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5TH WORKSHOP OF ALPINE GEOLOGICAL STUDIES FIELD TRIP GUIDE E1 LOWER INN VALLEY (SOUTHERN MARGIN OF THE NORTHERN CALCAREOUS ALPS, TRANSALP TRAVERSE)

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With 20 figures

1 Introduction

In the Lower Inn Valley area a nearly complete stratigraphic record of synorogenic deposits from the Early Cretaceous to the Late Oligocene on top of the Northern Calcareous Alps is present. The synorogenic sediments record changes in environment and tectonic regime during a period of intense tectonic activity that was characterized by continental collision between the Adriatic microplate (upper plate) and the European (lower) plate during the Eocene (e.g. Frisch, 1979). In the earliest Oligocene the peripheral foreland basin (Molasse basin) formed north of the Alpine orogen (Steininger et al., 1991) due to loading by the nappes. The Oligocene rocks preserved in the Inn Valley area were part of the foreland basin, also termed "Inneralpine Molasse" (Fuchs, 1976, 1980).

The study area comprises the Lower Inn Valley between Kramsach and Reit im Winkel in the eastern part of the Tyrol and the southernmost part of Germany (Fig. 1). The Oligocene sediments are preserved in a syncline-anticline system over 50 km lateral extent along the Inntal shear zone, which is a major fault system in the Eastern Alps with approximately 40 km offset (Ortner, 1996). In the investigated area, the Inntal shear zone separates two nappe units of the Northern Calcareous Alps, the Inntal nappe/Tirolic unit to the south and the Lechtal nappe/ Bajuvaric unit to the north in the structurally lower position.

The field trip will focus on following two topics:

- The sedimentary evolution of the Northern Calcareous Alps during the Oligocene and the interpretation of the depositional environment
- and the Oligocene and younger deformation in the area associated with slip along the Inntal shear zone. Just recently the Inntal shear zone attracted additional attention in the course of interpretation of the TRANSALP deep seismic line, which crosses the Inn Valley near the western end of the Oligocene deposits. A major reflector dips from the Inn Valley to the south. Therefore, the Inntal shear zone previously thought to be a subvertical shear zone seems to be a major south dipping thrust fault.

2 Stratigraphic framework

Oligocene sedimentation in the investigated area starts with fan-delta deposits (Lengerergraben Mb.) interfingering locally with bituminous marls (Bergpeterl Mb.), which accumulated in local restricted basins. Transgression due to rapid subsidence led to deposition of pelagic calcareous marls (Paisslberg Fm.). The Paisslberg Fm. onlaps the southern basin margin and is there in sedimentary contact with the Triassic bedrock. The Werlberg Mb. is a near-shore equivalent of the calcareous marls of the Paisslberg Fm. In most cases, a few meters of biogen-rich carbonates in various sedimentary settings (beach rock, rocky coast, reef, ...) underlie the Paisslberg Fm. The Paisslberg Fm. grades into the Unterangerberg Fm. by the increase in terrigenic input. The Unterangerberg Fm. consists of a thick series of turbiditic sand-mud couplets in a prodelta setting showing the progradation of a fluvial system approaching from the west. The basin is progressively filled up by clastic sediments. The advent of a fluvial system is marked by the onset of conglomerate deposition, initially in a marine environment (Höllgraben conglomerate), later under terrestric, fluviatile conditions (Oberangerberg Fm.).

3 Description of stops

3.1 Brugger Mühle near Wörgl

3.1.1 Location

The location of stop 1 is immediately east of Wörgl at the end of the village Brugger Mühle, at a turn of a road branching to Gasteig from the main road just below a quarry. (Fig. 2; ÖK 121, Bl. Neukirchen am Großvenediger, coordinates 47,4981°N/ 12,0972°E).

3.1.2 Main features to be observed

In the road cut the contact of the carbonates of the Werlberg Mb. to the underlying Triassic carbonates (Virgloria limestone) below, and, a few meters to the north, to the calcareous marls of the Paisslberg Fm. above, is exposed. This short section is the type section of the Werlberg Mb. (Ortner & Stingl, in press). The lowermost part of the section is built by a breccia made up of partly bored Virgloria limestone clast. The matrix content rapidly increases upsection and is composed of bioclasts with abundant solitary corals. In the upper part of the Oligocene carbonates Triassic limestone clasts are rare. The contact to the calcareous marls is a wavy surface, which originally was overgrown by corals now preserved in a thin layer of flattened corals on the surface. Karst voids filled with calcareous marls prove subaerial exposure of the Oligocene carbonates before rapid resubmergence and onset of deposition of calcareous marls.

This autochthonous carbonate facies delineates the southern margin of the basin (Werlberg S of Bad Häring, Bergpeterl quarry, S Kössen, S and E of Reit im Winkl), or rims isolated horsts surrounding the Häring basin (Osterndorf NE of Bad Häring, Kufsteiner Wald, Widschwendter Rücken; Fig. 1). It consists of pale limestones with lithoclasts and biogenics (coralline algae, foraminifera, corals, bryozoans etc.: Nebelsick et al., 2001). A remarkable feature are isolated rounded boulders of bioeroded limestones originating from a pebbly or rocky shore.

In the vicinity of this outcrop neptunian dykes with a polyphase fill are frequently observed. The oldest fills are flowstones alternating with spring tufas, which are characterized by their reddish color in the field. A second (younger) type of fill is bioclastic debris, comparable to the Oligocene carbonates observed in this outcrop. The youngest type of fill are calcareous marls, as observed in this outcrop. These fills are sometimes extremely rich in foraminifera. The neptunian dykes and the features in this outcrop record a history of subsidence, uplift and renewed subsidence of the basin margin, characteristic for sedimentation in a tectonically active region.

The Oligocene carbonates of this outcrop and the neptunian dykes seal brittle fault planes observed in the Triassic carbonates below, showing dextral shearing along WNW-striking fault planes.

3.2 Lengerer Graben

3.2.1 Location

Stop 2 is situated in the Lengerergraben valley between the mountains Pölven in the E and Paisslberg in the W. The lithological development can best be studied in the Schuhreissergraben creek at the western slope of the Pölven mountain (type section: Fig. 3, section 1). The outcrops are accessible ca. 1.1km SE of the center of the village Bad Häring (ÖK 90, Blatt Kufstein, coordinates 47,5033°N/ 12,1333°E).

3.2.2 Main features to be observed

Facies development of the Häring Fm., which includes the oldest Oligocene sediments in the area - as demonstrated by Stingl & Krois (1991) and Krois (1992) - clearly shows the possibility to separate two members. The "Lengerergraben Member" (basal series) comprises local coarse clastic wedges, the coal measures and bituminous marls in the hanging wall are termed "Bergpeterl Member". This stop is to study the coarse clastic deposits of the Lengerergraben Mb. (Fig. 5). Three lithofacies associations can be distinguished:

Facies A consists of massive, coarse-grained breccias and conglomerates, resting on a rugged erosional bedrock relief. They show structureless and chaotic textures, and consist solely of locally derived pebbles (Lower Triassic sandstones and Middle Triassic carbonates). The clastics are interpreted as proximal sediments of a small alluvial fan filling topographic lows and were transported mainly as cohesive debris flows with a small amount of fine-grained carbonatic matrix.

Facies B comprises a succession of coarse-grained to fine-grained stratified conglomerates. In the type locality they show bed thicknesses of up to 0.5 m. Graded beds, cross-bedded sets, imbricated clasts in

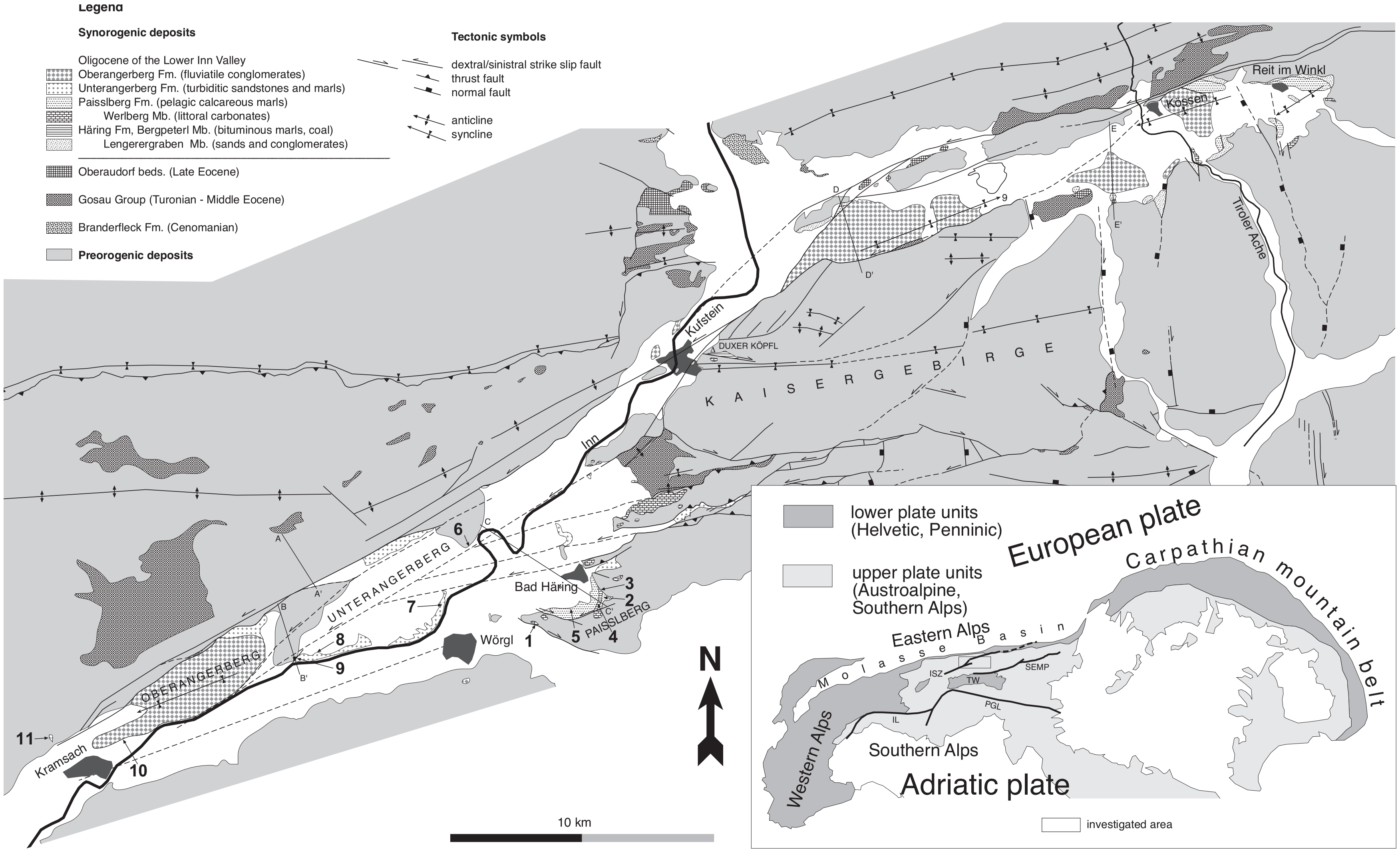


Fig. 1: Geological sketch map of the study area. A-A', ..., E-E' indicate positions of cross sections (Fig. 17). Inset: position of investigated area in the Alpine chain. ISZ ... Inntal shear zone, SEMP ... Salzachtal - Ennstal - Mariazell - Puchberg fault, TW...Tauern window, IL ... Insubric line, PGL ... Pustertal-Gailtal line, numbers with arrows ... field trip stops.

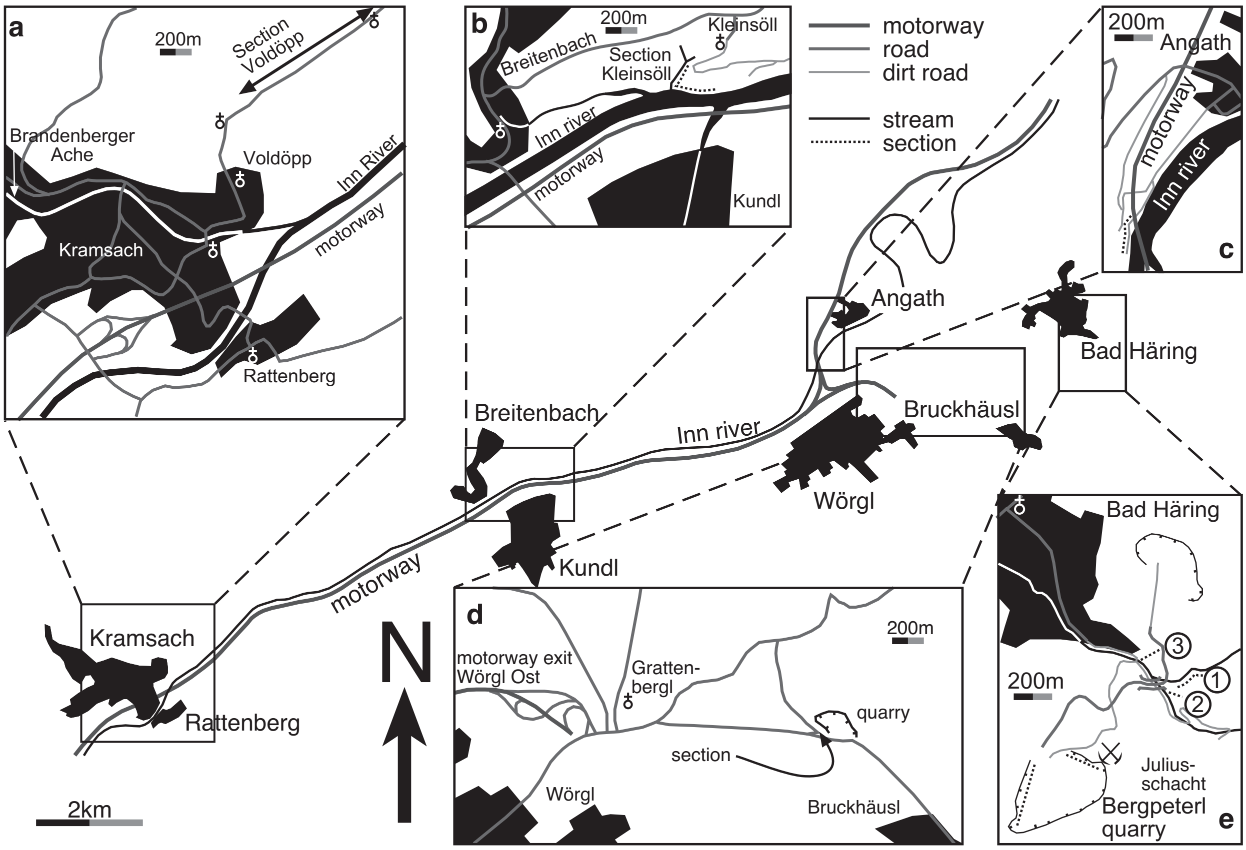


Fig. 2: Geographical sketch map of the study area with position of stops of field trip E1. a) stop 10 (Voldöpp section), b) stop 8 (Höllgraben section), c) stop 7 (section Angath), d) stop 1., e) Location of stops in the Häring area: Häring Fm.: 1–3 ... type section of the Lengerergraben Mb. (stop 2, see Fig. 5), Juliusschacht ... type section of the Bergpeterl Mb. (stop 4, Bergpeterl quarry ... type section of the Paisslberg Fm, stop 5.

the coarse-grained parts and additional flaser bedding and horizontal lamination in the finer-grained parts point to sedimentation from density-modified grain flows or as stream flow deposits in a channel network of fluvial origin.

Facies C (fine- to medium-grained carbonate sandstones and calcareous marls) shows horizontal lamination with graded bedding and rare ripple bedding. The sandstones are organized into coarsening- and thickening-upward sequences. The lower parts are fine-grained, laminated, and show a higher bituminous content (with pyrite concretions). The upper parts reach bed thicknesses of up to 5 cm and are less bituminous. Shell fragments and small plant remains are rare. The sandstones may be interpreted as turbidite-like sediments deposited in shallow water.

Intensive interfingering of facies B and C and some textural evidences for shear-strength lowering in the conglomerates due to water entrainment in a standing water body allow the recognition of an at least partly subaquatic fan delta body (Stingl & Krois, 1991). The overall lithologic development points to a shallow water, near-shore environment. The increase of total thickness and the increasing content of facies C towards the N indicate basin deepening towards the N or NW.

The Lengerergraben Mb. reflects a sedimentary evolution from subaerial alluvial fan deposits through fan delta conglomerates to carbonate sandstones of the prodelta area in shallow water at the mouth of a small fluvial system originating from the S. All occurrences of the Lengerergraben Mb. (type locality and some occurrences northeast of the Kaisergebirge mountain chain near Schwendt) are characterized by a solely locally derived clast spectrum of mainly Middle Triassic carbonates, which have been supplied from a southern source. The vertical trend of deepening is in contrast with models of fan delta evolution, which predict vertical shallowing and upward coarsening due to progradation of the fan into

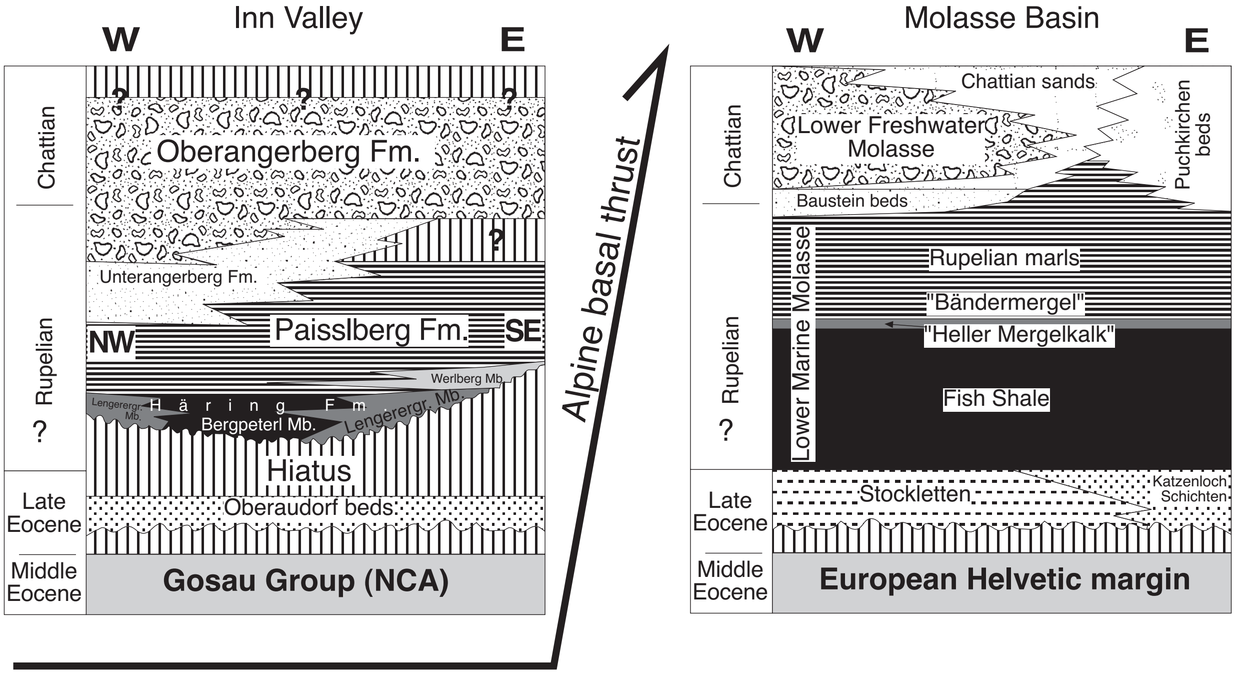


Fig. 3: left side: Lithostratigraphy of the Oligocene in the Inn Valley (modified from Ortner, 1996); right side: Facies development of the Oligocene of the German Molasse Basin (modified from Bachmann & Müller, 1991).

the basin. This means, that subsidence was faster than progradation of the fan delta.

3.3 Western end of Kalkbruch

3.3.1 Location

The outcrop is located at the western end of the Kalkbruch south of Häring (ÖK 90, Blatt Kufstein, coordinates 47,5083°N/12,1306°E).

3.3.2 Introduction

The "Bergpeterl Member" (Facies D in Stingl & Krois, 1991) comprises the well known coal measures and laminated bituminous marls („Häringer Kohle" and "Bitumenmergel"; Fig. 4). The main distribution area is restricted to the Häring area and the Duxer Köpfl near Kufstein (Fig. 1).

The sediments of the Bergpeterl Mb. overlie breccias of the Lengerergraben Mb. or the Triassic bedrock. The succession starts with a thick (1–10 m) coal measure. Above the coal, a series of regularly bedded bituminous carbonate sandstones rich in bivalve debris, bryozoans and other biogenic detritus follows. The bedding planes of these sandstones are locally rich in plant fossils, and most of the well preserved plant fossils (von Ettingshausen, 1853) were found in this unit. Upsection, the carbonate sand-

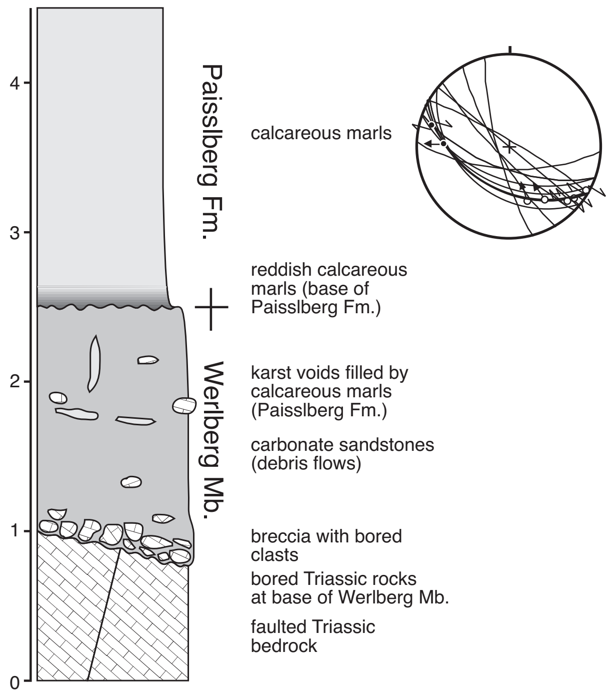


Fig. 4: section of the Werlberg Mb. at stop 1. Above: Orientation of neptunian dykes, sealed faults (open symbols) and faults sealed by neptunian dykes (black symbols).

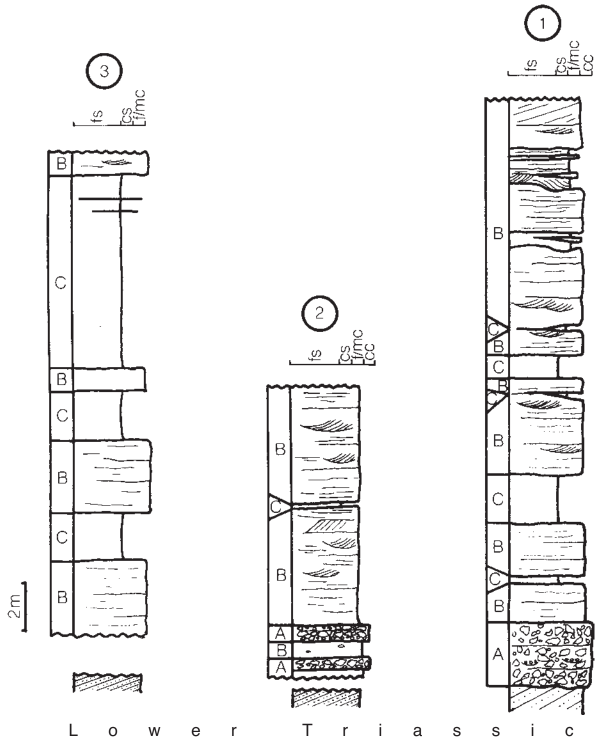


Fig. 5: Type section (1) of the Lengerergraben Mb. in the Schuhreißergraben valley (stop 2). Sections 2 (Lengerergraben valley) and 3 ("Burg") illustrate the lateral facies changes in transport direction. A, B, C refer to the facies associations of STINGL & KROIS (1991).

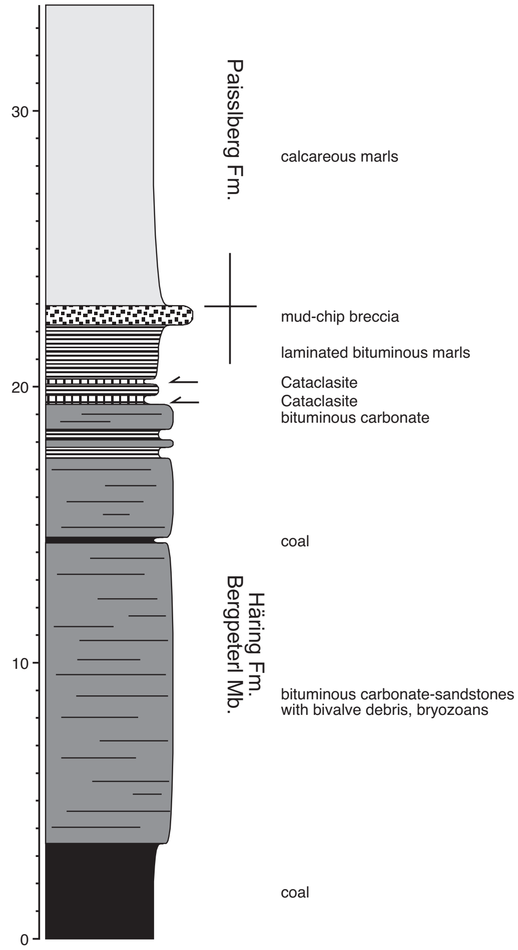


Fig. 6: Type section of the Bergpeterl Mb. in the Juliusschacht in the Bergpeterl quarry at stop 4.

stones start to alternate with thinly laminated bituminous marls, and the carbonate sandstones disappear. The very top of the Bergpeterl Mb. is marked by a coarse-grained fossiliferous layer (up to 20 cm in thickness), with reworked intraclasts, rare Triassic carbonates with borings, and small mud chips, (Heißel, 1956; Stingl & Krois, 1991; Krois, 1992).

3.3.3 Main features to be observed

On the southern side of the middle road to the quarry, the bituminous carbonate sandstones are exposed. Plant fossils are abundant. Between the lower and the middle road, boulders of bedrock (Wetterstein limestone) are surrounded by a matrix of bituminous marls. This breccia is interpreted as a scarp breccia, which formed along a fault inside the basin. In map view, these scarp breccias are arranged in W(NW)-E(SE)-direction. Together with the evidence of the sealed dextral faults (see section 4.1) we interprete this as evidence for active dextral shearing before deposition of the calcareous marls (Fig. 7).

3.4 Around the Juliuschacht in the Bergpeterl quarry

3.4.1 Location

The type locality and type section (Fig. 2) of the Bergpeterl Mb. of the Häring Fm. (see Fig. 3) is situated in the NE corner of the Bergpeterl quarry at the northern side of the Paisslberg mountain (ÖK 121, Neukirchen am Großvenediger, coordinates 47,4983°N/ 12,1233°E), in and near the socalled "Juliusschacht".

3.4.2 Main features to be observed

The northeastern part of the Bergpeterl quarry provides good exposures of the Bergpeterl Member of the Häring Fm. Thinly laminated bituminous marls alternating with equally bituminous carbonate sandstones are present. Slumping is common.

The bituminous marls and the calcareuos marls above are cut by a series of ENE-striking sinistral faults. Folding parallel to the fault planes points to a strong compressional component during sinistral shearing. Between steep faults, sinistral shearing led to folding with vertical axes (Fig. 8). In map view, these faults are cut by younger WNW-striking dextral faults (Fig.1). This is in contrast to the observation in outcrop 3.1, where similarly oriented faults are sealed by Oligocene rocks.

3.5 Central part of Bergpeterl quarry

3.5.1 Main features to be observed

The Paisslberg Fm. consists mainly of dark grey to greenish marls and marly limestones with an overall thickness of about 200 m of Early Oligocene age (NP22, Löffler, 1999). The lower part is more carbonatic, the upper one shows higher clay content. The Paisslberg Fm. also includes coarse limestone breccias and conglomerates (the former "Lithothamnienkalkbreccie"; Nebelsick et al., 1996, 2001; Fig. 9) and autochthonous shallow water carbonates mentioned by Heißel (1951) and Nebelsick et al. (2001). The wide distribution of these carbonates allows the separation of a mapable member within the Paisslberg Fm. (Werlberg Member, see stop 3.1).

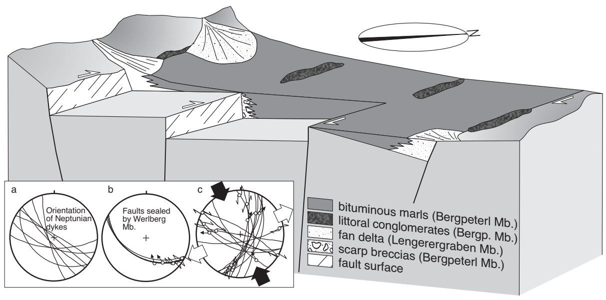


Fig. 7: Block diagram of the Inntal area during deposition of the Häring Fm. WNW-trending dextral faults dissected the area and formed half-graben shaped small restricted basins. Inset: a) Orientation of neptunian dykes filled by flowstones and debris from Werlberg Mb., b) WNW-trending dextral faults sealed by the Werlberg Mb. of the Paisslberg Fm., c) brittle fault plane data set compatible with a) and b) indicating NNW-SSE directed compression.

faults in outcrop Berpeterlbruch

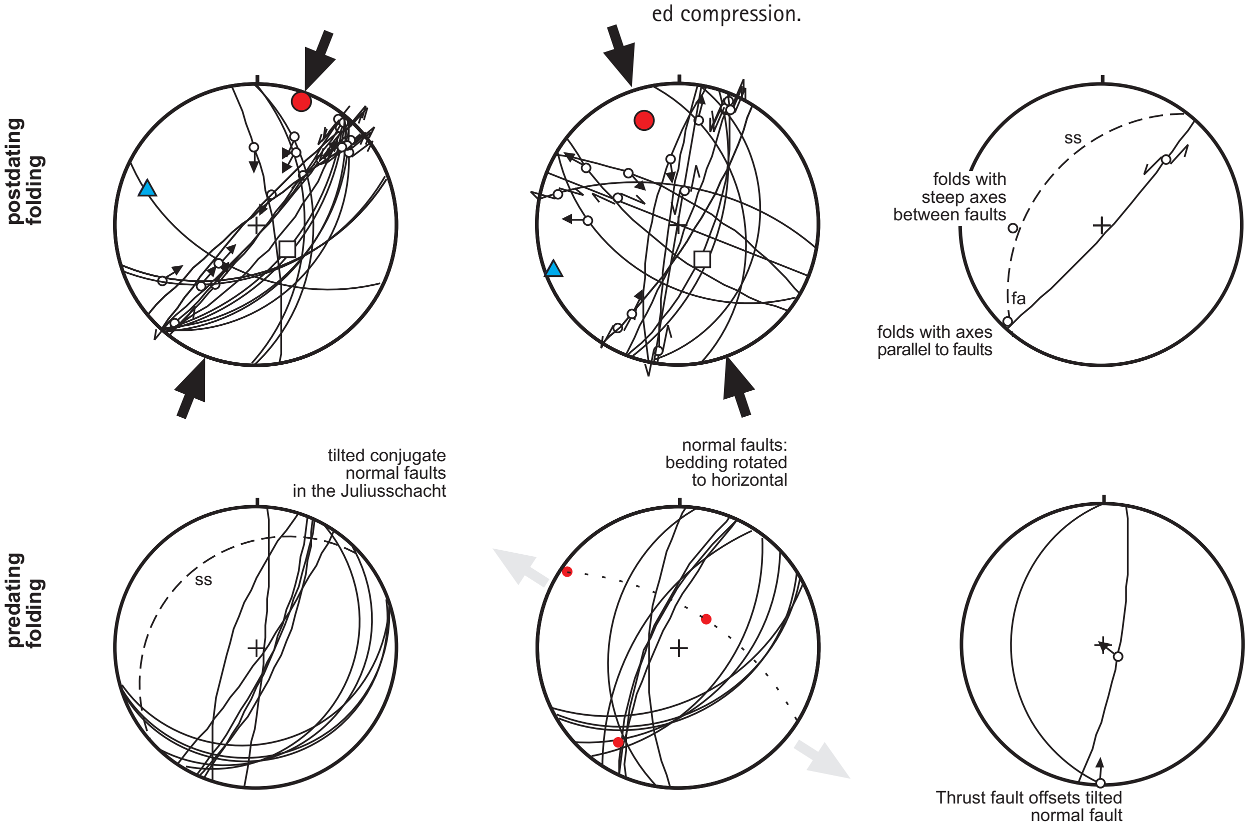


Fig. 8: Faults in the outcrop Bergpeterlbruch, stops 3 & 4. Tilted normal faults predate folding of Oligocene rocks and can possibly be seen in connection with Oligocene sinistral shearing in the area (see also stop 7). Dextral and sinistral shearing postdates folding, and in map view sinistral faults offset dextral faults.

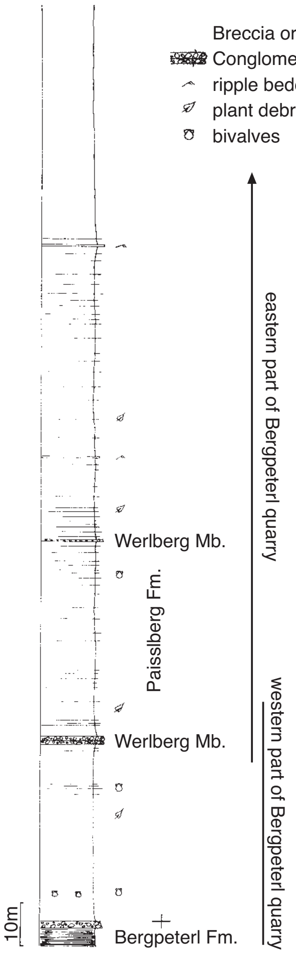


Fig. 9: Type section of the Paisslberg Fm. in the Bergpeterl quarry (with intercalations of carbonate breccias of the Werlberg Mb., see chapter 3.2.1.). For location see Fig. 1.

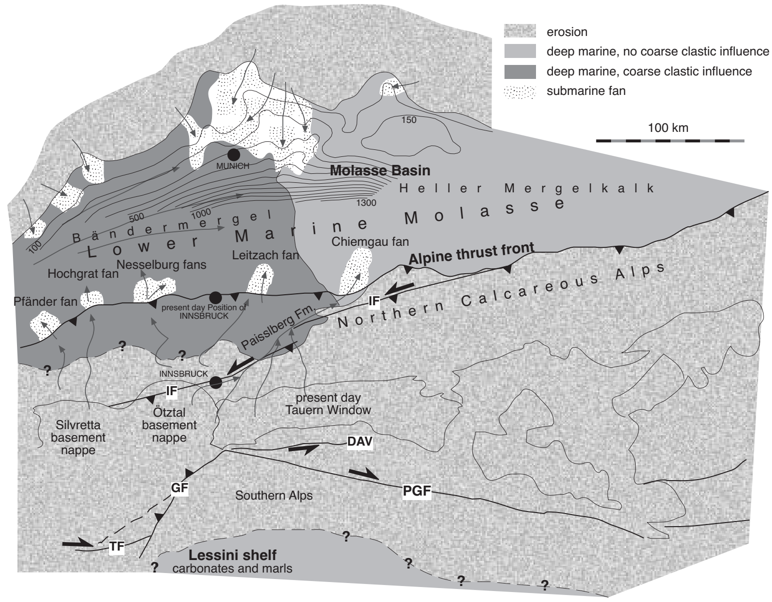


Fig. 10: Paleogeographical sketch of the Eastern and Southern Alps during the Middle Rupelian, at the transition from transgressive to highstand systems tract in Molasse Basin ("Heller Mergelkalk" = condensed section). Isolines in northern part of Molasse basin indicate increase of thickness of Rupelian deposits to the south. Alpine nappes are taken back to a possible Rupelian position following Freudenberger & Schwerd (1996). Major active faults at approximately 33 Ma: IF...Inntal shear zone (this study), TF...Tonale fault, GF...Giudicarie fault, DAV...Defreggen-Antholz-Vals line, PGF...Pustertal-Gailtal fault (Mancktelow et al. 1999). Most of the area of the Alpine orogen was subject to erosion. Generally, during the Early Oligocene the sedimentary cover of the central Alpine basement units was eroded.

The overall development indicates a transgressive trend within the marly sediments. As deduced from the increasing abundance of planktic foraminifera (Lühr, 1962; Lindenberg, 1965; Cicha et al., 1971; Hagn et al., 1981) sedimentation depth increases from 50–200 m in the lower part to 200–600 m (possibly up to 1000 m) in the higher part. Löffler (1999) also inferred water depths from the lower neritic to the upper bathyal zone from the analysis of mollusc faunas. The deepening of the sedimentation area responds to the combination of sea level rise and tectonic subsidence. The intercalation of coarse- to fine-grained debris flows and slumping horizons in the marls may result from local tectonic movements (Krois, 1992).

3.5.2 Suggested points of discussion

Facies differentiation in the basal part of the Paisslberg Fm. indicates contemporaneous carbonate production on intrabasinal highs and deposition of calcareous marls in deeper parts of the basin. The depositional area rapidly subsided from continental surface to bathyal depth from the Earliest Oligocene onwards. The distribution of horsts and grabens is clearly a result of local tectonic movements, whereas the regional subsidence must be a result of a more regional process, like the formation of a foreland basin. The paleogeography reconstructed for the Early Rupelian (Ortner & Stingl, in press) with a southern basin margin (Werlberg Mb.) exposed in the Inn Valley, and the basin open to the north is in favour of the foreland basin interpretation.

3.6 Kakirite Langkampfen

3.6.1 Location

The outcrop is located in a old gravel pit behind the motorway restaurant near Langkampfen (ÖK 89, Blatt Angath, coordinates 47,4822°N/12,0667°E).

3.6.2 Main features to be observed

The Inntal fault is directly exposed only in very few locations. In this outcrop light grey dolomite (Wetterstein dolomite) is pervasively sheared. In distinct shear zones, the dolomite is crushed to silt- to sand-size particles, and the shear zones are slightly cemented. Locally, clayey fault gouge is present in the shear zones, indicating that the outcrop is located at the contact between Oligocene rocks and Wetterstein dolomite. Between the shear zones, the rocks are broken to cm – to dm- size fragments. The kakirite has a thickness of at least 100m.

3.6.3 Suggested points of discussion

Can offset of the Inntal fault be estimated from the thickness of kakirites in the Inn Valley? The problem is, that the contribution of thrust faulting and strike slip faulting cannot be clearly separated. In this outcrop, the last increment of shearing was sinistral strike-slip faulting, but possibly kakirites formed in a thrust regime.

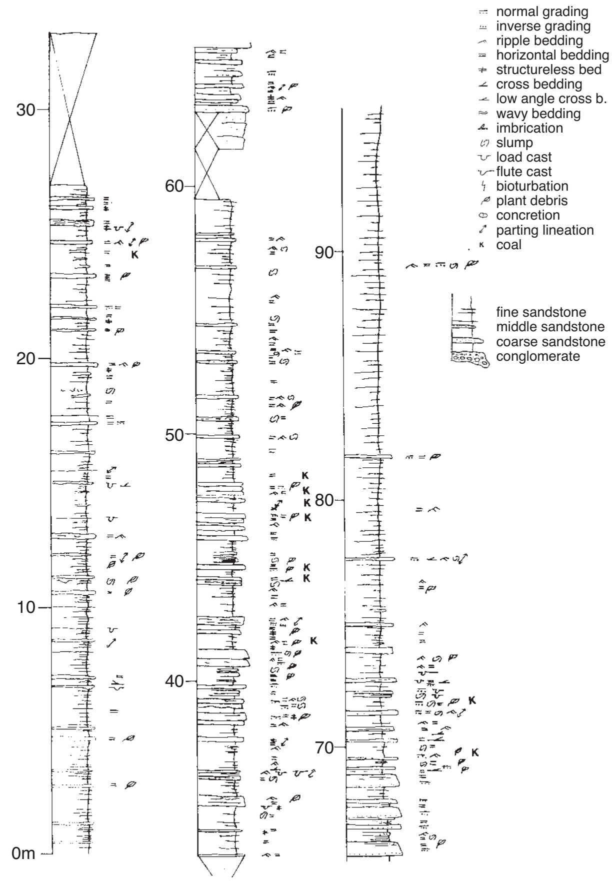


Fig. 11: Section Angath: Type section of the Unterangerberg Fm. at stop 7.

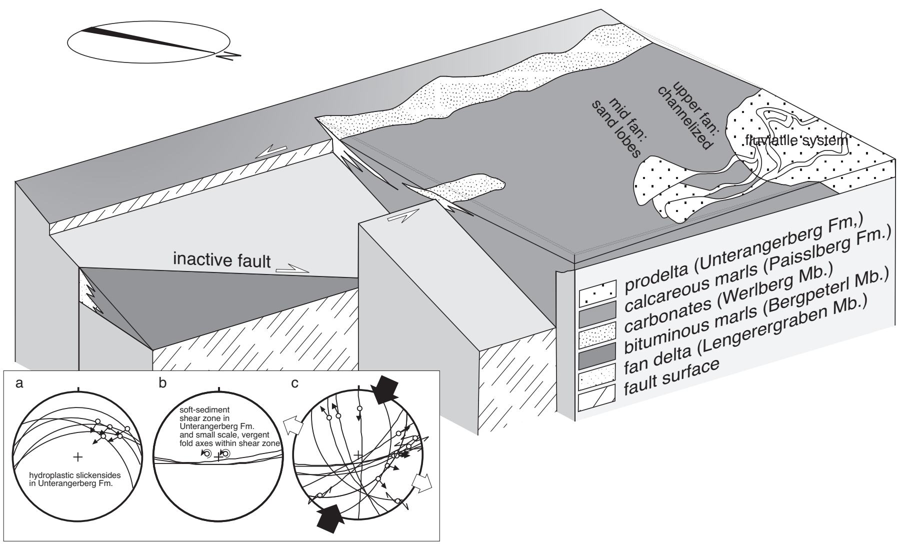


Fig. 12: Block diagram of the Inntal area during deposition of the Paisslberg and Unterangerberg Formations. Werlberg Mb. rims the southern margin of the basin and isolated horsts inside the basin. Fault blocks between active sinistral faults show half graben geometry. From the west, a fluviatile system approaches, with the Unterangerberg Fm. in a prodelta position. Inset: a) Top SW reverse faults with hydroplastic slickensides indicating activity before final lithification, b) shear planes in pseudoductile shear zone (great circles) and small scale fold axes with vergence of folds indicating a sinistral shear sense, c) brittle fault plane data set compatible with b) indicating NNE-SSW compression.

Fig. 13: Deformational structures in the Unterangerberg Fm. of the Unterangerberg. a) to e) illustrate progressive deformation by increasing bed-parallel shortening. a) incipient shortening leads to „crenulation" of the siltstone-marl-interface at the base of a siltsone bed. b) cuspate-lobate structure at the base of a sandstone bed. c) interaction of slumping and tectonic shortening at base of sandstone bed, both overprinting flute casts. d) formation of small scale blind thrusts above ramps, preserving a flat bed top. e) stacking of sandstone beds. f) shear zones with penetrative deformation.

3.7 Inn promenade near Angath

3.7.1 Location

The outcrop is located along the Inn promenade west of Angath (ÖK 89, Blatt Angath, coordinates 47,5000°N/12,0583°E).

3.7.2 Main features to be observed

The Unterangerberg Fm., developing from the Paisslberg Fm. by an increase in siliciclastic detritus, consists of sandstone-marl (or mudstone)-interbeddings with some fine-grained conglomerates, all arranged in fining-upward cycles. These small-scale cycles are stacked to fining-upward and thinning-upward large-scale cycles, reaching thicknesses from 1 to 20 meters. The overall trend in cycle stacking displays a coarsening- and thickening-upward development from base to top of the Unterangerberg Fm., culminating in the sedimentation of the Oberangerberg Fm.

Bedding type (graded, horizontal and ripple bedding) and sedimentary structures (typical sole marks) point to turbiditic sedimentation in a small submarine fan. The large-scale cycles can be interpreted as channel fills or levees of suprafan lobes in the distal to mid-fan area (Krois, 1992; Ortner, 1996). The entire Unterangerberg Fm. represents a coarsening- and thickening-upward megacycle, which indicates the progradation of the fan. Transport directions vary in a broad range, with an average trend from NW to SE, partly to NE.

The poorly developed foraminiferal fauna shows an increase of the abundance of benthic forms towards the top and indicates a Rupelian age (Hagn, 1960; Lindenberg, 1965; Hamdi, 1969).

The Unterangerberg beds are folded with WNW-trending axes in dekametric folds. West of the promenade along the Inn river, deformational structures in the Unterangerberg beds indicate synsedimentary top SW thrusting (Fig. 13, 14).

3.8 Kleinsöll

3.8.1 Location

The section Kleinsöll is located in a creek SW of the village of Kleinsöll and along the adjacent bank of the Inn river (ÖK 120, Blatt Wörgl, coordinates 47,4800°N/11,9867°E).

3.8.2 Main features to be observed

The Höllgraben section represents the lower boundary of the Oberangerberg Fm. Towards the top, the Unterangerberg Fm. is dominated by marly sedimentation (Fig. 15). The coarse-grained clastic sequence upsection consists of m-thick trough cross-bedded conglomerates with intercalated marls. The clast spectrum is dominated by Late Cretaceous and Paleogene pebbles (Moussavian, 1984).

While cross-bedded conglomerates are interpreted as submarine channel fills in the mid- to upper fan area, poorly stratified to structureless conglomerates represent submarine debris flows. The sequence of the Höllgraben conglomerate points to a transition from the mid-fan area to the upper fan and consists of an interfingering of channel fills, debris flows, and fine-grained unchannelized slope sediments (Ortner, 1996).

3.8.3 Suggested points of discussion

A topographic barrier must have formed during deposition of the upper part of the Paisslberg Fm. preventing the debris produced by erosion of the Alps being directly shed into the Molasse basin. This gives some indirect evidence of the existence of an steep fault forming a topographic barrier to the north.

3.9 Breitenbach

3.9.1 Location

The Breitenbach outcrop is located in a small creek, where it is crossed by a footpath with a wooden brigde (ÖK 120, Blatt Wörgl, coordinates 47,5211°N/11,9844°E).

3.9.2 Main features to be observed

In the Breitenbach outcrop, a thrust plane is exposed, which superimposes kakirites of the Hauptdolomite Fm. onto Oligocene marls of the Unterangerberg Fm. The generally south-dipping contact could be part of a major thrust of the Greywacke zone and the southerly adjacent units onto the Lechtal nappe of the Northern Calcareous Alps, as seen in the TRANSALP seismic section (Fig. 16).

3.9.3 Suggested points of discussion

The Northern Calcareous Alps are traditionally subdivided into thrusts of different age. The out of sequence thrusts as seen on the seismic section (Fig. 16) do not fit the traditional thrust architecture of the Northern Calcareous Alps. They cut the Bajuvaric nappe stack; only the contact between Tirolic and Bajuvaric nappes coincides with the thrust in the Inn Valley.

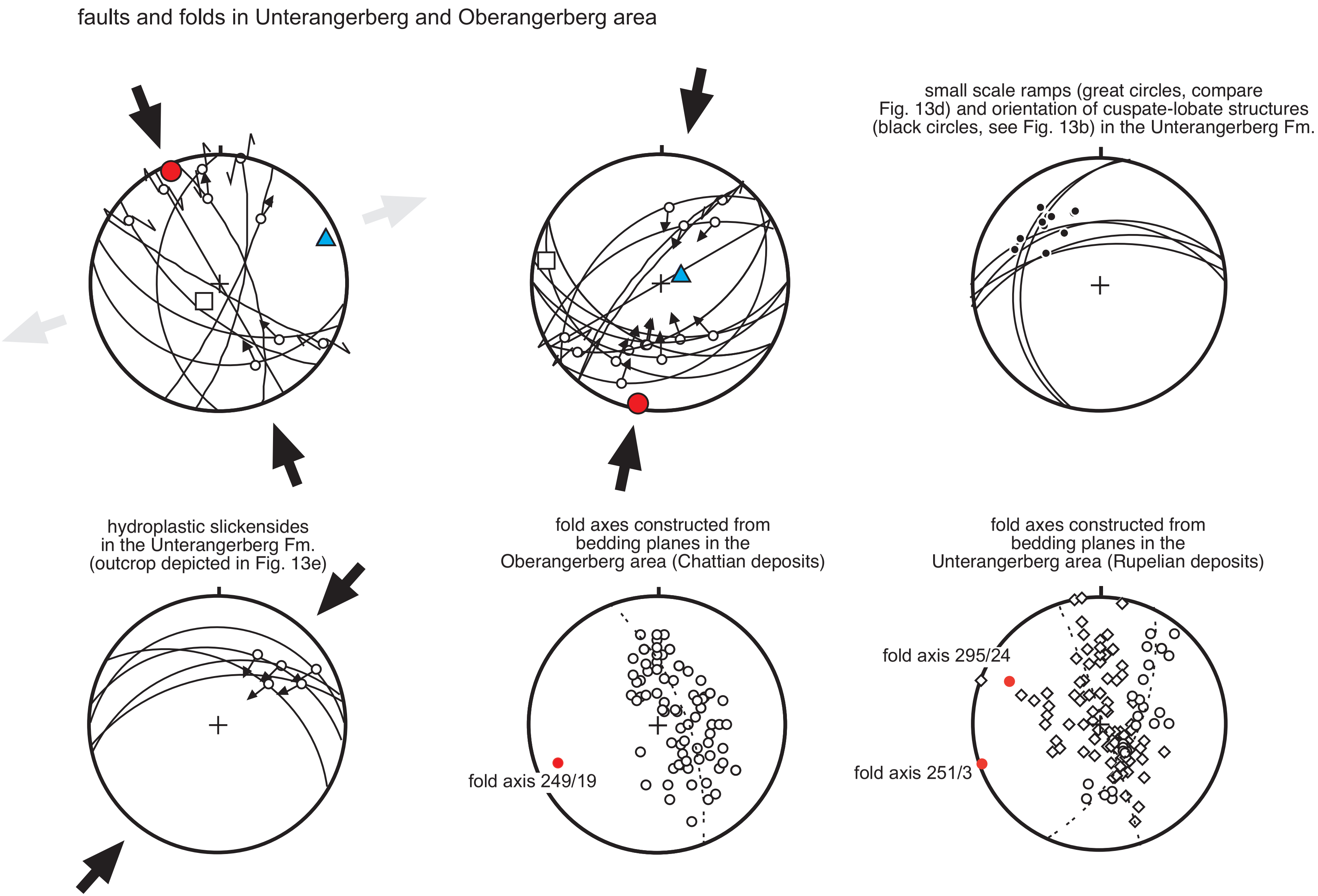


Fig. 14: Orientation of tectonic structures in the Unterangerberg- and Oberangerberg area.

3.10 Voldöpp

3.10.1 Location

The section Voldöpp lies along a small road from the northeatsern part of Kramsach to the Oberangerberg (ÖK 120, Blatt Wörgl, coordinates 47,4533°N/ 11,9100°E).

3.10.2 Main features to be observed

Section Voldöpp is designated as type section for the Oberangerberg Fm. (Fig. 18). The dominating lithofacies types present are component supported coarse conglomerate beds with or without normal grading with imbricated components. Occasionally planar cross bedding is observed in the topmost portion of conglomarate beds. Horizontal laminated sand- to siltstones, occasionally ripple cross bedding interrupt the conglomerate sedimentation. The coarse conglomerates of a slightly sinuous, braided river system (Krois & 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 Fm. is not unequivocal. Plant fossils (Cinnamomum cf. scheuchzeri and C. cf. spectabila Heer) indicate an Oligocene to Miocene age (Hamdi, 1969). Only the sequence stratigraphic interpretation of the succession provides some evidence for the lower boundary of the Oberangerberg Fm. 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 Fm., the erosional upper boundary of the Inn Valley Tertiary must still be within the Oligocene. Modelling of the thermal history of the Oligocene based on vitrinite reflectance data in the Häring - Oberangerberg area resulted in the prediction of a total thickness of 1300m of eroded sediment (Ortner & Sachsenhofer, 1996). More than 1000m thickness of the Oberangerberg Fm. is preserved north of the Kaisergebirge (Fig. 17, D–D').

3.11 Kramsach/Mariatal

3.11.1 Location

The outcrop is located at the western side of the road from Kramsach to Aschau near the Mariatal monastery (47,4528°N/11,8633°E).

3.11.2 Main features to be observed

Conglomerates of the Oberangerberg Fm. are in direct contact to Hauptdolomite Fm. Therefore the Oberangerberg Fm. seals part of the topography created during Oligocene shearing along the Inntal fault.

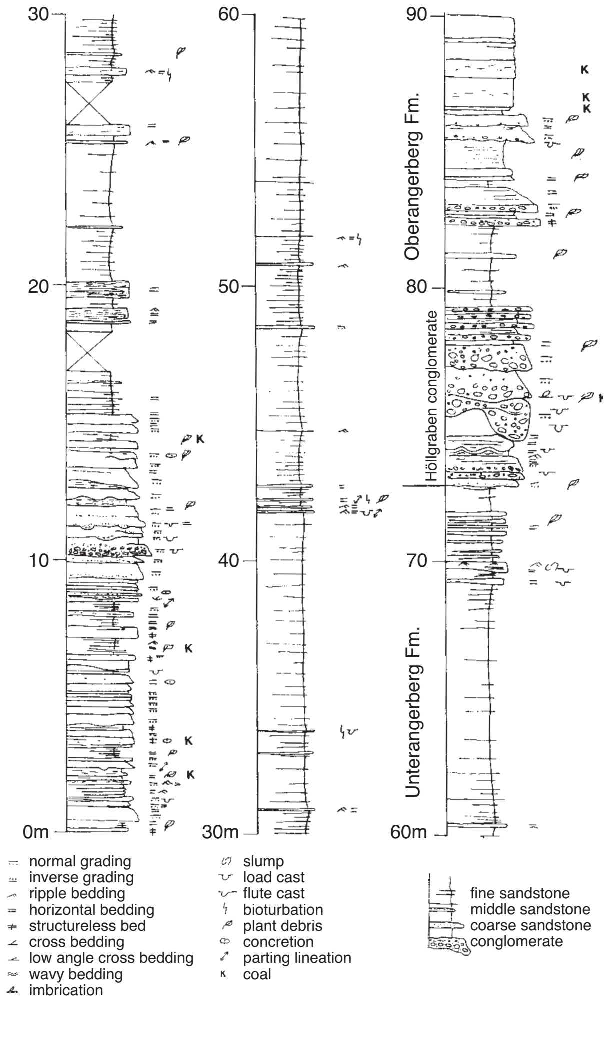


Fig. 15: Section Kleinsöll: Reference section for the upper boundary of the Unterangerberg Fm., and the base of the Oberangerberg Fm. (Höllgraben conglomerate) at stop 8.

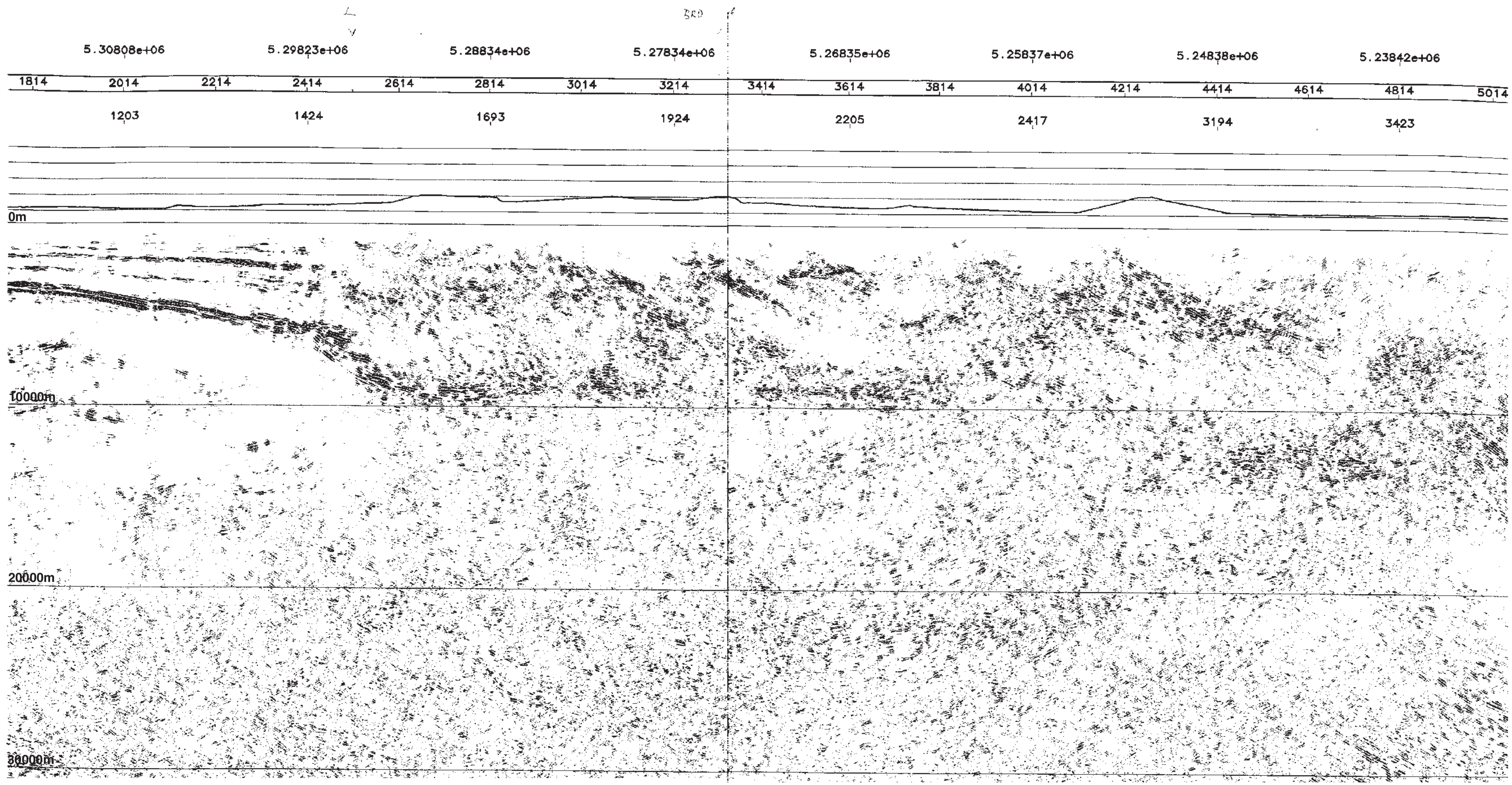


Fig. 16: Northern part of the TRANSALP seismic section from the southern Molasse Basin to south of the Inn Valley. The most prominent reflectors in the Northern Calcareous Alps are south-dipping, relativly straight thrusts.

3.11.3 Suggested points of discussion

The distribution of Oligocene coarse conglomerates along the Inntal fault indicates the presence of a fluvial system guided by an orogen-parallel, subvertical fault (Fig. 18). Augenstein deposits, only present south of the Inntal fault, are interpreted to be redeposited gravels belonging to old tributaries of a paleo-Inn fluvial system. Uplift of the Augenstein pene-plain might be a result of younger re-newed activity of the (thick skinned) thrust in the Inn Valley.

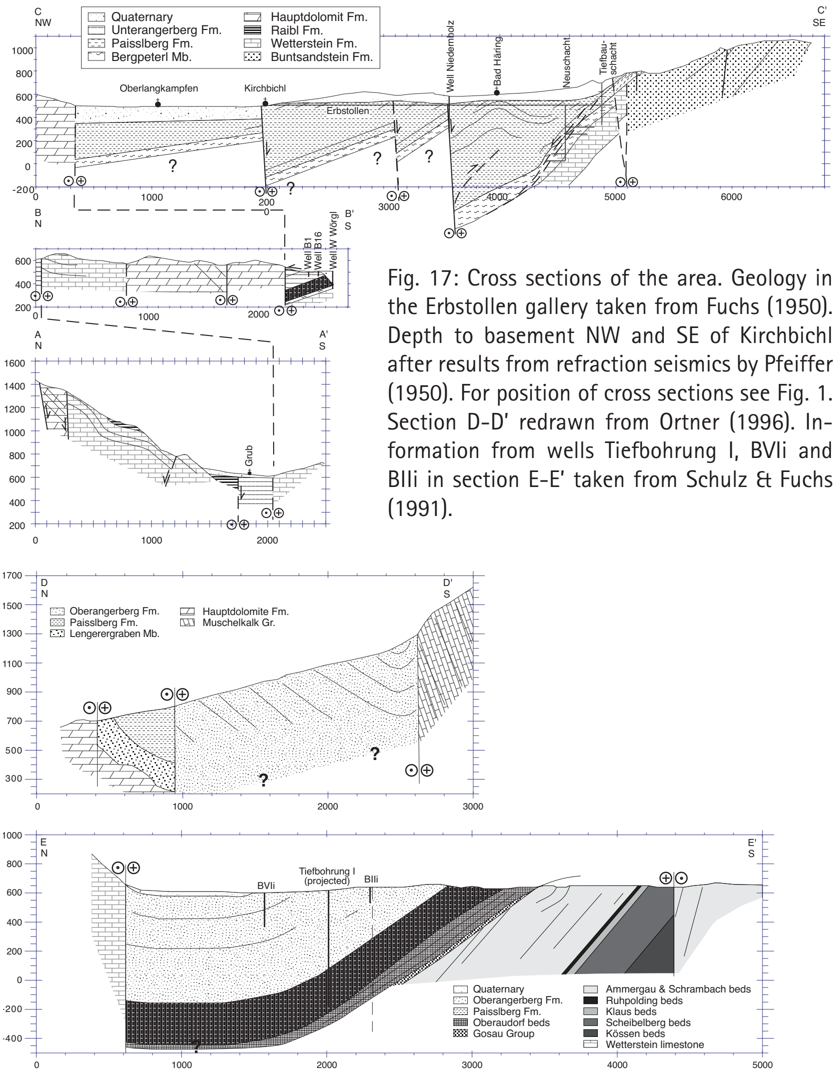


Fig. 17: Cross sections of the area. Geology in the Erbstollen gallery taken from Fuchs (1950). Depth to basement NW and SE of Kirchbichl after results from refraction seismics by Pfeiffer (1950). For position of cross sections see Fig. 1. Section D-D' redrawn from Ortner (1996). Information from wells Tiefbohrung I, BVIi and BIIi in section E-E' taken from Schulz & Fuchs (1991).

4 Additional information

4.1 Subsidence curves

The thermal and subsidence history of the Oligocene in the Lower Inn Valley was simulated by Ortner & Sachsenhofer (1996). Subsidence curves in accordance with the observed coalification indicate rapid or accellerating subsidence throughout the Oligocene and Early Miocene (Aquitanian) combined with a low heat flow (70 mW/m2; Fig. 20a). Subsequently, subsidence was slow until the Middle Miocene, when uplift and erosion started because of thrusting and shearing along the Inntal shear zone. The Molasse basin also rapidly subsided during Oligocene and Early Miocene and slowly subsided afterwards. Uplift in the Molasse basin started much later in the Late Miocene (Fig. 20b; Zweigel et al., 1998; Jacob et al., 1982; Homewood et al., 1986).

Remarkably the subsidence curves for both the Molasse basin and the Oligocene of the Lower Inn Valley do display uniform or even increasing subsidence throughout the Oligocene. Subsidence did not decrease, when the basin stopped becoming deeper, but started to fill, and the onset of limnofluviatile conditions near the Rupelian - Chattian boundary was not related to uplift.

Therefore, the stratigraphic development in the Molasse basin is generally controlled by eustasy (Zweigel et al. 1998), but the transgressive-regressive cycles were mainly dependent on the interplay between accomodation space and sediment input into the basin, both strongly affected by tectonics. Accomodation space was created by the flexural event after collision of the European and Adriatic plates in Eocene times (e.g. Homewood et al., 1986), as reflected by the subsidence curve. Sediment input was mainly controlled by erosion rates and thus by the tectonic history of internal parts of the orogen.

Previous studies of the tectonic development of the Oligocene in the Lower Inn Valley put forward a pull apart origin of the basin (Ortner, 1996; Ortner & Sachsenhofer, 1996). However, the open marine facies of the Paisslberg Fm. is not in accordance with a local basin, and the overall similarities in subsidence and sequence development between the Molasse basin and the Oligocene of the Lower Inn Valley rather calls for a genetic link between the two depositional areas.

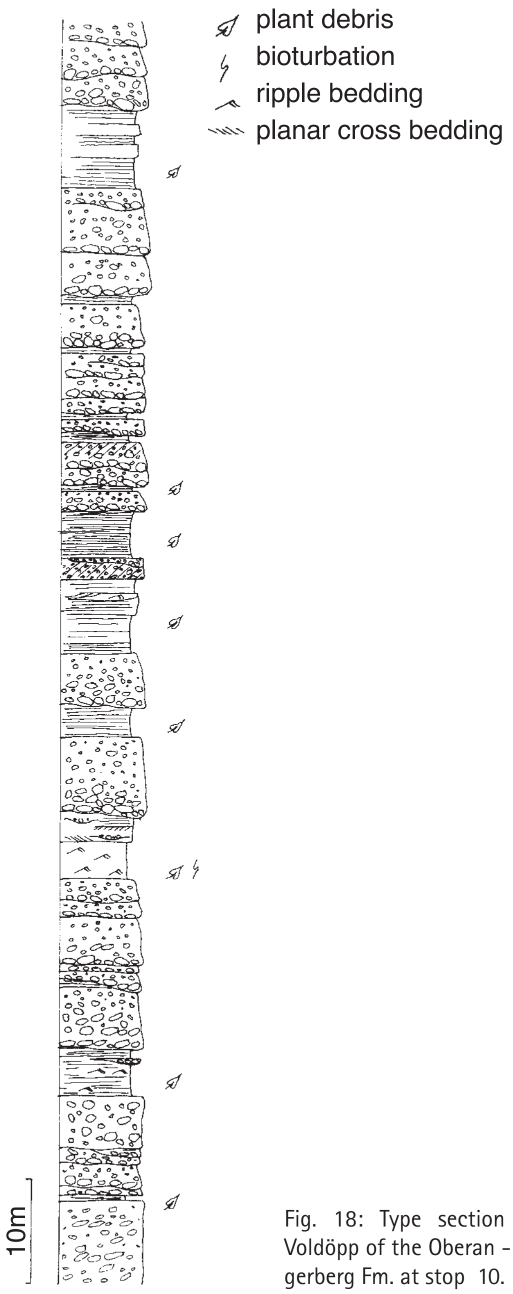


Fig. 18: Type section Voldöpp of the Oberan - gerberg Fm. at stop 10.

4.2 Basin formation and deformation

Basin formation and deformation were influenced by processes at two scales: 1) Evolution of the Alpine orogenic wedge and its foreland basin (Molasse basin) and 2) shearing along the Inntal fault. In the following paragraphs, local deformation is shortly discussed on the base of analysis of brittle fault planes and depositional geometries. A detailed sur - vey of brittle deformation in the investigated area will be published elsewhere (compare Ortner, 1996; Ortner & Sachsenhofer, 1996).

4.2.1 Shearing

Synsedimentary faulting can be reconstructed throughout the Oligocene. The faults below are thought to shape local topography in the area, but they cannot account for the overall subsidence of the basin.

4.2.1.1 Early Rupelian (D1)

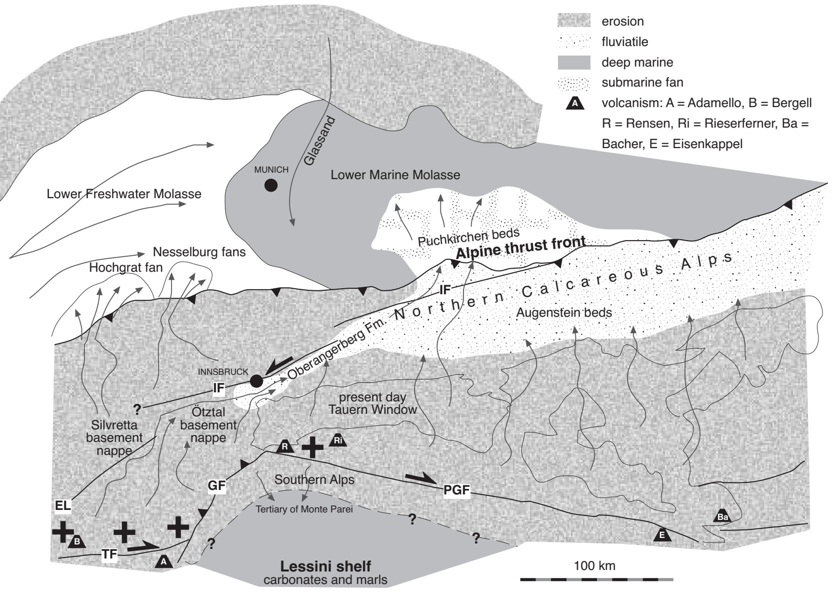
Scarp breccias in the Bergpeterl Mb. of the Häring Fm. are bound to WNW-ESE trending faults. Neptunian dykes in Mesozoic rocks underlying Oligocene sediments, which are filled by redeposited carbonates (Werlberg Mb.) and calcareous marls (Paisslberg Fm.) trend in the same direction (Figs. 4, 7a). In a few locations fault planes are sealed by carbonates of the Werlberg Mb. (Figs. 4,7b). Analysis of the sealed fault planes and comparable planes indicates NW-SE directed shortening accomodated by dominant WNW-trending dextral strike-slip faults and conjugated N-S trending sinistral strike-slip faults (Fig. 7c).

Vertical offset across dextral faults is in the range of a few tens of meters. Along the faults, elongate depressions with half graben geometry formed, filled by bituminous marls (e.g. Dux area; Fig. 2, 7).

4.2.1.2 Late Rupelian (D2)

The Unterangerberg Fm. was locally deformed prior to lithification. This led to formation of pseudoductile structures in the sediments (Fig. 13, 14). The Unterangerberg is cut by several shear zones with top SW displacement. In the hangingwall of the shear zones decametric, SW-verging folds developed. In an early stage of folding, layer parallel shortening led to the formation of cuspate-lobate folds at the interface of sandstone and marl layers with contrasting competence (Figs. 13b, 14). In - creasing shortening formed sets of conjugate ramp faults in sandstone beds (Figs. 13d, 14), sometimes with hydroplastic slickensides (Fig. 13e, 14), that often disappear within the bed. Near a major branch of the Inntal shear zone, a vertical E-W trending shear zone with sinistral sense of shear was observed. All these features of late Rupelian deformation can be integrated into a model of overall oblique thrusting along ENE-trending faults. Along

Fig. 19: Paleogeographical sketch of the Eastern and Southern Alps during the Chattian. Alpine thrust front drawn at present day position. Periadriatic volcanics were eroded, as documented by pebbles in Oberangerberg Fm. and Molasse basin. The western part of the Molasse basin was filled, the eastern part remained a deep marine basin. The Augenstein Fm. was deposited east of the Inntal fault on top of the Northern Calcareous Alps (Frisch et al. 1998). + indicates uplift. Major faults active faults at approximately 25 Ma: IF ... Inntal shear zone (this study), EL ... Engadine line (Schmid & Froitzheim, 1993), TF ... Tonale fault, GF ... Giudicarie fault, PGF ... Pustertal-Gailtal fault (Schmid et al., 1989). Southern Alps drawn following Luciani (1989) and Keim & Stingl (2000).



branches of the Inntal shear zone, strike-slip faults connected to the thrusts show sinistral displacements.

On a larger scale, the Paisslberg and Unterangerberg Formations successively buried the evolving topography. During sedimentation of the lower part of the Paisslberg Fm., the basin margin, or uplifted portions of fault blocks with (half-) graben geometry carried carbonate buildups (Werlberg Mb.). Debris flows transported material from these buildups into the basin (allochthonous carbonates of the Werlberg Mb.). Continued shearing increased the half-graben relief, resulting in large thicknesses of the Paisslberg Fm. adjacent to the faults, as documented by the outcrops in the Häring mine and the well Niedernholz (Fig. 17, cross section C-C'). Lateron, the local topography was completely covered by the Paisslberg and Unterangerberg Fms.

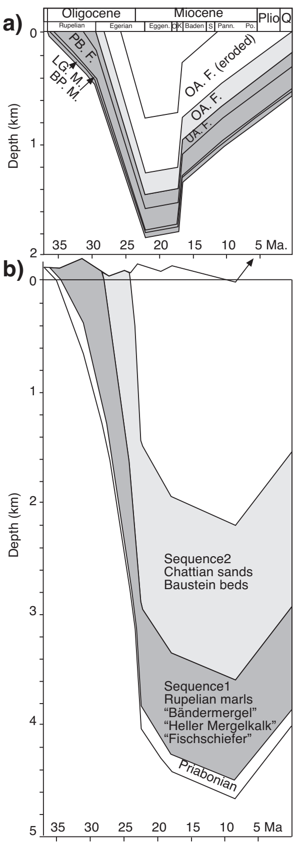


Fig. 20: a) Subsidence curve for the Oligocene in the Lower Inn Valley redrawn from Ortner & Sachsenhofer (1996).Timescale after Steininger et al. (1988/89) for Oligocene sediments and Steininger et al. (1990) for Miocene sediments. b) Subsidence curve for a well SSE of Munich in the Molasse basin simplified from Zweigel et al. (1998). Absolute ages taken from Harland et al. (1990) and Steininger et al. (1985). Minor differences between the curves due to differences in time scales. Abbreviations: BP. M. = Bergpeterl Mb., LG. M. = Lengerergraben Mb., PB. F. = Paisslberg Fm., UA. F. = Unterangerberg Fm., OA. F. = Oberangerberg Fm.

4.2.1.3 Chattian

During the Chattian, the river system depositing the Oberangerberg Fm. transported debris from the western part of the central Alps to the Chiemgau fan west of Salzburg at the southern margin of the Molasse basin, guided by the Inntal fault (Fig. 19). Conglomerates of the Augenstein beds, which are interpreted to represent redeposited remains of the Oberangerberg Fm. (Ortner & Sachsenhofer, 1996) are only found south of the Inntal shear zone, indicating that the Northern Calcareous Alps north of the shear zone formed a topographic barrier constraining the course of the paleo-Inn River (Fig. 19). Therefore, continued (?sinistral) activity of the Inntal fault zone throughout the Chattian is probable.

4.2.1.4 Post-Oligocene deformations

The main effect of post-Oligocene deformation was folding of the Paleogene deposits with WSW-trending axes (D3). Large scale folds several km in wavelength formed (e.g. cross section E - E', Fig. 17). Probably this deformation was accompanied by renewed thrusting on the Inntal thrust. The folds were cut by a set of ENE-striking, sinistral transpressive faults (D4) that reactivate faults formed during D2. In a late stage of this deformational event, N-S-striking oblique normal faults developed, which are interpreted to represent antithetic riedels to the Inntal fault zone. Dextral normal offset across these mostly east-dipping faults led to west-plunging fold axes in Oligocene deposits. Normal faults striking slightly oblique to the Inn Valley overprinted Quaternary rocks in the area west of Kufstein (D5). They were responsible for Quaternary graben formation in the Inn Valley.

4.2.2 Interpretation

NW-directed shortening during Early Rupelian (D1) possibly reflects northward translation and concurrent counterclockwise rotation of the Adriatic microplate (Peresson & Decker, 1997). Shortening was replaced by orogen-parallel extension during the Rupelian (see above) after crustal thickening in the Lepontine area by backthrusting along the Insubric line (Schmid et al., 1989). Central Alpine units moving towards the east in the Late Rupelian (contemporaneous to Niemet-Beverin/Turba extension) were delimited to the north by sinistral faults like the Inntal shear zone (D2; Fig. 8).

Post-Oligocene deformations in the area are mainly the effect of the formation of the Southalpine Indenter with its tip south of Innsbruck. Before the Middle Miocene, the area experienced mainly folding as documented in Oligocene sediments (D3). However, shortening in the meridian of Innsbruck led to backthrusting and uplift of the Tauern Window, and to major orogen-parallel extension, leading to eastward movement of Central Alpine units (Ratschbacher et al., 1991, Fügenschuh et al., 1997). Again, eastward moving blocks were delimited to the north by ENE-trending sinistral faults. The Inntal shear zone was reactivated (D4). Graben formation in the Inn Valley (D5) during the Quaternary might be an effect of adjustment of the Alpine wedge to isostatic uplift in its central parts.

In summary, Oligocene and Miocene brittle deformation in the Inntal area is the result of the interplay of local and far-field stresses controlled by double indentation of Adriatic crust into the Alps. Oligocene indentation in the Western Alps led to Insubric backthrusting and crustal thickening, followed by orogen-parallel extension. Miocene indentation in the Eastern Alps again led to thickening and subsequently orogen-parallel extension east of the Brenner meridian. Periods of crustal thickening led to kinematic coupling across the Periadriatic line, so that the NNW-SSE oriented far-field stress is observed in the Alps (D1, D3). During orogen-parallel extension, local stress fields controlled by large orogen-parallel faults delimiting extruding blocks are found in the Alps (D2, D4).

References

Bachmann, G. & Müller, M. (1991): Sedimentary and structural evolution of the German Molasse Basin. Eclogae Geologicae Helvetiae, **85**, 519–530, 6 Abb., Basel.

Cicha, I., Hagn, H. & Martini, E. (1971): Das Oligozän und Miozän der Alpen und der Karpaten. Ein Vergleich mit Hilfe planktonischer Organismen. Mitt. bayer. Staatssammmlg. Paläont. hist. Geol., **11**, 279–293, München.

Freudenberger, W. & Schwerd, K.(1996): Erläuterungen zur geologischen Karte von Bayern 1:500 000. – 329 p., 67 Abb., 21 Tab., 8 Taf., München.

Frisch, W. (1979): Tectonic Progradation and Plate Tectonic Evolution of the Alps. Tectonophysics, 60, 121–139, 8 Abb., 1 Tab., Amsterdam.

Fuchs, A.(1950): Bericht über tektonische Untersuchungen im Bergbaugebiet von Häring und in dessen Umgebung. Unpubl. Report, 10 p., 8 Taf., Kramsach.

Fuchs, W. (1976): Gedanken zur Tektogenese der nördlichen Molasse zwischen Rhone und March. Jahrbuch der Geologischen Bundesanstalt, **119**, 207–249, 1 Tab., 2 Taf., Wien.

Fuchs, W.(1980): Die Molasse des Unterinntales.- In: Oberhauser, R. (eds.): Der geologische Aufbau Österreichs, 152–155, 1 Abb., Wien (Springer).

Fügenschuh, B., Seward, D. & Mancktelow, N. (1997): Exhumation in a convergent orogen: the western Tauern window. Terra Nova, **9**, 213–217, 3 Abb., Oxford.

Hagn, H. (1960): Die stratigraphischen, paläogeographischen und tektonischen Beziehungen zwischen Mo -

lasse und Helvetikum im östlichen Oberbayern. Geologica Bavarica, **44**, 1–208, München.

Hagn, H., Hillebrandt, A. V., Lindenberg, H. G., Malz, H., Martini, E., Moussavian, E. & Urlichs, M.(1981): Kalkalpines Mesozoikum und Alttertiär zwischen Reit im Winkel und dem Inn. Exkursion C. In: Hagn, H. (ed.): Die Bayerischen Alpen und ihr Vorland in mikropaläontologischer Sicht, Geologica Bavarica, 82, 133–159, München.

Hamdi, B.(1969): Das Tertiär des Ober - und Unterangerberges im Unterinntal (Tirol). Unveröff. Diss. Univ. Innsbruck, 146 S., Innsbruck.

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G. & Smith, D. G.(1990): A geological time scale 1989. — 263 p., Cambridge.

Heissel, W. (1951): Beiträge zur Tertiärstratigraphie und Quartärgeologie des Unterinntals. Jahrbuch der Geologischen Bundesanstalt, **94**, 207–222, 2 Abb., 2 Taf., Wien.

Heissel, W. (1956): Zur Geologie des Unterinntaler Tertiärgebietes. Mitteilungen der Österreichischen Geologischen Gesellschaft, **48 (1955)**, 49–70, 1 Taf., Wien.

Homewood, P., Allen, P. A. & Williams, G. D.(1986): Dynamics of the Swiss Molasse Basin. In: Allen, P. A. & Homewood, P. (eds.): Foreland Basins, Special Publication Nr. 8 of the International Association of Sedimentologists, 199–217, 16 Abb., Oxford (Blackwell).

Jacob, H. Kuckelkorn, K. & Müller, M. (1982): Inkohlung und Tektonik im Bereich der gefalteten Molasse, insbesondere am Beispiel der Bohrung Staffelsee 1. Erdöl und Kohle, **35/11**, 510–518, 9 Abb., Leinfelden.

Keim, L. & Stingl, V. (2000): Lithostratigraphy and facies architecture of the Oligocene conglomerates at Monte Parei (Fanes, Dolomites, Italy). Rivista Italiana di Paleontologia e Stratigrafia, 106, 123–132, Milano.

Krois, P.(1992): Aspekte zu Sedimentologie und Fazies des inneralpinen Tertiärs (Oligozän) im Raum Häring-Angerberg, Tirol. Unveröff. Diss. Univ. Innsbruck, 158 S., 65 Abb., Innsbruck.

Krois, P. & Stingl, V. (1991): Faziesanalyse fluviatiler Sedimente – eine Fallstudie in den Oberangerberger Schichten (Oberoligozän, Tirol). Jahrbuch der Geologischen Bundesanstalt, **134**, 299–308, 9 Abb., Wien.

Lindenberg, H. G. (1965): Die Bolivinen (Foram.) der Häringer Schichten. Mikropaläontologische Untersuchungen im Alttertiär des Unterinntal-Gebietes. Boll. Soc. Pal. It., **4/1**, 64 - 160, 32 Abb., 8 Taf., Padova.

Löffler, S. - B. (1999): Systematische Neubearbeitung und paläoökologische Aspekte der unteroligozänen Molluskenfauna aus den Zementmergeln von Bad Häring (Unterinntal, Tirol). Tübinger geowiss. Arb., Reihe A, **54**, 207 p., Tübingen.

Luciani, V. (1989): Stratigrafia sequenziale del Terziario nella catena del Monte Baldo. Memorie di Scienze Geologiche, **41**, 263–351, 43 Abb., 1 Tab., 5 Taf., Padova.

Lühr, H. (1962): Geologische und mikropaläontologische Untersuchungen im Alttertiär von Häring/Tirol. Unveröff. Diss. TU München, 174 S., 16 Abb., 9 Taf., München.

Mancktelow, N. S., Meier, A., Viola, G. A. M., Müller, W., Fügenschuh, B., Seward, D. & Villa, I. (1999): The Periadriatic and adjacent fault systems in the Eastern Alps south and west of the Tauern window. In: Szekely, B., Frisch, W., Kuhlemann, J. & Dunkl, I. (eds.): 4th Workshop on Alpine geological studies, 21.–24. September 1999, Tübinger geowissenschaftliche Arbeiten 52, 7–9, Tübingen.

Moussavian, E. (1984): Die Gosau- und Alttertiär-Gerölle der Angerbergschichten (Höheres Oligozän, Unterinntal, Nördliche Kalkalpen). Facies, **10**, 1–86, Erlangen.

Nebelsick, J., Stingl, V., Ortner, H. & Krois, P. (1996): Sedimentologie und Palökologie der unteroligozänen Kalke des Unterinntaler Tertertiärs (Tirol). Sediment '96, Abstracts, 117, Wien.

Nebelsick, J., Stingl, V. & Rasser, M. (2001): Autochthonous facies and debris flows compared: Lower Oligocene carbonates of the Lower Inn Valley (Tyrol, Austria). Facies, **44**, 31–46, 4 Abb., 3 Tab., 2 Taf., Erlangen.

Ortner, H. (1996): Deformation und Diagenese im Unterinntaler Tertiär (zwischen Rattenberg und Durchholzen) und seinem Rahmen. Diss. Univ. Innsbruck, 234 S., Innsbruck.

Ortner, H. & Sachsenhofer, R. (1996): Evolution of the Lower Inntal Tertiary and Constraints on the Development of the Source Area. In: Liebl, W. & Wessely, G. (eds.): Oil and Gas in Alpidic Thrust Belts and Basins of Central and Eastern Europe, EAEG Spec. Publ. No. 5, 237–247, 8 Abb., 4 Tab., London.

Ortner, H. & Stingl, V. (2001): Facies and Basin Development of the Oligocene in the Lower Inn Valley, Tyrol/Bavaria. In: Piller, W. & Rasser, M. (eds.): Paleogene in Austria, Schriftenreihe der Erdwissenschaftlichen Kommissionen, **14**, 153–196, Wien (Österreichische Akademie der Wissenschaften).

Peresson, H. & Decker, K. (1997): The Tertiary dynamics of the northern Eastern Alps (Austria): changing palaeostresses in a collisional plate boundary. Tectonophysics, **272**, 125–157, Amsterdam.

Pfeiffer, A. (1950): Bericht über die refraktions-seismischen Untersuchungen im Auftrage der „Kohlenberg -

bau Häring" reg. Gen.m.b.H. Unpubl. Report, 8 p., Feuchten.

Ratschbacher, L., Frisch, W., Linzer, G. & Merle, O. (1991): Lateral extrusion in the Eastern Alps, Part 2: Structural analysis. Tectonics, **10/2**, 257–271, 8 Abb., 1 Tab., Washington.

Schmid, S. M. Aebli, H. R., Heller, F. & Zingg, A. (1989): The Role of the Periadriatic Line in the Tectonic Evolution of the Alps.- In: Coward, M. P., Dietrich, D. & Park, R. G. (eds.): Alpine Tectonics, 153–171, 8 Abb., Oxford.

Schmid, S. M. & Froitzheim, N. (1993): Oblique Slip and Block Rotation along the Engadine Line. Eclogae Geol. Helv., **86/2**, 569–593, 6 Abb., 1 Taf., Basel.

Schulz, O. & Fuchs, H. W. (1991): Kohle in Tirol: Eine historische, kohlenpetrographische und lagerstättenkundliche Betrachtung. Archiv für Lagerstättenforschung der Geologischen Bundesanstalt, **13**, 123–213, 60 Abb., 29 Tab., Wien.

Steininger, F. F., Bemor, R. L. & Fahlbusch, V. (1990): European marine/continental chronological correlations. In: Lindsay, E. H. et al. (eds.): European Neogene Mammal Chronology, 15–46 (Plenum).

Steininger, F. F., Rögl, F. Hochuli, P. & Müller, C. (1988/89): Lignite Deposition and Marine Cycles. The Austrian Tertiary Lignite Deposits – A Case History. Sitzungsber. math.-naturwiss. Kl. Österr. Akad. Wiss., **197**, 309–332, Wien.

Steininger, F. F., Wessely, G., Rögl, F. & Wagner, L. (1991): Tertiary Sedimentary History and Tectonic Evolution of the Eastern Alpine Foredeep. Giornale di Geologia, ser. 3, **48/1–2**, 285–295, Bologna.

Stingl, V. & Krois, P. (1991): Marine Fan Delta Development in a Paleogene Interior Alpine Basin (Tyrol, Austria). Neues Jahrbuch für Geologie und Paläontologie, Monatshefte, 7, 427–442, Stuttgart.

Von Ettingshausen, C. (1853): Die tertiäre Flora von Häring in Tirol. Abh. Geol. Reichsanst., **2**, 1–118, Wien.

Zweigel, J., Aigner, T. & Luterbacher, H.(1998): Eustatic versus tectonic controls on Alpine foreland basin fill: sequence stratigraphy and subsidence analysis in the SE German Molasse. In: Mascle, A. (ed.): Cenozoic foreland basins of western Europe, Special Publication of the London Geological Society No. 134, 299-323, London.

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