the surface, however, the Styrian basin represents a western marginal bay of the Pannonian plane without any marked topographical boundary between both. The basin fillings rest completely on alpine basement.

The most comprehensive study on stratigraphy, facies and tectonics of the Styrian basin in the past years was given by K. KOLLMANN (1965).

The Styrian basin is bounded, partly by faults, in the northeast by the Penninic Rechnitz area, in the northwest by the Palaeozoic of Graz and the superimposed Gosau Formation of the Kainach region. In the north, west and southwest it is surrounded by rocks of the Austro-Alpine crystalline. Its eastern and southeastern border is the *Südburgenländische Schwelle.* It is a subsurface ridge, which on the surface is marked only by a few small elevations of more or less metamorphosed Palaeozoic rocks. The main parts are covered by Neogene up to Pannonian beds and thus it is no morphological divide between the Styrian basin and the Pannonian basin.

The same rocks, which can be observed in the surrounding of the Styrian basin, are forming the basement, but their subsurface geology is not as well known as that of the Vienna basin, since only a few wells reached the pre-Tertiary sedimentary or the crystalline basement.

The Styrian basin is subdivided by the *Sausal Schwelle* into the small *West-Styrian basin* and the big *East-Styrian basin.* It is a north-south trending ridge of Palaeozoic phyllites; west of it the thickness of the beds is considerable smaller and the sedimentation is terminated sooner; east of it the total thickness of the Neogene is up to 3000 metres and the sedimentation extends up to the Pontian.

The sedimentation began during the Ottnangian; lacustrine to fluviatile loams, sands and gravels became deposited, locally intercalated by lignites *(Lower Eibiswald Beds).* In some subsidiary basins of the East-Styrian basin a first marine ingression took place during the Karpatian (Fürstenfeld subsidiary basin, Gnas subsidiary basin); Schlier became deposited. In the West-Styrian basin the lacustrine environment continued and several hundred metres thick clays, sands and gravels of the *Middle* and *Upper Eibiswald Beds* are to be found. In the north and in the south considerable *lignites* are intercalated, which are the basis of the most important lignite-mine of Austria (*Köflach/Voitsberg* west of Graz).

At the beginning of the Badenian, at the same time, when the actual Vienna basin became developed, a further marine ingression took place, covering the whole Styrian basin and spreading out upon adjacent areas (e. g. the Pinkafeld bay in the north). The facies is varying abundantly; in general, however, it is, very similar to that of the Badenian of the Vienna basin (*Tegel* and sands in the basins, *Leitha Limestone* on the coastal regions and on the ridges). The fault-tectonics during the Karpatian and the lowest Badenian were accompanied by an *andesitic-dazitic volcanism.* Big shield volcanoes were formed, but nowadays only small traces are to be found on the surface (Gleichenberg hills). Their large subsurface extension was mapped by exploration work on hydrocarbons.

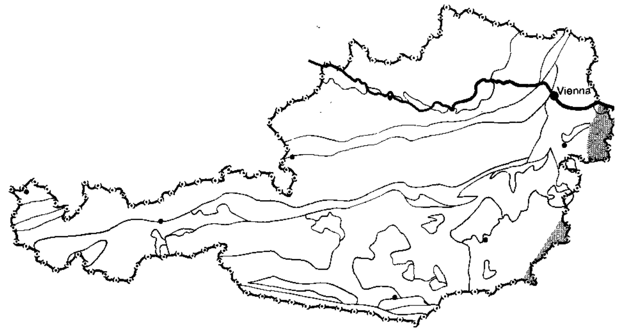
During the upper Badenian a regression took place, and large parts of the Styrian basin became land; the immediate connection with the Mediterranean area was cut off; an indirect connection continued via the Black Sea.

The ingression of the Sarmatian covered the whole East-Styrian basin and parts of the West-Styrian basin. The freshening increased and numerous intercalations of gravels occur. It is considered, that the bulk of debris of the Badenian and Sarmatian beds originated from the continent in the east (the latter Pannonian basin) and not from the Alps (K. KOLLMANN 1965).

During the Pannonian the sedimentation gradually came to an end in the East-Styrian basin. The lowest part of the Pannonian is common in the main parts of the basin, but subsidence stopped and warping started during the upper part of the Lower Pannonian. Pannonian beds are restricted to the north-easternmost parts of the Styrian basin. In contrary subsidence began east of the Südburgenländische Schwelle.

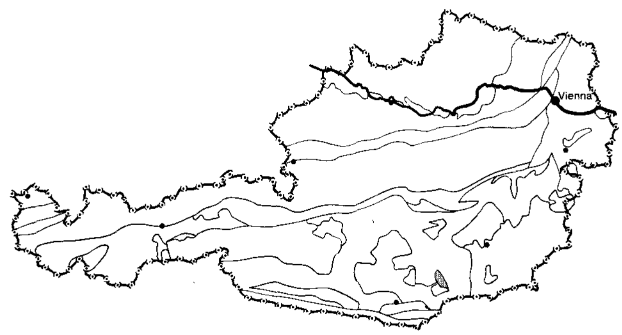
In the Styrian basin locally a final volcanism (?Dazian) occurs. *Basaltic* and *nephelinitic lavas* have raised through fissure vents; chimneys filled with tuffitic material are common (e. g. Klöch hill, Straden hill).

The Austrian Parts of the Pannonian Basin



Only very small areas of the western marginal regions of the big Pannonian basin are situated on Austrian territory. The biggest is the *Seewinkel*, the district east of the Lake Neusiedl; very small other parts are situated east of the Südburgenländische Schwelle in the south-easternmost district of Austria. In these areas the Pannonian is the prevailing stage and the beds are more than 1500 metres thick (in Hungary the border plane between the Sarmatian and the Pannonian can be observed in a depth of 2500 metres and more), whereas the older Neogene beds are developed very incompletely and with a thickness of only a few metres; locally they are lacking completely.

The Lavanttal Basin



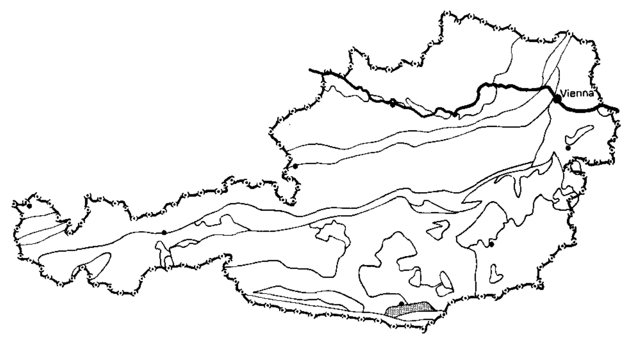
The Lavanttal basin is situated in Carinthia between the Saualpe massif in the west and the Koralpe massif in the east. It is fault-bounded and exhibits a section from the Karpatian up to the Lower Pannonian.

During the Karpatian and the Lower Badenian lacustrine and fluviatile gravels, sands and loams became deposited. The actual Lavanttal basin was formed by north—south trending faults at the beginning of the Badenian, but it was no earlier than during the Middle Badenian and caused by increasing subsidence, when a marine ingression could enter the basin. The connection with the sea was cut off during the Upper Badenian and brachyhaline and lacustrine sediments occur again.

A further short marine influence took place during the Sarmatian. Considerable seams of lignites are intercalated in Lower Sarmatian sediments. The middle part of the Sarmatian is lacking. The sedimentation ended with up to 400 metres thick clays, sands and gravels of the Lower Pannonian.

The *Lavanttal fault system,* to which the Lavanttal basin is connected, is a very important structural element of the Eastern Alps (P. Beck-Mannagetta). Concerning the basis of the Sarmatian, vertical displacements of 4000 to 5000 metres have to be considered.

The Klagenfurt Basin



South of the Central Alps and in a northern "Foredeep" of the Karawanken mountain range the Klagenfurt basin is situated. It comprises an incomplete series of strata from the Sarmatian and the Pannonian. The sediments are of lacustrine and fluviatile origin. Gravels and sands prevail, but in the lower part of the section also clay and lignites are occurring; the lignites are of no economic importance nowadays. The beds are considerably disturbed by faults and the southern marginal parts are overriden from the south by the Triassic of the Karawanken. The Pontian Sattnitz Conglomerate is disturbed too, but not overridden by the Karawanken (F. Kahler 1953).

Neogene Freshwater Sediments within the Alps

Along some generally east—west trending Alpine valleys locally remnants of Neogene freshwater sediments occur. In parts of the upper Enns valley at the border of the Northern Calcareous Alps and the Grauwackenzone coarse-grained gravels are to be found. The pebbles mainly consist of crystalline rocks or of quartz; pebbles of the Northern Calcareous Alps are very rare or lacking.

There exist close relationships with the *Augensteine* of the plateau-mountains of the Northern Calcareous Alps (e. g. Dachstein, Totes Gebirge, Rax). They are considered to be the re-deposited vestiges of a gravel cover on an early to middle Miocene peneplane on top of the entire Northern Calcareous Alps. It is supposed, that the gravels originated by fluviatile transport from the Central Alps and the Grauwackenzone in the south.

In the upper course of the Mur and the Mürz river some small basins of lignite-bearing freshwater beds are arranged. At the basis the beds generally comprise *lignite* or *brown-coal* seams, intercalated into clays and sands, unconformably superimposed by coarse-grained sediments. The age of the up to 1500 metres thick section (basin of *Fohnsdorf*) is considered to be middle Miocene.

Short Outline of the Glacial History of the Eastern Alpine Realm

The classical scheme of A. PENCK and E. BRÜCKNER, established at the turn of the century, distinguished four glacial periods within the Alps: *Günz, Mindel, Riss* and *Würm,* each named after Bavarian tributaries of the Danube. Further investigations, however, proved that before these some more glacial epochs must have existed. The total duration of these periods with cold climate is nowadays considered to have been two million years.

During the glacial periods the Alps were covered by a pattern of glaciers with a considerable thickness of ice which, within the Alpine region, is assumed to have buried all the landscape lower than approximately 2000 metres altitude. The big valley glaciers reached far into the foreland evidenced by big end moraines and other glacial phenomena. The sites of most of the lakes within the northern foothills of the Eastern Alps have been shaped by glacial activity.

In the non-glaciated periglacial foreland extensive accumulation terraces were deposited by rivers, which can be considered as the precursors of the nowadays tributaries of the Danube.

In the area of the end moraines sometimes an interfingering of the moraines with the terrace-deposits can be observed; thereby a correlation of the Pleistocene gravel terraces with the four main glacial epochs was possible:

Günz moraines — Older Gravel Cover (Ältere Deckenschotter)
Mindel moraines — Younger Gravel Cover (Jüngere Deckenschotter)
Riss moraine — High Terrace (Hochterrasse)
Würm moraine — Low Terrace (Niederterrasse)

Well-built steps of terraces can be observed at some places (e. g. in the Vienna district) along the course of the River Danube. During the cold periods a considerable loess cover was deposited; in some places, however, resedimented by rivers or lakes.

Within the Alps a strong erosion took place by the big glaciers: In the mountaineous regions big cirques became formed. The original V-shaped valley became U-shaped with oversteeped walls and considerably overdeeped. During interglacial or interstadial epochs, when the glaciers retreated, the oversteeped walls broke down and big landslides and rock falls occurred frequently. Most of the lakes of the Alpine valleys have either been caused by moraines of recessional stages or by glacier thresholds (e. g. the Salzkammergut area). In general the abundantly varying Alpine topography was mainly created by the repeated change of glacial and interglacial epochs, respectively by glacial and fluviatile erosion and accumulation.

The beginning of the Günz epoch is proved by radiometric dating to be 600.000 years b. pr. The actual ice epochs are considered to be comparatively short, while the interglacial periods lasted longer, and the climate was warmer than nowadays (for instance subtropic to Mediterranean climate during the Mindel/Riss interglacial epoch, proved by plant fossils in the *Hötting Breccia* near Innsbruck). The last big glacial epoch in the Alps was the Würm. Various methods of dating show that the main ice cover and the largest extension of the glaciers did not last longer than approximately 10.000 years between appr. 26.800 and 15.000 b. pr.

In the post-Würm period numerous changes of the climate took place, warmer and colder periods alternated comparatively quickly, each lasting for only several hundred years. Also in the most recent past glaciers oscillations occurred: At about 1870 a. Chr. the glaciers had a bigger extension than to day. If this is going to happen again, many of the Alpine hydro-power stations would be destroyed by the ice.

Mineral Deposits

Austrias mining tradition is about 4000 years old. We know that at least the copper ore of Mühlbach (south of Salzburg) was mined already in pre-historic times. The Hallstatt Culture of the Bronce Age was manly based on the mining of rock salt in the Salzkammergut district. During the Celtic-Roman era iron ores have been mined, as well as precious metals and zinc. A further culmination of mining occurred during the Middle Ages by the production of copper and silver ores. The final peak has been reached at the beginning of the industrial revolution.

Nowadays emphasis lies on the production of hydrocarbons, refractive and industrial minerals and raw materials for construction purposes.

Ores

Only in the Alpine part of Austria ores have been and still are subject of mining activities. There exists a big number of ore deposits, most of which were of economic interest in pre-historic and historic time. Nowadays only six mines are in operation.

While in former times the geologists mainly believed in a more or less unitaristic Alpine metallogeny (W. PETRASCHECK since 1926, E. CLAR & O. M. FRIEDRICH since 1933), today more detailed investigations show, that in many cases the deposits seem to be of synsedimentary stratiform origin during Variscan or pre-Variscan times.

In general the origin of the Alpine mineral deposits can be seen as a product of a polycyclic history. The different types of mineral deposits have to be classified according to the different phases of the Alpine orogeny (H. HOLZER 1980).

Iron-ore is mined, in the open-pit mine "Erzberg" in the northern Grauwackenzone in Styria. The siderite ore bodies (plus ankerite and breunnerite) are intercalated within Palaeozoic limestones. The annual production is about 3,8 million metric tons of ore containing about 28% Fe and 1,5—2% Mn. This type was supposed to be an example of the metasomatic siderite deposit of Alpine age, but nowadays the possibility of a Variscan intradiagenetic, vulcanic exhalative origin with considerable re-mobilisation and re-crystallisation during the Alpine era is discussed. There are many occurrences of sideritic iron-ores in the Grauwackenzone, and in marbles of the Austro-Alpine Crystalline, but nowadays all are of mineralogical interest only.

Other types of iron-ores are (according to H. HOLZER 1980):

bedded hematite-magnetite ores to magnetite-quartzites
jaspis-hematite
streaky magnetites in diabasic rocks
limonitic filling of carst cavities, spherosiderites, bean iron ore.

In Waldenstein in Carinthia hematite is mined for immediate application of rustproof coating.

Of considerable economic interest is the *scheelite ore* of Mittersill in Salzburg, only recently discovered. The ore is connected with Lower Palaeozoic rocks of the Schieferhülle of the Tauern window. According to R. HÖLL (1975), the mineralization is syn-sedimentary and stratiform, caused by Lower Palaeozoic basic volcanism.

Very common in various tectonic units of the Eastern Alps are *lead-zinc ores.* One of the most important ore districts is situated in the Drauzug and in the Karawanken mountain range. Today the mining activities are concentrated on the three mines of Predil/Raibl (Italy), Bleiberg-Kreuth (Austria) and Mezica/Miess (Yugoslavia). At Bleiberg-Kreuth in Carinthia, west of Villach, mainly Upper Triassic (Carnian) limestones and dolomites (Wettersteinkalk), but also Ladinian and Anisian carbonate rocks contain sphalerite and galena. There are different types of ore bodies, such as irregular shaped rich ore bodies, stratiform types, but also vein-typed ore bodies confined to joint fissures etc. The origin of the ores is a point of discussion; at the time being it is preferred to think of synsedimentary submarine origin: low temperature ore solutions penetrated the marine sedimentation area; syn- to post-tectonic concentrations are caused by re-mobilisation of primary metal contents.

Many other lead-zinc deposits are known in the Drauzug and in the Karawanken as well as in the Northern Calcareous Alps, mainly in Tyrol.

Lead-zinc ores, generally with a low content of *silver,* are common in Palaeozoic rocks of the Central Alps (Palaeozoic of Graz and Gurktal Nappe). The abandoned mine of Oberzeiring in Styria had a richer content of silver and was therefore an important site of silver production in the 14th century. In the Palaeozoic of Graz today research and prospection work on lead-zinc is being carried out with encouraging results. Of moderate economic importance in Austria is the mining of *stibnite,* which occurs nearly monomineralically in slightly metamorphosed (?Upper Cretaceous) carbonaceous shales of the Penninic Rechnitz window, and of *uranium,* for which a test-pit was in operation in Palaeozoic phyllites between Radstadt and Schladming. An extensive research programme on uranium has been carried out during the past years. Some considerable anomalies have been found in various units of the Alps, mainly in the Permo-Skythian stage. More detailed prospection work is going on.

Vein type of stratiform *copper ores* generally occur in all metamorphic units of the Eastern Alps, but also in non-metamorphic Permian sediments and vulcanites (the later as disseminated ore) of the Northern Calcareous Alps and the Southern Alps. The main deposits are found in the northern Grauwackenzone, either in form of tetrahedrite, rich in silver, or as chalcopyrite. The last copper mine at Mühlbach/Hochkönig in Salzburg, was closed down in 1977.

Not being mined today, but worth to be mentioned is a *gold* mineralization in the Central Alps (Tauerngold), mainly in form of quartz veins with native gold and various other minerals. But also other types of gold mineralization occur. Apart form pre-historic and Roman mining activities, gold mining reached its climax during the 14th and from the late 15th until the beginning of the 17th century. Last attempts to re-activate gold-mining date from the 19th century and from World War Two. In creeks and rivers rising from the gold-bearing areas, placer gold was panned with moderate success.

Further mining activites in former times existed on: *manganese ore* (in Palaeozoic and Mesozoic limestones), *chromite* (connected to serpentinite), *molybdenum* (by-product of the lead-zinc ore dressing, in the future probably extractable from the scheelite ore), *nickel-cobalt* (accessory of certain sulfide ores), *pyrites* and accompanying ores, *cinnabar, bauxite* (from the basis of the Upper Cretaceous Gosau Beds).

Coal and Lignite

In Austria nowadays mining of *lignites* is only carried out in Neogene beds of the Molasse Zone, the Styrian Basin and the intra-montaneous Neogene basin of Fohnsdorf in Styria. The main production of about 1,7 million metric tons a year (1977) is coming from the *Köflach—Voitsberg lignite district* in the Western Styrian Basin, where mining has been existing since the beginning of the 18th century. The lignites, partly mined on the surface, partly in the underground, occur within four seam horizons of the Karpatian stage and are arranged in several subsidiary basins with some difference in age and facies (W. Pohl 1976). They are covered by lacustrine beds of the Badenian (K. Kollmann 1965).

About 500.000 metric tons of lignite a year are mined in the *Salzach lignite district* in the Molasse Zone of Upper Austria. Three workable seams of the Badenian are developed.

In the *Wolfsegg—Traunthal lignite district* (Hausruck region in the Molasse Zone in Upper Austria) lignite of the Lower Pannonian is mined. The up to 60 metres thick lignite-clay series rests unconformably upon the Innviertel Formation (Ottnangian) and bears three seam horizons. This lignite district is the second-biggest of Austria, but the production, having started in the 18th century, has been decreasing since 1964 and is now about half a million metric tons a year (1977).

In 1979 the *brown coal* mine of Fohnsdorf in Styria was closed down, as the production of the Karpatian brown coal by underground mining (max. depth of 1130 m!) became more and more uneconomically.

Nowadays prospective areas, where exploration is going on, are in the southern Burgenland at the western border of the Pannonian basin (Upper Pannonian lignites have been proved by driling) and in the Lavanttal Neogene basin, where a lignite mine was working until 1968.

Anthracite occurs within Upper Carboniferous strata in the Gurktal Alps (e. g. Turrach), in the Brenner area south of Innsbruck and in the Carnic Alps in Carinthia. Mining of local importance took place during times of economic depressions, for the last time after World War Two.

Pit-Coal mainly occurs in three different Mesozoic formations of the Northern Calcareous Alps and of the Klippen Zone: in the Carnian (Upper Triassic) Lunz Beds, in the Liassic Gresten Beds and in Campanian beds of the Gosau Formation. According to the tectonic stress and the tectonic movements of these Alpine units, the coal beds vary strongly in thickness and extension. The production of pit-coal was of big local interest during the last century, especially for smelting of iron ores in Lower Austria, and in some places was reactivated in times of economic crises. The biggest pit-coal mine was that of Grünbach in the Gosau basin of the Neue Welt on the eastern border of the Northern Calcerous Alps, abandoned in 1965. During its 140 years of operation about 11 million metric tons of coal have been mined.

Peat was being cut in times of economic crises for local supply e. g. from bogs in the Bohemian Massif, in the upper Enns valley, in the area east of Salzburg, and in the Rhine valley.

Hydrocarbons

In 1980, the Congress' year, we are commemorating 50 years of oil production in Austria. It started in 1930 in the northern part of the Vienna basin. Until the end of 1978 more than 84 million metric tons of oil and more than 45 billion cubic metres of natural gas have been produced in Austria; the 1978 rate was 1,8 million metric tons of oil and 2,5 billion cubic metres of gas, meeting little less than 20% of Austria's oil and about 50% of Austria's gas demand.

In the *Vienna basin* nearly all beds of the Tertiary sedimentary filling can be productive, but also permeable beds of the basement as Palaeocene to Eocene sandstones of the Flysch Zone and Triassic carbonates (mainly dolomites) of the Northern Calcareous Alps. The main reservoir rocks are sands and sandstones of the Badenian (e. g. "Matzen oil sand" and gas deposit of Zwerndorf) and the Upper Triassic Hauptdolomit in the basement (e. g. oil deposit of the Schönkirchen deep structure and gas deposit of the Schönkirchen superdeep structure).

According to the geological history of the Vienna basin, the oil and gas deposits can be classified in to four sections (see fig. 20):

Slightly domed sands and sandstones of the upper part of the Neogene (Badenian to Pannonian); strictly speaking the filling of the subsiding Vienna basin; traps are partly also formed by faults.

The slightly folded older part of the Neogene (Ottnangian to Karpatian); strictly speaking the sediments of the Molasse era of the Vienna basin.

Burried hills on top of the basement (mainly Triassic dolomites).

Internal structures within the basement (thrust-slice structures of the Northern Calcareous Alps).

The depth of the deposits ranges between 500 metres and more than 6.000 metres (gas of Schönkirchen superdeep). The deepest hole is now being drilled by the well

Zistersdorf super-deep 1, which by the end of 1979 has reached 7.332 metres.

Until the end of 1978 the cumulative production from the Vienna basin amounted to 79,2 million metric tons of oil and 37,8 billion cubic metres of natural gas.

As source rocks both pelitic Neogene beds of the filling of the basin as well as more or less bituminous rocks of the basement of the Calcareous Alps have to be considered.

The second productive area is the *Molasse Zone.* Apart from the gas field of Wildendürnbach (discovered in 1960) in the northern part of Lower Austria near the border to Czechoslovakia the production in Upper Austria is the most significant one. Oil bearing beds are mainly Upper Eocene sandstones and nullipora limestones as well as reservoir rocks of the Upper Cretaceous, while gas deposits are mainly found in the Upper Oligocene Puchkirchen Formation and in the Lower Miocene Hall Formation.

Apart from a diminuitive but continuous gas production in Wels since 1892 and a production of a few thousand metric tons of heavy oil near Taufkirchen, the Molasse Zone became an oil province in 1956, when the oil field of Puchkirchen was discovered; gas is being produced since 1965.

Until the end of 1978 5 million metric tons of oil and about 7,5 billion cubic metres of gas have been produced cumulatively.

Oil shales (Ichthyolschiefer) occur in Austria mainly in the Upper Triassic Hauptdolomit and in Liassic shales in the Northern Calcareous Alps of Tyrol. The mining of a few hundred tons of rocks is the basis for a production of pharmaceutical products.

Geothermal Energy

Some resources of low enthalpy *geothermal energy* — discovered by oil exploration — can be assumed in the Styrian basin, in the Vienna basin and in some parts of the Molasse Zone. The existence of extractable *artensian hot water* in the Styrian basin and of a hot brine in the Vienna basin has been proved by wells. At present first utilization tests are being carried out.

Non-Metallic Mineral Deposits, Refractive and Industrial Minerals, and Raw Materials for Construction Purposes

The economical value of this heteorogenous group of mineral deposits is much bigger than that of ores, coal and lignite and hydrocarbons together. Some deposits of considerable significance are mentioned here.

Approximately until 1930 Austria had a world-wide monopoly of the mining of *magnesite.* Most of the about 50 deposits are of the spar-magnesite type within more or less metamorphosed Palaeozoic rocks. As for the ore deposits the origin is in discussion, but in the last years the assumption of a syn-sedimentary Variscan genesis became generally accepted.

In meta-sediments of the Moldanubicum of the Bohemian Massif mesocrystalline *graphites* containing 40—60% C are common and during the sixties have mainly been used for metallurgical purposes in the steel production. Nowadays cryptocrystalline graphites in Upper Carboniferous phyllites of the Grauwackenzone in Styria, containing up to 90% C, are of higher importance.

In Austria considerable reserves of *gypsum* and *anhydrite* are known, about 700.000 metric tons of which are mined a year. Most of the deposites have a core of anhydrite, covered by gypsum. The most important mines are situated in the Northern Calcerous Alps and exploit anhydrite and gypsum from the Upper Permian evaporite facies on the basis of the Northern Calcareous Alps. These deposits are genetically closely related to the Alpine *rock salt* deposits, which occur in the same evaporitic horizon *(Haselgebirge),* generally connected with the Hallstatt facies. Salt mining was of big importance in pre-historic (Hallstatt Culture) and historic (Middle Ages) times, but since then has been decreasing. The manner of mining is a leaching of the rock salt in artifical underground cavities (chambers) where upon a brine is obtained. During the past years leaching by wells was tested with success.

Kaolinite, bentonite and *refractory clays* are mined in various localities, generally connected to crystalline rocks or to Neogene volcanites (Styrian basin). Some other industrial minerals were being or are mined in Austria, as for instance *talcum, kyanite, diatomite, quartz* and *quartz-sands.*

In a mountaneous country like Austria obviously exists a big number of various hard rocks available for different kinds of construction purposes, while in the basins and valleys a lot of soft rocks, like gravels, sands and clays are to be found. In this paper only very few of the most important or most interesting ones can be mentioned.

Different *granites* and *diorites* of the Bohemian Massif are used in the stonemason industry, as e. g. the medium-grained Mauthausen granite for paving-stones in the streets of Vienna.

The Neogene (Badenian to Sarmatian) *Leitha Limestone* and *Detrital Leitha Limestone* of the Vienna and the Styrian basin have been one of the most common building materials for historic buildings in Vienna and Graz (e. g. St. Stephan's Cathedral, buildings of the Ringstrasse in Vienna, Opera house in Graz). It is easy to model but not very resistant against weathering and corrosion (SO_2). *Sandstones* of the Flysch Zone near Vienna have been used in huge masses for the regulating of the Danube and the Vienna river.

Some limestones of the Northern Calcareous Alps are used as "marbles" by sculptors and for decoration purposes, like the red to yellowish *Adnet Limestones* (Liassic) and the variegated "*Untersberg Marble*", a fine-grained breccia of the Gosau Formation. The thin-bedded *Oberalm Limestone* with chert (Upper Jurassic) often is used for the erection of walls along roads and for building bridges.

While in former times *natural cement-marls* have been used as raw material for the cement production (e. g. cement-marls of the Häring Beds in Tyrol, Cement-marls of the Flysch Zone), now a composition of clay, marl and limestone is used; the resources in Austria are very big.

Broken and crushed hard-rocks, mainly applied for road construction, are produced from several rock types. Because of their pronounced jointing the dolomites of the Northern Calcareous Alps are very suitable. Granulites of the Bohemian Massif and siliceous limestones of the Helvetikum of Vorarlberg are preferably used for railroad construction.

Gravel and *sand* deposits are very common in Austria in glacial and alluvial sediments of the young basins and big valleys and usually available around densely populated regions. However, problems concerning groundwater pollution may arise by their working.

Tertiary *sandy clays* and Quaternary *loams* and *loamy loess* are generally used in brick industry. The brickyards south of Vienna in the sandy clays of the Badenian and Pannonian were of great importance for the rapidly growing City of Vienna during the second half of the last century.

Ground Water. Though usually not classified as a raw material, a few words should be said about this very important stuff. Austria fortunately has big resources in ground- and spring-water of high quality, so that most of the densely populated regions can be supplied by spring- or pump-water, partly by deep artesian water. So the Vienna district is mainly supplied by two big water conduits coming from big carst-springs in the Northern Calcareous Alps: The older, more than 100 years old and about 100 km long one comes from the Schneeberg—Rax area south of Vienna, the younger, about 70 years old and about 220 km long pipe-line is coming from the southwest, from the Hochschwab mountains. Only a few bigger communities have to be provided by purificated river-water.

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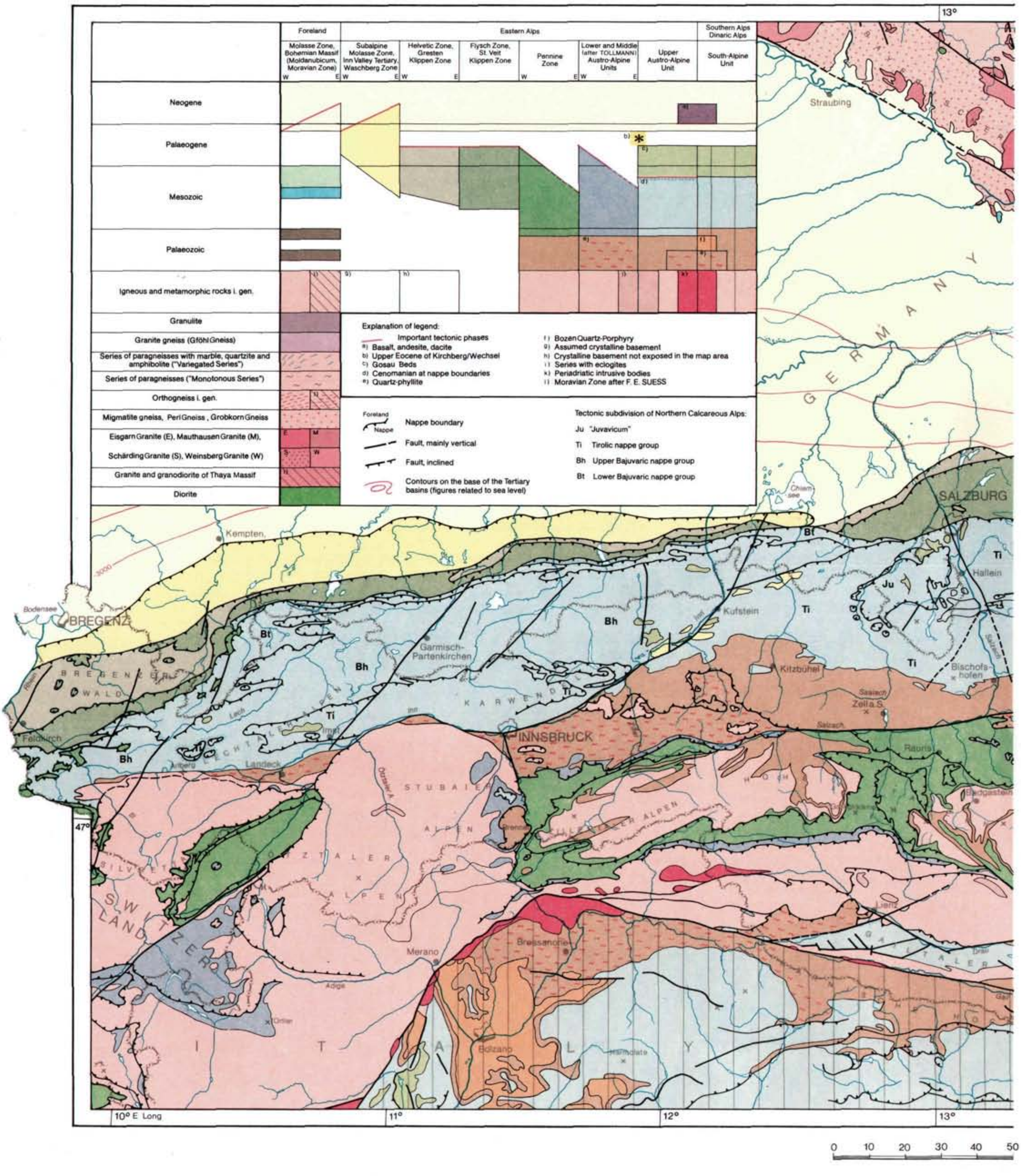

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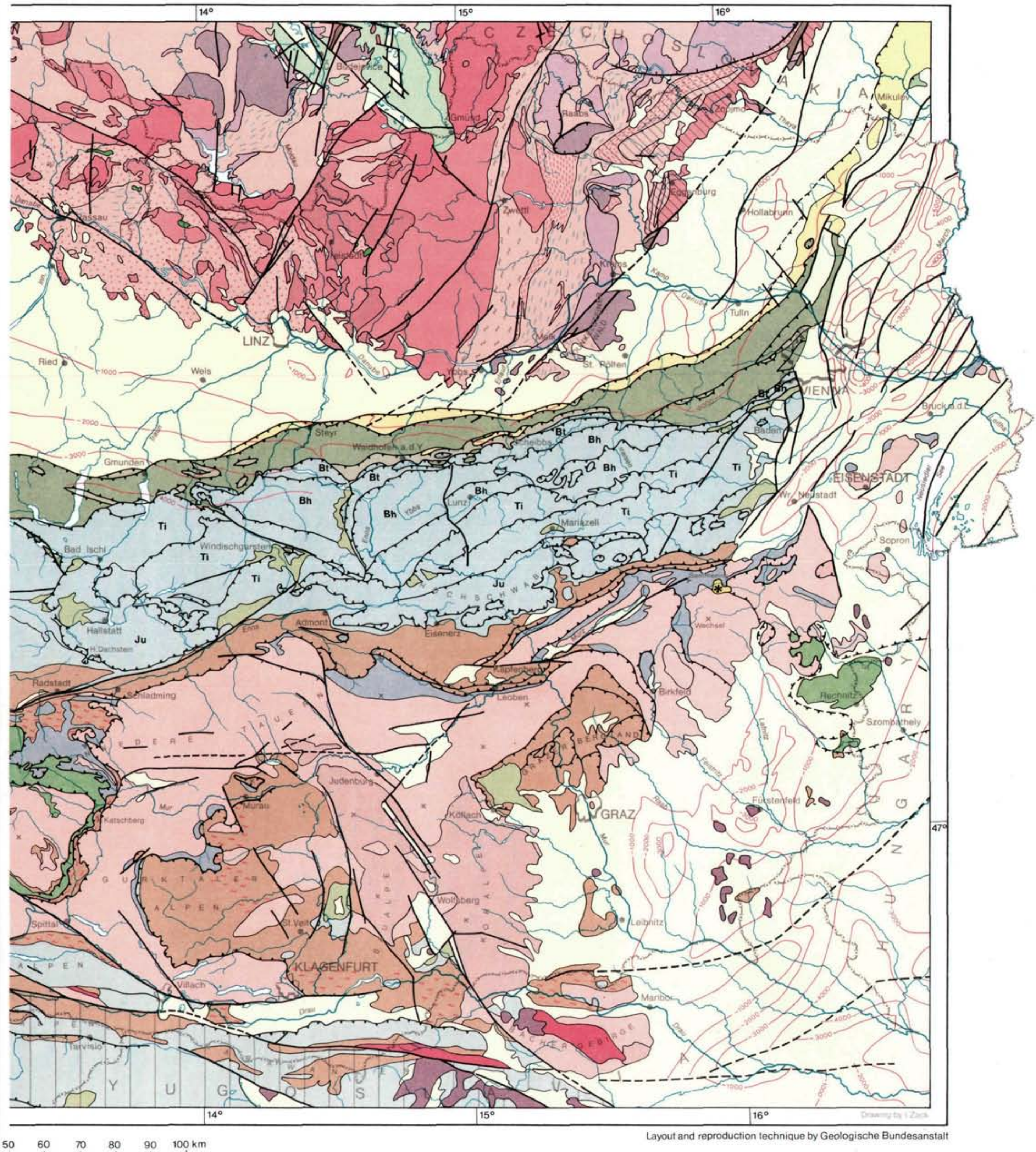

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