Source area and tectonic control on alluvial-fan development in the Miocene Fohnsdorf intramontane basin, Austria

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Abstract: Middle Miocene alluvial fans in the intramontane Fohnsdorf Basin of the Eastern Alps originated along normal faults and linked strike-slip faults in a continental half-graben setting. The fans display considerable facies differences. Debris flows of the Rachau fan are characterized by a sandy matrix and large boulders, whereas debris flows of the Apfelberg fan are characterized by higher silt and clay content and smaller clasts. Key control of debris-flow facies is the lithology contrast in the fan source areas. Sand, pebbles and large outsized boulders originated predominantly from the resistant augengneiss- and amphibolite-dominated hinterland of the Rachau fan, whereas a significant higher proportion of mud and silt and smaller boulders have been derived from the Apfelberg fan catchment, which was dominated by mica schists and marble.

Alluvial fans are recognized as sensitive recorders of the evolution of piedmont basins and their margins (e.g. Heward 1978; Nemec & Postma 1993; Blair & McPherson 1994; Lloyd *et al.* 1998). Alluvial fans constitute a widespread facies in intramontane basins due to strong local uplift and subsidence along faults within actively deforming orogens. Fans in intramontane settings show a high degree of diversity because of complex basin geometries, contrasting source areas over short distances, and different tectonic movements that influence fan geomorphology and facies.

This paper describes Neogene alluvial-fan deposits within a large intramontane basin of the Eastern Alps, the Fohnsdorf Basin of Styria (Sachsenhofer *et al.* 2000; Strauss *et al.* 2001). The purpose of this paper is to document the origin of significant facies differences between adjacent fans. Fan formation and stratigraphic evolution is attributed to faulting along basin margins, whereas fan sedimentology seems to be strongly controlled by different source-area lithologies.

Geological and palaeogeographical overview

The Miocene Fohnsdorf Basin is one of several intramontane, fault-bounded basins within the Eastern Alps of Austria (Sachsenhofer *et al.* 2000, 2003; Strauss *et al.* 2001, 2003). It is situated on metamorphic complexes of the Austroalpine tectonic unit that underwent a complex evolution of thrusting and metamorphism during Cretaceous–Palaeogene times. Intramontane basins developed during the Oligocene–Miocene along strike-slip faults as a response to lateral eastwards extrusion of central parts of the Eastern Alps (e.g. Ratschbacher *et al.* 1991). The Fohnsdorf Basin formed along one of these major strike-slip fault systems, the Mur-Mürz Fault (Decker & Peresson 1996), that bordered one of the extruding blocks. The fault linked these en echelon basins to the contemporaneous large pull-apart structure of the Vienna Basin (Ratschbacher *et al.* 1991; Decker & Peresson 1996).

The Fohnsdorf Basin subsided during the Early–Middle Miocene as a pull-apart along overstepping, E-W-trending strike-slip fault of the Mur–Mürz fault system (Fig. 1). Coarse and fine siliciclastics, coal seams and rare layers of limestone were deposited during the first basin stage (Strauss *et al.* 2001). Subsequently, tectonic stresses changed, and the strike-slip basin evolved into a half-graben with major subsidence concentrated in the southern part of the basin. During this time (MN 6, Middle–Late Badenian, Strauss *et al.* 2003) the Apfelberg Formation was deposited in the southern part of the basin (Figs 1 & 2). This more than 1000 m-thick formation is mainly composed of weakly consolidated conglomerate beds ('Blockschotter' of Polesny 1970).

Stratigraphic–structural setting of the Apfelberg Formation

The distribution of the Apfelberg Formation is limited to the SE 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–recent sediments, and outcrops are rare and patchy. Strata of the Apfelberg Formation have

From: HARVEY, A.M., MATHER, A.E. & STOKES, M. (eds) 2005. *Alluvial Fans: Geomorphology, Sedimentology, Dynamics*. Geological Society, London, Special Publications, **251**, 207–216. 0305–8719/05/$15

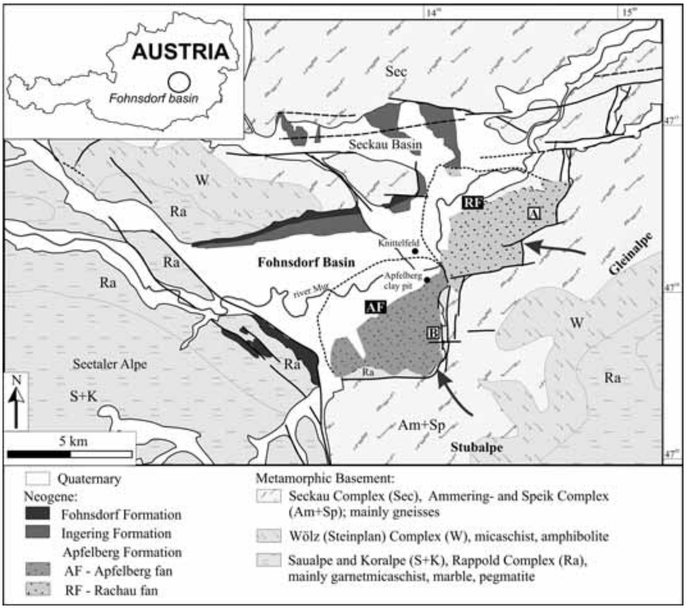

Fig. 1. Geological overview of the Fohnsdorf Basin and the basement complexes in the Eastern Alps of Austria. A is the position of Rachau fan logs of Figure 3; B is the position of proximal Apfelberg fan log of Figure 6.

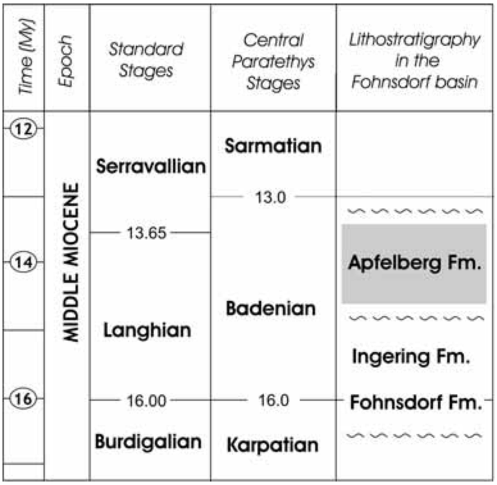

Fig. 2. Simplified stratigraphic chart of the Fohnsdorf Basin, based on Strauss *et al.* (2001, 2003), indicating the position of the Apfelberg Formation.

a tectonic dip of 10°–40° to the north; steeper inclinations are predominantly concentrated at the basin margins in the south. 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, the underlying gneisses and mica schists record the effects of extensive palaeoweathering under subtropical climatic conditions, for example a strong loosening and significant reddening of the bedrock.

The Apfelberg Formation at the SE margin of the Fohnsdorf Basin consists of a wedge-shaped conglomerate complex that tapers towards the NW. Mapping indicates a maximum thickness of more than 1000 m (Strauss *et al.* 2001). Based on conspicuous material and facies differences, a NE fan, the Rachau fan, has been distinguished from a SW fan complex, the Apfelberg fan (Strauss *et al.* 2003). 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 20–35 km^2. The Rachau fan is mainly characterized by clasts of orthogneisses and amphibolites from the Gleinalpe area to the east and SE (see Fig. 1), whereas clasts of the Apfelberg fan are composed predominantly of lithologies that can be matched with the Stubalpe units to the south. The boundary between the two fans is loosely defined due to poor outcrop conditions in this area. However, based on clast lithologies and heavy mineral data (Polesny 1970), an interfingering of conglomerate beds of the two fans can be mapped, defining a transitional zone between the fans. In a distal position the alluvial fans grade into a lacustrine delta complex, e.g. in the Apfelberg clay pit (Strauss *et al.* 2003).

Faults along the southern and SE 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 E–W-trending, steeply N-dipping fault planes could be attributed to NNW–SSE extension, with linked N–S-trending strike-slip faults (Fig. 1).

Sedimentology

The two fans of the Apfelberg Formation are distinguished by significant lithology and facies contrasts. In general, both fans can be classified as debris-flow-dominated.

Rachau fan

Outcrops of sediments of the Rachau fan are mainly located in the proximal part of the fan, whereas the distal parts are largely covered. In proximal areas, the deposits of the Rachau fan comprise mainly stacked sheets of thick-bedded, unsorted–very poorly sorted, matrix- to clast-supported conglomerates with maximum clast sizes ranging from cobbles to large boulders (Fig. 3). The debris is subangular–subrounded, comprising fragments of local bedrock, mainly augengneisses, orthogneisses, amphibolites and minor paragneisses and quartzites (Fig. 4a, b). The matrix is an unsorted mixture of angular finer grained gravel and sand. The clay content of the matrix is below 5%. Pebbles with modal diameters of 10–30 cm are dispersed within this matrix. Outsized clasts are common and reach diameters of more than 3 m. These extremely outsized boulders are concentrated in a few distinct beds. Between the conglomerate beds thin lenticular sand–granule layers are present.

Conglomerate bed boundaries are often indistinct and amalgamation is a common feature. Thicknesses of individual conglomerate beds range from 40 cm to more than 3 m. Where outcrop conditions permit, observations of individual beds over tens of metres reveal a sheet-like–broadly lenticular geometry. Most beds are internally massive and appear structureless. Crude horizontal stratification defined by subhorizontally oriented clasts is very rare. The bases of thick boulder beds are planar and show no obvious erosion. Some of the thinner beds with lenticular geometry display erosional, convex-downward bases and locally show low-relief scouring of a few tens of centimetres. Inversely graded basal parts, where the largest boulders in the bed are excluded from the lower third part, have been observed on several beds, and most outsized clasts are concentrated in the upper half of the beds. The fabric is mainly disorganized with no preferred clast orientation, and large boulders in nearly vertical positions are present. The tops of beds are often crudely normal graded and show transitions to interbedded sandstones. Large cobbles and boulders project above the surfaces of many beds.

The boulder conglomerate beds are sometimes separated by roughly horizontally stratified thinner conglomerate beds up to 80 cm thick, with organized fabric and rare lenses of fine–coarse sandstone. Weakly lithified sandstones display planar lamination locally marked by pebble stringers. These facies makes up less than 10% of the measured sections (Fig. 3). No distinct coarsening- or fining-upwards trends in maximum particle size could be observed.

Interpretation. The dominant boulder-bearing conglomerate facies of the Rachau fan is interpreted to represent deposits of a wide variety of debris-flow types from mudflows to largely cohesionless debris flows and transitions to sheetfloods (e.g. Postma 1986; Blair & McPherson 1994). The disorganized fabric, the presence of large outsized clasts, matrix-supported bed intervals and clasts in vertical position indicate deposition on a debris-flow-dominated alluvial fan (cf. Hubert & Filipov 1989; Blair & McPherson 1994). Although the number of measured beds is rather low and the variance is high, a crude correlation of maximum particle sizes (MPS, mean of 10 largest clasts of bed) and bed thickness (BTh, Nemec & Steel 1984) could be observed (Fig. 5), pointing also to debris-flow depositional processes. The conglomerates of the Apfelberg Formation represent mainly deposits of low cohesive debris flows, as determined by the low clay content of the beds and the predominance of a sandy matrix in most of the beds; mudflows with a strong clay-matrix support are not present due to the generally low clay content. The competence of these low cohesive flows was considerable, as large boulders were transported by flows with a dominantly sandy matrix and clay contents of around 5% (cf. Rodine & Johnson 1976). Inversely graded bed bases and the concentration of outsized clasts in the upper portion of the beds are attributed to the upwards movement out of basal shear horizons (Hubert & Filipov 1989). Above the shearing layer the coarse debris moved probably as a semi-rigid, high-strength plug. Crude normal grading and pebbly sandstones may indicate deposition by surging debris flows according to Nemec & Steel (1984). Normally graded bed tops with transitions to sandy layers indicate transitions from debris-flow transport to turbulent water flow in the late stages of flood events, a common feature of debris flows

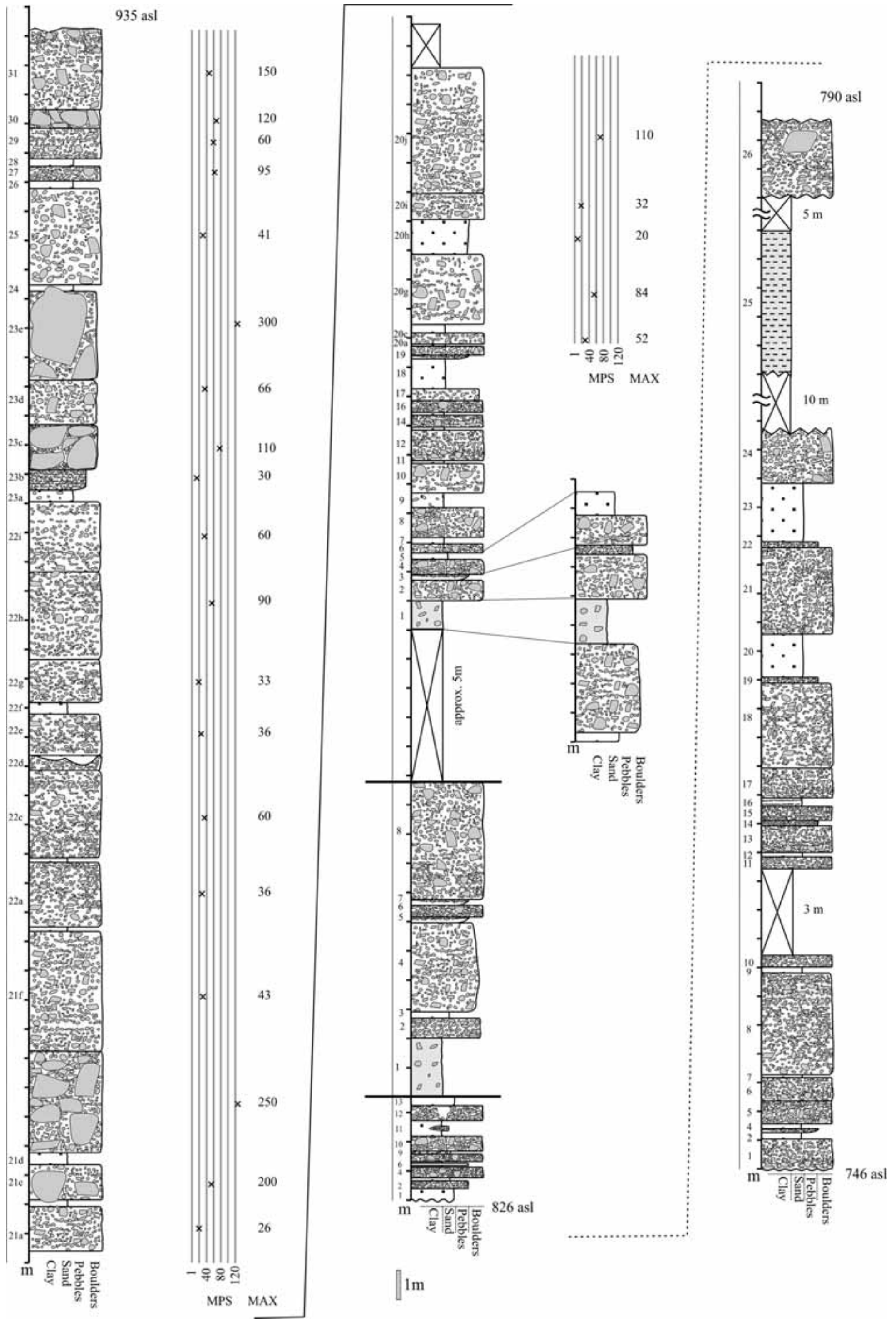

Fig. 3. Sedimentary logs through the Rachau fan deposits. MPS, mean particle size of 10 largest clasts of bed; MAX, diameter of largest component; asl, above sea level.

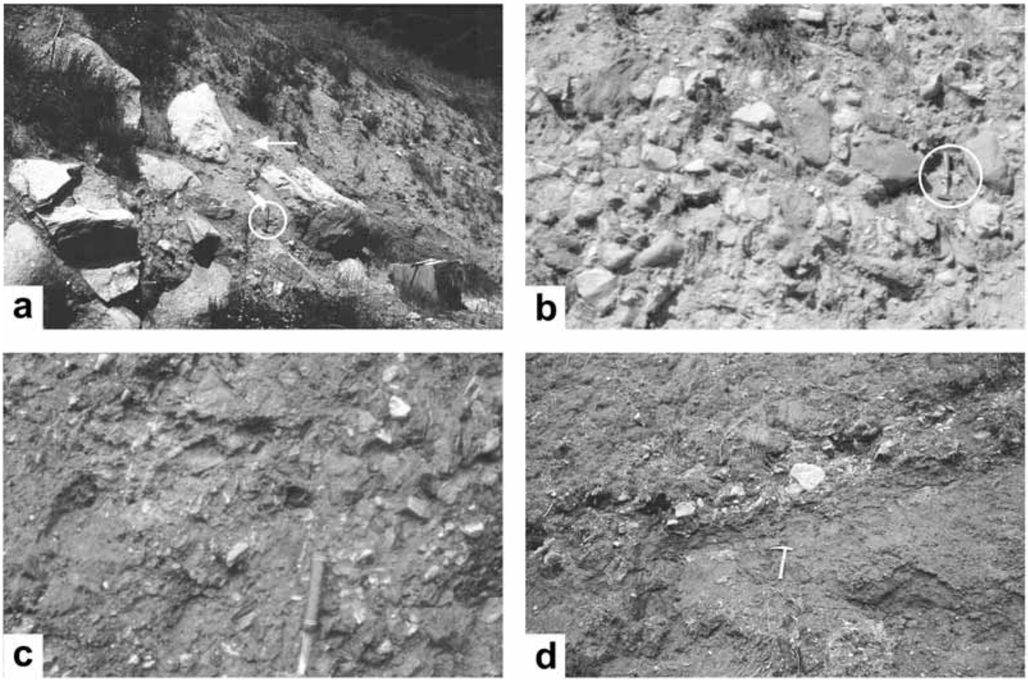

Fig. 4. Outcrop photographs of fan deposits of the Apfelberg Formation. (**a**) 3 m-thick debris-flow boulder bed (bed 23e of Fig. 3). Note the predominance of light-coloured augengneiss blocks. Top of the boulder bed with the sandy matrix interpreted as reworking and later infill of sand from the top of the layer. (**b**) Typical debris-flow conglomerate of the Rachau fan with predominantly clast-support, no preferred fabric and light-coloured sandy matrix (bed 21f of Fig. 3). (**c**) Typical debris-flow deposit of the proximal Apfelberg fan (bed 2 of Fig. 6) with maximum particle size up to 30 cm, and a dark, mica-rich and more clay-rich matrix compared to the debris flows of the Rachau fan. (**d**) Debris flows of the distal Apfelberg fan displaying generally smaller maximum clast sizes and predominant matrix-support in the lower bed.

(e.g. Blair & McPherson 1992). Some beds also show signs of later reworking by water flow, such as winnowing of the uppermost part of the beds and infiltration of a better sorted sandy matrix from the top.

Minor water-laid conglomerate and sandy layers are interbedded between the thick debris flows, and record either water flow in the late stages of flood events or reworking by intermittent stream flow and sheetfloods. These conglomerates are distinguished by their smaller clast sizes and bed thicknesses, crude horizontal stratification and local imbrication of clasts, and by a more lenticular geometry with some indications of erosion and channelling at their bases. Observed channels are a maximum of a few metres in diameter. Transport mechanism may include transitional types between dilute debris flows and streamflow, including sheetfloods (e.g. Wells & Harvey 1987; Blair 1999).

Apfelberg fan

Proximal sections (Fig. 6) of the Apfelberg fan are dominated by conglomerates with bed thicknesses generally below 2 m. 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 (Fig. 4c, d). Matrix-supported fabrics dominate in the proximal parts of the fan; in distal settings both matrix- and clast-supported fabrics are present. Detrital muscovite, chlorite and biotite flakes derived from mica schists and paragneisses are a conspicuous constituent of the matrix, and account for the dark grey–greenish colour. The fabric is generally disorganized with no preferred clast orientation. Crude horizontal stratification was observed rarely. Bed bases are generally planar and non-erosive, but scoured bases are also present. Both inverse and normal grading is extremely rare; outsized clasts occur mainly in the upper portions of beds.

In more distal positions of the fan, coarse conglomerates make up about 10–20% of the sections. Lenticular channel fills composed of conglomerates and sandstones are intercalated within fine-grained massive conglomerates with maximum particle sizes

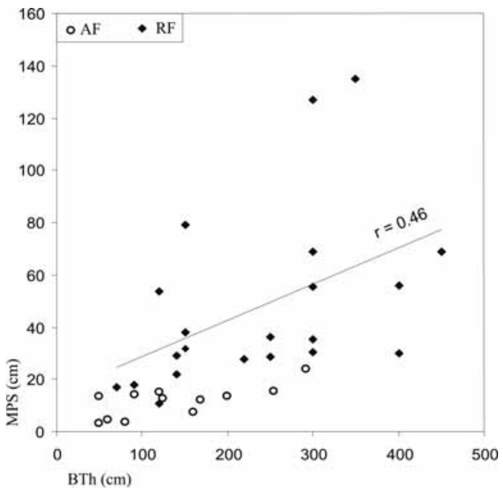

Fig. 5. MPS/BTh diagrams depicting bed thickness v. mean maximum particle size (arithmetic mean of 10 largest clasts) after Nemec & Steel (1984). Diamonds indicate measurements from the Rachau fan (RF) debris flows; circles indicate measurements from the Apfelberg fan (AF). Note that most of the debris flows of the Apfelberg fan fall into the lower left-hand corner.

of 5–10 cm. Grain-size curves (Fig. 6) document the poorly sorted nature of these conglomerates, interpreted as debris flows below, compared to the channelized deposits. The debris-flow matrix consists of an unsorted mixture of 10–25% of granules–pebbles, 30–50% of sand, 15–35% of silt and 5–15% of clay (Fig. 6). 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).

Interpretation. 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 (e.g. Hubert & Filipov 1989; Blair & McPherson 1998; Blair 1999). 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. 6), lower maximum particle sizes and lower bed thickness values (Fig. 5). Matrix-supported beds are more common than clast-supported ones compared to the Rachau fan, which points to transportation by more cohesive debris flows.

In distal-fan areas, fluvial channels with conglomerate and sandstone fills and finer-grained braid plain deposits, including coal layers, predominate over debris-flow deposits. Transitions to delta-plain deposits of a lacustrine fan-delta environment are present (Strauss *et al.* 2001, 2003).

Discussion

Alluvial fans generally form in settings where a hinterland with a steep relief lies adjacent to a lower gradient basin, separated by a strong change in the slope gradient, for example by a synsedimentary active fault (Heward 1978). Higher-gradient mountainous streams in the uplifted hinterland can transport coarse detritus to the faulted basin margin of a low-relief plain, where alluvial-fan deposition occurs (e.g. Lloyd *et al.* 1998). The occurrence of outsized clasts of a few metres in diameter throughout the whole succession of the Rachau fan calls for a high-gradient, constantly exposed hinterland providing a mountainous source area. Synsedimentary tectonic movements, as demonstrated by Strauss *et al.* (2001), along the prominent southern basin margin faults of the Fohnsdorf Basin provided the relief necessary for continuous fan development. Normal faulting along older sinistral E–W-trending strike-slip faults due to NNW–SSE extension resulted in an asymmetric, southwards-deepening half-graben, which was filled by the wedge-shaped clastic fans of the Apfelberg Formation (Fig. 7), a typical situation for a continental half-graben (Leeder & Gawthorpe 1987). A backstepping of normal faults and synsedimentary cracked pebbles could be verified for this stage (Strauss *et al.* 2001, 2003). Adjacent to the faults, the fan sediments were tectonically tilted to about 20°–40°s, thus the primary slope gradients cannot be reconstructed.

Although several factors can influence alluvial-fan sedimentation and facies, such as climate, catchment type, relief and tectonic setting, the fan facies of the Fohnsdorf Basin seem to be dependent 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 Rachau and Apfelberg fans have broadly similar areas and originated contemporaneously along normal or oblique basin-margin faults.

The major difference between the Rachau and the Apfelberg 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

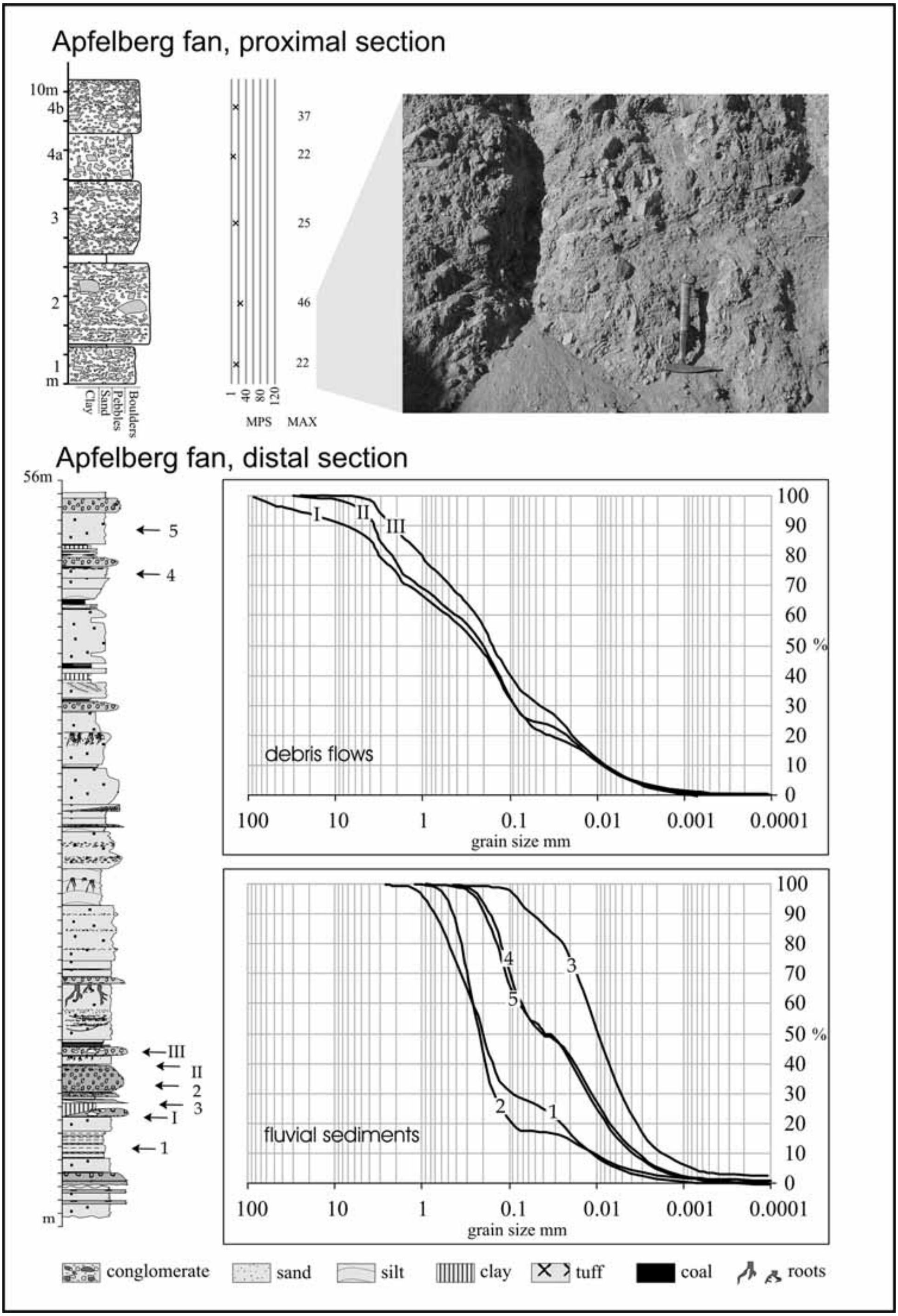

Fig. 6. Proximal and distal profiles of the Apfelberg fan with typical grain-size cumulative curves to distinguish debris flows and fluvial-channel conglomerates in the Apfelberg clay pit (standard sieve methods, sediment balance for sand fraction, and sedigraph analyser for the silt and clay fraction).

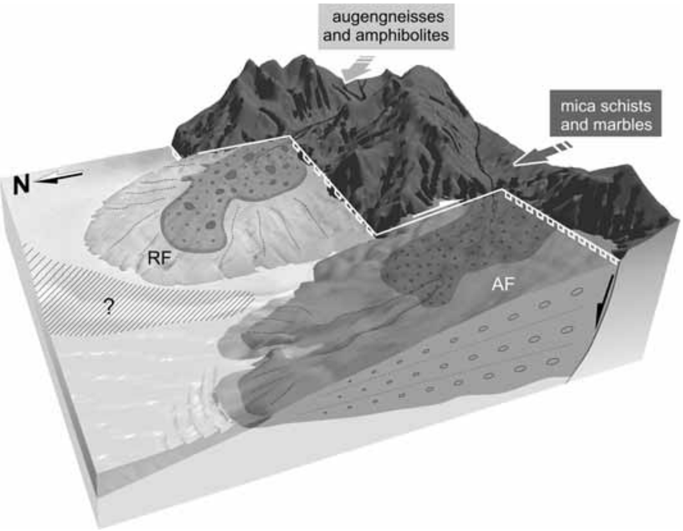

Fig. 7. Conceptual depositional model for the fans of the Apfelberg Formation in the intramontane Fohnsdorf Basin, indicating positions of basin-margin faults and evolution of fans due to faulting and different source areas. The distal portion of the Apfelberg fan grades into a lacustrine fan-delta plain (scale about 1:100 000).

the source areas of the fans. Striking differences exist in the clast lithologies (Table 1), the matrix composition and the heavy mineral compositions (Table 2) of the fan deposits. Clasts of the Rachau fan consist mainly of durable augengneisses, amphibolites and orthogneisses of the Gleinalpe area (mainly Amering and Speik metamorphic complexes; see Fig. 1), 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. These differences were also noted by Polesny (1970) based on heavy mineral samples that display a significantly higher amount of green 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.

The restriction of large outsized boulders, up to 3 m in diameter, to the Rachau fan is a rather unexpected phenomenon because this suggests that the largely non-cohesive debris flows of the Rachau fan had an apparently higher flow competence than the more clay-rich cohesive debris flows of the Apfelberg fan. This may be explained by two factors – either by a steeper relief and, thus, a higher fan gradient due to stronger tectonic movements along this segment of the basin-margin fault array, or again as a source-area lithology effect due to the higher resistivity of the Rachau fan lithologies against weathering. Given the tectonic reconstructions (Strauss *et al.* 2001, 2003) and the indications for strong normal faulting along the Apfelberg fan fault segment, which suggests no significant differences in Miocene fault movements in the hinterland of the two fans, we conclude that source lithologies played the main role. Strong weathering within the humid, subtropical climate of the Middle Miocene in this area (e.g. Steininger *et al.* 1989) may have reduced considerably the clast sizes of the easily weathered mica schists of the Apfelberg fan source area compared to the resistant gneiss and amphibolite lithologies in the Rachau fan hinterland. The gneisses reacted to tectonic stresses by rather widely spaced jointing and to weathering by slow grain-to-grain disintegration along joints into sand. This spheroidal weathering produced resistant, and thus significantly larger, blocks than the weathering of the strongly foliated, soft mica schists and paragneisses of the hinterland of the Apfelberg fan. The conspicuous rounding of these resistant gneiss boulders took place within the catchments, where these blocks are inferred to have been exposed for long

Table 1. *Clast composition data, Rachau fan (R-samples) and Apfelberg fan (A samples). 100 pebble counts, size fraction 2–20 cm. Data partly from Polesny (1970) and Worsch (1972) (Others include quartz, pegmatites, serpentinite)*

	Augengneiss	Amphibolite	Other gneisses	Quartzites	Mica schists	Marbles	Others
R1	52	17	21	6	3	0	0
R2	60	29	7	5	1	0	0
R3	52	26	14	7	1	0	0
A0	11	4	70	3	0	1	10
A1	0	0	0	3	78	19	0
A2	0	0	4	2	58	28	6
A3	0	0	4	2	55	36	1
A4	0	2	25	2	2	57	12
A5	8	7	45	20	2	7	11
A6	5	11	58	12	1	5	8
A7	0	3	0	1	47	43	6
A8	0	0	12	0	49	26	12
A9	0	6	4	1	33	50	5

Table 2. *Mean heavy mineral composition of sands from the Rachau fan (R, mean of three samples) and the Apfelberg fan (A, mean of six samples). Data from Polesny (1970)*

	Garnet	Hornblende	Zoisite	Epidote	Disthene	Titanite	Rutile	Tourmaline	Apatite	Amphibole
R	14.3	66.6	3.9	11.2	1.5	2.1	0.6	0.6	1.2	0.5
A	74.8	11.8	2.7	9.2	0.3	1.1	0.6	1.5	0.8	0.1

periods in stream beds, as normal floods would not have been able to transport them.

According to Wells & Harvey (1987) debris-flow-dominated successions are typical for alluvial fans with relatively small catchment areas and high slope gradients. Maximum slope gradients may be estimated as 2°–8° based on comparable debris-flow-dominated recent fans (e.g. Hubert & Filipov 1989; Blair 1999). 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, for example 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.

Bedrock lithology differences are, thus, regarded as the key factor causing the contrasting debris-flow facies of the two fans. In this respect fan development in the Fohnsdorf Basin displays a similar hinterland control to that of recent fans in Death Valley (Blair 1999) and the Rocky Mountains (Blair 1987).

This work is based on the diploma thesis of P. Strauss in the Fohnsdorf Basin and work within the Austrian Science Fund project FWF-P14370. The University of Vienna, the Styrian Government and the Stratigraphic Commission of the Academy of Sciences are thanked for financing this work. Thanks are due to G. Nichols and A.M. Harvey for constructive reviews.

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