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The Alpine sector of the Tethyan shelf – Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps

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Abstract

The nappe stack of the Northern Calcareous Alps (NCA), a part of the Austroalpine nappe complex, forms the uppermost tectonic unit of the Eastern Alps. The sedimentary successions represent the depositional history of northwestern sectors of the Tethyan shelf from Permian to Eocene times and give evidence for several orogenic events.

The stratigraphic succession starts with Permian continental to shallow marine siliciclastics and evaporites, transgressing on a Variscan metasedimentary basement. Deposition of siliciclastics continues until the end of the Early Triassic, when carbonate production became dominant. Middle to Late Triassic times are characterized by extended carbonate platforms and basins, influenced by terrigenous input from the European hinterland during the Early Carnian and the Latest Norian. The distal deeper shelf was the depositional site of pelagic limestones of the so-called Hallstatt facies, affected by synsedimentary diapirism of Permian evaporites. The adjacent Tethyan oceanic realm is represented only by olistolites in small tectonic klippen, incorporated into the Alpine nappe stack.

The Jurassic opening of the Penninic oceanic realm, coupled with the spreading of the Central Atlantic, separated the Austroalpine realm as a microcontinent from "stable Europe". Penninic spreading was partly compensated by strike-slip dissection of Apulia and compression/subduction of adjacent sectors of the Tethyan ocean. The sedimentary succession of the distal Austroalpine shelf became detached from its crystalline basement, forming the Juvavic nappe complex. Extended nappes, olistolites and syntectonic clastics were transported by gravity toward the Austroalpine radiolarite basins at the beginning of Late Jurassic. A cover of Late Jurassic to Early Cretaceous carbonates sealed this first orogenic event. Subsequent thrusting during "Austroalpine" (Hauterivian/Barremian) and "Mediterranean" phases (Early Turonian) led to a first mountain belt, a Cretaceous precursor of the today's Eastern Alps.

Introduction

One of the most prominent units of the Eastern Alps is the nappe complex of the Northern Calcareous Alps (NCA), forming a 500 kilometers long and 20 to 50 kilometer wide thrust belt of sedimentary rocks. Due to only local metamorphic overprint, the sedimentary features are mostly well preserved, offering the opportunity to reconstruct the depositional history of a segment of the Western Tethyan shelf.

The NCA consist of mountain ranges with impressive plateau mountains, which are a remnant of a Late Paleogene peneplain, faulted and uplifted since the Miocene (FRISCH et al., 1998). In the western and middle part, the highest peaks reach altitudes of up to 3,000 meters and are locally glaciated (Dachstein area). In the eastern part, elevations are up to 2,000 meters.

At their eastern end, the NCA are bounded by the Neogene Vienna basin. Below the Neogene sediments of the Vienna basin, however, the NCA nappe complex continues into the Western Carpathians (KRÖLL et al., 1993). Details of correlation are still under discussion. The uppermost tectonic unit of the NCA – the Juvavic Nappe complex – ends in the Slovakian part of the Vienna basin. Equivalent units occur again in the eastern part of the Western Carpathians.

In the Northern Calcareous Alps, Mesozoic carbonates predominate, but also clastic sediments are frequent at several stratigraphic levels. The succession begins in the Permian and extends locally into the Eocene (Gosau Group), but the Triassic rocks are the most prevailing ones.

Principles of the structural evolution

The succession of Mesozoic sediments of the NCA has largely lost its former crustal basement in the course of the Alpine orogeny. During Late Jurassic to Tertiary times, several stages of deformation (folding and thrusting) created a nappe complex which rests with overthrust contact on the Rhenodanubian Flysch Zone in the north and on Variscan basement (Greywacke Zone) in the south.

The Northern Calcareous Alps include the following succession of nappes from north to south, and from bottom to top (Figs. 1 and 8/B): The northern, frontal part of the NCA is built by the Bajuvaric nappes, with narrow synclines and anticlines. Toward the south they dip down below the overthrusted Tyrolic nappe complex. Due to their dominant dolo-

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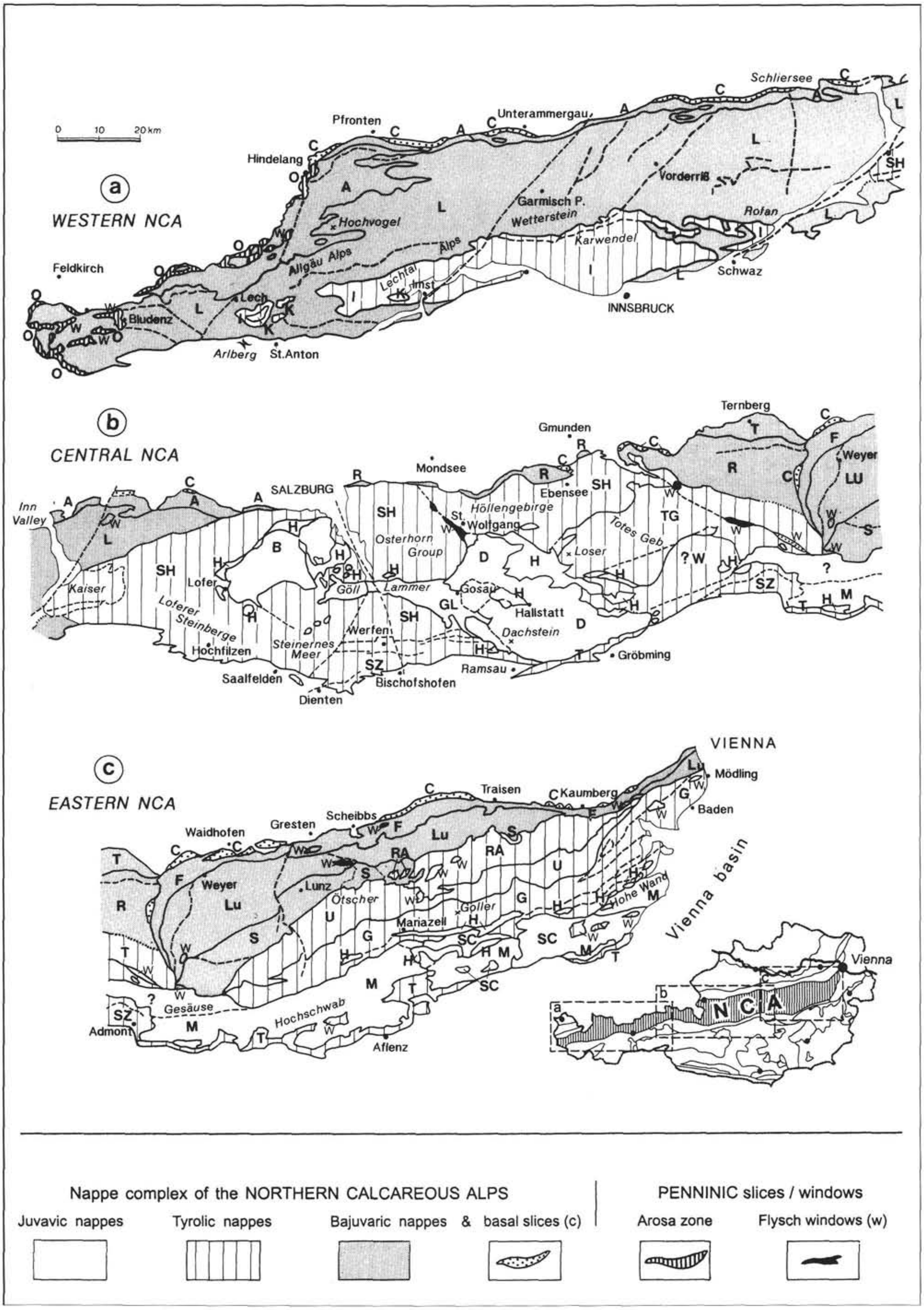
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a
WESTERN NCA
Feldkirch
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St.Anton
Imst
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INNSBRUCK
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CENTRAL NCA
Inn Valley
Kaiser
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Mondsee
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Ebensee
Ternberg
Weyer
Lofer
Loferer Steinberge
Hochfilzen
Saalfelden
Dienten
Steinernes Meer
Göll
Lammer
Werfen
Bischofshofen
Osterhorn Group
St. Wolfgang
Höllengebirge
Totes Geb.
Loser
Gosau
Hallstatt
Dachstein
Ramsau
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A C L SH H B D GL SZ T R F LU S TG M W ?
c
EASTERN NCA
VIENNA
Mödling
Baden
Traisen
Kaumberg
Scheibbs
Gresten
Waidhofen
Weyer
Lunz
Ötscher
Mariazell
Goller
Hohe Wand
Vienna basin
Gesäuse
Admont
Hochschwab
Aflenz
T R F Lu S RA U G H SC M SZ C W ?
a b NCA Vienna
Nappe complex of the NORTHERN CALCAREOUS ALPS
Juvavic nappes
Tyrolic nappes
Bajuvaric nappes & basal slices (c)
PENNINIC slices / windows
Arosa zone
Flysch windows (w)

← Fig. 1
The nappe complex of the Northern Calcareous Alps (after Plöchinger, 1995). Explanation of abbreviations: Northern Calcareous Alps: *Juvavic nappes:* B = Berchtesgaden nappe, D = Dachstein nappe, SC = Schneeberg nappe, H = Hallstatt units, M = Mürzalpen nappe, GL = Göll-Lammer unit. *Tyrolic nappes:* K = Krabachjoch nappe, I = Inntal nappe, SH = Stauffen-Höllengebirge nappe, TG = Totengebirge nappe, W = Warscheneck unit, SZ = Werfen imbricated zone, RA = Reisalpen nappe, G = Göller nappe, U = Unterberg nappe. *Bajuvaric nappes:* L = Lechtal nappe, R = Reichraming nappe, S = Sulzbach nappe, Lu = Lunz nappe, A = Allgäu nappe, T = Ternberg nappe, F = Frankenfels nappe, c = basal slices. Penninic units: O = Arosa zone, w = windows of the Rhenodanubian Flysch zone.

mitic lithology, the Tyrolic nappes exhibit internal thrusting and faulting and only minor folding. The Juvavic nappes represent the uppermost tectonic element, overlying the Tyrolic nappes. An additional subdivision into a "Lower" and an "Upper" Juvavicum was used previously. According to recent investigations, these terms seem to be not useful anymore.

The Greywacke Zone is thought to represent the Palaeozoic basement of the Mesozoic rocks of the Tyrolic nappes, remaining often several kilometers behind in the south during the nappe movements. Permian and Early Triassic siliciclastics clearly transgress onto Early Palaezoic rocks, but their sedimentary continuation into the Middle Triassic carbonates of the Tyrolic nappe complex is either covered by Juvavic nappes (eastern NCA) or disturbed by thrusts (middle NCA, Werfen imbricated zone).

Although large portions of the NCA indicate only anchimetamorphism (Kralik et al., 1987), investigations of the Conodont Color Alteration Index during the last years have revealed a considerable thermal overprint in parts of the Juvavic nappes, predating the oldest (Late Jurassic) overthrusts (Gawlick et al., 1994; Kozur and Mostler, 1992; Mandl, 1996).

Today there is a common assumption that the depositional realm of the NCA during the Permo-Triassic was a passive continental margin, which was formed on a Variscan basement (part of Pangaea) by rifting and spreading of the Tethys ocean (Fig. 2). That sector of the ocean that bordered the NCA and the Western Carpathians was also named "Hallstatt-Meliata-Ocean" by Kozur (1991) and it is thought to have been closed during Jurassic times. The position of this suture in the present nappe stack and the mutual palaeogeographic arrangement of the tectonic units is still a matter of controversial discussions (e.g. Haas et al., 1995; Kozur, 1991; Kozur and Mostler, 1992; Schweigl and Neubauer, 1997; Tollmann, 1976a, 1981).

Beginning in the Jurassic, the Austroalpine realm (including the NCA) became separated from its European hinterland by the birth of the transtensional basin of the Penninic

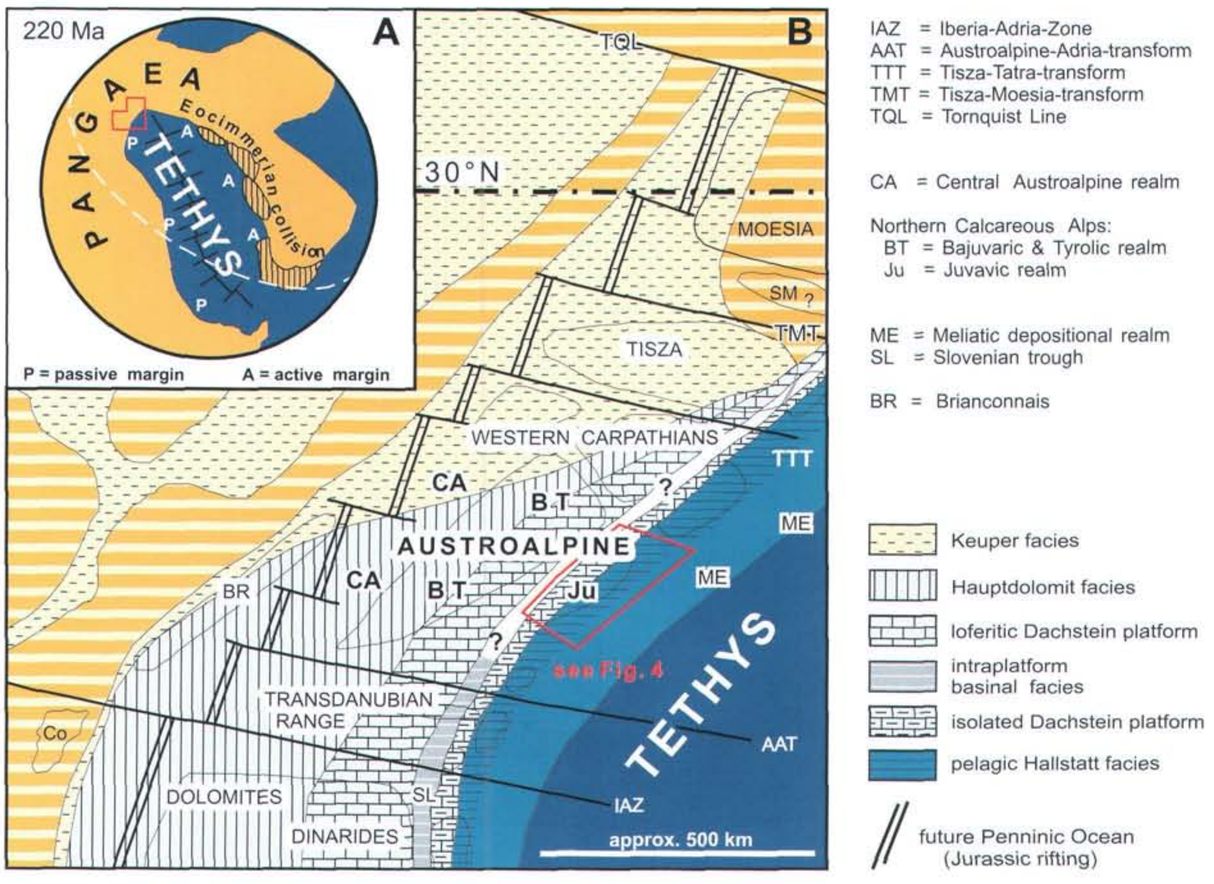


Fig. 2
The Alpine-Carpathian sector of the Triassic Tethyan shelf (after Haas et al., 1995, modified).

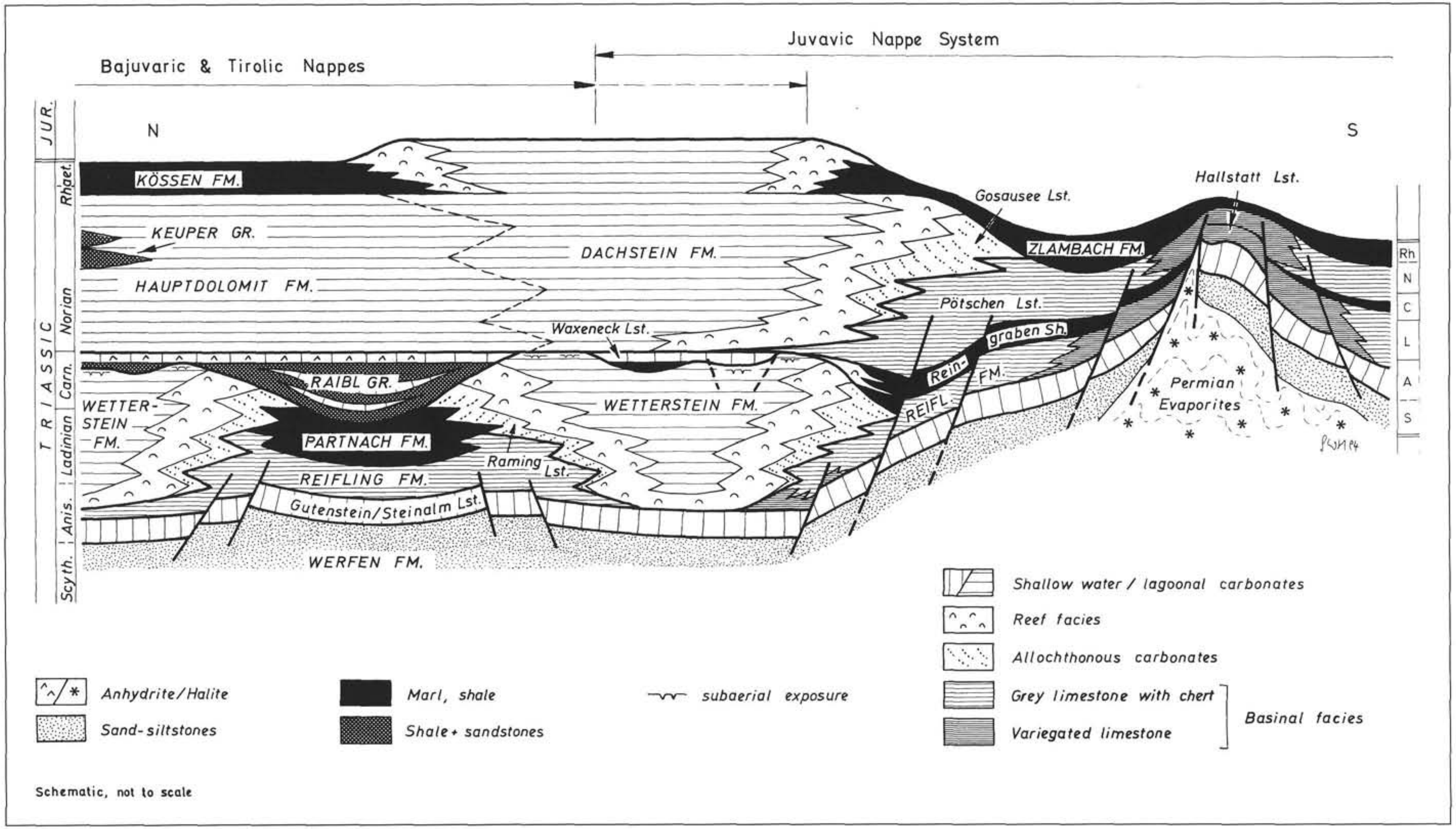


Fig. 3
Triassic stratigraphy of the Northern Calcareous Alps (middle sector).

ocean, which was linked by a major transform fault with the opening of the central Atlantic ocean. Contemporaneous compressional tectonics have affected the Tethyan ocean and the adjacent shelf of the Austroalpine realm, causing the first displacements of the Juvavic nappe complex.

Subduction processes at the southern margin of the Penninic Ocean have started in the Cretaceous, accompanied by crustal shortening within the Austroalpine crystalline basement and by nappe movements and deposition of synorogenic clastics in its sedimentary cover (DECKER et al., 1987; FAUPL and TOLLMANN, 1979; VON EYNATTEN and GAUPP, 1999). For details of the metamorphic evolution of the Eastern Alps and controversial discussions see FRANK (1987), HOINKES et al. (1999), THÖNI (1999), and NEUBAUER et al. (this volume). Late Cretaceous clastic sediments of the Gosau Group transgressed after a period of erosion onto the NCA nappe stack (e.g. WAGREICH and FAUPL 1994; FAUPL and WAGREICH, this volume).

Ongoing subduction of the Penninic realm toward the south below the Austroalpine units led to the closure of the Penninic Ocean. Beginning in the Late Eocene the sediments of the Rhenodanubian Flysch Zone became deformed and partly overthrusted by the nappes of the NCA.

The large-scale thrusts of the NCA over the Flysch Zone, the Molasse Zone and the European foreland are proven today by several drillings, which penetrated all units and reached the basement at depths of about 3000 to 6000 meters (e.g. SAUER et al., 1992).

The uplift of the central part of the Eastern Alps in the Miocene was accompanied by large strike-slip movements, e.g. the sinistral Salzach-Ennstal fault system, which also affected the NCA nappe complex (e.g. LINZER et al., 1995; DECKER et al., 1994; FRISCH et al., 1998).

Triassic depositional realms

General features

Reviews, detailed data and further references on Triassic depositional realms are given by TOLLMANN (1976a), LEIN (1987), KRYSTYN and SCHÖLLNBERGER (1972), MANDL (1984a), SCHLAGER and SCHÖLLNBERGER (1975), ZANKL (1971) and FLÜGEL (1981). A schematic representation of the Triassic sedimentary successions is shown in Figure 3.

The sedimentary succession of the NCA starts with Permian continental red beds, conglomerates, sandstones and shales of the Prebichl Formation, transgressively overlying Early Paleozoic rocks of the Greywacke Zone (Noric nappe). A Permian age is assumed due to local intercalations of acidic tuffs and pebbles of quartz porphyry, which are widespread in the European Permian. A marine facies of Permian sediments is the so-called Haselgebirge, a sandstone-clay-evaporite association containing gypsum and salt. This facies is frequent in the Juvavic units, exposed for example in the Hallstatt salt mine. The Late Permian (locally also Late Scythian) age is proven by pollen/spores (KLAUS, 1953, 1974) and confirmed by sulfur isotopes (PAK, 1974; PAK and SCHAUBERGER, 1981; SPÖTL, 1988a, b).

The Early Triassic is characterized by widespread deposition of shallow shelf siliciclastics of the Werfen Formation, containing limestone beds in its uppermost part with a poor fauna including Scythian ammonoids and conodonts.

From Middle Triassic times onward carbonate sedimentation prevailed. The dark Gutenstein Limestone/Dolomite is present in most of the NCA nappes. It can be laterally replaced in its upper part by light dasycladacean bearing carbonates, the Steinalm Limestone/Dolomite. During the Middle Anisian, a rapid deepening and contemporaneous block faulting of the so-called Reifling event caused a sea floor relief, responsible for the subsequent differentiation into shallow carbonate platforms (Wetterstein Formation and lateral slope sediments of the Raming Limestone) and basinal areas. The basins can be subdivided into the Reifling/Partnach basins and the Hallstatt deeper shelf, the latter one bordering the open Tethys ocean. Due to strong Alpine nappe tectonics, the original configuration of platforms and basins is still a matter of discussion. The transition from the Hallstatt depositional realm into oceanic conditions with radiolarites is not preserved in the NCA. We have indications of the existence of such an oceanic realm only in the form of olistolites of Ladinian red radiolarite in the Meliata Klippen in eastern sectors of the NCA.

The Wetterstein platforms in general show a platform progradation over the adjacent basinal sediments until the earliest Carnian ("Cordevolian"). Then carbonate production decreased rapidly, due to a sea-level lowstand. The platforms emerged and the remaining basins received siliciclastics from the European hinterland. The Reifling basin has been completely filled by clastic sediments of the Raibl Group, including marine black shales, carbonates, and marine to brackish sandstones (Lunz Fm.) containing coal seams. Local intra-platform basins and the Hallstatt realm toward the south also received fine-grained siliciclastics (Reingraben Shale) interbedded with dark cherty limestones and local reef debris ("Leckkogel facies"), derived from small surviving reef mounds at the basin margins.

As the sea-level started rising up again in the Late Carnian, carbonate production increased, locally filling a relief in the flooded platforms with lagoonal limestones (Waxeneck Limestone). The relief (several 10 meters) may be caused by erosion during the lowstand time and/or by tectonic movements. Towards the north, in the Lunz-Reifling area, partly hypersalinar conditions led to the deposition of limestones and dolomites with evaporitic (gypsum) intercalations (Opponitz Formation).

A transgressive pulse just below the Carnian/Norian boundary caused an onlap of pelagic limestones onto parts of the platform and initial reef growth on remaining shallow areas. Due to local differences in platform growth conditions, we can distinguish two different evolutions. In the central part of the NCA (e.g. Hochkönig, Tennengebirge, Dachstein area; Fig. 4/section A), the pelagic onlap represents only a short time interval and became covered by the prograding carbonate platform of Dachstein Limestone – see example of the type area below. In these areas, the Late Triassic reefs are situated approximately above the Middle Triassic ones.

A different evolution characterizes the eastern sector of the NCA. The latest Carnian pelagic transgression ("pelagic plateau") continues until the Late Norian and has been termed the Mürztal-type of the Hallstatt facies by LEIN (1987). Dachstein Limestone is only known from the Late Norian and the reefs are situated above the former platform interior, several kilometers behind the former Wetterstein reef front (Fig. 4/sections B, C). Such a configuration seems

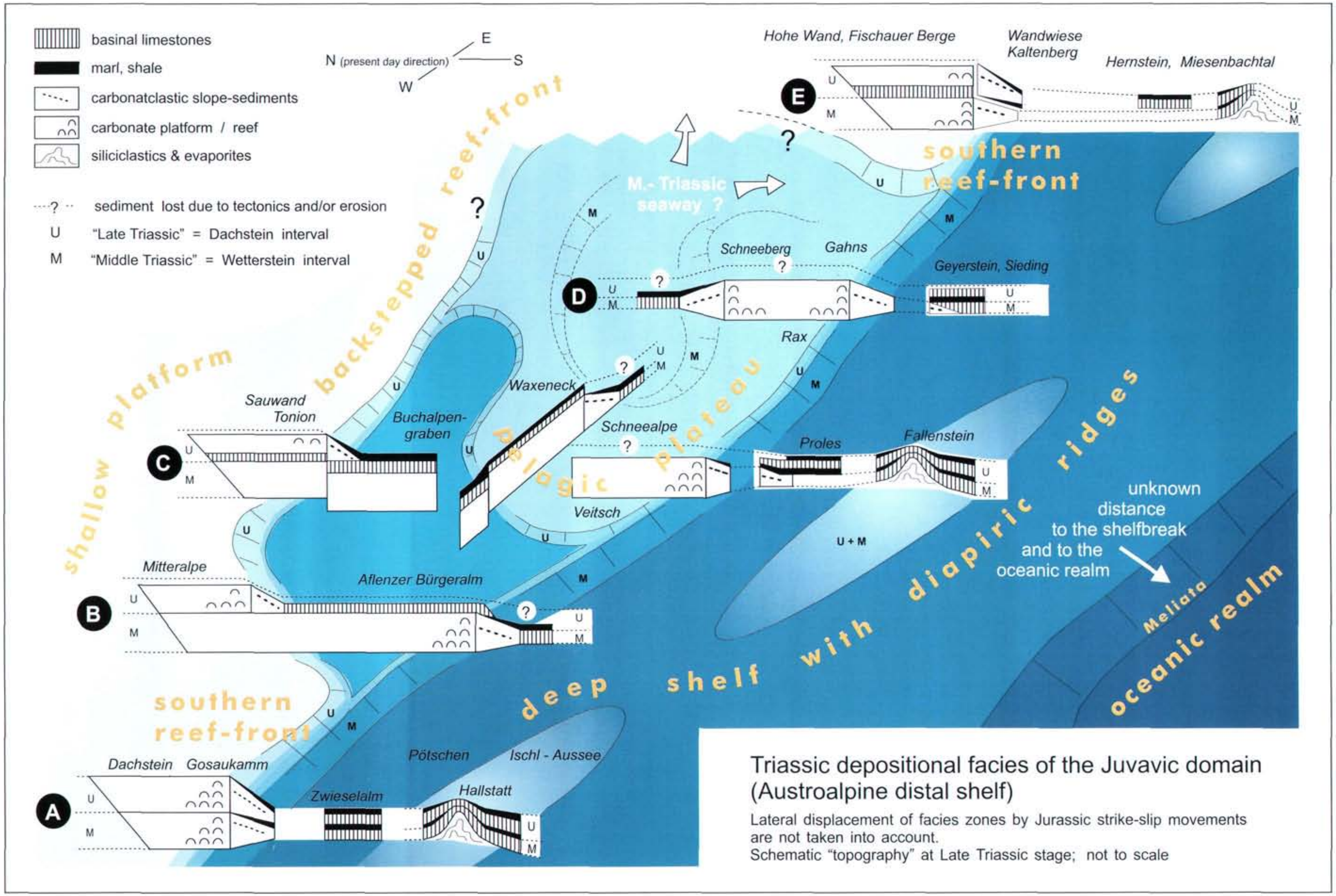


Fig. 4
Triassic depositional facies of the Juvavic domain (Austroalpine distal shelf).

to be typical also for the Western Carpathians (Slovakian karst and the Aggtelek Mountains). This "backstepped" reefs show transitions into the basinal facies of the black Aflenz Limestone in the eastern Hochschwab/Aflenz area and in the Sauwand- and Tonion Mountains. In contrast, the "Southern marginal reefs" of the central NCA (Fig. 4/section A) are connected by the allodapic Gosausee Limestone to the Pötschen Limestone of the Hallstatt facies realm.

The Hallstatt Group shows a great variability of variegated limestones, often with rapidly changing sedimentary features due to its mobile basement (diapirism) of Permian evaporites. Behind the Dachstein reefs, a large lagoonal environment extended all over the NCA with bedded Dachstein Limestones close to the reefs and the intertidal Hauptdolomit in distal sectors.

In the latest Triassic ("Rhaetian") once again increasing terrigenous influx reduced the areal extent of carbonate platforms. The Hauptdolomit area and parts of the Dachstein lagoon became covered by the marly Kössen Formation, bordered by Rhaetian reefs (famous examples are the Steinplatte and the coral limestone in the Adnet quarries).

In the Hallstatt realm, as well as in the intraplatform basin of Aflenz Limestone, the marly Zlambach Formation was deposited onlapping and interfingering with the Dachstein platform slope.

Towards the north, the carbonate shelf of the Northern Calcareous Alps passed into a siliciclastic shelf (Triassic "Keuper facies"), today mainly exposed in some Central Austroalpine nappes and Penninic units. Indications of this facies occur in the northeasternmost nappes of the NCA as intercalations of sandy shales within the Hauptdolomit.

The Dachstein mountains – an example of a shallow marine carbonate platform

The Dachstein nappe (Fig. 5) represents a sector of the Triassic distal shallow marine shelf, bordering the open marine deeper Hallstatt shelf of the Tethys ocean. Along its southern rim transitions from platform to basin are preserved, which are used as connecting links in palinspastic models (SCHLAGER, 1967; LEIN, 1976; MANDL, 1984a, b; MANDL et al., 1987).

Anisian carbonates are followed after the Pelsonian drowning event by pelagic limestones (Reifling Lst., Hallstatt Lst.). The initial stage of the growth of the Wetterstein carbonate platform is nowhere exposed, but progradation of the platform toward the basin during Ladinian to Early Carnian is well preserved. Typical sedimentary features are reef breccias, platform-derived massive to bedded allodapic limestones and distal carbonate turbidites. Secondary dolomitization affected large parts of the platform carbonates, especially the lagoonal interior.

During the Early Carnian sea-level lowstand the platform emerged. Frame-building organisms (mainly calcisponges) became restricted to a narrow belt (Leckkogel facies of the Reingraben Fm.) along the former platform slope, their detritus can be found within adjacent dark limestones and shales (FLÜGEL et al., 1978). As suggested by facies distribution and ages of superimposing strata the emerged platform had been exposed to remarkable erosion, creating a relief of several tens of meters.

A Sea-level rise in the Late Carnian at first led to lagoonal conditions (Waxeneck Lst.) mainly in local depressions of the eroded Wetterstein platform. Contemporaneous dolomites with relictic reef structures are thought to represent Waxeneck marginal reefs. Adjacent bedded dark dolomites with breccia layers and pelagic intercalations are interpreted as slope sediments of this interval. In the contemporaneous basin (Pötschen Limestone), breccias ("Cidaris Breccia") of a distal slope origin occur.

In the latest Tuvalian, a distinct transgressive pulse led to widespread pelagic conditions, covering the drowning platform. The prevailing relief caused a complex pattern of local reef patches separated by depressions, where massive micritic crinoidal limestones were deposited. They exhibit a mixture of components from the platform interior, of reef debris, crinoids and pelagic biogens (ammonoids, conodonts, radiolarian, filaments). A deeper depression (Plankenalm area, see Fig. 5) contains bedded allodapic limestones similar to the Gosausee Limestone.

This initial stage of Dachstein platform growth was rapidly terminated within the Early Norian by lagoonal limestones, while the reefs became concentrated at the platform margin. The open platform situation changed into a rimmed platform configuration, characteristic of the Dachstein facies: The lagoonal platform interior exhibits cyclic bedded, inter- to subtidal "Lofer facies", which grades toward the north by an increase of intertidal dolomites into the Hauptdolomit facies. In central and eastern sectors of the NCA, the cyclic meter-sized bedding of the Dachstein Limestone is a characteristic morphological feature, well visible along the steep slopes as well as on the karstified top of the large plateau mountain ranges.

FISCHER (1964) has given a description of this phenomenon, which remains a classic even now, named by him "Lofer cycle". It is based on sequences from the plateaus of the Dachstein and the Loferer Steinberge. The cyclicity is caused by an interbedding of lagoonal limestones, thin layers of variegated argillaceous material and intertidal/supratidal dolomites and dolomitic limestones.

The main sediment is a light-coloured limestone (layer C, thickness up to some meters), containing oncoids, dasycladacean and codiacean algae, foraminifera, bryozoa, gastropoda, large megalodontids and other bivalves. The weathered and solution-riddled surface of this limestone is overlain and/or penetrated by reddish or greenish argillaceous limestone (layer A), which may include limestone clasts and which is interpreted as a former terrestrial soil. Layer A is commonly not developed as a distinct bed, because of its erosional origin; however, remnants of A are abundant infillings in veins, cavities and biomoldic pores (gastropod and megalodontid shells). Layer B consists of intertidal carbonates of a variety of rock types like "loferites" or birdseye limestone of laminated or massive type, non-loferitic lutites and intraclasts. The flat or crinkled lamination represents filamentous algal mats, also characteristic of modern tidal flats. Fenestral pores and mud cracks seem to be the result of shrinkage of unconsolidated sediment due to desiccation. All types of layer B are more or less dolomitic, some of them formed as contemporaneous brittle surface crusts, as shown by intraclasts, demonstrating the intertidal/supratidal setting.

FISCHER (1964) explains the formation of the cyclothems by periodic fluctuations of the sea-level which is superim-

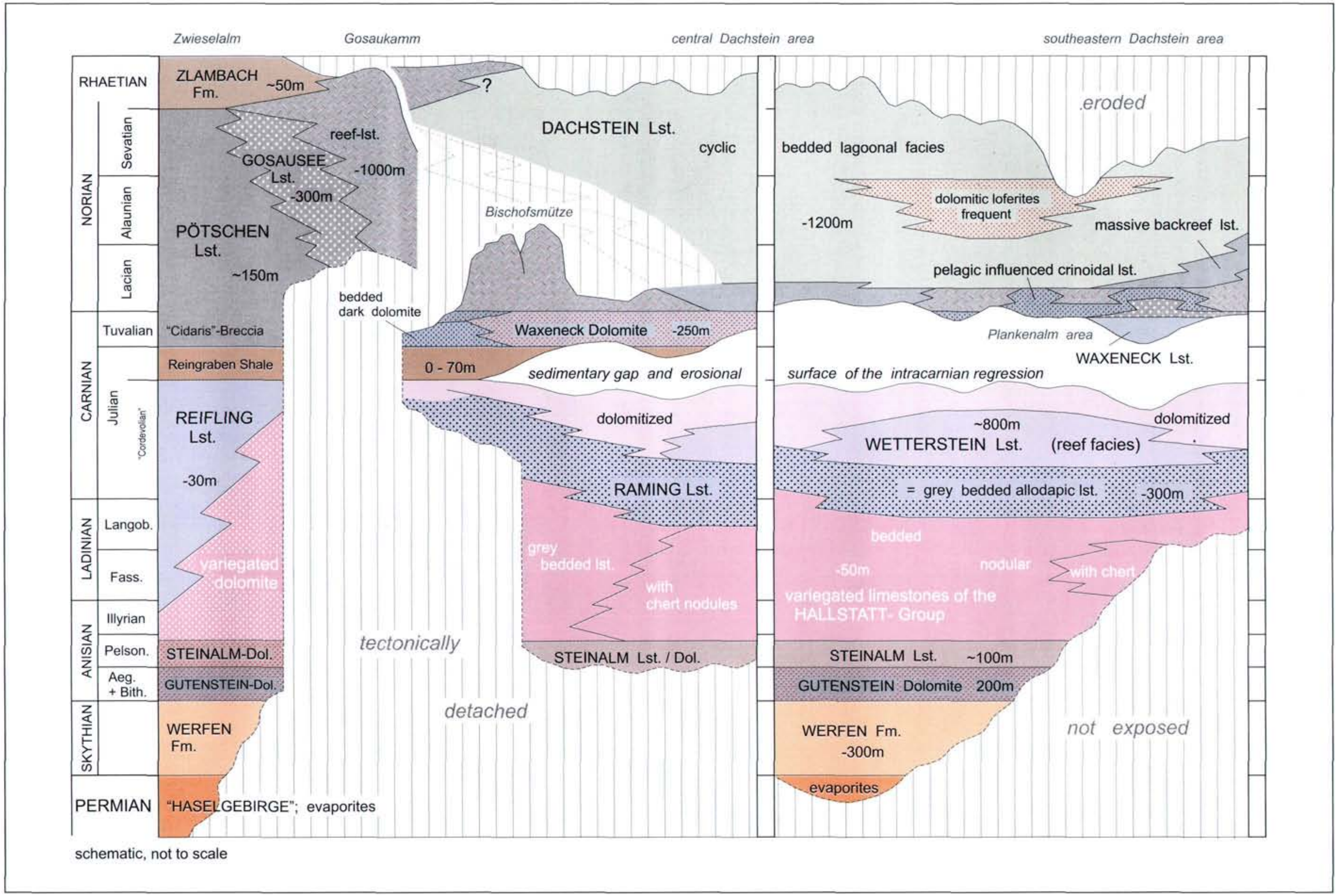


Fig. 5
Stratigraphy and facies of a Triassic carbonate platform (Dachstein nappe; Juvavic nappe complex). Detail of Fig. 4, section A.

posed on the general subsidence. An amplitude of up to 15 m and 20,000 to 100,000 years is assumed for one cycle. Because this model does not explain the gradual lateral transition into the Hauptdolomit Formation and the lateral wedging of intertidal and supratidal sediments within short distance, ZANKL (1971) proposed an alternative model: Current activity and sediment producing and binding algae created mud mounds and tidal mud flats. Subsidence and eustatic sea-level fluctuations of centimeter amplitudes and periods of several hundred years may have modified growth pattern and shape of the tidal flats by erosion and transgression.

The Dachstein reefs are connected to the lagoonal area by a narrow back-reef belt (BÖHM, 1986), showing massive to thick bedded limestones with ooids, oncoids and other coated grains, "black pebbles", grapestones, algaes and reef debris.

Paleontological and microfacial research on the Dachstein reefs is summarized in FLÜGEL (1981). Reports on the macrofauna are given by ZAPFE (1962, 1967), a recent study of corals was done by RONIEWICZ (1995). Sedimentological and biofacial details from the Gosaukamm have been reported by WURM (1982) and from the Grimming mountain by BÖHM (1986). The massive Dachstein reef limestone of the Gosaukamm is dominantly composed of coarse-grained rud-/floatstones and reef debris with only small, widely distributed reef patches (frameworks built mainly by calcisponges; less frequent are corals, solenoporaceans and encrusting organisms). Fauna and flora of the patch reefs and the detrital limestones is very rich. More then 50 species contribute to the construction of the reef framework, while more than 60 species must be regarded as benthonic reef-dwellers. Pelagic elements from the open sea are known like *Heterastridium,* ammonites and conodonts.

The investigations by WURM (1982) at the Gosaukamm have shown that the associations of foraminifera and of calcareous algae are significant for distinct environments within the reef zone.

A large scale bedding (some 10 meters) can be seen. The original dip of the reef slope was not 30° as visible today, but about 10-15°, inferable from displaced geopetal fabrics.

Slope and nearby basin-facies are characterized by carbonate-clastic sediments, which were derived from the platform, as well as from the slope. These sediments are summarized under the term "Gosausee Limestone", which is often referred to in literature as "Pedata Schichten" according to the locally abundant brachiopod *Halorella pedata*. Exposures can be mainly found around the Gosau lakes and on the southwestern slopes of the Gosaukamm. Details of sedimentology and cyclicity of this bedded calciturbiditic limestone are given by REIJMER (1991). According to this author the variations in turbidite composition can be attributed to fluctuations in sea-level and resulting flooding and exposure of the platform. The resulting variation of platform sediment production could be matched with Milankovitch quasi-periodicities.

In the western Gosaukamm area (Rossmoos), the terrigenous Rhaetian Zlambach Formation is preserved, showing onlapping and interfingering with the uppermost Dachstein Limestone. The marls and limestones contain a rich coral fauna – well known since FRECH (1890). Additional elements are non-segmented calcareous sponges, spongiomorph hydrozoans, bryozoans, brachiopods, ammonites (*Choristoceras haueri* MOJS.), echinoderms, serpulids, and solenoporaceans.

The microfacies of Zlambach limestones is characterized by abundant reworked corals with encrusting organisms (e.g. *Nubecularia, Tubiphytes*) and some calcisponges and bryozoans. A packstone fabric is common and grain contacts often show stylolites. Miliolid and textulariid foraminifera are found in the micritic matrix (TOLLMANN and KRISTAN-TOLLMANN, 1970). FLÜGEL (1962) interpreted the environment as off-reef shoals within a muddy basin, somewhat deeper than and near to the forereef of the Gosaukamm reef.

The deeper and distal part of the Zlambach basin facies is not preserved at the Gosaukamm, but several kilometers to the northeast, at the type locality within the Hallstatt unit of Ischl-Aussee (for details see BOLZ, 1974; PILLER, 1981; MATZNER, 1986).

The Hallstatt facies – the deep shelf environment

Attention has been drawn to the variegated limestones of Hallstatt since the beginning of the geological research in the Northern Calcareous Alps in the 19th century, due to its local richness in cephalopods; for the first time about 500 species have been described from these strata. Mojsisovics's ammonite chronology (MOJSISOVICS, 1873, 1875, 1902), based on this fauna, has been widely used after several revisions as a standard for Triassic time.

SCHLAGER (1969) established the first lithostratigraphic subdivision of the Hallstatt successions based on distinct lithological features. Additional work, like reinvestigation of classical ammonite sites (KRYSTYN et al., 1971), correlation of lithostratigraphy and conodont zonation (e.g. KRYSTYN, 1980) and studies on the lithological variability of the Hallstatt successions (e.g. MANDL, 1984a) led to a picture which is shown in Fig. 6.

It also became clear that the two subfacies types, the Pötschen Facies (grey cherty limestones, marls, shales) and the Salzberg Facies (variegated Hallstatt limestones) do not belong to two different nappes in the Salzkammergut area, as suggested in previous works (e.g. MEDWENITSCH, 1958; TOLLMANN, 1976b). Lateral transitions between this subfacies can be demonstrated at nearly each stratigraphic level. Syndepositional block faulting and local uplift due to salt diapirism of the Permian evaporites are thought to be the reasons for the differentiation into basinal areas and intrabasinal ridges with reduced sedimentation. Syndepositional faulting is well documented (SCHLAGER, 1969) by numerous sediment-filled fissures at several stratigraphic levels at a scale of millimeters to some meters in width and up to 80 meters in depth, cutting down at a maximum from Sevatian red limestone into Anisian dolomites. Faulting is sometimes accompanied by block tilting and rotation, causing sedimentary gaps, discontinuities with breccias, and remarkable differences in sediment thicknesses of nearby successions.

The pelagic sedimentation of the Hallstatt facies has started with the drowning of the Steinalm shallow platform (dasycladaceean limestone) during the Pelsonian. This stratigraphic event is also widespread in other parts of the

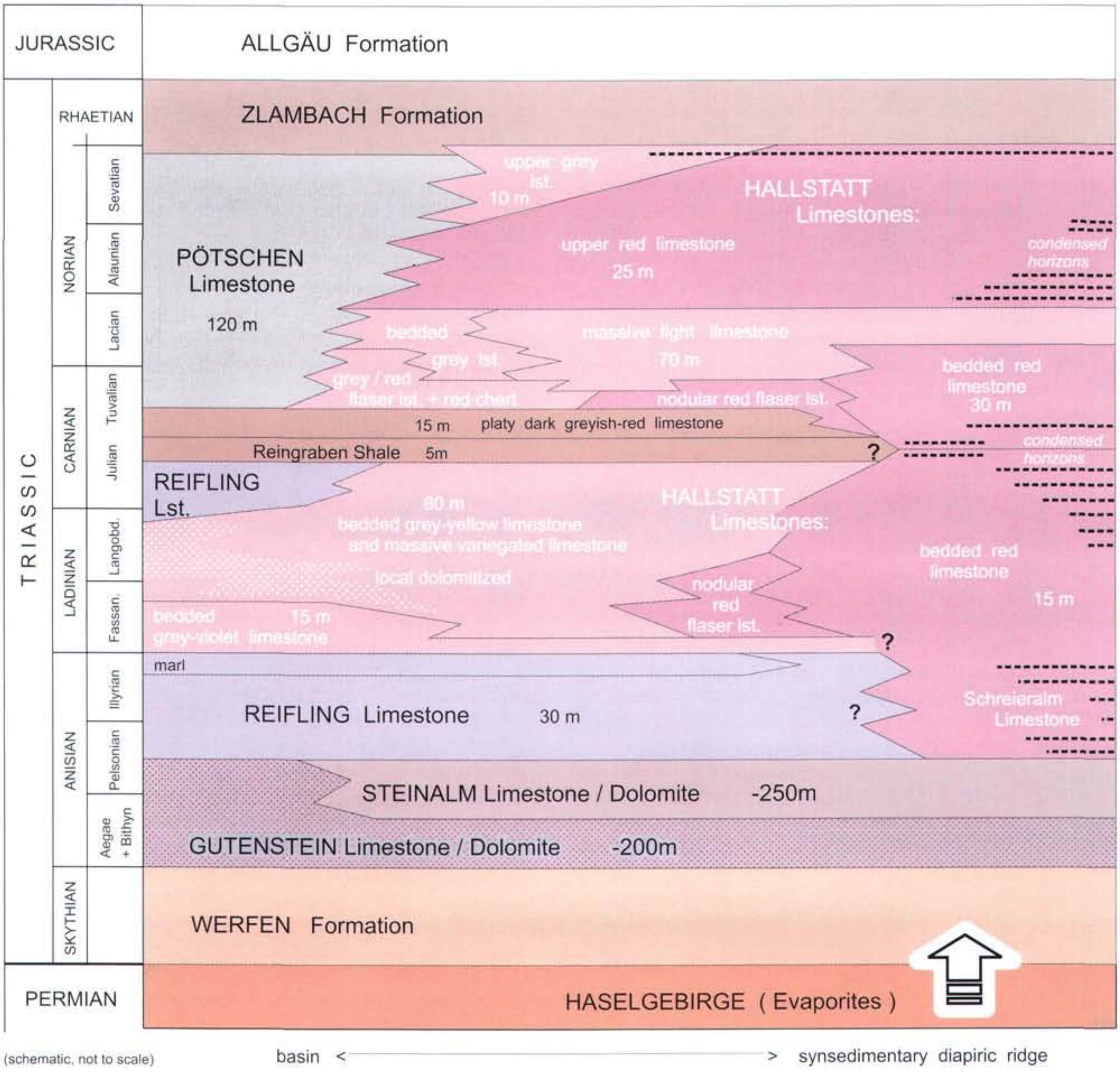


Fig. 6
Stratigraphy and lithological diversity of the Hallstatt Limestone succession (Juvavic nappe complex). Detail of Fig. 4, section A.

NCA. Grey cherty limestone (Reifling Limestone) represents the deeper basin, whereas red Schreieralm Limestone covers shallow horst structures; transitional types are not known yet. In the Late Anisian, a marl horizon of a few meters in thickness is frequent in the basin.

Beginning with the Ladinian, a characteristic lithological succession developed, which is repeated in a similar manner after the terrigenous Reingraben event also in the Late Triassic: Within the basin, the deposition of grey cherty limestones continued (Reifling and Pötschen Lst.); towards the ridges, they pass laterally either via variegated cherty limestones into bedded red limestones or via bedded grey transitional types into light-colored massive limestones. The red Hallstatt limestones, covering the top of the diapiric ridges, frequently show subsolution horizons and condensation (ferromanganese crusts). For example, the thickness of the "upper red limestone" can be reduced within a lateral distance of 200 meters from about 25 meters to zero (KRYSTYN et al., 1971). The Early Carnian Reingraben Shales and accompanying platy limestones are missing in some sections of red limestones. They are replaced by thick ferromanganese crusts, containing condensed cephalopod faunas.

Most of the classical ammonite sites are situated in red limestones within layers with reduced sedimentation and subsolution. Beside the cephalopods, certain coquina layers ("styriaca beds", "monotis beds") can be used as lithostratigraphic as well as chronostratigraphic marker beds in the Norian.

The Hallstatt limestone succession is terminated by increasing terrigenous input in the latest Norian and Rhaetian (Zlambach Marl). Early to Middle Jurassic sediments (spotted marls of the Allgäu Formation) are preserved only in a few localities. Late Jurassic radiolarites and limestones, resting on Hallstatt sequences, do not belong to the sequence in a strict sense, because they represent a matrix and a sealing "neoautochthonous" cover during and after displacement and gravitational transport of Hallstatt units during the Oxfordian tectonic event.

The Jurassic deepening and the onset of nappe movements

At the beginning of the Jurassic, the Austroalpine shelf drowned completely. Basinal conditions prevailed until the Early Cretaceous the only exception being the local Plassen carbonate platforms (latest Jurassic – Early Berriasian) in the southern NCA, especially in the realm of Juvavic nappes (see Fig. 7).

Drowning and synsedimentary faulting caused a complex seafloor topography with sedimentation of reddish/grey crinoidal limestones (Hierlatz Lst.) and red ammonoid limestones (Adnet and Klaus Lst.), mainly above former carbonate platforms and grey marly/cherty limestones (e.g. Allgäu Fm.) in the troughs in between.

Early Hettangian is often missing at the base of Hierlatz Limestone, e.g. at the type locality. The reason for this is still under discussion, wether this is due to subaerial exposure or submarine non-deposition,. Neptunian sills and dykes filled with red or grey Liassic limestones are frequent, cutting down into the Norian shallow water carbonates for more than 100 meters.

According to BÖHM (1992) and BÖHM and BRACHERT (1993) Adnet- and Klaus Limestones are bioclastic wackestones, mainly made up of nannoplankton (*Schizosphaerella*, coccoliths) and very fine-grained biodetritic material. After globigerinids evolved in the Middle Jurassic, they also became a major component of these sediments along with the tiny shells ("filaments") of probably planktonic juvenile forms of the bivalve *Bositra*. The macrofauna mainly consists of crinoids and in some places very abundant brachiopods and ammonites. Strong condensation, Fe/Mn stained hardgrounds and deep-water stromatolites, are frequent. According to KRYSTYN (1971), the Klaus Limestone at the type locality unconformably covers the Late Norian Dachstein Limestone and contains an ammonite fauna indicating Late Bajocian.

The greatest water depth was reached in the Oxfordian, characterized by widespread radiolarite deposits, the Ruhpolding Formation and equivalents (DIERSCHE, 1980). The beginning of radiolarite deposition migrated from south toward north, starting in earliest Callovian in the Strubberg basin (Lammer area), according to GAWLICK and SUZUKI (1999). Contemporaneously, breccias, olistolites and large sliding blocks occur as a consequence of the Juvavic gravitational nappe movements. This first pulse of Alpine orogeny caused a new seafloor topography in the Late Jurassic. Shallow water conditions especially above large Juvavic "sliding units" led to the deposition of platform carbonates (Plassen Lst., Tressenstein Lst.), whereas pelagic limestones (Oberalm Lst.) filled the basins in between (FENNINGER and HOLZER, 1972; STEIGER and WURM, 1980).

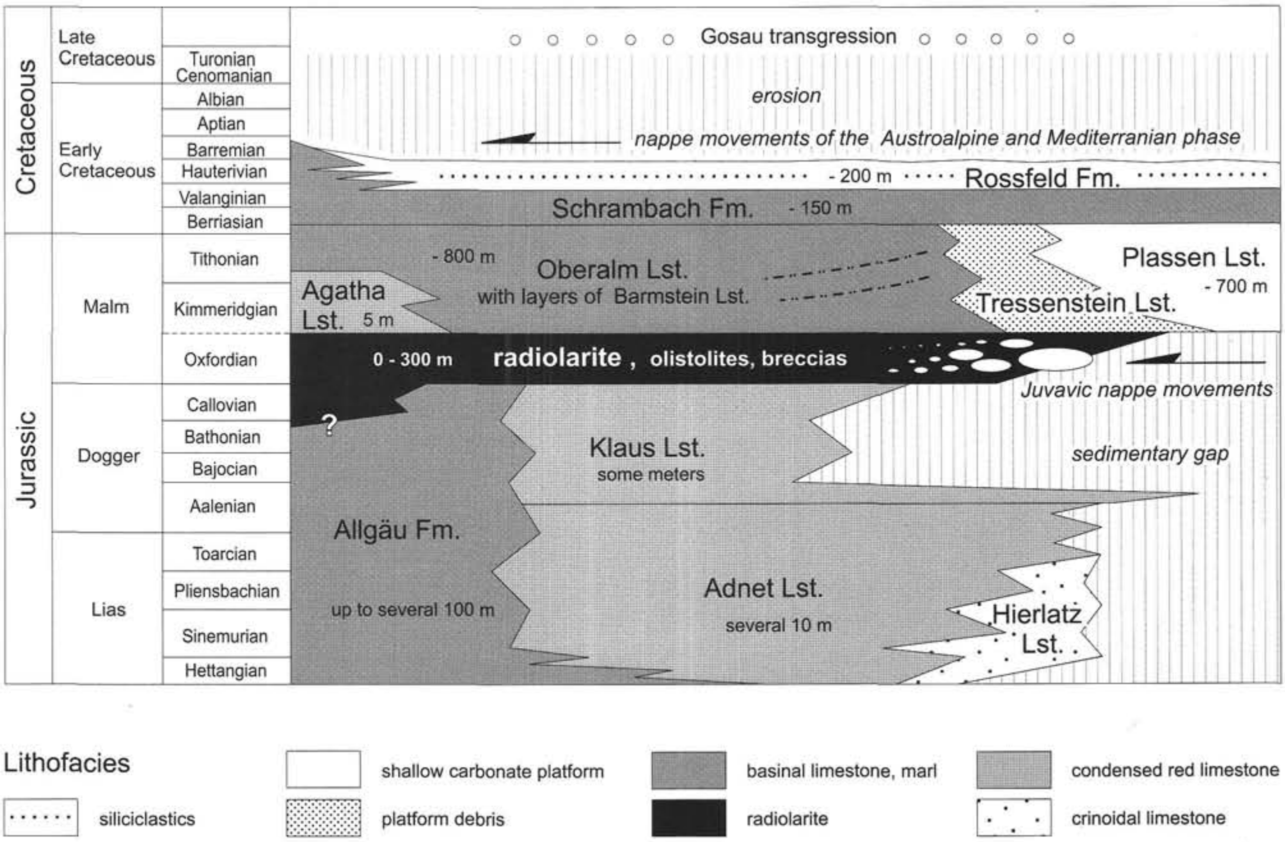
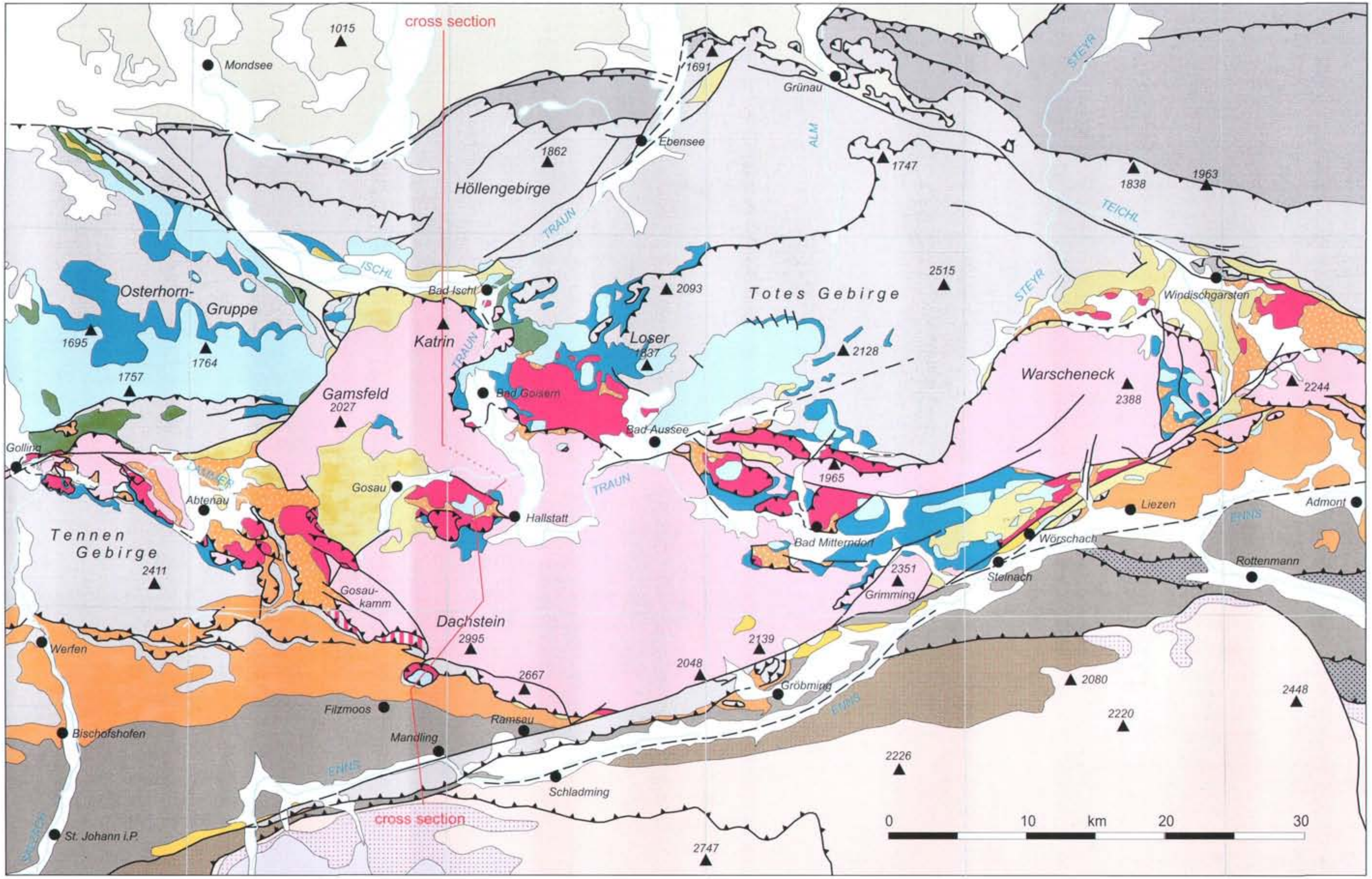
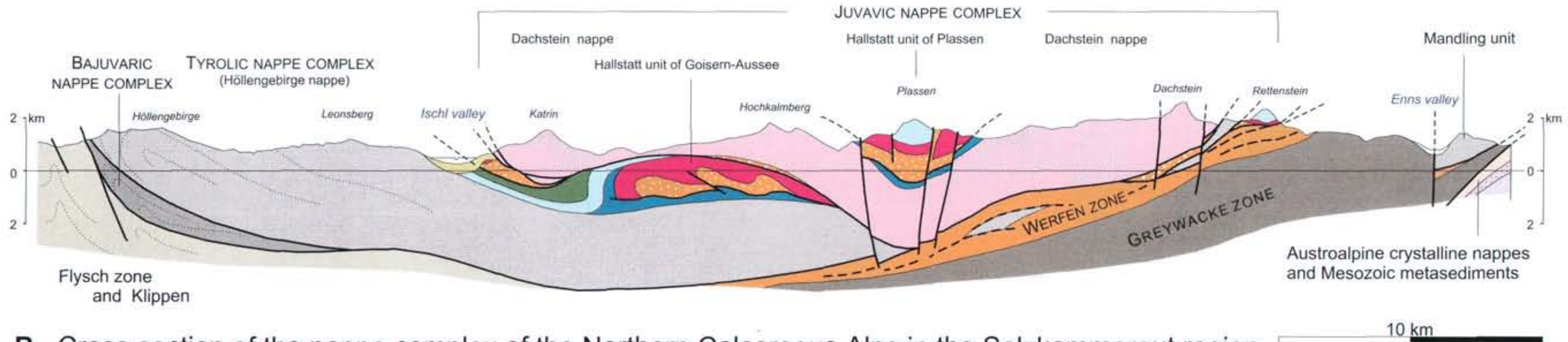


Fig. 7
Jurassic to Early Cretaceous stratigraphy of the Northern Calcareous Alps (middle sector); (after BÖHM, 1992, modified).

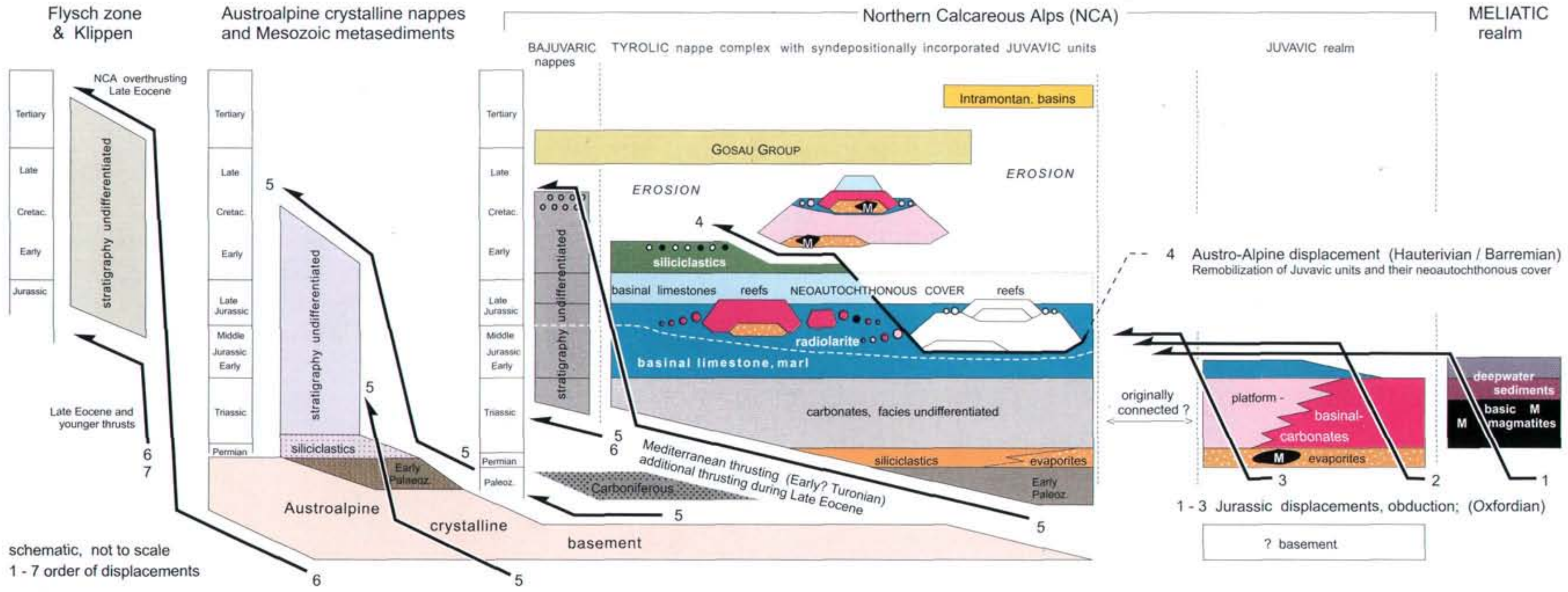


A. Geological map of the Salzkammergut Region.

Fig. 8
Geology of the middle sector of the Northern Calcareous Alps. A – Geological map. B – Cross-section. C – Tectonic evolution.



B. Cross section of the nappe complex of the Northern Calcareous Alps in the Salzkammergut region.



C. Interaction of sedimentation and tectonical displacements in the middle sector of the Northern Calcareous Alps.

As indicated by microfossils, the facies of Late Jurassic carbonates persists into the Early Cretaceous. Deepening and increasing terrigenous input caused a gradual transition into the marly aptychus limestones of the Schrambach Formation. The syntectonic clastic facies of the Rossfeld Formation replaced the deep water carbonates since the Late Valanginian, filling a trench-like structure in front of the advancing nappes (FAUPL and TOLLMANN, 1979; FAUPL and WAGREICH, this volume).

The deposition of the Rossfeld Formation took place during the crustal shortening within the Austroalpine basement. This tectonic process caused an uplift of southern sectors of the NCA, thrusting and remobilisation of the Juvavic Nappes and metamorphism in the Austroalpine crystalline nappes below.

The Salzkammergut – an example for Jurassic nappe movement

The uppermost tectonic elements of the Northern Calcareous Alps are traditionally summarized under the term Juvavicum (Juvavum was the Latin name of Salzburg). From our recent point of view they represent those parts of the Austroalpine distal shelf area, which initially became detached from their basement during the Late Jurassic, caused by the closure of the westernmost part ("Hallstatt-Meliata sector") of the Tethys ocean. Repeated compressional tectonics affected the NCA additionally between Neocomian to Eocene, while large strike-slip faults dissected the nappe pile during Miocene.

Due to this deformation history, a complex pattern of tectonic units was created in the Juvavic realm (see Fig. 8A,B). The dissection of the Triassic sediments mainly followed facies boundaries, often resulting in "unifacial" tectonic bodies. Therefore, the original configuration of platforms and basinal areas especially has been a matter of longlasting and controversial discussion.

Detailed mapping of facies distribution within distinct tectonic units, accompanied by biostratigraphic control, has revealed a great amount of information about general facies trends and the relation between different facies types. The orientation of platform to basin transitions within the larger Juvavic units provides a framework for palinspastic restoration of the Juvavic realm. According to our recent knowledge, all transitions from platform to open marine conditions are oriented in a similar manner, facing toward the south. A "Dual Shelf Model", as it has been recently proposed for the NCA by some authors (KOZUR and MOSTLER, 1992; SCHWEIGL and NEUBAUER, 1997), is in contradiction to the visible facies patterns. If the Juvavic units had indeed originated from an opposite southern shelf, separated from the Tyrolic shelf by an ocean (Meliata realm), the Juvavic units should also exhibit facies gradients of opposite orientation.

The NCA represent the carbonatic shallow shelf area and its transition into deeper pelagic conditions (Figs. 2, 4 and 8C). The adjacent oceanic realm is preserved in the Eastern Alps only as a few and small "exotic klippen" (MANDL and ONDREJICKOVA, 1991, 1993; KOZUR and MOSTLER, 1992). Triassic deep-water sediments (red radiolarite) are there preserved as olistolites in a Jurassic matrix of dark shales and greenish radiolarite. Representatives of the Triassic oceanic crust are not proven. Candidates for such an origin are tholeiitic pillow basalts and serpentinite fragments within the melange of Permian evaporites along the basal thrusts of several Juvavic nappes (KIRCHNER, 1979, 1980; KOZUR and MOSTLER, 1992; VOZAROVA et al., 1999). Unfortunately, we still have no clear evidence of their magmatic age until now.

The detachment of the Triassic to Jurassic shelf sediments from their basement (Fig. 8C) started at about the beginning of the Late Jurassic (PLÖCHINGER, 1976; TOLLMANN, 1981, 1987; GAWLICK et al., 1999). Jurassic syntectonic clastics (GAWLICK, 1996), as well as the "sandwich" of Juvavic units, demonstrate the first displacement from the Hallstatt deeper shelf (Pötschen- and Salzberg-facies) and gravitative transport onto and across the drowned Triassic shallow shelf. Rocks derived from the Meliata oceanic realm should have also been mobilized before or during this phase. With time, the detachment encroached on the Triassic platform margins and at last on the platforms themselves, creating the large Juvavic nappes like the Dachstein- or the Mürzalpen nappe. These large nappes carry tectonical outliers of Hallstatt facies on the one hand, while on the other hand they were transported onto similar Hallstatt outliers, resting in Jurassic basins of the future Tyrolic nappes. Such multiple stacking of Triassic rocks of different depositional realms is a common feature of the Juvavic nappe complex, the time of the initial stacking is restricted to the Ruhpolding interval (Late Jurassic). After this first phase of intensive movements, a period of tectonic inactivity lasted until the Early Cretaceous. The Juvavic units became covered by marine Late Jurassic to Early Cretaceous carbonate sediments of platform- and basinal facies.

A next phase of tectonic activities (Hauterivian to Barremian) mobilized the western segments of the Juvavic units again: the Dachstein nappe, the Reiteralm nappe and accompanying Hallstatt outliers were transported onto the Neocomian clastics of the Roßfeld trough also containing ophiolitic detritus (chromite). A subsequent uplift exposed large parts of the Eastern Alps to weathering and erosion before the Late Cretaceous Gosau transgression.

Conclusions

The sedimentary rocks of the Northern Calcareous Alps reflect the tectonosedimentary evolution of the Eastern Alpine sector of the Tethyan shelf. The stratigraphic succession starts in the Permian with evaporites and siliciclastics and continues with shallow platform carbonates and basinal limestones from the Middle to Late Triassic. The opening of the Penninic ocean separated the Austroalpine realm from stable Europe. The Austroalpine shallow shelf drowned and reached its greatest depth at the end of the Middle Jurassic. Penninic rifting was accompanied by transpressional deformation of the Tethyan margin of the Austroalpine microplate, resulting in extensive sliding tectonics of Juvavic platform- and basin-successions into the Tyrolic radiolarite basins. Late Jurassic to Early Cretaceous carbonates sealed this first tectonic event. The beginning of crustal shortening within the Austroalpine basement at the end of the Early Cretaceous initiated the main nappe movements in its sedimentary cover.

These principles of geodynamic evolution of the Salzkammergut area are currently used as a working hypothesis for revealing the complex geological history of the eastern part of the NCA. As known from excursions and discussions with Slovakian colleagues, this model may also be valid for the Carpathian counterparts of the Northern Calcareous Alps, especially for the Inner Western Carpathians.

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