Neogene pull-apart basins in the Eastern Alps (Austria)

By

WILFRIED GRUBER, REINHARD F. SACHSENHOFER & MICHAEL WAGREICH

With 13 figures

Field Trip Guide

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Addresses of the authors:
Wilfried Gruber
HOT Enginering GmbH
Parkstrasse 6
8700 Leoben
Austria
Email: wgruber@hoteng.com

Reinhard F. Sachsenhofer
Montanuniversitaet Leoben
Department Angewandte Geowissenschaften
Lehrstuhl Erdölgeologie
8700 Leoben
Austria
Email: reinhard.sachsenhofer@unileoben.ac.at

Michael Wagreich
University of Vienna
Department of Geodynamics and Sedimentology
Althanstrasse 14
1090 Vienna
Austria
Email: Michael.wagreich@univie.ac.at

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Content

Abstract

Neogene basins within the Eastern Alps of Austria exemplify the typical formation and evolution of intramontanous pull-apart basins of late orogenic stages. The Neogene Fohnsdorf and Leoben basins were formed along the sinistral Mur-Mürz fault system during the late stage of the Alpine orogeny. Despite of great differences in sediment thickness (Fohnsdorf: >2 km; Leoben: 400 m), the sedimentary successions in both basins are largely similar.

Basin formation commenced in early Miocene time with the deposition of coarse-grained alluvial-fluvial sediments (Fohnsdorf Formation) characterized by large differences in thickness and local, immature facies. During middle Miocene times a single thick coal seam (top of Fohnsdorf Formation) and lacustrine deposits (Ingering Formation) were laid down including sapropelitic deposits and redeposited bivalve shell layers. This succession was controlled by high subsidence rates characteristic for pull-apart basins giving evidence for sinistral strike-slip movements along the Mur-Mürz fault system. A significant brackish influence during this time interval is unique for the Fohnsdorf Basin. Moreover coal deposition in the Fohnsdorf Basin occurred in a low-lying mire, whereas Leoben coal originated from a raised mire.

When subsidence rates decreased, deltaic sediments filled the lakes from the north. South-directed sandy delta foreset propagation resulted in a large coarsening upward cycle topped by fluvial conglomerates.

The subsequent half-graben phase in the Fohnsdorf Basin is characterized by alluvial fan deposits of middle Miocene age (Apfelberg Formation). Two distinctly different alluvial fans entered the basin from the south, characterized by different types of debris flows. Northwards, and upwards within the succession, alluvial fans grade into deltaic to fine-grained lacustrine sediments including minor coal layers and rare tuffs.

After the deposition of the lower to middle Miocene basin fill, a calcite tufa system ("Mariabucher Sinter") originated at the southwestern margin of the Fohnsdorf Basin, probably related to dextral strike-slip and a positive flower structure along the Pöls-Lavanttal fault system. Isotope composition indicates that fluids originated from formation waters of the Miocene basin fill.

1. Topics and area of the field trip

Neogene pull-apart basins are located in the lowlands and hilly areas of the Eastern Alps. They formed during the final stages of the Alpine orogeny and are a consequence of lateral escape along major strike-slip faults (RATSCHBACHER et al. 1991). Along the Mur-Mürz fault system, one of these large sinistral strike-slip faults, several small basins subsided as pull-aparts and half-grabens (DECKER & PERESSON 1996, NEUBAUER et al. 2000). Although the thickness of the basin fill varies significantly from a few hundred metres (e.g., Leoben Basin) to more than 2 km (e.g., Fohnsdorf Basin), the general stratigraphic succession is largely similar in all basins:

Typically, these intramontane basins are filled from bottom to top by alluvial-fluvial sediments, a single thick coal seam, lacustrine and deltaic rocks. This sequence reflects the high subsidence rates characteristic for these tectonically controlled basins (SACHSENHOFER et al. 2003). Outcrops with alluvial-fluvial conglomerates at the base of the basin fill, coal seams and organic-rich mudstones, coarse sediments at basin margin faults, lacustrine-to-

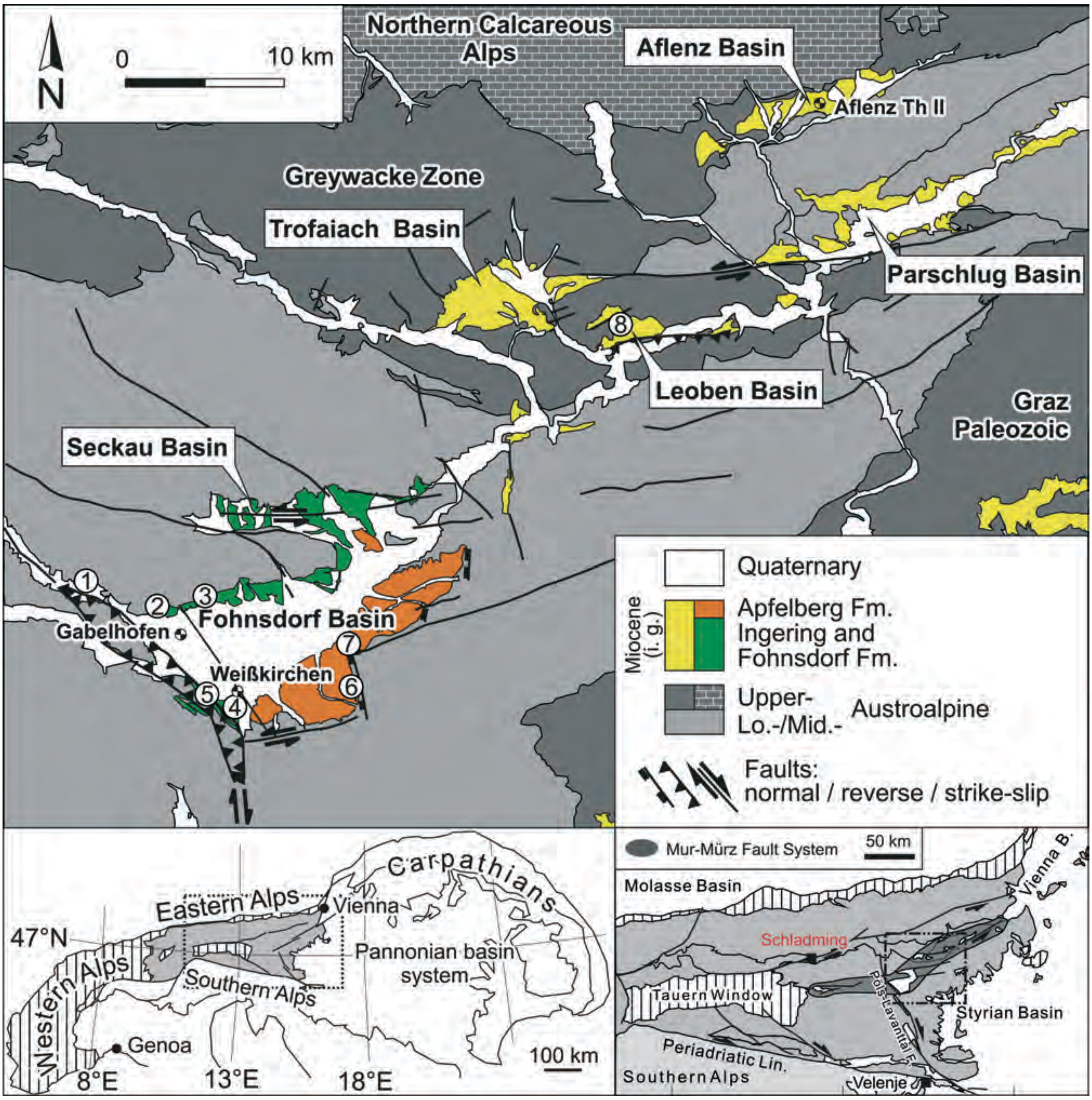

Fig. 1: Sketch map of the study area (modified from Decker & Peresson 1996, Neubauer et al. 2000). Line in the Fohnsdorf Basin represents the seismic section shown in Fig. 6. The location of field trip stops are indicated (1 to 8). The insets show the study area within the Eastern Alps and the Alpine-Carpathian realm.

brackish fine-grained lacustrine strata, and Miocene lacustrine deltaic rocks in the Leoben and Fohnsdorf basins will stimulate discussions on a wide variety of topics including:

· Basin formation and basin inversion during continental collision.
· Sedimentation in pull-apart basins.
· Palaeogeography of the Miocene Alps.
· Coal accumulation in low-lying and raised mires.
· Petroleum source rocks in pull-apart basins.
· Natural resources (coal, coal-bed-methane, geothermal energy, bentonite, construction material).

The location of the field trip area within the Eastern Alps is shown in Fig. 1.

2. Introduction

2.1. Neogene intramontane basins along the Mur-Mürz fault system

Miocene subsidence of small fault-bounded intramontane basins is interpreted as a result of orogen-parallel extension and eastward lateral extrusion of central parts of the Eastern

Alps between major sinistral and dextral wrench faults (e.g., RATSCHBACHER et al. 1991, DECKER & PERESSON 1996). Along the Mur-Mürz fault system (MMF, Fig. 1) several small-scale en-echelon basins such as the Fohnsdorf Basin, the Leoben Basin, the Trofaiach Basin and the Parschlug Basin formed during the Miocene between left-stepping ENE-striking faults (e.g. SACHSENHOFER et al. 2000, 2003, STRAUSS et al. 2001).

The Fohnsdorf Basin is the largest of these basins. It is situated at the junction of the sinistral ENE-trending Mur-Mürz fault system and the dextral NW-trending Pöls-Lavanttal-fault system (PLF; POLESNY 1970, STRAUSS et al. 2001), which were active during Miocene lateral extrusion (DECKER & PERESSON 1996). In contrast, the Leoben Basin (SACHSENHOFER et al. 2010) is a relatively small basin. To the NE, the Mur-Mürz fault system continues into the Vienna Basin Transfer Fault (HINSCH et al. 2005). This fault array and the Pöls-Lavanttal-fault system are considered to delimit one of the major wedges extruding out of the Alpine collision zone to the E (Fig. 1). Extrusion-related intramontane basins have been interpreted as pull-apart basins (DECKER & PERESSON 1996, WANG & NEUBAUER 1998) and extensional half-grabens (NEUBAUER et al. 2000).

2.2. Geological setting and stratigraphy of the Fohnsdorf Basin

The Fohnsdorf Basin comprises an area of about 120 km² (Fig. 1) and a preserved maximum thickness of Cenozoic deposits of about 2000 m according to deep mining, borehole data and seismic sections (SACHSENHOFER et al. 2000a, b). The basin formed on top of Variscan-Alpine metamorphic basement rocks of the Austroalpine unit (SCHUSTER et al. 1999). Neogene strata of the basin fill are largely covered by Quaternary deposits and only a few outcrops of Miocene sediments, mainly along the basin margins, are accessible (POLESNY 1970, STRAUSS et al. 2001, 2003, HÖLZEL & WAGREICH 2004). The Fohnsdorf Basin subsided during the Early to Middle Miocene as a pull-apart along overstepping, east-west trending sinistral strike slip faults of the Mur-Mürz fault system (Fig. 1). Subsequently, tectonic stresses changed, and the strike-slip basin evolved into a halfgraben with major subsidence concentrated in the southern part of the basin (STRAUSS et al. 2001).

The lithostratigraphic subdivision of the Fohnsdorf Basin is based on PETRASCHECK (1926) and POLESNY (1970) and was redefined by SACHSENHOFER et al. (2000) and STRAUSS et al. (2001, 2003). Three lithostratigraphic units can be identified (Fig. 2):

(1) The Fohnsdorf Formation (Early/Middle Miocene; Upper Karpatian to Lower Badenian) was deposited during the early pull apart stage of basin formation, during E-W extension and sinistral strike-slip movement along the Mur-Mürz fault system. The succession is characterized by up to 800 m thick alluvial sediments, mainly breccias, conglomerates and sandstones, including an up to 15 m thick coal seam at the top.

(2) The Ingering Formation (Lower/Middle Badenian) comprises lacustrine to brackish prodelta and fan delta sediments with a maximum thickness of 2000 m. The succession displays a coarsening upward trend, interpreted as a result of delta progradation (SACHSENHOFER et al. 2000, HÖLZEL & WAGREICH 2004). In the lower parts of the formation, pelitic rocks comprising *Congeria* breccias and thin sandy layers of a prodelta facies dominate, overlain by sands with cross bedding interpreted as delta front facies, which grades into quartzite conglomerates and gravelly sands of a delta front to delta plain facies. These deposits form part of a southward prograding delta complex into a lake where a brackish influence can be discerned from geochemistry for the lower part of the formation

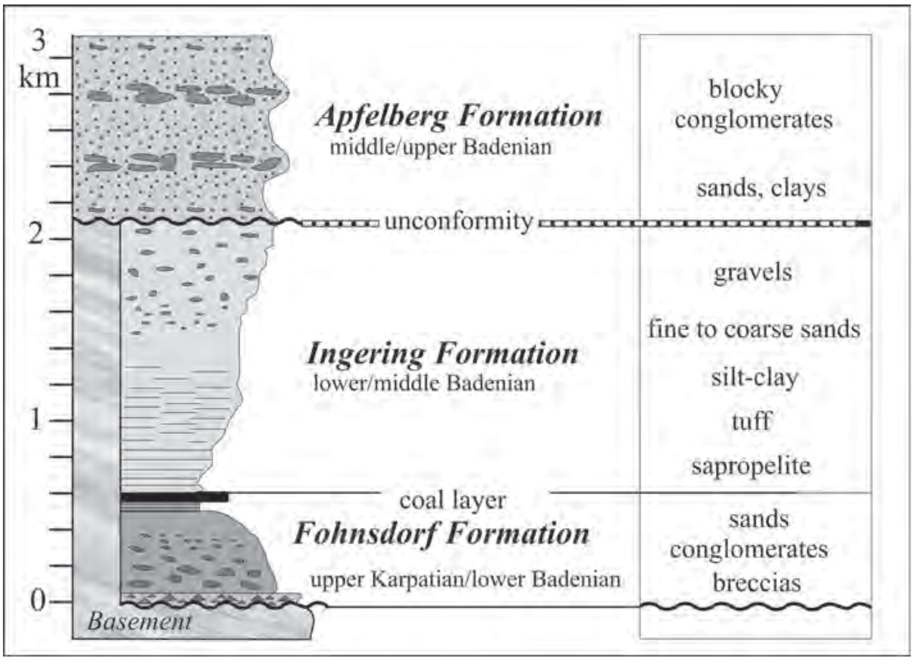

Fig. 2: Sedimentary column in the Fohnsdorf Basin (STRAUSS et al. 2001).

(Sachsenhofer et al. 2003). Heavy mineral and grain size data indicate that the sediments were transported over a short distance and were derived mainly from the northwest (Hölzel & Wagreich 2004). Fission track data from a tuff within the Ingering Formation point to an early to middle Badenian age (14.9 Ma; Strauss et al. 2003).

(3) The Apfelberg Formation (Middle?/Upper Badenian) was deposited during NNW-SSE extension and development of a half-graben. A fission track age from zircons of a tuff layer from the Apfelberg clay pit gave an age of 15.5 ±0.8 Ma which may be slightly too old in relation to the mammal fauna which indicates MN6 (Middle to Late Badenian; Strauss et al. 2003).The Apfelberg Formation is unconformable overlying both the lower formations and metamorphic basement. The formation comprises coarse, syntectonic deposition along normal faults at the southern basin margin. Typical sediments of the Apfelberg Formation are highly immature and matrix supported conglomerates, sandstones and silts with beds containing outsized clasts with sizes up to 30 m³. Conglomerates were deposited mainly from mass flows on alluvial fans (Wagreich & Strauss 2005). In the Apfelberg claypit braided channel-fill sediments can be observed between debris flows, overlain by fine-grained sediments deposited on the subaquatic delta platform. The facies of the sediments indicates a combination of distal alluvial fan/flood plain and a lacustrine fan delta environment. The composition of the coarse-grained sediments and heavy mineral spectras give evidence for two local source areas to the south. Alluvial fan sedimentology was strongly controlled by different source area lithologies.

2.3. Geological setting and stratigraphy of the Leoben Basin

The Neogene basin in the north of Leoben is split by a basement high into the Seegraben and Tollinggraben subbasins (Fig. 3). Basin formation was multiphase and started as a southward tilted halfgraben in a general strike-slip setting (Neubauer et al. 2000, Sachsenhofer et al. 2010). Subsequent deformation was by N-S shortening leading to reverse faulting along the southern basin margin. Sedimentation commenced in small troughs within the phyllitic basement, with the deposition of up to 50 m of coarse grained clastic sediments and thin coaly layers (Lackenschweiger 1937, see Tollinggraben-Seegraben section in Fig. 3). An up to 16 m thick coal seam may overly these alluvial sediments, but normally rests directly on the Paleozoic rocks. The seam is generally poor in ash and sulphur. The high quality of the coal reflects its formation in a raised mire (Gruber & Sachsenhofer 2001). Four laterally persistent intraseam tuffs altered by the acidic environment into kaolinite are present. Both, humic and sapropelic coals occur above the upper tuff (Petrascheck 1926).

The seam is covered by up to 18 m of sapropelic shales, which contain fish remains and a fossil flora with more than 400 species (Ettingshausen 1888). Recently a tuff layer near the base of the sapropelic shales has been dated

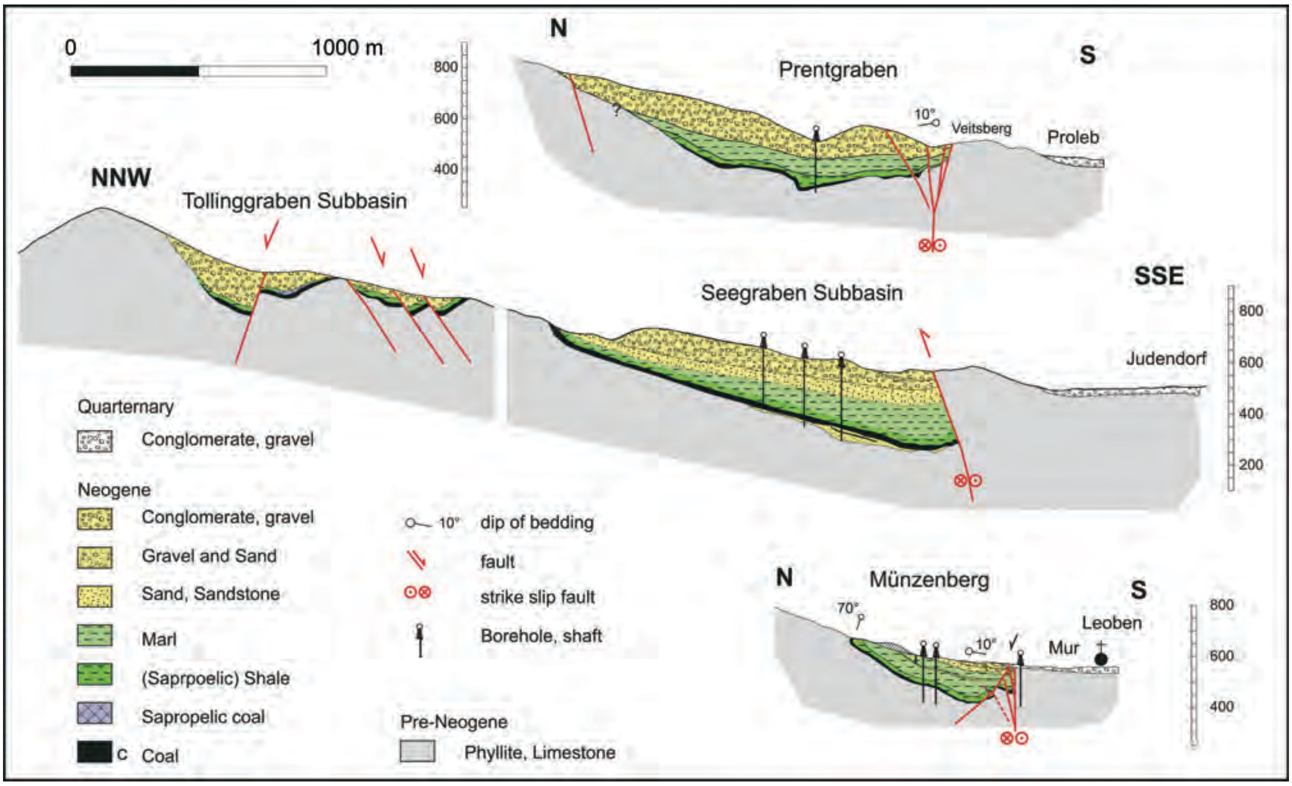

Fig. 3: N-S-trending sections through the Leoben Basin (Sachsenhofer et al. 2010; complied from Petrascheck 1926 and unpublished data from the mining authority).

using the apatite fission track method and yielded an age of 14.9 ± 0.7 Ma (Sachsenhofer et al. 2010). The sapropelic shales grade upwards into marls and sandstones (Lackenschweiger 1937). This sequence thickens towards the south to a maximum of 140 m. The increase in thickness towards the southern parts of the basin points to higher subsidence near the main fault, the early onset of southward tilting or subsequent erosion in the north. Up to 60 m of conglomerates ("Hauptkonglomerat") unconformable overlay major parts of the deeper strata and encroach on surrounding basement rocks. Marly sandstones and conglomerates ("Hangendkonglomerat") form the top of the Miocene strata. A rich vertebrate fauna was found 240 m above the coal seam (Mottl 1970, Weber & Weiss 1983). The sections displayed in Fig. 3 provide information on the basin structure. The main tectonic element of the Leoben basin is a fault along its southern margin. It enters the basin as a sinistral strike slip fault from the east, forming probably a negative flower structure. In the central part of the basin the main fault is turned over into a reverse fault. In the eastern part of the basin the coal seam forms two NW-SE oriented synclines (section Prentgraben in Fig. 3). Dip directions in the sedimentary cover change along a N-S section from generally south to gently north. In the central and western parts of the main basin the deepest section is developed as an asymmetric trough. The major part of the basin is formed by the southward dipping northern limb. Along the formerly mined pinchout of the coal at the northern margin near Münzenberg the seam is turned over to a northward dip of 75 deg (section Münzenberg in Fig. 3; Petrascheck 1926).

3. The Field Trip

3.1. Basin Tectonics

Stop 1: Quarry Oberkurzheim/Pöls (optional stop)
Topic: basement geology and faulting along the Pöls-Lavanttal fault
Coordinates (WGS84): 014°35'10" E, 47°14'00" N

The quarry Oberkurzheim is situated within marbles (probably from Devonian limestones) of the Rappold crystalline complex (Fig. 4). Dextral strike-slip faulting along the Pöls-Lavanttal-fault system is evident from calcite slickenslide fibres. In addition, north-directed thrust structures were reconstructed and interpreted as part of a positive flower structure along the Pöls-Lavanttal-fault system which also affected the eastern basin margin of the Fohnsdorf Basin. Older sinistral strike-slip faulting may be attributed to the primary basin margin fault.

Fig. 4: Foto of a large fault at the entrance into the quarry Oberkurzheim.

3.2. Sedimentology of the Fohnsdorf Basin

Stop 2: Abandoned open cast mine Dietersdorf, base of Fohnsdorf Formation
Topic: Sedimentology of the Fohnsdorf Formation; coal sedimentology; breccias
Coordinates: 014°39'19" E, 47°12'45" N

The abandoned open cast mine Dietersdorf (outcrop 2 in Fig. 5) was covered and cultivated in the last years. The unconformity and onlap of the basin fill onto the metamorphic basement is visible in the upper part of the outcrop, where strongly weathered, brownish garnet-bearing mica schists are exposed. The sediments of the Fohnsdorf Formation dip at an angle of c. 15° to the south. At the base, matrix-rich breccias of debris-flows occur, overlain by fine sandstones and silts with coal layers. Plant fragments and fish remains were found within these sediments which mark the transition from alluvial-fluvial to lacustrine environments.
The top of the Fohnsdorf Formation is formed by a coal seam, up to 15 m thick, which was largely excavated in the open cast mine. The coal (sub-bituminous A coal) is rich in sulphur and ash reflecting its deposition in a low lying, rheotrophic mire with brackish influence (Gruber & Sachsenhofer 2000, Bechtel et al. 2001). Four stages of the evolution of the Fohnsdorf coal seam are shown in Fig. 6.
Organic-matter rich fine-grained rocks ("Brandschiefer") are exposed at the southern margin of the former mine.

Stop 3: Sillweg hiking path, base of Ingering Formation
Topic: Sedimentology of the base of the Ingering Formation; *Congeria* limestones; sapropelites; prodelta silts and sands
Coordinates: 014°42'00" E, 47°13'11" N

After the deposition of the coal seam subsidence increased significantly and a moderately deep lake was formed with deposition of sapropelites and pelitic prodelta strata. This lacustrine-deltaic succession forms a more than 1000 m thick coarsening-upward cycle (Hölzel & Wagreich 2004), indicating decreasing subsidence rates and/or increasing sediment supply. According to seismic data the lake was filled by a large delta from the north. Low organic carbon/sulphur ratios of both coals and overlying shales (Sachsenhofer et al. 2000a, b, 2003) indicate brackish-marine influx. Heavy mineral spectra rich in garnet,

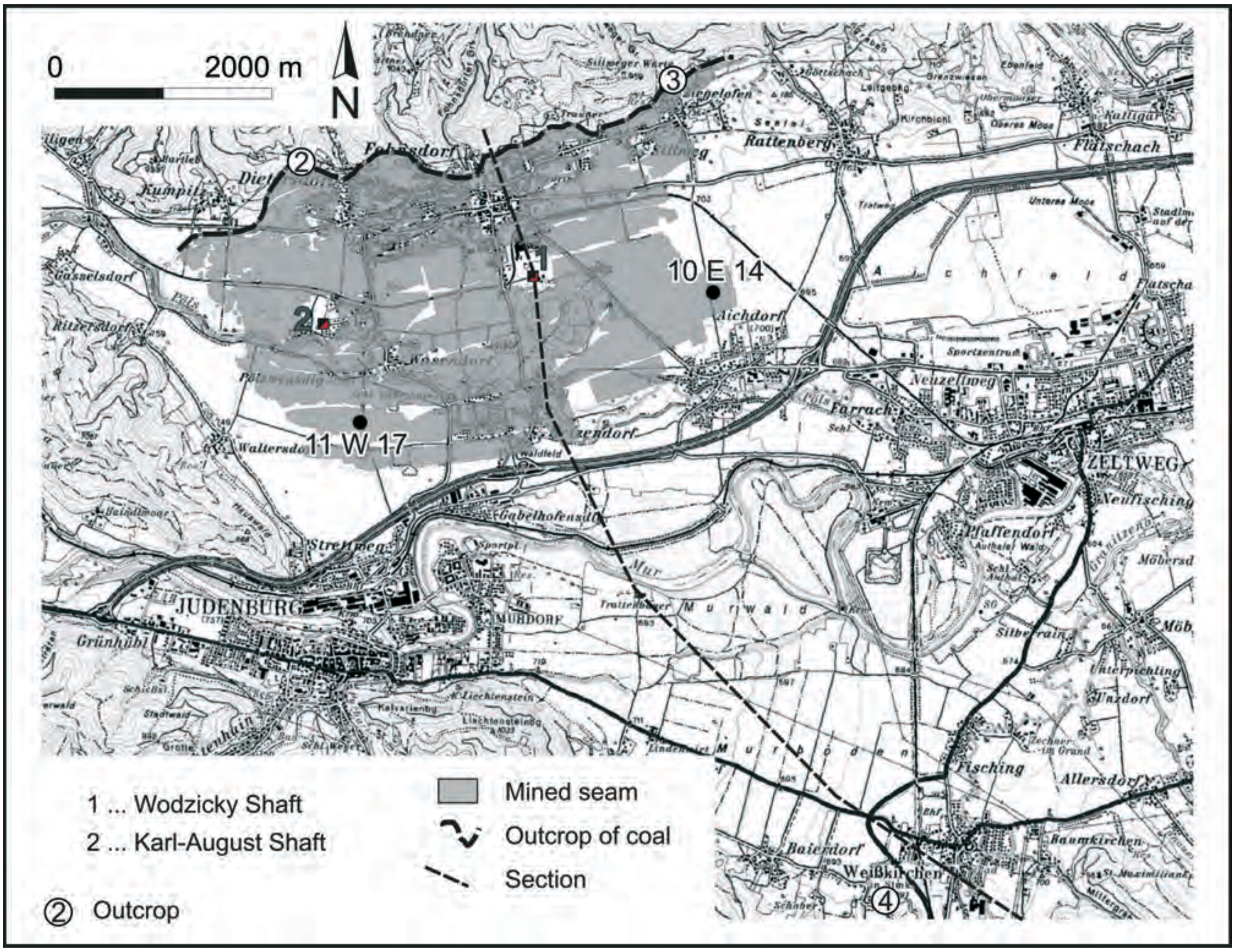

Fig. 5 Map of underground workings in the Fohnsdorf Basin showing the geometry of the coal seam. Areas without mining activity include safety pillars (shafts and settlements) and zones where the coal was faulted out by W-E and SW-NE trending normal faults (SACHSENHOFER et al. 2010).

dominating quartz and micaschist pebbles as well as palaeocurrent data indicate a northern provenance from the basement north of the Seckau Subbasin.

At Sillweg, the Ingering Formation starts above a coal layer with bivalve-bearing dark limestones (*Congeria*) and sapropelites ("Brandschiefer", POLESNY 1970) which indicate flooding of the mire. Above that, lacustrine marly to fine-grained sandy prodelta deposits crop out. The water depth of the lake was probably several hundred meters during this time interval.

Soft-sediment deformational structures such as boudins, S-verging folds, rotated faults and rotated clasts were described from *Congeria* breccias and intervening fine-grained sediments. They result from increasing sediment load and southward sediment failure of mass flows on the depositional delta slope (HÖLZEL et al. 2006).

Stop 4: Weißkirchen clay pit, Ingering Formation (optional stop)

Topic: Sedimentology of the Ingering Formation; delta sands and silts

Coordinates: 014°44‘03" E, 47°08‘54" N

As strata dip generally southward the Weißkirchen clay pit, which is only opened for a short period every year, exposes strata of the upper part of the Ingering Formation. Silty to sandy sediments crop out and characterize the main part of the basin infill during southward progradation of the delta. Seismic sections through the basin clearly display large fore-set packages (Fig. 7).

Stop 5: Maria Buch tufa and Fohnsdorf Formation

Topic: southwestern basin margin tectonics; basal basin fill of the Fohnsdorf Formation; tufa dykes; late Miocene flower structure and geomorphology

Coordinates: 014°42‘13" E, 47°09‘09" N

The small quarry west of village Maria Buch exposes coarse-grained conglomerates of the Fohnsdorf Formation which are cross-cut by younger dykes and veins of tufaceous limestone ("Maria Bucher Sinter"). These white limestones have been extensively used as a local building stone, e.g. for the churches of Maria Buch and Weißkirchen.

The outcrop shows conglomerates with well-rounded clasts

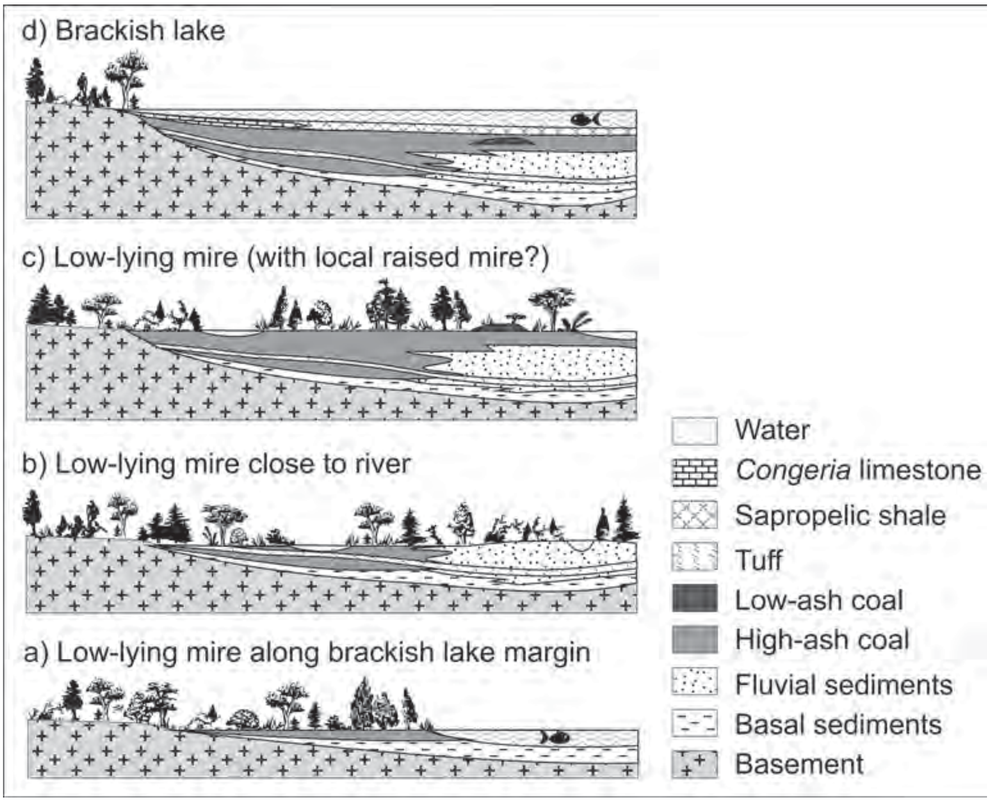

Fig. 6: Cartoon illustrating four stages of the evolution of the Fohnsdorf seam (GRUBER & SACHSENHOFER 2001).

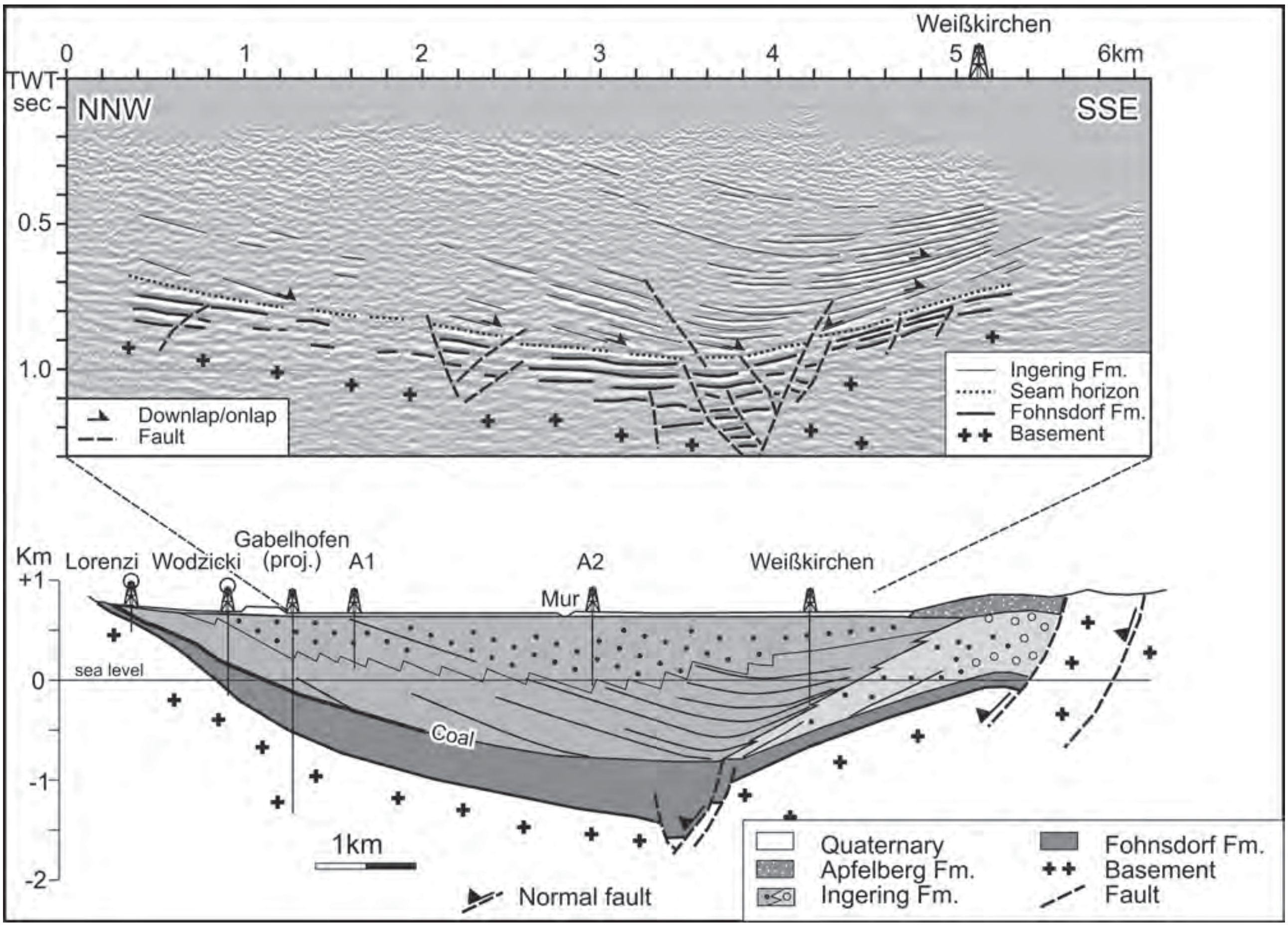

Fig. 7: Seismic line and interpreted section through the Fohnsdorf Basin (SACHSENHOFER et al. 2003).

and a sandy matrix that are attributed to the Fohnsdorf Formation. Clasts are derived from the local surrounding basement, i.e. pegmatites, marbles, garnet mica schists, biotite gneisses.

The calcitic tufa limestones are interpreted as feeder dykes. They show a fibrous to equigranular appearance and dark-light lamination is common. Several special types of tufa limestones appear, e.g. large crystals ("Pfeifensinter", "Kugelsinter", "Erbsenstein",…). Stable isotope data ($\delta^{13}C$ 0.3 - -0.1 ‰ VPDB, und $\delta^{18}O$ -13.3 - -11.4 ‰ VPDB) as well as strontium isotope data indicate a fluid source within formation waters of the Miocene basin fill and argue against dissolution of basement marbles. The tufa dykes and veins follow largely sinistral fault planes and show overprint by slickenslides, which suggests a late Miocene age for the tufa, probably contemporaneous to the formation of a transpressive flower structure along Pöls-Lavanttal-fault system.

The positive flower structure along the Pöls-Lavanttal-fault system clearly is a younger feature relative to the early/middle Miocene basin fill of the Fohnsdorf Basin. The flower structure cuts through the original pull-apart basin structures and deformed basin strata as visible in seismic sections. A late Miocene age is corroborated by contemporaneous basin subsidence along the Pöls-Lavanttal-fault system in the Lavanttal Basin to the south of the Fohnsdorf Basin (Strauss et al. 2001).

Stop 6: Gföller forest road basin margin fault and Apfelberg Formation

Topic: southeastern basin margin tectonics; basal Apfelberg Formation

Coordinates: 014°50‘38" E, 47°09‘50" N

The distribution of the Apfelberg Formation is limited to the southeastern part of the Fohnsdorf basin. Good exposures can be found in the proximal, hilly part at the basin margins along road cuts and incised creeks, whereas the more distal parts of the Apfelberg Formation in the basin centre are largely covered by Quaternary to recent sediments. Strata of the Apfelberg Formation have a tectonic dip of 10 to 40° to the north. The sediments are largely undeformed with the exception of strata deposited directly adjacent to the faults at the basin margins (Strauss et al. 2001). Contacts with the underlying metamorphic basement are often faulted. Where original sedimentary contacts are preserved as at Gföller, the underlying gneisses and mica schists record the effects of extensive palaeoweathering under subtropical climatic conditions, e.g. a strong loosening and significant reddening of the bedrock.

The Apfelberg Formation consists of a wedge-shaped conglomerate complex, which tapers northwestward. Mapping indicates a maximum thickness of more than 1000 m (Strauss et al. 2001, Wagreich & Strauss 2005). Based on conspicuous material and facies differences, a northeastern fan, the Rachau fan, has been distinguished from a southwestern fan complex, the Apfelberg fan (Strauss et al. 2003, Wagreich & Strauss 2005; Fig. 8). Both fans display an elongate fan-like aerial extent, although later erosion has modified this, especially along northern fan margins due to southward tilting of the basin. Reconstructed fan areas based on today's outcrops, facies mapping and the distribution of clast lithologies (Polesny 1970) are of the order of 20 to 35 km^2. Clasts of the Apfelberg fan are composed predominantly of lithologies that can be matched with the Stubalpe units to the south. In a distal position the alluvial fans grade into a lacustrine delta

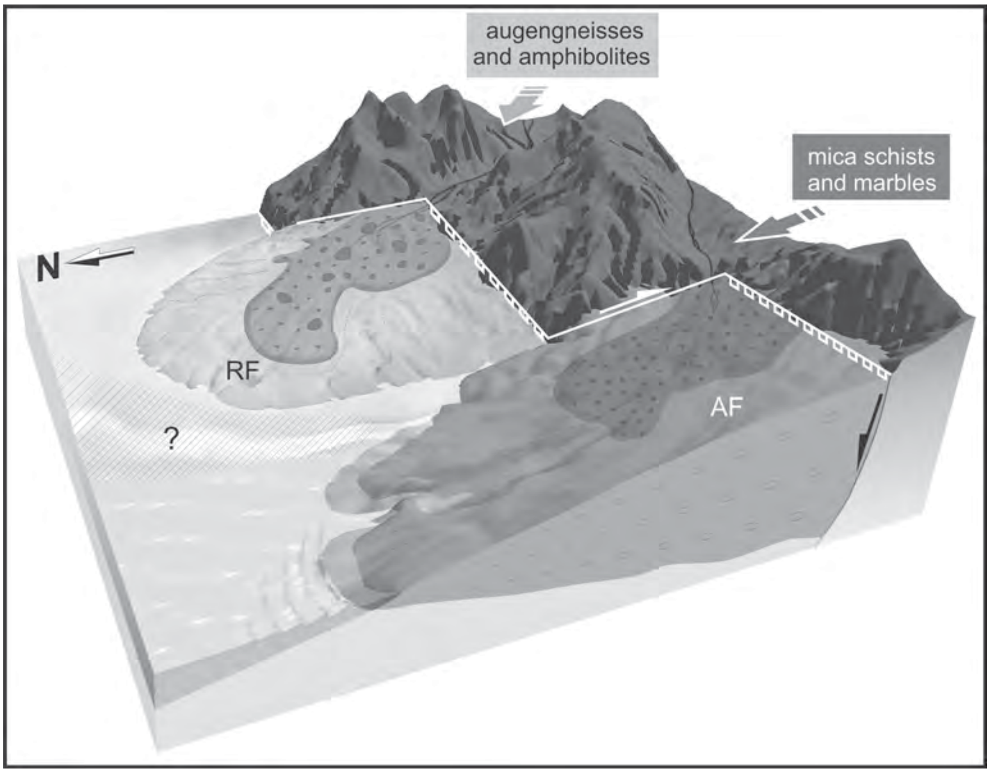

Fig. 8: Conceptual depositional model for fans of the Apfelberg Formation indicating position of basin-margin faults and evolution of fans due to faulting and different source areas. The distal parts of the fans grade into a lacustrine fan-delta (Wagreich & Strauss 2005).
RF - Rachau fan,
AF - Apfelberg fan.

complex, e.g. in the Apfelberg clay pit (STRAUSS et al. 2003). Faults along the southern and southeastern basin margin record several deformational phases. On the basis of cross-cutting relationships an older phase of sinistral strike-slip movement could be separated from a younger phase of normal faulting, followed by compression (STRAUSS et al. 2001). Normal faulting along east-west trending, steeply north-dipping fault planes could be attributed to NNW-SSE extension, with linked north-south trending strike-slip faults (Fig. 1).

The outcrop along the Gföller forest road exposes basement rocks and the basal Apfelberg Formation. Gneisses of the Ammering-Speik complex are juxtaposed to marbles and garnet mica schists of the Rappold complex which indicates a minimum normal fault displacement of 500 m (Fig. 9). The Apfelberg Formation outcrop is dominated by conglomerates. Clasts are mainly composed of garnet mica schists and mica-rich paragneisses, and varying amounts of marbles, amphibolites, quartzites and pegmatites. Clast sizes are generally below 20 cm; outsized clasts reach diameters of 45 cm and are extremely rare. Matrix-supported fabrics dominate. Detrital muscovite, chlorite and biotite flakes derived from mica schists and paragneisses are a conspicuous constituent of the matrix, and accounts for the dark grey to greenish colour. The fabric is generally disorganized with no preferred clast orientation. Crude horizontal stratification was observed rarely.

The majority of the beds in the proximal portion of the Apfelberg fan consist of debris flows. Distinctive features for debris flows are matrix-supported conglomerates, outsized clasts in upright position and high silt and clay contents in the matrix. Grain size curves are similar to recent debris-flow deposits in terms of their largely unsorted texture and the significant clay contents. However, the debris flows show significant differences in grain size and matrix content to those from the Rachau fan. Debris flows of the Apfelberg fan display higher overall matrix contents, higher silt and clay proportions of the matrix (Fig. 10), lower maximum particle sizes and lower bed thickness values (Fig. 11). Matrix-supported beds are more common than clast-supported ones compared to the Rachau fan, which points to transportation by more cohesive debris flows.

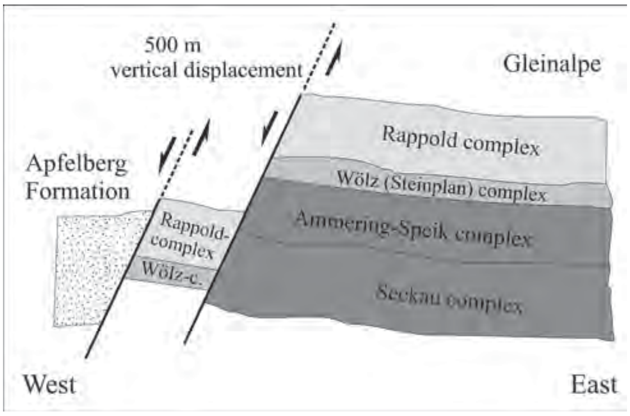

Fig. 9: Schematic W-E profile across the basin margin at Gföller showing large scale vertical displacement of basement units (STRAUSS et al. 2003).

Stop 7: Apfelberg clay pit, Apfelberg Formation

Topic: sedimentology of the Apfelberg Formation; alluvial fans and fan-delta deposits

Coordinates: 014°50‘27" E, 47°11‘50" N

The outcrop situation in the temporarily active clay pit Apfelberg changes strongly due to mining activity. The description below stems from logging during years 2000-2001; since then, the outcrop changed strongly, especially the upper, fine-grained part of the succession is now almost completely covered.

The outcrop behind the brickyard shows fluvial channels with conglomerate and sandstone fills and some debris flow deposits of a distal fan environment (WAGREICH & STRAUSS 2005). Coarse conglomerates make up about 10 to 20% of the sections. Lenticular channel fills composed of conglomerates and sandstones are intercalated within fine-grained massive conglomerates with maximum particle sizes of 5-10 cm. Grain size curves (Fig. 10) document the poorly sorted nature of these conglomerates, interpreted as debris flows, compared to the channelized deposits. The debris flow matrix consists of an unsorted mixture of 10-25% of granules to pebbles, 30-50% of sand, 15-35% of silt and 5-15% of clay (Fig. 10). Debris-flow deposits show distinctive correlations of bed thickness to maximum particle size (Fig. 11).

These distal fan deposits interfinger with planar stratified sheet sandstones, coal and tuff layers, including thin non-marine mollusc shell beds with vertebrate remains (STRAUSS et al. 2003). The upper part of the succession comprises finer-grained braid plain deposits including coal and tuff layers. Transitions to delta-plain deposits of a lacustrine fan-delta environment are present (STRAUSS et al. 2001, 2003).

Fan facies of the Apfelberg Formation seem to be dependant mainly on lithology variations in the hinterland of the fans. The fans have developed contemporaneously under essentially identical climatic and tectonic conditions. A similar catchment type with a generally similar relief can be inferred for both fans based on their adjacent position and general relief reconstructions for the Miocene (e.g., FRISCH et al. 2001).

The major difference between the Apfelberg and the Rachau fans, which is regarded as the critical factor causing the differences in debris flows and thus fan facies, was apparently the lithology of the bedrock in the source areas of the fans. Striking differences exist in the clast lithologies, the matrix composition and the heavy mineral compositions of the fan deposits (WAGREICH & STRAUSS 2005). Clasts of the Rachau fan consist mainly of durable gneisses of the Gleinalpe area (mainly Amering and Speik metamorphic complexes; see Fig. 2) whereas the Apfelberg fan comprises material from the Stubalpe units (including the Rappold Complex and the Steinplan Complex), mainly soft mica schists, mica-rich paragneisses and quartzites, marbles, pegmatites and minor amphibolites. Heavy mineral samples display a significantly higher amount of green

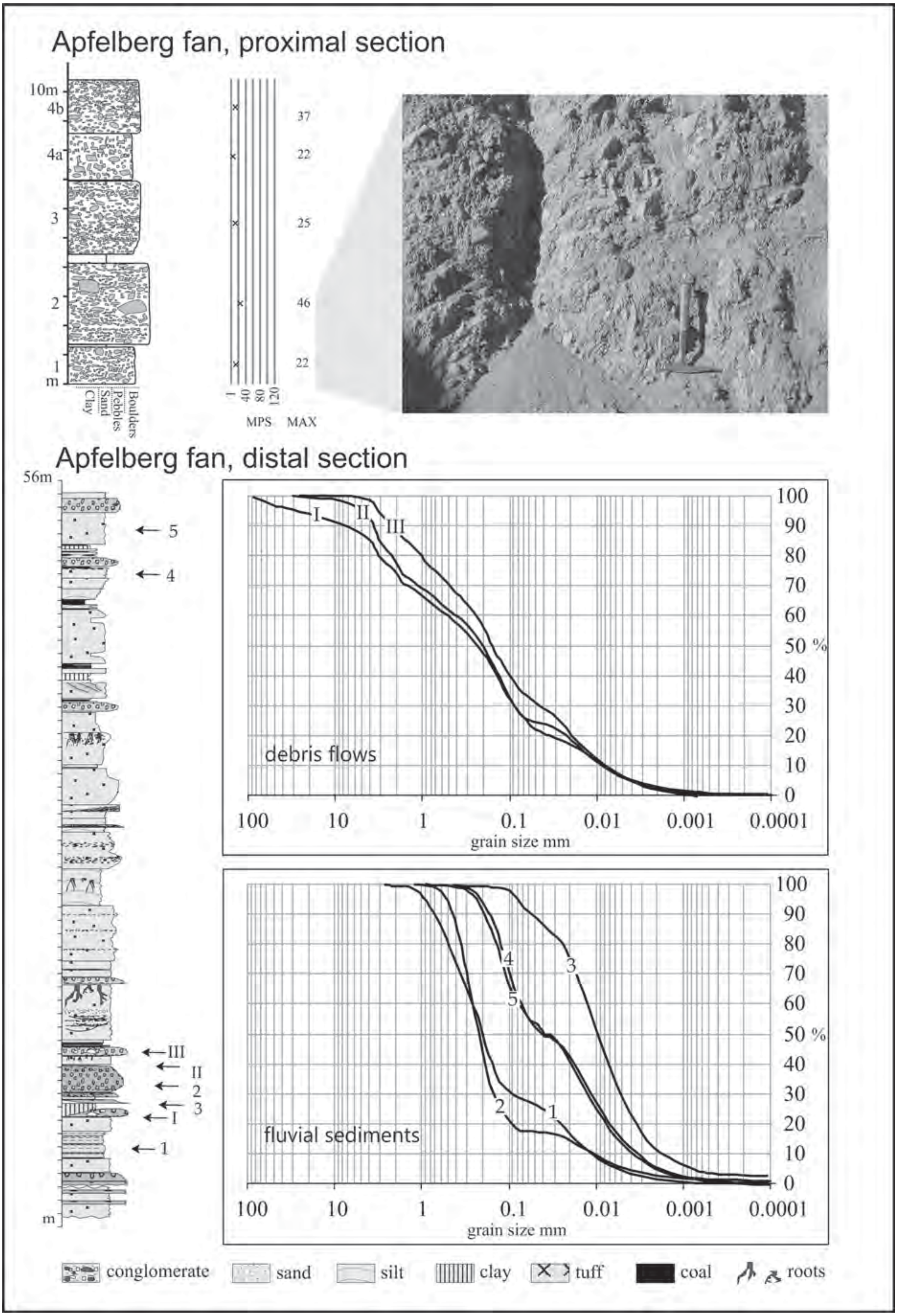

Fig. 10 Proximal and distal profiles of the Apfelberg fan with typical grain size cumulative curves to distinguish debris flows and fluvial channel conglomerates in the Apfelberg clay pit (standard sieve methods, sediment balance for sand fraction, and sedigraph analyser for the silt and clay fraction).

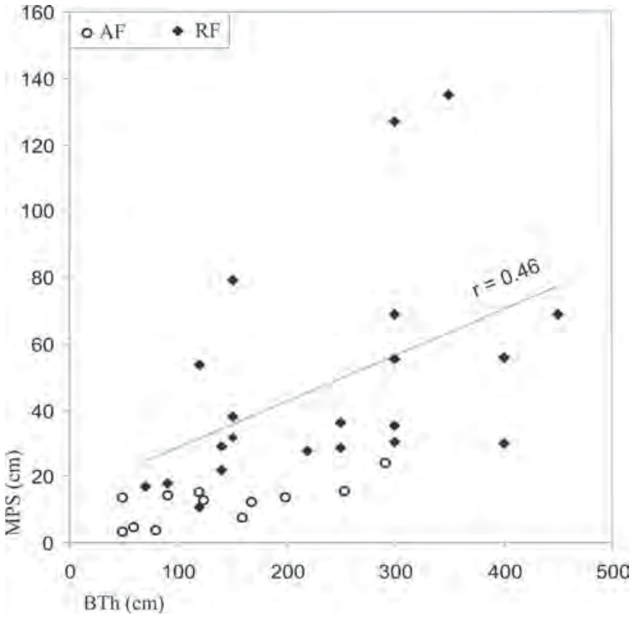

Fig. 11: MPS/BTh diagrams depicting bed thickness vs. mean maximum particle size (arithmetic mean of ten largest clasts) after NEMEC & STEEL (1984). Diamonds indicate measurements from the Rachau fan (RF) debris flows; circles indicate measurements from the Apfelberg fan (AF). Note that most of the debris flows of the Apfelberg fan fall into the lower left corner.

hornblende in sands from the Rachau fan, whereas the Apfelberg fan displays extremely garnet-rich assemblages. The change in the source area type is due to a major fault/thrust contact between the Gleinalpe and the Stubalpe units and the considerably higher Miocene erosional surface. Striking differences in source lithologies also control the type and grain size distribution of the debris flow matrix. The matrix of the Apfelberg fan debris flows is more clay- and silt rich, reaching up to 40 % of the total size distribution. This is interpreted as a consequence of the breakdown and strong weathering of prevailing foliated mica-rich lithologies in the source area; whereas the more sand-dominated matrix of the Rachau fan deposits is the product of the weathering of augengneisses and orthogneisses into single sand-sized quartz and feldspar grains.

Debris flows of the Apfelberg Formation fans probably originated at the transition from mountainous streams into the unconfined basin by failure of unsorted gravelly sediment of the hinterland as a result of the rapid addition of water, e.g. during strong rains. The hinterland of the Apfelberg fan can be expected to contain a higher proportion of muddy soils and a flatter morphology as a result of weathering of softer lithologies in comparison to the Rachau fan.

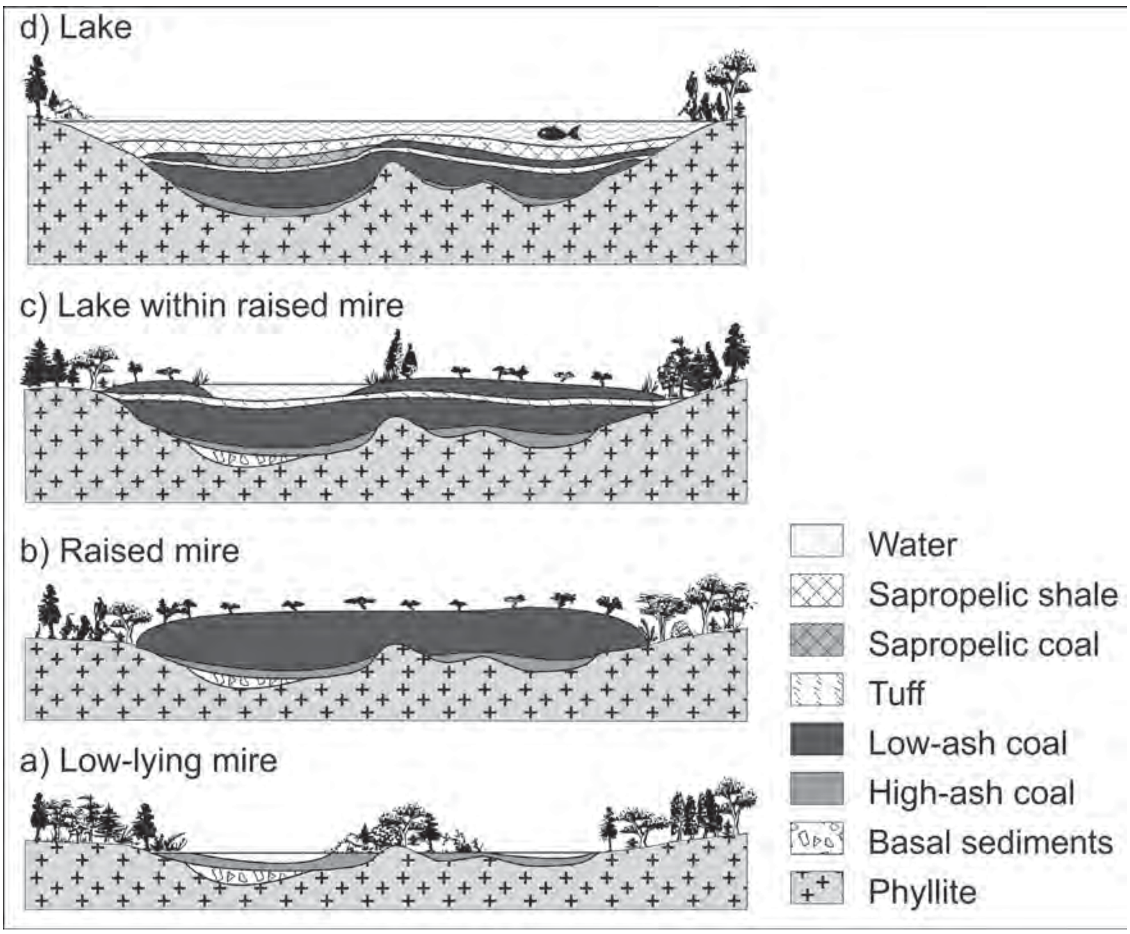

Fig. 12: Cartoon illustrating four stages of the evolution of the Leoben seam (GRUBER & SACHSENHOFER 2001).

3.3. Sedimentology of the Leoben Basin

Stop 8: Leoben Seegraben/Moskenberg, Leoben Basin
Topic: Sapropelic shale ("Brandschiefer"), fluvial conglomerates ("Seegraben Conglomerate")
Coordinates: 015°05'28" E, 47°23'57" N

Coal in the Leoben Basin formed in a raised mire environment (Gruber & Sachsenhofer 2001; Fig. 12). Sapropelic shales ("Brandschiefer") overlying the coal seam were deposited in a lake during the drowning stage of the raised mire. The fine-grained, organic matter-rich rocks, several meters thick, are exposed in a collapsed mine gallery (outcrop 8 in Fig. 13).
Southwest of the collapsed mine gallery coarse-grained fluvial conglomerates form a prominent cliff. Although the contact between the different lithologies is not exposed, it is obvious that the stratigraphic distance between the sapropelic shales and the conglomerates is low. This suggests a rapid change in depositional environment.
In the Tollinggraben Subbasin the conglomerate rests directly on the coal seam. In contrast, along the southern basin margin the conglomerate is separated from the coal seam by a coarsening upward succession several hundred meters thick. This is a consequence of syn-sedimentary southward tilting of the Leoben Basin.
Conglomerate component diameters are decreasing from north to south (Höfer 1903) pointing to sediment transport from the north. On the other hand Petrascheck (1929) documented a change in the component spectrum from the footwall (grey, brown and red carbonates, probably Triassic origin) to the hangingwall (quartzite and phyllite originating from the Greywacke unit) and claimed additional infill from the south.

4. Concluding remarks

The basins along the Mur-Mürz fault system provide great opportunities to study the relation between the late stage evolution of mountain building, basin formation, and sedimentology. Typical Alpine intramontaneous pull-apart basin fills developed under warm to moderate humid climate conditions, characterized by alluvial fan, fluvial to lacustrine depositional systems and significant coal deposition. However, these basins also attracted attention because of their great potential in raw materials. The latter aspect is discussed in this final section.
The most important mineral commodity in these basins is

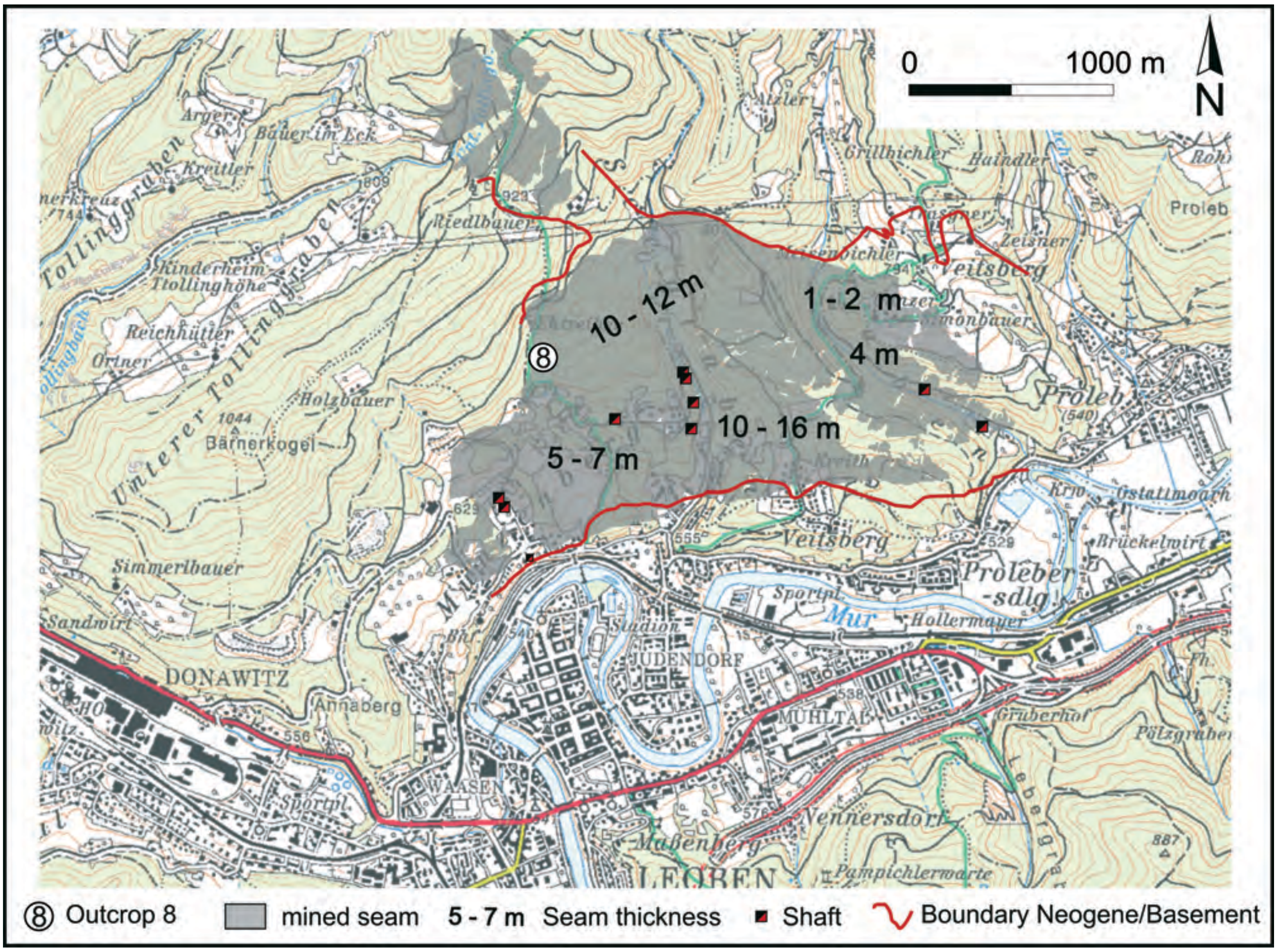

Fig. 13: Map of underground workings in the Leoben Basin reflecting the geometry of the coal seam. Note that the outcrop line of Miocene sediments overlaps the seam area because of reverse faults along the southern basin boundary (Sachsenhofer et al. 2010).

coal. Typically the seams in pull-apart basins are very thick. For example, the Pliocene Velenje pull-apart basin (see Fig. 1 for location of Velejne) hosts a lignite seam, more than 150 m thick (Markic & Sachsenhofer 2010). In the Fohnsdorf and Leoben basins, the seams contain sub-bituminous coal, up to 15 m thick. In the basins along the Mur-Mürz fault system these coals were mined underground till the 1970s.

The Fohnsdorf coal was known to be rich in methane (c. 30 m² CH_4/t coal). Sachsenhofer et al. (2000a) assume a bacterial origin of the methane. In the year 1943 101 miners were killed in a mine disaster. Starting in the 1950s the methane was produced in the mine by boreholes drilled into the fine-grained overburden of the seam (Feyferlik 1958). Borehole Weißkirchen 1 was drilled in 1999 to explore the coal-bed-methane potential of the southern part of the basin. Unfortunately the well did not reach the seam horizon.

Tuff layers occur both in the Fohnsdorf and Leoben basins. Neutral to slightly alkaline conditions during coal formation, a result of brackish influence, resulted in the transformation of the tuff into bentonite. Temporarily the bentonite was mined together with the coal (Weber & Weiss 1983).

Sediments rich in sapropelic organic matter typically overlie the coal seams in pull-apart basins. In the Fohnsdorf and Leoben basins these rocks contain up to 20 % organic carbon and a type II kerogen (Gruber & Sachsenhofer 2001). These rocks have not been used in the basins along the Mur-Mürz fault system. However, similar rocks (containing a type I kerogen) overlying a thick coal seam in the Fushun pull-apart basin (China) are currently mined as an oil shale (Liu et al. 2009).

Reconstructed thermal histories indicate a slightly enhanced paleo-heat flow (65-70 mW/m, Sachsenhofer et al. 2000a), which corresponds to enhanced present-day geothermal gradients. The geothermal well Gabelhofen Th1, drilled in 1995 produces 1.8 l/sec water mit with a temperature of 51°C from a depth of 1045 m (Sachsenhofer et al. 2000b). The water is used to supply the Fohnsdorf spa.

In addition the Neogene basins provide raw material for brickyards (e.g., Apfelberg) as well as construction material.

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