# MESOZOIC TECTONOSTRATIGRAPHY OF THE EASTERN ALPS (NORTHERN CALCAREOUS ALPS, AUSTRIA): A RADIOLARIAN PERSPECTIVE

# MEZOZOJSKA TEKTONOSTRATIGRAFIJA VZHODNIH ALP (SEVERNE APNENIŠKE ALPE, AVSTRIJA): RADIOLARIJSKA PERSPEKTIVA

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## ABSTRACT

**Mesozoic tectonostratigraphy of the Eastern Alps (Northern Calcareous Alps, Austria): a radiolarian perspective**

The topic of the field trip is the Mesozoic geodynamic evolution in the Western Tethys realm well recorded in deep-water settings, especially in the radiolarian-bearing sedimentary rocks and radiolarites in the Eastern Alps (Northern Calcareous Alps). The well preserved Mesozoic sedimentary successions deposited in the Northern Calcareous Alps reflect two different Wilson cycles with its mountain building processes:

Evolution of the Neo-Tethys Ocean to the south/southeast: The Middle Triassic oceanic break-up (Late Anisian) was followed by the Middle Triassic to Middle Jurassic passive margin evolution and later by Middle to early Late Jurassic thrusting related to ophiolite obduction and subsequent latest Jurassic to Early Cretaceous mountain uplift of the Neo-Tethys orogen to the south of the todays Northern Calcareous Alps.

Evolution of the Alpine Atlantic Ocean (named Penninic Ocean in the Eastern Alps) to the north/northwest: The Late Early to Middle Jurassic oceanic break-up was followed by the Middle Jurassic to Late Cretaceous passive margin evolution and Late Cretaceous to Palaeogene subduction of the Penninic realm, Palaeogene collision and subsequent Neogene mountain uplift with its gravitational collapse (Lateral Tectonic Extrusion) of the Alpine orogen s.str.

For another orogenesis in the "Mid-Cretaceous" (Aptian-Cenomanian), i.e. between these two well recognizable

## IZVLEČEK

**Mezozojska tektonostratigrafija Vzhodnih Alp (Severne Apneniške Alpe, Avstrija): radiolarijska perspektiva**

Ekskurzija je posvečena mezozojski geodinamični evoluciji zahodne Tetide. Ta je dobro zabeležena v globokomorskih okoljih, še posebej v radiolaritih in drugih radiolarijskih sedimentnih kamninah v Vzhodnih Alpah, katerih del so Severne Apneniške Alpe. Dobro ohranjena mezozojska sedimentna zaporedja v Severnih Apneniških Alpah odražajo dva različna Wilsonova cikla z gorotvornimi procesi.

Prvi cikel se nanaša na razvoj oceana Neotetida na jugu do jugovzhodu. Oceanskemu razpadu v srednjem triasu (zgornjem aniziju) je sledil razvoj pasivnega roba do srednje jure in pozneje, v srednji in zgornji juri, narivanje, povezano z obdukcijo ofiolitov. Na koncu jure in v spodnji kredi se je dvigal Neotetidin orogen, lociran južno od današnjih Severnih Apneniških Alp.

Drugi cikel je povezan z razvojem oceana Alpski Atlantik (imenovanega Peninski ocean v Vzhodnih Alpah) na severu do severozahodu. Oceanskemu razpadu proti koncu spodnje jure in v srednji juri je sledil razvoj pasivnega roba od srednje jure do zgornje krede in subdukcija Peninika v zgornji kredi in paleogenu. Sledila je kolizija v paleogenu, v neogenu pa nadaljnje dviganje orogena z gravitacijskim kolapsom (lateralnim tektonskim iztiskanjem) Alpskega orogena *sensu stricto*.

Obstajajo še dokazi za orogenezo v "srednji kredi" (aptij-cenomanij) med tema dvema dobro prepoznavnima Wilsonovima cikloma, vendar geodinamično ozadje te orogene-

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Wilson cycles, the geodynamic background has not been well explored or explained yet. This "Mid-Cretaceous" orogenesis draws a veil over the older Mesozoic plate configuration and has generated controversial discussion about the geodynamic evolution and palaeogeography in Triassic to Early Cretaceous times. However, this orogenesis is not connected to the Neo-Tethys or the Alpine Atlantic Wilson cycle.

The field trip will focus on Triassic to Early Cretaceous deep-water, radiolarian-bearing sedimentary rocks deposited during the geodynamic history of the Neo-Tethys in different basins: rift-basins, shelf areas to continental slope, oceanic domains, and trench-like foreland basins. Special emphasis will be on the Jurassic to Early Cretaceous history, i.e. the geodynamic evolution before the "Mid-Cretaceous" tectonic motions and the influence of the evolution of two oceanic domains on the depositional environment above a drowned Triassic shelf (Apulian or wider Adria plate) between the Neo-Tethys Ocean to the south/southeast and the Alpine Atlantic Ocean to the north/northwest.

The geodynamically triggered interplay between carbonate production, siliciclastic/volcanic input and deposition of siliceous rocks/radiolarites in combination with the asynchrony of basin formation frequently allows the calibration of radiolarians with e.g., ammonoids, conodonts, calpionellids and other organisms. Following the Middle Triassic (Late Anisian) Neo-Tethys oceanic break-up and the demise of shallow-water carbonate production, deposition of Middle Triassic (Late Anisian to Ladinian) radiolarian-bearing, mainly carbonate deep-water sediments is widespread all over the shelf. Deposition of radiolarites in the Eastern Alps is limited to the outer shelf/continental slope and the Neo-Tethys oceanic domain to the south/southeast. Widespread shallow-water carbonate production started again in the latest Middle Triassic (Late Ladinian) and lasted until the end of the Triassic, interrupted only by short-lasting siliciclastic intervals ("Mid-Carnian" turnover, Lunz event). In the Late Triassic huge carbonate platforms were formed. Deposition of Late Triassic open-marine and radiolarian-bearing sediments is therefore limited mainly to the outer shelf region and radiolarites were deposited only on the Neo-Tethys ocean floor.

In Jurassic times, after the demise/drowning of the Late Triassic carbonate platform, calcareous siliceous sediments were again deposited widely. Rifting in the Alpine Atlantic realm to the north/northwest started in the Early Jurassic with oceanic break-up occurring from the Early/Middle Jurassic boundary onwards. The opening of the Alpine Atlantic to the north/northwest and, contemporaneously, the onset of convergence in the Neo-Tethys to the south/southeast worked in concert with radiolarite deposition culminating in the Middle Jurassic. Radiolarites were deposited practically all over the drowned continent except the areas of the Adriatic Carbonate Platform. Obduction of Neo-Tethys derived ophiolites since the Middle Jurassic led to the formation of a thin-skinned orogen with the formation of trench-like foreland basins in front of the advancing ophiolites. In these basins sedimentary mélanges with a radiolaritic-argillaceous matrix were deposited until the early Late Jurassic. Kimmeridgian-Tithonian shallow-water carbonate production on upper surfaces of the nappes restricted radiolarite

ze še ni dobro raziskano ali pojasnjeno. "Srednjekredna" orogeneza zakriva starejšo mezozojsko konfiguracijo plošč, kar je vzrok za kontroverzno razpravo o geodinamičnem razvoju in paleogeografiji od triasa do spodnje krede. Ta orogeneza ni bila povezana z Wilsonovim ciklom Neotetide ali Alpskega Atlantika.

Fokus ekskurzije je na radiolarijskih globokomorskih sedimentnih zaporedjih na robu Neotetide od triasa do spodnje krede. Zaporedja so bila odložena v različnih okoljih: v riftnih bazenih, na šelfu in kontinentalnem pobočju, v oceanu in v predgornih bazenih. Poseben poudarek bo na evoluciji v juri in spodnji kredi oziroma na geodinamičnem razvoju pred "srednjekrednimi" tektonskimi premiki. Poudarjen bo vpliv razvoja dveh oceanov na sedimentacijsko okolje, ki se je diferenciralo, ko se je potopil triasni šelf (Apulijska ali širša Jadranska plošča) med Neotetido na jugu/jugovzhodu in poznejšim Alpskim Atlantikom na severu/severozahodu.

Geodinamična evolucija in medsebojni vplivi med produkcijo karbonatov, siliciklastičnim ali vulkanskim vnosom in odlaganjem kremenični sedimentov/radiolaritov v kombinaciji z asinhronim oblikovanjem bazenov omogočajo, da se v določenih obdobjih radiolariji pojavljajo skupaj z drugimi organizmi, npr. amonoidi, konodonti in kalpionelidami. Po razpadu Neotetide v srednjem triasu (zgornjem aniziju) in prenehanju produkcije karbonatov v plitvi vodi so bili po celotnem šelfu razširjeni srednjetriasni (zgornjeanizijski do ladinijski) radiolarijski, predvsem karbonatni globokomorski sedimenti. Odlaganje radiolaritov je bilo v Vzhodnih Alpah omejeno na zunanji šelf in kontinentalno pobočje ter na oceansko območje Neotetide na jugu/jugovzhodu. Razširjena produkcija karbonatov v plitvi vodi se je ponovno vzpostavila na koncu srednjega triasa (v zgornjem ladiniju) in je trajala do konca triasa. Prekinjena je bila s kratkotrajnimi siliciklastičnimi intervali (»srednjekarnijski« obrat, dogodek Lunz). V zgornjem triasu so nastale obsežne karbonatne platforme. Odlaganje zgornjetriasnih globokomorskih sedimentov in sedimentov, ki vsebujejo radiolarije, je bilo torej omejeno predvsem na območja zunanjega šelfa, radiolariti pa so se odlagali zgolj na oceanskem dnu Neotetide.

V juri, po potopitvi zgornjetriasne karbonatne platforme, so se s kremenico bogati karbonatni sedimenti ponovno odlagali na širšem območju. V spodnji juri se je začel tudi rifting na severu/severozahodu, ki je na meji med spodnjo in srednjo juro privedel do oceanizacije Alpskega Atlantika. Odpiranje Alpskega Atlantika na severu/severozahodu in sočasni začetek konvergence v Neotetidi na jugu/jugovzhodu sta hkrati delovala na poglabljanje bazenov na kontinentalnem robu, tako da je odlaganje radiolaritov v srednji juri doseglo višek. Radiolariti so se odlagali tako rekoč po celotnem potopljenem območju razen na Jadranski karbonatni platformi. Obdukcija ofiolitov z območja Neotetide od srednje jure dalje je privedla do oblikovanja tankoslojnega orogena in nastanka jarkom podobnih predgornih bazenov pred napredujočimi ofioliti. V teh bazenih so se do začetka zgornje jure odlagali melanži z radiolaritno-glinastim vezivom. V kimmeridgiju in tithoniju se je na novo nastalih pokrovih vzpostavila plitvovodna karbonatna produkcija, radiolariti pa so ostali omejeni na preostale globokovodne bazene. Zaradi dvigovanja orogena od zgornje jure (od titho-

deposition to remaining deep-water basins. In the frame of mountain uplift from the latest Jurassic (Tithonian) onwards the palaeotopography becomes overprinted by unroofing. Remaining deep-water foreland basins were successively filled in the Early Cretaceous by the erosional products of the uplifted Middle-Late Jurassic Neotethyan orogen.

During this field trip in one of the most classical areas of the world, the central Northern Calcareous Alps with its world-wide known touristic highlights, we will visit locations documenting the interplay between siliciclastic input, volcanic activity, carbonate production, various tectonic motions and deposition of radiolarian-bearing siliceous rocks to radiolarites.

*Key words:* Western Tethys realm, Triassic, Jurassic, Radiolarites, Palaeogeography

nija) naprej in posledično erozije se je paleotopografija popolnoma spremenila. Preostali globokomorski predgorni bazeni so bili v spodnji kredi drug za drugim zapolnjeni z materialom, erodiranim z dvignjenega srednje do zgornjejurskega orogena Neotetide.

Ekskurzija je speljana po enem najbolj klasičnih območij sveta, osrednjih Severnih Apneniških Alpah, s svetovno znanimi turističnimi znamenitostmi. Obiskali bomo lokacije s sedimentnimi zaporedji, iz katerih lahko razberemo medsebojno povezanost med vnosom siliciklastitov, vulkansko dejavnostjo, produkcijo karbonatov, različnimi tektonskimi dogajanji ter odlaganjem radiolaritov in drugih kremeničnih kamnin z radiolariji.

*Ključne besede:* Zahodna Tetida, trias, jura, radiolariti, paleogeografija

# 1 INTRODUCTION

Triassic–Jurassic/Early Cretaceous siliceous sedimentary rocks and radiolarites play a crucial role for palaeogeographic and geodynamic reconstructions of the Western Tethyan realm and occur widespread in the different orogenic belts around the Mediterranean. Their deposition is related to two oceanic realms, the Tethyan and the Atlantic oceanic systems and the con-

tinental realm in between (wider Adria since Jurassic times with the Eastern Alps as part of it, the field trip area: Figure 1).

In the eastern Mediterranean mountain ranges (Eastern and Southern Alps, Western Carpathians, units in the Pannonian realm, Dinarides, Albanides, Hellenides) the deposition of Triassic–Jurassic/Early
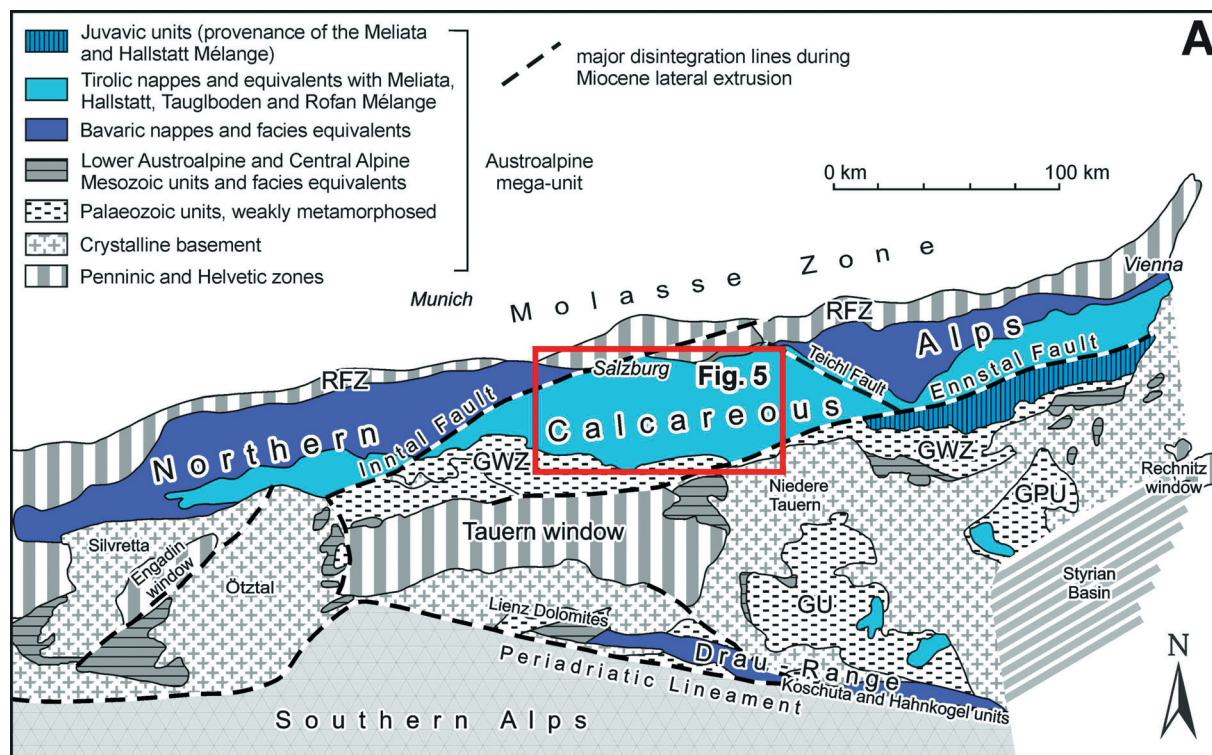


*Figure 1: Tectonic sketch map of the Eastern Alps and field trip area (marked by the red box) in the central Northern Calcareous Alps (compare Figure 5; after Tollmann 1977; Frisch & Gawlick 2003; modified). GPU Graz Palaeozoic unit; GU Gurktal unit; GWZ Greywacke Zone; RFZ Rhenodanubian Flysch Zone.*

Cretaceous siliceous sedimentary rocks and radiolarites is characteristic for specific stratigraphic levels (Figure 2). Related to specific events they were deposited widespread in open shelf areas, not only in the oceanic domains but also in deep-water foreland basins (Late Jurassic to Early Cretaceous). We discuss these radiolarite events on basis of the sedimentary evolution and tectonostratigraphy of the Northern Calcareous Alps as part of the Eastern Alps (Figs. 3, 4).

Herein follows a brief summary of the most important tectonostratigraphic and other events and its effect on the sedimentological record and biological response for Triassic to Early Cretaceous times. For a more detailed explanation interested readers are referred to the publication of GAWLICK & MISSONI (2019) with references therein.

Rifting in the Neo-Tethys Ocean (= Meliata-Hallstatt, Maliac, Dinaride, Pindos/Mirdita, Vardar oceans) began in the Late Permian, the oceanic break-up followed in the Middle Triassic (Late Anisian) and intra-oceanic convergence started around the Early/Middle Jurassic boundary followed by ophiolite obduction and formation of an orogen during Middle-Late Jurassic (Bajocian to Oxfordian) times (see GAWLICK & MISSONI 2019 for a recent overview, and references therein). Rifting in the Alpine Atlantic (= Magura/Vah, Penninic, Piemont, Ligurian oceans) started shortly after the Triassic/Jurassic-boundary in the Middle/Late Hettangian, followed by continental break-up in the late Early Jurassic (Toarcian), and closure started in the Late Cretaceous.

Triassic sedimentation in the eastern Mediterranean mountain ranges was triggered by the evolution of the Neo-Tethys, whereas in Jurassic to Early Cretaceous times sedimentation was controlled by both the evolution of the Neo-Tethys and the Alpine Atlantic. Whereas in the Eastern and Southern Alps, the Western Carpathians and units in the Pannonian realm, the Alpine Atlantic has a direct influence on the depositional record, this influence is minor in the Dinarides-Albanides-Hellenides because these areas are shielded by the Adriatic Platform (VLAHOVIĆ et al. 2005). Jurassic to Early Cretaceous sedimentation was therefore controlled by the opening of the Alpine Atlantic Ocean to the north/northwest (break-up in the Toarcian: RATSCHBACHER et al. 2004), the partial closure of the Neo-Tethys Ocean to the south/southeast from the Early/Middle Jurassic boundary onwards, the Middle Jurassic to Early Cretaceous mountain building process related to Middle to early Late Jurassic ophiolite obduction, and latest Jurassic to Early Cretaceous mountain uplift and unroofing (MISSONI & GAWLICK 2011a; GAWLICK & MISSONI 2019; GAWLICK

et al. 2020a and references therein). Whereas the more southern orogenic belts (Dinarides, Albanides, Hellenides) were little affected by the Atlantic related rifting in Jurassic times, the Eastern and Southern Alps, Western Carpathians and some units in the Pannonian were affected by both events: closure of the Neo-Tethys to the east/southeast and opening of the Alpine Atlantic to the north/northwest.

Radiolarites were deposited on the Neo-Tethys passive margin and as sedimentary cover of the Neo-Tethys oceanic crust, beginning in the Late Anisian (GAWLICK et al. 2008; OZSVÁRT et al. 2012). Radiolarites are the typical sedimentary rocks deposited (often accompanied with volcanics) in Late Anisian to Ladinian times in the Dinaride-Hellenide mountain chain (for a recent review, see GAWLICK et al. 2012a). In contrast, radiolarites are only rarely reported from the Triassic sedimentary shelf successions of the Alpine–Carpathian mountain belt. In this domain radiolarian-rich cherty limestones were mainly deposited (Figure 3) and often the radiolarians are recrystallized and/or not well preserved. The oldest widespread deposited radiolarites related to the Neo-Tethys Ocean were formed in Late Anisian to early Late Ladinian times, in both the Neo-Tethys ocean and in the (distal) passive margin setting, where the water depth did not exceed a few hundred metres.

The peak event of radiolarite deposition was in the Late Anisian (Illyrian), a period characterized by intense volcanism, restricted carbonate production and a relative high sea-level. The second more short-lasting radiolarite event followed the demise of the Late Ladinian - Early Carnian shallow-water platform cycle (Wetterstein Carbonate Platform) in the Middle Carnian (upper Julian), but was restricted to not filled intra-platform basins formed between the Wetterstein Carbonate Platform pattern before they became filled by siliciclastics (e.g. Eastern and Southern Alps, Western Carpathians) (Figure 3). This is in contrast to the southern orogenic belts (e.g. Hellenides, Albanides, Dinarides) where deposition of siliciclastic sedimentary rocks is restricted to the northern Outer Dinarides. Radiolarites and/or siliceous claystones were deposited in the oceanic domain, but were sparse in the distal margin. Mid-Carnian radiolarites or radiolarian-rich cherty limestones therefore occur more rarely, but also in in the Dinarides.

The peak of this radiolarite event predates the "Mid Carnian Pluvial Event" (OGG 2015 and references therein) and can be related to a sea-level lowstand (Göstling Formation in the Northern Calcareous Alps with rich radiolarian faunas – KOZUR & MOSTLER 1981). The Late Carnian to Norian is characterized by carbonate platform formation elsewhere in the West-
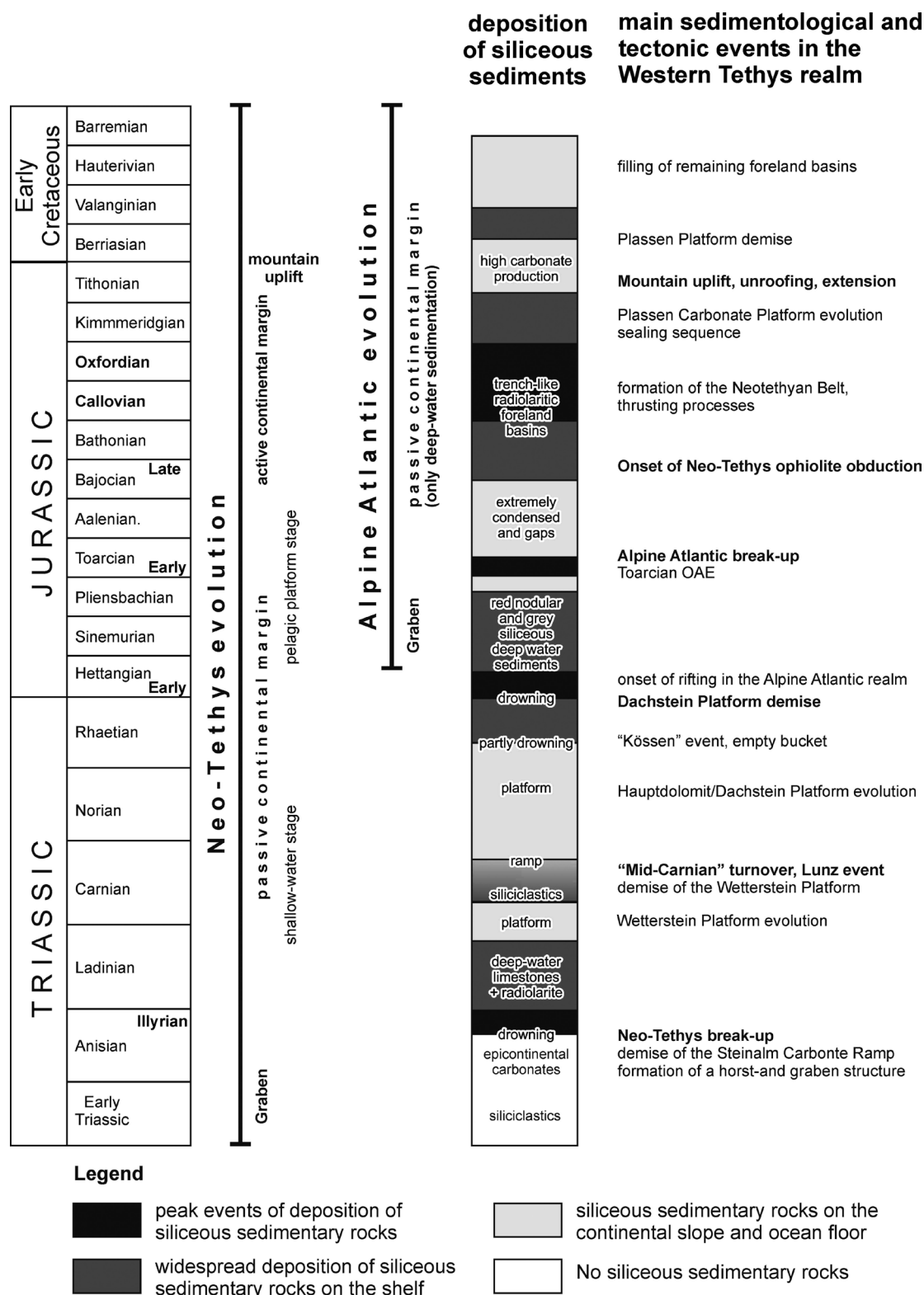
Figure 2: Triassic to Early Cretaceous geological time scale and frequency of radiolarite deposition related to different events in the sedimentary record of the Western Tethyan realm. During the peak event times spans siliceous sedimentary rocks and radiolarites were deposited not only in the oceanic domains. They were formed widespread also on the shelf areas in relatively shallow-water depths (maximum 200–300 m) and in deep-water foreland basins.

ern Tethys realm (Hauptdolomit/Dachstein Carbonate Platform) (Figure 3). In the northern orogenic belt the Rhaetian siliciclastic "Kössen event" decreased the carbonate production in certain areas and in deepened lagoons siliceous marls were deposited (Figure 3). In addition, in the Rhaetian in some areas of the distal Neo-Tethys passive margin radiolarian-rich sediments were deposited related to the partial drowning of the Late Triassic platform due to the increase of siliciclastics and the formation of deep lagoonal areas (e.g. Kössen Basin in the Eastern and Southern Alps, Western Carpathians).

The final drowning of the Late Triassic platform around the Triassic/Jurassic boundary is widespread followed by radiolarite deposition or radiolarian-rich siliceous marly limestones in the earliest Jurassic distal
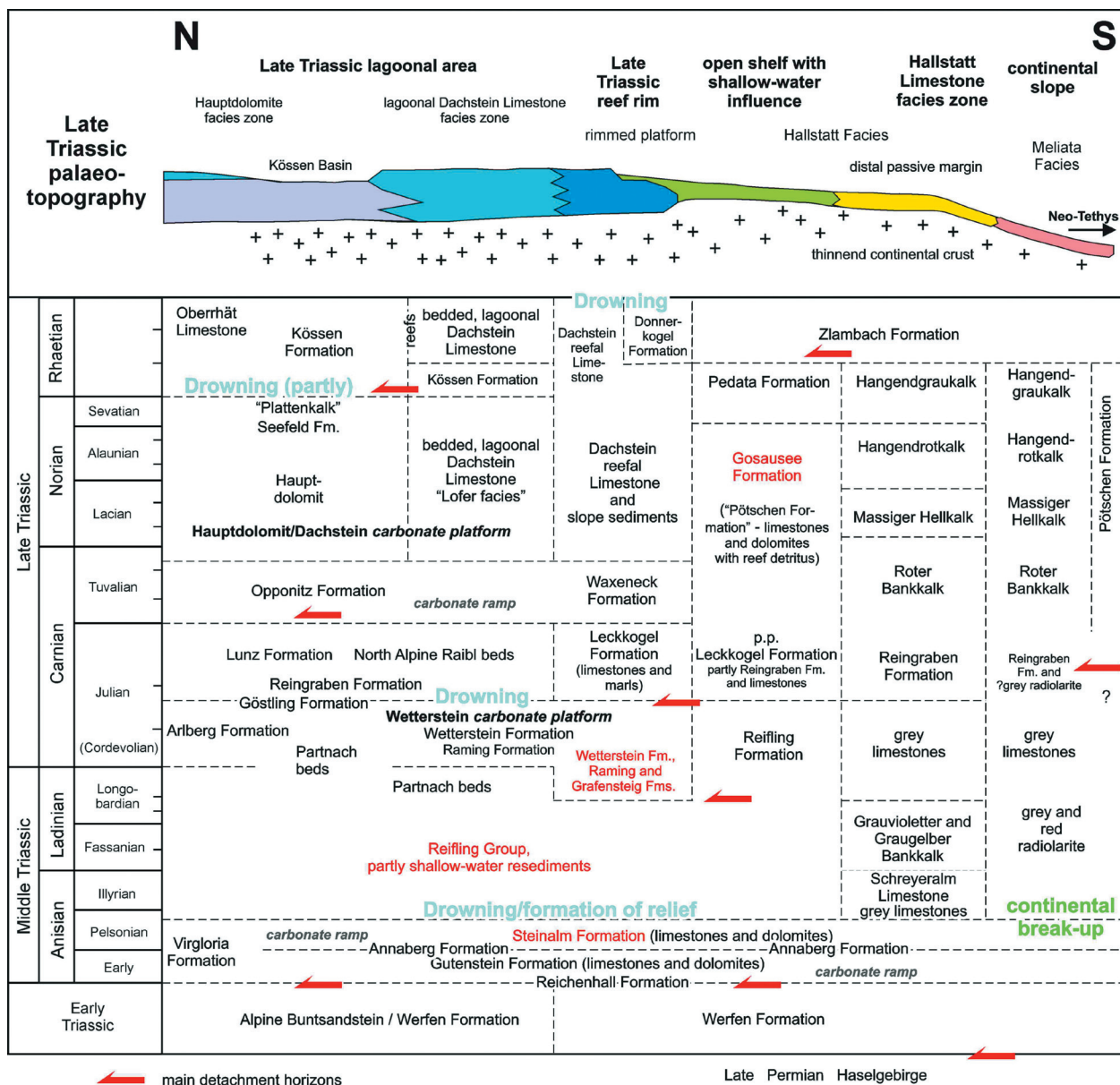


Figure 3: Simplified lithostratigraphic table of Triassic Formations in the central Northern Calcareous Alps with some important tectonostratigraphic events (added after Gawlick & Missoni 2019) and latest Triassic palaeotopography with indication of the different facies zones. Some important detachment horizons are indicated (Missoni & Gawlick 2011a, b) because of their importance during Middle to early Late Jurassic nappe stacking and disintegration of the sequence in the course of the northward propagating ophiolite obduction and formation of trench-like foreland basins in front of the advancing nappes filled with sedimentary mélanges (Figure 4). North-South after present directions. Formations indicated in red will be visited during the field trip.

passive margin setting and in former deep lagoon areas (sea-level lowstand to sea-level rise). In the deep lagoon grey cherty limestones, rich in radiolarians and spicules, were deposited (Figure 4). The Toarcian black shale event, with deposition of radiolarian-rich sedi-

ments, is contemporaneous with the eruption of two large igneous provinces (Karoo and Ferrar) and the break-up of the Alpine Atlantic (NEUMEISTER et al. 2015 and references therein), which was contemporaneous with the onset of intra-oceanic subduction in
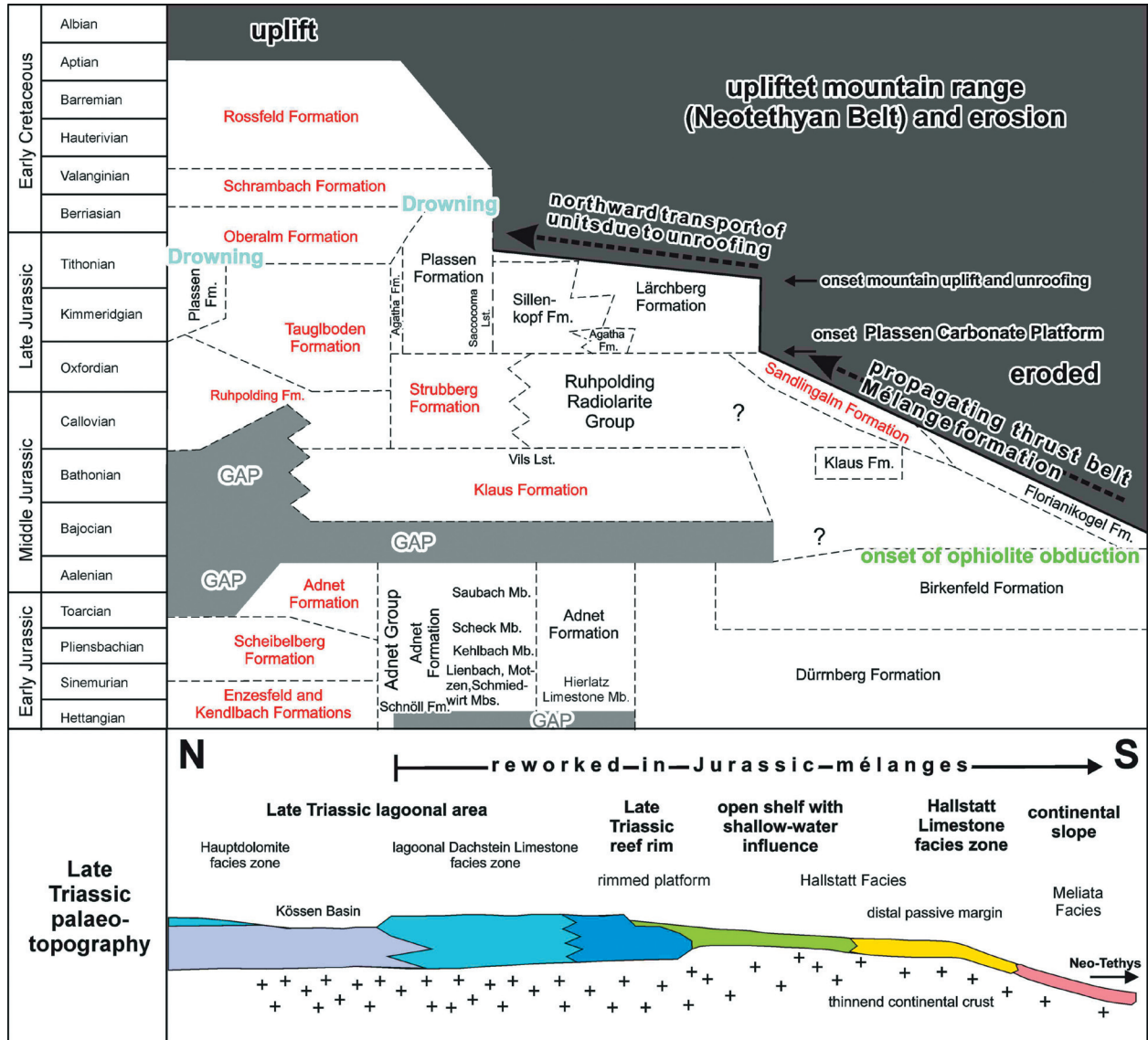


Figure 4: Simplified lithostratigraphic table of Jurassic to Early Cretaceous formations in the central Northern Calcareous Alps (after Gawlick & Missoni 2019) and latest Triassic palaeotopography with indication of the different facies zones. After the drowning of the Late Triassic Hauptdolomite/Dachstein Carbonate Platform, deposition in Early to early Middle Jurassic times followed the latest Triassic palaeotopography. In the Middle Jurassic the situation changed due to the onset of north-directed ophiolite obduction. In Middle to early Late Jurassic times the former outer passive margin became imbricated. In front of the northward propagating thrust belt deep-water trench-like foreland basins were formed and filled with the erosional products from the advancing nappe stack (= sedimentary mélange formation). During a period of relative tectonic quiescence, the Plassen Carbonate Platform sealed the older tectonic structures before mountain uplift and unroofing started in the Tithonian. This resulted in the stepwise destruction of the Plassen Carbonate Platform, which became either uplifted and eroded or drowned. During the Early Cretaceous the erosional products of the uplifted orogen filled the remaining deep-water foreland basins. Of the different Bathonian to Oxfordian trench-like basins and the Early Cretaceous foreland basins, we will visit resediments from the whole Triassic to Middle Jurassic outer continental margin and the Neo-Tethys Ocean. Formations indicated in red will be visited during our field trip.

the Neo-Tethys Ocean (KARAMATA 2006) and therefore easily recognized (sea-level highstand). Strong Middle Jurassic rifting in the Alpine Atlantic and onset of ophiolite obduction in the Neo-Tethys resulted in the Bathonian-Oxfordian radiolarite event with the peak in the Callovian-Oxfordian (Figure 2). On the Neo-Tethys-side new trench-like basins began filling with argillaceous-radiolaritic carbonate-clastic sedimentary mélanges from Bathonian times onwards (Figure 4). These radiolarites were deposited in a relative deep-water setting. From the latest Oxfordian/ Kimmeridgian onwards a new carbonate platform pattern was formed on top of the obducted ophiolites and the rising nappe fronts (Figure 4). Therefore, on the Neo-Tethys-side intense carbonate production hampered widespread radiolarite deposition from the Kimmeridgian onwards. In the underfilled foreland basins between these platforms siliceous limestones with radiolarians were deposited, whereas more to the Alpine Atlantic-side radiolarites were still formed. In the Tithonian, the uplift and unroofing of the Neotethyan Belt (MISSONI & GAWLICK 2011a) started with intense

erosion and the foreland basins received more and more resediments from the northward gliding units due to unroofing. In the earliest Cretaceous the transport of erosional products to the north was shielded by the still existing Late Jurassic to earliest Cretaceous carbonate platform pattern (Plassen Carbonate Platform). In addition, the now blooming calcareous nannoplankton in deep-water settings produced micritic limestones in rock forming quantities and siliceous marly limestones were deposited. From the Middle/ Late Berriasian onwards, after the final drowning of the Plassen Carbonate Platform, more and more siliciclastic material became transported to the north.

In the underfilled foreland basins, intercalated mass transport deposits in the prograding delta fronts during sea-level lowstands contain the whole reworked Middle-Late Triassic radiolarite sequence from the obducted Neo-Tethys ophiolites and all materials from the ophiolitic mélange (KRISCHE et al. 2014). Northward of these underfilled foreland basins in direction to the outer southern passive continental margin of the Alpine Atlantic Ocean, siliceous marls were deposited widespread.

# 2 THE FIELD TRIP

During the field trip in the Salzburg and Berchtesgaden Calcareous Alps and Salzkammergut (Figure 5), we will visit almost the entire Triassic to Early Cretaceous sedimentary history (Figures 3, 4), excepting the Early Triassic, with special emphasis on siliceous sedimentary rocks and radiolarites. In the Clessinsperre section we will observe the evolution from an Early to Middle Anisian shallow-marine ramp (Gutenstein to Steinalm Formations) to Late Anisian – Ladinian deep-water siliceous limestones (Reifling Formation) followed by the onset of the latest Ladinian to earliest Carnian Wetterstein Carbonate Platform (Figure 3). At Mt. Mehlstein (optional) we will visit radiolarian-bearing siliceous dolomites to limestones of the Gosausee Formation (Figure 3). The section Mörtlbach will provide an Early Jurassic (Hettangian) to Late Jurassic (Oxfordian) succession (Kendlbach/Enzesfeld Formations to Tauglboden Formation: Figure 4). In the area of the Mischenirwiese and at the footwall of Mt. Sandling we will see the Sandlingalm Basin fill (Bathonian to Oxfordian). Around Mt. Hochkranz or in the Lammer valley we will visit the Lammer Basin fill (Callovian to Oxfordian) and in the Tauglboden valley and the Fludergraben area we will visit the whole Tauglboden Basin fill (Oxfordian to Tithonian). The Leube quarry will provide insights in the latest Jurassic to Barremian sedimentary evolution.

## 2.1 Triassic

### *Clessinsperre near Saalfelden – Middle Triassic*

Further reading: GAWLICK et al. (2021) and references therein. For radiolarians see KOZUR & MOSTLER (1981)

The Clessinsperre section (PIA 1924), located on the southern rim of the Steinernes Meer Mts. northeast of the town Saalfelden (Figure 5), represents the type locality of the Steinalm Formation (PIA 1930). At the section Clessinsperre (Öfenbachgraben) a continuous succession from the early Anisian Gutenstein Formation, deposited under restricted conditions, to the Late Ladinian – Early Carnian Wetterstein Carbonate Platform is exposed (Figure 6).

The section in the Öfenbachgraben starts with dark-grey decimeter-bedded Gutenstein Limestone directly followed by the light- to medium-grey thick-bedded Steinalm Limestone. Microfacies characteristics change from dark-grey micritic limestones (Gutenstein Formation) very poor in organisms to microbial-dominated medium to light-grey limestones, indicating a still restricted environment. Other organisms are very rare in this part of the roughly 70 meter-thick Steinalm Limestone succession. More open-marine conditions are only observed in the upper part, and the

algae and foraminifera-bearing horizon is restricted to the uppermost part of the Steinalm Limestone (Pia 1912, 1930; Wagner 1970; Ott, in Tollmann 1976), about one meter below the base of the deepening sequence (Figure 6). The algae are moderately preserved and the assemblage is dominated by *Oligoporella* species.

The highest part of the "Steinalm Formation" consists of shallow-water material with some millimeter-thick deep-water intercalations, i.e. this part of the Steinalm Limestone indicates that the decrease in carbonate production was not abrupt. These deep-water intercalations contain filaments, ostracod shells and a few recrystallized radiolarians. To attribute this part of the succession to the Steinalm Formation or the Reifling Formation is a matter for discussion. Due to the appearance of deep-water organisms it should rather be the base of the Reifling Formation, but the overall lithology fits better to the Steinalm Formation. The thin open-marine intercalations are hard to detect and mostly invisible in outcrops. In fact, it is a transitional part in the section from the shallow-water Steinalm Formation s. str. to the deep-water Reifling Formation s. str., not described to date due to the lack of appropriate sections or simply overlooked. The drowning sequence s. str., i.e. the demise of the shallow-water Steinalm Carbonate Ramp is here represented by decimeter-bedded grey siliceous limestones, i.e. the Reifling Formation (Tollmann 1976 for details), here Late Pelsonian in age (Gawlick et al. 2021). However, in the first (Late Pelsonian) beds shallow-water debris is still common. Above the Early Illyrian ammonoid-rich horizon (Broili 1927; Schnetzer 1934; Assereto 1971) siliceous radiolaria-filament wackestones predominate. Beside conodonts (Gawlick et al. 2021 and references therein), new species of well-preserved radiolarian faunas were described by Kozur & Mostler (1981).

The age of the Reifling Formation is Late Anisian to Late Ladinian, dated by conodonts. In the Illyrian and Late Ladinian intercalations of volcanic ashes are characteristic. Upsection of these volcanic ash layers,
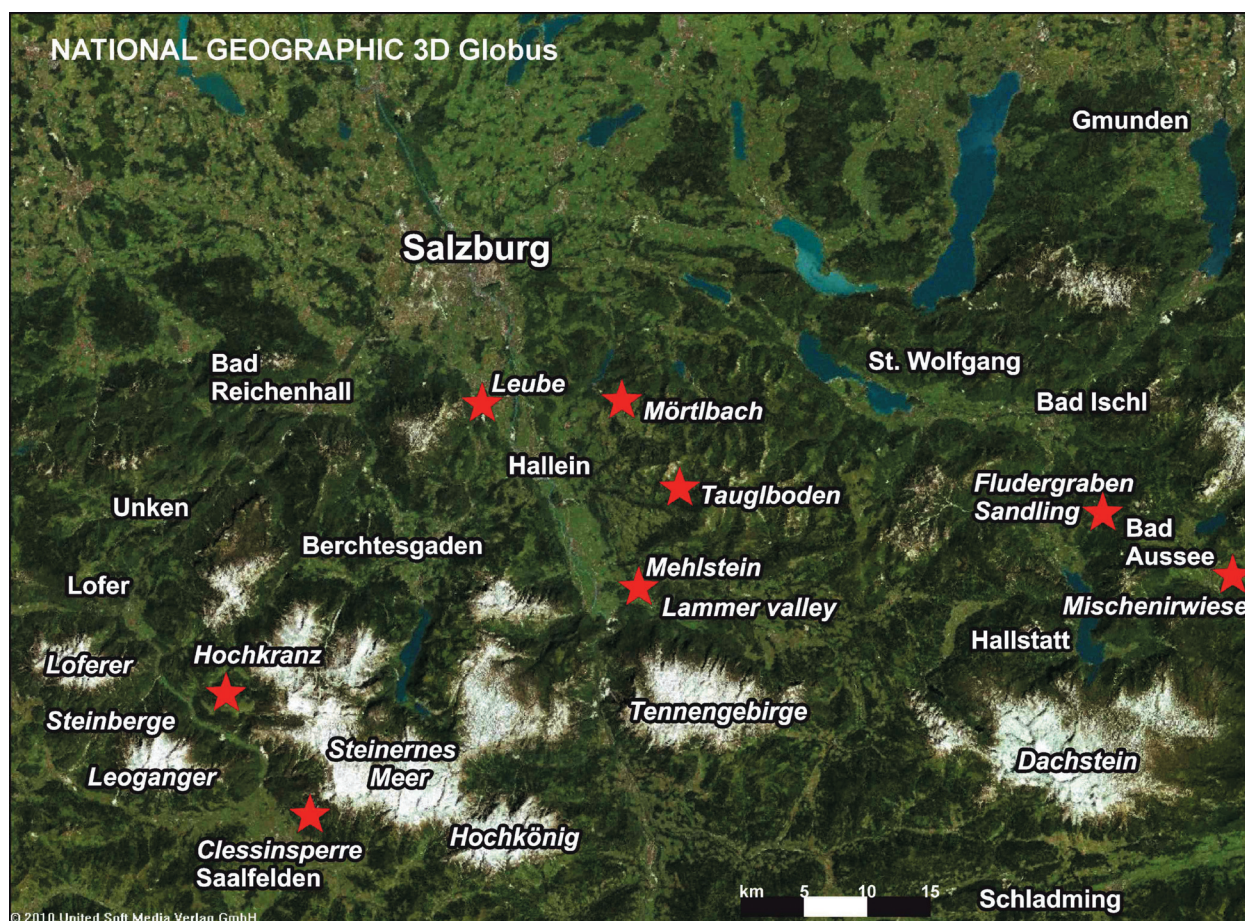


*Figure 5: Satellite image of the central Northern Calcareous Alps (compare Figure 1) with the planned localities (red stars), which will be visited during this field trip in the Salzkammergut area, the Salzburg and Berchtesgaden Calcareous Alps.*

the first shallow-water resediments of the prograding Wetterstein Carbonate Platform occur; further upsection we will see the dolomitized Wetterstein Carbonate Platform (Late Ladinian to Early Carnian). Due to intense dolomitization, the typical microfacies of the Wetterstein Carbonate Platform are fore-reef carbon-

ates, but subsequent reefal and back-reefal carbonates topped by lagoonal carbonates are barely visible. Dolomitization of the Wetterstein Carbonate Platform is a widespread phenomenon, especially in the Tirolic Nappe of the Northern Calcareous Alps.
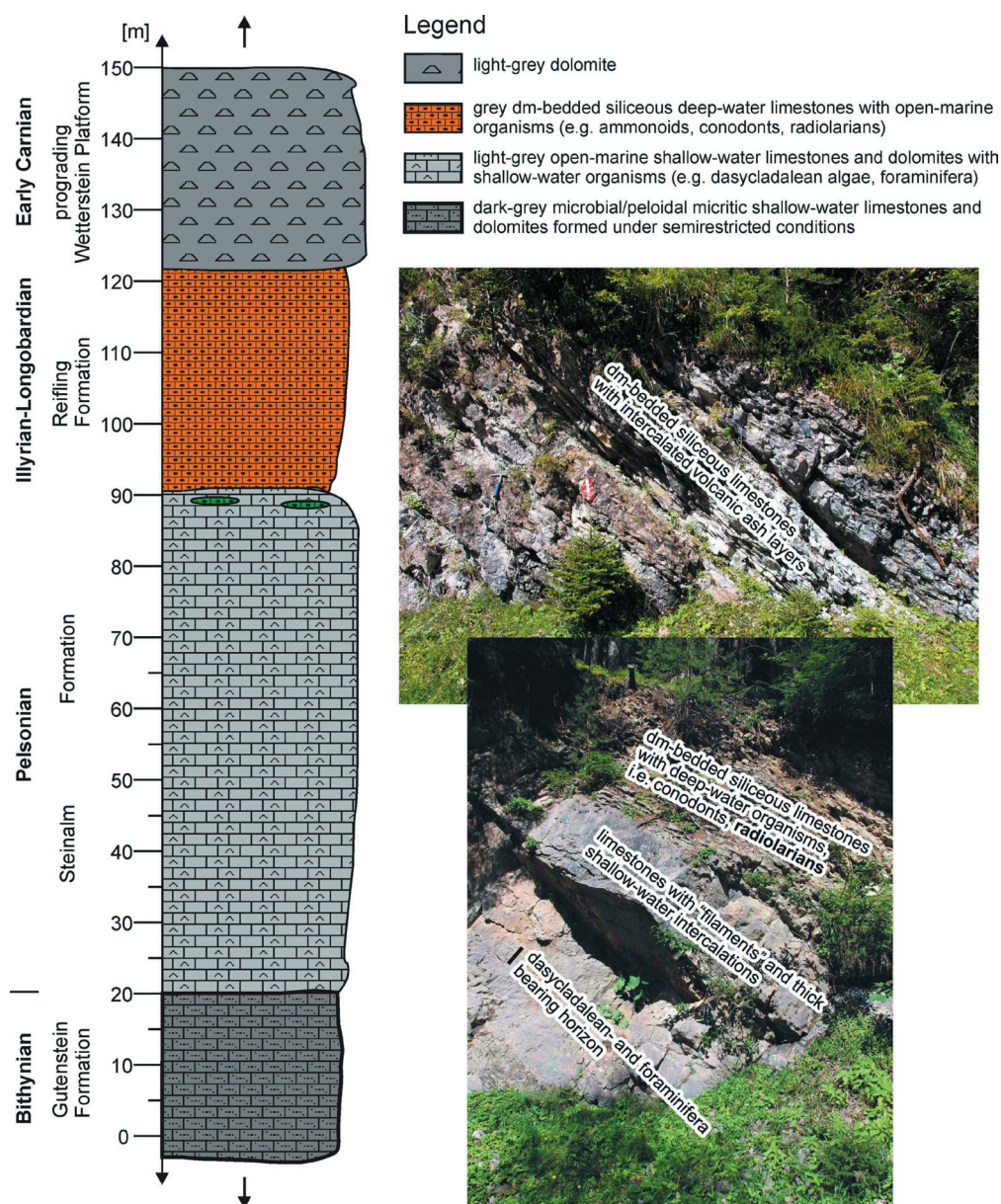


*Figure 6: Clessinsperre section north of the town Saalfelden with different formations/ages, modified after Gawlick et al. (2021). In this section the shallow-marine Steinalm Limestone directly overlies the Gutenstein Formation without intercalated deeper-water limestones (Annaberg Formation). The lower photo shows the drowning unconformity: thick-bedded to massive Steinalm Limestone overlain by the grey siliceous decimeter-bedded deep-water limestones of the Reifling Formation. The topmost Steinalm Limestone consists of a mixture of shallow-water material and deeper-water organisms; thin-shelled bivalves (filaments) and crinoids indicate a rapid deepening in the Late Pelsonian. The upper part shows the Middle-Late Illyrian decimeter-bedded deep-water siliceous limestones of the Reifling Formation with intercalated volcanic ash layers (bentonites). This part contains in some layers a relatively rich radiolarian fauna, as described by Kozur & Mostler (1981).*

*Mehlstein – Late Triassic (optional)*

The Upper Triassic (Tuvalian to Middle Norian) sedimentary sequence of Mt. Mehlstein is an allochthonous block in the Callovian-Oxfordian sedimentary Hallstatt Mélange in the Lammer valley (GAWLICK 1996, 2004). The sedimentary succession consists of grey cherty limestones and siliceous basinal dolomites (Figure 7). The grey bedded limestones with chert nodules and chert layers contain only recrystallized radiolarians, whereas the Norian siliceous and in parts organic rich basinal dolomites contain relatively well preserved pyritized radiolarians beside conodonts (GAWLICK & DUMITRICA, in preparation). The provenance area of Mt. Mehlstein is the reef-near facies belt (Figure 3), which became imbricated since the Callovian. The thickness of the decimeter-bedded grey cherty limestones is in comparison with the meter-bedded to massive siliceous dolomites relatively low. Dolomite formation is interrupted only during the Late Carnian transgressive cycle and the late Lacian regressive cycle. Dolomite formation ended in the Late Alaunian contemporaneous with the culmination of the late Middle/Late Norian tectonic motions.

## 2.2 Jurassic

In the Alpine-Carpathian domain the sedimentation pattern diachronously changed from carbonate to siliceous deposition in the Middle Jurassic (SCHLAGER & SCHÖLLNBERGER 1974). Also the tectonic regime changed. A characteristic new feature was the formation of trench-like radiolaritic basins with up to 2000 metres of sediment infill in their south-eastern oceanward parts, characterized by rapid subsidence due to tectonic load. In contrast, their north-western continentward edges were characterized by uplift and condensed sedimentation or erosion. The derivation of the resedimented components differs. In the south-eastern basin group, the material was shed either from the Triassic to Early Jurassic distal, hemipelagic to pelagic continental margin (Hallstatt and Meliata Zones) or from the Zlambach facies and the Dachstein reef rim zone. In contrast, in the north-western basin group the material was derived from the Triassic to Middle Jurassic lagoonal area (Dachstein and Hauptdolomit facies zones) (Figs. 4, 5).

Each reconstruction of the Jurassic tectonic movements depends on detailed studies on components and
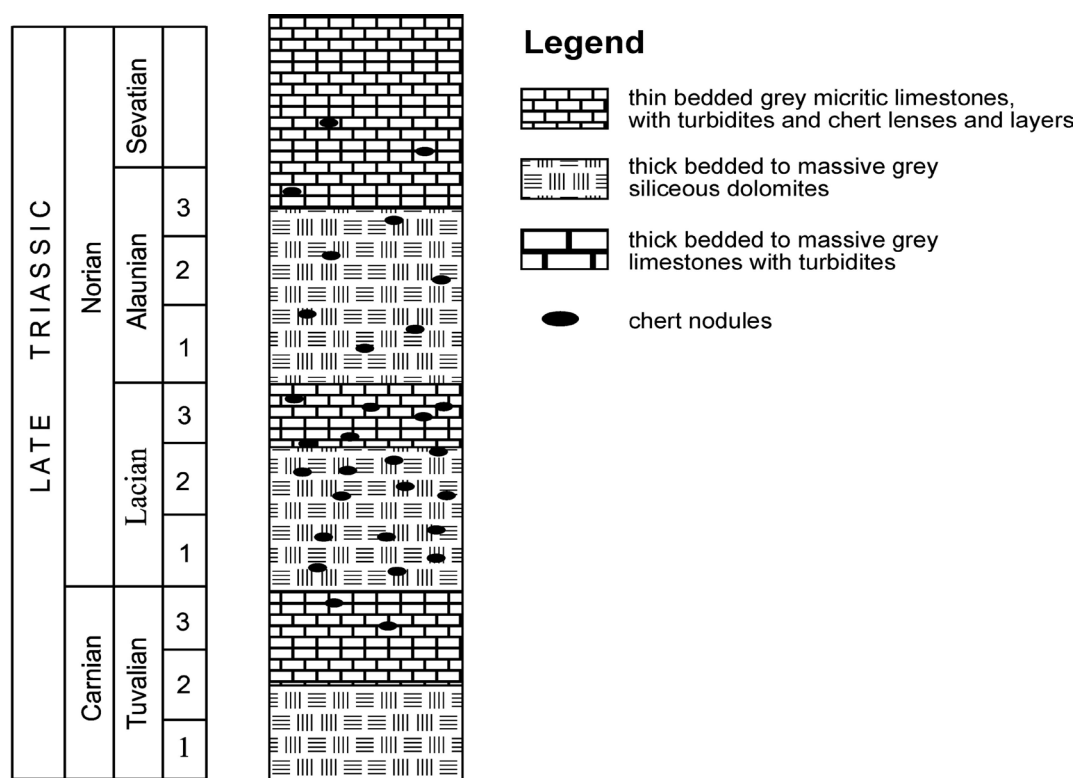


*Figure 7: Generalized Late Triassic sedimentary succession of Mt. Mehlstein in the village Unter Scheffau, modified and complemented after Gawlick (1998). The Norian siliceous bituminous basinal dolomites contain in certain levels relatively well preserved pyritized radiolarians.*

stratigraphy of the siliceous matrix sediments. The following different carbonate-clastic, radiolaritic sequences with characteristic Middle to Late Jurassic sedimentation in the Northern Calcareous Alps can be distinguished at the moment (from south to north, except the Sillenkopf Basin which represents a remnant radiolaritic basin between the Lärchberg and the Plassen Carbonate Platform):

Florianikogel Basin with the Florianikogel Formation (Figure 5): Its ?Bajocian to Callovian matrix contains material from the Hallstatt Salzberg and Meliata facies zones (Mandl & Odrejičková 1991, 1993; Kozur & Mostler 1992) as well as volcanogenic greywacke layers as erosional products derived from the Neo-Tethys oceanic crust (Neubauer et al. 2007). This basin fill is similar to the Meliata Formation in the sense of Kozur & Mock (1985) in the Western Carpathians (Kozur & Mock 1997; Mock et al. 1998; Gawlick & Missoni 2019).

Sandlingalm Basin group with the Sandlingalm Formation (Gawlick et al. 2007a; Gawlick & Missoni 2019 and references therein): These ?Bajocian/Bathonian to Late Oxfordian basins contain only material from the Hallstatt Salzberg facies zone and limestones of the Meliata Zone (Pötschen Formation without shallow-water material).

Lammer Basin with the Strubberg Formation (Gawlick & Missoni 2019 and references therein): This Early Callovian to Middle Oxfordian basin contains mainly material from the Zlambach facies zone and the Dachstein Limestone reefs (Gawlick 1996; Missoni & Gawlick 2011a).

Tauglboden Basin with the Tauglboden Formation: In this Early Oxfordian to Tithonian basin (Huckriede 1971; Gawlick et al. 2009a) the first phase of resedimentation started in the Early Oxfordian (Gawlick et al. 2007a) with material derived from the lagoonal Dachstein Limestone facies zone and ended around the Middle/Late Oxfordian boundary. Following a period of tectonic quiescence and low sediment supply in latest Oxfordian to Early Tithonian the second phase of intense resedimentation had its climax in Late Tithonian and was accompanied by an overall extensional regime (Missoni & Gawlick 2011a, b). The change from older Triassic to Middle Jurassic clasts in the first phase to clasts of Late Jurassic reefal sediments in the second phase is characteristic (Steiger 1981; Gawlick et al. 2005).

Rofan Basin with the Rofan Breccia: Resedimentation started in the Late Oxfordian (Gawlick et al. 2009a) with material derived from the Hauptdolomit facies zone (Figs. 5, 6; Wächter 1987) and prevailed until the Oxfordian/Kimmeridgian boundary or Early

Kimmeridgian. By that time the sedimentation changed to mostly carbonate detritus, derived from a carbonate platform to the south (Wolfgangsee Carbonate Platform - Gawlick et al. 2007b).

Sillenkopf Basin: Another type of basin represents the Kimmeridgian to ?Tithonian Sillenkopf Basin with the Sillenkopf Formation and components of mixed palaeogeographic origin (Missoni et al. 2001). The spectra of clasts in the Sillenkopf Formation prove the following provenance areas: A) The accreted Hallstatt units and an overlying Late Jurassic shallow-water carbonate platform, B) a deeply eroded hinterland further south (probably a part of the crystalline basement of the Northern Calcareous Alps), and C) an ophiolite nappe pile probably carrying an island arc (Missoni & Kuhlemann 2001; Gawlick et al. 2015), similar to the obducted ophiolites which acted as source for radiolaritic-ophiolitic mélanges in the Dinaridic/Albanide realm.

The radiolarite basins A to E were formed in sequence, propagating from a south-east to north-west direction (= from the Meliata to the Hauptdolomit facies zone), in the time span from the Bajocian to the Oxfordian/Kimmeridgian boundary. Basins A and C were accreted and overthrusted, basin B only partly. Basins D, E, F, and partly B existed in Kimmeridgian to early Early Tithonian time as remnant basins in between newly formed shallow-water carbonate platform areas of the Plassen Carbonate Platform sensu lato, which was formed since the Late Oxfordian (Auer et al. 2009).

During this field trip through the central Northern Calcareous Alps (Figure 2) we will study, as one topic, deep-water basin fills with its underlying and overlying sedimentary successions: Sandlingalm Basin fill, Lammer Basin fill, Tauglboden Basin fill.

The onset and drowning/demise of carbonate platforms (Plassen Carbonate Platform sensu lato) on top of the nappe stack and their progradation over the radiolarite basins and the remaining starved deep-water basins between the platforms is not a topic of this field trip.

## Sandlingalm Basin

This basin fill contains blocks up to kilometre-size, derived exclusively from the Hallstatt Salzberg facies zone (various coloured Hallstatt Limestone sequence) and – in rare cases – mixed with components from the Meliata facies zone (including cherty Pötschen Limestone without reefal detritus) in a radiolaritic or radiolaritic-argillaceous matrix. The sedimentary succes-
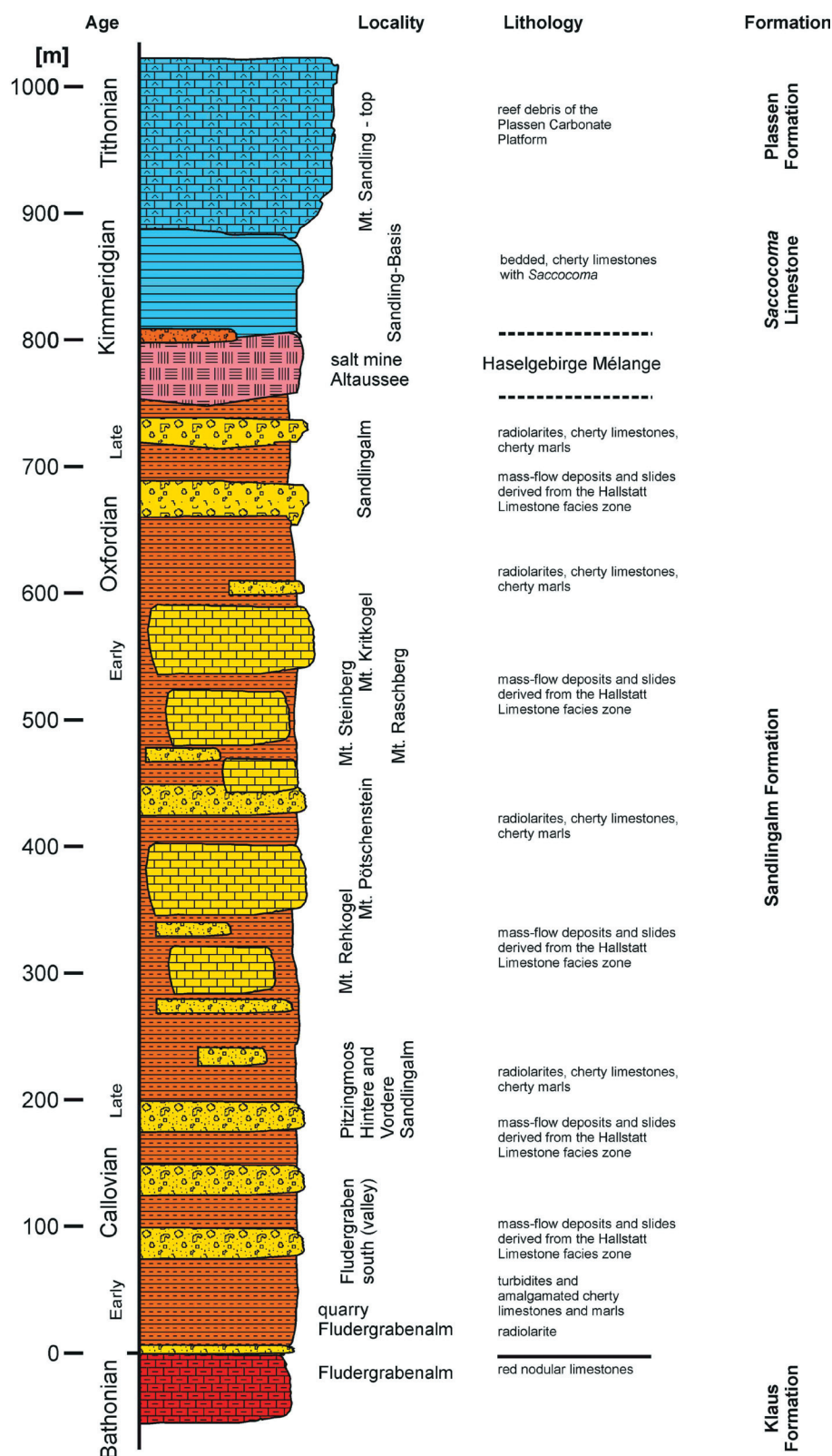
**Age**

[m]

1000 — Tithonian

900 — Kimmeridgian

800 —

700 — Late / Oxfordian

600 — Early

500 —

400 —

300 —

200 — Late / Callovian

100 — Early

0 — Bathonian

**Locality**

Mt. Sandling - top

Sandling-Basis

salt mine Altaussee

Sandlingalm

Mt. Kritkogel

Mt. Steinberg

Mt. Raschberg

Mt. Pötschenstein

Mt. Rehkogel

Pitzingmoos Hintere and Vordere Sandlingalm

Fludergraben south (valley)

quarry Fludergrabenalm

Fludergrabenalm

**Lithology**

reef debris of the Plassen Carbonate Platform

bedded, cherty limestones with *Saccocoma*

Haselgebirge Mélange

radiolarites, cherty limestones, cherty marls

mass-flow deposits and slides derived from the Hallstatt Limestone facies zone

radiolarites, cherty limestones, cherty marls

mass-flow deposits and slides derived from the Hallstatt Limestone facies zone

radiolarites, cherty limestones, cherty marls

mass-flow deposits and slides derived from the Hallstatt Limestone facies zone

radiolarites, cherty limestones, cherty marls

mass-flow deposits and slides derived from the Hallstatt Limestone facies zone

mass-flow deposits and slides derived from the Hallstatt Limestone facies zone

turbidites and amalgamated cherty limestones and marls

radiolarite

red nodular limestones

**Formation**

Plassen Formation

*Saccocoma* Limestone

Sandlingalm Formation

Klaus Formation

*Figure 8: Schematic section of the Sandlingalm Basin fill in the area around Mount Sandling: Fludergrabenalm – Fludergraben – Pitzingmoos – Mt. Rehkogel – Sandlingalm – Mount Sandling. During the field trip we will visit nearly the whole basin fill starting at the Fludergrabenalm. Slightly modified after Gawlick et al. (2007a).*

sion of the Sandlingalm Basin is composed of various slide masses. Resedimentation of Hallstatt blocks in this basin started in the Late Bathonian and ended in the Middle Oxfordian.

Following the emplacement of the Haselgebirge Mélange around the Oxfordian/Kimmeridgian (Missoni & Gawlick 2011a), deposition of grey siliceous deep-water limestones began in basinal areas as part of the Plassen Carbonate Platform (compare Gawlick et al. 2010 for the field trip area). Aside from the early Plassen Carbonate Platform sensu lato, these basinal limestones, were deposited on top of slide masses sealing the chaotic basin fill whereas on top of the nappe fronts carbonate platforms were established.

We will visit the type-area of this basin in the central Salzkammergut area north of the small towns Altaussee and Bad Mitterndorf.

Most samples from the Sandlingalm Basin contain rich, well-preserved radiolarian assemblages.

### Mt. Sandling area

Further reading: Suzuki & Gawlick (2003), Gawlick et al. (2007a, 2010, 2012), Gawlick & Missoni (2019) and references therein, Suzuki & Gawlick (2020).

In the Sandlingalm area we will visit two different basin fills: The proximal Tauglboden Basin fill and the Sandlingalm Basin fill (see below).

In the Mount Sandling area the Sandlingalm Basin is situated directly south of the Tauglboden Basin (see below). The tectonic contact is a sharp strike-slip fault. The sedimentary succession of the Sandlingalm Basin



*Figure 9: Radiolarite quarry west of the Fludergrabenalm. Slump deposits of reddish radiolarite are intercalated in dark-grey dm-bedded radiolarites, which are in parts laminated. Fine-grained turbidites consist of open-marine limestones from the open-marine distal shelf (Hallstatt Limestone facies).*

fill (Figure 8) starts with red nodular limestones of the Early Jurassic Adnet and the Middle Jurassic Klaus Formation (*Bositra* Limestone), whose upper part is siliceous with a well preserved radiolarian fauna. Upsection are red radiolarites which turn rapidly to green-grey radiolarites with intercalated carbonate turbidites (Figure 9) followed by the first mass transport deposits with dm-sized-blocks. The provenance area of the different limestone and siliceous marl components is the distal shelf area, i.e. the Hallstatt Limestone facies zone and the continental slope (Meliata facies zone). The Lower Jurassic cm- to dm-sized components correspond to the Lower Jurassic Dürrnberg Formation, which we plan to visit in the Teltschengraben area (see below). Upsection in the basin fill Lower Jurassic components decrease and older components started to be redeposited. In addition, the component size of the redeposited Hallstatt sequence increases and the basin fill reflects a coarsening-upward cycle, as typical for foreland basin fills and advancing nappes.

### Mischenirwiese and Teltschengraben (optional)

Further reading: O´Dogherty et al. (2008, 2017) and references therein.

In the area around Bad Mitterndorf, a Sandlingalm Basin filled with several mass transport deposits consisting of reworked material from the outer shelf (Hallstatt Limestone facies) and km-sized slide blocks is preserved. The component spectrum differs slightly from that in the type area around Mount Sandling indicating that the Sandlingalm Basin fills are in fact a series of imbricated trench-like basins fills in front of the advancing nappe pile. In all Sandlingalm Basin fill areas the components derive from the Triassic to Early Jurassic outer shelf, i.e. the various coloured Hallstatt Limestone facies zone.

In the Teltschengraben a slide of uppermost Lower Pliensbachian (*Gigi fustis* – *Lantus sixi* Radiolarian Zone of Carter et al. 2010) cherty marls and cherty limestones is embedded in Callovian radiolarites. The wacke- to packstones are in parts rich in crinoids and frequently contain recrystallized radiolarians; well-preserved radiolarians also occur in a few layers. The detection of this slide is important because it is one of the few Pliensbachian siliceous sedimentary sequences with a well preserved radiolarian fauna in the whole Western Tethyan Realm (compare Cifer et al. 2020). Some new taxa could be described from this succession. The outcrop is situated in a steep valley and is therefore optional (further reading O´Dogherty et al. 2008).

The Mischenirwiese section (Figure 10) northwest of Bad Mitterndorf (for details see O'DOGHERTY et al. 2017) consists of a slightly folded but complete Late Bajocian/Bathonian to Oxfordian-?Kimmeridgian radiolarite succession. This nearly 100 m thick radiolarite succession represents the distal part of the Sandlingalm Basin where intercalated mass transport deposits and big slides are missing. The isolated, highly diverse and well-preserved radiolarian assemblages have been used by O'DOGHERTY et al. (2017) for a detailed taxonomic study. Two new families, 6 new genera, and 2 species were described from the Mischenirwiese section.



*Figure 10: Mischenirwiese section: cross-section in the small valley from the Steinwand to the Mischenirwiese. Modified after O'Dogherty et al. (2017).*

**Lammer Basin**

The palaeogeographic position of this Callovian-Oxfordian basin fill was in the former lagoonal area of the Late Triassic Dachstein Carbonate Platform, i.e., it took a middle shelf position. The basin fill is characterized mainly by reworked material from the Dachstein reef facies belt and the reef-near open-marine grey Hallstatt facies/Gosausee Limestone facies. Two different reworked successions can be reconstructed: (I) A Middle to Late Triassic open-marine succession with re-sedimented material from the reef rim, and (II) a Middle to Late Triassic open-marine to shallow-water sequence from the reef rim facies zone. Material from the upper continental slope or the Hallstatt Limestone facies zone occur re-mobilized and transported in a piggy-back manner together with its substratum (GAWLICK & MISSONI 2015), a km-sized slide block from the open shelf area showing shallow-water influence. The matrix consists of dark-grey to black siliceous limestones to radiolarites, argillaceous

siliceous marls, and manganese-enriched shales to carbonates. The Haselgebirge Mélange (Late Permian evaporites - TOLLMANN 1976) with the Hallstatt Limestone mélange was thrust over the basin fill around the Oxfordian/Kimmeridgian boundary. The subsequent Kimmeridgian to Early Cretaceous foreland basin sedimentation sealed the older structures and basin geometries (MISSONI & GAWLICK 2011a).

Depending on the field trip route we will visit the Lammer Basin fill either in the type area or in the area of Mount Hochkranz.

The preservation of the radiolarians in the Lammer Basin is moderate to poor. Only few samples contain moderate to well-preserved radiolarian assemblages. In most cases the radiolarians are completely recrystallized.

*Lammer valley*

Further reading: GAWLICK (1996), GAWLICK & SUZUKI (1999), GAWLICK et al. (2012) and references therein, GAWLICK & MISSONI (2015).

The type area of the Lammer Basin fill is situated in the western Lammer valley between Golling to the west and Abtenau to the east (details in GAWLICK, 1996). In this area the complete, coarsening- upward basin fill of nearly 2000 m thickness is preserved, The slides in the higher part of the basin fill are km-sized blocks from the Late Triassic Dachstein reef belt. We will visit the lower to middle part of the basin fill in detail. Above the Upper Triassic (Rhaetian) lagoonal Dachstein Limestone, the Lower Jurassic sequence is composed of grey cherty limestones (Hettangian to Pliensbachian), followed by Upper Pliensbachian to Lower Toarcian mass transport deposits consisting of reworked Adnet Limestones and subsequent Middle Jurassic *Bositra* Limestones after a gap. In the Callovian, limestone deposition changed to deposition of siliceous sedimentary rocks: radiolarites (first reddish, later grey to black), siliceous limestones, and argillaceous-siliceous marls. First mass transport deposits appear in the argillaceous-siliceous marls in the latest Callovian below a manganese carbonate level that was formed around the Callovian/Oxfordian boundary. Upsection, i.e. in the Early to Middle Oxfordian, the amount of intercalated mass transport deposits and the reworked component size increases. In this part of the basin fill the reworked material was derived exclusively from the open shelf area adjacent to the reef rim. Upsection follow km-sized blocks with complete Carnian to Rhaetian sedimentary successions from this facies belt. These blocks carry, in a piggy-back manner,
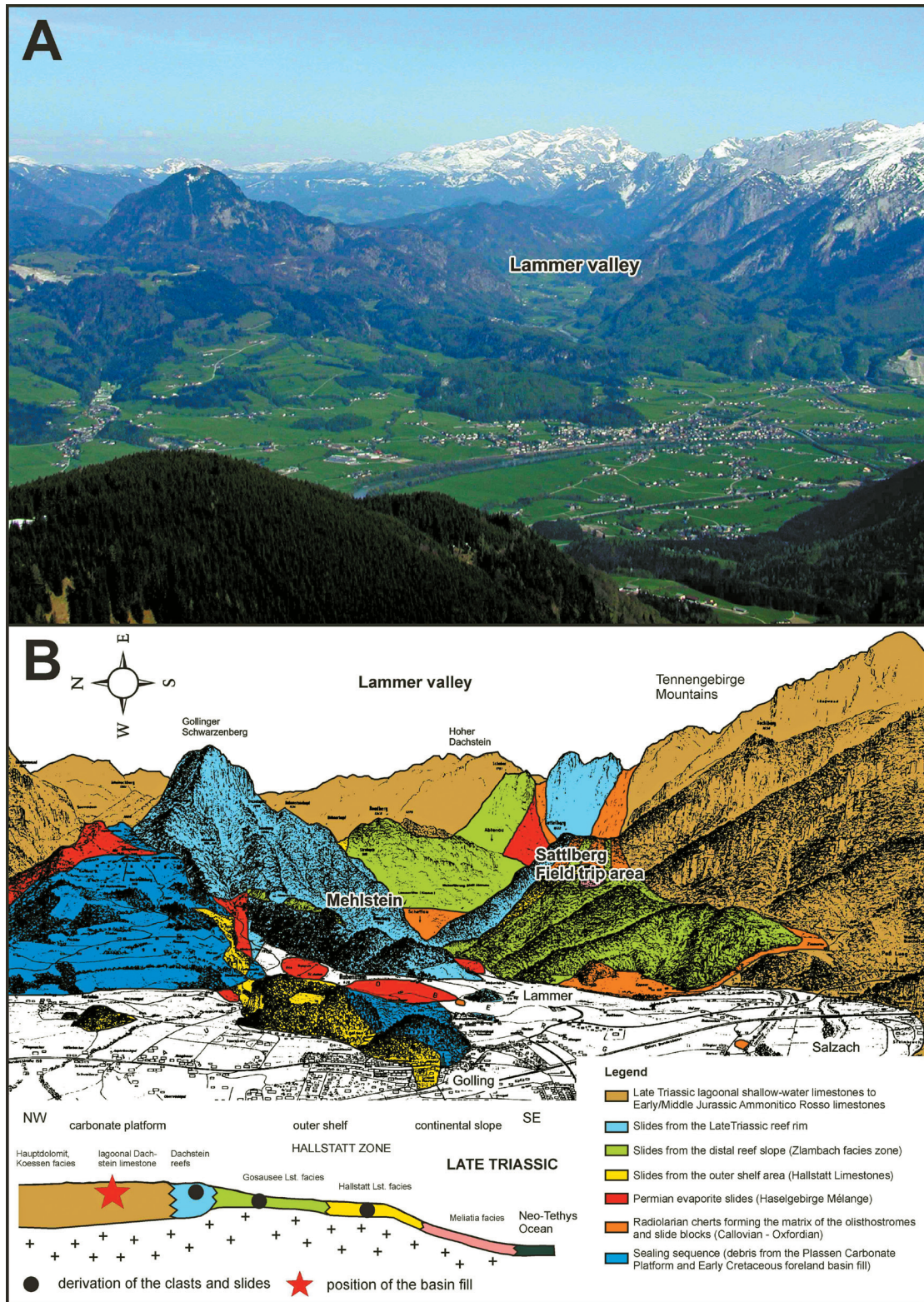
*Figure 11: A: Photo from the west showing the type area of the Lammer Basin fill, and B: Geological interpretation (modified after Gawlick et al. 2012 and Gawlick & Missoni 2015). The basin fill with a coarsening-upward trend consists exclusively of allochthonous material of different age and provenance from the outer shelf area of the northwestern Neo-Tethys passive continental margin.*

material from the outer shelf transitional to the continental slope, i.e. the Meliata facies zone. Characteristic for this reworked sedimentary succession are Middle Triassic (Upper Anisian to Ladinian) radiolarites (GAWLICK & MISSONI 2015). Later huge slides from the Late Triassic reef belt were transported into the Lammer Basin. In addition, Hallstatt Limestone blocks with complete Upper Anisian to Upper Norian sedimentary successions and Upper Permian evaporites appear in the northwestern part of the Lammer Basin fill.

Moderately preserved radiolarian assemblages occur throughout the whole siliceous sedimentary succession, i.e. in the matrix of the different mass transport deposits and slides (GAWLICK & SUZUKI 1999). The entire basin fill is sealed by a relatively flat lying Kimmeridgian to Aptian sedimentary sequence (Figure 11).

### Hochkranz (optional)

In the area of Mount Hochkranz, west of St. Martin in the Saalach valley, a fill similar to that of the Lammer Basin type area (Lammer valley) is preserved. The basin fill in the area around Mount Hochkranz is in direct continuation to the west of the Lammer valley and can be traced all along the way from the Lammer valley to the Mount Hochkranz area (MISSONI & GAWLICK 2011a, b). Whereas in the Lammer valley the most proximal part of the basin fill is preserved, in the Mount Hochkranz area a more distal part of the basin fill is preserved. Also the component spectrum is slightly different. Outer shelf components are missing as well as components from the more basin ward depositional realm of the reef rim.

The relatively thick radiolarite succession (various coloured radiolarites) below the first mass transport deposits consists of grey to dark-grey radiolarites and siliceous limestones with moderately preserved radiolarian faunas. Slump deposits and sediment creeping is a characteristic sedimentological feature for this radiolaritic sequence. After deposition of the manganese-rich horizon the first mass transport deposits are intercalated in a siliceous-radiolaritic matrix. The component spectrum reflects a reworked Late Triassic sedimentary sequence from the Dachstein reef rim facies zone. The basin fill shows a coarsening-upward trend and is sealed by the limestones of the prograding Kimmeridgian-Tithonian Plassen Carbonate Platform (Mount Hochkranz).



Figure 12: 12 A: Callovian rhythmic radiolarite sequence from the deeper part of the Lammer Basin fill in the area of Mount Hochkranz. With grey laminated radiolarite beds. 12 B: Field view of the coarsening upward cycle of the distal Lammer Basin Fill topped by shallow-water limestone of the Plassen Carbonate Platform (Mount Hochkranz).

## Tauglboden Basin

### Fludergraben/Knerzenalm area

The sedimentary succession starts with Rhaetian lagoonal Dachstein Limestone with megalodonts. Below the drowning sequence corals in situ are preserved. Drowning of the Dachstein Platform is characterized by the change from shallow-water lagoonal limestones to condensed red nodular limestones with crinoids, ammonoids and foraminifera (Adnet Formation). Red nodular limestone formation continued until the Middle/Late Jurassic boundary. In the Middle Jurassic this red nodular limestone is characterized by hardground formation (Klaus Formation). Directly above, deposition of red radiolarites began, These soon turned to

grey to black radiolarites indicating a change in the basin geometry. Slump deposits are a characteristic feature of this basal part of the basin fill. Some metres upsection, the first turbidites and mass transport deposits occur in the sedimentary succession. The component spectrum in these mass transport deposits reflects the Upper Triassic to Middle Jurassic sedimentary succession of the lagoonal Dachstein Limestone facies belt. Note that instead of a complete Lower Jurassic red nodular Adnet Limestone succession, grey cherty limestones begin to appear indicating a Lower Jurassic basinal sequence south of the Tauglboden Basin, which is not preserved anymore. In total the Tauglboden Basin (Figure 13) fill reflects a coarsening-upward cycle.

The base of the Fludergraben section (Figure 14) is important for the calibration of radiolarian faunas with ammonoids. Suzuki & Gawlick (2020) studied the radiolarian faunas from the lowermost part of the radiolarite succession and discussed the biostratigraphic ranges of several species and proposed some promising marker species for the Oxfordian.

In the area north of Mount Sandling, the proximal Tauglboden Basin fill is preserved. The thickness is nearly 900 m.

The preservation of radiolarians in the Tauglboden Basin is moderate to poor. Only a few samples contain moderate to well-preserved radiolarian assemblages. In most cases the radiolarians are completely recrystallized. The best radiolarian assemblages appear in the proximal Tauglboden Basin.

### Tauglboden

Further reading: Schlager & Schlager (1969, 1973), Diersche (1980), Gawlick et al. (1999, 2009, 2012).

In the Tauglboden area west of the small town Kuchl in the Salzach valley we will visit the central part of the Tauglboden Basin fill (Figure 15). This basin is located in the Late Triassic Hauptdolomit facies belt. In the Tauglboden valley a complete Lower Jurassic to Upper Jurassic sedimentary sequence is preserved with radiolarite deposition beginning in the Early Oxfordian (Huckriede 1971). Red bedded radiolarites 5-10 cm-thick formed first. Next, radiolarite-beds changed to grey due to the change in the basin geometry upsection, and some laminated radiolarites were deposited with intercalated turbidites and mass transport deposits. In addition, some volcanic ash layers, mostly at the base of the mass transport deposits, are intercalated in the succession. Both the change in the colour of the radiolarites and the occurrence of

first reworked material indicates the change in the depositional environment from an open and fully oxygenated basin floor to the geometry of a deep trench-like foreland basin. The sedimentology of the Tauglboden sequence and especially the sedimentological features of the different mass transport deposits and breccias were studied in detail by Schlager & Schlager (1969, 1973) and in a more regional context by Diersche (1980).

Detailed component analysis and age dating of the radiolaritic matrix was carried out by Gawlick et al. (1999) and later by Gawlick et al. (2012). The component spectrum reflects a complete Upper Triassic to Middle Jurassic sedimentary sequence from the facies zone of the open lagoon of the Dachstein Carbonate Platform, i.e. Norian Dachstein Limestone, Lower Rhaetian Kössen marls, Rhaetian Dachstein Limestone, lower Lower Jurassic Scheibelberg Formation, upper Lower Jurassic Adnet Formation, *Bositra* Limestone (Klaus Formation) and Callovian radiolarites. This component spectrum contrasts with that of the Lammer Basin fill to the south. In addition, resedimentation in the Tauglboden Basin started later as in the Lammer Basin. This clearly indicates the propagation of the nappe stack to the north.

The first part of the basin fill is characterized by a coarsening-upward trend: the intercalated mass transport deposits in the argillaceous-radiolaritic matrix increase in thickness and also the component size increases. More and more slump deposits occur in the sequence. According to radiolarian ages, the base of the Tauglboden Formation and the top of the coarsening cycle are the same age, i.e. Early to Middle Oxfordian. Upsection follows a series of dark grey dm-bedded radiolarites to cherty limestones without turbidites or mass transport deposits. Slump deposits are also missing. Higher up again mass transport deposits and dm-thick volcanic ash layers appear. This part of the sequence is early Tithonian in age based on radiolarian assemblages and forms the base of a fining-upward cycle ending in the Berriasian. The latest Oxfordian to earliest Tithonian represents a condensed part of the sequence with relative tectonic quiescence, i.e. a starved basin. In the early Tithonian a new cycle in the basin fill began. Whereas the Oxfordian part of the basin fill reflects a compressional regime expressed in a coarsening-upward cycle, the Tithonian part of the basin fill reflects an extensional regime with accompanied intense explosive volcanism, and is expressed in a fining-upward cycle. This extension is related to mountain uplift and unroofing (Missoni & Gawlick 2011a, b) of the Neotethyan orogenic belt, as known in the Dinarides (Gawlick et al. 2020 and references therein).
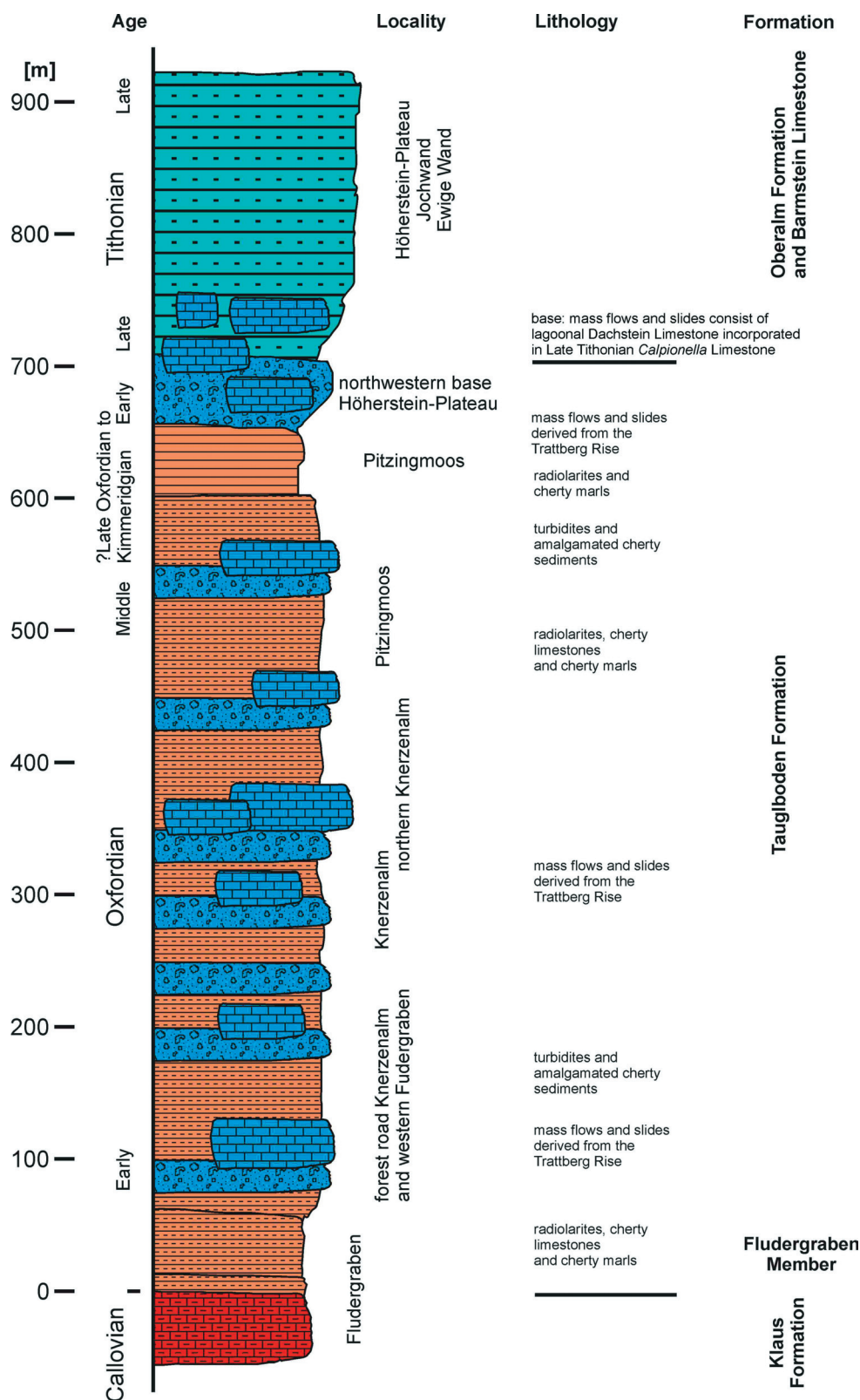
*Figure 13: Schematic section of the Tauglboden Basin fill in the area north of Mount Sandling: Fludergraben – Knerzenalm – Höherstein. During the field trip we will visit nearly the whole basin fill starting in the Fludergraben. Slightly modified after Gawlick et al. (2012).*

*Figure 14: Fludergraben section. A: Red nodular limestones with ammonoids from the Callovian/Oxfordian boundary overlain by thin-bedded Oxfordian red radiolarite. B) Thin bedded grey radiolarite with intercalated mass transport deposit from the lower part of the Tauglboden Basin fill in the Fludergraben valley.*

The component spectrum of the Early Tithonian part of the basin is similar to that of the Oxfordian part of the basin fill, but in contrast, Jurassic components are rare and Dachstein Limestone and Kössen Formation components dominate. Also during the Tithonian, radiolarites become more and more carbonate and preservation of radiolarians is very poor. Higher in the section (in the latest Tithonian) the first shallow-water components from the prograding Plassen Carbonate Platform appear in the mass transport deposits.

### Mörtlbach valley

Further reading: DIERSCHE (1980), GAWLICK et al. (2012).

In the Mörtlbach valley section, i.e. along the parking place on the road to Krispl, a complete uppermost Triassic to Oxfordian sedimentary sequence is exposed (Figure 16). The section starts with Rhaetian Dachstein Limestone transitional to the Kössen Basin overlain by grey cherty limestones of the Scheibelberg Formation, 6-8 m in thickness. These grey cherty limestones with spicules and rare recrystallized radiolarians are overlain by reworked red nodular limestones of the Adnet Formation, forming a series of mass transport deposits. This part of the section is late Pliensbachian to early Toarcian in age. Upsection follows a thin layer of marly limestones of Aalenian age, rich in *Bositra* shells. After a gap, expressed by a ferromanganese horizon, deposition of a 1 m thick Callovian black thick-bedded to massive radiolarite started. Upsection the colour of the radiolarite changed to red. This 15 m thick part of the section consists of dm-bedded red massive radiolarites with claystone intercalations and is Late Callovian to Early/Middle Oxfordian in age. Only in a few beds the preservation of the radiolarians is good. In most beds the radiolarians are recrystallized and poorly preserved. Up-section in the Early-Middle Oxfordian the red radiolarite passed into grey radiolarites and cherty limestones. These siliceous sedimentary rocks are laminated and indicate a change in the basin geometry. In addition, few volcanic ash layers and fine-grained turbidites are intercalated in the succession but the clasts are too small to determine their stratigraphic age. Upsection the clasts become coarser and consist mainly of Upper Triassic lagoonal Dachstein Limestone and rare Jurassic components. The component spectrum is identical to that of the Tauglboden valley to the south.

The thickness of this part of the sequence does not exceed 10-20 m (details in DIERSCHE, 1980), and
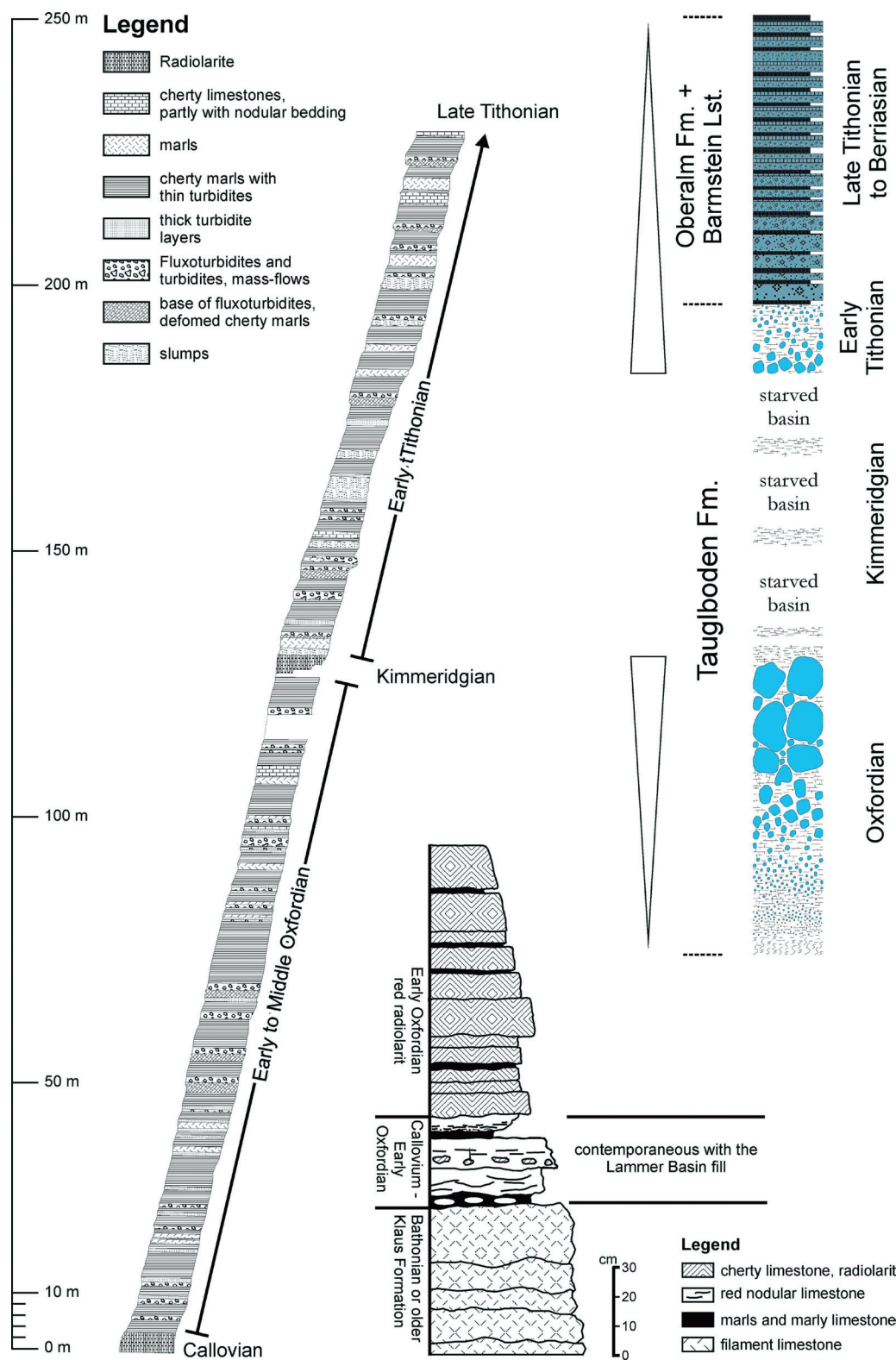
*Figure 15: "Idealized section" of the Tauglboden Formation in the type-area (see Schlager & Schlager 1973 for details). Redrawn after unpublished data of M. and W. Schlager, printed with permission of W. Schlager (Amsterdam) in Gawlick (2000). Ages of the different parts of the section according to Huckriede (1971), Gawlick et al. (1999, 2012) and unpublished data. Basal part of the section according to Huckriede (1971), from Gawlick et al. (2012), modified. Sedimentological trends after Missoni & Gawlick (2011a).*

*Figure 16: Sedimentary succession along the parking place on the road to Krispl. Right section with photographs after Böhm (1992), modified and completed for the Callovian-Oxfordian part of the section. Left section from Diersche (1980). Modified after Gawlick et al. (2012).*
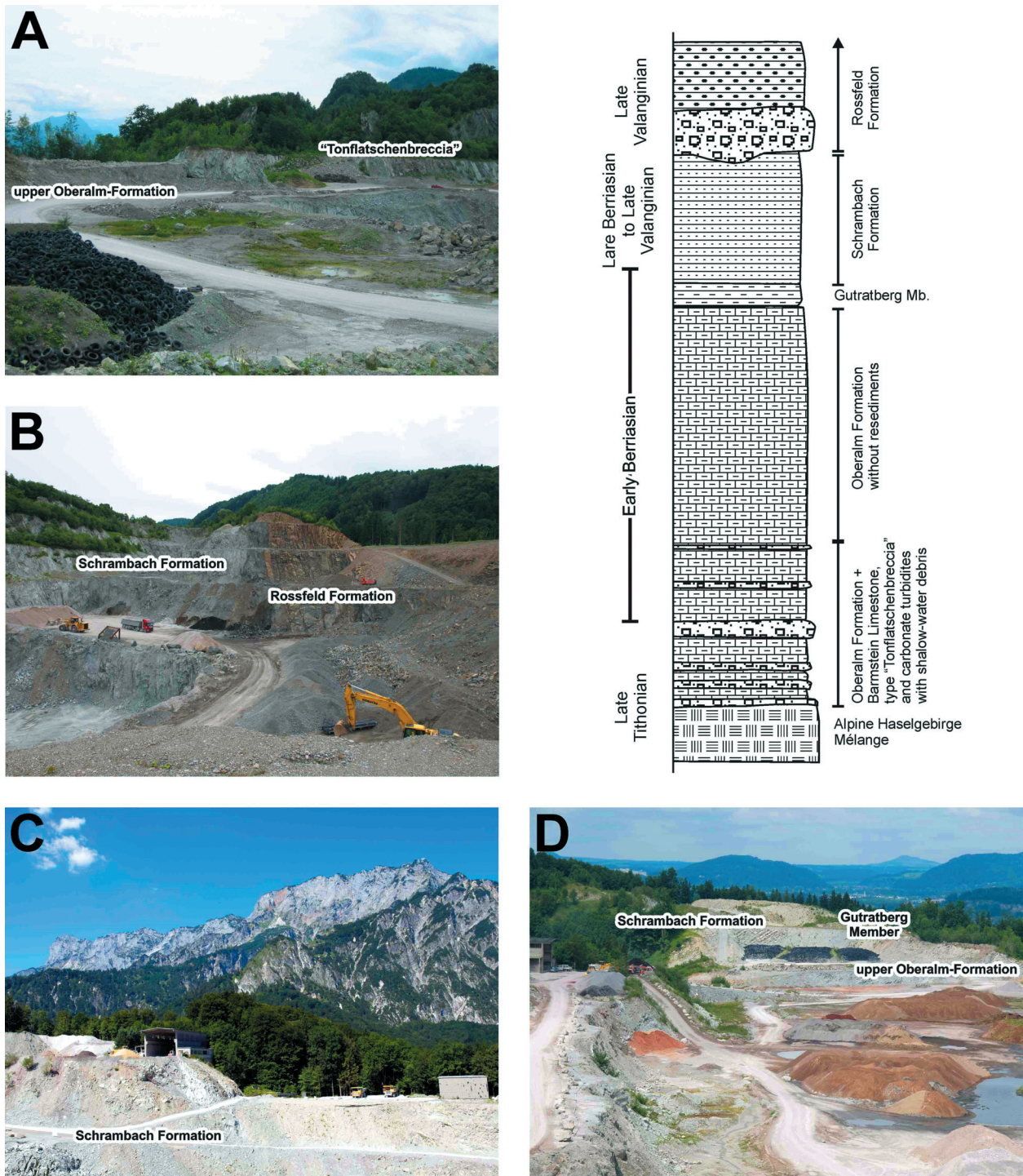
*Figure 17: Different views of the Leube quarry and formations that will be visited. Due to the fact of ongoing exploitation in the quarry the outcrop situation and available parts of the succession may change. A: Northwestern part of the quarry with the Lower Berriasian part of the succession. B: Northern part of the quarry with the Lower Berriasian upper Oberalm Formation, the Middle Berriasian Gutratberg Member of the Oberalm Formation, and the Upper Berriasian Schrambach Formation. C: Eastern side of the quarry with the part of the succession studied in detail for magnetostratigraphy, gamma ray spectrometry, AMS studies, and geochemical analysis (Grabowski et al. 2016, 2017a, b). D: Southern part of the quarry with the transition from the Schrambach Formation to the Rossfeld Formation.*
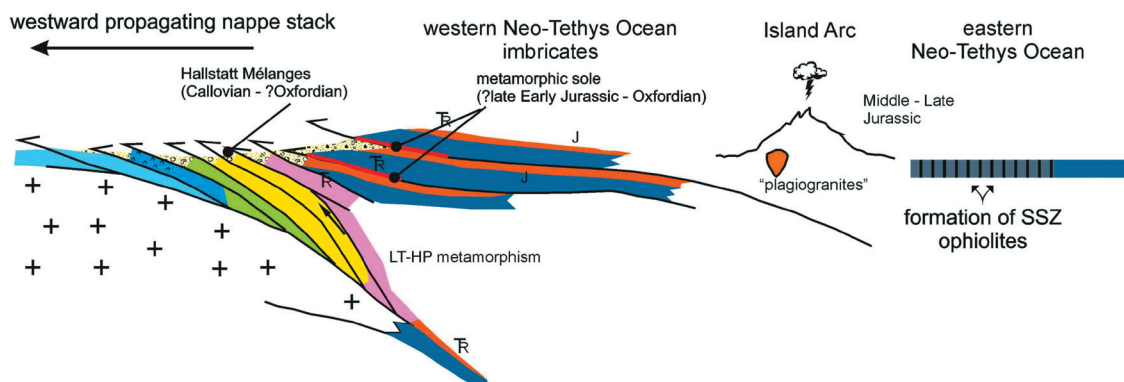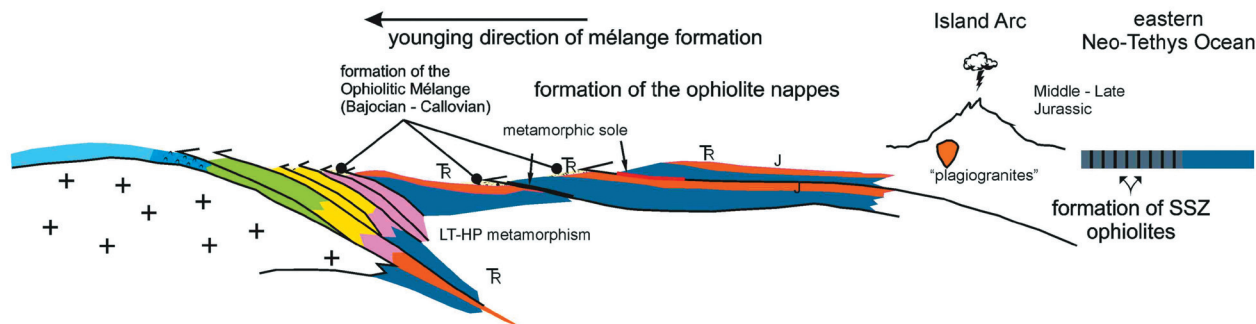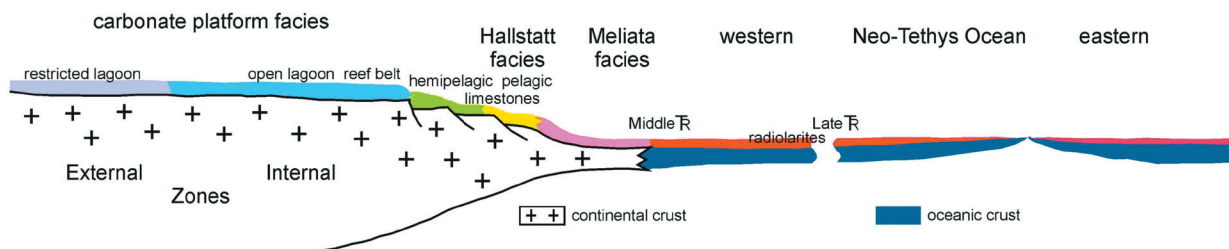
Figure 18: Triassic–Jurassic geodynamic evolution of the western Neo-Tethys margin after Gawlick & Missoni (2019) with a few modifications. A: Middle Triassic to Early Jurassic passive margin configuration. For details of the stratigraphic evolution, see Figure 3 and Figure 4. Continental break-up and generation of Neo-Tethys oceanic crust started around the Middle/Late Anisian boundary. B: Onset of ophiolite obduction started in the Bajocian and the formation of ophiolitic mélanges in the oceanic realm since the Early/ Middle Jurassic boundary. From Bajocian time the ophiolitic mélanges in sub-ophiolite positions contain reworked blocks from the continental slope (Meliata facies zone). Concerning the position and formation of the plagiogranites see Michail et al. (2016). C: Late Middle Jurassic to early Late Jurassic propagating ophiolite obduction and imbrication of the former Neo-Tethys passive margin, resulting in the formation of a thin-skinned orogen. Trench-like basin and sedimentary mélanges formed in front of the propagating nappe stack. Some of the southern basin groups became sheared off and transported in northwest-/west-ward directions. The deeper parts of the imbricate stack of the outer shelf underwent low temperature – high pressure (LT-HP) metamorphism.

the thickness of the intercalated turbidites is only 10-20 cm. This section was formed on the northern slope of the Tauglboden Basin and represents a very distal part.

### Leube quarry

Further reading: Krische et al. (2013, 2014, 2018) and references therein, Bujtor et al. (2013).

In the Leube quarry south of Salzburg (near to the villages Gartenau and St. Leonhard) we will visit the uppermost Jurassic to Lower Cretaceous sedimentary rocks. Here in several tectonic slices, separated by Miocene strike-slip faults, sedimentary successions from the higher Oberalm Formation including the Barmstein Limestone to the Roßfeld Formation are well preserved (Figure 17).

A detailed description of the section, the history of investigations in the quarry and a description/definition of the formations is given by Krische et al. (2018). New studies since 2018 (Hirschhuber et al. 2019; Hirschhuber 2020) result in a more detailed subdivision of the different tectonic slices in the quarry.

The Leube quarry provides one of the best preserved and exposed uppermost Jurassic to Early Cretaceous sedimentary successions in the central Northern Calcareous Alps. New calpionellid data, in combination with ammonite, microfacies and lithology analyses, form the basis for a detailed, revised biostratigraphy of this time interval (Krische et al. 2013) that gave rise to further very detailed investigations. Additionally, the investigation of hemipelagic basinal sedimentary sequences is very important for a better understanding of the Late Jurassic to Early Cretaceous evolution of the central Northern Calcareous Alps and also allows new insights into the development of the Late Jurassic to Early Cretaceous shallow-water carbonate platform at the southern rim of the basin (Plassen Carbonate Platform sensu stricto). The remarkably rich Late Berriasian ammonite fauna (Bujtor et al., 2013) reveals strong biogeographic connections toward the Tethyan faunas along the northern margin of the Tethys; many are reported for the first time from Austria.

The results achieved in the Leube quarry contribute to an improvement of the palaeogeographical and geodynamical model of the Northern Calcareous Alps for this time span. For this field trip, published results are combined with the recently obtained and still unpublished ones, which are here presented for the first time.

## 2.3 Geodynamic history

Further reading: Frisch & Gawlick (2003), Missoni & Gawlick (2011a, b), Gawlick et al. (2012), Gawlick & Missoni (2019) and references therein.

The Middle-Late Jurassic mountain building process in the Western Tethyan realm was triggered by west- to northwestward-directed ophiolite obduction onto the wider Adriatic shelf. This southeastern to eastern Adriatic shelf was the former passive continental margin of the Neo-Tethys, which started to open in the Middle Triassic. Its western parts closed from around the Early/Middle Jurassic boundary with the onset of east-dipping intra-oceanic subduction. Ongoing contraction led to ophiolite obduction onto the former continental margin since the Bajocian. Trench-like basins formed concomitantly within the evolving thin-skinned orogen in a lower plate situation. Deep-water basins formed in sequence with the northwest-/westward propagating nappe fronts, which served as source areas of the basin fills. Basin deposition was characterized by coarsening-upward cycles, i.e. sedimentary mélanges as synorogenic sediments. The basin fills became sheared successively by ongoing contractional tectonics with features of typical mélanges. Analyses of ancient Neo-Tethys mélanges along the Eastern Mediterranean mountain ranges allow both, a facies reconstruction of the outer western passive margin of the Neo-Tethys and conclusions on the processes and timing of Jurassic orogenesis. Comparisons of mélanges identical in age and component spectrum in all eastern Mediterranean mountain belts confirm a single Neo-Tethys Ocean model in the Western Tethyan realm, instead of multi-ocean and multicontinent scenarios.

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