Field Trip B2: Triassic to Early Cretaceous geodynamic history of the central Northern Calcareous Alps (Northwestern Tethyan realm)

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Content

Abstract

The topic of this field trip is to get to know and understand the sedimentation of Austria's Northern Calcareous Alps and its tectonic circumstances from Triassic rifting/drifting to Jurassic collision/accretion, and the Early Cretaceous "post-tectonic" sedimentary history. The Northern Calcareous Alps as part of the Eastern Alps is one of the most prominent Alpine areas. Together with the Carpathians, the Southern Alps and the Dinarides, they constituted an up to 700 km wide and approximately 2000 km long shelf strip of the northwestern Tethys margin.

The Triassic sedimentation was controlled by Early to early Middle Triassic extension, the break-up of the Neotethys in the early Middle Triassic and the formation of huge carbonate platforms in the late Middle to Late Triassic. The Jurassic sedimentation in this realm was controlled by the palaeogeographic position of the depositional area between two oceans and their evolution, respectively: the Neotethys Ocean to the east resp. southeast and the Alpine Atlantic to the west resp. northwest. The opening of the Central Atlantic Ocean with its continuation into the Alpine Atlantic (= Ligurian-Penninic Ocean) leads to a new Mediterranean plate configuration. The "Apulian" plate was formed. Successive spreading of the Alpine Atlantic is mirrored by the closure of parts of the Neotethys Ocean resulting in an early deformation of a former Triassic carbonate shelf since late Early Jurassic time. Nappe thrusting was sealed by Late Jurassic carbonate platforms. Uplift of the orogen since latest Jurassic was followed by the filling-up of the remaining foreland basin in Early Cretaceous times.

Deformation and accretion started in the Neotethys Ocean with intra-oceanic thrusting in the late Early Jurassic. This thrusting process resulted in the obduction of the accreted ophiolites onto the outer shelf in Middle Jurassic times as demonstrated for example in the Dinarides. The former Triassic to Early Jurassic passive continental margin with its huge Triassic carbonate platforms took a lower plate position in this developing thin-skinned

orogen. Thrusting started in the outer shelf region and successively propagated towards the inner shelf. In the late Middle Jurassic contractional tectonics reached the inner parts of the shelf and affected the Triassic carbonate platforms. Deep-water trench-like basins formed in sequence in front of advancing nappes: Thus the initial first trench-like basins formed in the south. Later, in the early Late Jurassic, further trench-like basins formed farer to the north. The trench-like basins accumulated thick successions of gravitatively redeposited sediments deriving from the accreted older sedimentary sequences. In the Late Jurassic to Earliest Cretaceous this mountain building process is sealed by the onset of shallow-water carbonate platforms. Shallow-water platform carbonates were formed on top of the nappe stack whereas hemipelagic limestones or radiolarites were deposited in the former radiolaritic trench-like basins. Latest Jurassic uplift of the orogen led to the destruction of this platform/basin pattern and resulted in a diachronous drowning of the platform (central and northern part) resp. uplift and erosion of the platform in the more southern areas. In the Early Cretaceous the remaining basins were filled up by the erosional products of the older nappe stack including material from the obducted ophiolites.

This Triassic to Early Cretaceous evolution of the Northern Calcareous Alps is best preserved in their central region. During the field trip we will visit some of the finest outcrops documenting this earliest phase of Alpine mountain building and degradation.

1 Introduction

As introduction a short outline of the whole Permian/Triassic to Early Cretaceous sedimentary and geodynamic evolution of the northwestern Neotethys realm (e.g., Eastern and Southern Alps, Western Carpathians, Pannonian realm, Dinarides) is provided in order to better understand the topics of the field trip (Fig. 1). We will see Late Permian to Middle Jurassic rocks from different provenance areas as reworked, differently sized (millimetre to square kilometre) components in the late Middle to early Late Jurassic deep-water basin successions. Beside age dating of the matrix sediments, unravelling the derivation of these components is of great importance for the reconstruction of basin formation during that time span. The overall geodynamic evolution is crucial for the initiation of the large-scaled mass movements into these deep-water basins and the time-equivalent to subsequent formation of carbonate platforms. The Eastern Alps, especially the Northern Calcareous Alps (Fig. 2) as part of this northwestern Neotethyan realm, provide an excellent opportunity to study this story. More than 150 years of geological investigations form a solid data base with many topics still controversially discussed and remaining open questions. Not only the geodynamic models are controversial but there is also still no consensus on the palaeogeographic configuration of today's mountain puzzle in this region (details in MISSONI & GAWLICK, 2011a).

There is a large number of contrasting palaeogeographic reconstructions of the Alpine Belt and adjacent regions for the Late Triassic to Jurassic period (e.g., FRISCH, 1979; HAAS et al., 1995; GAWLICK et al., 1999a, 2008; STAMPFLI & BOREL, 2002; SCHMID et al., 2004, 2008; STAMPFLI & KOZUR, 2006, and many others; compare ZACHER & LUPU, 1999). Our reconstruction of the Austroalpine domain´s tectonostratigraphic evolution follows a causal approach. It is based on the tectonic events steering the depositional areas´ development and the deposition of the different sedimentary successions (= formations and lithostratigraphic names), respectively. The formations are classified in respect of their event-related deposition within a palaeogeographic domain. The subordinate control of the history of the Austroalpine domain was the situation of the latter as part of a continent between two oceanic domains: the Alpine Atlantic Ocean (= South Penninic/Piemont/Ligurian Ocean) to the west/northwest related to the Central Atlantic Ocean (e.g., FRISCH, 1979; LEMOINE & TRÜMPY, 1987 - the term “Alpine Tethys“ should not be used in order to avoid confusion: e.g., DAL PIAZ, 1999; STAMPFLI & BOREL, 2002; SCHMID et al., 2004, 2008; STAMPFLI & KOZUR, 2006) and the Neotethys Ocean to the south/southeast (not Meliata Ocean - compare KRYSTYN et al., 2008) (Figs. 3, 6).

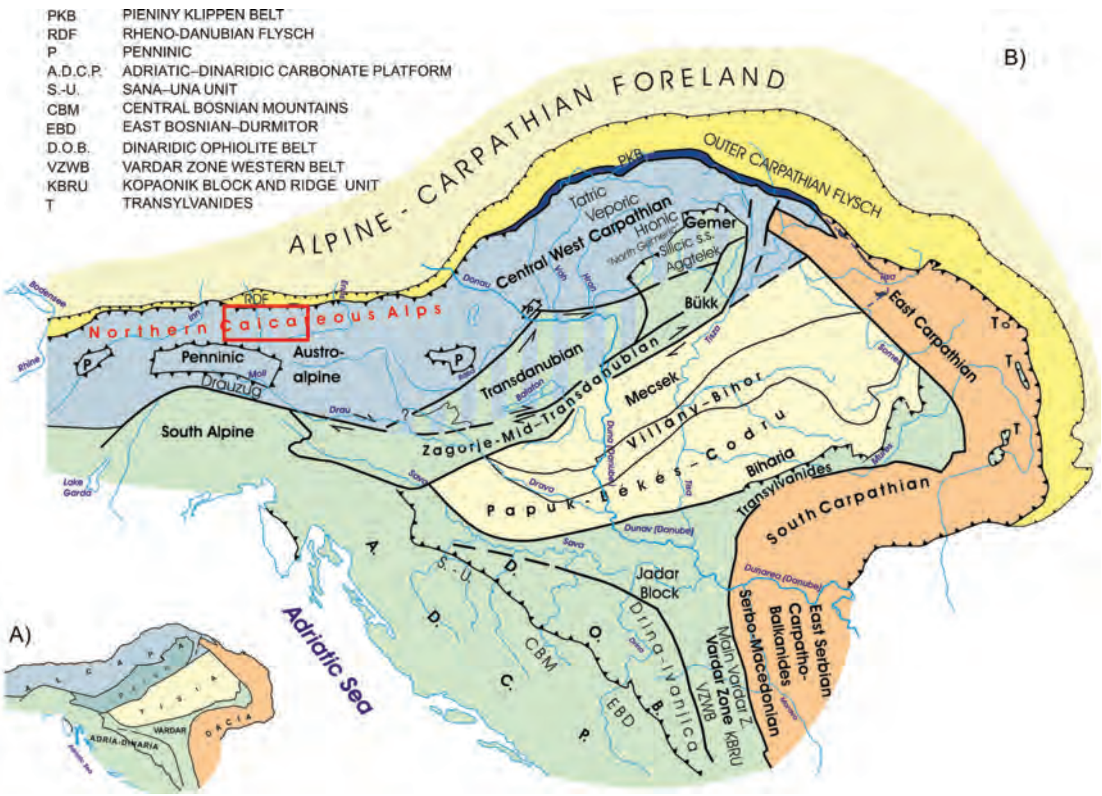


Figure 1: A) Mega-units and mountain belts in the Alpine-Carpathian-Dinaride-Pannonian realm. **B**) Most important tectonic mega-units/nappe systems in the Alpine-Carpathian-Dinaride-Pannonian realm with more detailed names of the different units and the area of the field trip indicated (after KOVACS et al., 2010, 2011). For the Austroalpine mega-unit and the exact geographic position of the Northern Calcareous Alps see Fig. 2.

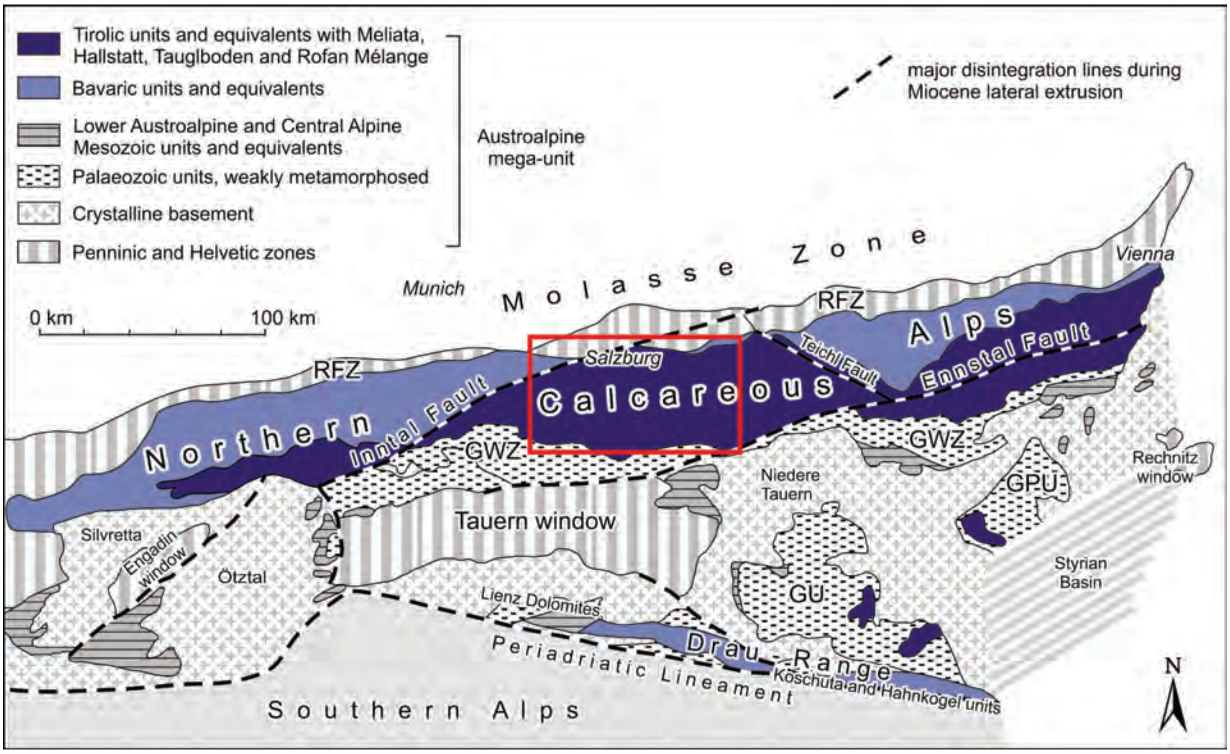


Figure 2: Tectonic sketch map of the Eastern Alps and field trip area (compare Fig. 8; after TOLLMANN, 1977; FRISCH & GAWLICK, 2003). *GPU* Graz Palaeozoic Unit; *GU* Gurktal Unit; *GWZ* Greywacke Zone; *RFZ* Rhenodanubian Flysch Zone.

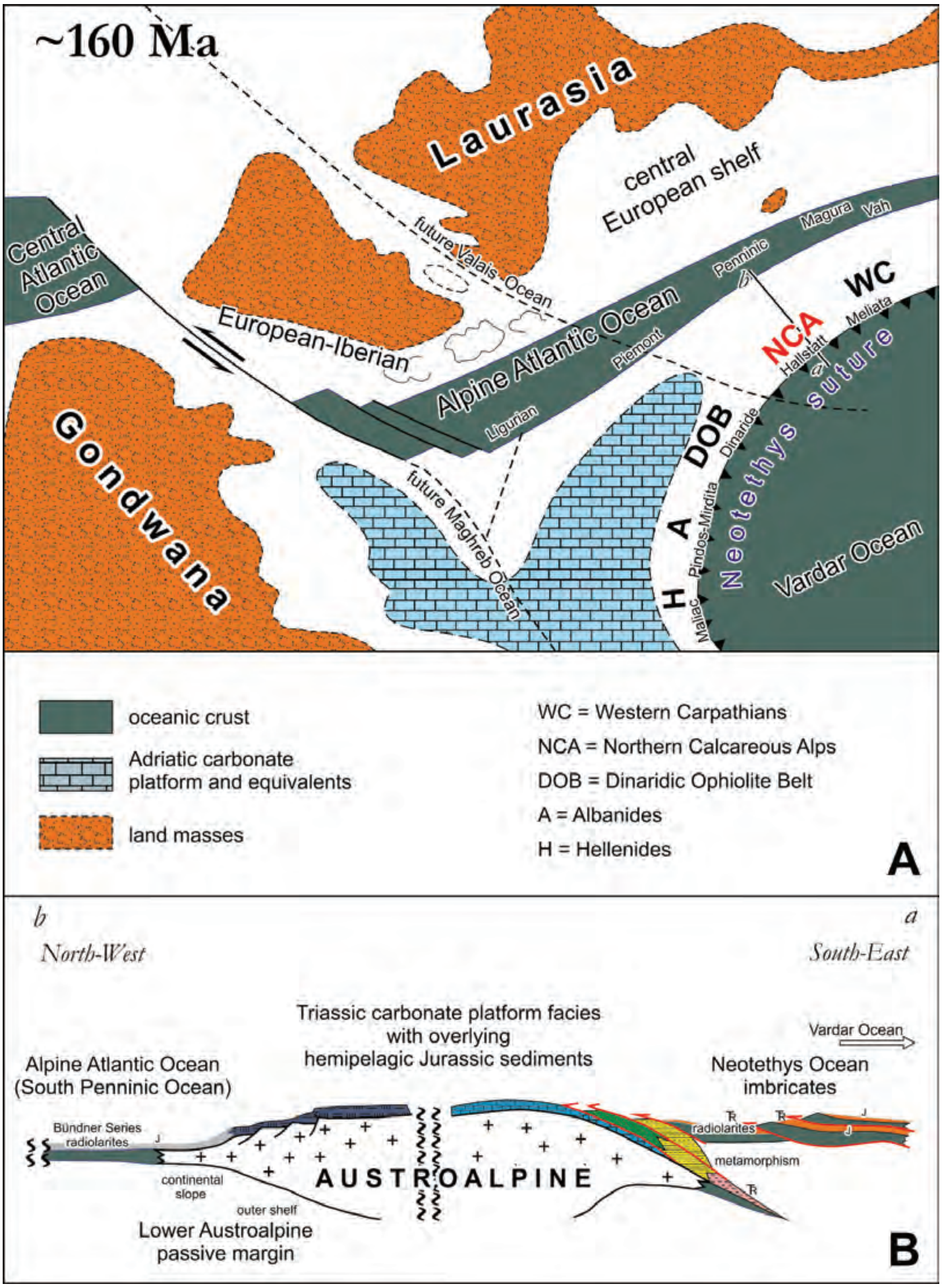


Figure 3: A) Palaeogeographic position of the Northern Calcareous Alps as part of the Austroalpine domain in Late Jurassic time (after FRISCH, 1979; GAWLICK et al., 2008). In this reconstruction the Northern Calcareous Alps are part of the Jurassic Neotethyan Belt (orogen) striking from the Carpathians to the Hellenides. The Neotethys suture is equivalent to the obducted West-Vardar ophiolite complex (e.g., Dinaridic Ophiolite Belt) in the sense of SCHMID et al. (2008) = far-travelled ophiolite nappes of the western Neotethys Ocean in the sense of GAWLICK et al. (2008) (see ROBERTSON, 2012 for discussion). The eastern part of the Neotethys Ocean remained open = Vardar Ocean (compare Figs. 16–22). Toarcian to Early Cretaceous Adria-Apulia carbonate platform and equivalents according to GOLONKA (2002), VLAHOVIC et al. (2005), and BERNOULLI & JENKYNS (2009). **B**) Schematic cross section reconstructed for Middle to Late Jurassic times. It shows the passive continental margin of the Lower Austroalpine domain facing the Penninic Ocean to the northwest (e.g., TOLLMANN, 1985; FAUPL & WAGREICH, 2000) and the lower plate position and imbrication of the Austroalpine domain in relation to the obducted Neotethys oceanic crust (after GAWLICK et al., 2008). Compare FRISCH (1979, 1980a, b).

In Triassic to Early Cretaceous times the Northern Calcareous Alps, together with the Western Carpathians, the Dinarides, the Albanides, the Hellenides and other regions, formed a continuous NNE-SSW trending belt facing the north-western margin of the Neotethys Ocean (Fig. 3) and undergoing the same history: Formation of oceanic crust since Late Anisian, onset of inneroceanic thrusting in late Early Jurassic, ophiolite obduction in Middle-Late Jurassic, followed by the formation of shallow-water platforms, extensional collapse due to tectonic thickening and mountain uplift before the Jurassic/Cretaceous boundary, and infilling of the foreland basins with the erosional products of this orogen in the Early Cretaceous. The detailed documentation of the geodynamic evolution as synthesized in MISSONI & GAWLICK (2011a, b) clearly demonstrates that a prominent orogenic event with oceanic accretion, fold thrust belt formation and foreland basin creation has taken place in that period. The regional importance of this event affected the complete western margin of the Neotethys margin; therefore the name Neotethyan Belt for this Jurassic orogen was introduced by MISSONI & GAWLICK (2011b).

What you will see:

- the Late Triassic shallow-water carbonate platform: restricted lagoon, open lagoon, reef to open shelf sedimentary rocks,
- formation of a palaeotopography in the latest Triassic due to siliciclastic influence and the response of the carbonate factories. Formation of a deep lagoon,
- Early Jurassic open marine sediments sealing the Late Triassic palaeotopography (pelagic platform),
- formation of Middle to early Late Jurassic deep-water radiolaritic trench-like basins due to out-of-sequence thrusting with the deposition of fine-grained organic rich sediments intercalated by olistostromes and huge slides,
- large scale mass movements from an accretionary wedge in adjacent trench-like basins; each basin fill is characterized by a coarsening-upward cycle,
- onset of shallow-water carbonate platforms on an uplifted nappe stack, progradation of shallow-water carbonates over older deep-water basins,
- formation of starved basins in between carbonate platforms as result of the interplay of tectonics and carbonate production,
- carbonate platform collapse due mountain uplift associated with extensional tectonics,
- Early Cretaceous drowning of carbonate platforms due to siliciclastic input.

To see the complete, very complex passive to active continental margin evolution from Late Triassic to Early Cretaceous in the central Northern Calcareous Alps (Salzburg and Berchtesgaden Calcareous Alps). This area is a geological highlight in one of the most classical geological areas of the world.

Classical concept and historical alternatives

The classic tectonic subdivision of the Northern Calcareous Alps (compare Fig. 2) (in its fundamentals established by HAUG, 1906, later modifications by, e.g., HAHN, 1913; KOBER, 1923; SPENGLER, 1951; PLÖCHINGER, 1980; TOLLMANN, 1985) defined three nappe groups. These are, from bottom to top: Bavaric, Tirolic, and Juvavic nappe group (in the central Northern Calcareous Alps today only preserved in the Hallstatt Mélange). This tectonic concept, established in the Berchtesgaden Alps and in the Salzkammergut area, was widely accepted. Later, a subdivision into three tectonic units (“Stockwerke“ *sensu* LEBLING et al., 1935) was proposed: the Tirolic unit (“Tirolische Einheit“ *sensu* HAHN, 1913) at the base, overlain by the Lower Juvavic unit (“Tiefjuvavische Einheit“: Hallstatt nappes), and the Upper Juvavic unit (“Hochjuvavische Einheit“: Berchtesgaden and Dachstein nappes). Subsequently, in the salt-mine of Hallein MEDWENITSCH (1962) subdivided the Lower Juvavic nappe into a Lower (“Untere Hallstätter Decke“: Zlambach nappe - grey Hallstatt facies rocks) and an Upper Hallstatt nappe (“Obere Hallstätter Decke“: Sandling nappe - variously coloured Hallstatt Limestone nappe). In this concept fragmentary blocks of Lower Juvavic

Hallstatt Limestones (TOLLMANN, 1976b) framed the Upper Juvavic nappes (TOLLMANN, 1985 for details and figures).

In an alternative concept, evaporites, subsumed as Alpine Haselgebirge (Permian salt-claystone succession; Haselgebirge Mélange according to SPÖTL et al., 1998), acted as a ductile paste and motor of gravitational tectonics. Gravitational tectonics in the Juvavic units should have started in the Oxfordian (e.g., TOLLMANN, 1981, 1987; MANDL, 1982; LEIN, 1985; 1987a) or Late Tithonian (PLÖCHINGER, 1974, 1976, 1984), leading to Late Jurassic to Early Cretaceous sliding of Alpine Haselgebirge and Hallstatt Limestone successions towards the north. According to these models (summarized in, e.g., TOLLMANN, 1987; LEIN, 1987b), sliding began in a phase of enhanced radiolarite sedimentation when troughs with marine sedimentation were arranged along the median longitudinal axis of the Northern Calcareous Alps (DIERSCHE, 1980). Mainly based on ammonite stratigraphy (summarized in DIERSCHE, 1980), the onset of radiolarite sedimentation was estimated as Oxfordian. Hence, the radiolarite basins were filled up by deep-water cherty limestones to radiolarites with intercalated breccias and turbidites. Slump folds are characteristic features in these sediments (e.g., GARRISON & FISCHER, 1969; SCHLAGER & SCHLAGER, 1973; DIERSCHE, 1980; TOLLMANN, 1987).

The formation of the generally asymmetric radiolarite basins was attributed to extensional tectonics (e.g., SCHLAGER & SCHLAGER, 1973; DIERSCHE, 1980; VECSEI et al., 1989). Another group of authors attributed basin formation and breccia mobilization to strike-slip tectonics (e.g., FISCHER, 1965; WÄCHTER, 1987; FRANK & SCHLAGER, 2006; ORTNER et al., 2008).

Current concept

In the current concept, based on new results, we follow:

1) The tectonic subdivision of the Eastern Alps of TOLLMANN (1977) with some modern modifications (FRISCH & GAWLICK, 2003; compare SCHMID et al., 2004) (Fig. 2),
2) The palaeogeographic reconstructions of KRYSTYN & LEIN in HAAS et al., (1995) with some modifications (Fig. 6), and
3) The concept that the Jurassic geodynamic history of the Austroalpine domain mirrors its palaeogeographic position between two oceanic domains (Fig. 3):
   I. To the west (northwest) the newly formed Penninic Ocean as part of the Alpine Atlantic, where continental extension started around the Triassic/Jurassic boundary or in the Hettangian, with the first oceanic crust formed in the late Early Jurassic (Toarcian), and
   II. to the east (southeast) the Neotethys Ocean, in which closure started before the Early/Middle Jurassic boundary.

The Juvavic nappe stack represented the Jurassic accreted wedge of the Northern Calcareous Alps (FRISCH & GAWLICK, 2003). It became completely eroded in the sector of the central Northern Calcareous Alps with remnants of this nappe complex only preserved in the Middle to Late Jurassic radiolaritic trench-like (wildflysch) basin fills (GAWLICK & FRISCH, 2003). Most probably the huge blocks on top of the basin fills represent remnants of the overthrusting nappes. These basins were situated in front of the propagating thrust belt or on top of them and were later overthrusted. In these radiolaritic basins all sedimentary rocks of the Meliata facies zone, the Hallstatt facies belt and from the reefal belt of the Triassic carbonate platform occur as redeposits. Some blocks show the effect of transported metamorphism (GAWLICK & HÖPFER, 1999; MISSONI & GAWLICK, 2011a; compare FRANK & SCHLAGER, 2006).

In the Bajocian the sedimentary evolution in the southern (palaeogeographically southeastern - Fig. 3) part of the Tirolic realm as well as in the Hallstatt realm differed from that in the northern (palaeogeographically northwestern - Fig. 2) part. Deep-water trench-like basins formed in front of advancing nappes. The first basin group in the southern parts of the Northern Calcareous Alps received mass-flow deposits and large, up to nappe sized slides which derived from the Hallstatt Zone (= Hallstatt Mélange). The thickness of the basin fills may reach up to 2.000 metres. The nappe stack carrying the Hallstatt Mélange is defined as Upper Tirolic nappe (group) (Fig. 7).

The second basin group, the Tauglboden and the Rofan trench-like basins in the north were subjected to high subsidence and sedimentation rates in the Oxfordian to earliest Kimmeridgian. The Trattberg Rise was eroded and supplied the Tauglboden Basin to its north with mass-flow deposits and slides. The nappe carrying the Tauglboden Mélange is defined as lower Tirolic nappe. On the other hand, the Rofan Basin was carried by the lowermost Tirolic nappe. It formed later than the Tauglboden Basin and received the material from the Hauptdolomit facies zone (Brunnwinkl Rise).

2 Overall geodynamic and sedimentary evolution

Following a major post-Variscan regression and Permian crustal extension (e.g., SCHUSTER & STÜWE, 2008), sedimentation in the northwestern Tethyan realm started in the Middle/Late Permian with coarse-grained siliciclastic sediments in the northwest (Alpine Verrucano - compare TOLLMANN, 1976a, 1985) and evaporites to the southeast (Alpine Haselgebirge: TOLLMANN, 1976a, 1985) due to early Neotethyan crustal extension (SCHUSTER et al., 2001). In the Early Triassic, siliciclastic sedimentation continued with the deposition of the Alpine Buntsandstein in the northwest and with deposition of the marine Werfen Beds in the southeast (Fig. 4). Around the Early/Middle Triassic boundary, carbonate production started with the build-up of carbonate ramps (top Werfen Formation, Gutenstein and Steinalm Formations: Fig. 4). The opening event with open marine influence is manifested below the Middle Anisian Steinalm Formation (LEIN et al., 2010). Shallow-water carbonate sedimentation with overlying hemipelagic carbonates (GALLET et al., 1998) as the result of a partial drowning event due to the final break-up of the Neotethys Ocean in the late Pelsonian (LEIN & GAWLICK, 2008) dominated in the entire Eastern Alps in the Middle Triassic. In late Middle to early Late Triassic times, the Wetterstein Carbonate Platform was formed (Fig. 4). This platform was overlain by siliciclastic sediments of the Lunz and Northalpine Raibl Formations or by the Reingraben Formation (*Halobia* Beds) in the Hallstatt realm (HORNUNG, 2007; KRYSTYN, 2008). After this siliciclastic event a new carbonate ramp built up in Tuvalian time (Opponitz and Waxeneck Formations). On top, the classic Late Triassic Hauptdolomit/Dachstein Carbonate Platform was formed during optimum climatic and geodynamic conditions in the Norian and Rhaetian.

At the Triassic/Jurassic boundary, the carbonate production rate significantly decreased. This occurred in connection with an environmental crisis that led to mass extinction and was accompanied by a sea-level drop (compare SEPKOSKI, 1996). Regardless of the causes of this mass extinction, which are intensively debated (summarized e.g., in PÁLFY, 2008), these environmental events left a signature in the Austroalpine domain (e.g., HILLEBRANDT & KRYSTYN, 2009; RICHOZ et al., 2012).

Earliest Jurassic sediments are missing on top of the morphologic highs (former Hauptdolomit/Dachstein Carbonate Platform). Only in basinal areas sedimentation was continuous (HILLEBRANDT & KRYSTYN, 2009). Lack of sufficient sediment supply led to drowning of the Hauptdolomit/Dachstein Carbonate Platform in Late Hettangian times due to a sea-level rise. The spread and morphology of the facies zones in the Early to early Middle Jurassic followed in general the Triassic inventory (Fig. 5) except in the lower Austroalpine units and equivalents.

Later on, a horst and graben morphology developed (BERNOULLI & JENKYNS, 1974; EBERLI, 1988; KRAINER et al., 1994) and triggered breccia formation along submarine slopes and escarpments, mainly in Late Pliensbachian to Early Toarcian times (BÖHM et al., 1995). An increasing pelagic influence was manifested in the Early to Middle Jurassic sediments (GARRISON & FISCHER, 1969; BÖHM, 1992). Breccia formation in late Early Jurassic time is mostly interpreted as a result of the opening of the Ligurian/Penninic (= Alpine Atlantic) Ocean (e.g., BERNOULLI & JENKYNS, 1974; EBERLI, 1988; KRAINER et al., 1994), named Penninic Ocean in the Eastern Alpine realm (compare Fig. 3). Whereas the older part of the Early Jurassic sequences near to the Penninic realm (Lower Austroalpine passive continental margin) shows the typical features of a rifted margin (e.g., EBERLI, 1988), the other areas of the Austroalpine were only slightly influenced by these rifting processes. In contrast, late Early Jurassic (Late Pliensbachian to Early Toarcian) tectonics affected mainly the Dachstein Limestone facies belt (Fig. 5) and resulted in a completely new palaeogeographic setting. Meanwhile the Lower Austroalpine passive margin was not or only mildly influenced by these tectonic processes.

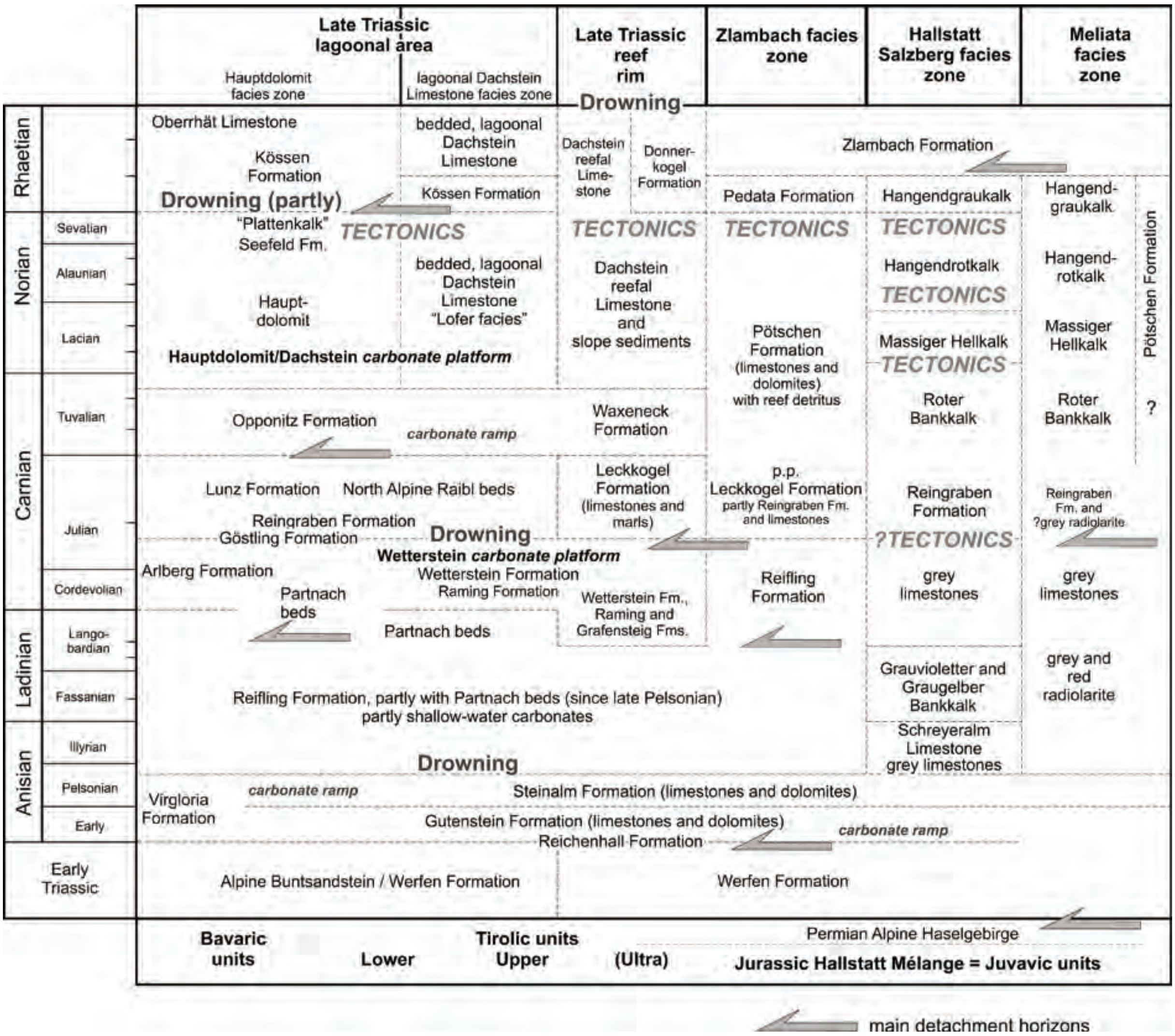
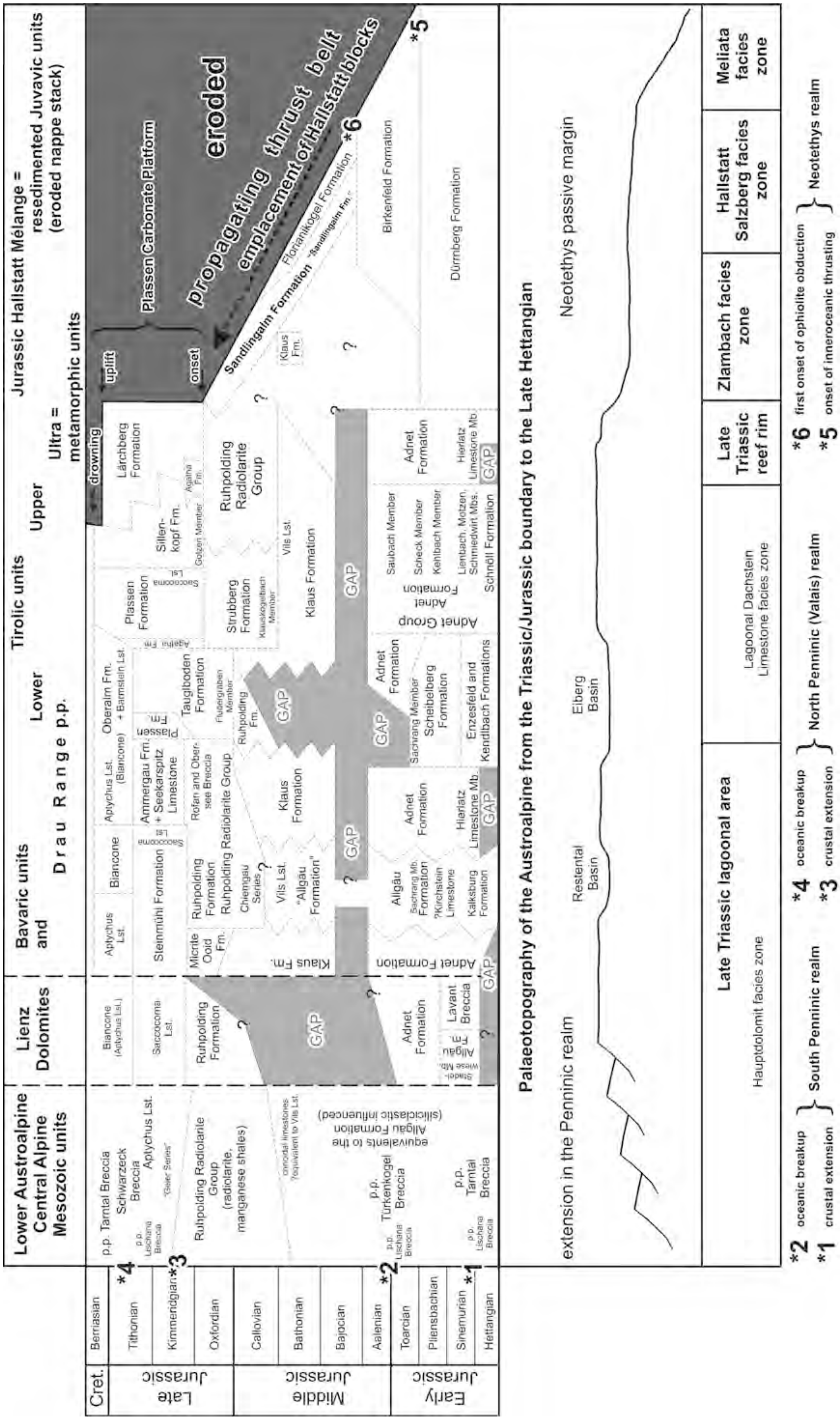


Figure 4: Lithostratigraphic table of Triassic formations and tectonic events in the central Northern Calcareous Alps (modified after TOLLMANN, 1985; GAWLICK & FRISCH, 2003; PILLER et al., 2004; MISSONI & GAWLICK, 2011a, b). The main detachment horizons are indicated because of their importance during Jurassic nappe stacking and disintegration of the sequence in the course of mélange formation. The colours of the different facies belts in this figure correspond to the colours in the other figures, clarifying the provenance of the different clasts and slides in the Jurassic basin successions (after MISSONI & GAWLICK, 2011a). Compare also Fig. 6.

Figure 5 (next page)**:** Stratigraphic table with lithostratigraphic names and main tectonic events of the Jurassic in the Austroalpine realm with their variations depending on the palaeogeographic position (after GAWLICK et al., 2009a; compare Fig. 4, Fig. 6). In red the sedimentary succession which will be visited during the field trip. Bavaric units, Tirolic units, Hallstatt Mélange = Northern Calcareous Alps.


Lower Austroalpine Central Alpine Mesozoic units
Lienz Dolomites
Bavaric units and Tirolic units
Drau Range p.p.
Lower
Upper
Ultra = metamorphic units
Jurassic Hallstatt Mélange = resedimented Juvavic units (eroded nappe stack)
Cret.
Late Jurassic
Middle Jurassic
Early Jurassic
Berriasian
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliensbachian
Sinemurian
Hettangian
eroded
propagating thrust belt
emplacement of Hallstatt blocks
Plassen Carbonate Platform
uplift
onset
drowning
Sandlingalm Formation
Florianikogel Formation
Birkenfeld Formation
Dürrnberg Formation
Ruhpolding Radiolarite Group
Klaus Formation
Adnet Formation
Adnet Group
Allgäu Formation
GAP
Palaeotopography of the Austroalpine from the Triassic/Jurassic boundary to the Late Hettangian
extension in the Penninic realm
Neotethys passive margin
Restental Basin
Eiberg Basin
Late Triassic lagoonal area
Hauptdolomit facies zone
Lagoonal Dachstein Limestone facies zone
Late Triassic reef rim
Zlambach facies zone
Hallstatt Salzberg facies zone
Meliata facies zone
*2 oceanic breakup
*1 crustal extension
South Penninic realm
*4 oceanic breakup
*3 crustal extension
North Penninic (Valais) realm
*6 first onset of ophiolite obduction
*5 onset of inneroceanic thrusting
Neotethys realm

Many authors interpreted the above described change in the late Early Jurassic as a result of the opening of the Penninic Ocean (e.g., EBERLI, 1988; KRAINER et al., 1994). In contrast, FRISCH & GAWLICK (2003), GAWLICK et al. (2009a) and MISSONI & GAWLICK (2011a, b) attributed this “event“ to the onset of subduction in the Neotethys Ocean realm.
In late Early to Middle Jurassic times the situation generally changed also in the former (Triassic) carbonate platform area due to the partial closure of the Neotethys Ocean (Fig. 3). Concerning the active margin, the Austroalpine domain attained the lower plate position (GAWLICK et al., 1999a). The tectonics of this time span were characterized by a propagating thrust belt in front of the overriding ophiolite nappe stack, as proven in the Albanides and Dinarides (GAWLICK et al., 2008, 2009b). In the Eastern Alps and the Northern Calcareous Alps, respectively, the obducted ophiolite nappe stack is not preserved. Here, only pebbles in the Late Jurassic to Early Cretaceous deep-water sedimentary successions prove this ophiolite obduction stage (summarized in GAWLICK et al., 2009a; KRISCHE et al., in press). The same story is visible in the southern Western Carpathians (FROITZHEIM et al., 2008; KOVACS et al., 2011; HAAS et al., 2011).

Middle Jurassic northwest-directed thrusting caused the formation of deep-water trench-like basins in front of the propagating nappes which obliquely cut through former facies belts. Tectonic shortening decreased in Late Jurassic time. In contrast to the Triassic evolution, shallow-water carbonates are generally missing in the Austroalpine domain during most time of the Jurassic until the Late Oxfordian, when new shallow-water carbonate ramps and platforms established (Fig. 3) and sealed the main tectonic shortening structures. They existed until the Early Cretaceous. Siliciclastic influenced sediments occurred in the southern Northern Calcareous Alps in the Kimmeridgian and in the more northward parts in the Early Cretaceous (Fig. 3).

NW-SE directions refer to Triassic-Jurassic palaeogeographic reconstructions. North-South geographic directions refer to the Present as a result of a complex rotation history of the Eastern Alps since Late Cretaceous (e.g., HAUBOLD et al., 1999; CSONTOS & VÖRÖS, 2004; THÖNY et al., 2006; PUEYO et al., 2007).

3 Palaeogeography, sedimentary successions and stratigraphy

The reconstruction of the Triassic palaeogeography, i.e., the facies zones of the shallow-water Hauptdolomit/Dachstein Carbonate Platform and its gradual transition to the hemipelagic Hallstatt Zone, has been arranged in a characteristic shore parallel fashion (Fig. 6) (LEIN, 1985; KRYSTYN & LEIN 1995 in HAAS et al., 1995; GAWLICK et al., 1999a). Their Late Anisian to Early Jurassic sedimentary succession represented an open marine, distal periplatform setting on the Triassic European continental margin facing the Neotethys Ocean (= Meliata Ocean or Meliata-Hallstatt Ocean according to, e.g., KOZUR, 1991; SCHWEIGL & NEUBAUER, 1997a; NEUBAUER et al., 2000; STAMPFLI et al., 2001; STAMPFLI & KOZUR, 2006).
The variegated Hallstatt Salzberg facies represents the oceanward belt on this margin, giving way to siliceous limestones and radiolarites towards the Neotethys Ocean (= Meliata facies; Fig. 6). In the sedimentary environment of the Hallstatt Salzberg facies with relatively stable hemipelagic conditions for at least 40 Ma, the existence of large intermediate shallow-water carbonate platforms is quite unrealistic (GAWLICK & BÖHM, 2000). Only the Zlambach facies zone received shallow-water debris from the large, flat-topped Triassic carbonate platforms.

3.1 Hauptdolomit facies zone

Triassic

The Hauptdolomit facies zone is preserved only in the lower structural units of the Northern Calcareous Alps (Bavaric and in parts Tirolic nappes). Permian and Early Triassic sediments are mostly missing in these profiles as a result of the usage of shallower detachment levels during younger tectonic movements (TOLLMANN, 1985). The thickness of the Middle and Late Triassic formations (Fig. 4) can only be roughly estimated due to the polyphase tectonic history, but could be around 4-5 km (BRANDNER, 1984).

Carbonate production started around the Early/Middle Triassic-boundary with carbonate ramp sediments above the Alpine Buntsandstein (STINGL, 1989) and the evaporitic Reichenhall Formation. The lower Gutenstein Formation was formed in a restricted, periodically hypersaline lagoonal area. The overlying Steinalm Formation (in case with the Annaberg Formation – LEIN et al. (2010) – between) represent sediments of more open marine conditions, partly forming small build-ups and reefal structures created particularly by calcareous algae and microbial mats. The Gutenstein and Steinalm Formations are named Virgloria Formation in the western Northern Calcareous Alps (PILLER et al., 2004). In Late Anisian time a large part of this (Steinalm) carbonate ramp was drowned and widespread basinal carbonate sedimentation took place (grey, cherty limestones of the Reifling Formation) (BECHSTÄDT & MOSTLER, 1974, 1976; KRYSTYN, 1991; KRYSTYN & LEIN, 1996). According to GAWLICK (2000a) and MISSONI & GAWLICK (2011a) the hemipelagic carbonatic basins were separated from the open shelf area by the growing Wetterstein carbonate platforms to the southeast in the Late Ladinian (Langobardian) (compare KRYSTYN & LEIN, 1996; LEIN et al., 2012). The Reifling sedimentation was replaced by fine-grained siliciclastic deposition of the Partnach Beds. During Early Carnian, after a regressive/transgressive cycle the Wetterstein Carbonate Platform (Arlberg and Wetterstein Formations) started to prograde into this facies belt (BRANDNER & RESCH, 1981; KRYSTYN & LEIN, 1996; LEIN et al., 2012). South of the rapidly southeastward (towards the Dachstein Limestone facies zone) prograding platform (Raming Formation as slope deposits: LEIN, 1989), a basinal area prevailed in Early Carnian (Cordevolian) time. The youngest sediments in these basinal areas were the organic-rich grey, cherty limestones of the Göstling Formation. As consequence of the Lunz/Reingraben event (SCHLAGER & SCHÖLLNBERGER, 1974; LEIN et al., 1997; recently renamed as Carnian Pluvial Event), the Wetterstein Carbonate Platform drowned nearly in the whole area in Julian time and deposition of siliciclastic sediments (Lunz and Northalpine Raibl Formations) took over (TOLLMANN, 1976a, 1985; KRAINER, 1985). These siliciclastic deposits filled the basinal areas between the Wetterstein Carbonate Platforms, with the result of a uniform topography at the end of this siliciclastic event. In the Late Carnian, the siliciclastic input decreased rapidly and a new carbonate ramp was established (Opponitz-Waxeneck carbonate ramp). The transition between the early Late Carnian “Northalpine Raibl Formation“ and the more carbonatic sedimentation farer to the south is gradual. Around the Carnian/Norian-boundary this carbonate ramp passed in the Late Triassic Hauptdolomit/Dachstein Carbonate Platform (for details see TOLLMANN, 1976a, 1985; GAWLICK & BÖHM, 2000). The Hauptdolomit ranges from ?latest Carnian/earliest Norian to the Middle/Late Norian, with newly formed intraplatform basins in Middle to Late Norian times (e.g., Seefeld Formation) (TOLLMANN, 1976a; DONOFRIO et al., 2003; compare BECHTEL et al., 2007). In the Late Norian, opening of the restricted Hauptdolomit lagoon resulted in deposition of the “Plattenkalk“. In Early Rhaetian the lagoon deepened and renewed siliciclastic input led to deposition of the mixed terrigenous-carbonatic Kössen Formation (stratigraphic details in GOLEBIOWSKI, 1990a, 1991). In Late Rhaetian, the Kössen Formation was in many places overlain by shallow-water carbonates including reefal build-ups in some areas (Oberrhät Limestone: FLÜGEL, 1981). Within the Hauptdolomit facies zone, these shallow-water carbonates prograded from north towards south.

Jurassic

In the earlier Early Jurassic, the sedimentation was mainly controlled by the Late Triassic topography (Fig. 5; BÖHM, 2003; GAWLICK & FRISCH, 2003; GAWLICK et al., 2009a). Only in the westernmost part of the Austroalpine domain extensional tectonics led to the formation of the southeastern (Lower Austroalpine and equivalents) passive continental margin of the (South) Penninic Ocean (FRISCH, 1979; EBERLI, 1988; HÄUSLER, 1988) as part of the Central Atlantic system (Fig. 3, details of the whole evolution in GAWLICK et al., 2009a). Near to the future oceanic realm (start of sea-floor spreading in Late Toarcian: RATSCHBACHER et al., 2004) asymmetric, breccia-filled basins are common features (e.g., EBERLI, 1988). The influence of this extensional process decreased in eastern direction towards the Dachstein Limestone facies zone. Therefore, in most areas block tilting was relatively mild in the Hauptdolomit facies zone in direction towards the Dachstein Limestone facies belt.

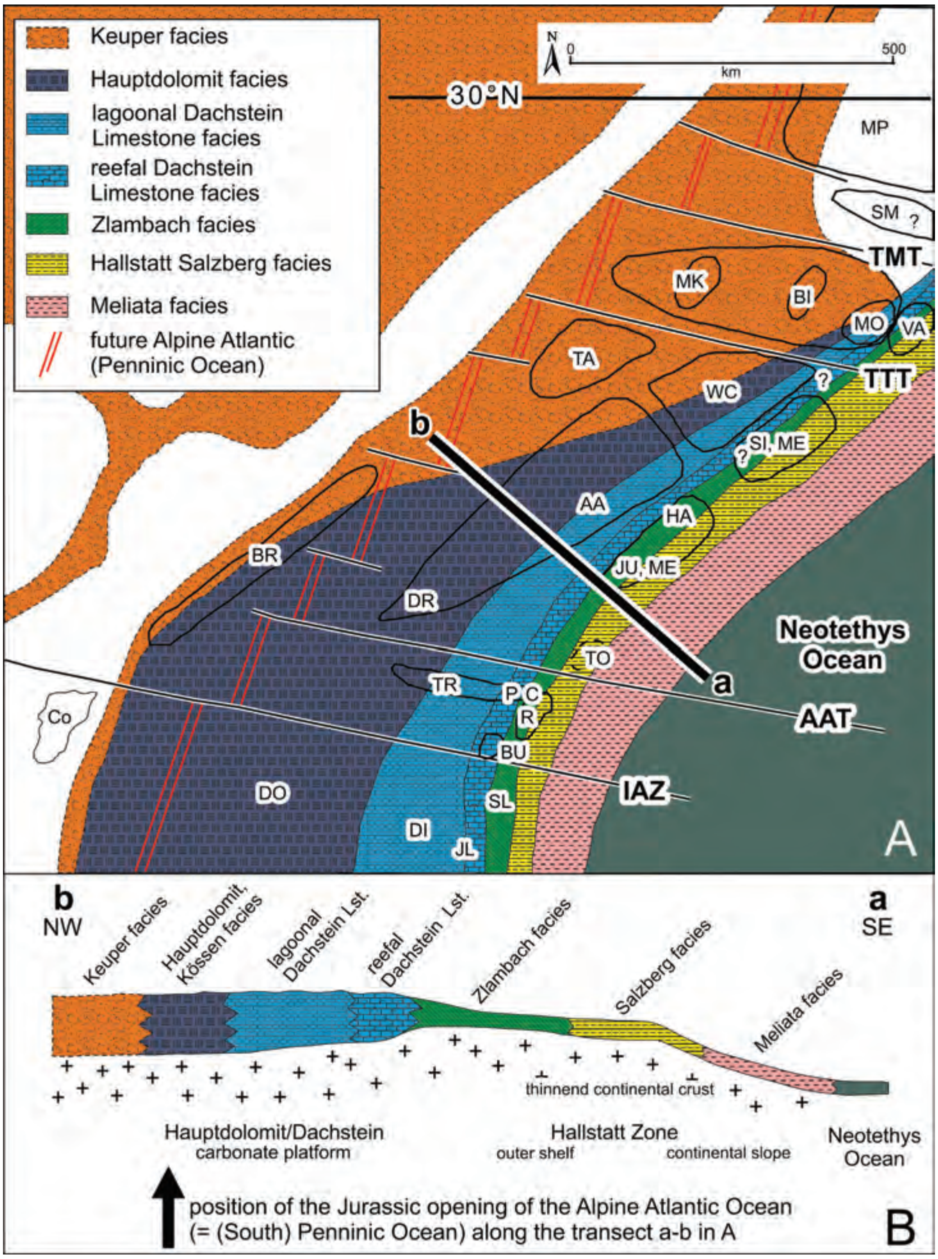


Figure 6: A) Late Triassic palaeogeographic position and facies zones of the Austroalpine domain as part of the northwestern Neotethys passive margin, modified after KRYSTYN & LEIN in HAAS et al. (1995) and GAWLICK et al. (1999a, 2008). **B**) Schematic cross section (for position, see line a-b in A) showing the typical passive continental margin facies distribution across the Austroalpine domain in Late Triassic time (after GAWLICK & FRISCH, 2003). Compare Fig. 3.
IAZ = Iberia-Adria Zone transform fault, AAT = future Austroalpine-Adria transform fault, TTT = future Tisza-Tatra transform fault, TMT = future Tisza-Moesia transform fault, AA = Austroalpine, BI = Bihor, BR = Briançonnais, BU = Bükk, C = Csovar, Co = Corsica, DI = Dinarids, DO = Dolomites, DR = Drau Range, HA = Hallstatt Zone, JU = Juvavicum, JL = Julian Alps, ME = Meliaticum, MK = Mecsek, MO = Moma unit, MP = Moesian platform, P = Pilis-Buda, R = Rudabanyaicum, SI = Silicicum, SL = Slovenian trough, SM = Serbo-Macedonian unit, TA = Tatricum, TO = Tornaicum, TR = Transdanubian Range, VA = Vascau unit, WC = central West Carpathians. For other reconstructions of the western Tethyan realm see, e.g., SENGÖR (1985a, b); CHANNELL et al. (1990, 1992); DERCOURT et al. (1986, 1993); MARCOUX & BAUD (1996); CHANNELL & KOZUR (1997); STAMPFLI & BOREL (2002); STAMPFLI & KOZUR (2006).

The Rhaetian shallow-water carbonates were overlain by red and grey crinoidal limestones in the Hettangian and Sinemurian, partly with a gap in the depositional record (EBLI, 1997). On top of the Rhaetian Kössen Formation cherty and marly bedded limestones were deposited (Kalksburg Formation and Kirchstein Limestone). These sediments progressed gradually into the hemipelagic Allgäu Formation (Sinemurian to ?Bathonian). In the depositional areas of the Adnet and Enzesfeld Formations, condensed sedimentation prevailed partly until the late Middle Jurassic. Red limestone deposition resumed in the form of the Steinmühl or Klaus Limestones (Bajocian to Tithonian; KRYSTYN, 1971, 1972). In the Callovian to Oxfordian there was a widespread deepening of the depositional environment, which resulted in the sedimentation of cherty limestones, cherty marls, and radiolarites. In basinal areas on top of the Allgäu Formation, dark grey cherty marls and cherty limestones were deposited. These were formerly interpreted as early to late Middle Jurassic Allgäu Formation (EBLI, 1997; PILLER et al., 2004), but are in fact time equivalents of the Ruhpolding Radiolarite Group (Chiemgau series) in the sense of GAWLICK & FRISCH (2003), followed by *Saccocoma* Limestone. On the Early to Middle Jurassic topographic highs, red condensed limestones or condensed radiolarites were deposited (Callovian to Kimmeridgian). In the Kimmeridgian the siliceous sedimentation passed gradually to a marlier and then limier one, which is characteristic for the Tithonian to Early Berriasian (Ammergau Formation, Aptychus beds, Biancone). Typical Aptychus beds beside Biancone were deposited in the Late Tithonian.

3.2 Dachstein Limestone facies zone

Triassic

In the Dachstein Limestone facies zone (mainly preserved in the Tirolic unit) the stratigraphic and facial evolution reflects the intermediate passive margin setting between the Hauptdolomit facies zone and the Hallstatt facies belt (Fig. 6). The thickness of the Middle and Late Triassic formations is slightly higher compared to that in the Hauptdolomit facies zone.

Carbonate production began in the Late Olenekian, slightly earlier than in the Hauptdolomit facies zone (MOSTLER & ROSSNER, 1984), followed by the evaporitic Reichenhall Formation around the Olenekian/Anisian-boundary. Increased carbonate productivity started also around the Early/Middle Triassic-boundary with carbonate ramp sediments (Gutenstein and Steinalm Formations) above the Alpine Buntsandstein/Werfen Formation and the evaporitic Reichenhall Formation. In Late Anisian time, large part of this carbonate ramp drowned and widespread basinal sedimentation took place, with dolomites predominating, (Reifling Formation) (e.g., MISSONI & GAWLICK, 2011a). The siliciclastic influenced Partnach Formation was deposited in the northern part of this facies belt, whereas in the more southeastern part of this facies belt the Wetterstein Carbonate Platform was formed since the Late Ladinian (KRYSTYN & LEIN, 1996). Transitional to the hemipelagic open shelf areas, the Raming and Grafensteig Formations (HOHENEGGER & LEIN, 1977) were formed. This platform drowned in Julian time nearly in the whole facies belt in the wake of the Lunz/Reingraben event (SCHLAGER & SCHÖLLNBERGER, 1974; recently renamed as Carnian Pluvial episode: SIMMS & RUFFEL, 1989). Siliciclastic (e.g., Lunz/Raibl Formation, Reingraben Formation) and carbonatic sediments (Cidaris Limestone) were deposited. As in the Hauptdolomit facies belt, these siliciclastic rocks filled the basinal areas between the Wetterstein Carbonate Platforms, leading to a nearly uniform topography at the end of the siliciclastic event. In the Late Carnian the siliciclastic input decreased rapidly and a new carbonate ramp was established. The Opponitz Formation was deposited under shallow-water, partly evaporitic conditions in the northern part of the Dachstein facies belt. Towards south, the environment passed gradually to a more open marine one, however, with the shallow-water Waxeneck Formation in the southern part of the Dachstein Limestone facies zone (KRYSTYN et al., 1990). Around the Carnian/Norian-boundary, this carbonate ramp passed into the lagoonal to reefal Dachstein Limestone platform. The Dachstein Limestone ranged from the lowermost Norian to the Late Norian, without recognised intraplatform basins in the Middle or Late Norian. In Early Rhaetian, the northern part of the Dachstein Limestone lagoon deepened by siliciclastic input and changed to the mixed terrigenous-carbonatic sedimentation of the Kössen Formation, intercalated by the "*Lithodendron*" reef limestone (GOLEBIOWSKI, 1990, 1991). In the Late Rhaetian, the Kössen Formation was occasionally overlain by shallow-water, partly reefal carbonates (Oberrhät Limestone or Rhaetian Dachstein Limestone). The Rhaetian Dachstein Carbonate Platform (FLÜGEL, 1981; SCHÄFER & SENOWBARI-DARYAN, 1981) prograded from south towards north.

The southern part of the Dachstein Limestone facies zone, i.e., the reef rim (Upper Tirolic nappe), represented the transitional area from the lagoonal area to the open marine shelf (reef rim and transitional zone to the Hallstatt facies zone). The early Middle Triassic sedimentary succession of this transitional area is similar to those of the other parts of this facies belt. An Early Ladinian transition of the Reifling Formation into the Hallstatt Limestone is partly preserved. The formation of the Wetterstein Carbonate Platform started in the Late Ladinian. It rapidly prograded towards southeast (Raming Formation: LEIN, 1989). The Lunz/Reingraben event affected these areas only peripheral with thin, fine-grained siliciclastic sediments (Reingraben Beds). In some areas, shallow-water organisms survived the event as recorded in the Julian Leckkogel Formation (DULLO & LEIN, 1982). The Leckkogel Formation passed gradually into the Late Carnian Waxeneck Formation (LEIN in KRYSTYN et al., 1990) and later into "Hallstatt Limestones" (eastern Northern Calcareous Alps, Mürzalpen nappe; LEIN, 1987b) or the Norian to earliest Rhaetian reefal Dachstein Limestone (ZANKL, 1969; FLÜGEL, 1981; KRYSTYN et al., 2009; RICHOZ et al., 2012) which drowned in Early Rhaetian time (KRYSTYN et al., 2009: Donnerkogel Formation). In fact, in this palaeogeographic area a vertical mixture of basinal sediments, fore reef to back reef sediments, and partly lagoonal sediments occurred, reflecting sea-level fluctuations and possibly ?extensional tectonic movements (LEIN, 1985; GAWLICK, 1998, 2000a; GAWLICK & BÖHM, 2000; compare MISSONI et al., 2008: strike-slip tectonics). In Late Norian time, in some areas of this facies belt hemipelagic sequences were deposited in newly formed basins (Mürztal facies, Aflenz facies: LEIN, 1982, 1985, 2000; TOLLMANN, 1985).

Jurassic

In the Early Liassic, the sedimentation was controlled by the topography of the Late Triassic Hauptdolomit/Dachstein Carbonate Platform (Fig. 5, BÖHM, 2003; GAWLICK & FRISCH, 2003). On top of the Rhaetian shallow-water carbonates red condensed limestones of the Adnet Group (Hettangian to Toarcian: BÖHM 1992, 2003) were sedimented, partly above a depositional gap. On top of the Rhaetian Kössen Formation cherty and marly bedded limestones (Scheibelberg Formation: Hettangian to Toarcian; Kendlbach Formation: Hettangian: BÖHM, 1992, 2003; EBLI, 1997; KRAINER & MOSTLER, 1997) were deposited in the transitional areas to the Rhaetian Kössen Basin crinoidal or sponge spicula rich limestones of the Enzesfeld Formation (Hettangian to Sinemurian: BÖHM, 1992). In the Late Pliensbachian and Early Toarcian, a horst and graben morphology developed (BERNOULLI & JENKYNS, 1974; KRAINER et al., 1994) and triggered breccia formation along submarine slopes and escarpments (BÖHM et al., 1995). On the horsts, the Toarcian and most of the Middle Jurassic (if deposited) are either characterized by starved sedimentation and ferro-manganese crusts or by a hiatus. In contrast, the grabens were filled with deep-water carbonates and breccias shed along fault scarps. Neptunian dykes developed in various places. In these newly formed basinal areas grey bedded limestones were deposited, whereas the topographic highs were covered by condensed red limestones of the Klaus Formation (e.g., KRYSTYN, 1972).

This sedimentation pattern diachronously changed dramatically in the late Middle Jurassic (GAWLICK & FRISCH, 2003) when deposition of radiolarian cherts, radiolarian-rich marls and limestones of the Ruhpolding Radiolarite Group commenced (DIERSCHE, 1980). For details see the description below.

3.3 Hallstatt facies zone (preserved in the reworked Jurassic Hallstatt Mélange)

The mostly condensed Triassic to Early Jurassic hemipelagic succession was deposited in an outer shelf depositional setting (Fig. 4, Fig. 6).
The Hallstatt facies zone (i.e., Hallstatt Zone) is subdivided into three facies zones:

a) Zlambach/Pötschen facies zone (grey Hallstatt facies, Zlambach/Pötschen facies with shallow-water allodapic limestone intercalations from the Dachstein reef rim).
b) Hallstatt Limestone facies zone (red or variously coloured Hallstatt facies or Hallstatt Salzberg facies) (for newest review see KRYSTYN, 2008).
c) Meliata facies zone (LEIN, 1987a; GAWLICK et al., 1999a); including the Pötschen Limestone *sensu stricto* (compare MOSTLER, 1978). Recently the depositional area of the Pötschen Limestone without shallow-water influx (Pötschen Formation *sensu stricto*) has been interpreted as transitional facies from the Meliata facies belt (continental slope) to the oceanic realm (MISSONI & GAWLICK, 2011a, b, compare GAWLICK et al., 2008).

Remnants of this facies belt are only present in the Middle to Late Jurassic radiolaritic trenches and on top of them, where all sedimentary rock types of the Hallstatt facies belt from the Triassic platform transitional area to the Meliata facies zone occur (for details: GAWLICK & FRISCH, 2003; GAWLICK et al., 2009a, 2012; MISSONI & GAWLICK, 2011a).

Zlambach facies zone (Gosausee facies)

Early Triassic as well as Early and Middle Anisian sediments of this facies belt are not preserved within continuous sections. Fine-grained siliciclastic sediments of the Werfen Formation only occur as components together with components of the Gutenstein and Steinalm Formations and the complete reconstructable hemipelagic Late Anisian to Early Jurassic succession of this facies belt (GAWLICK, 1996; GAWLICK et al., 2012). Late Anisian to Ladinian Reifling Limestone is also proven in the form of small components within late Middle Jurassic mass-flow deposits (GAWLICK, 1996, 2000b). The oldest continuously preserved sections start with well bedded, chert-rich limestone or hemipelagic dolomite of earliest Carnian age (GAWLICK, 1998). The Julian *Halobia* Beds did not form a uniform, laterally persistent sedimentary layer in this facies belt but are partly preserved in some sections (MANDL, 1984). In Late Carnian to Middle Norian times, mostly well-bedded cherty hemipelagic limestones of the Pötschen Formation with shallow-water allodapic limestone intercalations were deposited in more distal shelf areas (LEIN, 1985; GAWLICK, 1998; MISSONI & GAWLICK, 2011a), probably transitional to the red or variously coloured Hallstatt facies zone (LEIN, 1981; LEIN & GAWLICK, 1999). Hemipelagic dolomites (Pötschen Dolomite similar to the Baca Dolomite of the Slovenian Trough and equivalents in the Cukali area of Albania) and bedded cherty limestones occurred in more proximal position near to the transitional area of the carbonate platforms and ramps. Here the carbonate platform facies and evolution is reflected in the carbonate basinal facies (REIJMER & EVERAAS, 1991). Due to sea-level fluctuations occasionally shallow-water carbonates were deposited also (GAWLICK, 1998). Terrigenous input and synsedimentary tectonics (strike-slip related movements according to MISSONI et al., 2008), led to more complex sedimentary facies patterns in Late Norian to Early Rhaetian times. This is expressed e.g. in different lithologies of the Pedata Formation: e.g., Pedata Plattenkalk, Pedata Dolomite, Pedata Limestone (MANDL, 1984; GAWLICK, 1998, 2000a). Also the basinal areas of the Mürzalpen facies and Aflenz facies were deepened during this time interval (LOBITZER, 1974; LEIN, 1982). Since Rhaetian times (KRYSTYN, 1987, 2008) the marly Zlambach Formation was deposited, which passed gradually into the Early Jurassic Dürrnberg Formation (GAWLICK et al., 2001, 2009a). The youngest known sediments in the Hallstatt facies zone are thick cherty to marly successions of the Toarcian to Aalenian Birkenfeld Formation (GAWLICK et al., 2009a; Missoni & GAWLICK, 2011a, b).

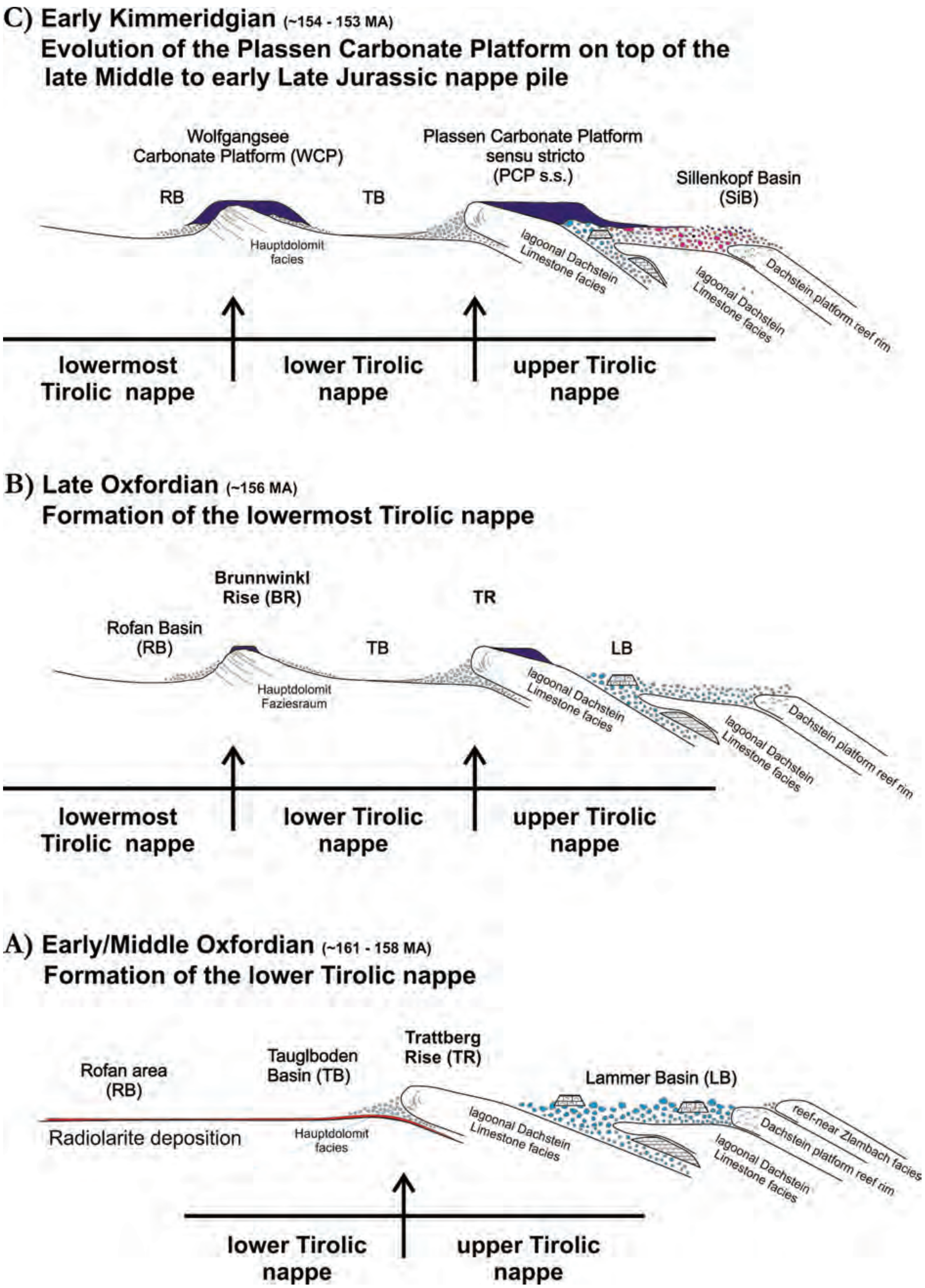
Hallstatt Limestone facies zone

As distal continuation of the Zlambach facies zone (grey Hallstatt facies), the red or variously coloured Hallstatt facies (LEIN, 1987a; KRYSTYN, 2008) sedimentation started with the drowning of the Steinalm carbonate ramp in Anisian (Late Pelsonian) time. Early Triassic Werfen Formation is only proven as components in Late Triassic Hallstatt Limestone (LEIN, 1981). The Middle Anisian Steinalm Formation followed stratigraphically the lower Anisian Gutenstein Formation. Between these two shallow-water formations the more open marine Sulzkogel and Rabenkogel Members of the Annaberg Formation (LEIN et al., 2010) indicate the first flooding related to the continuing thinning of the underlying continental crust (LEIN, 1987a). Hemipelagic sedimention started in late Middle Anisian with the condensed red Schreyeralm Limestone (e.g., KRYSTYN et al., 1971; TOLLMANN, 1985), contemporaneous with the break-up of the Neotethys Ocean (GAWLICK et al., 2008), followed by the Grauvioletter-Graugelber Bankkalk (Ladinian), the Hellkalk (Late Ladinian to Early Carnian), *Halobia* Beds (Julian), the Roter Bankkalk (Tuvalian), the Massiger Hellkalk (Lacian), the Hangendrotkalk (Alaunian to Sevatian), the Hangendgraukalk (Sevatian to Early Rhaetian) (KRYSTYN, 1980, 2008) and the Zlambach Marls (Rhaetian: KRYSTYN, 1987, 2008). These passed gradually into the Early Jurassic Dürrnberg Formation which is overlain by the Birkenfeld Formation (see above).

Meliata facies zone to Neotethys Ocean

The Meliata facies zone represents the most distal part of the Triassic shelf area, the continental slope and the transition to the Neotethys Ocean. Rare remnants of this facies belt are described from the eastern (MANDL & ONDREJICKOVÁ, 1991, 1993; KOZUR & MOSTLER, 1992) and from the central Northern Calcareous Alps (GAWLICK, 1993; KRISCHE et al., in press). These remnants occur partly as metamorphosed isolated slides (Florianikogel area) or as breccia components in Middle/Late Jurassic or Cretaceous successions. A general stratigraphic reconstruction shows Middle Triassic radiolarites and partly cherty marls followed by Early Carnian *Halobia* Beds and Late Carnian to Early Rhaetian Hallstatt Limestone (red and grey). Younger sediments are so far not proven, but a similar sedimentary succession like in the Hallstatt Limestone facies zone can be expected. The Meliata facies zone is thought to have been the most oceanward facies belt underlain by continental crust, incorporated in the evolving imbricate wedge during the closure of the western part of the Neotethys Ocean (starting in the late Early Jurassic as mentioned by GAWLICK & FRISCH, 2003; GAWLICK et al. 2009a; MISSONI & GAWLICK 2011a, b). Recently also sequences of the Pötschen Limestone *sensu stricto* have been interpreted to derive from the transitional area of the Meliata facies zone to the Neotethys Ocean (MISSONI & GAWLICK, 2011a, b; compare GAWLICK et al.; 2008, 2009b). Remnants of the Neotethys Ocean are very

Figure 7 (next page)**:** Oxfordian to Kimmeridgian tectonic and sedimentary evolution of the southern Northern Calcareous Alps and nappe subdivision. **A**) After the Middle Jurassic imbrication of the Middle Triassic to Early Jurassic Hallstatt facies belt, a new nappe front was formed in the lagoonal Dachstein Limestone facies zone (= Trattberg Rise). North of this nappe front a new deep-water basin was formed (= Tauglboden Basin). In contrast to the more northern regions (Rofan Basin area), where thin radiolarite sequences were deposited, the sedimentation in the Tauglboden Basin was characterized by an up to 800 m thick succession, consisting of radiolarites, slump deposits and different types of mass flows and slides. The Trattberg Rise separated the upper Tirolic nappe from the lower Tirolic nappe. **B**) Due to further tectonic shortening in the younger Middle or Late Oxfordian, a new nappe front established further north (= Brunnwinkl Rise). This uplifted nappe front domain supplied the newly created Rofan Basin to its north with eroded material (mass flows and slides). The lower Tirolic nappe was subdivided in a lowermost and a lower Tirolic nappe. In the Late Oxfordian first shallow-water carbonates were deposited, initially only in the area of the Trattberg Rise and later, from the Oxfordian/Kimmeridgian boundary onwards, also in the area of the Brunnwinkl Rise (compare Fig. 20). The Plassen Carbonate Platform started sealing the older nappe structures. **C**) In the Early Kimmeridgian the Plassen Carbonate Platform rapidly prograded over the adjacent basins. The Plassen Carbonate Platform *s. str.* prograded unidirectionally towards south: The Trattberg Rise was uplifted and shielded the Tauglboden Basin to its north. In contrast the Wolfgangsee Platform prograded both in southern and northern directions.


C) Early Kimmeridgian (~154 - 153 MA)
Evolution of the Plassen Carbonate Platform on top of the late Middle to early Late Jurassic nappe pile
Wolfgangsee Carbonate Platform (WCP)
Plassen Carbonate Platform sensu stricto (PCP s.s.)
Sillenkopf Basin (SiB)
RB
TB
Hauptdolomit facies
lagoonal Dachstein Limestone facies
lagoonal Dachstein Limestone facies
Dachstein platform reef rim
lowermost Tirolic nappe
lower Tirolic nappe
upper Tirolic nappe
B) Late Oxfordian (~156 MA)
Formation of the lowermost Tirolic nappe
Brunnwinkl Rise (BR)
TR
Rofan Basin (RB)
TB
LB
Hauptdolomit Faziesraum
lagoonal Dachstein Limestone facies
lagoonal Dachstein Limestone facies
Dachstein platform reef rim
lowermost Tirolic nappe
lower Tirolic nappe
upper Tirolic nappe
A) Early/Middle Oxfordian (~161 - 158 MA)
Formation of the lower Tirolic nappe
Trattberg Rise (TR)
Tauglboden Basin (TB)
Rofan area (RB)
Lammer Basin (LB)
Radiolarite deposition
Hauptdolomit facies
lagoonal Dachstein Limestone facies
lagoonal Dachstein Limestone facies
Dachstein platform reef rim
reef-near Zlambach facies
lower Tirolic nappe
upper Tirolic nappe

scarce in the Northern Calcareous Alps. First ophiolite derived detritus occur in the Kimmeridgian Sillenkopf Formation (MISSONI et al., 2001; MISSONI, 2003; MISSONI & GAWLICK, 2011a, b) and more massive in the Early Cretaceous Rossfeld Formation (e.g., FAUPL & TOLLMANN, 1979; FAUPL & POBER, 1991; VON EYNATTEN & GAUPP, 1999; SCHWEIGL & NEUBAUER, 1997a, b), whereas sedimentary rocks of the Neotethys ocean floor (Triassic radiolarites) were only described from pebbles which occur in the basal parts of the Gosauic sequence in the southeastern Northern Calcareous Alps (SUZUKI et al., 2007). There they occur together with ophiolite rocks and Middle Jurassic amphibolites (SCHUSTER et al., 2007), most probably representing remains of the metamorphic soles as known from the Dinaride/Mirdita ophiolites (e.g. KARAMATA, 2006). Recently Triassic radiolarites from the Neotethys Ocean floor together with ophiolite material were detected also in the Early Cretaceous Rossfeld Formation in the central Northern Calcareous Alps (KRISCHE et al., in press).

Middle Jurassic to Early Cretaceous geodynamic evolution

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 2.000 metres of sediment infill (GAWLICK, 1996) in their south-eastern, oceanward parts. This region was characterized by rapid subsidence due to tectonic load. In contrast, the northwestern, continentward edges of the Alpine-Carpathian domain were characterized by uplift and condensed sedimentation or erosion. The derivation of the resedimented components differs. In the southeastern 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 northwestern basin group, the material derived from the Triassic to Middle Jurassic lagoonal area (Dachstein and Hauptdolomit facies zones) (Fig. 6).

Each reconstruction of the Jurassic tectonic movements depends on detailed studies on the components and the 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 (from south to north, except the Sillenkopf Basin which represents a remnant radiolaritic basin between the Lärchberg and the Plassen Carbonate Platform):

A. Florianikogel Basin with the Florianikogel Formation (Fig. 5): Its ?Bajocian to Callovian sediments contain material from the Hallstatt Limestone and Meliata facies zones (MANDL & ODREIJICOVÁ, 1991, 1993; KOZUR & MOSTLER, 1992; GAWLICK et al., 2009a) (Fig. 4, Fig. 6) and also include volcanogenic greywacke layers with erosional products derived from the Neotethys 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). For complications see AUBRECHT et al. (2010, 2012).

B. Sandlingalm Basin group with the Sandlingalm Formation (Fig. 5): These ?Bajocian/Bathonian to Late Oxfordian basins contain only material from the Hallstatt Limestone facies zone and limestones of the Meliata Zone (including the Pötschen Formation without shallow-water material; Fig. 4).

C. Lammer Basin with the Strubberg Formation (Fig. 5, Fig. 7): This Early Callovian to Middle Oxfordian basin contains mainly material from the Zlambach facies zone and the Dachstein Limestone reefs (GAWLICK, 1996; GAWLICK & FRISCH, 2003; MISSONI & GAWLICK, 2011a) (Fig. 5).

D. Tauglboden Basin with the Tauglboden Formation (Fig. 5, Fig. 7): 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. After 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 Jurassic reefal sediment clasts in the second phase is characteristic (STEIGER, 1981; GAWLICK et al., 2005).

E. Rofan Basin with the Rofan Breccia (Fig. 5, Fig. 7): Resedimentation started in the Late Oxfordian (GAWLICK et al., 2009a) with material derived from the Hauptdolomit facies zone (Fig. 5, Fig. 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 Late Jurassic carbonate platform to the south (Wolfgangsee Carbonate Platform - GAWLICK et al., 2007b, 2009a).

F. Sillenkopf Basin (Fig. 5, Fig. 7): The Kimmeridgian to ?Tithonian Sillenkopf Basin represents another type of basin. Its Sillenkopf Formation basin fill contains 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), 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 southeast to northwest (= 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 times as remnant basins in between newly formed shallow-water carbonate platform areas of the Plassen Carbonate Platform *sensu lato*, the evolution of which commenced in the Late Oxfordian (AUER et al., 2009).

Another important tectonic pulse is related to mountain uplift, which started in Late Tithonian times. These relatively unexplored tectonic event and its influence on the tectonics which is partly reflected in the sedimentary record, was recently investigated in detail by KRISCHE (2012). This tectonic event resulted in the northward transport of the Haselgebirge Mélange, in parts including Hallstatt Mélange fragments, in the area of the Tauglboden basin. Mountain uplift and increasing erosion resulted in the diachronously drowning of the different parts of the Plassen Carbonate Platform (details in GAWLICK et al., 2009a, 2012). After the final drowning of the Plassen Carbonate Platform in Berriasian times (GAWLICK & SCHLAGINTWEIT, 2006) the erosional products of the uplifted mountain belt reached the northern part of the central Northern Calcareous Alps. Detailed component analysis of different mass-flows deposits in the Early Cretaceous Rossfeld Formation prove e.g. the existence of Triassic ophiolites south of the today´s Northern Calcareous Alps and it´s subophiolitic mélange (KRISCHE et al., in press). Components of the Triassic carbonate platforms or deep-shelf sediments were found nowhere in the Rossfeld formation, as stated by MISSONI & GAWLICK (2011a) for the type-locality or KRISCHE (2012) for all localities of the Rossfeld Formation in the central Northern Calcareous Alps. However, this result is another argument that the classical interpretations of an Early Cretaceous nappe thrusting model has to be changed.

4 The Field Trip

The main aim of this field trip is to understand the sedimentation of Austria's Northern Calcareous Alps and its tectonic circumstances from Triassic rifting/drifting to Jurassic collision/accretion, and the Early Cretaceous "post-tectonic" sedimentary history.
Another topic of this field trip through the central Northern Calcareous Alps (Fig. 8) is the study of the following deep-water basin fills with their underlying and overlying sedimentary successions:

- Sandlingalm Basin fill,
- Lammer Basin fill,
- Tauglboden Basin fill,
- Sillenkopf Basin fill (optional).

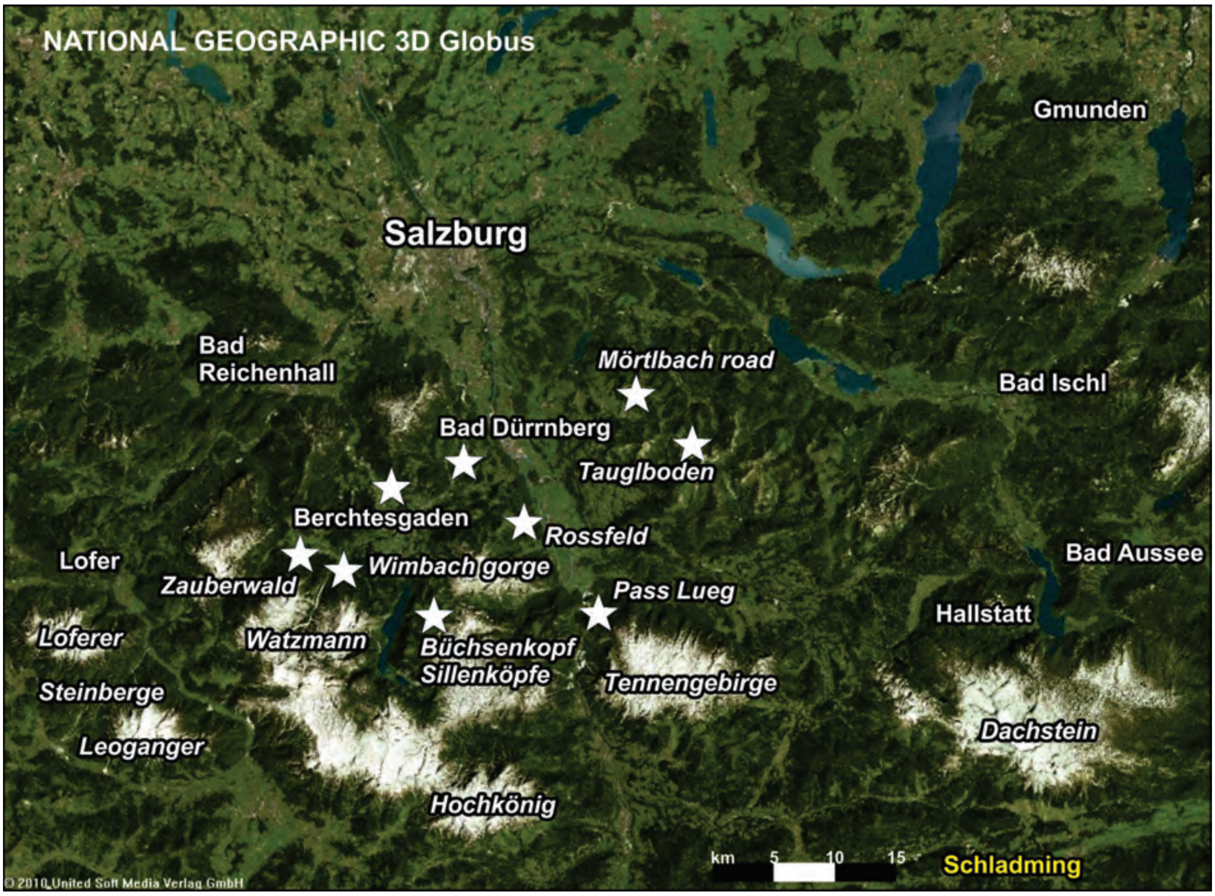


Figure 8: Satellite image of the central Northern Calcareous Alps, showing the localities which will be visited during this field trip (red stars). Around Pass Lueg and on the road along the Mörtlbach valley we will study the Norian/Rhaetian Hauptdolomit/Dachstein lagoon of the Hauptdolomit/Dachstein carbonate platform including the formation of the Rhaetian Kössen Basin (empty bucket). In the Wimbach gorge and on the road along the Mörtlbach valley we will study the Early-Middle Jurassic sequences. In the Bad Dürrnberg and Berchtesgaden area (Zauberwald) we will study the Sandlingalm Basin fill, in the Osterhorn block the Tauglboden Basin fill and the overlying resediments of the Plassen Carbonate Platform *s. str*. South of Berchtesgaden in the Nationalpark we will see the Lammer Basin fill (Büchsenkopf) and the Sillenkopf Basin fill (optional). For the Early Cretaceous we will visit the type-locality of the Rossfeld Formation (Rossfeld) which provides and also an excellent overview on the geological features in a regional scale of the Berchtesgaden and Salzburg Calcareous Alps.

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 the second main topic of this field trip. We will have a look at the following parts and phenomena of the Plassen Carbonate Platform *sensu lato*:

- the fore-slope shedding of the Plassen Carbonate Platform sensu stricto (central platform),
- resediments from the Lärchberg Carbonate Platform (southern platform, optional).

On some days of the field trip, we will cross different basin fills and parts of the Plassen Carbonate Platform, respectively. To avoid confusion, the stop descriptions were sorted according to the different topics and not in strict chronological order according to the way of walking or driving.

4.1 The Late Triassic: Dachstein/Hauptdolomit Carbonate Platform

Hauptdolomit, Norian lagoonal Dachstein Limestone (Lofer cycles). Early Rhaetian Kössen Formation – formation of an empty bucket (Kössen Basin). Rhaetian reefal and lagoonal Dachstein Limestone.

4.1.1 Hauptdolomit (Mörtlbach road)

The Norian Hauptdolomit was deposited under partly restricted and hypersaline lagoonal conditions (e.g., CZURDA & NICKLAS, 1970; FRUTH & SCHERREICKS, 1984, 1985). Typical features are stromatolithic layers, shrinking structures, ripple marks, mud clasts and dolomitized grainstones with foraminifera, algae and gastropods. In the field trop area the thickness of the Hauptdolomit may reach 1500 metres, mainly light to middle grey dolostones. FRUTH & SCHERREICKS (1984) distinguished eight different facies units (Fig. 9) with limited water exchange and euxinic conditions (ZANKL, 1971).
We will visit an characteristic outcrop on the road along the Mörtlbach valley in direction to the village Krispl.

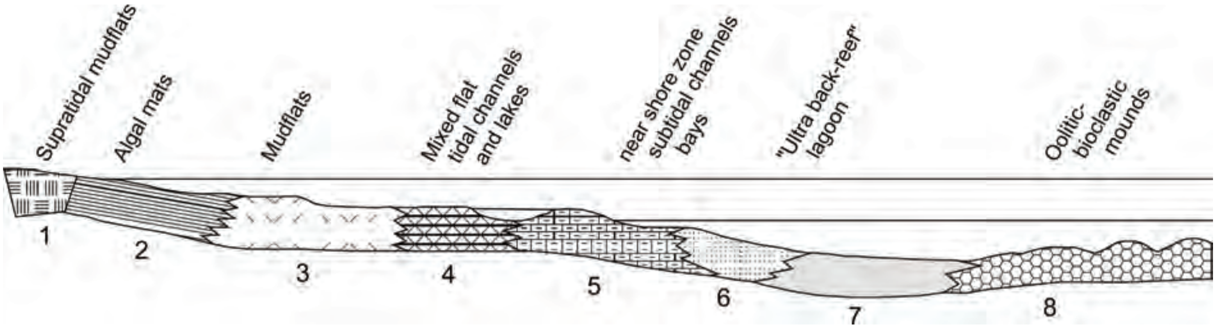


Figure 9: Eight facies units have been distinguished in the Hauptdolomit Fm. (after FRUTH & SCHERREIKS, 1984). They are interpreted to correspond to environmental belts, ranging from supratidal through subtidal.

4.1.2 Lagoonal Dachstein Limestone: The classical Lofer cycle (Pass Lueg)

Text from RICHOZ et al. (2012): In the central and eastern Northern Calcareous Alps, 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 top of the large plateau mountain ranges. Meter-scale cycles were recognized as early as 1936 by SANDER. FISCHER (1964) gave a description of this phenomenon, which remains a classic even now. Based on sequences from the plateaus of the Dachstein and the Loferer Steinberge, FISCHER termed these units "Lofer cycles". The cycles are interbedding of lagoonal limestones, thin layers of variegated argillaceous material, thin layers of intertidal to supratidal laminated or fenestral 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, gastropods, 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 are interpreted as former terrestrial soils. 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 birds-eye limestone of laminated or massive type, non-loferitic mudstone and intraclasts. The flat or crinkled lamination is interpreted as 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 superimposed 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 centimetre amplitudes and periods of several hundred years may have modified growth pattern and shape of the tidal flats by erosion and transgression. FISCHER (1964) interpreted the ideal Lofer cycle: disconformity, A, B, C as an upward-deepening facies trend. HAAS (1991, 1994) proposed a symmetrical ideal cycle, whereas GOLDHAMMER et al. (1990) and SATTERLEY (1994) proposed a shallowing upward interpretation. ENOS & SAMANKASSOU (1998) pointed to the lack of evidence for subaerially exposure and interpreted it as rhythmic cycle with allocyclicity as the predominant control. HAAS et al. (2007, 2009) and HAAS (2008) however provided several evidences for subaerially exposure and related karstification. HAAS et al. (2010) pointed a differential development of the Lofer Cycle on the Dachstein Range between internal area and sections situated near the margin of the platform. The cycles shown by HAAS et al. (2010) can be summarized:

The disconformity displays erosion features and karstification in both internal and marginal areas.

- Facies A is reddish or greenish, argillaceous, 1 mm to 10 cm thick. It is a mix of storm redeposited carbonate mud, air transported carbonate and argillite, blackened intraclast and consolidated sediment. It is thicker with pedogenese trace in marginal sea than in internal area.
- Facies B (stromatolites, loferites) is usually present in the internal part of the range, but absent in the marginal area.
- Facies C is a peloidal bioclastic wackestone in the platform area, whereas in the reef-near zone it is an oncoidal packstone or grainstone.

The differences can be explained by the setting. The marginal zone, near the offshore edge developed oncoid shoals, whereas stromatolites develop preferentially on the slightly deeper platform interior, protected by the shoals. The sea-level drop affected both areas, but the longer shoals allowed for the development of paleosoils in the marginal part. This model reinforces the shallowing-upward trend of FISCHER (1964).

At Pass Lueg itself a "Lofer Cyclothem" with partly reworked stromatolite, brecciated layers and bioclastic limestones rich in megalodontids, corals and echinoderm (FLÜGEL et al,. 1975) is exposed (Fig. 10). Several species of *Megalus, Parmegalus, Conchodus* have been described, but each levels are usually rich in individuals but poor in species number (FLÜGEL et al., 1975).

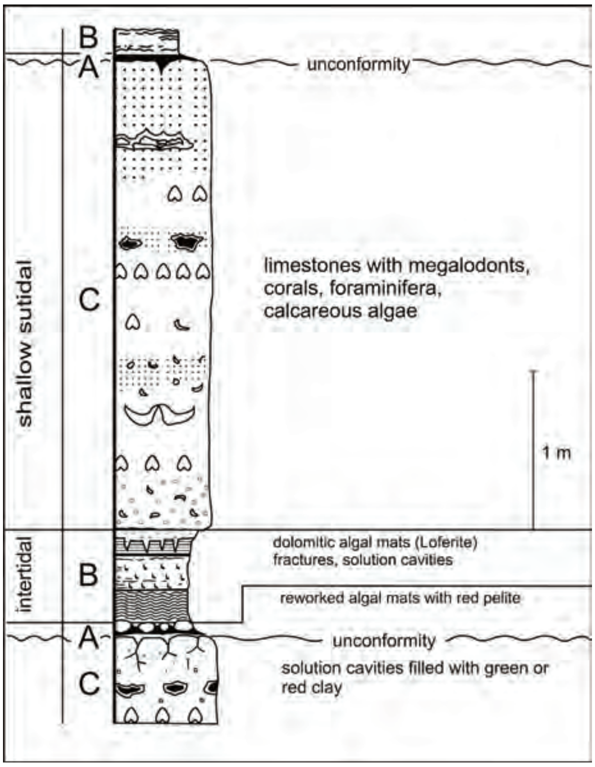


Figure 10: Schematic sketch of the Lofer cycle of the bedded Dachstein limestone (after FISCHER, 1964, 1975).

4.1.3 The Kössen Basin (Pass Lueg and Mörtlbach road)

In the Rhaetian increasing terrigenous influx reduced the areal extent of the Hauptdolomit/Dachstein platform. The Hauptdolomit facies zone and parts of the Dachstein lagoon became covered by the marly Kössen Formation. The newly formed Kössen Basin (empty bucket, intrashelf basin) was bordered in the south by a new reefal belt, which prograded in Rhaetian times rapidly to the north. In the Early Rhaetian subtidal mixed lime and clay bearing bioclastic rocks dominate. During this time the Kössen Basin had is southernmost extension. Whereas in the southernmost part of the Kössen Basin predominantly Middle to Late Rhaetian shallow-water limestones were deposited more northward basinal conditions prevailed (Eiberg Basin) (compare GOLEBIOWSKI, 1990a, 1991, RICHOZ et al., 2012).

North of Pass Lueg we will visit the sedimentary evolution of the southern Kössen Basin and a complete Rhaetian sequence (Fig. 11): The Early Rhaetian marly Hochalm Member is badly exposed. The overlying sediments became rich in corals. The "*Lithodendron* Limestone" is the most important lithofacies marker of the Kössen Formation. Whereas near the southern rim this level is overlain by shallow-water lagoonal Dachstein Limestone this level marks in the central basin (Fig. 12) a deepening below the wave base (GOLEBIOWSKI, 1990a, 1991; RICHOZ et al., 2012) and a transition phase between a deep, open marine lagoon (lower Hochalm Member) and the intraplatform basin deposition milieu of the Eiberg Member.

Reefal and shallow-water carbonate platform sedimentation was terminated at the end of the Rhaetian when the whole Austroalpine carbonate shelf was affected by subaerially exposure (BERNECKER et al., 1999). In contrast, in the Eiberg Basin deposition continued. In this basin the Triassic-Jurassic GSSP at Kuhjoch is situated (details in HILLEBRANDT & KRYSTYN, 2009; HILLEBRANDT & KMENT, 2011; RICHOZ et al., 2012).

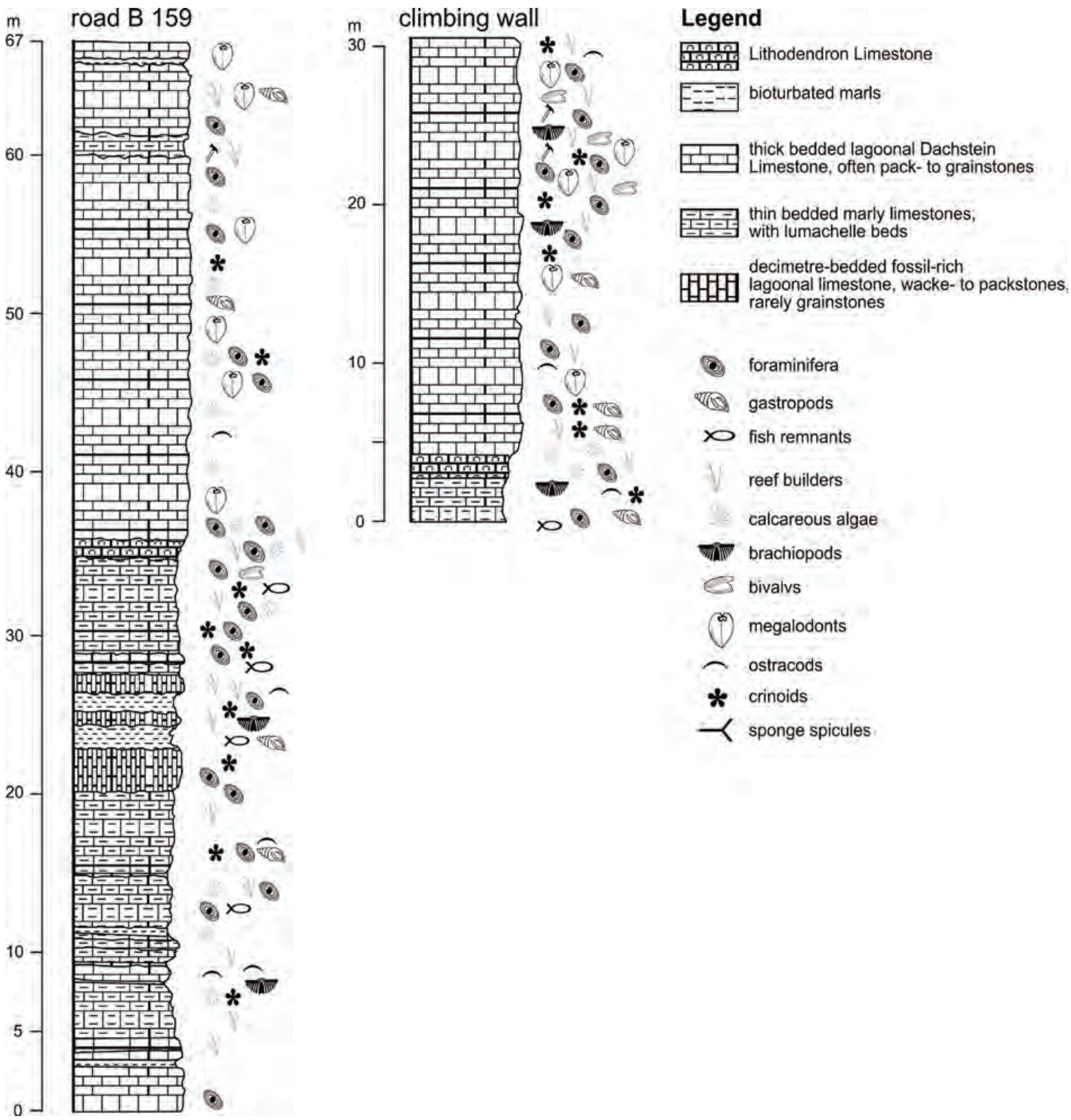


Figure 11: Section Rhaetian limestones succession (Kössen Formation and Dachstein Limestone) near the B 159 north of Pass Lueg (northern Tennengebirge Mts.). Partly modified after GAWLICK (1996, 2000a).
Section 1: Section near the road B159 from Pass Lueg to Luegwinkl.
Section 2: Section near the climbing wall north of Pass Lueg.

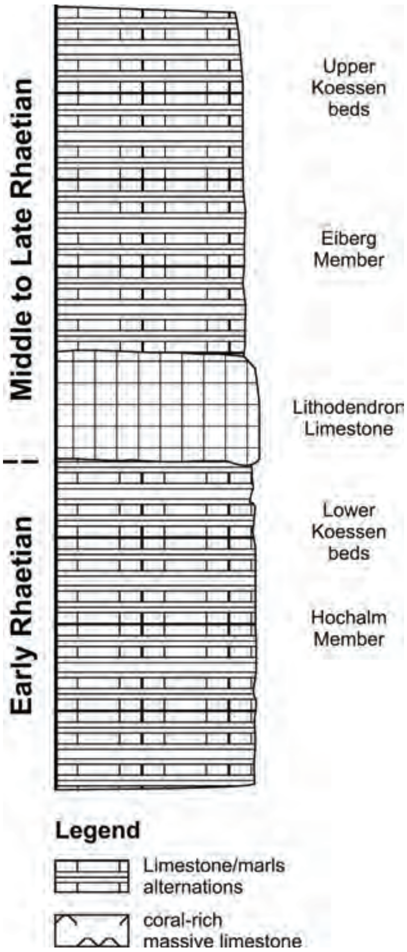


Figure 12: Sedimentary sequence of the Kössen beds in the Mörtlbachgraben (schematic). This succession is characteristic for a central Kössen Basin position (Eiberg Basin).

4.2 Jurassic

4.2.1 Hettangian to Aalenian

The Hettangian to Aalenian period was controlled by the following factors:

A) the end-Triassic morphology and biotic crisis,
B) crustal extension in the Penninic realm and in the adjacent Austroalpine domains resulted in the breakup of the South Penninic Ocean in the Toarcian (Figs. 13, 15), and
C) the onset of inneroceanic thrusting around the Pliensbachian/Toarcian boundary in the Neotethys Ocean.

In the earliest Jurassic four west-east (palaeogeographically southsouthwest to northnortheast) trending basins existed in the Austroalpine realm:

1) due to crustal extension the newly formed Bündner Schiefer Basin in the area of the evolving Penninic Ocean as part of the Alpine Atlantic,
2) the Allgäu (Restental) Basin (group) as northernmost basin in the Northern Calcareous Alps,
3) the Eiberg (Scheibelberg) Basin along the central axis of the Northern Calcareous Alps, and
4) the Hallstatt Zone (distal passive margin, "Hallstatt Basin" according to older references) facing the Neotethys Ocean (Figs. 5, 13–15).

Only in the basinal areas sediments were deposited in the earliest Jurassic, whereas the Late Triassic highs (with Rhaetian shallow-water sedimentation) may have emerged and did not receive any sediments. This is the reason, why a hiatus/gap exists between the Triassic and Jurassic sediments on top of most Rhaetian shallow-water carbonates of the Northern Calcareous Alps.

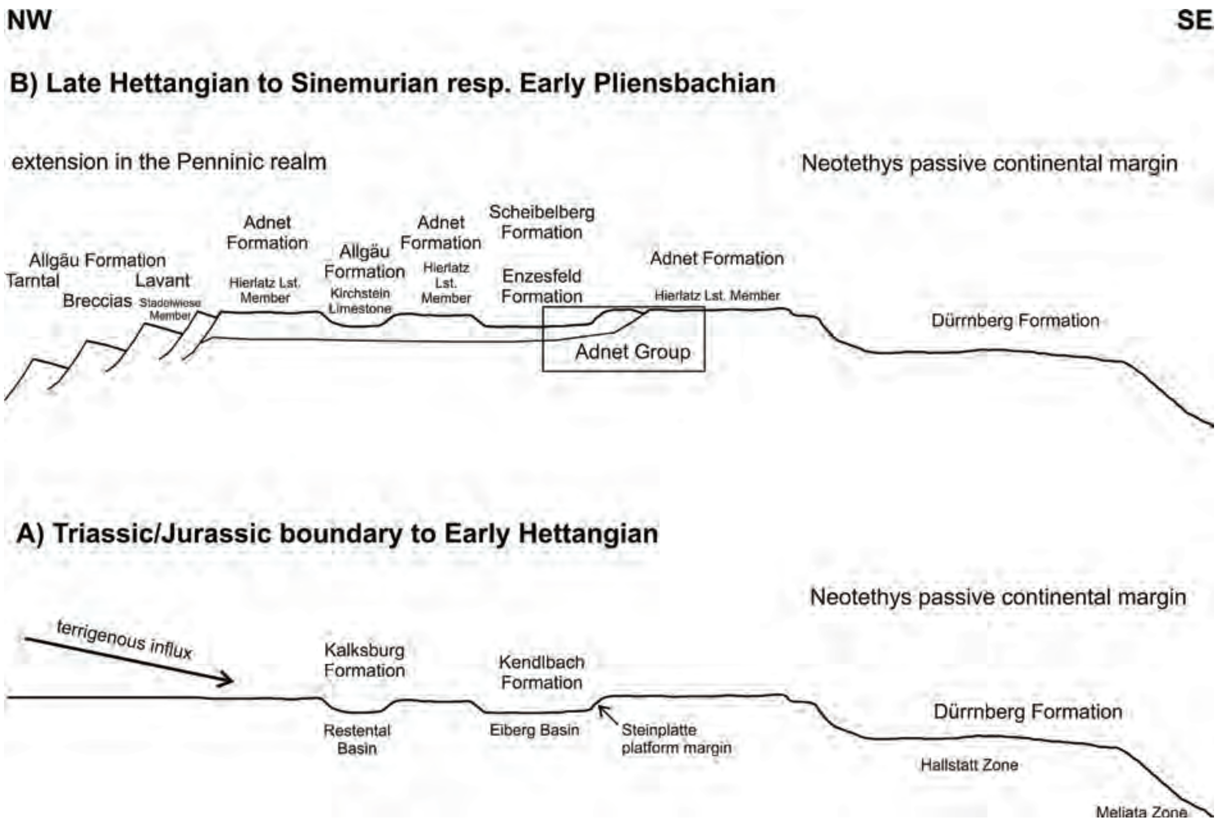


Figure 13: Two profiles showing the palaeotopographic situation in the Austroalpine domain. **A**) Sedimentation in the earliest Jurassic was controlled by the end-Triassic morphology of the exposed or drowned Hauptdolomit/Dachstein Carbonate Platform s. l. with the Eiberg Basin in a central position (e.g., GOLEBIOWSKI, 1991; KUERSCHNER et al., 2007; BONIS et al., 2009) and the Restental Basin (= later Allgäu Basin; GOLEBIOWSKI, 1990b) in a more continent-ward position. **B**) Later in the Early Jurassic (Late Hettangian) crustal extension in the Penninic realm controlled the basin formation, geometry and sedimentation. The Early Rhaetian Kössen beds below the Rhaetian Dachstein Limestone (south of the Eiberg Basin) and Oberrhät Limestone (north of the Eiberg Basin) could have formed the detachment horizon (line in upper profile), on which Penninic crustal extension affected also the Tirolic realm of the Northern Calcareous Alps in the Late Hettangian/Early Sinemurian. Breccia formation on the Penninic passive continental margin lasted from Late Hettangian to Early Pliensbachian times.

Figure 14 (next page)**:** Formations of the Adnet Group (according to BÖHM et al., 1999; BÖHM, 2003, modified) and transition to the Kendlbach, Enzesfeld and Scheibelberg Formations as well as to the Hierlatz Limestone Member. Arrows indicate gravitational transport induced by tectonic activity. For details see text.

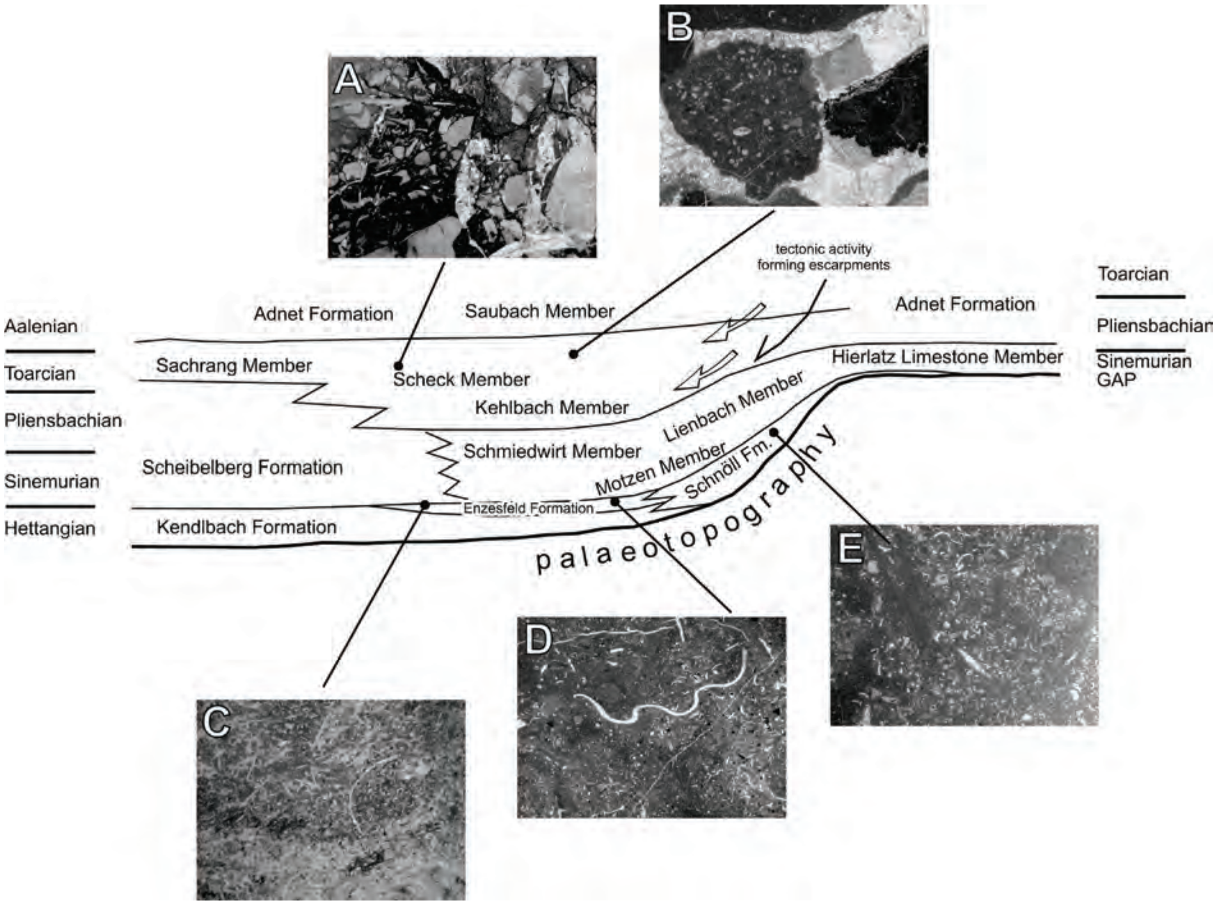
A) Distal Scheck Member, clasts occur in a red marly matrix. Sample Ber 24/21, Wimbach gorge (Tirolic units, Berchtesgaden Calcareous Alps). Width of photo: 1.4 cm.

B) Scheck Member of the type locality in Adnet (Tirolic units, Salzburg Calcareous Alps). Between different clasts occur a sparry calcite cement. Sample C 187. Width of photo: 0.5 cm.

C) Distal Enzesfeld Formation: Spicula- and echinoderm-rich packstone with some bivalves. Sample H 27, Hatschek quarry in Ebensee (Tirolic units, Salzkammergut area). Width of photo: 0.5 cm.

D) Intermediate Enzesfeld Formation from the type locality: wackestone to packstone with small scaled bivalves, ammonoidea and foraminifera (e.g., *Involutina liassica* (JONES)), slightly bioturbated. Width of photo: 1.4 cm.

E) Upper Schnöll Formation of the type locality in Adnet. Echinoderm- and foraminifera-rich wackestone to packstone with marls, slightly bioturbated. Width of photo: 1.4 cm.



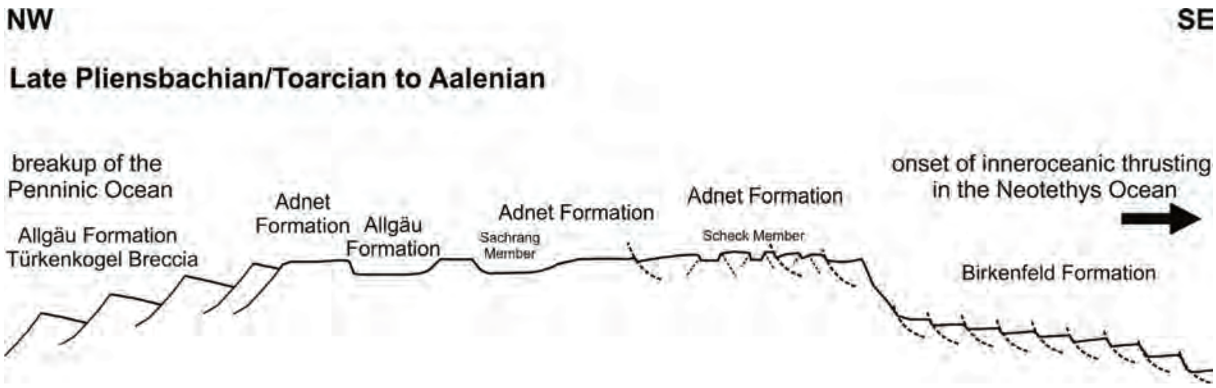


Figure 15: Palaeotopographic profile with formations in the time span Late Pliensbachian to Aalenian. The Lower Austroalpine domain was controlled by the final breakup of the South Penninic Ocean in Toarcian times (RATSCHBACHER et al., 2004), whereas the tectonic movements on the continental margin facing the Neotethys Ocean (Hallstatt Zone and later Tirolic units) was controlled by normal faulting due to the onset of eastward dipping inneroceanic thrusting in the Neotethys Ocean (e.g., GAWLICK et al., 2008). Therefore the newly formed horst-and-graben morphology is interpreted probably as a fore-bulge in the Austroalpine lower plate (compare Fig. 3).

4.2.2 Bajocian to Tithonian

The Bajocian to Tithonian period was mainly controlled by following factors:

A) the Toarcian/Aalenian morphology after the breakup of the South Penninic (Piemont) Ocean, especially in the Lower Austroalpine to the (westernmost) Bavaric units,
B) the onset of inneroceanic subduction processes in the Neotethys realm and the formation of a propagating thrust belt. Thrusting started in the outer shelf area (Meliata and Hallstatt Zones) in Bajocian and prograded towards the Tirolic realm in Oxfordian times.
C) the newly formed carbonate platform on top the nappe stack since the Late Oxfordian,
D) the gravitational collapse of this carbonate platform around the Early/Late Tithonian boundary due to uplift in the south and normal faulting in the north.

The Middle to Late Jurassic orogeny resulted in the destruction of the Neotethys-ward Middle Triassic to Early Jurassic passive continental margin (the Triassic south-eastern margin of Europe; Fig. 6) which had experienced crustal extension since Late Permian time. In late Early to Middle Jurassic times the geodynamic regime became convergent and inneroceanic subduction in the Neotethys Ocean commenced. As a consequence, the continental margin become tilted, progressively imbricated with the distal shelf area of the Meliata and Hallstatt Salzberg facies zones involved in stacking first, and obducted by ophiolites. Trench-like basins formed in front of advancing nappes.

As expression of this evolution in the Pliensbachian, sedimentation in the Hallstatt Zone changed from condensed cherty limestones to far more rapidly deposited massive dark-grey, clay-rich siliceous marls and cherty limestones (O´DOGHERTY & GAWLICK, 2008). The thickness of the sediments increased accordingly. In Late Toarcian to Aalenian times a thick siliceous marly-sedimentary succession was deposited. This change is interpreted as an effect of tilting and faulting of the distal passive margin due to the onset of thrusting in the Neotethys oceanic realm. Late Early to early Late Jurassic inneroceanic subduction is proven by metamorphic soles in the Dinarides (176-157 Ma: KARAMATA, 2006), the Albanides (174-162 Ma: DIMO-LAHITTE et al., 2001), and the Hellenides (181-172 Ma: RODDICK et al,. 1979; SPRAY & RODDICK, 1980). As an expression of this change, in the Dachstein Limestone facies zone a forebulge horst-and-graben morphology evolved in Late Pliensbachian to Toarcian times.

Thrusting in the Neotethys Ocean passive margin domain started in Bajocian time, creating the Meliata and distal Hallstatt nappes by imbrication of the outermost part of the former passive continental margin (Fig. 16). The Florianikogel Basin (Meliata Mélange) is the most oceanward preserved relic of a Middle Jurassic trench-like radiolarite basin in the Northern Calcareous Alps (Fig. 17). In the next stage of thrusting the Sandlingalm Basin group established. This comprised material mainly from the Hallstatt Salzberg facies zone. Parts of these older two basin fills became remobilised in the later stages of orogeny and can be found as resediments in the younger basin successions.

Further continuous shortening established the proximal Hallstatt nappes (Fig. 18, Fig. 19). Farer to the northwest in front of these nappes, new basins formed in the area of the former Dachstein Limestone lagoon in the Callovian and existed until the Oxfordian (Lammer Basin). Continentwards a flexural bulge with red nodular limestone deposition established and prevailed in the area of the later Tauglboden Basin until the Callovian/Oxfordian boundary. Initially the Lammer Basin received local material from the adjacent nappe front. Later, in the Middle/Late Callovian to Middle Oxfordian, the Zlambach facies zone became imbricated and uplifted. After that, predominantly eroded material from this facies domain was shed into the Lammer Basin.

Further tectonic shortening caused ongoing obduction of ophiolites, as proven in the Dinarides (SCHMID et al., 2008) or the Albanides (GAWLICK et al., 2008), and partial detachment and NW-directed transport of the older, south-eastern basin groups. Around the Callovian/Oxfordian boundary a northwestward shift of the Lammer Basin axis can be correlated with the formation of a new nappe front in the Dachstein Limestone reef zone, from which material was shed into this basin. Farther to the southeast, the evaporitic

Haselgebirge Mélange (SPÖTL, 1989; SPÖTL et al., 1998) was formed (Fig. 20). It contains Late Jurassic authigenic feldspars (154-145 Ma: SPÖTL et al., 1996, 1998), which are interpreted as being related to fluid circulation and mélange formation. The Haselgebirge Mélange carries metamorphosed Hallstatt Limestone, Pötschen Limestone, and Dachstein reefal limestone blocks as well as volcanic rocks, partly with sodic amphiboles (KIRCHNER, 1980a, b), and oceanic basalts, which were metamorphosed under HP/LT conditions (VOZÁROVÁ et al., 1999) (compare GAWLICK & HÖPFER, 1999; FRANK & SCHLAGER, 2006).

In the Early Oxfordian, thrust propagation established the upper Tirolic nappe front northwest of the Lammer Basin (Fig. 19) in the area of the Triassic Hauptdolomit lagoon, with the Trattberg Rise as its topographic expression. This rise was an area of intense erosion and the source region for breccias and mass flows in Early to Late Oxfordian times. Continued tectonic shortening led to thrusting over the southeastern margin of the Tauglboden Basin. In ?Middle/Late Oxfordian times, tectonic shortening again propagated northwestwards and the Brunnwinkl Rise was formed (Fig. 19, Fig. 20). This was the northwestern tectonic front of the Jurassic Northern Calcareous Alps nappe stack, with the Rofan Basin in its foreland.

In Late Oxfordian time, ongoing ophiolite obduction, salt flow and tectonic uplift of metamorphosed slices of the Hallstatt zone resulted in the creation of a chaotic mélange. The evaporitic Haselgebirge Mélange squeezed out in front of the arriving ophiolite nappes and took position on top of the Sandlingalm Formation around the Oxfordian/Kimmeridgian boundary (Fig. 21). In contrast, in the northwestern part of the preserved nappe stack north of the Hallstatt imbricates, a period of relative tectonic quiescence began. At that time the Plassen Carbonate Platform *sensu lato* started its progradation (Figs. 20, 21). Also the Kimmeridgian to Early Tithonian cherty limestones on top of the mélanges are part of the evolution of the Plassen Carbonate Platform *sensu lato* with the Wolfgangsee Carbonate Platform in the northwest, the Plassen Carbonate Platform *sensu stricto* in central position, and the Lärchberg Carbonate Platform in the southeast. Radiolaritic basins remained as starved basins in between the individual platforms (Fig. 21). At that time only the Sillenkopf Basin received Late Jurassic shallow-water debris, together with exotic clasts. Originating from a southern source area, the latter were transported into the Sillenkopf Basin through channels.

The Kimmeridgian to Early Tithonian time interval was characterized by platform progradation over the adjacent basins. Whereas into the Sillenkopf Basin material was supplied from the platforms on both sides, the Tauglboden Basin was shielded by the uplifted Trattberg Rise in its south (Fig. 22). In the imbricated wedge slight uplift started (Fig. 22).

In the late Early Tithonian, the uplift of the Juvavic nappe pile to the southeast led to northwestward gliding of several mélange blocks along low-angle planes, including the far-travelled “Sandlingalm“ Hallstatt Mélange onto the “Lammer“ Hallstatt Mélange (Fig. 23). Concomitantly, the Plassen Carbonate Platform *sensu stricto* on top of the former Trattberg Rise extensionally collapsed and the Wolfgangsee Carbonate Platform further northwest drowned. The already deeply eroded ramp anticline of the former Trattberg Rise became sealed by hemipelagic sediments with intercalated reef-slope sediments from a newly formed reef rim. In contrast, the southeastern nappe stack with the Lärchberg Carbonate Platform became uplifted around the Jurassic/Cretaceous boundary. The second metamorphic cycle around 145-135 Ma can most probably be correlated with the increasing heat-flow due to the uplift of the stacked Juvavic (Fig. 23) units in the southeasternmost part of the Northern Calcareous Alps.

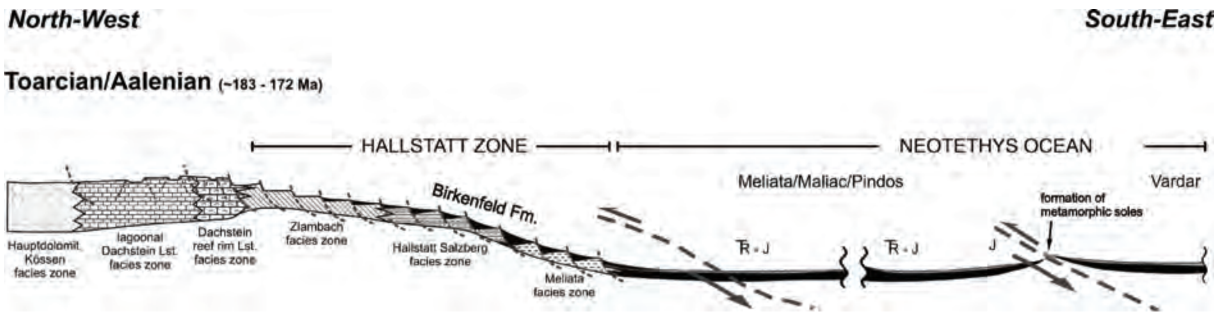


Figure 16: Reconstruction of the Toarcian/Aalenian to Callovian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). See text for further explanation. NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Onset of inneroceanic southeastward subduction in Neotethys Ocean (GAWLICK et al. 2008; for discussion see: KARAMATA, 2006). Late Early to early Late Jurassic inneroceanic subduction is proven by metamorphic soles in the Dinarides (176-157 Ma: KARAMATA, 2006), Albanides (174-162 Ma: DIMO-LAHITTE et al., 2001), and Hellenides (181-172 Ma: RODDICK et al., 1979; SPRAY & RODDICK, 1980). Occurrences of supra-subduction volcanics in the ophiolite belt of Albania reflect an inneroceanic subduction stage (SHALLO & DILEK, 2003; KOLLER et al., 2006). Contemporaneously, the first ophiolithic mélanges were formed (BABIC et al., 2002). Slight south-eastward tilt of distal continental margin, formation of half-grabens in the Hallstatt Zone and horst-and-graben structure in Dachstein Limestone facies zone since the Late Pliensbachian (Adnet Scheck event: BERNOULLI & JENKYNS, 1974; BÖHM et al., 1995) belong to this event. In the Hallstatt Zone the normal faults cut into the Rhaetian Zlambach marls which probably acted as source area for the clay content in the Birkenfeld Formation beside eroded ophiolites. After MISSONI & GAWLICK, (2011a).

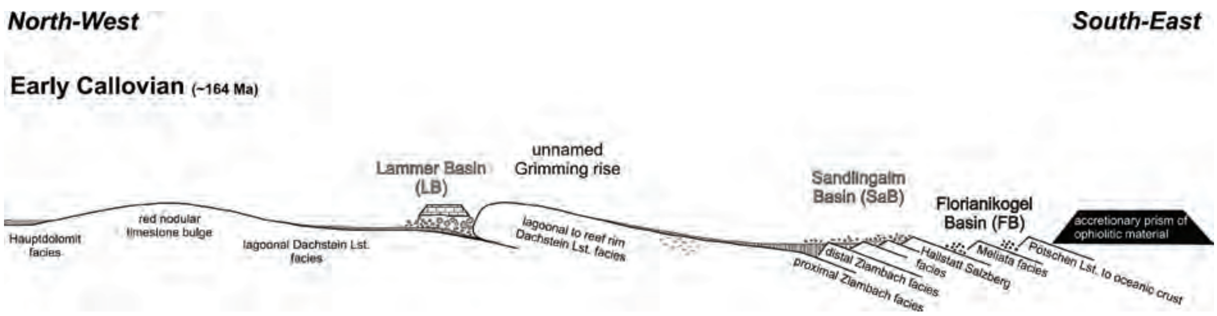


Figure 17: Reconstruction of the Early Callovian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. The Florianikogel Basin (?Bajocian-Callovian; *FB*) constitutes the oldest radiolaritic trench-like basin in the most oceanward position. In the Early Callovian continentward propagation of thrusting led to the formation of the Sandlingalm Basin (*SaB*) in the Hallstatt Zone and to the formation of the Lammer Basin (*LB*) in the lagoonal Dachstein Limestone facies zone. In this early stage of the Lammer Basin only local material was shed from nearby source regions. Continentward a flexural bulge formed which was characterized by red nodular limestone deposition. This bulge with condensed sedimentation prevailed until the Callovian/Oxfordian boundary (e.g., HUCKRIEDE, 1971; MANDL, 1982) in the area of the later Tauglboden Basin. After MISSONI & GAWLICK (2011a).

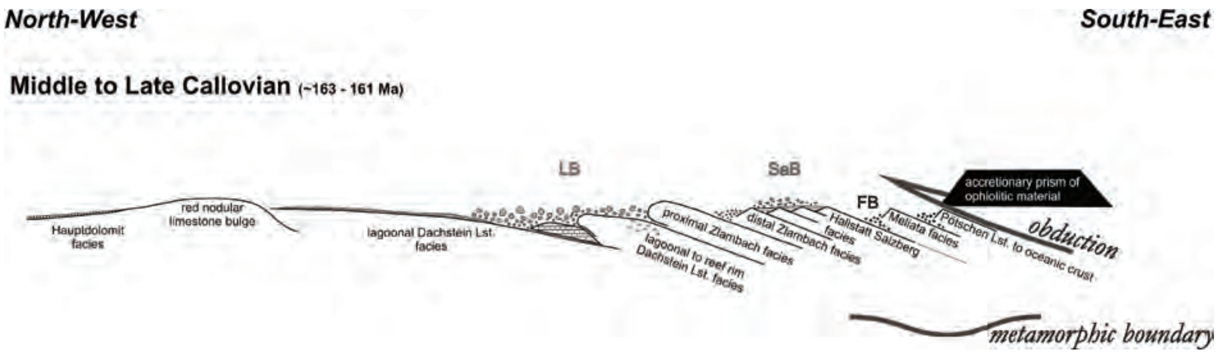


Figure 18 (previous page)**:** Reconstruction of the Middle to Late Callovian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Further tectonic shortening led to the formation of nappe fronts in the Zlambach facies zone. These nappe fronts shed material into the Lammer Basin in Middle Callovian to Middle Oxfordian times. FB: Florianikogel Basin. SaB: Sandlingalm Basin. LB: Lammer Basin. After MISSONI & GAWLICK (2011a).

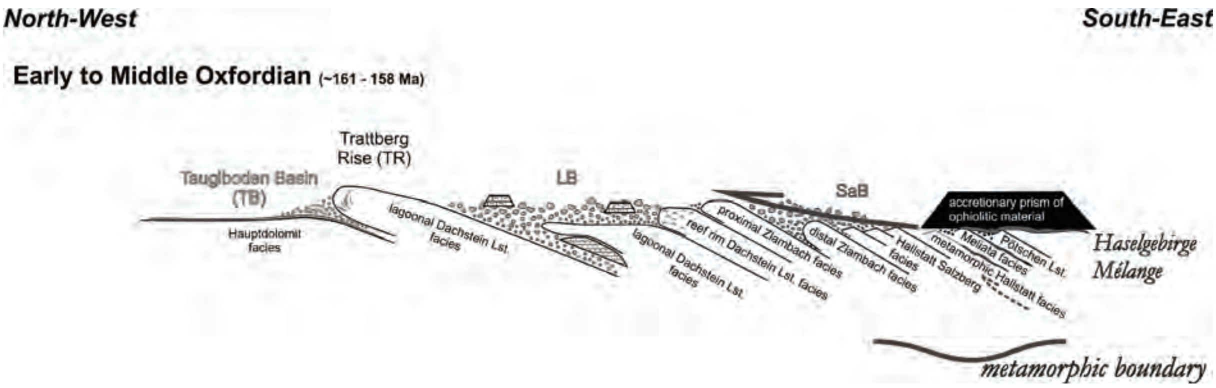


Figure 19: Reconstruction of the Early to Middle Oxfordian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Due to further tectonic shortening and ongoing obduction of ophiolites (Dinarides: SCHMID et al., 2008; Albanides: GAWLICK et al., 2008), the southern basin groups were sheared off and transported towards northwest. Contemporaneously, the basin axis in the Lammer Basin propagated northwestward, too, and the newly formed nappe front in the Dachstein reef rim zone shed its eroded material into this basin. The next nappe front formed in the transitional area of the lagoonal Dachstein Limestone facies zone to the Hauptdolomit facies zone. Eroded material from the uplifted hangingwall (Trattberg Rise) was shed into the newly formed Tauglboden Basin. SaB: Sandlingalm Basin. LB: Lammer Basin. After MISSONI & GAWLICK (2011a).

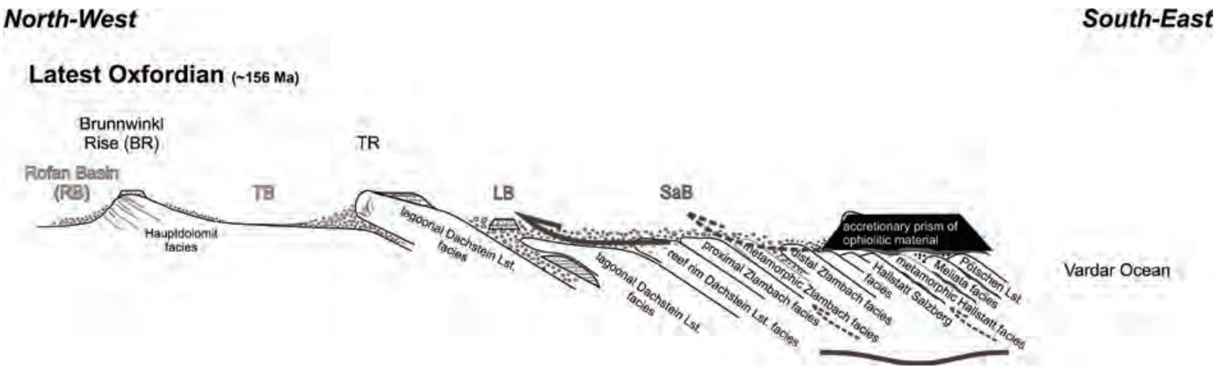


Figure 20: Reconstruction of the Latest Oxfordian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Ongoing obduction of the ophiolites, salt flow and tectonically uplifted metamorphosed slices of the Hallstatt Zone resulted in the formation of a chaotic mélange. Northwestward thrusting led to emplacement of a Sandlingalm Basin sheet on top of the Lammer Basin and upramping of the Trattberg Rise (*TR*) onto the south-eastern rim of the Tauglboden Basin. At the northwestern edge, the Brunnwinkl Rise (*BR*) formed as a new nappe front, with the Rofan Basin (*RF*) as trench-like basin in front. The evaporitic Alpine Haselgebirge squeezed out in front of the arriving ophiolite nappes and was emplaced on top of the Sandlingalm Formation until the Early Kimmeridgian. SaB: Sandlingalm Basin. LB: Lammer Basin. After MISSONI & GAWLICK (2011a).

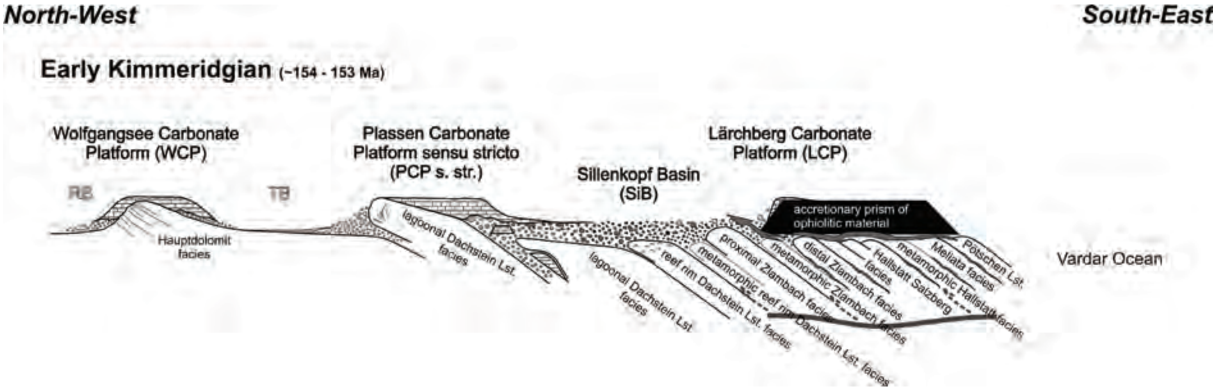


Figure 21: Reconstruction of the Early Kimmeridgian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Around the Oxfordian/Kimmeridgian boundary, the formation of shallow-water carbonates on top of the imbricated structures including the obducted ophiolites started. These platforms are summarized as Plassen Carbonate Platform *sensu lato* with the Wolfgangsee Carbonate Platform (*WCP*) in the northwest, the Plassen Carbonate Platform *sensu stricto* (*PCP s. str.*), and the Lärchberg Carbonate Platform (*LCP*) in the southeast. Radiolaritic basins remained as starved basins in between the individual platforms. Delivery of exotic material persisted only into the Sillenkopf Basin (*SiB*). After MISSONI & GAWLICK (2011a).

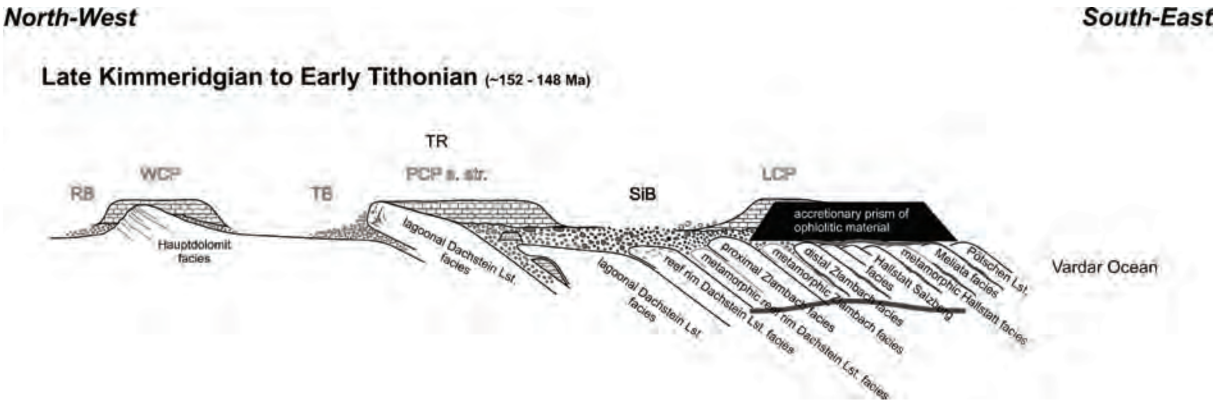


Figure 22: Reconstruction of the Late Kimmeridgian to Early Tithonian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. This time interval was characterized by platform progradation towards the adjacent basins. Whereas platforms on both sides supplied material into the Sillenkopf Basin, the Tauglboden Basin was shielded to the south by the uplifted Trattberg Rise. In the stacked wedge slight uplift started. WCP: Wolfgangsee Carbonate Platform. TB: Tauglboden Basin. PCP *s. str.*: Plassen Carbonate Platform *sensu stricto*. SiB: Sillenkopf Basin. LCP: Lärchberg Carbonate Platform. After MISSONI & GAWLICK (2011a).

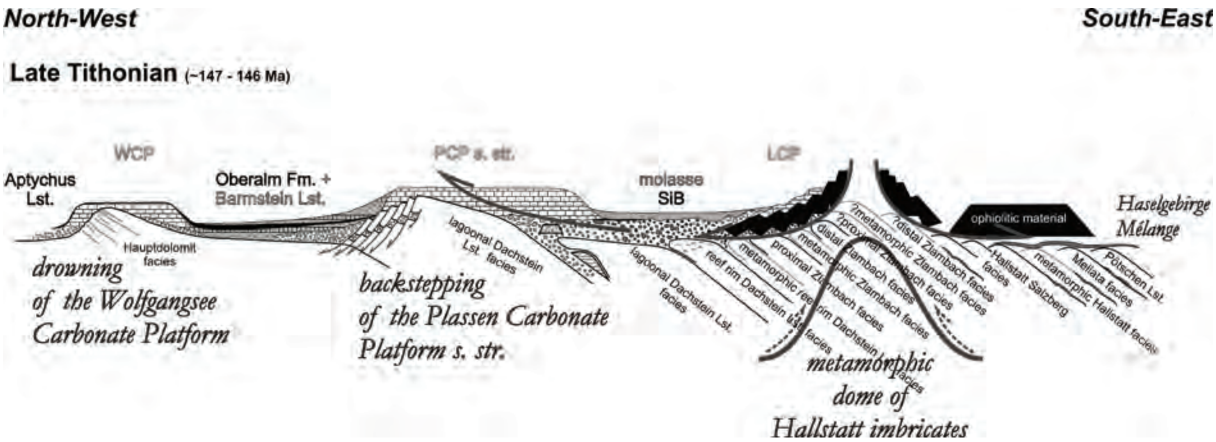


Figure 23 (previous page)**:** Reconstruction of the Late Tithonian geodynamic evolution. Absolute ages after GRADSTEIN et al. (2004). NW-SE directions refer to Triassic-Jurassic palaeogeographic coordinates. Uplift of the metamorphic dome in the eastern part led to the formation of high- and low-angle normal faults and likely also to strike-slip faults. This led to northwestward transport of several mélange slices and uplift and erosion of parts of the Lärchberg Carbonate Platform (*LCP*). At the northwestern edge, the Trattberg Rise broke down and the Plassen Carbonate Platform *sensu stricto* (*PCP s. str.)* built a new reef rim to the north and shed an enormous amount of carbonate material from there (Oberalm Limestone with intercalated Barmstein Limestone = mass flows consisting mainly of reefal material). Contemporaneously the Wolfgangsee Carbonate Platform (*WCP*) drowned (GAWLICK & SCHLAGINTWEIT 2010). After MISSONI & GAWLICK (2011a).

Section Wimbachklamm: Early Jurassic to basal Lammer Basin fill

In the Wimbach gorge section south of Berchtesgaden belong to the Watzmann Block. Here a complete Early to Middle Jurassic sedimentary sequence is preserved (according to MISSONI, 2003). The section starts with grey cherty limestones above Rhaetian lagoonal Dachstein Limestone. The contact is slightly faulted. Characteristic for the lower (Hettangian – Sinemurian) part of the succession are slumpings and oligomictic breccia layers (Fig. 24). Above these basal part a well bedded series of grey cherty limestones was deposited (?Late Sinemurian to Pliensbachian). This series is topped by mass flows and slumps consisting of

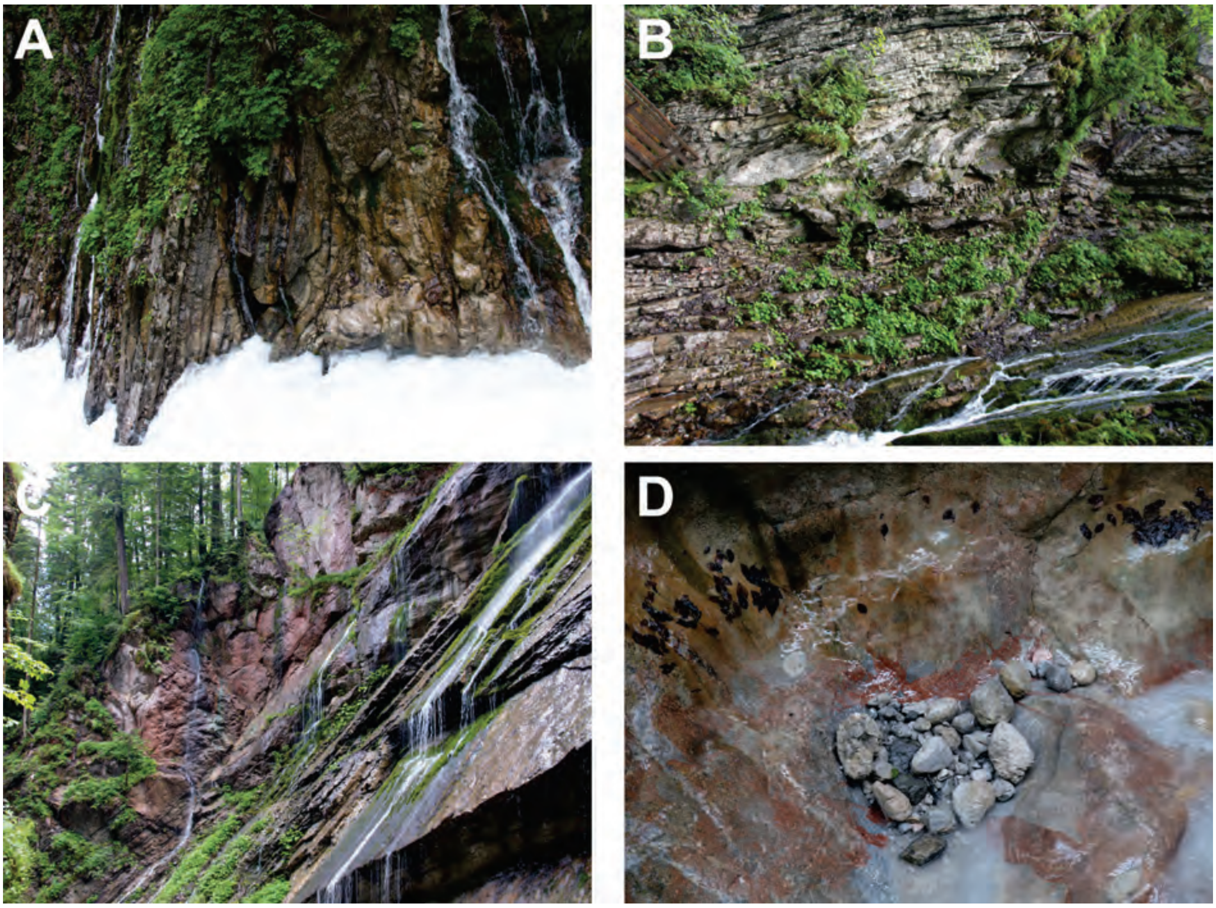


Figure 24: Early-Middle Jurassic sedimentary succession of the Wimbach gorge.
A) Oligomict mass flow and slumping in the ?Late Hettangian - Sinemurian part of the succession.
B) Slump fold in the lower part of the succession (?Late Hettangian – Sinemurian).
C) Mass flow of red nodular Adnet Limestone on top of the well bedded grey cherty limestones (Late Pliensbachian to Toarcian).
D) Carbonate breccia with red *Bositra*-Limestone matrix. This breccia-type occurs normally below the Lammer Basin fill, preserved not in this section but nearby in the Kühroint area (MISSONI et al., 2005).

red Adnet limestones (Late Pliensbachian to Toarcian). Above the red nodular limestones of the higher Adnet Formation were deposited. On top of these Adnet limestones a polymictic breccia follows: the red matrix consists of *Bositra*-Limestone (Middle Jurassic, most probably Bathonian), the clasts are Late Triassic lagoonal Dachstein Limestone and Early Jurassic limestones. Upsection, above these breccias, follow radiolarites of Callovian age. This succession documents clearly the two Early Jurassic tectonic events. The first (Hettangian-Sinemurian) event is related to the Alpine Atlantic extension and is followed by a period of quiet deposition. The second tectonic event (Late Pliensbachian-Toarcian) is related to the onset of contractional tectonics in the Neotethys Ocean. In Middle Jurassic times the formation of new basins started with deposition of carbonate breccias consisting of local material. Rapid deepening of the basin led to radiolarite deposition (Callovian).

Section Mörtlbachgraben: Early Jurassic to Tauglboden Basin fill

Another Jurassic section, but in a more northernward position as the Wimbach gorge section, is the section Mörtlbach valley in the Osterhorn Block (Fig. 25). The Jurassic developed above the Kössen Basin. The section starts with grey cherty limestones of Sinemurian to Early Pliensbachian age. The thickness of this sequence does not exceed 5 metres. These grey cherty limestones are overlain by reworked red nodular limestones forming a series of mass-flow deposits. This interval is rich in red marls making up the matrix of the different mass flows. The age of this interval is Late Pliensbachian to Toarcian. The lower Middle Jurassic (Aalenian) is preserved in the form of a very thin layer of *Bositra*-rich marly limestones. On top of these Aalenian sedimentary rocks, a ferro-manganese horizon reflects a long lasting depositional gap (Bajocian to Bathonian). Above, a black massive radiolarite of Callovian age was deposited. The thickness of the black radiolarite is about 1 metre. It changes colour upsection into a reddish radiolarite. The age of the more than 15 metres thick red radiolarite is Late Callovian to Oxfordian, most probably earliest Oxfordian according to radiolarian associations. Still in the Early to Middle Oxfordian the red radiolarite passed into dark-grey radiolarites and cherty limestones. The radiolarites of this part of the section are laminated and contain the first fine-grained turbidites. The clasts are too small to be determined regarding their stratigraphic affiliation. Upsection the turbidites become coarse-grained. The components mainly consist of Late Triassic lagoonal Dachstein Limestone, whilst Early to Middle Jurassic clasts occur only seldom. This component spectrum is identical to that of the Tauglboden valley resediments in the south. So is the age of the radiolarian rich background sediment: Early to Middle Oxfordian. In contrast to the thick succession in the Tauglboden valley, the thickness of the northern Tauglboden Basin succession does not exceed a few tens of metres (details in DIERSCHE, 1980) with a maximal thickness of the intercalated mass flows of only 10-20 centimetres.

The components in the different turbiditic layers exclusively derive from the lagoonal Dachstein Limestone facies zone. The component spectrum is identical with the one known from the Taugl valley to the south.

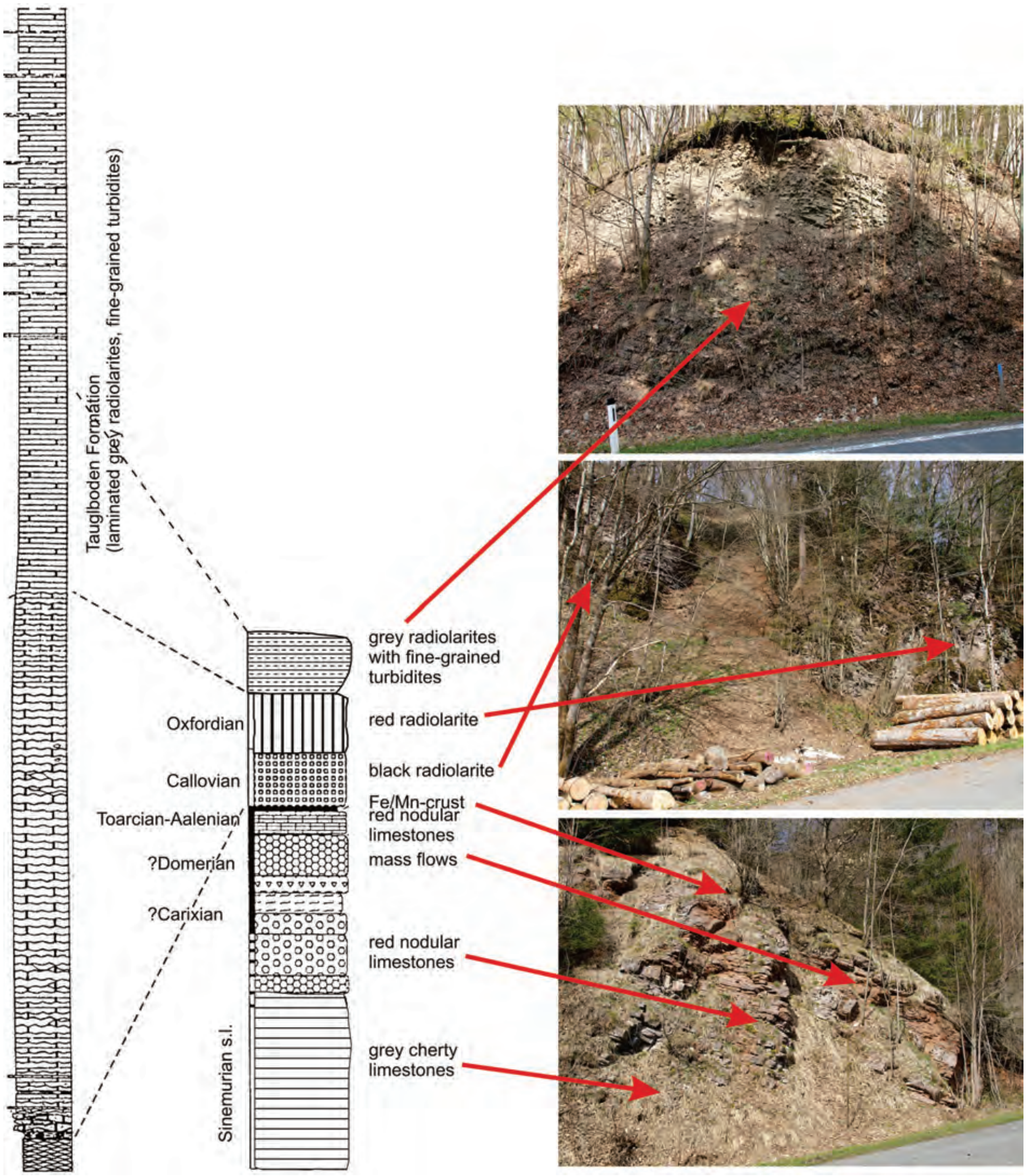


Figure 25: Stratigraphy and facies of the Early to early Late Jurassic section along the road to the village Krispl in the Mörtlbach valley (compare GAWLICK et al., 2012). Right section with photographs after BÖHM (1992), modified and completed for the Callovian-Oxfordian part. Left section from DIERSCHE (1980).

Locality Zauberwald and Berchtesgaden and Bad Dürrnberg area: Sandlingalm Basin

The Sandlingalm Basin fill contains blocks up to kilometre-size, which derived exclusively from the Hallstatt Limestone facies and the Meliata facies zones (including cherty Pötschen Limestone without reefal detritus) in a radiolaritic matrix. The sedimentary succession of the Sandlingalm Basin is composed of various slide masses in a Callovian-Oxfordian radiolaritic matrix (Fig. 26). Resedimentation of Hallstatt blocks in this basin started in the Early Callovian and ended around the Oxfordian/Kimmeridgian boundary with the emplacement of the Haselgebirge Mélange (MISSONI & GAWLICK, 2011a) and the subsequent sedimentation of grey siliceous deep-water limestones started. These limestones belong to the basinal sequence aside the early Plassen Carbonate Platform *sensu lato* and were deposited on top of slide masses sealing the chaotic basin fill (compare Figs. 17–22).

In the Zauberwald area the lower part of the basin fill is outcropping: different mass-flows consisting exclusively of Late Triassic red and grey Hallstatt Limestone clasts occur in a dark-grey to black Callovian radiolaritic matrix (details in MISSONI 2003).

In the whole area of Berchtesgaden to Bad Dürrnberg many slides of Hallstatt Limestone successions exist; for history of investigations and new data see e.g. GAWLICK et al. (1999a), MISSONI (2003), MISSONI & GAWLICK (2011a).

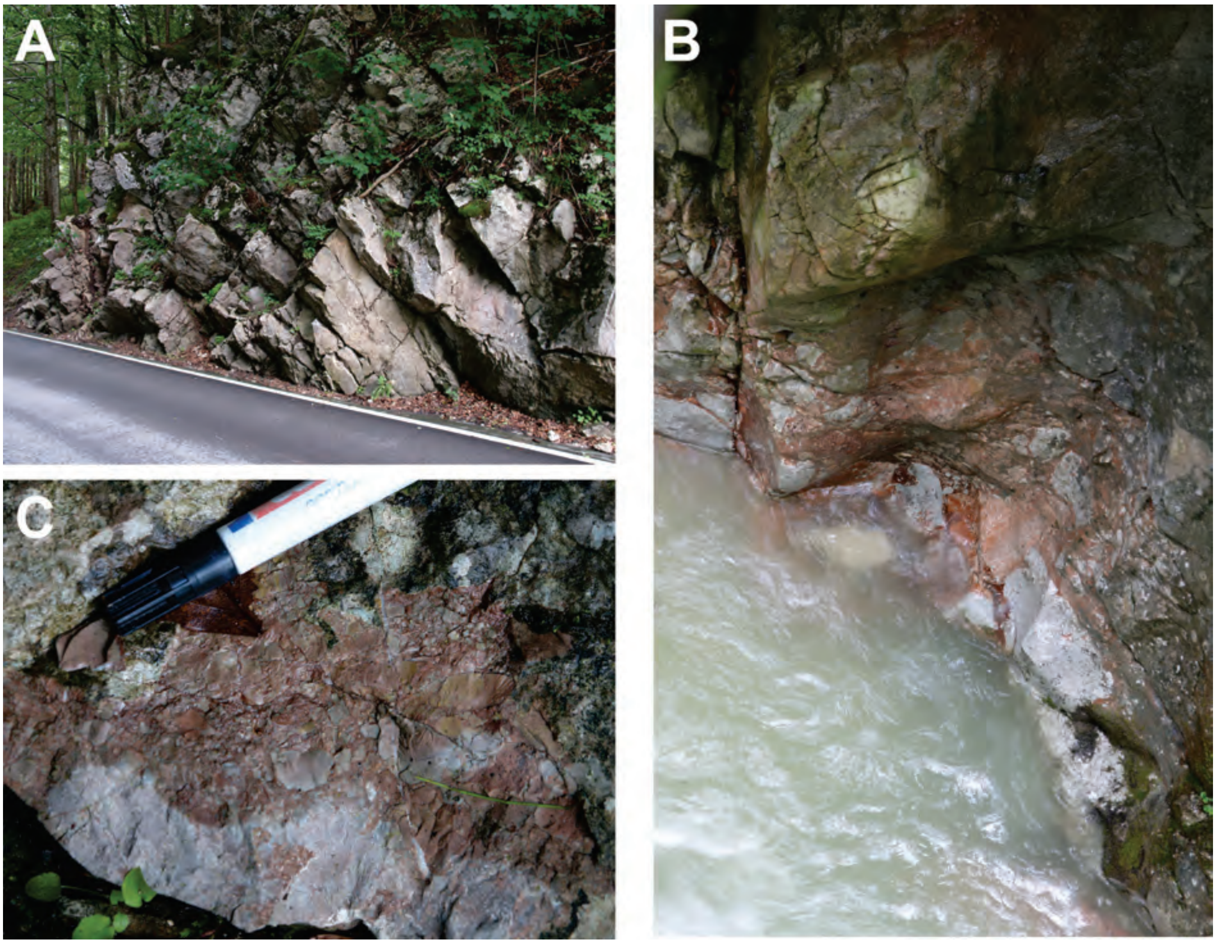


Figure 26: Sandlingalm Formation in the Zauberwald area.
A) Outcrop situation along the road. Different mass-flow deposits which consists of Hallstatt Limestone clasts. The mass flows area surrounded by a weathered landscape which consists of the radiolaritic matrix.
B) Polymictic mass-flow deposit in the gorge (Marxenklamm) on the forest road in direction Zauberwald. Red and grey Hallstatt Limestones clasts occur in a reddish-greyisch cherty matrix.
C) Polymictic breccia in the Zauberwald area. Most clasts are angular. The rare matrix consists of reddish radiolarian-rich cherty limestones.

Büchsenkopf area: Lammer Basin

In general, the sedimentary record of the Lammer Basin fill in the Salzburg and Berchtesgaden Alps documents a shift of depocentres within the basin (MISSONI & GAWLICK, 2011a, b): in an early stage of sedimentation the original depocentre of the basin was filled by slide blocks which derived from the accreted proximal Zlambach facies zone. The northern depocentre, after a shift of the basin axis, received material from the reefal part of the Late Triassic carbonate platform.

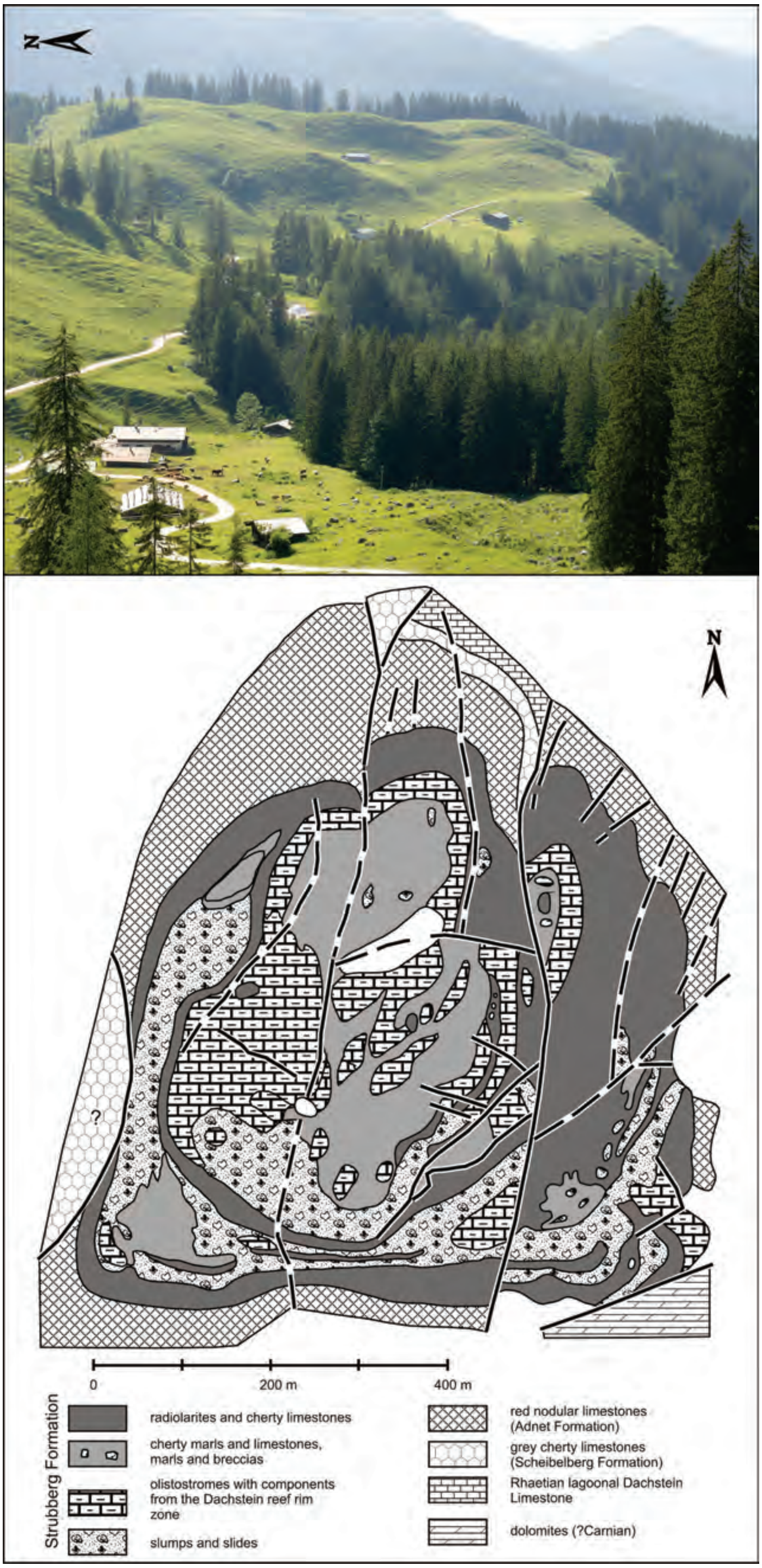


Figure 27: Photo and geological map of the Büchsenkopf area in the southern Berchtesgaden Calcareous Alps (based on DIERSCHE, 1978, after GAWLICK et al., 2003 and MISSONI, 2003).

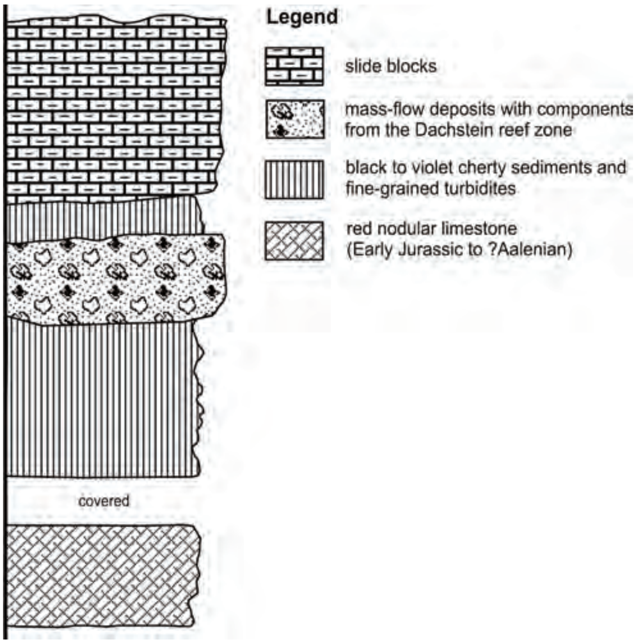


Figure 28: Generalized sedimentary succession of the Büchsenkopf area. The contact between the Early to Middle Jurassic red nodular limestones is not exposed. The black radiolarites below the first mass-flow deposits are dated as Callovian by means of radiolarians. The first resediments occurred in the Oxfordian according to GAWLICK et al. (2003) and MISSONI (2003). The thickness of the whole preserved succession does not exceed 150 metres. The section is not to scale.

The Büchsenkopf area (Fig. 27) comprises a complete Late Triassic to Late Jurassic sequence. The oldest sedimentary rock in the area is the Rhaetian lagoonal Dachstein Limestone which is overlain by Early Jurassic red nodular limestones (BRAUN, 1998). Middle Jurassic red nodular *Bositra* Limestones are missing. The black radiolarite (Callovian: GAWLICK et al., 2003; MISSONI, 2003) directly overlies the red nodular limestones (Adnet Formation) with a depositional gap in between. Resedimentation in the area started around the Callovian/Oxfordian boundary but more likely in the Early Oxfordian. Several polymictic olistostromes occur intercalated in black radiolarites to cherty limestones and, more seldom, argillaceous marls. Tens of metres sized slides make up the top of the preserved Büchsenkopf area sequence (Fig. 28).

The components of the different mass-flow deposits derive exclusively from the reef slope to reef area of the Late Triassic Dachstein Limestone carbonate platform. Upsection, on top of the Büchsenkopf sequence, larger slides of several hundred metres thickness (Fig. 29) occur. Fig. 29 shows the whole Late Triassic to early Late Jurassic sedimentary succession. The base of the succession is represented by Rhaetian lagoonal Dachstein Limestone. It is overlain by red nodular limestones of Early to Middle Jurassic age. Upsection follows a some hundred metres thick succession of radiolaritic sediments with intercalations of mass-flow deposits (= Büchsenkopf series). The sequence is topped by a several hundred metres thick slide from the Dachstein reef slope area (Mt. Jenner).

The radiolarians from the cherty limestones and radiolarites directly below the contact yielded a Callovian to Early/Middle Oxfordian age (MISSONI, 2003). The upper part of the sequence might have been eroded during the emplacement of the huge slide (compare MISSONI & GAWLICK, 2011a).

The matrix of these huge slides consists of dark grey to black cherty marls, cherty limestones and radiolarites, dated by means of radiolarians as Oxfordian (MISSONI, 2003). In the Berchtesgaden Calcareous Alps the deposition of the radiolarites of the Lammer Basin fill started in the Callovian and ended in the Oxfordian (MISSONI, 2003; MISSONI et al., 2005; MISSONI &, GAWLICK 2011a), similar as in the type region to the east.

Figure 29: Late Triassic to early Late Jurassic sedimentary sequence in the southern Berchtesgaden Calcareous Alps topped by a huge slide of Dachstein reef slope origin. After MISSONI & GAWLICK (2011a). View from the west (Büchsenkopf area).

Tauglboden valley: Tauglboden Basin

The Tauglboden Formation is composed of Oxfordian to Early Tithonian cherty matrix sediments with intercalated polymictic breccias and mass-flow deposits derived from the Trattberg Rise to the south (GARRISON & FISCHER, 1969; SCHLAGER & SCHLAGER, 1973; DIERSCHE, 1980), i.e., the lagoonal Dachstein Limestone facies zone. For a detailed description see GAWLICK et al. (2012).

Where the Urban valley approaches the Taugl valley (Fig. 30), the contact between the Early to Middle Jurassic red nodular limestones and the overlying radiolarite sequence is exposed. The age of the red nodular limestones is Late Bathonian to Early Callovian according to HUCKRIEDE (1971) and BÖHM (1992). On top of the red nodular limestone, a condensed layer contains rhyncholiths of Oxfordian age (HUCKRIEDE, 1971). The microfacies of the upper part of the red nodular limestone correspond to that of the overlying red radiolarite: Radiolarians from these red radiolarites yielded an Early to Middle Oxfordian age (GAWLICK, 2000b). The radiolarian associations are similar to the radiolarian associations of the grey laminated radiolarites higher in the section. Both the lithology and the colour of the radiolarites change gradually. The radiolarites turn from red over reddish grey and medium grey to finally dark-grey colours. The grey radiolarites are fine laminated. The clay content increases upsection and several few centimetres thick clay layers are intercalated between the radiolarite beds.

About five metres above the contact between the red nodular limestone and the radiolarite succession, the first coarse-grained mass-flow deposits are intercalated in the radiolarite sequence. The up to 20 cm thick breccia layers overlie the radiolarite beds practically without basal erosion; obviously the breccia layers show the characteristics of channels deposits. Below the breccia layers a layer of green volcanic ash is locally preserved.

The components in the mass-flow deposit derive exclusively from the lagoonal Dachstein facies zone. Components of the Early Rhaetian Kössen Formation are rare whilst components of Rhaetian lagoonal Dachstein Limestone strongly predominate. Early to Middle Jurassic clasts occur in rock-forming quantities, too. Early Jurassic grey cherty limestones (Scheibelberg Formation), chert nodules and red nodular limestones (Adnet Formation) dominate. In contrast, Middle Jurassic *Bositra* Limestone components are seldom.

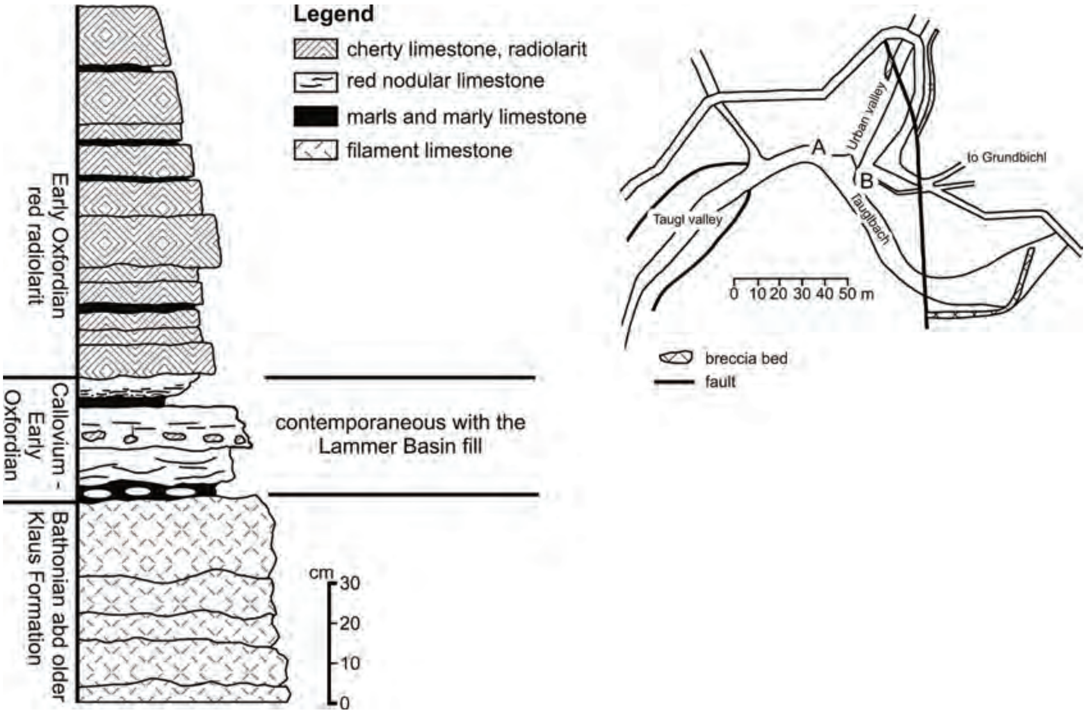


Figure 30: Area of the Urban creek/Taugl creek in the central Salzburg Calcareous Alps, exposing excellent sections of the succession around the boundary Klaus Formation/radiolarite (Tauglboden Formation) in the. The drawn detailed section is from west of the Urban valley (A). An equivalent section is seen east of the Urban creek (B). Redrawn after HUCKRIEDE (1971).

A strongly variable outcrop situation is met on the walk along the forest road Kesselstrasse. In a small valley beside the forest road and along the forest road there are some good outcrops giving an insight into the early phase of the Tauglboden Basin evolution. The age of the succession along the road is still Early to Middle Oxfordian as proven by radiolarians. Dark grey to black laminated radiolarites with changing clay content, slump deposits and mass flows are the typical sedimentary features of the succession. The slump deposits consist partly of cherty sediments without older components, large blocks of older components incorporated in the argillaceous matrix, and debris flows. Generally, the older clasts are the same as in the basal breccia layers along the Taugl road, but Jurassic clasts are both smaller in number and older in age. The erosion cut into the Norian lagoonal Dachstein Limestone.

In the curve before the waterfall, a only few metres thick succession of dark grey to black radiolarites to cherty limestones free of mass flows intercalations occurs on top of the amalgamated sequence. The radiolarites from this amalgamated series below yielded still an Early to Middle Oxfordian age. Thus the whole around 200 metre thick sequence is Early to Middle Oxfordian in age.

Above this radiolarite succession again a thick radiolarite sequence with slumps and mass flows occur along the way. Here, several metres above this mass flow free radiolarites, some layers of volcanic ashes (metabentonites – GAWLICK et al., 1999b) of ten centimetres thickness are intercalated in the sequence. Radiolarians from these volcanic ash layers yielded an Early Tithonian age (GAWLICK et al., 1999b). This means, that the time span Latest Oxfordian to Early Tithonian is characterized by a starved sequence. The volume of material shed into the basin decreased rapidly in the Late Oxfordian. In comparison, the Kimmeridgian was characterized by radiolarite deposition.

Later, in the Early Tithonian, a new depositional cycle with mobilisation and redeposition of large volumes of rocks started. The series again is characterized by slump deposits, mud and debris flows. Whereas the older components in the different chaotic deposits were still the same as in the Early to Middle Oxfordian sequence, the content of Jurassic clasts was very low. Reworked Norian to Rhaetian clasts are dominating the component spectrum.

Radiolarites in this part of the succession are scarce, with cherty marls and cherty limestones being the typical matrix sediment. The preservation quality of the radiolarians in these matrix rocks is generally very bad.

By reaching the waterfall we will see a several tens of metres thick sequence of dark-grey well bedded cherty marls and cherty limestones, intercalated by several slump deposits, mud flows and debris flows (Fig. 31). The series is also characterized by the intercalation of semi-consolidated volcanic ash layers.

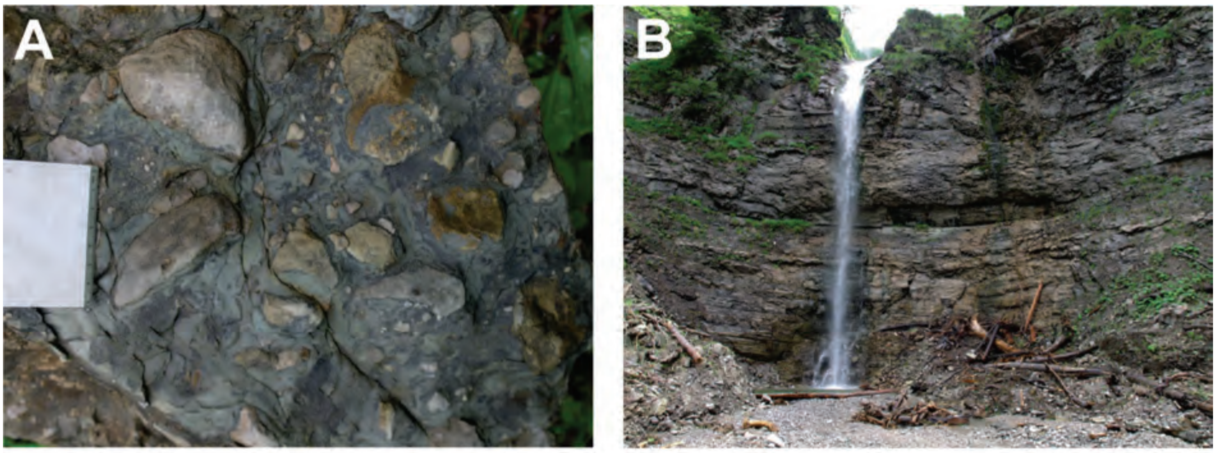


Figure 31: A) Early to Middle Oxfordian mud flow with large boulders of Late Triassic lagoonal Dachstein Limestone on top of well-bedded grey laminated radiolarites. Kesselstrasse forest road, Taugl valley. **B**) Early Tithonian sedimentary succession with slump deposits, mud flows and debris flows in a matrix of cherty marls and cherty limestones. Waterfall Kesselstrasse, Taugl valley.

4.3 Early Cretaceous

The increase of clastic material supply caused the drowning of the Plassen Carbonate Platform *sensu stricto* in Middle to Late Berriasian time and the establishment of a sedimentary succession with increasing siliciclastic input. The Valanginian to Barremian evolution is documented by an increasing supply of siliciclastic and ophiolitic-related detritus into the former Tauglboden/Oberalm Basin area (Rossfeld Molasse - GAWLICK et al., 2008). Ongoing uplift of the Juvavic nappe stack in the Early Cretaceous was accompanied by continued erosion and further northwestward gliding of several mélange blocks along low-angle faults in the Valanginian. In the Valanginian and in the Late Barremian, mass-flow deposits with mixed exotic and local material occurred, best explained by regressive cycles at this time (GRADSTEIN et al., 2004). The Rossfeld foreland basin fill and equivalents to the south represents the final stage of the mountain building process along the Neotethys suture (Fig. 3). Around the Barremian/Aptian boundary or in the Early Aptian these basins became filled (FUCHS, 1968; PLÖCHINGER, 1968; FAUPL & TOLLMANN, 1979). This is marked by a facies change to fresh-water conditions with local remnants of coal and amber (PLÖCHINGER, 1968).

Roßfeld road

The Roßfeld area along the Roßfeld road is the type area of the Early Cretaceous Roßfeld Formation (Fig. 32).

In the Rossfeld Basin type area, which represents the westward continuation of the Tauglboden Basin north of the Trattberg Rise of Mt. Kehlstein, the sedimentation lasted until the ?Barremian (TOLLMANN, 1985). Around the Early/Late Tithonian boundary the sedimentation changed from the radiolaritic Tauglboden Formation to the Late Tithonian to Middle Berriasian hemipelagic limestones of the Oberalm Formation intercalated with slope breccias of the Barmstein Limestone (GAWLICK et al., 2005).

In the Late Berriasian (not Valanginian) (MISSONI & GAWLICK, 2011a; KRISCHE, 2012; BUJTOR et al., 2013) a slight increase of the fine-grained siliciclastic material led to the sedimentation of the Schrambach Formation (TOLLMANN, 1985; RASSER et al., 2003). The change from hemipelagic carbonates to siliciclastically influenced siliceous carbonates and marls occurred contemporaneously with the drowning of the Plassen Carbonate Platform sensu stricto to the south (GAWLICK & SCHLAGINTWEIT, 2006). The Rossfeld Formation overlies the Schrambach Formation and is characterized by a coarsening upward trend.

In former interpretations the Rossfeld Basin was a newly formed Early Cretaceous flysch basin in a migrating foredeep in front of advancing Juvavic nappes (FAUPL & TOLLMANN, 1979; TOLLMANN, 1985; FAUPL & WAGREICH, 2000; NEUBAUER et al., 2000; FRANK & SCHLAGER, 2006). The sedimentation should have been terminated by the overthrust of these nappes, documented by the Hallstatt outliers on top of the Rossfeld Formation. By this interpretation mass-flow deposits, intercalated in calcareous sandstones and cherty limestones of the upper Rossfeld Formation should contain the complete component spectrum of the arriving nappes (e.g., PESTAL et al., 2009) as documented in the Jurassic basins.

However, new results on the uninvestigated carbonate components in these mass flows of the type locality (MISSONI & GAWLICK, 2011a) and all surrounding areas (e.g., Leube quarry, Weitenau area, Bad Ischl: KRISCHE, 2012) show clearly that not a single component of the so-called "Juvavic nappes" exist in the Rossfeld Formation. Triassic-Jurassic components from the Hallstatt Zone (Hallstatt and Pötschen Limestones) or Triassic shallow-water carbonate components of the Upper Tirolic Berchtesgaden unit as well as components of the Alpine Haselgebirge are completely absent.

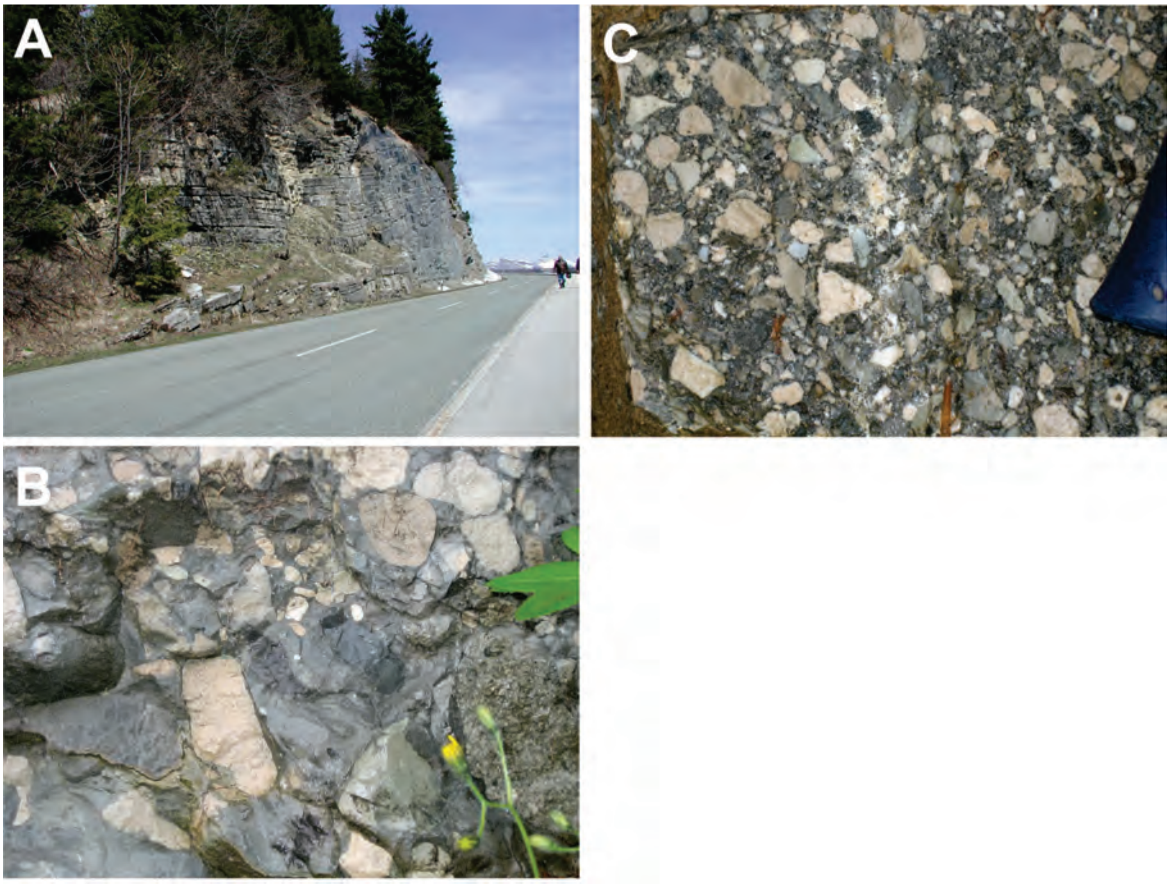


Figure 32: A) Ross Formation at the Hahnenkamm locality on the Rossfeld Panorama road. Calcareous sandstones with intercalated mass-flow deposits. **B**) Coarse-grained polymictic breccia of the Rossfeld Formation along the Rossfeld Panorama road. Beside the dominating carbonate clasts (Late Jurassic – Early Cretaceous) few radiolarite components (Triassic and Jurassic radiolarites) occur. **C**) Finer-grained polymictic breccia. Beside the dominating carbonate clasts radiolarites and ophiolitic grains occur.

Beside the already known siliciclastic, volcanic, and ophiolitic components (POBER & FAUPL, 1988; FAUPL & POBER, 1991; SCHWEIGL & NEUBAUER, 1997b; EYNATTEN et al., 1996; EYNATTEN & GAUPP, 1999; FAUPL & WAGREICH, 2000) occur only Late Jurassic to Early Cretaceous shallow-water carbonates and Triassic and Jurassic radiolarites. For details on component analysis see KRISCHE (2012), KRISCHE et al. (in press).

In addition from the Rossfeld Panorama road the Trattberg Rise (Fig. 33) to the south and the Lammer and Tauglboden Basin fills to the east resp. northeast are visible (Fig. 34).

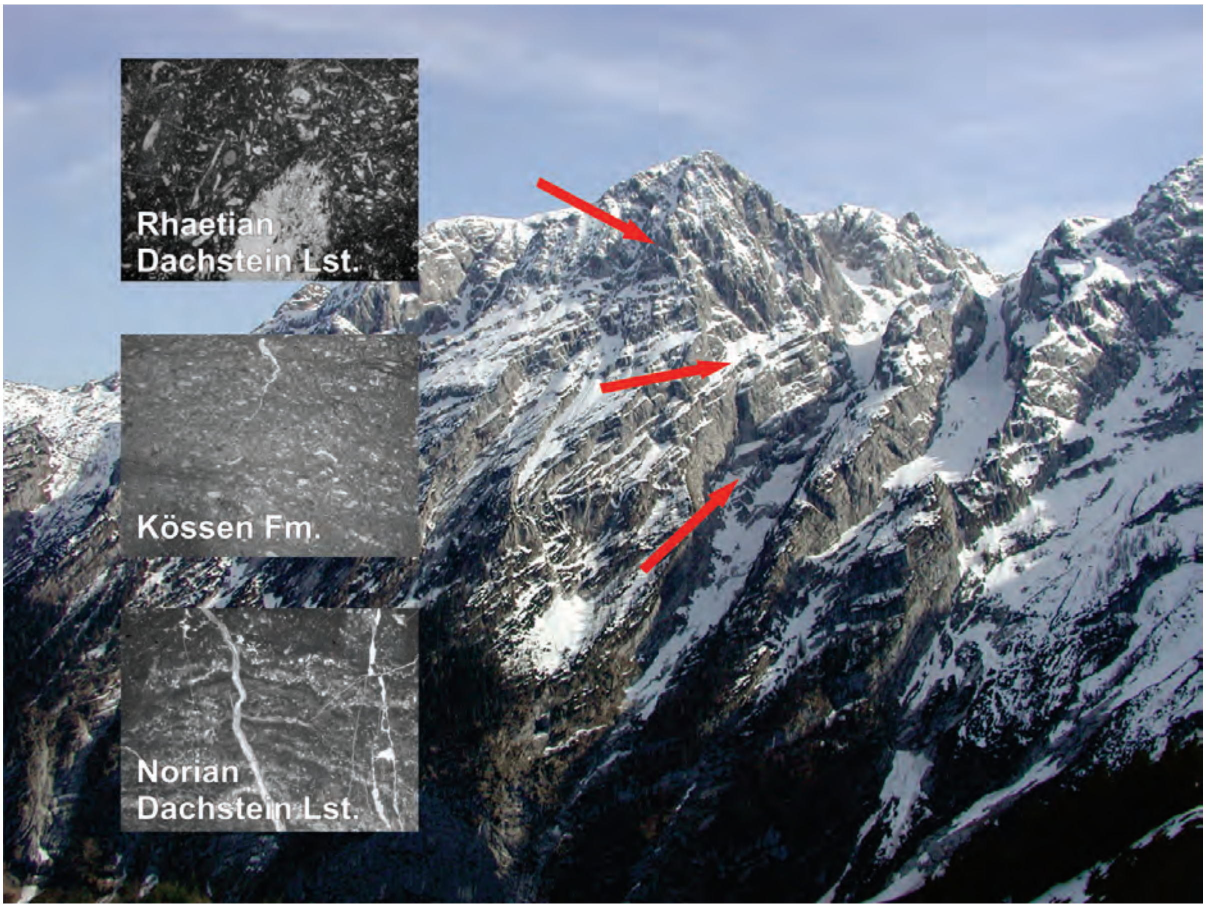


Figure 33: Late Triassic sedimentary succession of the Trattberg Rise, Mt. Hohes Freieck east of Mt. Hoher Göll. Insets show typical microfacies of the Late Norian to Rhaetian succession. The Rhaetian reef faces the Kössen Basin to the north. This clearly documents the palaeogeographic position of the area near the southern rim of the Kössen Basin and far away from the Dachstein Limestone reef zone facing the Hallstatt Zone.

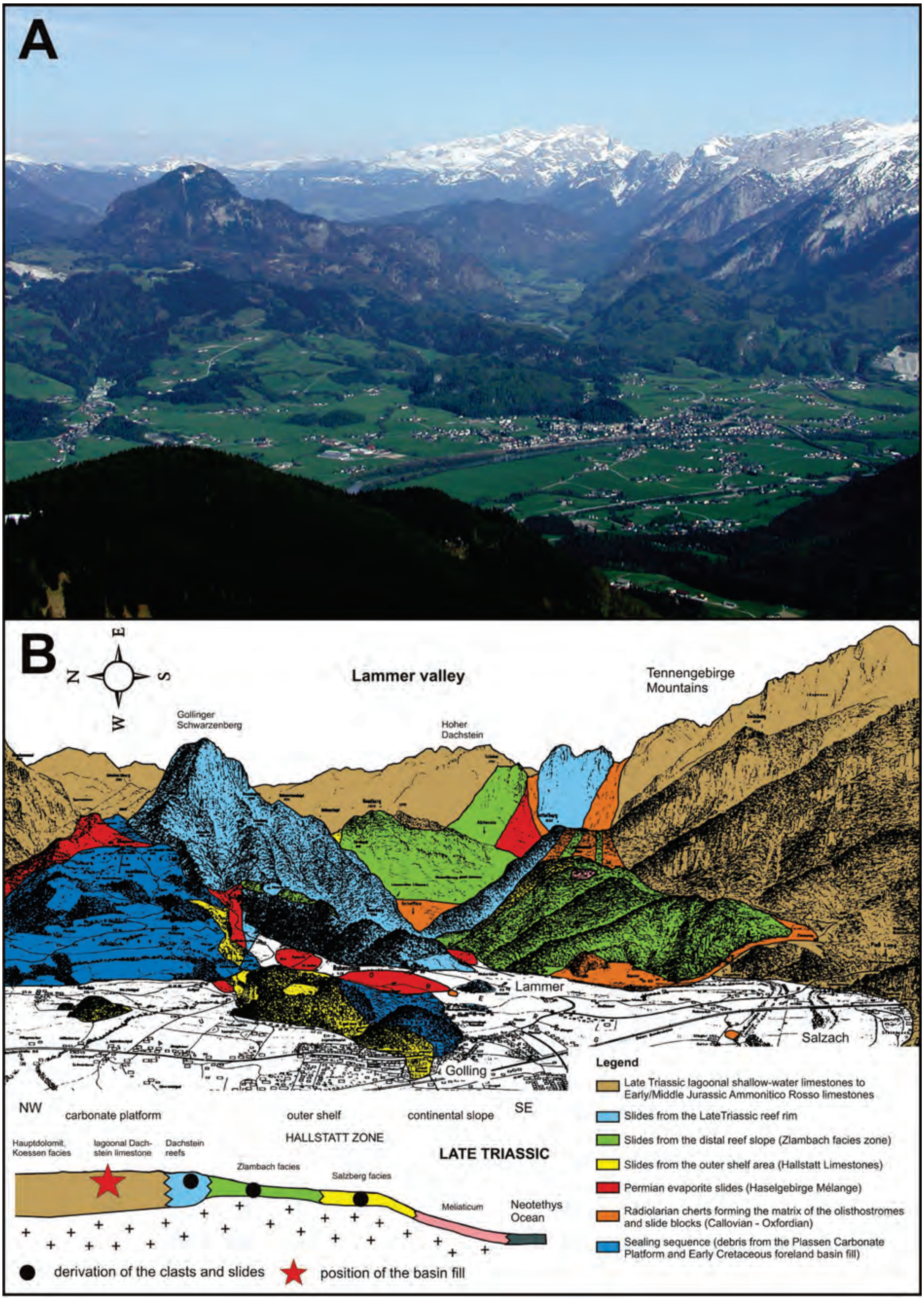


Figure 34: A) View from the west showing the type area of the Lammer Basin fill. **B**) Geological interpretation of the landscape picture. The basin fill consists of allochthonous material of different age and facies provenance, which generally derives from the outer shelf area transitional to the Neotethys Ocean.

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