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# *Field trip to the Northern Alps between Munich and the Inn Valley*

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## ABSTRACT

**This field trip leads from Munich through the nappe stack of the Northern Alps. The folded Molasse zone, which clearly reacted to the tectonic events in the alpine collision zone. The Flysch zone covers the underfilled deep sea basin along the Cretaceous pre-collisional active margin. The Helvetic nappes carry Cretaceous to Paleogene sediments that show strong facies differentiation due to an increasingly unstable European platform. These will be visited in two isolated windows. A cross section through a good part of the Northern Calcareous Alps along the Valepp Valley will give insight into the structure of the fold-and-thrust belt and the pre- and post-Gosau phase deformation. Sedimentological response to Late Cretaceous geodynamic processes will, finally, be studied in the famous Muttekopf area and its spectacular outcrops**

## INTRODUCTION

The Eastern Alps represent a double-vergent orogen, which formed during the collision of the European plate in a lower tectonic position with the Adriatic microplate in an upper tectonic position. The Eastern Alps are widely covered by the Austroalpine nappes that include the Northern Calcareous Alps and their basement, e.g., the Greywacke- and Quartzphyllite zones and the Ötztal-Stubai-Silvretta crystalline complexes, which derive from the Adriatic microplate and camouflage deeper units. Only the Tauern window (TRANSALP field trip, part 1, Lammerer et al., this volume, Chapter 7) allows a deeper look down to the Penninic ocean units and to the cover and basement of the European plate (Schmid et al. 2004). This part 2 of the TRANSALP field trips series covers the northern front of the alpine orogenic wedge in the area between Munich and the Inn Valley. The trip follows in part the TRANSALP seismic line (Lüschen et al., 2004, 2006). It includes from north to south, or from bottom to top:

(1) The wedge-shaped peripheral foreland Molasse sediments, which are folded close to the Alpine front (Bachmann and Müller, 1992; Lemcke, 1988; Roeder, 2009; Schmidt-Thomé, 1955; Schwerd et al., 2011).
(2) The small zone of Cretaceous to Eocene cover rocks of the Helvetic zone, a nappe complex, which is detached from the stable European plate and thrust over the Molasse basin (Schwerd, 1996).
(3) The Rhenodanubian Flysch nappes, which comprise Early Cretaceous to Upper Eocene turbiditic sequences

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that developed along the front of the approaching Austroalpine nappes within the Alpine Tethys basin (Hesse, 1974; 1982; this volume, Chapter 5).

(4) The Austroalpine nappes of the Northern Calcareous Alps, which are part of the Adriatic Plate (Schmid et al., 2004). They are detached from their basement south of the Inn valley. The stratigraphic succession starts with Late Permian clays and evaporites and reaches the Late Cretaceous and Paleogene cover successions.

During the Eo-Alpine orogeny in Mid Cretaceous to Early Paleogene times, its nappes were deformed and metamorphosed in their southern parts (Gawlick and Königshof, 1993; Handy and Oberhänsli, 2004). During this phase, the tectonic transport was mainly directed west in the Central Alps and northwest in the Northern Calcareous Alps (Ratschbacher, et al. 1989; Eisbacher and Brandner, 1996). Three main nappes compose the Northern Calcareous Alps in the vicinity of the TRANSALP line. The Allgäu nappe is only visible in a small and poorly exposed strip on the northern rim. It is heavily dissected and thicknesses of the units are generally small. The Lechtal nappe covers most of the area and the entire Valepp section, which will be visited in the course of this field trip. The Inntal nappe crops out south of the Inn Valley and to the west of the Achensee (Auer and Eisbacher, 2003; Tollmann, 1973, 1976). During a Miocene phase of lateral escape, the sinistral Inn Valley Fault formed (Frisch et al., 1998; Ratschbacher et al., 1989, Neubauer et al., 2000).

(5) The Late Cretaceous–Paleocene Gosau basins and the Inner Alpine Tertiary (Wagreich and Faupl, 1994; Ortner, 2001).

This field trip has a duration of six days, beginning and ending in Munich. The detailed description of the second day is provided by Hesse (this volume, Chapter 5). The trip consists of both roadside stops, and of long hikes between mountain huts.

## DAY 1. THE MOLASSE BASIN SOUTH OF MUNICH

(Total driving distance: 130 km, total walking distance: 5 km.)

### Introduction to the Molasse Basin

The Molasse basin spans ~1000 km from France through Switzerland and Germany to Austria. At Lake Geneva, it measures ~20 km in width and it widens in Bavaria, up to ~130 km. Further east, it passes into the Vienna Basin and the foredeep of the Carpathians. Beneath the Molasse sediments, Mesozoic strata or crystalline basement occur (Fig. 1). The Molasse Basin was formed when the European continental lithosphere was elastically bent under the weight of the Helvetic and Austroalpine nappes, and by its own sediments. This effect extends until the area of Nürnberg (Doppler et al., 2002). Thus, the 2°–4° southward dip of the Swabian and Franconian Jura is also attributed to the bending of the European plate under the load of the Alpine nappes and the weight of Molasse sediments Fig. 2). The Molasse sediments alone have been shortened by more than 24 km in the sector of the TRANSALP line (Fig. 3). The change from the underfilled flysch stage to a filled or overfilled Molasse stage in mid Oligocene times seems to be connected with the breakoff of the subducting European slab under the Alps, causing accelerated exhumation, rapid isostatic surface uplift and erosion in the Alps (von Blanckenburg and Davies, 1995; Sinclair, 1997a, 1997b; Kissling et al., 2007; Lippitsch et al., 2003).

About 20 million years ago, during the Miocene, a large part of the Molasse area was again inundated by a shallow sea (Upper Marine Molasse). Its northern limit is marked by a cliff line and by boreholes carved by lithophagous mollusks into the Jurassic limestones. This phase of accelerated subsidence in the Eggenburgian, at ca. 20 Ma, coincides with the onset of rapid exhumation of the Tauern window, which was thrust northward along a deep reaching reverse fault, the Sub-Tauern ramp. This additional load might have caused an episode of enhanced subsidence in the foreland of the Eastern Alps and a marine transgression.

Since late Eocene times, ~56,000 km$^3$ of sediments have been deposited, their provenance being mainly from the rising Alps in the foreland basin. Smaller amounts were also added from northern areas, e.g., from the Bohemian Massif (Kuhlemann, 2000; Kuhlemann et al., 2001a, 2001b). Close to the Alpine front, the Molasse reaches 4000–5000 m in thickness, and locally even higher (Müller 1970). Main deposition phases started in early Oligocene with the deep marine ("Flyschmolasse") of the Deutenhausen beds or the Fish-shales in the Swiss Molasse, and it lasted until late Miocene times (Fuchs, 1976; Lemcke, 1983, 1988).

Porous rocks contain small hydrocarbon deposits all over the Molasse basin (Roeder and Bachmann, 1997). In Großaitingen, near Augsburg, the largest oil field was opened in Bavaria in 1979. Some 40,000 tons of crude oil of excellent quality were produced here annually; over a million tons have so far been

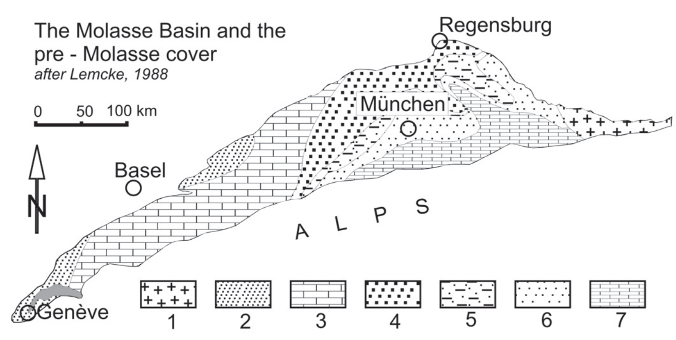


Figure 1. The Mesozoic rocks under the Molasse sediments. 1—Hercynian metamorphics and granites; 2—Early Triassic Buntsandstein; 3—Middle Triassic Muschelkalk; 4—Late Triassic Keuper sand and clay; 5—Liassic shale; 6—Dogger sand and marl; 7—Malm limestone. After Lemcke (1988).

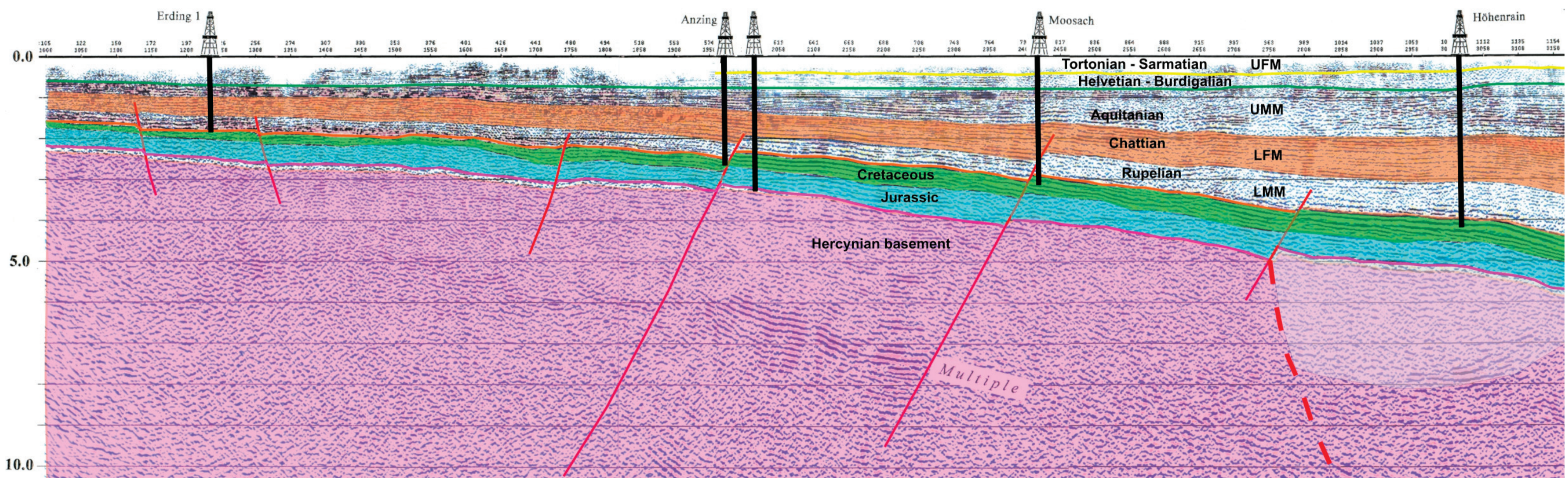


Figure 2. Vibrosiesmic reflectors (TRANSALP) and drillholes in the foreland Molasse, depth-migrated. Legend: LMM—Lower Marine Molasse; LFM—Lower Freshwater Molasse; UMM—Upper Marine Molasse; UFM—Upper Freshwater Molasse. Deep wells from left to right: Erding 1, Anzing 1, Anzing 2, Moosach 1, Höhenrain (after Lüschen et al., 2006). Length of section: 86 km, vertical scale in kilometers.

recovered from this small deposit. More important for many years have been the coal deposits. The brackish and freshwater sediments of the Cyrenen strata contain up to 26 seams of pitch-coal, which was mined at Peiting, Peißenberg, and several other places until 1971 (Gillitzer, 1914, 1955; Geissler, 1975; Lemcke, 1988). Recently, prospecting activities have successfully concentrated on thermal water for electric power plants and heating. In the area close to the Alps, the pore fluid pressure is still enhanced due to tectonic processes, which caused problems for deep drillings (Lemcke, 1988; Müller and Nieberding, 1996).

Two large synclines developed over triangle structures—the Murnau syncline and the Rottenbuch syncline. The anticlines are missing (see Fig. 7), only in the section of the Ammer River at the Echelsbacher Bridge an anticline is developed (see Fig. 8).

Due to the prevailing depositional environment—marine or terrestrial—the formations of the Molasse zone are divided into four groups:

- Lower Marine Molasse (Untere Meeresmolasse; UMM), Rupelian, from ca. 34 to 28 Ma.
- Lower Freshwater Molasse (Untere Süßwassermolasse; USM), Chattian and Aquitanian, ca. 28 to 22 Ma.
- Upper Marine Molasse (Obere Meeresmolasse; OMM), Burdigalian and Langhian, ca. 22 to 16 Ma.
- Upper Freshwater Molasse (Obere Süßwassermolasse; OSM), Serravallian, Tortonian and Pontian, ca. 16 to 5 Ma.

## Itinerary

From Munich, Luisenstrasse 37 (Institute of Geology), we take the highway 952 to Starnberg, and from there the interstate highway B2 to Pähl (46 km). (Fig. 4).

### *Stop 1-1. Parking lot at Hirschbergalm East of Pähl; Pähl Gorge*

(47°54′36″N; 11°11′12″E; coordinates refer to WGS 84 datum)

From the parking lot we ascend to the viewpoint of a small circular hill (687 m) on top of a ground moraine. This is one of several glacier mill kames in the area, which are formed by

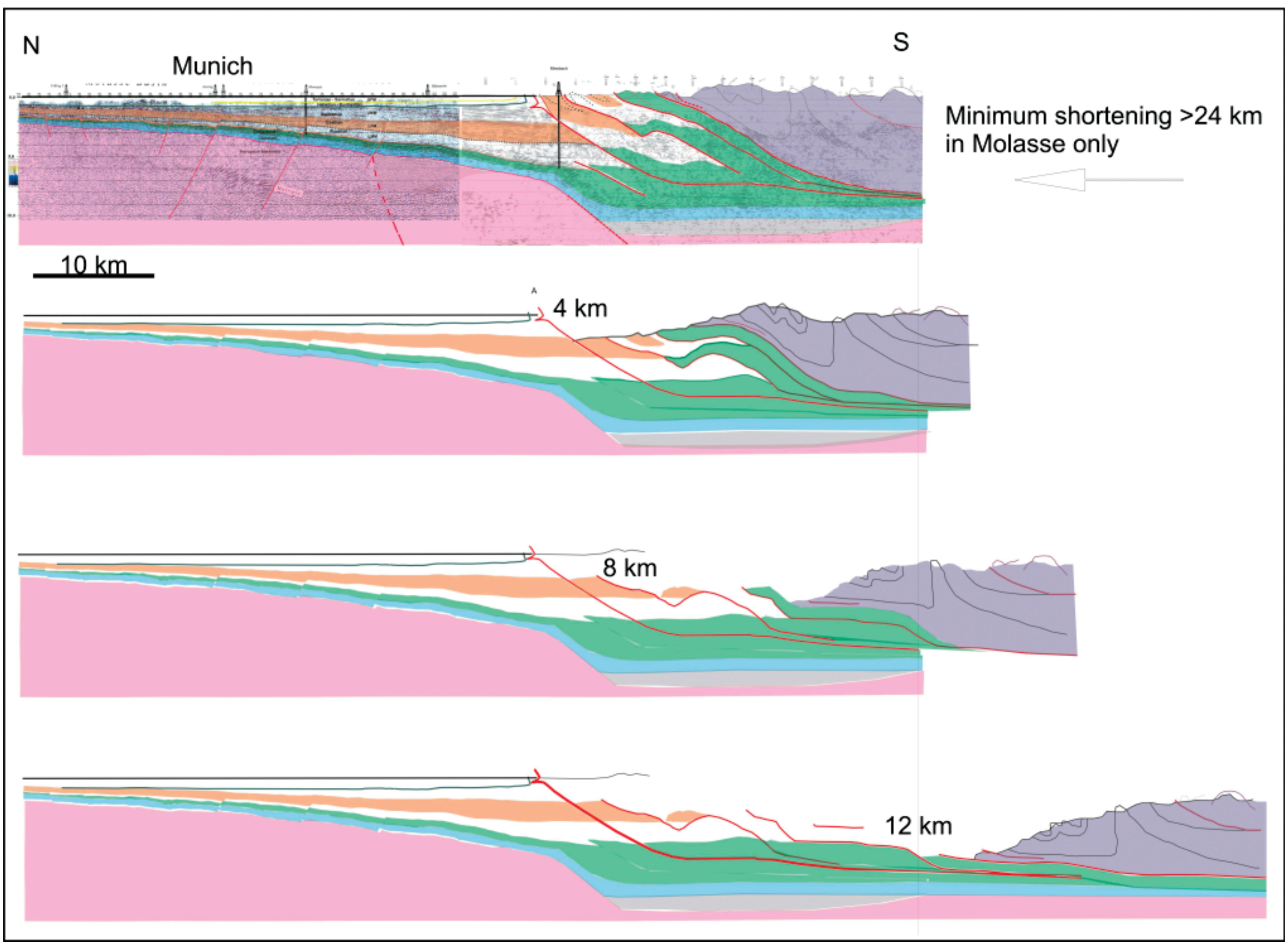


Figure 3. Restoration of the subalpine Molasse (by using 2DMove software)

sediments fallen into glacier mills of the last glacial period. The glaciers retreated from around 20,000–14,000 years ago (Würm glaciation; Jerz, 1993). To the west, the flat silt plain of the Ammersee extends far to the south, indicating the much larger expansion of the lake in early post-glacial times. Behind, the western lateral moraine forms an elongated ridge, incised by late glacial dewatering channels. The small village of Raisting is built on an alluvial fan at the mouth of a glacial meltwater creek, which was running along the lateral moraine of a recession stage. To the southwest, the Hohenpeißenberg, our next stop, can be seen in front of the Northern Calcareous Alps.

From the top of the hill, we head northward for 300 m, cross the main road (use caution because of fast cars!) and climb 10 m down to the Pähl creek. At the cut bank, a whitish fine-grained till from the Würm ground moraine is exposed. It contains unsorted scratched gneiss or amphibolite cobbles from the Central Alps. This marks the transfluent glacier stream, which crossed the Northern Calcareous Alps at the Fernpass and at Seefeld and was flowing along the Loisach valley.

We walk for 200 m along the course of the Pähl Golf Club and descend along a steep trail (caution: may be slippery after rainfalls!) 40 m down to the creek. The Pähl creek comes down in a scenic waterfall over a conglomerates layer from an outwash plain of the Mindel glacial period (380,000–400,000 yr. B.P.), . Within these cross-bedded conglomerates, pebbles from the Central Alps are completely missing due to a different stream pattern of the Mindel glaciers in comparison to the later Würm glaciation (100,000–15,000 yr. B.P.; Jerz, 1993).

We follow the creek downstream for another 300 m and encounter, on the southern cut bank, yellowish marls and fine sandstone with mica of the Upper Freshwater Molasse (Miocene, 15–5 Ma). These are deposits from a lazy river running from the area of Salzburg westward and parallel to the Alpine chain into the Rhone River—a pattern completely different from the subsequent, recent river system (Lemcke, 1984, 1988; Herbst, 1985) (Fig. 5).

***Stop 1-2. Hohenpeißenberg 988 m***
(47°48′05″N; 11°00′57″E)

We continue by car from Pähl via Weilheim, along road 472 to Hohenpeißenberg, for 26 km.

The Hohenpeißenberg is situated at the contact between the undeformed Foreland Molasse and the folded Subalpine Molasse (Figs. 6 and 7). The strata here are bent in a large monocline to a vertical position and are even overturned at the tip of the "unfolded" Molasse (Fig. 8). From the viewpoint at the top, we have a great view over the Northern Calcareous Alps and the ridges of the Molasse folds to the south and of the flat Molasse foreland and the Ammersee glacier basin to the north.

Like in the Pähl Gorge, the summit area consists of Upper Freshwater Molasse deposits, but here they are in a different facies. We find coarse unsorted conglomerates with pressure

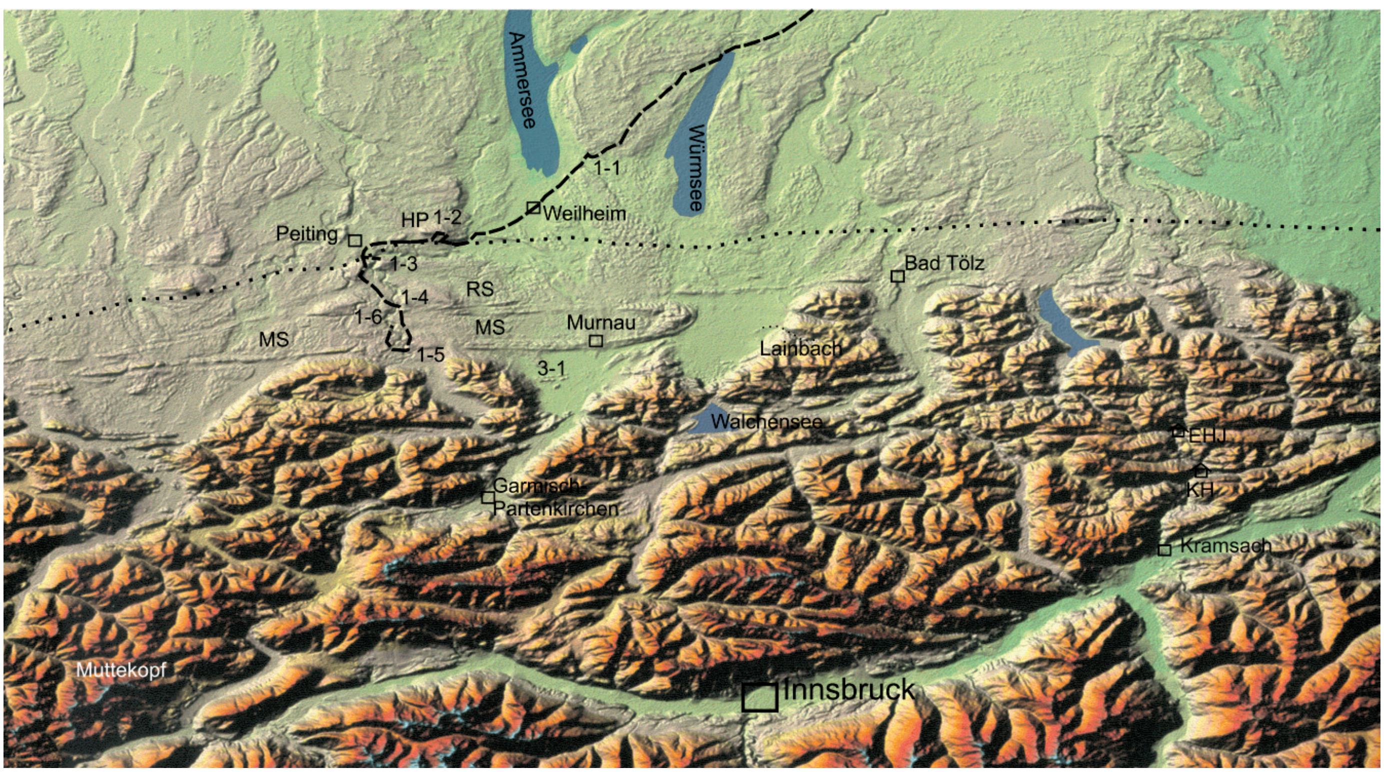


Figure 4. Digital elevation model (Shuttle Radar Topography Mission [SRTM]; courtesy: Deutsche Gesellschaft für Luft- und Raumfahrt, Oberpfaffenhofen).

solution dents in some pebbles. Like other promontory hills—for example, the Rigi in Switzerland, the Pfänder in Austria, the Auerberg near Kempten, and the Irschenberg south of Munich—the Hohenpeißenberg represents an alluvial fan at the mouth of Neogene rivers leaving the Alps.

Between 500,000 and 1,000,000 tons of a pitch-coal was mined annually at the Hohenpeißenberg and at nearby Peiting from 1930 to 1971, but smaller activities reach back to the sixteenth century. The 26 mined coal seams reach only between 0.3 and 1.2 m in thickness. The coal seams were relatively highly contaminated by marly or sandy host rock and contained only 50–90% of usable coal (Geissler, 1975; Gillitzer, 1955).

We descend a small trail down to the village of Hohenpeißenberg at the guesthouse Hanslbauer and to an abandoned small quarry, where overturned glauconitic sandstones of the Upper Marine Molasse are exposed. The 70° south-dipping fine-grained strata represent the base of the "unfolded" Molasse at the overturned limb of a fold-propagation-fold, or a triangle zone beneath, or a combination of both (Fig. 8).

***Stop 1-3. Schnalshöhlen***

(47°46′14″N; 10°57′07″E)

From Hohenpeißenberg, we continue along road 472 by car to Peiting, where we turn south and take road 23, a section of the "romantic road" through Bavaria ("Romantische Strasse"), for one kilometer to Ramsau (total distance 8.5 km). After passing the few houses of Ramsau we turn left and enter a small gravel road, pass an open gravel pit and park at the forest edge. We follow the path down to the Ammer river (90 m elevation difference).

From post Holocene gravel, a spring of calcite-oversaturated water flows out on the slope and along its way, travertine precipitates and builds small levees and sinter terraces. We cross the Ammer River on a wooden bridge and climb up 60 m on the eastern side of the steep slope, where we reach the Schnals caves.

Sandstone, fine conglomerate, and marl of the Lower Freshwater Molasse occur in an overhanging cliff. Horizons of impure coal seams extend for several meters. The sandstones were mined in former times for glass production and are therefore called Glassande (glass sands). We find still traces of the mining activities in the caves.

The high quartz content and the heavy mineral spectrum of rutile, zircon, tourmaline, and andalusite are typical for a provenance from the Bohemian Massif (Füchtbauer, 1964, 1967). This is confirmed by cross-bedding indicating transport from north to south. The glass sands represent sediments from rivers flowing from north to south along the inclined Molasse surface. They formed a delta into the small relic sea close to the alpine front. Terrestrial plant fossils (*Daphnogene*, a laurel genus plant) and brackish water fossils (e.g., *cyrena*, a brackish-water mussel) indicate a marginal marine environment.

***Stop 1-4. Echelsbach Bridge***

(9 km from Ramsau; 47°42′38″N; 10°58′34″E)

The Echelsbach bridge was built in 1929 across the Ammer gorge in Melan-Spangenberg construction. It measures 183 m in length, and it is 76 m high. At that time, it was the highest steel-arch bridge in the world. Joseph Melan, a Bohemian engineering professor in Vienna, had first described a reinforced concrete construction, in which he replaced the expensive and particularly complex support structure over deep ravines with a steel skeleton-arm, which was then covered with concrete. According to this proposal, two steel arches were built from both sides freely into the air, which met accurately in the middle. Munich Professor Heinrich Spangenberg extended the application of this design. He placed gravel ballast to preload the steel arch structure and replaced it later step by step with an equally heavy concrete coating. This prevented uneven deformation of the structure during concreting.

On the opposite cliff of the gorge, the 40° north-dipping basal strata of the Upper Freshwater Molasse, the Bausteinschichten (building rock strata) crop out. They are exposed in a small old quarry at the eastern slope 50 m south of the bridge. Cross-bedded gray to yellowish sandstones and fine conglomerates contain plant fossils.

***Stop 1-5. Meyersäge***

(47°39′01″N; 10°59′58″E; Echelsbacher bridge–Saulgrub–Altenau–Meyersäge; 11 km from Stop 4)

We follow the Ammer River for 600 m northward, where we encounter the early Oligocene Deutenhausen beds, the oldest

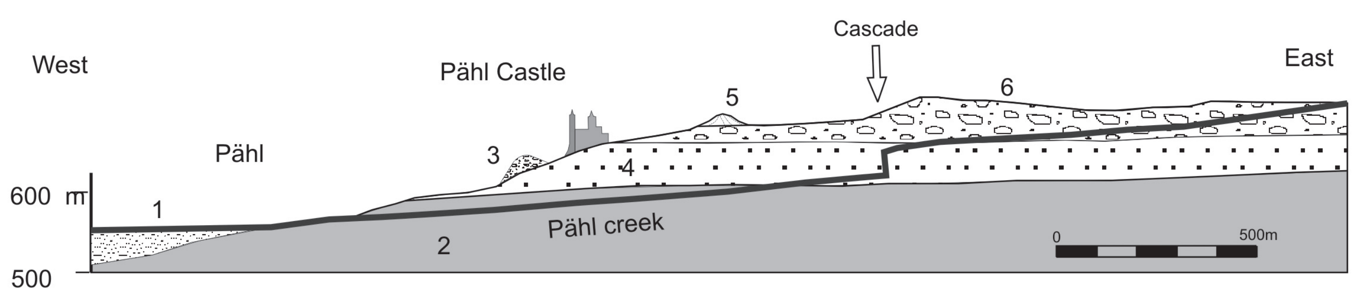


Figure 5. Cross section along the Pähl Gorge: 1—lake sediments of the silted Ammersee; 2—Upper Freshwater Molasse fine sands and sandy marls; 3—regression moraine of the Pähl stage; 4—Mindel ice stadial conglomerates; 5—glacier mill deposit; 6—ground moraine of the latest glaciation (Würm glaciation).

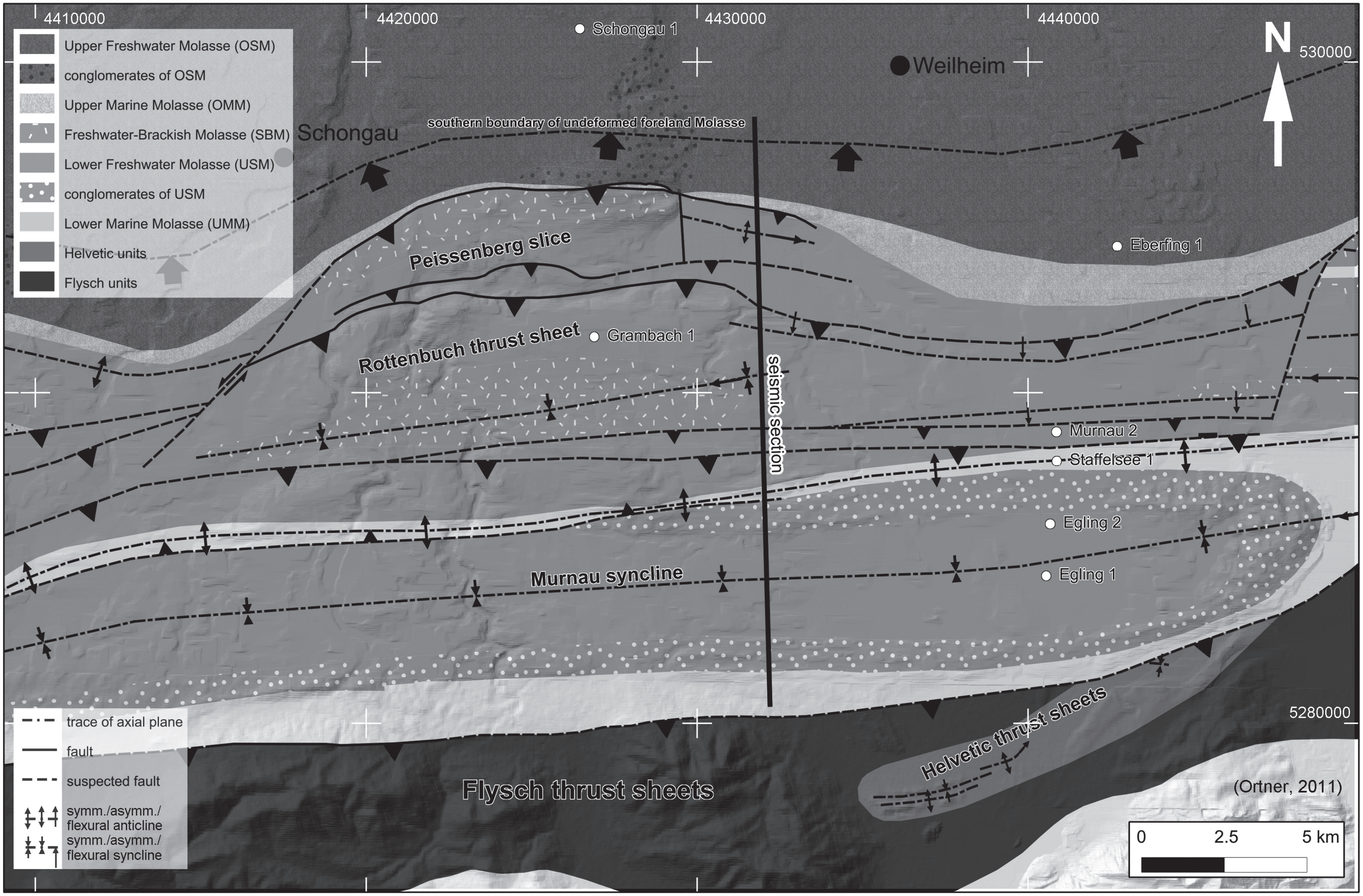


Figure 6. Tectonic map of the Peissenberg segment of the Subalpine Molasse (compiled from Gillitzer, 1914, 1955; Geissler, 1975; Scholz, 2003; and the geologic maps 1:25.000 of the Bavarian Geological Survey). The trace of the seismic section (see Fig. 7) is schematic. White circles: exploration wells. Coordinates: Deutsches Hauptdreiecksnetz, GK-Zone 4. Figure drafted by H. Ortner, 2011.

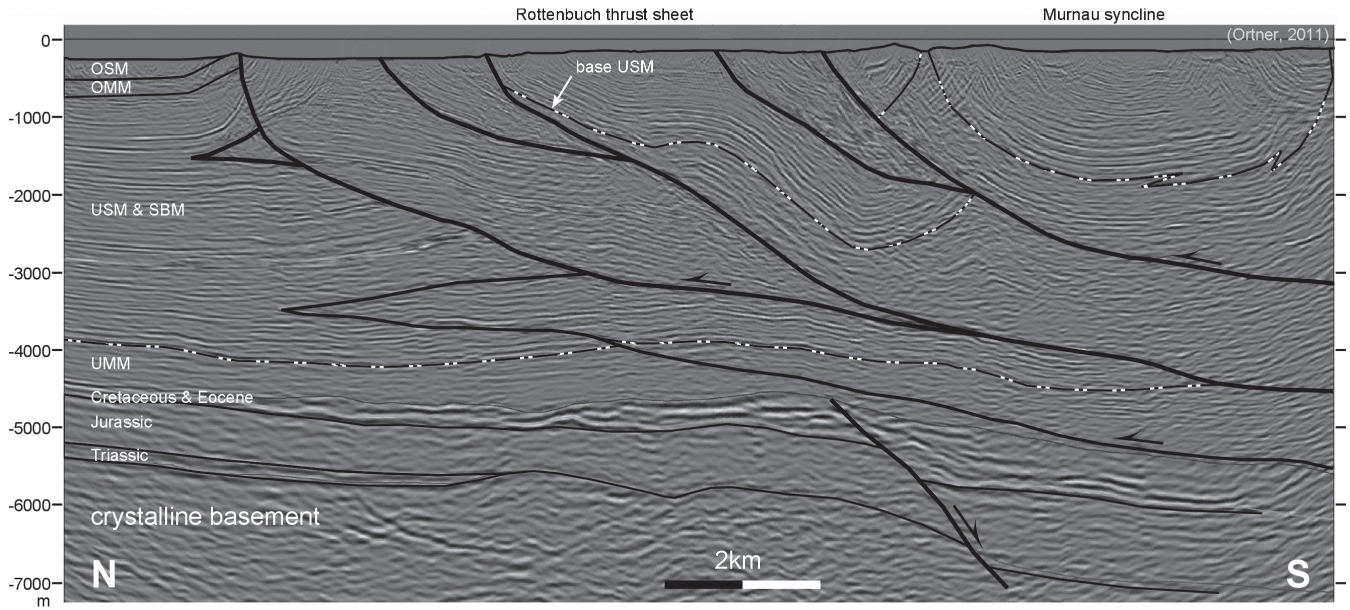


Figure 7. Seismic section across the Subalpine Molasse (adapted from Schuller et al., 2009). OSM—Upper Freshwater Molasse (Obere Süßwassermolasse); OMM—Upper Marine Molasse (Obere Meeresmolasse); USM—Lower Freshwater Molasse (Untere Süßwassermolasse); SBM Freshwater-Brackish-Molasse (Süß-Brackwassermolasse, Cyrenenschichten). Figure drafted by H. Ortner, 2011.

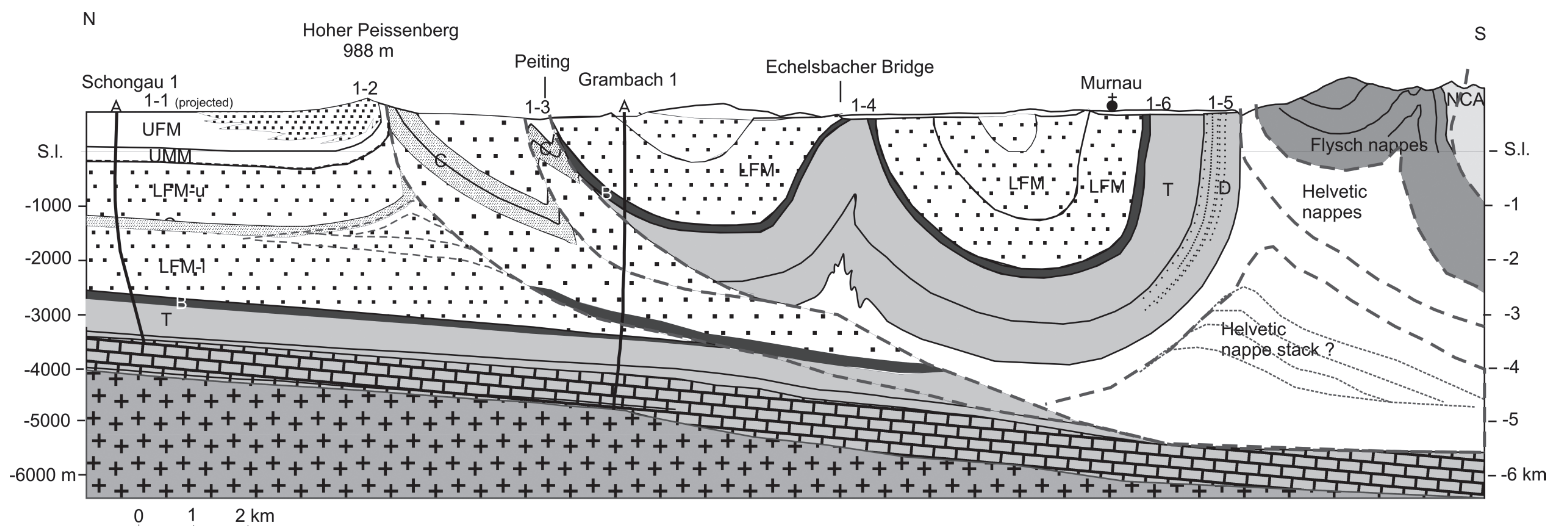


Figure 8. Cross section from Schongau to the frontal thrust of the Northern Calcareous Alps (right end). Legend: Helv.—Helvetic nappes, D—Deutenhausener beds; T—Tonmergel beds of the Lower Marine Molasse; B—Baustein beds; LFMl—Lower Freshwater Molasse, lower part; C—Cyrenen transitional delta sediments, contains coal seams; LFMu—Lower Freshwater Molasse, upper part; UMM—Upper Marine Molasse; UFM—Upper Freshwater Molasse. Modified after Grottenthaler and Müller (2011) and Schmidt-Thomé (1955).

strata of the Molasse zone here and the southern end of the Molasse. Within the vertical or overturned claystones and marls, up to several meters thick banks of sandy turbidites are intercalated. Gravel, sand, and clay were deposited in different depositional centers, such as deltas, coastal and shelf areas, but also as deeper marine formations of the continental slope, from submarine canyons to deep basins, like the fish shales of Switzerland.

We recognize complete and incomplete Bouma cycles and a great variety of sole marks (e.g., groove casts, flute casts, load casts), convolute bedding, and slump structures. Some bedding planes are coated with plant remnants or even thin lenses of asphalt from oil migration. The Deutenhausen beds are considered as deep water sediments by Lemcke (1988). In contrast, Maurer et al. (2002) claim a "less deep" environment.

***Stop 1-6. Scheibum***
(47°39′55″N; 10°59′14″E)

We wade through the shallow water and cross the tributary Halbammer river over a water–channel bridge, which feeds the electrical power plant of the German Railway Company (DB). We follow the channel for one kilometer and encounter the Scheibum at the narrowing of the valley. The clays and marls of the marine Molasse show channels filled with fine-grained sandstones and occasional distal turbiditic beds (Fig. 9).

When crossing the Lower Marine Molasse boundary, the sandy material increases in the transition zone, and layers of fine conglomerates and several thin coal seams up to 30 cm in thickness indicate the growing terrestrial influence. Along a network of fissures within the conglomerate, asphalt occurs as a sign of oil migration.

A thick vertical layer of red coarse conglomerate with broken and sheared pebbles shows clear inclined bedding, indicating transport from south (after back rotation). This is the base of the Weißach beds, which reach a thickness of 1400 m.

From here we walk back to the cars and drive 38 km to the Weilheim Naturfreundehaus (overnight lodging; 47°49′43″N; 11°07′32E″).

## DAY 2. FLYSCH ZONE

For a description, see Hesse (this volume, Chapter 5).

## DAY 3. HELVETIC NAPPES OF UPPER BAVARIA

Helvetic units form large mountain ranges in the Swiss Alps and in the Allgäu Alps of southwestern Bavaria, but they occur only in isolated small windows along a narrow strip south of the Molasse zone in the sector of the TRANSALP line.

The Helvetic units formed in a shallow shelf sea at the southern margin of the European continent, comprising sediments of Early Cretaceous (Barrêmian) to Paleogene (Lower Oligocene, Latdorfian) age. In the Paleogene, the Helvetic sedimentary environment was geographically separated in two basins by the Intrahelvetic High, present regionally as submarine high or island chain, respectively. Thus, a northern (Adelholzen facies; present in the locality Rohrdorf) and a southern (Kressenberg facies; locality Hinterhör) facies are distinguished by lithological and sedimentological characteristics in the foreland of the Alps in Upper Bavaria. Both Helvetic units record mirror tectonic processes taking place in the course of the alpine orogenesis.

***Stop 3-1: Abandoned Quarry of the Hartsteinwerk Werdenfels, South of Murnau***
(47°37′48″N; 11°09′00″E; from Weilheim to Murnau and Grafenaschau—29 km drive from Weilheim—then 1 km walking; Fig. 10)

The large quarry (1.1 km diameter) was abandoned in 2000 due to environmental problems in the protected high moor area. Its strata dip steeply to the south and were deeply excavated, and the bottom of the quarry is now filled with groundwater. Visible at the northern wall of the quarry are the marly brownish basinal sediments of the Drusberg beds and the platform limestone of the Schrattenkalk member, both Early Cretaceous in age (Barrêmian–Aptian). The overlying Garschella formation

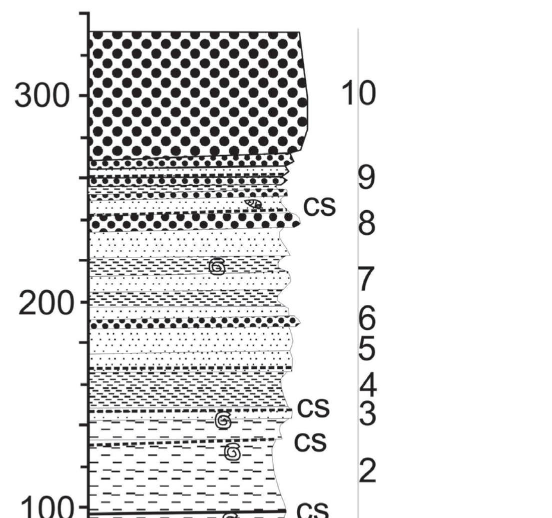


Figure 9. Columnar section of the transition zone of the Lower Marine Molasse to the Lower Freshwater Molasse at the Scheibum. 1—Rupelian marine clays and marls (Tonmergelschichten); 2–8—Bausteinschichten, marine; 2—Late Rupelian marine clays and marls; 3—marls with thin coal seams; 4—marls and fine-grained sandstone; 5—sandstone and some marl; 7—alternating marl and sandstone; 8—gray conglomerate, topped by the Echelsbach-Scheibum coal seam of 25–35 cm; 9—alternating conglomerates and marls containing small coal seams; 10—reddish conglomerate of the Lower Freshwater Molasse; foreset beds indicate sediment transport to the north.

(Aptian–Cenomanian) contained up to 60 m of a weathering-resistant glauconitic quartzite, that was mainly quarried. It served as a base for railroad tracks. The glauconitic quartzite is a condensed sandstone with quartz matrix and rich in fossils (belmnites, cephalopods, gastropods; Schwerd, 1996). Within this formation a piece of amber was found by a worker, and it is now preserved in the Museum of Murnau (Schlossmuseum). The formation is relatively rich in phosphorite along several horizons, which may indicate rising deepwater. Along the southern rim of the quarry, the Seewer limestone crops out. The deepwater limestone contains also centimeter-sized phosphorite nodules.

***Stop 3-2. Quarry Hinterhör ("Mühlsteinbruch")***
(47°46′40″N; 12°09′18″E)

From Stop 3-1 we drive to Altenbeuern, District of Rosenheim, Upper Bavaria (105 km). The abandoned quarry east of the village is hidden in the woods, and it belongs to one of Bavaria's most beautiful geotopes.

In the abandoned Quarry Hinterhör the equivalents of the "Roterz," the "Schwarzerz," and the "Nebengestein" (local name: "Mühlsandstein") of the early Eocene southern Helvetic Kressenberg facies (Cuisian–Lutetian) are present. The latter is a gray-colored, middle- to coarse-grained calcareous quartz-sandstone of fluvial origin, which was used to manufacture millstones from the year 1489 until 1860. Impressive traces of this ancient industry are still preserved.

***Stop 3-3. Quarry of the Südbayerische Portland-Zementwerk Gebrüder Wiesböck and Co. Gmbh, Southeast of Rohrdorf, District of Rosenheim, Upper Bavaria***
(7°47′20″N; 12°10′55″E; 4 km from Stop 3-2)

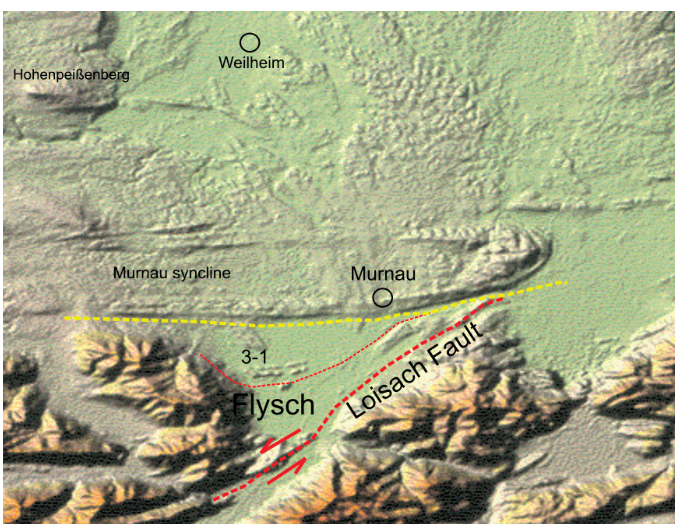


Figure 10. Position of the Helvetic Kögel in the Murnau Moor area. The Murnau syncline plunges to the west here and marks the southern margin of the Molasse zone north of the yellow line. Stop 3-1 is situated in a small Helvetic window marked by the two small parallel ridges in the moor.

Three lithostratigraphic formations of the Helvetic group are present in the concrete quarry of Rohrdorf (Fig. 11): the northern Helvetic Adelholzen Formation and the Stockletten Formation, with intercalated slumps and turbiditic beds of the "Lithothamnium Limestone" (Buchholz, 1989).

Based on differences in lithology, sedimentology and fossil contents (in particular large foraminifera of the genera *Nummulites*, *Assilina*, and *Discocyclina*) the Adelholzen Formation (lower Lutetian–lower Bartonian) is further divided into seven subunits (Fig. 12), from the bottom to the top these are: Nummulitenköpfl, Ramberg, Höllgraben, Schneckengraben, Fadengraben, Rohrdorf, and Spirka Members (Heyng, 2003). The lithological succession, with marly sands at its bottom and limestones and pelagic marls at the top, reflects a general trend of subsidence of the northern Helvetic sedimentary basin in the period of sedimentation of the Adelholzen Formation. This trend started in the lower Lutetian and it is continuing with sedimentation of the overlying Stockletten Formation (Hagn, 1981). Sharp lithological boundaries between the different members indicate a gradual deepening of the Helvetic sedimentary environment, probably reflecting a more step-by-step flow of tectonic processes in the course of the alpine orogenesis. The overlying Stockletten Formation of Priabonian age is dominated by pelagic sedimentation, and thus it mainly comprises marls and marly limestones rich in pelagic foraminifera (*Globigerina*). Several intensely bioturbated beds of blue-gray sandy marls with high contents of fine-grained glauconite and quartz are visible predominantly in the lower parts. In the upper parts (late Priabonian) of the Stockletten Formation several beds with varying thickness of the Lithothamnium Limestone are present (Figs. 13A, 13B), which reveal different facies types (slump facies, breccia facies, coarse- and fine-grained turbiditic facies; Buchholz, 1989) according to genesis. These beds were formed by event-sedimentation (slumps, turbidity currents), probably triggered by increasing tectonic disturbances in the course of the alpine orogenesis in the late Priabonian (Figs. 13C, 13D). The major part of highly diverse components, such as algal detritus, echinoderms, mollusks, solitary corals, and clasts of various lagoonal sediments, originate from an algal reef-complex with an associated lagoon to the north, situated at the northern margin of the Helvetic basin.

From Rohrdorf we drive 78 km to the Kaiserhaus, Valepp Valley, for overnight lodging. The Kaiserhaus got its name because the Austro-Hungaric Emperor Franz Joseph and his famous wife Elisabeth ("Sissi") stayed there many times, and visitors can still sleep in their beds.

## DAY 4. SECTION THROUGH THE NORTHERN CALCAREOUS ALPS

***Hint:*** The geological maps 1:50.000 of this area—sheet 89 (Angath) and sheet 120 (Wörgl)—can be downloaded for free from the Geologische Bundesanstalt Wien: http://www.geologie.ac.at/.

The strata of the Northern Calcareous Alps were deposited, together with those of the Southern Alps, on the southeastern

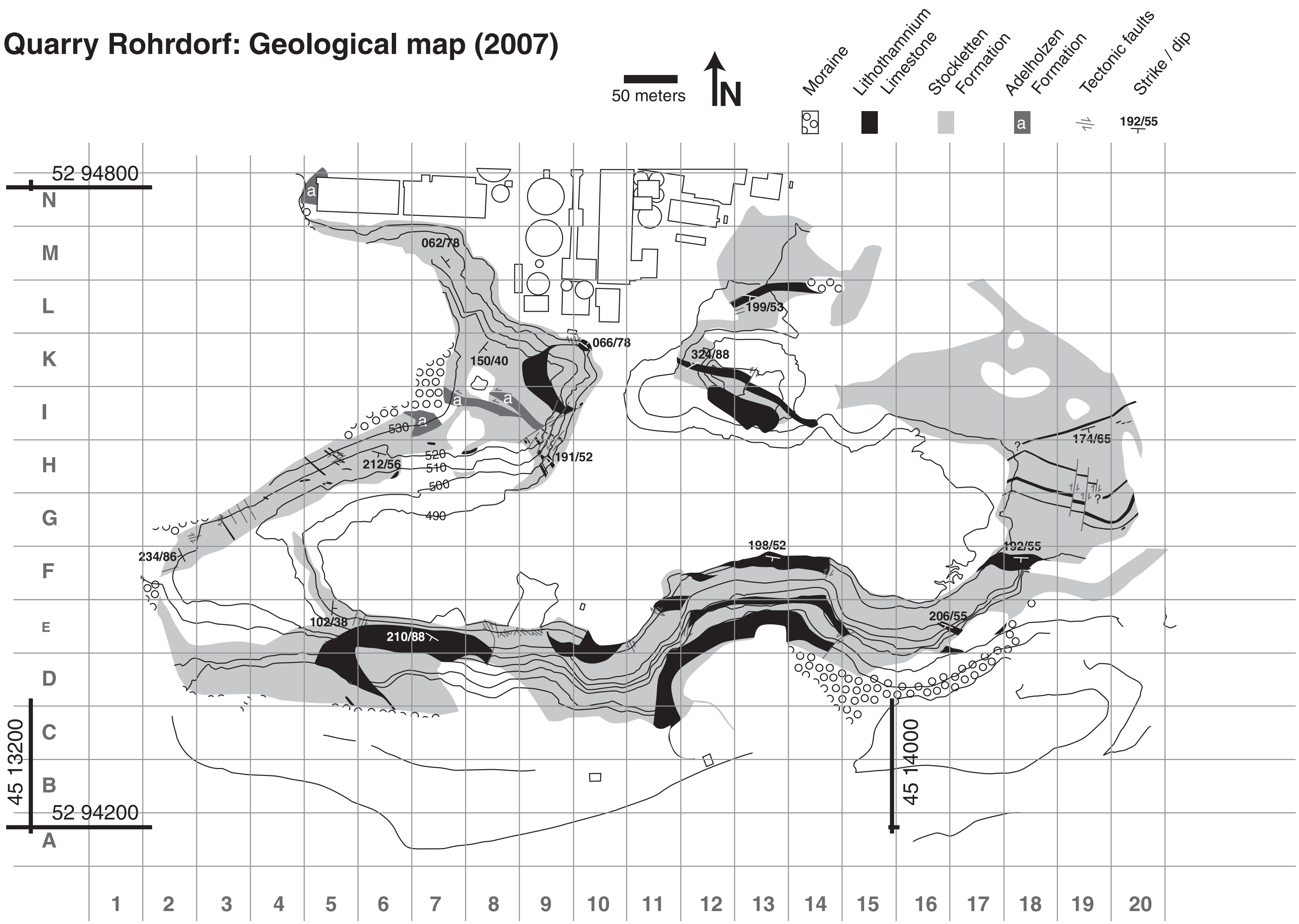


Figure 11. Geologic map of the Rohrdorf quarry.

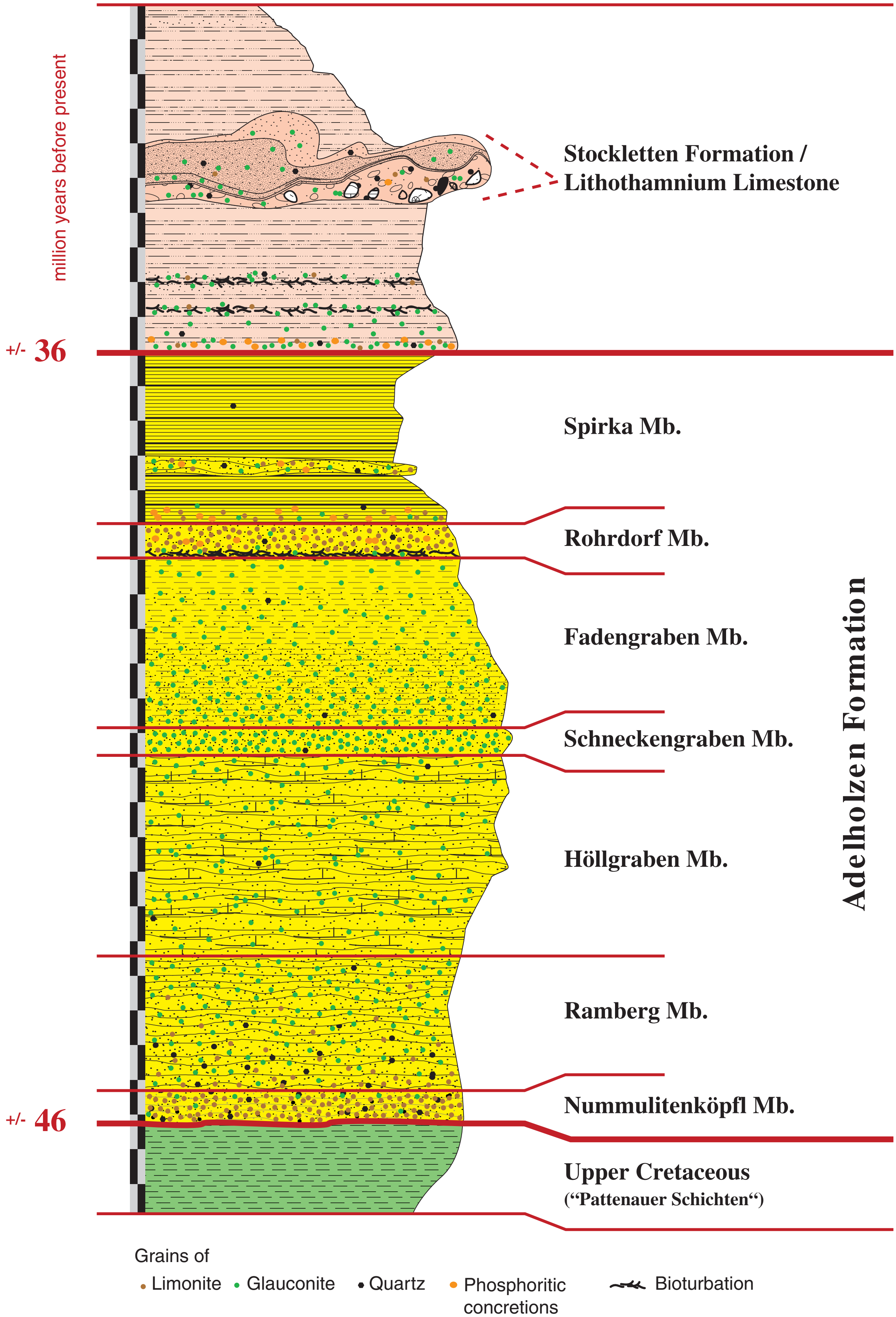


Figure 12. Geologic section of sediments outcropping in the Rohrdorf quarry (Adelholzen Formation; Stockletten Formation; Lithothamnium Limestone).

margin of the disintegrating Pangea in a hot and dry environment. Its post-Variscan sedimentary history starts with Late Permian to Early Triassic red fanglomerates (Verrucano) and sandstones or playa sediments with clay and evaporites, locally containing thick salt layers (Haselgebirge) that were mined since Neolithic times. Those salt layers acted as main detachment horizon during nappe transport.

From Mid Triassic times on, a carbonate platform developed over a large area in a tropical tidal sea, which has no actual comparison. (Haas et al., 1995; Mandl, 1984).

In general, deepwater facies occurs in the southeast, along the outer shelf to the Hallstatt-Meliata Ocean (Hallstatt facies). Water depth was shallow in the central parts, the depositional realm of the Inntal-, Lechtal- and Allgäu nappes. To the north, the terrestrial Germanian Keuper has some influence to the facies which becomes impure and sandy.

In the Ladinian, a broad belt of isolated carbonate platforms formed. Shallow lagoons were surrounded by a reef belt and a fore-reef zone (Wetterstein limestone), where the reef interfingers with basinal sediments (Partnach beds). Algae (*dasycladacea)* are frequently found in the lagoonal, bedded Wetterstein limestone or dolomite. A short phase of sea-level drop correlates with the Raibl beds, mostly represented by dolomites, limestones, evaporites, cargneuls, sandstones and, occasionally, coal seams. The Raibl beds pile up under the Wamberg anticline where they were drilled at Vorderriss 1 for nearly 3000 m—mostly anhydrite and shales (Bachmann and Müller, 1981). They form another detachment horizon. The relief of the floor of the shelf platform was smoothed at the end of the Karnian stage and a broad tidal sea extended for the entire area. Up to 2000 m of Hauptdolomit were deposited in just 10 million years.


Figure 13. (A, B) Faulted beds of Lithothamnium limestone (fine-grained turbiditic facies) in the southern part of the quarry Rohrdorf. (C, D) slump facies of Lithothamnium limestone, northern area (grid square I 13 in Fig. 9). Photos: A. Heyng, August 2007.

From now on the carbonate platform starts to break apart. Local basins form, e.g., the Seefeld basin north of Innsbruck. In its stagnant waters, countless fish are well preserved in the blackshales. Even tar has been distilled until recently for medical purposes.

The basin was filled partly by turbidites and slump masses (Brandner and Poleschinski, 1986; Donofrio et al., 2003).

Facies changes with basins (Kössen beds) and patch coral reefs (Rhaetian reef limestone) characterize the latest Triassic stage. After a short regressive phase, the Jurassic strata indicate rapid deepening due to tectonic extension of the whole area. Fissures in late Triassic rocks, slump masses, and deep basins below the calcite compensation depth (CCD) and submarine highs with condensed strata characterize this time span. Cherts and Late Jurassic aptychus limestones and Early Cretaceous aptychus marls were deposited in the Valepp area.

Starting in Mid Cretaceous times, the Northern Calcareous Alps experienced a first compressive phase (Eoalpine phase) and even a low-grade metamorphism in its southeastern parts (Frey et al., 1999; Gawlick et al., 1994). In the Valepp area, the late Cretaceous Gosau transgresses over deeply eroded and folded Triassic rocks.

The Valepp valley offers the most accessible and nearly straight section through most of the Northern Calcareous Alps. Its orientation is normal to the fold axes trend (Fig. 14). The Valepp River and the Brandenberger Ache deeply incised into Triassic dolomites and limestones that form two large anticlines of 10 km in wavelength and several kilometers in amplitude (Figs. 15A, 15B). The folding of the Guffert Anticline must have partly taken place earlier than Late Cretaceous during the Eoalpine phase. After restoring the post-Gosau thrusts along the Alpine front, the Gosau horizon becomes flat and attains a position close to sea level (Fig. 16).

***Stop 4-1. Gosau Transgression South of Pinegg***

(47°30′45″N, 11°53′53″E)

From Kaiserhaus we drive to Pinegg and then continue for 2 km along the road to Brandenberg. At a roadcut, a transgressive surface of Gosau sandy limestones is exposed. It is marked by colonies of thick-shelled mussels (*Rudists*), which once settled along the rocky shore of the Gosau sea. The well-bedded Hauptdolomit below dips steeply (65°) to the south. Two hundred meters southward, a gently dipping thick-bedded, coarse-grained hybrid Gosau arenites contains plant remnants and phosphorite nodules.

We then drive back to the Kaiserhaus and park. From here and for the rest of the day, we hike northward along the Valepp valley to the Erzherzog Johann Klause (overnight lodging) and beyond (total hiking distance ~12 km).

***Stop 4-2. Kaiserklamm***

(47°32′25″N; 11°55′00″E; Wetterstein anticline, Gosau unconformity)

From the Kaiserhaus we hike 2 km on a small secured trail through the Kaiserklamm gorge. We cross through the Wettersteinkalk, the oldest exposed Triassic member here, which forms a large anticline (Guffert anticline) with the Kaiserhaus in its center (Fig. 15A). At the entrance of the gorge, the limestone is massive and the gorge is extremely narrow, but it widens when the limestone becomes bedded. At the northern end of the gorge, red Gosau breccias lie in angular unconformity over 60° north-dipping Middle Triassic limestone. The breccia is monomict, with clasts derived from the Wetterstein limestone, and beds gently dipping to the west. More than 2000 m of Jurassic and Triassic sediments were eroded in Early Cretaceous times over the anticline in the Triassic rocks (Fig. 16).

***Stop 4-3. Trauersteg Bridge***

(47°33′03″N; 11°54′14″E; northern limb of the Gosau syncline)

We already crossed the small Gosau basin, and to the west of the bridge, purple-red sandstones and fine conglomerates dip 50° southward. Some 50 m behind the outcrop, a subvertical wall of gray Hauptdolomit marks the faulted contact to the Gosau sediments here. The sedimentary succession records deepening, from alluvial fan deposition (cross bedding, sand lenses, and channel fillings) of a continental environment, to beach-derived conglomerates and shallow-marine hummocky cross-bedded sandstones (Sanders, 1998) (compare introduction to Day 6 and Stop 6-1).

***Stop 4-4. Bridge over the Brandenberger Ache***

(47°33′17″N, 11°53′38″E; 1 km NNW of Stop 2)

We cross the faulted contact of Gosau beds and Hauptdolomit and discover an anticline only after careful observation.

The Gosau beds are cut along a northeast-striking, steep fault. Red, angular, poorly sorted clasts mark the base of the contact. Striations gently plunging to the west indicate strike-slip movements. From here we move for about 2 km farther to the north in gently northward-dipping Hauptdolomit until, after passing a gentle syncline, the thick brittle rocks are heavily fractured and crushed into a tight overturned anticline. We cross through the overturned limb for another 500 m and find the still overturned Plattenkalk, Kössen beds (covered by vegetation along the road) and encounter the massive Rhetian reef limestone. Liassic red limestones and cherts can be found in the scree, but are not exposed along the road. The aptychus limestones that follow are intensely sheared due to the Achental thrust, which crops out in this position.

From here northward we pass the Neokom Aptychenschichten, Cretaceous marls and marly limestones in upright position.

***Stop 4-5. North of Erzherzog Johann Klause***

(47°34′53″N, 11°53′18″)

We follow the forest road northward and cross the Marchbach on a high bridge, built over the contact between Cretaceous and Jurassic aptychus beds. The Jurassic beds show tight overturned asymmetric folds of small wavelength, indicating top to north movement along the Achental thrust.

***Stop 4-6. Reichsteinalm***
(47°35′28″N, 11°54′05″E)

We continue upward through folded Malm aptychus beds and reach the base of the Jurassic strata 200 m beyond the Reichsteinalm. At this locality, the Jurassic succession is extremely incomplete. Within a few meters, the following succession is observed: Rhaetian reef limestone; red Hierlatz limestone; nodular Adnet limestone; white, thin-bedded limestones with radiolarians; red nodular limestone (?Klaus limestone, Doggerian); and red and gray slumped limestones of the Ammergau-Formation.

The cherts and cherty limestones show nice slump folds and disrupted strata at the edge of a slump horizon, which extends for more than 10 km to the east. In red Liassic limestones, a set of strike-slip faults is indicated by fiber crystals of calcite.

A massive light-gray Rhaetian reef limestone follows to the north and forms a steep cliff. It is cut by fissures, which are filled with red Jurassic crinoidal limestones and red marls, indicating Early Jurassic extension. Within the reef limestones, corals may be seen both in life position and reworked. Around the corner, brownish Kössen marls and limestones are remarkably well

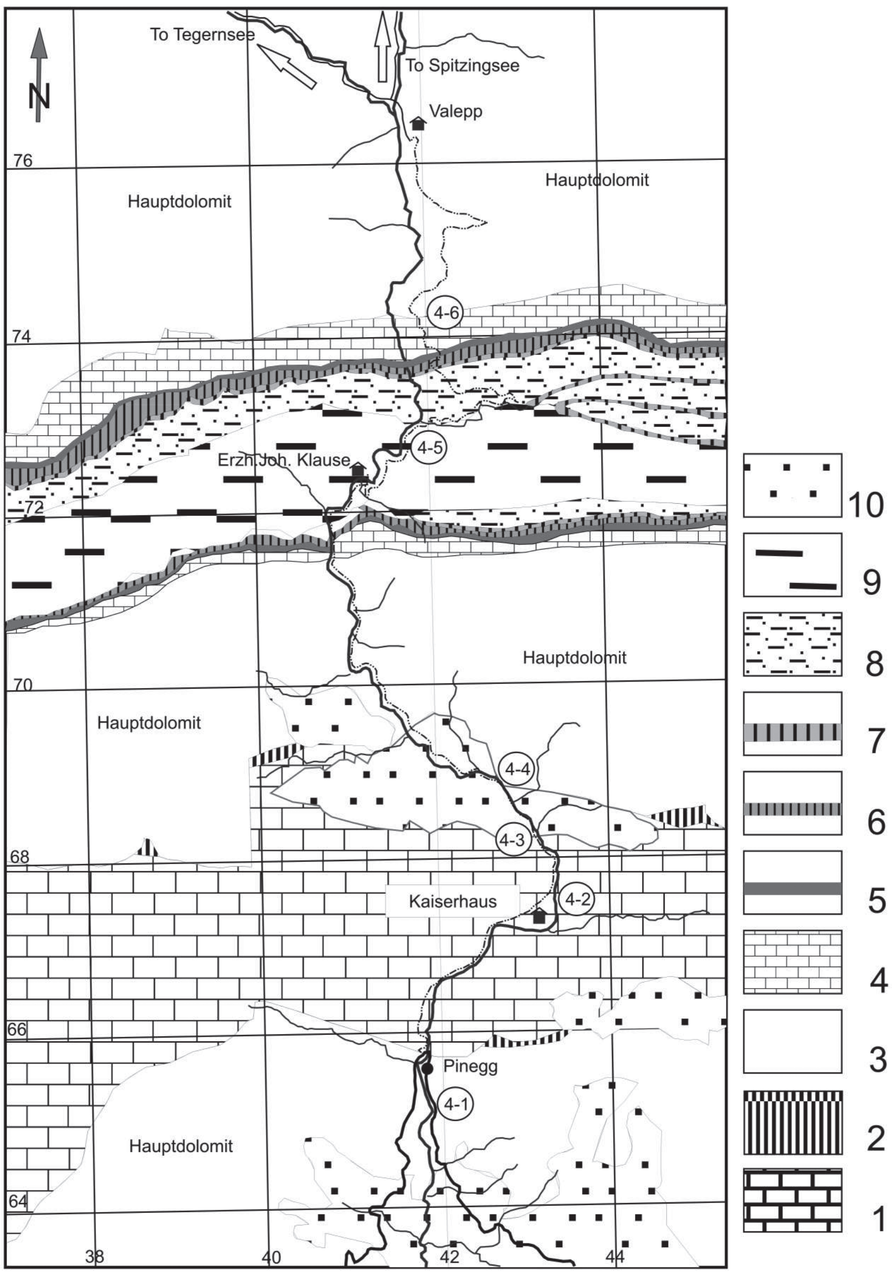


Figure 14. Geological sketch map of the Valepp Valley (2 km grid). Legend: 1—Wettersteinkalk, massive to thick bedded limestone and dolomite, (Ladinian); 2—Raibler Schichten, evaporates, cargneuls, and sandstones (Carnian); 3—Hauptdolomit, thick or medium bedded dolomite, up to >2000 m in thickness (Norian); 4—Plattenkalk, well-bedded limestone on top of the Hauptdolomit (Rhaetian); 5—Kössen beds, marls, and thin lumachelle limestone beds alternating; 6—Late Rhaetian reefal limestones with corals (thecosmilia clathrata) and reef detritus limestone; 7—nodular limestone or crinoid limestone, red or gray with chert, locally cherts (Liassic); 8—Aptychenschichten, light-gray aptychus limestones and marls, well bedded (Malm); 9—Neokom Aptychenschichten, marls, limy marls, spotted marls (Early Cretaceous); 10—Gosau formation, red or gray breccia, conglomerate, sandstone and clay; south of the Kaiserhaus: glauconitic sandy limestones with rudists and glauconite limestones and horizons full of thick-shelled gastropods (*actaeonella*).

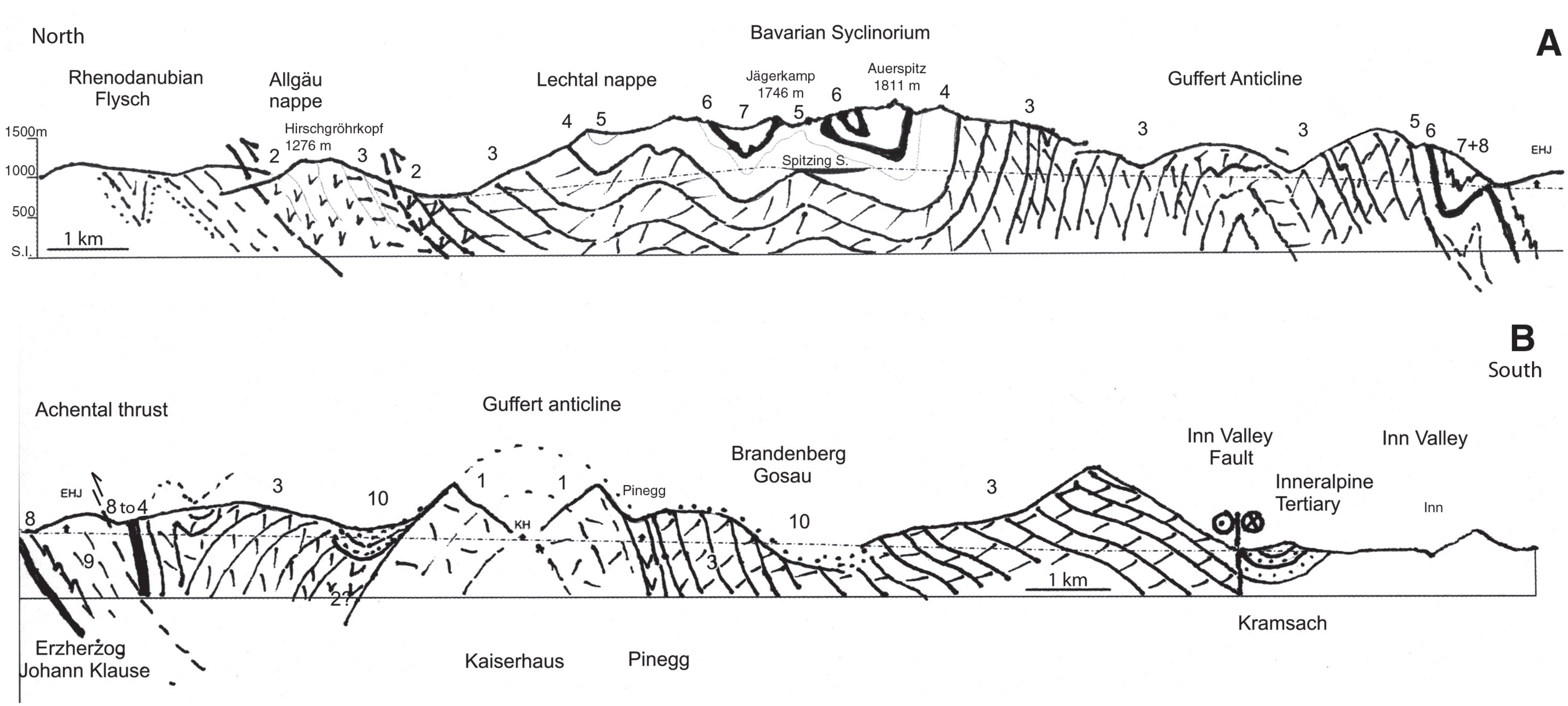


Figure 15. (A) Cross section through the northern part of the Valepp gorge. (B) Cross section through the southern part of the Valepp gorge. For legend of formation numbers, see Figure 14.

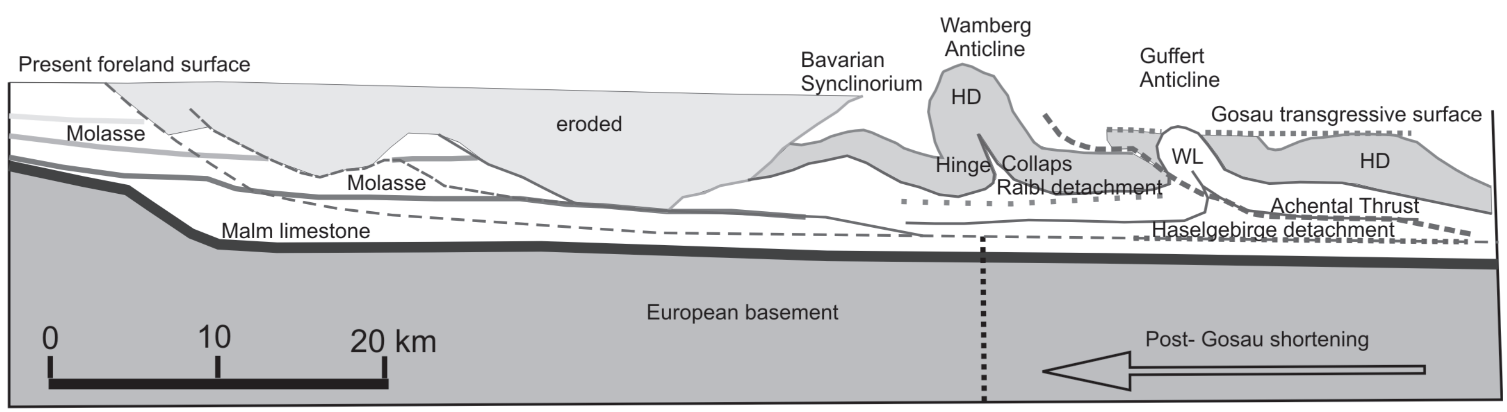


Figure 16. Restoration of the Northern calcareous Alps to pre Gosau tectonic configuration. The Guffert anticline is clearly a Pre-Gosau structure. Reconstruction by means of 2DMove software (Midland Valley Inc., Glasgow).

exposed. Continuing into the Plattenkalk, again signs of slumped material are visible, showing the general tectonic activity at the end of Triassic and beginning of the Jurassic era (Schlager and Schöllnberger, 1973).

From here, we walk back to the Erzherzog Johann Klause for overnight lodging.

## DAY 5

We leave the Valepp, study the Inneralpine Molasse, and proceed to the Muttekopf area.

In the eastern Inn Valley the remains of the wedge-top of the peripheral Alpine foreland basin (Molasse basin) are preserved (Fig. 17). The Oligocene rocks of the Inn were also termed "Inneralpine Molasse" (e.g., Fuchs, 1976). The Oligocene sediments are preserved in a syncline-anticline system over 50 km of lateral extent along the Inntal shear zone, which is a major fault system in the Eastern Alps with approximately 40 km of sinistral offset (Ortner et al., 2006). The sedimentary succession of the "Inneralpine Molasse" is closely related to the Subalpine Molasse (Ortner and Stingl, 2001): Eocene–Lower Oligocene carbonates and marls record deepening from shallow-marine to pelagic conditions. Increased deposition of siliciclastic material in pro-delta turbidites in the late early Oligocene shows progradation of a delta system, until late Oligocene fluviatile conglomerates indicate a continental environment.

The Inntal shear zone is a major sinistral ENE-striking fault that was active during post-collisional shortening from the early Oligocene to the late Miocene, and it is probably still active (Ortner, 2003; Ortner et al., 2006; Reiter et al., 2007). The Oligocene and Miocene activity was tied to the exhumation of the Tauern Window in the internal Eastern Alps. Ductile thickening, stacking and folding in the Tauern Window was accompanied by E-directed stretching. The Inntal shear zone was the northern limit of east-directed flow of material (Figs. 17, 18). The analysis of brittle structures along the Inntal shear zone shows sinistral transpression (Ortner, 2003; Ortner et al., 2006).

The TRANSALP deep seismic line crosses the Inn Valley near the western end of the Oligocene deposits. A key feature, recognized already in the earliest interpretations of the TRANSALP seismic data, is the south-dipping reflections in the depth range between 4000 and 10,000 m at CDP 5000–5200 (number 6 in Fig. 18), which continue to great depth (e.g., TRANSALP Working Group, 2002). These are believed to be related to Miocene crustal stacking in the Tauern Window, which is kinematically connected to the Inntal shear zone (see above). The apparent continuation to the surface is a south-dipping zone across which seismic reflectivity decreases upward (Brixlegg thrust, number 8 in Fig. 18). At the surface, the seismic contrast coincides with the contact between the Northern Calcareous Alps and the Greywacke zone, which originally was the low-grade metamorphic basement of the Northern Calcareous Alps. The Greywacke zone was emplaced onto the Northern Calcareous Alps by the Brixlegg thrust. Oligocene sediments preserved on the hanging wall of the Brixlegg thrust (Fig. 18) preclude major post-Oligocene vertical offset; therefore the Brixlegg thrust is interpreted as a Paleogene out-of-sequence thrust (Ortner et al., 2006).

### *Stop 5-1. Oberangerberg and Volldöpp*

(47°27′10″N/11°53′33″E)

The section Voldöpp lies along a small road from the northeastern part of Kramsach to the Oberangerberg. In the morning, we walk back to the Kaiserhaus (10 km hiking) and proceed by car 15 km down to the Inn Valley to study the Inneralpine Molasse at Volldöpp.

The section Voldöpp is designated as type section for the Oberangerberg Formation, one of the sedimentary units of the Inneralpine Molasse. A succession of typical continental Molasse-type conglomerates crops out in the Oberangerberg area (Fig. 17). The dominating lithofacies types present are component-supported coarse conglomerates with or without normal grading, with imbricated components. Occasionally planar cross-bedding is observed in the topmost portion of conglomerate beds. Horizontally laminated sandstones to siltstones, and occasionally ripple cross-bedding, interrupt the conglomerate sedimentation. The coarse conglomerates of a slightly sinuous, braided river system (Krois and Stingl, 1991) indicate perennial high-energy runoff. The main facies elements are channel fills with longitudinal bars and large-scale ripples. The scarcity of overbank fines (levees, crevasse splays and floodplain deposits, mud-filled abandoned channels) supports the model of a highly mobile channel system. Transport directions derived from imbricate clasts and cross-bedding are oriented from NW-W to SE-E.

Biostratigraphic dating of the Oberangerberg Formation is debatable. Plant fossils (*Cinnamomum* cf. *scheuchzeri* and *C.* cf. *spectabila* Heer) not indicate an Oligocene to Miocene age (Hamdi, 1969). Only an interpretation of the succession based on sequence stratigraphy provides some evidence for the lower boundary of the Oberangerberg Formation to be near the base of the Chattian. As the first pebbles from rocks of the Bernina, Err, and Julier nappes in the Upper Engadine Valley appear in the Aquitanian of the Molasse zone, and are lacking in the Oberangerberg Formation, the erosional upper boundary of the Inneralpine Molasse must still be within the Oligocene. Modeling of the thermal history based on vitrinite reflectance data in the Häring-Oberangerberg area resulted in the prediction of a total thickness of 1300 m of eroded sediment (Ortner and Sachsenhofer, 1996). More than 1000 m thickness of the Oberangerberg Formation is preserved north of the Kaisergebirge (Ortner and Stingl, 2001).

### *Stop 5-2*

From Volldöpp we drive via Innsbruck to Hoch-Imst (106 km), and ascend by cable lift to the Alpjoch (2100 m); from here we hike along a narrow mountain trail, which cuts well exposed Gosau sediments. We reach the Muttekopf Hütte (1934 m) after 1 hour of hiking.

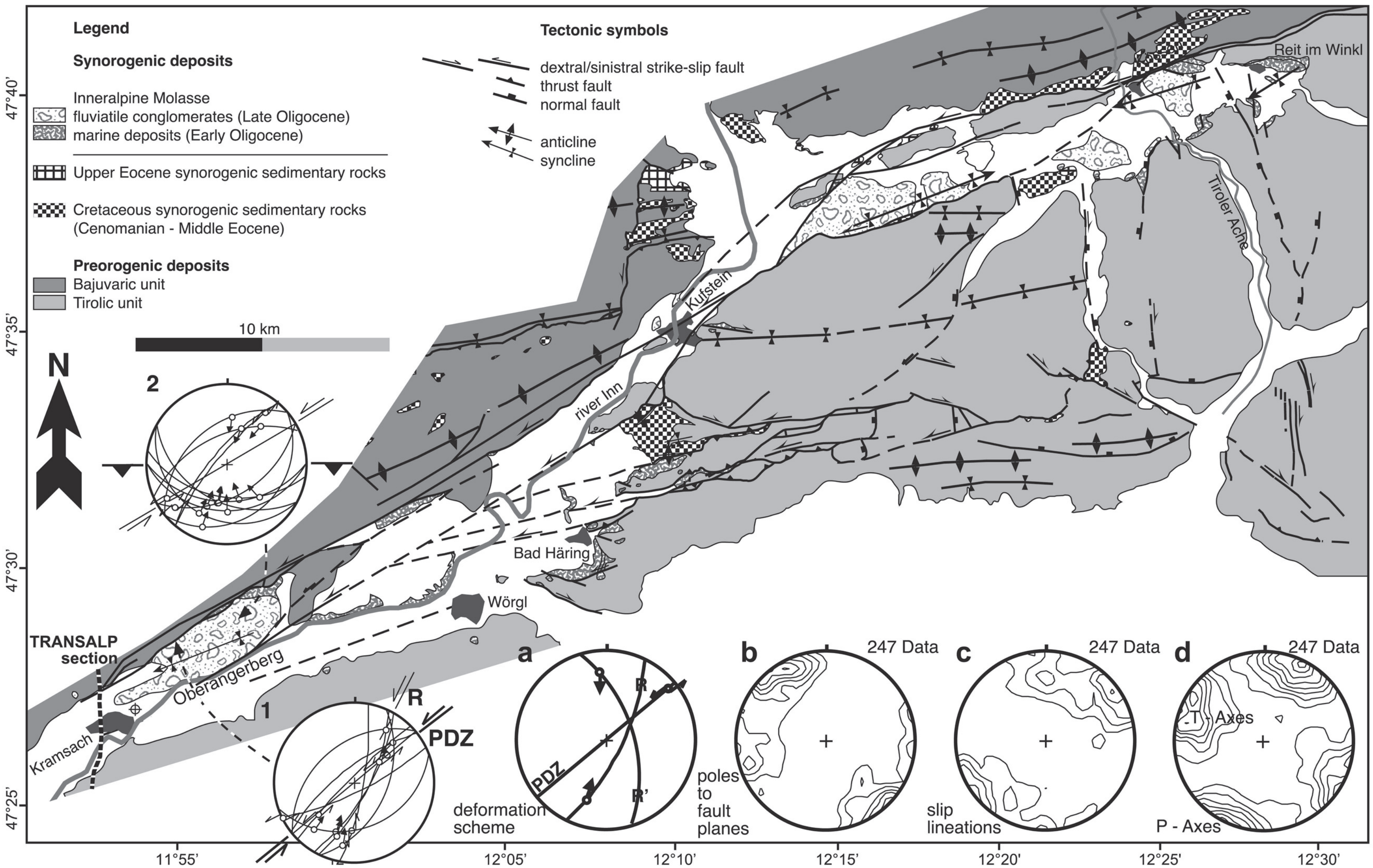


Figure 17. Geological sketch map of the Inneralpine Molasse of the Inn valley (adapted from Ortner et al., 2006). Diagrams: Miocene brittle deformation of the Inntal shear zone from data measured in 14 stations in Oligocene rocks. Two examples from stations at the Oberangerberg are given in diagrams 1 and 2. PDZ—principal displacement zone, R—Riedel shear; a—typical fault pattern observed in data sets associated with sinistral shearing across the Inntal shear zone with oblique reverse slip on Riedel and Anti-Riedel shears; b—contour plot of poles to all fault planes measured associated to sinistral shearing across the Inntal shear zone, indicating that the majority of fault planes is subvertical to steeply south-dipping; c—contour plot of all slip lineations measured associated to sinistral shearing across the Inntal shear zone, indicating that slip across the Inntal shear zone was essentially horizontal; d—contour plot of all compression and tension axes, which were calculated using an angle between fault plane and P-axis of 30°. The maximum densities give approximate mean orientations of NNE and ESE for $\sigma_1$ and $\sigma_3$, respectively, irrespective of complexities regarding the boundary conditions of shearing.

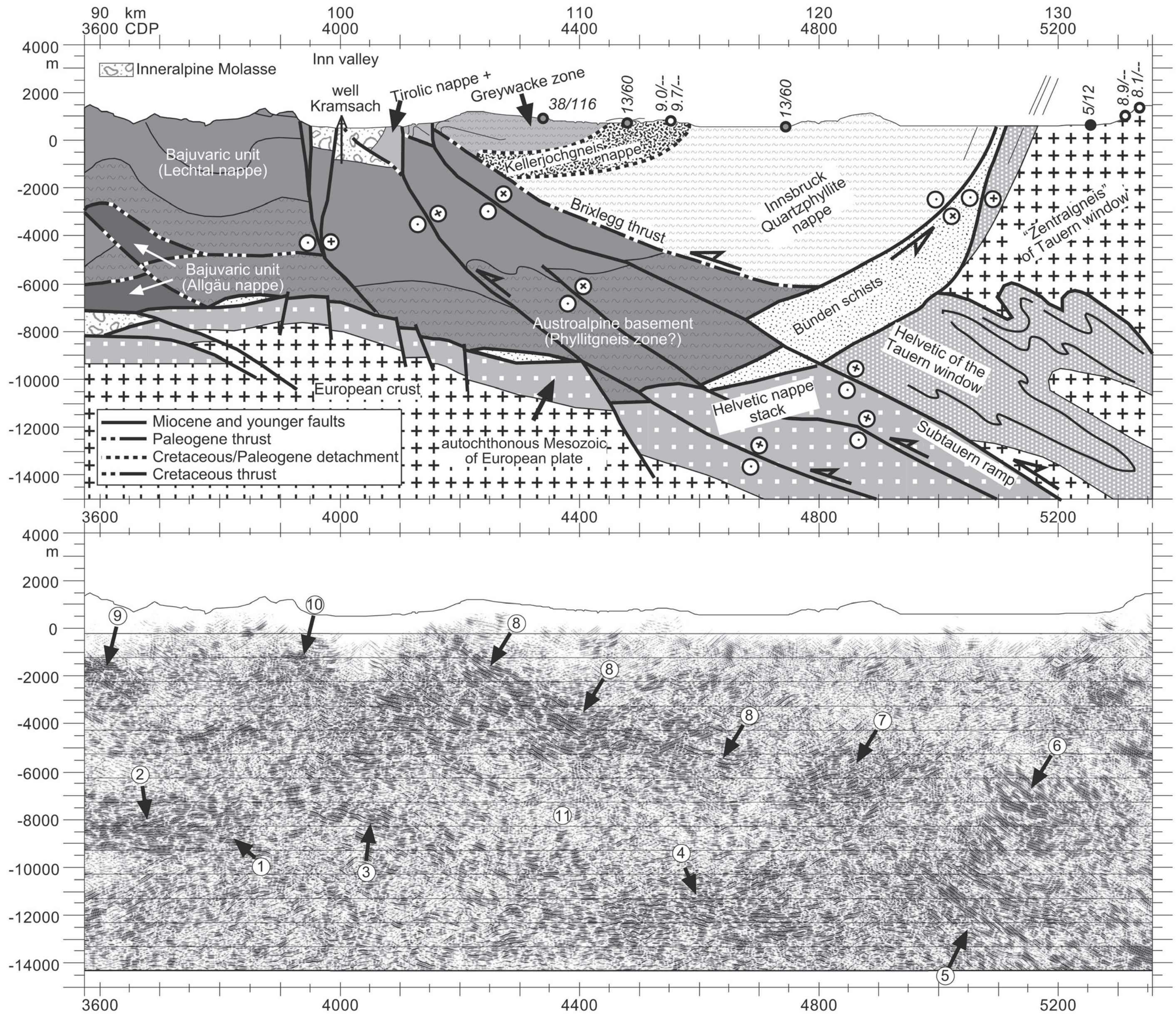


Figure 18. The TRANSALP seismic section from CDP 3600 to CDP 5300 (adapted from Ortner et al., 2006). Bottom: Migrated seismogram (Lüschen, 2002, personal commun.). Numbers refer to explanations in text. Top: Interpretation of the seismogram. Interpretation of Northern Calcareous Alps north of the Inn valley taken from Auer and Eisbacher (2003). Black circles—apatite fission-track ages by Most et al. (2003); gray circles—apatite/zircon fission-track ages by Angelmaier et al. (2001); white circles—apatite fission-track ages by Grundmann and Morteani (1985).

## DAY 6. MUTTEKOPF GOSAU: CONIACIAN TO ?PALEOCENE SEDIMENTATION IN A THRUST-SHEET–TOP BASIN—THE GOSAU GROUP OF THE MUTTEKOPF AREA

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

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. 19). 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 the formation of several (progressive) angular unconformities within the sedimentary succession (Ortner, 2001; Figs. 19, 20).

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 alluvial fan succession up to 300 m thick 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 siltstones to sandstones of the "Inoceramus" marl unit contain a variety of marine fossils 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, 1994b, 2001; Fig. 20): All three sequences are dominated by vertically stacked, upward-fining, 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 (Fig. 20). 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, outside the field trip area). The three sequences can also be distinguished by clast- and heavy-mineral compositions (Ortner, 1994a, 1994b). The age of the deposits of the Upper Gosau Subgroup is poorly constrained. The turbiditic marls occasionally contain corroded nannoplankton 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 is Early Campanian to Early Maastrichtian or younger, and Sequence 3 is Late Maastrichtian to ?Danian (Oberhauser, 1963; Dietrich and Franz, 1976; Lahodinsky, 1988; Wagreich, 1993–1995, personal commun.).

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:

(1) megabreccia association, made of fluidized mud-rich conglomerates, slabs of other facies associations of the Upper Gosau Subgroup, and house-sized clasts of Triassic rocks;

(2) 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 gray turbiditic marls; and

(3) thin-bedded turbidite association, with cm-thick sandstones (Bouma Tb or Tc intervals) alternating with dark-gray 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.

The Upper Gosau Subgroup of Muttekopf was deposited during transpressive fold growth (Ortner et al., 2010). Kilometric folds are segmented by and kinematically linked to dextral tear faults. In the segments between the tear faults, depositional units overlap the folds, but clear wedging toward the anticlines can be observed. Growth strata above tear faults show combined rotational offlap-onlap-overlap, caused by changes in strike instead of changes in dip (l.c.). The principal unconformity connects to the tear fault.

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 conglomerates is an important process accompanying downslope creeping of sediment packages. Fluidization is commonly associated with downward and upward injection of conglomerate into neighboring deposits.

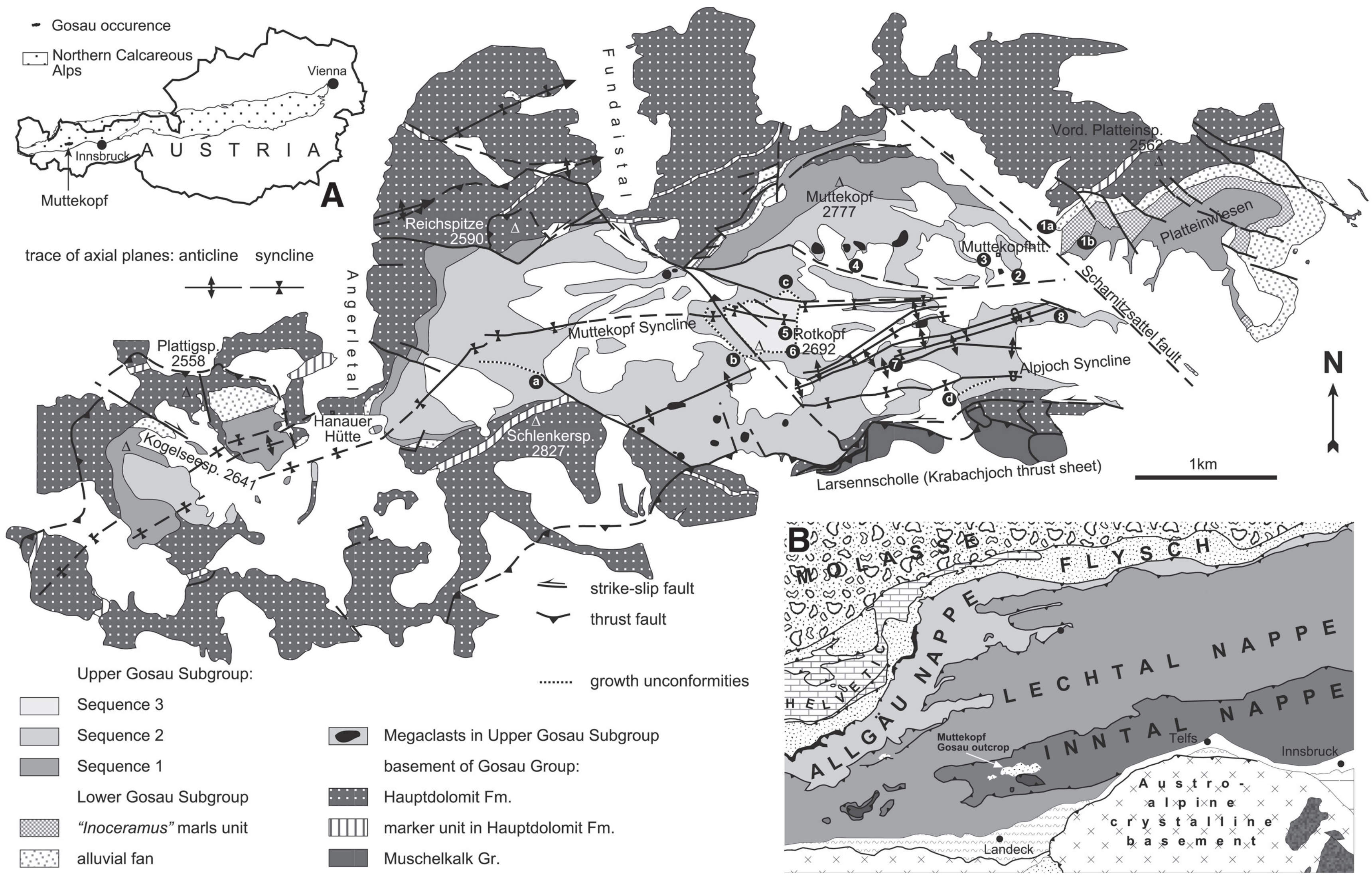


Figure 19. Geologic sketch of the Gosau outcrop at Muttekopf and location of Stops 1–8 (modified from Ortner and Gaupp, 2007). Growth unconformities: a—Schlenkerkar unconformity; b—Fundais unconformity; c—Rotkopf unconformity; d—Alpjoch unconformity. Inset A: Location of the Muttkopf outcrop in Austria. Inset B: Tectonic position of the Gosau Group at Muttekopf on the thrust sheets of the western Northern Calcareous Alps.

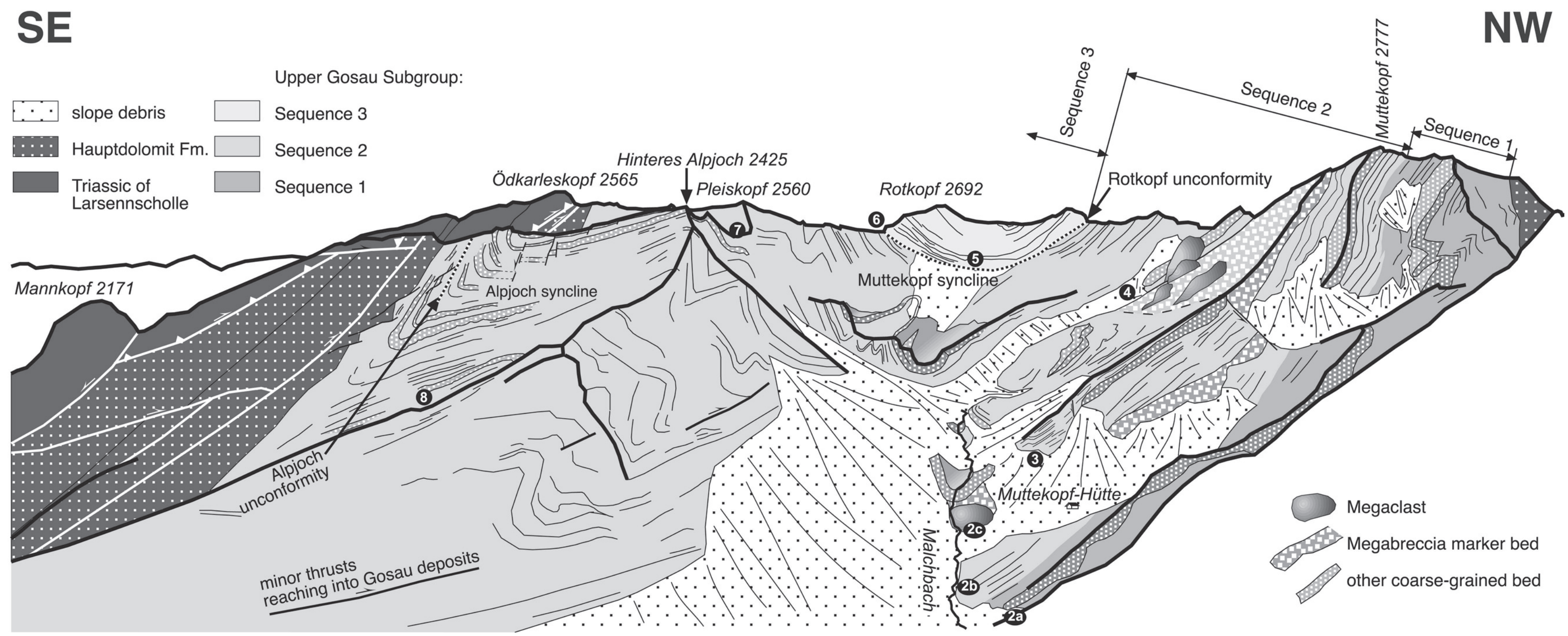


Figure 20. Panoramic view of the excursion area at Muttekopf from the east, showing the three sequences and the tectonic structure within the Upper Gosau Subgroup (modified from Ortner and Gaupp, 2007). Stops 2–8 are indicated.

***Stop 6-1. ?Coniacian to Santonian Succession of the Lower Gosau Subgroup and Transition to the Upper Gosau Subgroup***

(50 m in elevation above and along the path from Muttekopfhütte to Platteinwiesen, 600 m ENE of Muttekopfhütte)

***Stop a.*** Clast supported, partly matrix-free conglomerates with crude trough stratification, sieve deposits with red, sometimes laminated mud and pebbles exclusively composed of Hauptdolomit Formation Conglomerates with perfectly rounded dolomite clasts and chert found as blocks on the way to Stop b.

***Stop b.*** 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.

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

***Stop 6-2. 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.)

***Stop a.*** Thin-bedded turbidite association, cm-thick silt- to sandstones alternating with black dolomitic marls, overlain by a nonlayered conglomerate bed with flame structures and minor normal faults at the base; diffuse internal shear planes within the conglomerate.

***Stop b.*** Thick-bedded turbidite association, dm- to m-thick sandstones alternate with m-thick yellowish marls overly a matrix rich coarse-grained conglomerate.

***Stop c.*** Giant block of Upper Rhaetian limestone within a conglomerate bed of Sequence 2. Karstic dikes on the surface of the block.

We discuss the bathymetry of the Upper Gosau Subgroup and the mechanism of deposition of coarse-grained beds (high-density turbidites versus debris flows).

***Stop 6-3. Fluidized Layers and N-Vergent Folds in Thick-Bedded Turbidites of Sequence 2***

(150 m WSW of Muttekopfhütte)

Sediment transport directions are indicated by flute casts and tool marks at the base of sandstone beds. Isoclinally folded sandstone beds in a conglomerate matrix show plastic deformation within the sandstone beds. Shingle-like stacking of sandstone slabs and semi-brittle deformation within N-vergent folds with stacking of horses in the forelimb of the fold and local plastic deformation arise questions about tectonic deformation versus gravity-induced deformation. Surface or subsurface fluidization and significance of fold axes within fluidized layer will be discussed.

***Stop 6-4. Giant Blocks ("Blaue Köpfe") in Megabreccia Layer of Sequence 2***

(2300 m, at junction of trails 600 m S of the Muttekopf summit)

Giant blocks of Upper Rhaetian limestone projecting out of a chaotic breccia layer of the Megabreccia association. The mode of sediment transport of giant blocks will be discussed.

***Stop 6-5. 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 the Rotkopf [2692 m].)

We observe conglomerates containing abundant brick-red marl intraclasts, injection of marl clasts by conglomerate dykes, and systematic sandstone-filled joints in coarse sandstone. White calcite-rich marls alternating with m-thick sandstones occur in the hinge of the syncline.

Panoramic view of the Muttekopf syncline toward the west from the Rotkopf summit, submarine topography around the Große Schlenkerspitze, anticlinal crest within Gosau deposits east of Schlenkerspitze. We discuss the origin of overpressure in breccia beds and the geometry of syntectonic sediments in the vicinity of the Schlenkerspitze.

***Stop 6-6. Rotkopf Unconformity at Pleisjoch (2560 m) and Pleiskopf (2580 m)***

Erosional steps at the Rotkopf unconformity leave two possibilities: Is the Rotkopf unconformity a growth unconformity or an erosional unconformity?

In the sediments a fluidization of conglomerate produces flame structures and injection of conglomerate into sandstone. A channel-like geometry of Sequence 3 may be seen from the Pleiskopf.

***Stop 6-7. Hydroplastic Deformation of Conglomerates***

(Locality: 50 m S of the saddle located 340 m west of the Hinteres Alpjoch.)

Meter-scale asymmetric linear flames of marl into conglomerate are found here, together with a conglomerate sill with clasts up to 20 cm in diameter intruded downward into sandstone.

Here are some questions that can be addressed at this locality: Are the linear flames an expression of dewatering, or are these 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 6-8. Panoramic View of the Hinteres Alpjoch from the Vorderes Alpjoch, Mountain Station of the Chairlift (2121 m)***

A change of the geometry of the Alpjoch syncline in Sequence 2 can be observed from here. The tight chevron fold in the outer layers grades into an open fold in the inner layers (Fig. 20, left). In addition, there is a rotative onlap across the Alpjoch unconformity. To the left, the tectonic contact of the Larsenn klippe to the Gosau sediments can be seen (Fig. 20). The relevance of geometric and mechanic fold models for the geometry of syntectonic sediments and unconformities related to fold growth will be discussed here.

## DAY 7

From Muttekopf descend to Imst, then drive back to Munich via the Fernpass and Garmisch-Partenkirchen (150 km).

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