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SYNOROGENIC SEDIMENTS OF THE WESTERN NORTHERN CALCAREOUS ALPS

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General Introduction

The main objective of this field trip is to demonstrate the Cretaceous syntectonic sediments of the Northern Calcareous Alps (NCA) in the western part of the Eastern Alps (Fig. 1). Today most of the crystalline basement rocks of the NCA are tectonically or erosionally removed, or have lost their information on this early phase of Alpine orogeny because of late Alpine metamorphic overprint. The Cretaceous synorogenic sediments thus are particularly important for the reconstruction of early Alpine geodynamics.

Geodynamic evolution of the Eastern Alps and NCA

The Eastern Alps were involved in two orogenies (Fig. 2): the first closed the Meliata ocean during the Cretaceous, whereas the second orogeny closed the Penninic ocean during the Cenozoic (Thöni and Jagoutz, 1993; Froitzheim et al., 1994, 1996; Faupl and Wagreich, 2000; Neubauer et al., 2000). The first orogeny caused stacking of nappes within the Adriatic microplate, which was in a foreland position with respect to the closure of the Meliata ocean to the southeast (e.g. Neubauer, 1994; Froitzheim et al., 1996; Fig. 2a). In the NCA, which presently form the northernmost part of the Adriatic microplate, thin-skinned nappes were sheared off their original basement and transported to the northwest over a distance of tens of kilometers (Linzer et al., 1995; Eisbacher and Brandner, 1996; Ortner, 2003a; Auer and Eisbacher, 2003). Initial stacking of the Allgäu-, Lechtal- and Inntal thrust sheets was directly related to this event.

The second, Cenozoic orogeny gave the Eastern Alps much of their present structure and was related to the closure of the Penninic ocean separating the Adriatic microplate and the European plate between the Early Jurassic and the Eocene (e.g. Frisch, 1979; Schmid et al., 1996). Cenozoic orogeny led to accretion of material from the lower plate to the Alpine orogen. Sedimentary units from the Penninic ocean (Rhenodanubian Flysch nappes), the southern passive margin of the European plate (Helvetic nappes) and from the northern Alpine foreland basin (allochthonous Molasse) were successively incorporated into the Alpine wedge (Fig. 2b).

What are synorogenic sediments?

Commonly, the onset of synorogenic sedimentation in a carbonate-dominated passive margin succession such as the NCA is defined by the onset of siliciclastic deposition. During orogeny basement units in the internal mountain belt will be uplifted and eroded, supplying siliciclastic detritus to the external belt. However, the Helvetic European margin has numerous siliciclastic ingressions in the passive margin succession, so this criterion might not be reliable. Synorogenic sediments in mountain belts often display stratal geometries related to fold growth during sedimentation. Growth strata are well known from e.g. the Sevier thrust belt (DeCelles, 1994), the Andean chain (Zapata and Allmendinger, 1996; Verges et al., 2007), the Pyrenees (Riba, 1976; Puigdefabgras et al., 1992) and are found predominantly in siliciclastic (l.c.), but also in carbonatic successions (Masaferro et al., 2002; Eichenseer and Luterbacher, 1992). In the NCA, growth strata geometries were described from the Gosau Group at Muttekopf (Ortner, 2001) and depicted in cross sections of the Branderfleck-Fm. by Kockel et al. (1931), however angular unconformities were described from various synorogenic formations (e.g. Brinkmann, 1934; Wopfner, 1954; Faupl, 1983; Wagreich, 1986; Sanders, 1998) and partly interpreted in terms of extensional tectonics.

Thrusting and synorogenic sedimentation in the NCA

The transect of the NCA across the Allgäu and Lechtal Alps is a unique place to study the dynamics of thrusting and coeval synorogenic sedimentation because of

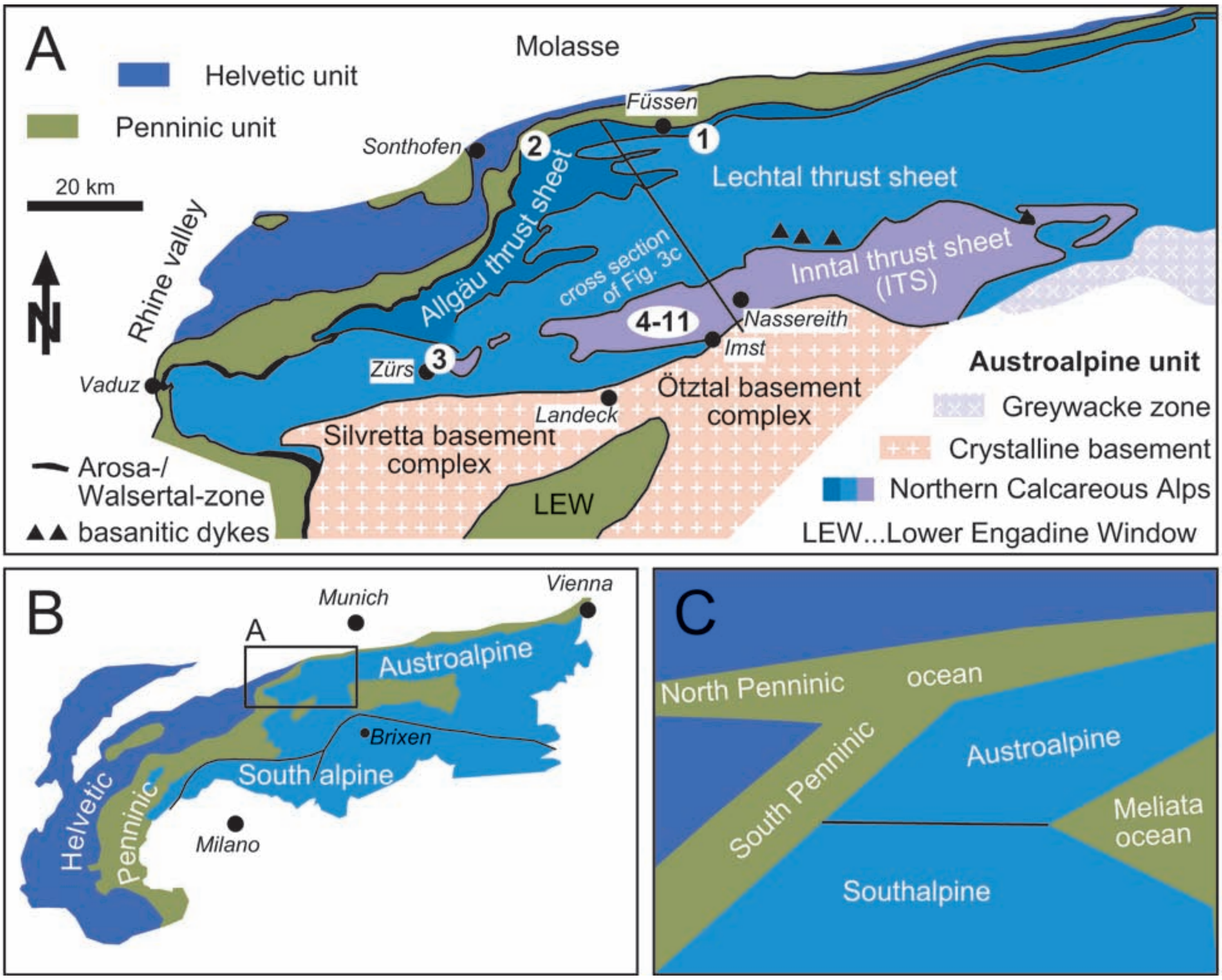


Fig. 1: A) Geologic sketch and approximate location of outcrops. The field trip starts and ends in Nassereith, continues to Füssen (stop 1) and Hindelang (stop 2) near Sonthofen. On the second day, outcrops near Zürs (stop 3) and Imst (stop 4) will be visited. The last day will be spent near Imst (stops 5-11). B) Location of the Excursion area within the Alpine arc. C) Simplified paleogeographic sketch of the Alpine realm at the Jurassic-Cretaceous boundary.

partly spectacular outcrop conditions. Thrust activity in the NCA started, when these were still deeply submerged and pelagic conditions prevailed. The thrust planes were emergent and therefore superimposed the hanging-wall units onto the youngest synorogenic deposits of the footwall (Fig. 3a). As a consequence, the hanging-wall was uplifted above sea level and eroded. Subsidence brought the nappe stack from subaerial to shallow marine and finally deep marine conditions (Gaupp, 1982; Wagreich, 1993). Folding within the thrust sheet created piggy-back basins that were filled by growth strata.

The process of nappe stacking can be further refined using a ramp-flat model (Ortner, 2003). As the thrust sheet climbs up the ramp and relative sea level falls on top, small isolated carbonate platforms or build-ups grow on top (Fig. 3a, bottom). These are eroded during further uplift of the thrust sheet, and bioclastic debris is redeposited into the adjacent basin. Submarine topography causes instability and hence collapse of the flanks of the ramp anticline, redepositing large olistoliths into the basin. In a later stage, the thrust sheet starts to deform internally. Material eroded from the flanks of evolving anticlines is deposited into the synclines on top of an (angular) erosional unconformity, and continuous fold growth leads to the development of angular unconformities within the deposits (growth strata; Fig. 3a, top).

The synorogenic sedimentary successions of the western NCA can be compared to specific positions in such a model:

Upper Footwall sedimentation: On the upper footwall flat (1 in Fig. 3a) below the thrusted units, conformable onset of synorogenic sedimentation probably records dis-

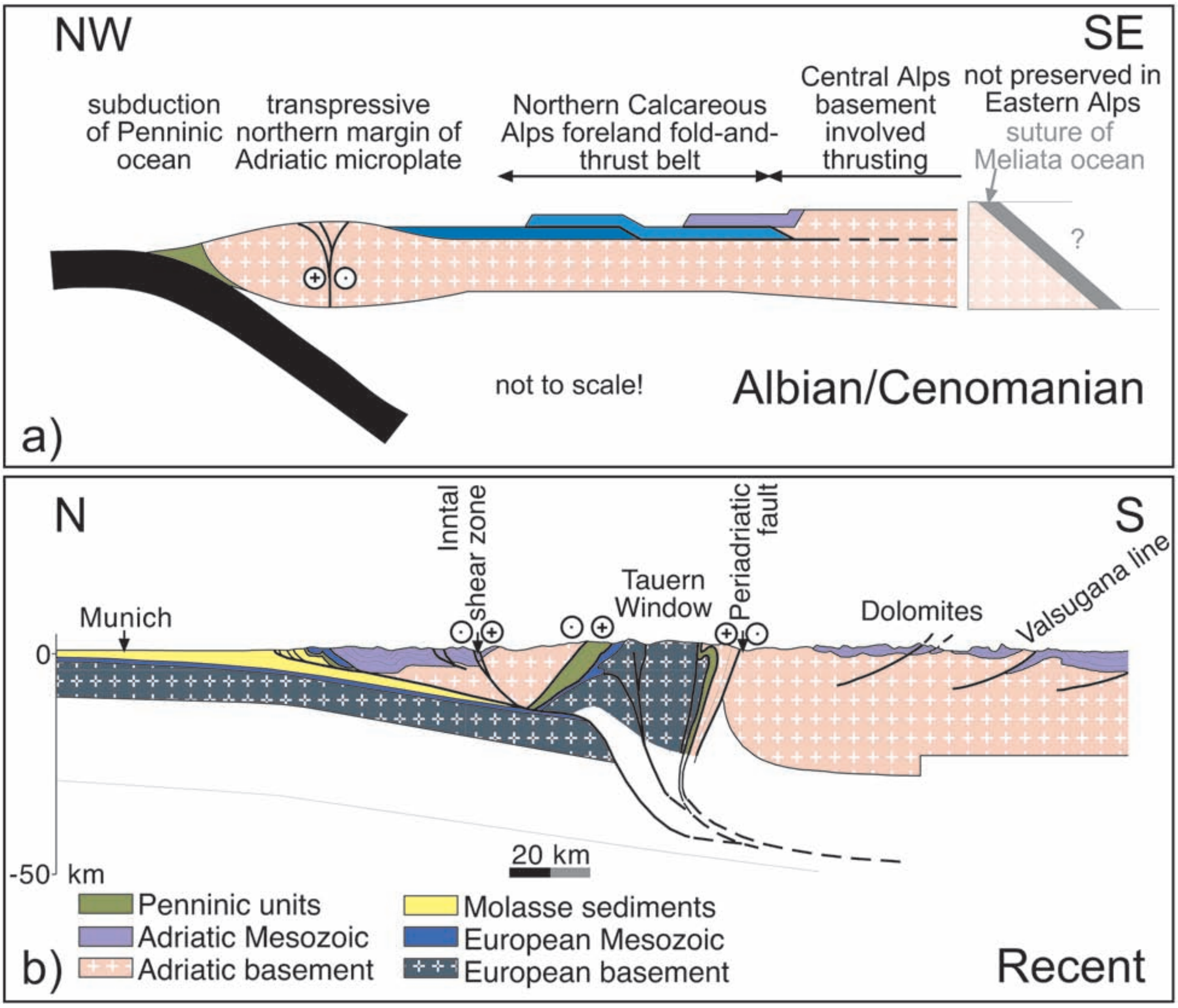


Fig. 2: Conceptual models illustrating the two stages of Alpine orogeny in Eastern Alps. a) Cretaceous orogeny, when today's Eastern Alps were in a foreland position to the closure of the Meliata ocean (modified from Wagreich, 2003a), and b) Cenozoic orogeny, in which the Eastern Alps formed the upper plate during closure of the Penninic ocean (modified from Lammerer and Weger, 1998).

tant onset of contraction related to orogeny, and deposition of shallow water biogenic detritus shows the approaching of the thrust unit. The youngest sediments below the thrust record the minimum age of thrusting at the point of observation. This situation is comparable to Aptian-Albian synorogenic sedimentation of the Tannheim and Losenstein Fms. on top of the Allgäu thrust sheet (ATS), which are overlain by the Lechtal thrust sheet (LTS) and to Albian-Cenomanian synorogenic sedimentation of the Lech Fm. on top of the southern LTS, which is overlain by the Inntal thrust sheet (ITS) (Fig. 3b). The uppermost Lech Fm. locally contains shallow water detritus transported by gravity flows ("Urgonian"; Schlagintweit, 1991; Leiss, 1992) and thereby records the destruction of carbonate buildups at the flanks of the approaching ITS. Several large slabs and boulders of Mesozoic rock within the Lech Fm. were interpreted as olistoliths by May and Eisbacher (1999).

Thrust-sheet-top sedimentation: On top of the thrust unit, where structural thickening has taken place, unconformable transgression of terrestric sediments on deeply eroded older rocks records exhumation. The Branderfleck Fm. on top of the northern LTS and of the Gosau Group on top of the ITS are found in this structural position (2 in Fig. 3a).

In the foreland and the hinterland of the structure, undisturbed synorogenic sedimentation will continue (Fig. 3a). The Cenomanrandschuppe (CRS) formed the northern continuation of the ATS prior to the Campanian, when it was overthrust by the LTS. The CRS has a conformable and continuous synorogenic sedimen-

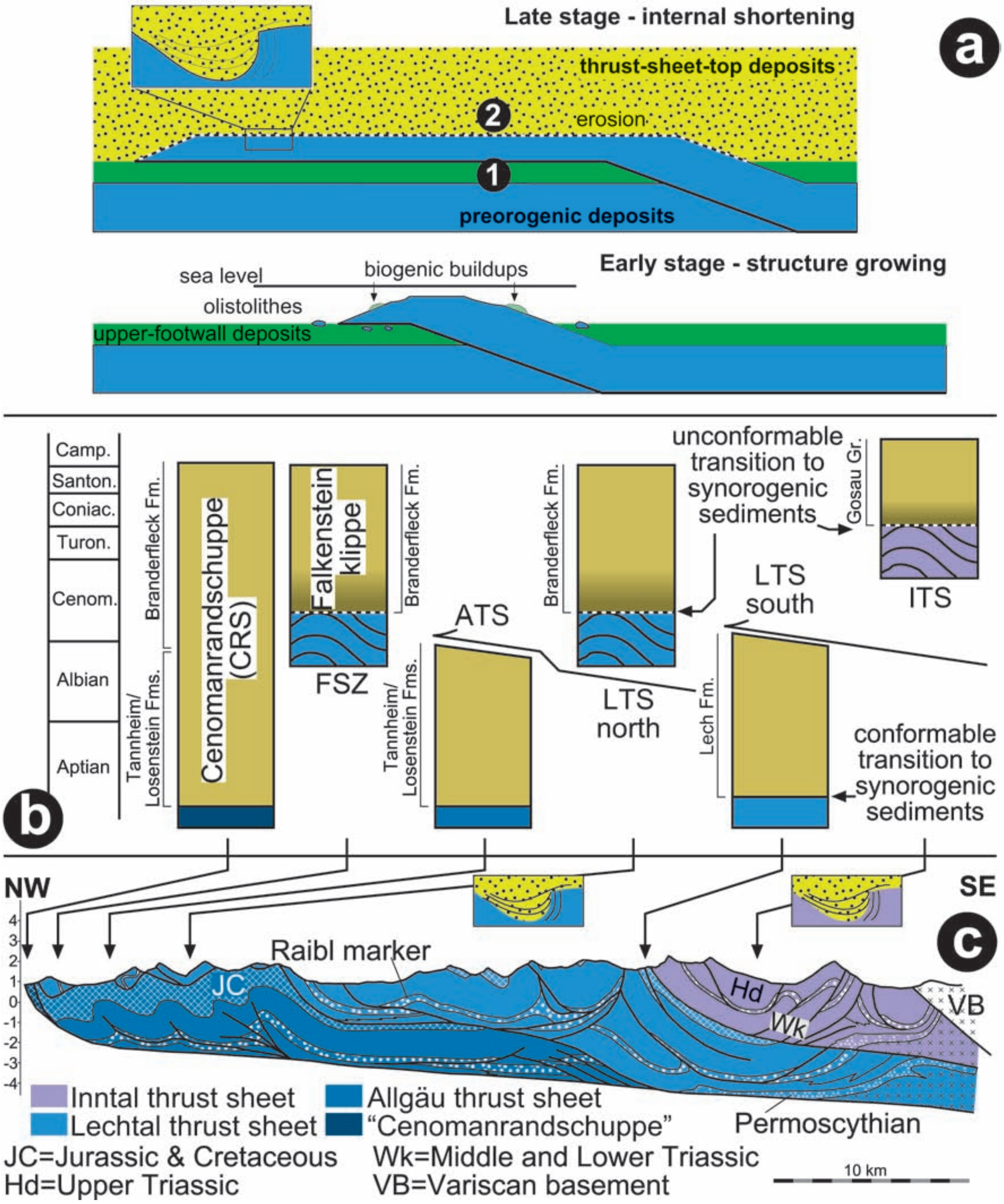


Fig. 3: The relationship of thrusting and synorogenic sedimentation. A) Ramp-flat model illustrating the effects of thrusting in a deep marine environment during an early stage (bottom) and a late stage (top). B) Distribution and timing of synorogenic sedimentation in the western part of the Northern Calcareous Alps. CRS = "Cenomanrandschuppe", a frontal slice of the Allgäu thrust sheet, FSZ = "Falkensteinzug", a klippe forming the northern continuation of the Lechtal thrust sheet. C) Cross section of the Northern Calcareous Alps along field trip transsect, simplified from Eisbacher et al. (1991).

tary succession from the Aptian to the Campanian, overlapping both Upper Footwall sedimentation below and thrust-sheet-top sedimentation on top of the LTS. The CRS formed the foreland during thrusting of the northern LTS. The hinterland in relation to the northern LTS record conformable sedimentation up the Cenomanian, and was then overthrust by the ITS. It forms the upper footwall in relation to thrusting of the ITS.

The lower Cretaceous to Santonian sediments studied during stops 1 - 3 of the field trip document synorogenic deposits related to thrusting of the LTS. Aptian deposits document the change from passive to active margin sedimentation in the upper footwall below the LTS. The later Albian to Santonian thrust-sheet-top deposition took place in synclines parallel to the LTS front (slope apron basins, cf. Wagreich, 2003a). Syn- and postsedimentary nappe thrusting caused intensive deformation and amputation of these sediments. Outcrops are therefore poor and sandwiched between thick and competent carbonate successions but contain valuable information on sedimentary processes, source rock lithologies, and space-time relations of nappe movements (e.g., Gaupp, 1982; Eynatten et al., 1997; Ortner, 2003; Gaupp and Eynatten, 2004).

Spectacular outcrops of deposits related to thrusting of the ITS will be visited during stops 4 to 11 of the field trip. Condensed Jurassic to Cenomanian deposits of the southern LTS are in the footwall of the Inntal thrust. The Upper Coniacian to ?Paleocene Gosau Group on top of the ITS locally includes terrestrial to shallow-marine facies associations, the main part consists of deep-water hemipelagic and turbiditic deposits (e.g., Wagreich and Faupl 1994) of the Upper Cretaceous Gosau Group.

Part I: Aptian to Santonian sedimentation at the northern Austroalpine plate margin

Geological setting and stratigraphy

The Aptian to Santonian siliciclastic rocks were deposited on the northernmost and structurally deepest nappes of the NCA, the ATS and the LTS, which are thrusted over Penninic units (Fig. 1B). Two outliers are isolated from the main nappe bodies: The "Cenoman-Randschuppe" (CRS) is the northernmost frontal part of the ATS, the "Falkensteinzug" (FSZ) is a klippe of the northern LTS (Figs. 1B and 3C).

The siliciclastic sedimentary succession (upper footwall deposits below the Lechtal thrust) develops continuously from the underlying Lower Cretaceous pelagic carbonate rocks. The latter are composed of micritic limestones (Ammergau-Fm., formerly "Aptychenschichten") reflecting the late passive margin stage at the Austroalpine-Penninic plate boundary. Carbonate sedimentation continued up to the Barremian/lower Aptian. Siliciclastic sedimentation started in the Aptian with a pelitic interval composed of marls and marly shales (Tannheim-Fm.; Zacher, 1966; Wagreich, 2003a) reflecting an increased input of fine-grained detrital material. These pelitic hemipelagic sediments grade upsection into coarser grained deposits composed of marls, shales, sandstones, pebbly mudstones and conglomerates (lower/middle Albian to uppermost Albian, Losenstein-Fm., Löcsei, 1974; Gaupp, 1982). These sediments were in part deposited by turbidity currents and reflect deeper water conditions. The Losenstein-Fm. as well as the Tannheim-Fm. are restricted to the structurally deepest tectonic units (CRS and ATS, Fig. 3C). The Branderfleck-Fm. has a stratigraphic range from the Lower Cenomanian to the Coniacian/?Santonian, locally up to the Lower Campanian (Gaupp, 1982; Weidich, 1990). The lower part of the Branderfleck-Fm. (Cenomanian/lower Turonian) is characterized by calclithites (cf. Garzanti, 1991), polymictic carbonate breccias, and olistostroms mostly composed of carbonate detritus derived from disintegrating mobile nappe fronts. The upper part of the Branderfleck-Fm. (Turonian and younger) is dominated by pelites and sandy turbidites. Their composition reflects increased siliciclastic input. The sediments of the Branderfleck-Fm. were deposited on CRS, FSZ, and the northern part of the LTS, but not on the ATS (Gaupp, 1982, Fig. 3B).

On the southern part of the LTS Cretaceous siliciclastic sedimentation of the Lech Fm. (Eynatten 1996; formerly named "Lechtaler Kreideschiefer") starts in the Aptian and reaches into the Late Albian/?Cenomanian (Winkler, 1988). These sediments develop continuously from the underlying Ammergau-Fm. (upper footwall deposits below the Inntal thrust), but differ from the Tannheim- and Losenstein-Fms. to the north in terms of grain size (usually no conglomerates or pebbly mudstones), sedimentary facies, and composition (see chapter "Provenance of siliciclastic detritus"). The Lech-Fm. is restricted to the LTS. At the Mohnenfluh area and farther to the west, where the Lechtal thrust ends in a tight anticline and is replaced by the younger (post-Turonian) Mohnenfluh thrust (May and Eisbacher, 1999), Cenomanian/Turonian coarse-grained sediments occur on top of sediments of the Lech-Fm. We consider these coarse-grained sediments to be equivalents of the Branderfleck-Fm. to the north.

The stratigraphic ranges and the three-dimensional distribution pattern of specific sedimentary units on top and between different tectonic units give insight to the regional extent and timing of nappe thrusting. The complete set of sedimentary formations can only be observed in the CRS (Fig. 3B). In the northern part of the LTS and in the FSZ, sediments of the Branderfleck-Fm. unconformably rest on older Mesozoic rocks. Aptian and/or Albian sediments are not reported from these two units. On the other hand rocks of the Tannheim- and Losenstein-Fms. were exposed on the ATS, but no rocks of the Branderfleck-Fm. occur on this nappe. This implies that the ATS has already been overthrusted by structurally higher tectonic units (FSZ, LTS) by the end of the Albian (Gaupp 1982). This holds true for the main body of the ATS apart from its western termination where Turonian sediments occur also on the ATS. A comparable scenario is suggested for the LTS (southern part) where sedimentation was tectonically terminated in the upper Albian (?Cenomanian) by overthrusting of the ITS (Fig. 3).

Provenance of siliciclastic detritus

Sedimentary structures indicating directions of clastic transport are scarce within the tectonized stratigraphic units. Detailed petrographic and geochemical work is necessary to decipher paleogeographic positions and lithological composition of the source areas (Eynatten 1996).

The sediments of the Tannheim-, Losenstein-, and Branderfleck-Fms. are derived from a source area located to the northwest, most probably in a Lower Austroalpine position near the transpressive plate boundary to the Penninic ocean. This source area was built up by continental as well as oceanic crustal rocks. The latter are documented by serpentinite fragments in the light mineral spectra and by chrome spinel in the heavy mineral spectra. Chrome spinel chemistry suggests harzburgite and subordinate Iherzolite host rocks. Chrome spinel chemistry through time can be interpreted as showing a trend from a more mid-ocean-ridge setting (Albian) to a more island-arc setting (Turonian) of the eroded peridotites/?ophiolites (Pober and Faupl 1988, Eynatten 1996). The continental crustal rocks comprise Mesozoic carbonate rocks, Variscan low-grade metamorphic rocks and high-pressure metamorphic rocks, and subordinate post-Variscan late Paleozoic metasediments. The high-pressure rocks are documented by detrital glaucophane and phengite, the latter yield early Carboniferous Ar/Ar cooling ages (Eynatten et al. 1996).

The sediments from the Lech-Fm. are derived from a source area located at the southeastern margin of the Austroalpine. This provenance area was composed of the northwestward propagating initial Alpine nappe pile including peridotites from the overthrusted suture zone of the Vardar-/Meliata ocean. The continental crustal source rocks comprise Mesozoic carbonate rocks and crystalline basement rocks but no high-pressure metamophic rocks. The chemistry of detrital white mica and garnet of the southeastern provenance area is clearly different from that of detrital minerals of the northwestern provenance area (Eynatten, 1996; Eynatten and Gaupp, 1999).

Description of stops

The investigated sedimentary rocks are generally sandwiched between more competent carbonate rocks. Thus, outcrop qualities are usually moderate to low within these tectonized sequences.

Stop 1: Branderfleck (Cenomanian to Santonian, thrust-sheet-top deposits of the northern Lechtal thrust sheet)

Locality: Five substops (a-e) between the top station of the "Tegelberg" cable car (1707 m NN) and the Ahornspitze (1780 m NN). This area is located 2 to 3 km E of the town of Füssen (Fig. 1A). The outrop area includes the type locality of the Branderfleck-Fm. (Gaupp 1980) which ist exposed within an NW-SE striking syncline at the northern margin of the LTS (Fig. 3C).

Stratigraphy (Gaupp & Weidich in Gaupp et al. 1982, Weidich 1984)

- Turonian to Coniacian/?Santonian shales with sandstones and olistostroms (Upper Branderfleck-Fm.)
- Cenomanian carbonate breccias and megabreccias (Lower Branderfleck-Fm.)

Main features to be observed

- Stop 1a: view of the Füssen topographic "embayment" at the alpine front with several morphologic features formed during the last glacaiation
- Stop 1b: carbonate breccias of the lower Branderfleck-Fm.
- Stop 1c: shales and turbiditic sandstones of the upper Branderfleck-Fm. within the center of the syncline
- Stop 1e: relatively complete section of the upper Branderfleck-Fm. (Fig. 4)

Suggested points of discussion

- sedimentary facies and depositional processes
- provenance of siliciclastic detritus and radiometric ages of individual detrital minerals
- evolution of the sedimentary facies and of the source area from the Aptian to the Santonian: tectonics vs. eustatic control

Stop 2a: Krähenwand (Lower Cretaceous up to Albian, Upper footwall deposits of the Allgäu thrust sheet)

Locality: 2 km NNE of Bad Hindelang and 8 km E of Sonthofen, at the southern slope of the Spieser at 1330 to 1350 m NN altitude. From Hindelang we follow the steep footpath alongside the creek "Hirschbach" to the outcrop "Krähenwand". Due to nappe tectonics this section is in an overturned position with the Ammergau-Fm. at the top and the Losenstein-Fm. at the base (Fig. 5): The latter is overthrusted by the Triassic "Hauptdolomit" of the frontal LTS/FSZ.

The walk to the outcrop is dangerous during heavy rainfall. In the case of bad weather we choose an alternative stop near the village Unterjoch.

Stratigraphy (Risch 1971, Gaupp 1980: p. 183)

- lower Albian to middle Albian grey shales and sandstones (litharenites) (Losenstein-Fm.)
- upper Aptian to lowermost Albian grey to dark grey, sometimes reddish and greenish marls and marly shales (Tannheim-Fm.)
- lower Cretaceous (up to lower Aptian) white to light grey or greenish micritic limestones (Ammergau-Fm.)

Main features to be observed

- transition from passive margin pelagic carbonates (Ammergau Fm.) to incipient active margin sedimentation: marls and shales (Tannheim-Fm.) and sandstones (basal Losenstein-Fm.).
- gravity driven massflow deposits of the Losenstein-Fm. (outcrop and cobbles within creek)

Suggested points of discussion

- facies types of coarse-grained Losenstein deposits
- sandstone petrography, heavy minerals, and mineral chemistry
- transition passive to active margin as documented by the chemistry of marls and shales (Fig. 5)
- provenance of siliciclastic detritus

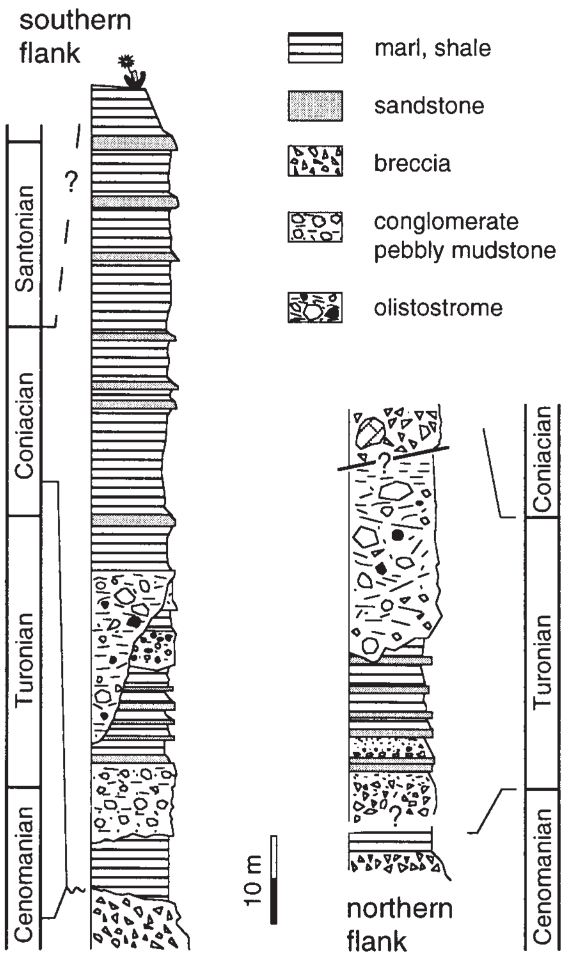
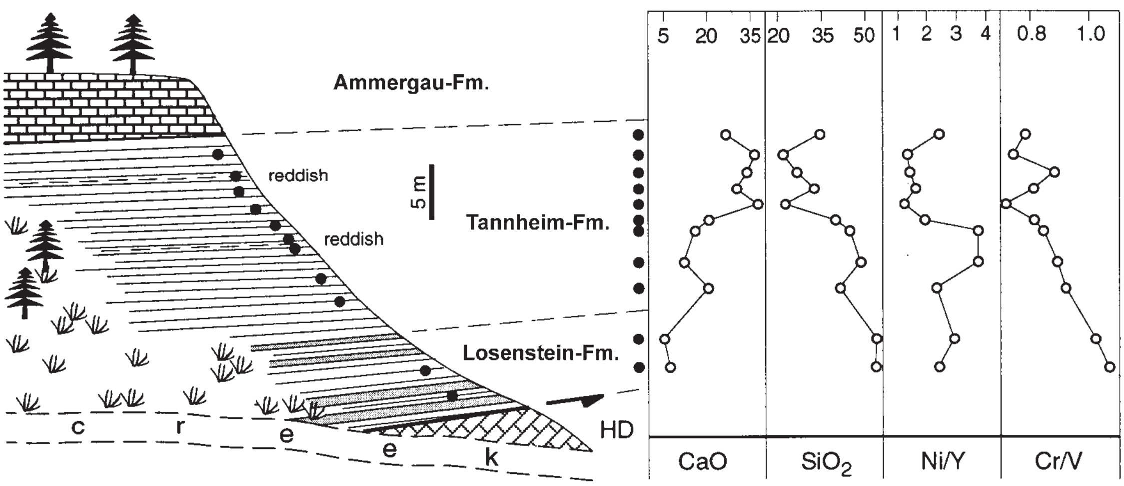


Fig. 4: Stratigraphic section of the type locality of the Branderfleck Fm. (Stop 1). Note the Turonian documentation gap at the southern flank of the syncline.

Fig. 5: Outcrop sketch of the Krähenwand section at stop 2a and chemical variation of marls and shales from the Tannheim and Losenstein Fms. Note the overturned position of the section, which was overthrust by Triassic Hauptdolomite (HD) at Albian times.



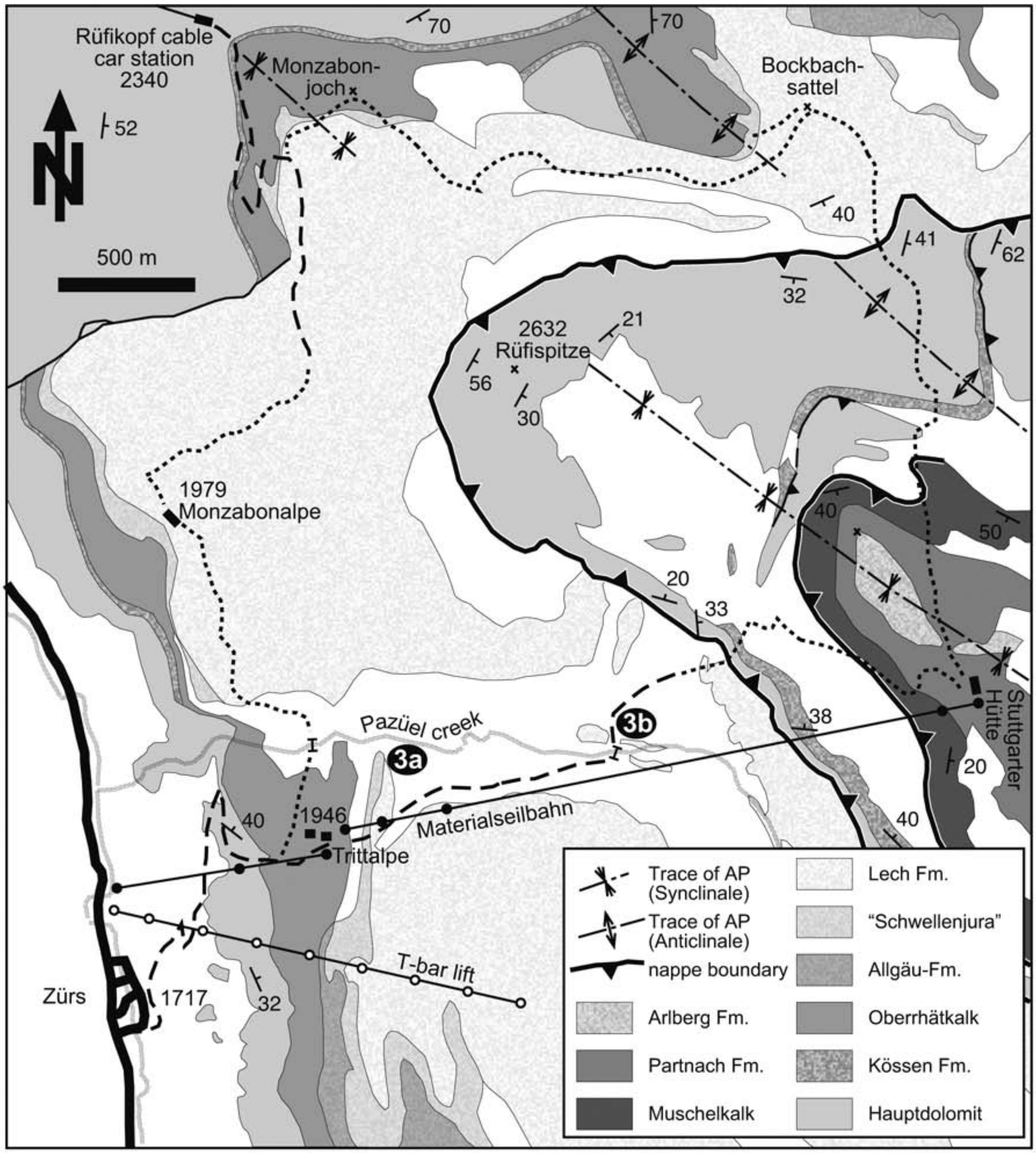


Fig. 6: Geologic sketch of the excursion area at Trittalpe. Note the nappe stacking pattern; Hauptdolomit and Kössen Fm. of the Inntal thrust sheet is thrust upon the Lech Fm. of the Lechtal nappe, and the Muschelkalk and Partnach Fm. of the Krabachjoch klippe is thrust upon the Kössen Fm. of the Inntal nappe.

Stop 2b: Weissenbach / Unterjoch (Lower Cretaceous up to Albian, Cenoman Randschuppe)

Locality: Forest road and creek 1 km W' of Unterjoch / Bad Hindelang. Tectonized slivers of syn-tectonic clastic sediments, deposited in front of the advancing LTS.

Stratigraphy: Richter (1978), Gaupp (1980), Gaupp et al. (1982)

- upper Aptian to lowermost Albian grey to dark grey, sometimes reddish and greenish hemipelagic marls and marly shales (Tannheim-Fm.)
- lower Albian to late Albian grey shales and sandstones (litharenites) (Losenstein-Fm.)
- late Albian to Cenomanian calclithitic coarse breccias and olistostromes (Triassic-Jurassic carbonate clasts, likely derived from the frontal anticline of the advancing LTS (Fig. 3)

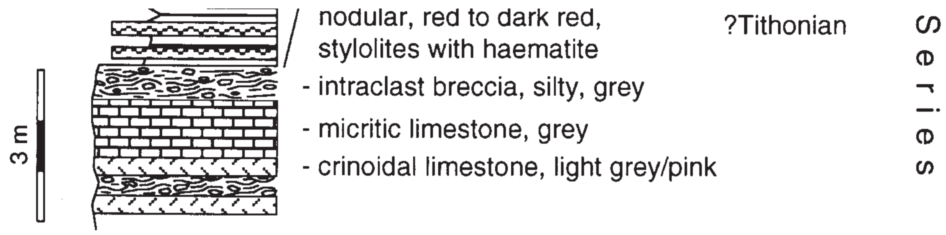


Fig. 7: Stratigraphic section of the Jurassic/lower Cretaceous Transitional Series at Stop 3a.

Suggested points of discussion

- Factors controlling the transition from turbiditic deposition with "exotic" clasts from northern provenances to intra-orogenic sources with olistostromatic sedimentation

Stop 3: Trittalm (Jurassic to Lower Cretaceous transitional series and Aptian/Albian siliciclastics, Upper footwall deposits of the southern Lechtal thrust sheet)

Locality: Dirt road E of the "Trittalm" 1,5 km NE of the small village of Zürs (Fig. 6). Upper Jurassic to Cretaceous rocks in the E-W striking Lechtal syncline within the LTS (Leiss, 1990).

Stratigraphy (Koch and Stengel-Rutkowsky, 1959, Doert and Helmcke, 1976, Wagreich pers. comm. 1994):

- upper Aptain to upper Albian/?Cenomanian grey to dark grey marly shales with sandy intercalations (Lech-Fm.)
- Jurassic/Lower Cretaceous "Transitional Series" (up to Aptian/?Albian): grey intraclast breccias, radiolarites, reddish nodular carbonates (partly with ferric iron crusts), and light grey partly yellowish carbonate breccias and crinoidal calcarenites.

Main features to be observed

- Stop 3a: condensed facies of a Jurassic/Lower Cretaceous submarine swell environment ("Transitional Series") in the southern part of the LTS (Fig. 7).
- Stop 3b: sedimentary facies of the Lech-Fm., excellent view of the nappe stacking pattern toward the west (Lechtal nappe – Inntal nappe – Krabachjoch klippe; Fig. 6) and of one of the mega-olistoliths, the Roggspitze, toward the south.

Suggested points of discussion

- facies and environment of the Jurassic/Lower Cretaceous "Transitional Series"
- depositional environment and provenance of the siliciclastic rocks of the Lech-Fm.

Part II: Coniacian to ?Paleocene sedimentation in a thrust-sheet-top basin: the Gosau Group of the Muttekopf area

Geological setting and stratigraphy

The Gosau Group is an Upper Cretaceous, synorogenic carbonatic–siliciclastic sedimentary succession, which unconformably overlies deformed Triassic to Jurassic rocks (Wagreich and Faupl, 1994; Sanders et al., 1997). Generally, deposition started in a terrestrial environment, which subsided to neritic conditions (Lower Gosau Subgroup). After a pronounced subsidence event deep marine conditions prevailed (Wagreich, 1993), and the Upper Gosau Subgroup was deposited. The relationship between the contracting orogenic wedge and the coeval major subsidence is not well understood at present, and different models have been put forward (e.g. Wagreich, 1993; Froitzheim et al., 1997). The younger, deep marine part of the sedimentary succession (Upper Gosau Subgroup; Wagreich and Faupl, 1994) was deposited during transport of the thin-skinned nappes of the Northern Calcareous Alps over tectonically deeper units (Fig. 1). In the Muttekopf area, internal deformation of the moving nappe led to the formation of fault-propagation folds in the subsurface of the Gosau sediments and hence to formation of several (progressive) angular unconformities within the sedimentary succession (Ortner, 2001; Figs. 8, 9).

Sedimentation of the Lower Gosau Subgroup in the Muttekopf area began near the Coniacian-Santonian boundary with deposition of a few meters of braided-river deposits followed by an up to 300 m thick alluvial fan succession, that is restricted to the easternmost part of the Gosau outcrops (Plattein). Upsection, conglomerates with perfectly rounded clasts representing a transgressive lag are intercalated below thick neritic deposits ("*Inoceramus*" marl unit). The silt- to sandstones of the "*Inoceramus*" marl unit contain a variety of marine fos-

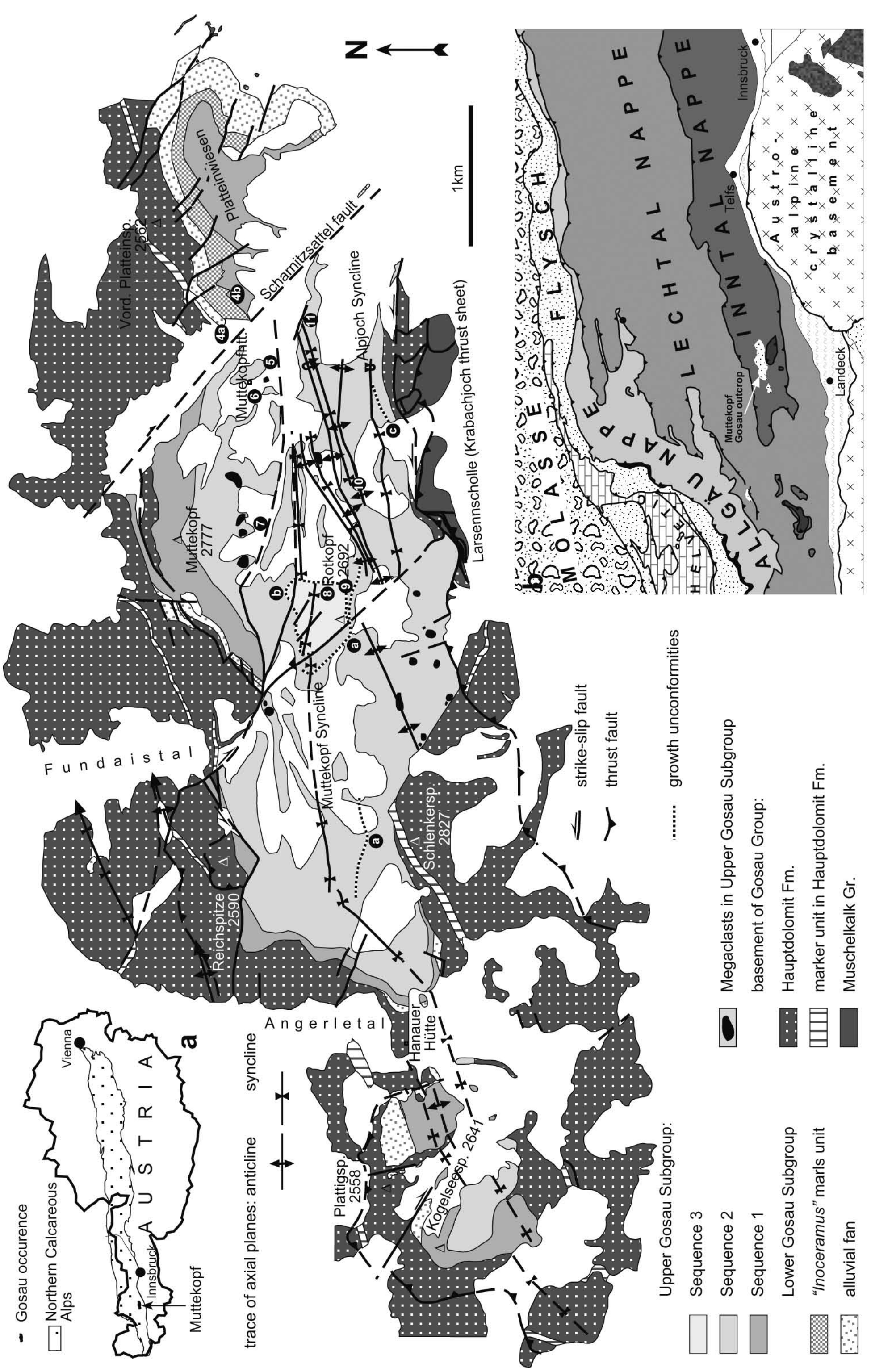


Fig. 8: Geologic sketch of the Gosau outcrop at Muttekopf and location of stops 4-11. Inset a: Location of the Muttkopf outcrop in Austria. Inset b: Tectonic position of the Gosau Group at Muttekopf. a...Schlenkerkar unconformity, b...Rotkopf unconformity, c...Alpjoch unconformity.

sils that were used to date the rocks to the Coniacian – Santonian boundary (Ampferer, 1912; Leiss, 1990).

The deep marine Upper Gosau Subgroup mass transport complex is divided into three sequences (Ortner, 1994a, 2001; Fig. 9): All three sequences are dominated by vertically-stacked, upwardfining, laterally continuous, unchannelized conglomerates and sandstones that display little to no lateral variation in facies. The boundary between Sequence 2 and 3 is the Rotkopf unconformity

(Figs. 9). The boundary between Sequence 1 and Sequence 2 is the base of the 2nd fining upward sequence, which is significantly below the most prominent unconformity in the area (Schlenkerkar unconformity, not in excursion area). The three sequences can also be distinguished by clast- and heavy mineral compositions (Ortner, 1994a, b). The age of the deposits of the Upper Gosau Subgroup is poorly constrained. The turbiditic marls occasionally contain corroded nannoplancton and rare foraminifera. According to these data, the upper part of Sequence 1 has an age of Late Santonian to Early Campanian or younger, Sequence 2 Early Campanian to Early Maastrichtian or younger and Sequence 3 Late Maastrichtian to ?Danian (Oberhauser, 1963; Dietrich and Franz, 1976; Lahodinsky, 1988; Wagreich, pers. comm. 1993–1995).

The deposits are organized in facies associations, which are related to proximal or distal sedimentation in relation to a sediment source. Each sequence has a proximal facies association at the base and a distal facies association at the top. The associations are:

- Megabreccia association, built by fluidized mud-rich conglomerates, slabs of other facies associations of the Upper Gosau Subgroup and hotel-size clasts of Triassic rocks
- Thick-bedded turbidite association, with m-thick mud-rich conglomerates, grading into sandstones that often display complete or amalgamated Bouma-sequences, which in turn grade into m-thick yellowish to light grey turbiditic marls
- Thin-bedded turbidite association, with cm-thick sandstones (Bouma Tb or Tc intervals) alternating with dark grey to black calcite-free marls, which are sometimes laminated. Thick conglomerate beds are irregularly intercalated

The occurrence of calcite-free marls in the most distal facies association and a bathyal trace fossil association (Gröger et al., 1997) led to the conclusion of sedimentation below (a local) CCD.

Post-depositional surface to subsurface sediment remobilization is an important aspect of the Gosau Group of Muttekopf, which contributed substantially to the observed sediment geometries (Ortner, 2007). Active shortening and fold growth of km-scale folds stimulated continuous surficial sediment remobilization (slumping), but also tectonic deformation of soft sediment. Changing rheologies of conglomerates, sandstones and marls during increasing lithification caused a vast array of structures related to tectonic deformation, whereas slump-related structures are restricted to the earliest stages of lithification. Intrastratal fluidization of conglomerate layers is an important process accompanying downslope creeping of sediment packages. Fluidization is commonly associated with downward and upward injection of conglomerate into neighbouring deposits.

Description of stops

Due to the high Alpine character of the excursion area, the sequence and selection of stops during the field trip might change according to weather conditions.

Stop 4: ?Coniacian to Santonian succession of the Lower Gosau Subgroup and transition to the Upper Gosau Subgroup

Locality: 50 Hm above and along the path from Muttekopfhütte to Platteinwiesen, 600 m ENE of Muttekopfhütte

Main features to be observed

- Stop 4a: Clast supported, partly matrix-free conglomerates with crude trough stratification, sieve deposits with red, sometimes laminated mud and pebbles exclusively composed of Hauptdolomit Fm. Conglomerates with perfectly rounded dolomite clasts and chert found as blocks on the way to stop 4b
- Stop 4b: Fossiliferous foliated siltstones ("*Inoceramus*" marl unit) in contact with sandstones and conglomerates of the Upper Gosau Subgroup
- View to the west of refolding of fluidized layer by N-vergent folds of stop 6

Suggested points of discussion

- facies and environment of conglomerates which are interpreted to be deposited on the upper- to mid-fan of a semiarid alluvial fan (Haas, 1991)
- Mechanism of subsidence from subaerial to deep marine conditions in a contracting thin-skinned fold-and-thrust belt

Stop 5: Succession at the transition from Sequence 1 to Sequence 2 of the Upper Gosau Subgroup

Locality: along the Malchbach, 300 m SE and S of Muttekopfhütte

Main features to be observed

- Stop 5a: Thin-bedded turbidite association, cm-thin silt- to sandstones alternating with black dolomitic marls, overlain by a structureless conglomerate bed with flame structures and minor normal faults at the

base; diffuse internal shear planes within the conglomerate
- Stop 5b: Thick-bedded turbidite association, dm- to m-thick sandstones alternate with m-thick yellowish marls overly a matrix rich coarse-grained conglomerate
- Stop 5c: Giant block of Upper Rhaetian limestone within a conglomerate bed of Sequence 2. Karstic dykes on the surface of the block

Suggested points of discussion

- Bathymetry of the Upper Gosau Subgroup
- Mechanism of deposition of coarse-grained beds (high-density turbidites versus debris flows)

Stop 6: Fluidized layers and N-vergent folds in thick bedded turbidites of Sequence 2

Locality: 150 m WSW of Muttekopfhütte

Main features to be observed

- Sediment transport directions indicated by flute casts and tool marks at the base of sandstone beds
- Isoclinally folded sandstone beds in a conglomerate matrix, plastic deformation within the sandstone beds
- Shingle-like stacking of sandstone slabs
- Semi-brittle deformation within N-vergent folds with stacking of horses in the forelimb of the fold and local plastic deformation

Suggested points of discussion

- Tectonic deformation versus gravity-induced deformation
- Surface or subsurface fluidization?
- Significance of fold axes within fluidized layer

Stop 7: Giant blocks ("Blaue Köpfe") in megabreccia layer of Sequence 2

Locality: 2300 m, at junction of paths 600 m S of Muttekopf summit

Main features to be observed

- Giant blocks of Upper Rhaetian limestone projecting out of a chaotic breccia layer of the Megabreccia association.

Suggested points of discussion

- Sediment transport of giant blocks

Stop 8: Sequence 3 succession in the core of the Muttekopf syncline

Locality: 2460 m, along the path to Pleisjoch, and (optional) on the way scrambling up to Rotkopf (2692 m)

Main features to be observed

- Conglomerates containing abundant brick-red marl intraclasts, injection of marl clasts by conglomerate dykes, systematic sandstone-filled joints in coarse sandstone
- White calcite-rich marls alternating with m-thick sandstones in the very core of the syncline
- Panoramic view of the Muttekopf syncline toward the west from the Rotkopf summit, submarine topography around Große Schlenkerspitze, anticlinal crest within Gosau deposits east of Schlenkerspitze

Suggested points of discussion

- Origin of overpressure in breccia beds
- Geometry of syntectonic sediments in the vicinity of Schlenkerspitze

Stop 9: Rotkopf unconformity at Pleisjoch and Pleiskopf

Locality: Pleisjoch (2560 m) and Pleiskopf (2580 m)

Main features to be observed

- Erosional steps at Rotkopf unconformity
- Fluidization of conglomerate and flame structures and injection of conglomerate into sandstone
- Channel-like geometry of Sequence 3 seen from Pleiskopf

Suggested points of discussion

- Is the Rotkopf unconformity a growth unconformity or an erosional unconformity?

Stop 10: Hydroplastic deformation of conglomerates

Locality: 50 m S of saddle 340 m west of Hinteres Alpjoch

Main features to be observed

- Meter-scale asymmetric linear flames of marl into conglomerate
- Conglomerate sill with clasts up to 20 cm in diameter intruded downward into sandstone

Suggested points of discussion

- Are the linear flames an expression of dewatering or are the structures actually mullions formed during bedding-parallel shortening at a rheologic interface in wet sediment?
- Why does the conglomerate intrude downward, when lithostatic pressure decreases upward?

Stop 11: Panoramic view of Hinteres Alpjoch

Locality: Vorderes Alpjoch, station at top end of chairlift (2121 m)

Main features to be observed

- Change of geometry of Alpjoch syncline in Sequence 2 from tight chevron fold in outer layers to open fold in inner layers (Fig. 9, left)
- Rotative onlap across Alpjoch unconformity
- Tectonic contact of the Larsenn klippe to Gosau sediments (Fig. 9, far left)

Suggested points of discussion

- Relevance of geometric and mechanic fold models for the geometry of syntectonic sediments and unconformities related to fold growth

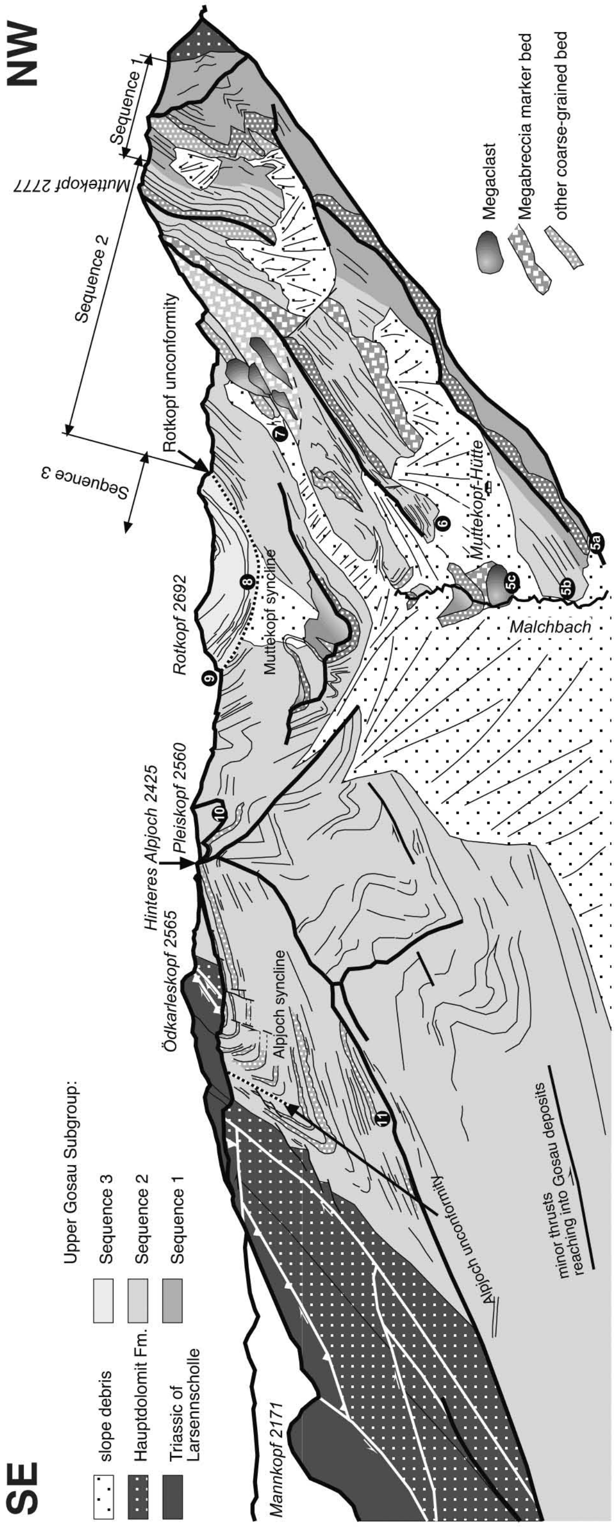


Fig. 9: Panoramic view of the excursion area at Muttekopf from the east, showing the three sequences and the tectonic structure within the Upper Gosau Subgroup. Stops 5–11 are indicated.

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