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INITIATION AND DEVELOPMENT OF A FAULT-CONTROLLED, OROGEN-PARALLEL OVERDEEPENED VALLEY: THE UPPER ENNS VALLEY, AUSTRIA

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ABSTRACT

The paper focuses on modelling the development of the orogen-parallel fault-controlled overdeepened Upper Enns Valley, Eastern Alps. A decrease in relief in the Middle Miocene, an increasing relief from Pliocene to recent times and the interplay between tectonically controlled differential uplift and denudation resulted in a morphology that is reflected by planation surfaces on valley slopes at elevations of about 1100 m. The Upper Enns Valley separates the crystalline basement of the Niedere Tauern in the south from the Greywacke Zone and the Northern Calcareous Alps in the north. The Upper Pleistocene Ramsau Conglomerate covers the Greywacke Zone on the northern valley slope and is suggested to have important information for reconstruct the history of overdeepening of the Upper Enns Valley in several steps. The formation of the Enns Valley started in Early to Middle Miocene and continued to recent times. Valley formation occurred under uplift along the ENE-trending, orogen-parallel transtensional Salzach-Enns strike-slip zone. The southern block suffered a much higher exhumation than the northern block. We interpret the asymmetric drainage pattern, with short northern tributaries to the Enns Valley and long southern ones, to indicate northward tilting of the entire region. Furthermore, Quaternary processes, such as uplift and cyclic glaciations, interfered with neotectonic activity. The provenance of the Upper Pleistocene Ramsau Conglomerate from the southern side of the valley and the presence of a terrace at 1100 m indicates that the Enns Valley was filled from the present base at ca. 820 m above sea level up to that elevation during Late Pleistocene times. Post-Ramsau Conglomerate glacial overdeepening scoured the Enns Valley and resulted in epigenetic and regressive incision of southern tributaries. The channels of the southern tributaries have knick zones, reflecting gradient changes between flat and steep reaches. The suggested continuity of the southern planation surfaces and the top of the Ramsau Conglomerate (at ca. 1100 m) is interpreted to represent a relic former valley bottom. Although close to the Salzach-Enns fault, pronounced knick zones along southern tributaries are interpreted to result from glacial overdeepening rather than from neotectonic activity.

Ziel der Studie ist die Entwicklung des gebirgsparallelen, störungsgebundenen, übertieften Oberen Ennstales. Reliefabbau im Mittelmiozän, Hebung von Pliozän bis heute und die Wechselwirkung zwischen tektonisch kontrollierter differenzieller Hebung und Denudation spiegeln sich in spezieller Morphologie wider, nämlich in Verebnungen der höher gelegenen Talhänge und Täler im Süden. Das Obere Ennstal bildet den Grenzbereich zwischen dem kristallinen Sockel der Niederen Tauern im Süden und der Grauwackenzone bzw. den Nördlichen Kalkalpen im Norden. Das oberpleistozäne Ramsau-Konglomerat überlagert die Grauwackenzone und wird benutzt, um die stufenweise Talentwicklung des Oberen Ennstales zu rekonstruieren. Die Bildung des Ennstales entlang der ENE-verlaufenden transtensionalen Salzach-Enns Störungszone begann im Untermiozän und dauert noch an. Im Gebirgsblock des Südens erreicht die Exhumation höhere Werte als im Norden. Das asymmetrische Entwässerungsnetz mit kurzen Nebenflüssen aus dem Norden und ungleich längeren aus dem Süden lässt auf eine Verkippung nach Norden schließen. Quartäre Prozesse wie Hebung und zyklische Vereisungsperioden interferieren mit neotektonischer Aktivität. Sedimentanlieferung aus dem Süden und eine Terrasse in ca. 1100 m Seehöhe lassen den Schluss zu, dass das Tal im Pleistozän von ca. 820 m an seiner Basis bis zu dieser Höhe mit Sedimenten (Ramsau-Konglomerat) gefüllt war. Eine Kontinuität der Verebnungen im Süden mit der Obergrenze des Ramsau-Konglomerates (1100 m) wird als Relikt eines ehemaligen Talbodens angesehen. Glaziale Übertiefung führte zu epigenetischem und regressivem Einschneiden der südlichen Nebenflüsse, die durch Knickzonen zwischen steilen und flachen Flussbereichen gekennzeichnet sind. Trotz der Nähe der Salzach-Enns Störung werden die Knickzonen eher als Resultat glazialer Übertiefung und weniger als eine Folge neotektonischer Aktivität interpretiert.

1. INTRODUCTION

This contribution describes the evolution of the Upper Enns Valley in Austria that follows the sinistral transtensional strike-slip Salzach-Enns Fault (Fig. 1), one of the most important faults related to the eastward extrusion of the Eastern Alps (Ratschbacher et al., 1989, 1991).

Surface uplift and subsidence have a pronounced expression on the Earth´s surface because of the interplay between uplift and erosion, and consequently the export of clastic material. Asymmetric drainage basins, changes of river gradients, formation of triangular facets along active faults and the formation of pressure ridges all play a key role in geomorphological changes due to tectonism (e.g. Keller and Pinter, 1999; Burbank and Anderson, 2001). Short- and long-term changes of geomorphology can be induced by the interference of tectonic activity, surface uplift and climate change, when, for example, glacial processes are involved. In particular, climate may control erosion and rock-uplift rates over short-time scales (Brocard et al., 2003; Norton et al., 2007; Ouimet et al., 2008). However, the final topographic evolution has to be seen in the context of both the external forces and tectonic activity.

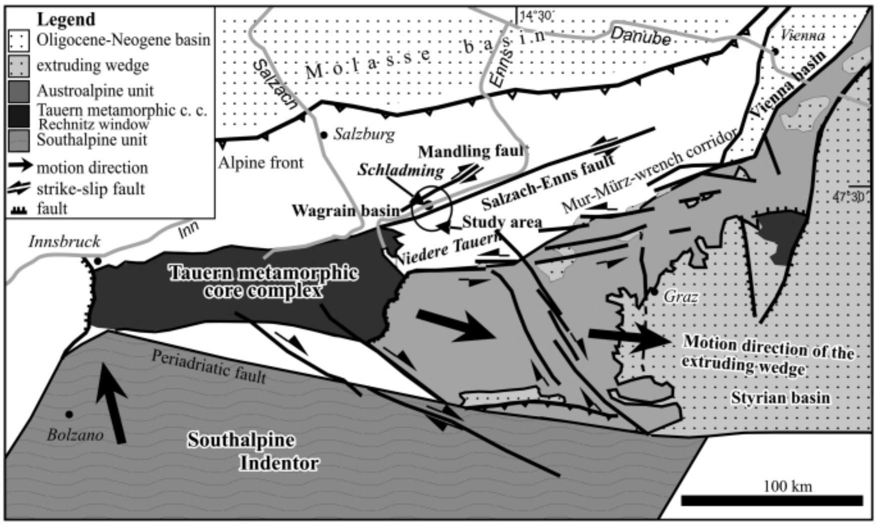

FIGURE 1: Simplified tectonic map showing location of principal strike-slip faults and the location of the study area.

Morphology, drainage pattern, glaciation and tectonic activity along the valley-parallel active Salzach-Enns Fault Zone (Reinecker and Lenhardt, 1999), which generates regionally moderate seismicity (Lenhardt et al., 2007), are the most important parameters in this work. The relationship between longterm overall uplift, tectonic activity, river incision and glacial scouring have been used to reveal several stages of landscape formation and to develop a possible model of evolution of the glacially overdeepened Upper Enns Valley in the uplifting Eastern Alpine orogen. The subsurface shape of the overdeepened valley has not been discussed due to the lack of data (see, e.g. Hoffmann and Schrott, 2002; Schrott et al., 2002).

2. MATERIALS AND METHOD

Our work was based on an assessment of topographic maps ÖK 25V, 1:25 000, Blatt 127 (1) Schladming Nord, (2) Schladming Süd, the Geologische Karte der Republik Österreich, 1:50 000, 127 Schladming (including material presented in Mandl and Matura, 1995), and a digital elevation model (DEM) portraying the present topographic surface.

The study site was first investigated by detailed field inspection, including mapping, measurements of structural parameters and an inventory of sedimentary clasts within the Upper Pleistocene Ramsau Conglomerate. The existing literature on overdeepening and geomorphic markers and the tectonic evolution of the Eastern Alps (Neubauer, 1988; Ratschbacher et al., 1991; Wang and Neubauer, 1998; Frisch et al., 2000a, b; Frisch et al., 2001; Székely et al., 2002; Schlunegger and Schneider, 2005; Schmid et al. 2005; Reitner and van Husen, 2007;) provided general information about the development of a fault-controlled valley like the Upper Enns Valley.

3. GEOLOGICAL SETTING

The Upper Enns River flows from W to E at an elevation of ca. 800 m to 700 m, with an average gradient of ca. 0.5 % (Fig. 2A). The valley flanks differ significantly in geomorphology and geology. The southern side (Niedere Tauern) has a rugged topography with steep slopes and deeply incised rivers, mostly ending in canyons. The northern side (Northern Calcareous Alps) forms impressive rock faces, in part ca. 1,000 m in height (e.g. Dachstein south face), and extensive karst plateaus at an elevation of ca. 2,200 m (Fig. 2A). The easternmost present-day glaciers of the Alps cover parts of the Dachstein plateau. The Salzach-Enns-Mariazell-Puchberg (SEMP) Fault is one of the major faults in the Eastern Alps that formed during Miocene lateral extrusion (Ratschbacher et al., 1989). The Salzach-Enns strike-slip fault, as a part of the SEMP line, trends ENE (Neubauer, 1988; Ratschbacher et al., 1991; Wang and Neubauer, 1998) and is presumed to run along the southern edge of the Enns Valley in the study area. The fault is largely hidden by the Holocene valley fill.

Morphological and geological features north and south of the Enns Valley show clear differences (Fig. 2B), although all geological units trend ca. E–W. The Upper Enns Valley separates the Schladming-Wölz basement and the Ennstal Quartzphyllite zone, both parts of the Niedere Tauern in the south, from the Greywacke Zone and the Northern Calcareous Alps with the Dachstein Massif to the north (Figs. 2A, B). In addition, the ENE-trending Mandling Fault transects the Greywacke Zone; the Mandling wedge, comprising Mesozoic rocks of the Northern Calcareous Alps, is exposed to its south. This unit is thought to be a strike-slip duplex derived from the Northern Calcareous Alps, implying major dextral displacement along the Mandling Fault (Neubauer, 2007; unpublished data; Fig. 2B). The cut-off of the Northern Calcareous Alps along the Mandling Fault occurs in the SW. The Mandling wedge is, therefore, a displaced piece of the southernmost Northern Calcareous Alps.

The Upper Pleistocene Ramsau Conglomerate covers the Greywacke Zone (Fig. 2B). Provenance analysis of the Ram-

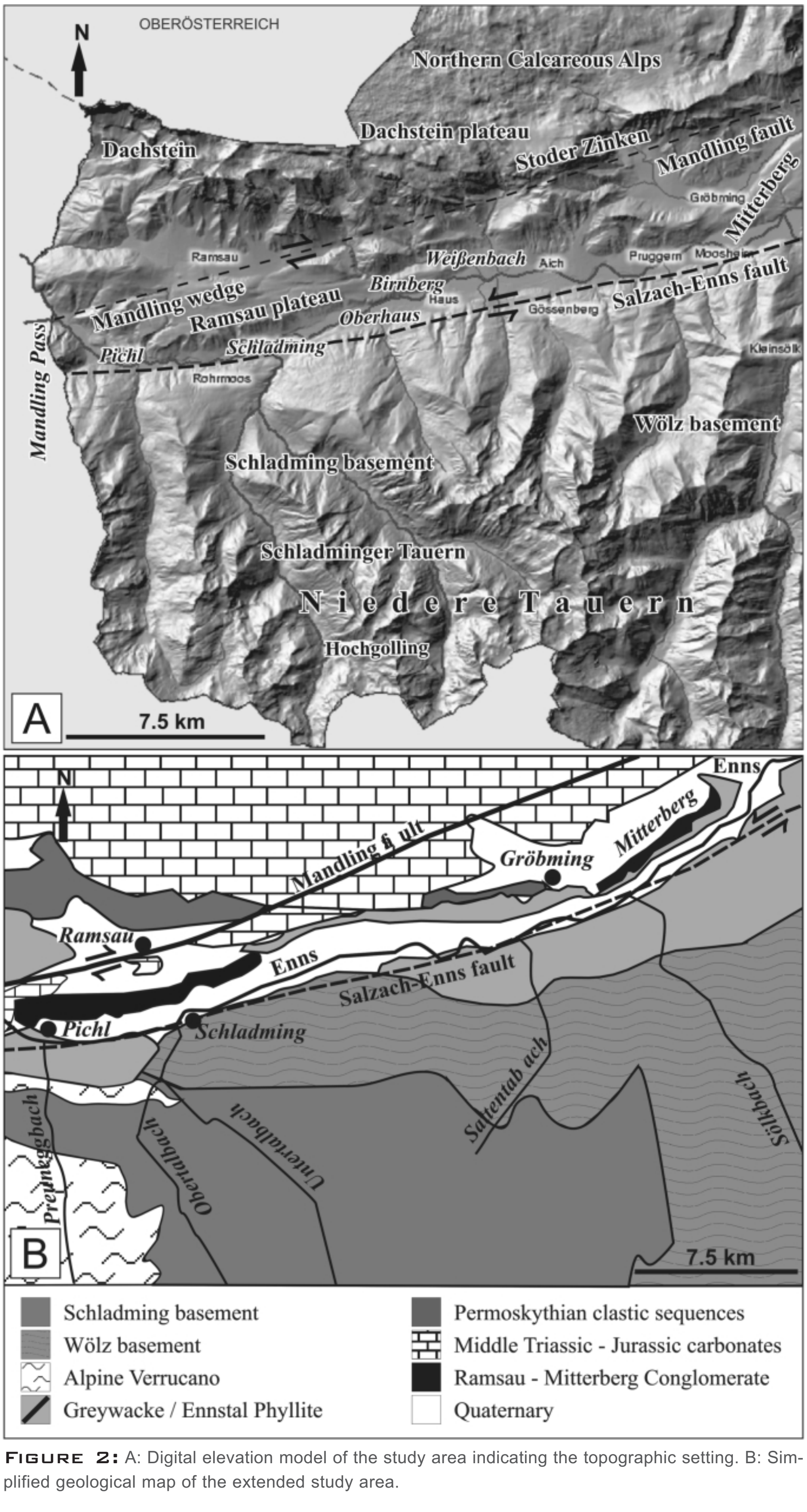

Figure 2: A: Digital elevation model of the study area indicating the topographic setting. B: Simplified geological map of the extended study area.

sau Conglomerate shows in general a material supply from the southern side of the Enns Valley (Keil, 2008).

The landscape in the study area comprises three main tectonic units. (1) The Schladming-Wölz basement, with gneisses, granites, micaschists, the Alpine Verrucano Formation and the Ennstal Quartzphyllite of the Niedere Tauern, (2) the Austroalpine Palaeozoic unit (Greywacke Zone) with soft lithologies, and (3) the Permo-Mesozoic cover rocks dominated by thick Triassic carbonate sequences.

The overall evolution of the drainage system of the Eastern Alps including orogen-parallel fault-controlled valleys was in two main stages: (1) From Early Oligocene to Early Miocene times, the overall drainage system of the Eastern Alps was directed towards the north (cf Frisch et al., 1998); this pattern developed before the activation of the large strike-slip faults during lateral extrusion. (2) Around the Oligocene/Miocene boundary, the catchment area was affected by N–S shortening and lateral extrusion (Ratschbacher et al., 1989, 1991; Wang and Neubauer, 1998; Frisch et al., 1998, 2000a, b; Kuhlemann et al., 2001a, b; TRANSALP Working Group, 2002). Activity along the faults associated with the pulse of lateral extrusion switched the drainage direction to the east, replacing the north-directed system. (3) At about 10 Ma, the drainage pattern was probably similar to the present one. At the Pliocene/Quaternary boundary (ca. 2.6 Ma), the drainage system reached conformity with the present one (Frisch et al., 2000a; van Husen, 2000).

A relief evolves toward equilibrium between uplift and incision (Keller and Pinter, 1999). However, mountain rivers are generally not in equilibrium, as climate fluctuations modify not only their channels but also the entire profile of a valley. Consequently, in the Eastern Alps, the present-day relief should be mainly seen as the result of long-lasting vertical orogenic motions, the Quaternary glaciations and the activity of the rivers (Székely et al., 2007). Any explanation for the evolution of a relief is speculative; both isostatic and erosional effects, as well as recent surface processes, must be taken into account.

The Upper Enns Valley shows weak seismicity, reaching magnitudes of 4.1 (Reinecker and Lenhardt, 1999; Lenhardt et al., 2007). Székely (2001) noted the flat-iron type of morphology on the southern slope of the Enns Valley and suggested possible neotectonics along the SEMP fault.

The broadly west–east trending fault-controlled depressions formed during Neogene strike-slip tectonics were filled by the Palaeo-Enns River, fed by tributaries from the south. Between Early/Middle Miocene and Pliocene times vertical movements ceased (Dunkl et al., 2005) and surface uplift occurred from Pleistocene to recent time (Frisch et al., 2000a, b; Reinecker, 2000; Frisch et al., 2002).

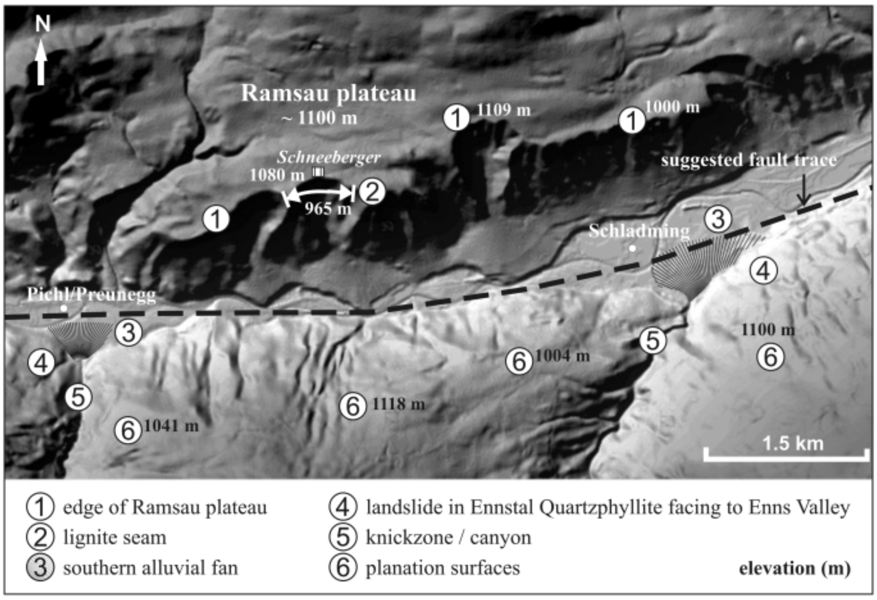

FIGURE 3: Morphology of the Enns Valley in the Schladming sector.

Initiation and evolution of the Upper Enns Valley covered the period from the Early Miocene to recent times. During the Miocene, it was evolved as a fault-controlled valley, whilst Pleistocene glaciations played a major role in shaping the present-day overdeepened Enns Valley (Spaun, 1964; van Husen, 1968, 1981).

Glacially overdeepened valleys are of special interest not only for interpreting the Quaternary but also economically (e.g. groundwater resources). Longitudinal valleys (Inn Valley, Enns Valley) follow the major strike-slip fault zones (Ratschbacher et al., 1991; Frisch et al., 2000a; Köck et al., 2000) and consequently, both tectonics and glaciation have to be considered when interpreting overdeepening of valleys. Glacial erosion caused rapid exhumation, whilst isostatic uplift elevated the rocks during and after deglaciation (England and Molnar, 1990; Gudmundson, 1994; Pinter and Brandon, 1997; Frisch et al., 2000a; Kuhlemann et al., 2001a).

4. CONSTRAINTS ON VERTICAL MOTION

The Schladming Basement Complex, which reaches elevations of 2,862 m, exhibits a young morphology, with steep slopes (Reinecker, 2000) (Hochgolling, Fig. 2A). The steeply dipping, Ennstal Quartzphyllite represents a zone of easily eroded rocks that are affected by extensive landsliding, particularly in regions facing north, towards the Enns Valley (Mandl and Matura, 1995). Apatite fission track ages reveal that at least the western part of the Niedere Tauern was still at a depth of ca. 3 km during Early Miocene times (Hejl, 1997, 1998; Frisch et al., 2000a; Reinecker, 2000).

The Greywacke Zone and Mandling wedge reach maximum altitudes of only 1,300 to 1,760 m. The Dachstein Limestone forms a plateau with an elevation of ca. 2,200–2,400 m and peaks up to near 3,000 m. This plateau is a karstified, Late Eocene to Early Oligocene (pre-~30 Ma) planation surface, locally covered by rare remnants of Oligocene to Lower Miocene gravels (Augenstein Formation), now uplifted to its present elevation (Frisch et al., 2001, 2002).

The Upper Pleistocene Ramsau Conglomerate is a significant part of the landscape of the northern slope of the Upper Enns Valley between Pichl/Enns and Weissenbach/Haus (Fig. 2A, B). The base of the Ramsau Conglomerate lies at an elevation of ca. 820 m in the west (Pichl/Enns) and ca. 780 m in the east (road to Birnberg near Oberhaus railway station), whilst its top forms an impressive planation surface, the Ramsau plateau. We interpret the base of the Ramsau Conglomerate as a former valley bottom, which can be followed along the Enns Valley, as at Mitterberg, SE of Gröbming (Fig. 2B) (van Husen, 1987). A widespread lignite seam (or lignitic coal; Weber and Weiss 1983, Weiss 2007), which was mined and sporadically used until the end of the Second World War, is intercalated in the conglomerates at an elevation of ca. 965 m. Although this has been ^{14}C-dated to 31 ± 1.2 ka (uncalibrated; van Husen, 1981), the age remains uncertain and some workers argue for deposition during the Riss/Würm Interglacial (Sachsenhofer, 1988). A map of the mine shows faults with offsets of ca. 2.5 m, consistent with faults measured at

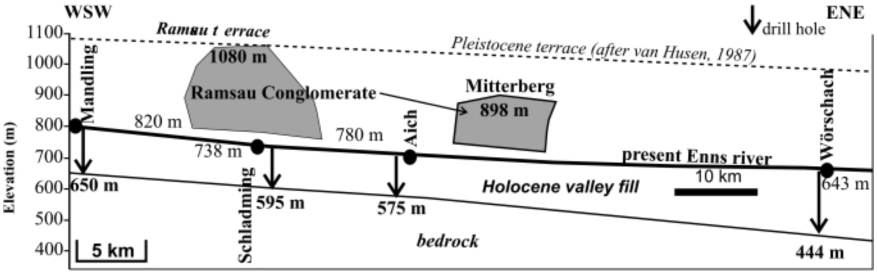

FIGURE 4: Sketch of glacial overdeepening in the Upper Enns Valley, for locations see Figure 5. Sources of drill hole data: STEWEAG, 1978; other data from drilling in Mandling valley.

the surface of the Ramsau Conglomerate, documenting Quaternary tectonic activity (Keil, 2008). Moraines and Holocene sediments cover the Ramsau Conglomerate but these are not affected by the faulting.

Digital elevation models (Digitaler Atlas Steiermark, 2008), though only available at low resolution indicate characteristic features of the Enns Valley close to Schladming (Fig. 3). The southern boundary of the Ramsau plateau displays sharp-edged scars (Fig. 3, point 1). Fine-grained sediments promote water outlet, resulting in steep trenches which dissect the escarpment of the Ramsau plateau, and, in one trench, the aforementioned lignite seam is intercalated with the Ramsau Conglomerate (Schneebergleiten, Fig. 3, point 2).

The southern tributary valleys form large alluvial fans (Fig. 3, point 3). A poor drainage network has led to landslides in the Ennstal Quartzphyllite facing the Enns Valley (Fig. 3, point 4). During the Würm glaciation, the Enns Valley was filled by the Enns Valley Glacier to an elevation of ca. 2,000 m (van Husen, 1987; Schmid et al., 2005), whilst, at the same time, it scoured the valley to a depth of 120–130 m beneath the present surface (van Husen, 1968; Becker, 1987). Glacial retreat caused the tributaries to incise by regressive erosion to adjust to the new base level, forming canyons and knick points in the longitudinal stream profiles (Fig. 3, point 5; see Swiss examples in Schlunegger and Schneider, 2005). Near the knick points, the valleys, which incise into the Ennstal Quartzphyllite, are narrow. The steep valley flanks display sharp edges along terraces at altitudes between 1,000 and 1,100 m (Fig. 3, point 6). These terraces likely represent post-LGM (last glacial maximum) ice-margin terraces of the retreating Enns Valley Glacier.

5. GLACIAL OVERDEEPENING OF THE UPPER ENNS VALLEY

Glacially overdeepened valleys form in the ablation area of a glacier due to a higher ice velocity which increases the debris load at the base (Reitner and van Husen, 2007).The longitudinal Enns Valley did not have a uniform level in preglacial time (Penck and Brückner, 1909) although the drainage divide between the Salzach and Enns valleys lies ca. 15–20 km further west of Mandling than Penck and Brückner (1909) proposed (either located near Eben/Pongau or between Wagrain and Flachau). Penck and Brückner (1909) also suggested that the Mandling Pass at Mandling (Fig. 2A), which forms a water gap of the Enns River today, divides two terraces of different heights; the western is inclined towards the Salzach Valley in the west and the eastern towards the east.

Ice discharge is high at valley junctions (e.g. Mandling Valley with Enns Valley). The ablation areas of the interconnected glaciers of Enns, Traun and Salzach formed long overdeepened stretches of the valleys during Würm glaciation (van Husen, 2000). Recent drillings and geophysical surveys have documented the sediment thicknesses in the Enns Valley (Fig. 4); these showed that between Mandling (800 m. above sea-level – m.a.s.l) and Wörschach (Fig. 4), glacial overdeepening was greater extent than previously pre-

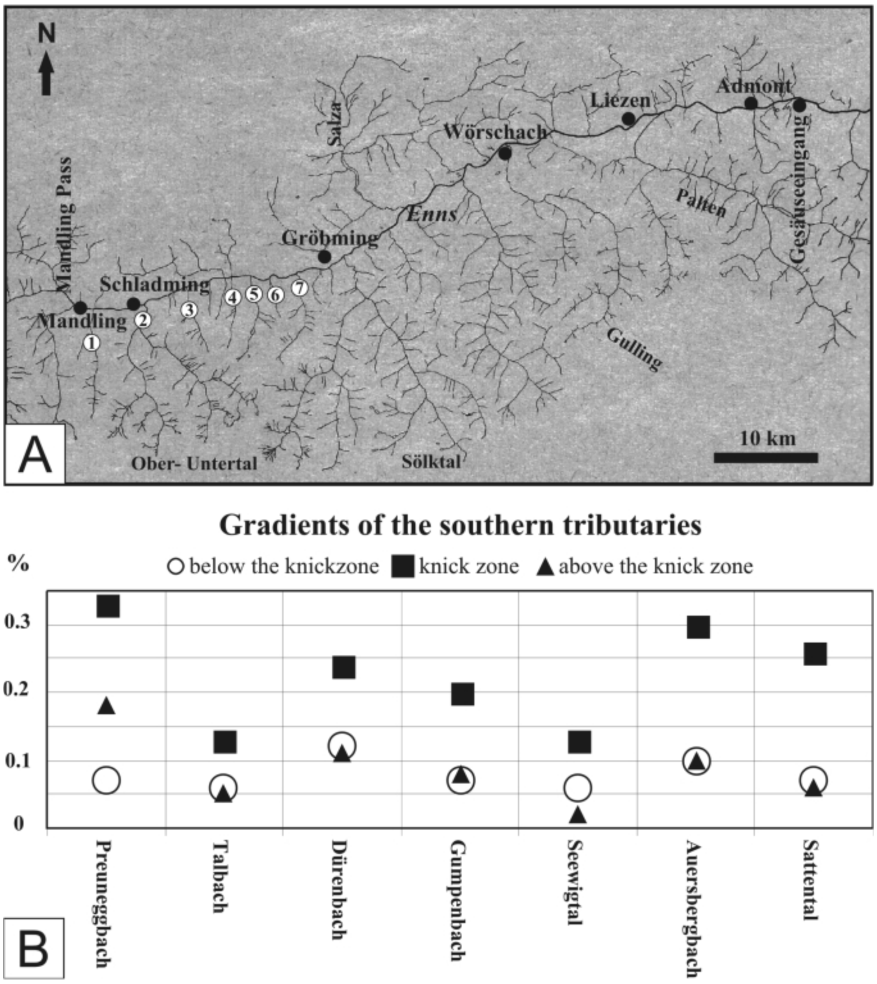

FIGURE 5: A: Enns River drainage pattern from source to Gesäuseeingang illustrating the asymmetry of the Enns Valley; only the main tributaries are labelled. Explanation for asymmetry: (1) morphological differences north and south of the valley due to different lithologies (see Fig. 2B), and (2) northward tilting of the fault-bounded river network. Numbers 1-7 indicate locations of tributaries in Figure 5B.
B: River gradients of seven southern tributaries, showing the differences between below and above the last knick point before their confluence with the Enns River (calculation: elevation difference/length of the reach, according to Burbank and Anderson, 2001). The gradients of the flat reaches are in the order of ca. 0.1% or less. The gradients at knickzones are much higher with a maximum of 0.33 %.

sumed (Becker, 1981, 1987). However, Penck and Brückner (1909) assumed a valley bottom at ca. 590 m above sea-level between Irdning (673 m.a.s.l) and Wörschach (643 m.a.s.l), based on drillings that did not reach bedrock under a peat layer. At Mandling, the valley floor filling is about 150 m thick, with the overdeepened bedrock at 650 m.a.s.l. The Upper Enns Valley has a rather constant gradient of about 0.5 %, which shows conformity with the gradients of 0.5 to 0.3 % set up by Frisch et al. (2000a). Drillings in Schladming and Aich resulted in a valley-floor filling of 120–130 m, the overdeepened bedrock lies between 595 and 575 m.a.s.l.

6. ASYMMETRIC DRAINAGE PATTERN OF THE UPPER ENNS VALLEY

The longitudinal valley of the Enns River, which has an average gradient of 0.21 % from source to mouth, shows an asymmetric drainage pattern (Zötl, 1960). Less than 15 % of the drainage area lies in the north of the study area although between the source and Gesäuseeingang (Fig. 5A), about 31 % of the water supply comes from the northern tributaries (Fig. 5A). The Enns River mostly flows along the south side of the valley, except where large alluvial fans from the southern tributaries force it towards the northern margin. The gradients of tributaries of the Enns River are not smooth; downstream reaches with gentle gradients are separated from reaches with high gradients by pronounced knick points (Fig. 5B). The steep segments suggest tilting in a downstream direction, indicating a northwards tilting in the study area. The drainage area south of the Enns River in the study area covers ca. 247 km² (A_r) compared to the total drainage area of ca. 365 km² (A_t), which includes all the area between the drainage divides north and south of the Enns Valley (Digitaler Atlas Steiermark, 2008). The Asymmetry Factor of 68 [$AF = 100 (A_r/A_t)$] (Keller and Pinter, 1999; Pinter, 2005) confirms the apparent northward tilting (see Discussion section). Although variable in orientation and dissected into several blocks (Frisch et al. 2001), the overall tilting of the Dachstein palaeosurface is towards the north, similar to other mountain blocks in the eastern Northern Calcareous Alps (e.g. Tennengebirge, Untersberg).

7. DISCUSSION

Evidence given above showed that moderate recent faulting has occurred along the Salzach-Ennstal Fault, consistent with stress conditions causing moderate earthquakes during NE–SW-oriented compression (Reinecker and Lenhardt, 1999; Keil, 2008).

7.1 GLACIAL OVERDEEPENING OF THE ENNS VALLEY

Glacial overdeepening in the Enns Valley, which approximately follows the SEMP fault, increases towards the Gesäuseeingang (Fig. 5), where the deepest bedrock beneath the sedimentary valley infill has been found by seismic investigations (Schmid et al., 2005), although the thickness of infill is still under discussion (Schmid et al., 2007). The cause of the glacial overdeepening is uncertain; ice discharge was generally high at valley junctions (e.g. Mandling Valley with Enns Valley), as the ice load increased, and this might have been the case at the Mandling pass, as discussed above. Tectonic subsidence can also cause overdeepening of valleys (Reitner and van Husen, 2007). In the Western Alps, valley infills deposited since the last glacial maximum are up to 450 m thick (e.g. Brocard et al., 2003). In the Eastern Alps, boreholes not reaching a pre-Quaternary basement suggest that overdeepening is ca. 400 m thick (van Husen, 2000); recent seismic profiling in the eastern Enns Valley showed ca. 480 m of possible, but not proved Quaternary sediments above bedrock (Schmid et al., 2005). The amount of fill depends on the relationship between the main river and its tributaries in terms of both water and debris discharge (van Husen, 2000). Glacial

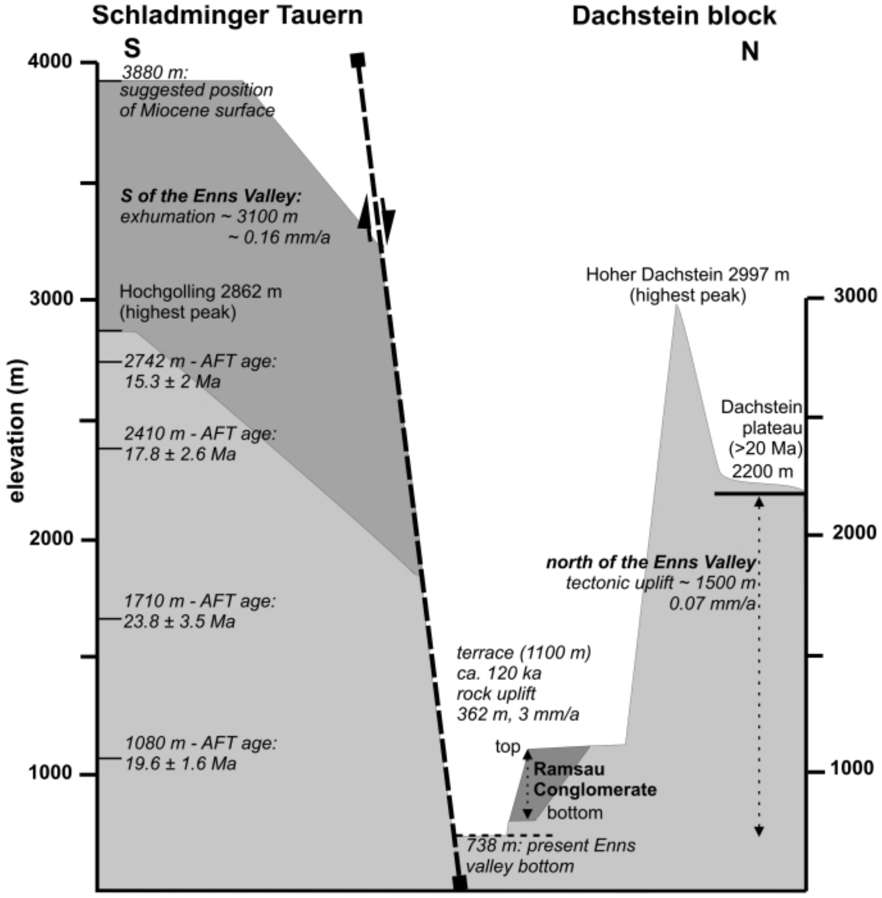

FIGURE 6: Schematic sketch outlining the surface uplift and exhumation of rocks in the study area.

valley overdeepening led to a steepening of valley slopes in Quartzphyllite areas south of the Enns River, although deglaciation also contributed to the instability of these slopes. The higher incision rates may have been induced either by tectonic activity or by enhanced water discharge due to deglaciation; the former are often underestimated. Kuhlemann et al. (2002) estimated an average tectonic uplift of ca. 0.3 mm/a, which is low compared to the regional uplift of ca. >1 mm/a. The incision rate in steep channels that have waterfalls can be very high (Ouimet et al., 2008). However, surface processes can induce a tectonic feedback (Cloetingh and Ziegler, 2007).

The actual amount of overdeepening is still uncertain for the Upper Enns Valley in the study area. Becker (1981) assumed that overdeepening of the Enns Valley had already occurred before the Würm glaciation, as the volume of the Riss Glacier was bigger and only a thick ice-load could develop such an overdeepening.

Canyons, gorges, and increased stream gradients are characteristic features of the southern tributaries before their confluence with the Enns River. The questions to answer are, which external and internal forces contributed to form the main valley and the tributary valleys, which relative roles neotectonics and glaciation played in the northward tilting forced by differential tectonic uplift.

7.2. Asymmetry of the Drainage pattern

Northward tilting, quantitatively derived from the Asymmetry Factor, should be interpreted with caution. The distinct pattern and the geometry of the drainage network (long tributaries from S and short ones from N) indicate morphological asymmetry. On the other hand, rock types differ between N and S of the valley (Fig. 2B). The effect of karstification is thought to have played a minor role; there is evidence that the cave in the Dachstein south face extends northwards as a subsurface drain (Seebacher, 2006). Similar asymmetric drainage patterns can be found around the Tauern window, which is clearly the effect of long-term uplift of the central part of the Tauern window, tilting previous thrust and normal faults.

Periodic alternation of accumulation and erosion, frost penetration and thawing occur in mountainous regions such as the study area (Habbe, 1993; Leeder, 1999). However, not only climate fluctuations cause perturbations but also tectonics. Tectonically undisturbed rivers have a graded profile, steeper near the source and flatter in lower reaches of the river (Keller and Pinter, 1999; Burbank and Anderson, 2001; Pinter, 2005).

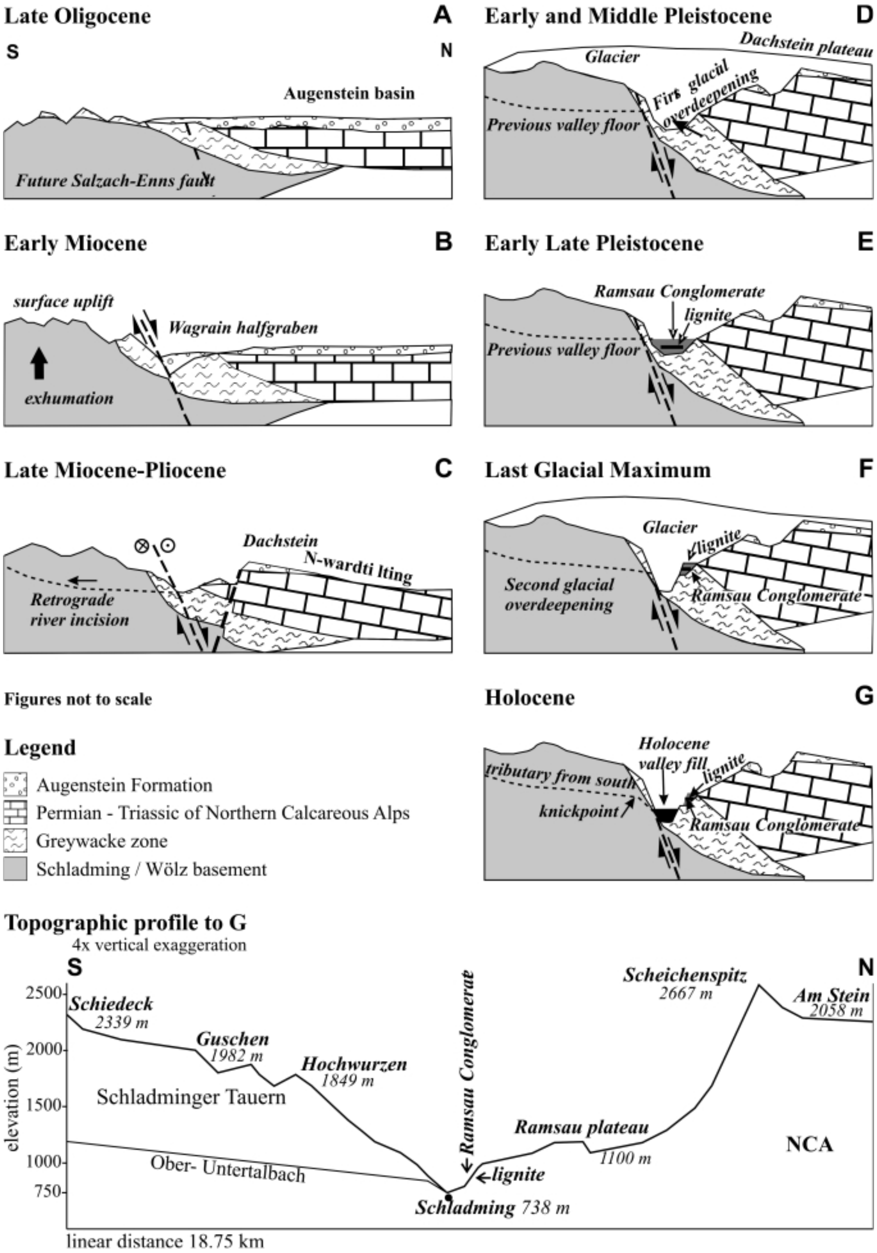

Figure 7: Tectonic model for the evolution of the Enns Valley (for description, see text).

7.3 Planation surfaces

Signs of a former valley bottom and planation surfaces in the Upper Enns Valley were noted by Penck and Brückner (1909) and van Husen (1987), such as at the knick points at Sölktal – Mitterberg (elevation ca. 900 m) and Obertal/Untertal/Preuneggtal – Ramsau (elevation 900–1,000 m). Parts of these former valley bottoms were dissected due to subsequent river entrenchment. Planation surfaces have been preserved on both sides of the Upper Enns Valley (Fig. 3). Their elevations above the active channel of the Enns River are supposed to record the interplay between uplift rates and incision. The planation surfaces south of the Enns Valley, at ca. 1,000–1,100 m, suggest a continuously glacially overdeepened U-shaped valley bottom, with the Ramsau plateau as upper level of infill.

7.4 UPLIFT AND EXHUMATION HISTORY

Two differential processes characterize the uplift history of the study area: (1) tectonically driven long-term surface uplift and (2) short-term post-glacial unloading.

Fission track data (Hejl, 1997, 1998; Reinecker, 2000) indicate that the Schladminger Tauern area has experienced strong erosion since the end of the Oligocene (23.3 Ma) in terms of long-term uplift (Fig. 6). This resulted in a Neogene surface uplift and relative displacement of ca. 1,000 m compared to the southern area of the Gurktal Mountains (Reinecker, 2000) and the NCA to the north. We take the example of a specific apatite fission track age that is representative of a number of similar age results (Hejl, 1998; Reinecker, 2000) that are in part significantly younger (up to 14 Ma) and taken at higher elevations (ca. 2,700 m). The Miocene AFT age of 19.6 ± 1.6 Ma indicates exhumation and relative rock uplift (Hejl, 1997, 1998) compared to the area north of the Enns Valley. The sample from the Schladming basement had enough tracks to determine a significant length distribution. Its unimodal mean track length of 13.76 µm indicates slow continuous cooling since Miocene times. Assuming a constant geothermal gradient in the order of 30°C/km, this reflects a denudation rate of ca. 107 m/Ma between 23 and 16 Ma (slope regression line reflects this rate; Hejl, 1997). Thus there was an exhumation of ~ 2,000 m between the early Miocene and the end of the Miocene, and of another 800 m since the end of the Miocene (5.2 Ma). Greater tectonic uplift on the southern side of the Upper Enns Valley compared to the northern side caused differential motion along the SEMP fault (Fig. 6) including the possible effect of northward tilting (see above). The Dachstein palaeosurface, which was covered by the Oligocene/lower Miocene Augenstein Formation is now exposed at an elevation of ~ 2,200 m and was a sort of piedmont close to the Molasse Sea at ca. 20 Ma (Frisch et al., 2001).

This is markedly different to the Niedere Tauern area, where the above mentioned unit with the fission track age of 19.6 Ma (taken at an elevation of 1,080 m) was covered by an at least 2800 m thick rock column. This means that there is minimum difference in surface uplift of ca. 1,700 m between the northern and southern flanks of the Enns Valley, representing the minimum value of vertical differential motion between the two blocks along the SEMP fault. Note that this value also includes the effects of northward tilting.

The surface of the Ramsau Conglomerate and correlative terraces of the Enns and Steyr and their tributaries can be traced along the entire Enns Valley down to the Danube as base level, showing a continuous profile with a low gradient and minor incision in between (van Husen, 2000). Consequently, this feature can be interpreted as either rock uplift or base level lowering. A further argument for rock uplift (as defined by England and Molnar, 1990) is that geodetic measurements indicate a present-day differential uplift of 1.5 mm/year between the foreland and the Tauern area within the Alps (Frisch et al., 2001; Ruess and Höggerl, 2002). This suggests that uplift rates can vary locally and might have accentuated the higher short-term uplift rates in the study area.

The only age-data for the Ramsau Conglomerate is the uncalibrated ^{14}C age for the lignite seam of ca. 31 ka (van Husen, 1981). This young age would imply an incision or uplift of the Enns Valley of ca. 360 m since 31 ka. We suggest a formation age of about 120 ka during the Eem Interglacial, during a warm interstadial period. Short-term uplift indicates a vertical displacement or river incision of ca. 3 mm/a assuming the early late Pleistocene age of the Ramsau Conglomerate (calculation: elevation difference between the valley bottom at Schladming [740 m.a.s.l], taken as a reference point, and the top of the Ramsau Conglomerate [1100 m.a.s.l]/120 ka; 360/120 = 3 mm/year). We estimate that similar uplift rates occurred in the tributaries west and east of the Ramsau Conglomerate. This extremely high value mirrors the climatic impact of glacial and interglacial times, resulting in higher incision rates of the tributaries that dissected the terrace and led to a relative uplift. This short-term uplift was not necessarily driven by tectonics. The fast uplift rates do not infer a change in surface elevation of the entire region but might be the result of isostatic compensation (England and Molnar, 1990; Székely et al., 2002; Bishop, 2007)). In the working area, this could be the effect of unloading by deglaciation after the Würm glaciation.

7.5 MODEL FOR INITIATION AND FURTHER DEVELOPMENT OF THE UPPER ENNS VALLEY

1. From Oligocene to early Miocene times (Fig. 7A), the overall drainage system was northwards directed. Both palaeosurfaces and provenance analysis indicated transport from south to north (Frisch et al., 2002); no major W-E–trending orogen-parallel valley existed between the later-formed Niedere Tauern and the Northern Calcareous Alps.
2. Lateral extrusion, together with the formation of a large strike-slip faults in the middle Miocene, led to the formation of an orogen-parallel depression initially forming a sedimentary basin from Wagrain to Stoderzinken along the future Enns Valley (~16 Ma) (Frisch et al., 2000a; own observations) (Fig. 7B).
3. The uplifting Niedere Tauern created incised rivers with V-shaped valleys (Pliocene) (Fig. 7C).
4. Glacial overdeepening during an interglacial period, such as the Mindel/Riss Interglacial, resulted in U-shaped valley formation, with a valley bottom between 690 and 740 m.a.s.l. at that time (Fig. 7D). Overdeepening of the Enns Valley likely occurred before the Würm glaciation due to the large ice-mass of the Riss Glacier.
5. After the retreat of the Riss Glacier, the Ramsau Conglo-

merate (including the lignite seam) was deposited in the Enns Valley during the Riss/Würm Interglacial. It filled the valley up to an elevation of about 1,100 m (Fig. 7E), and predated the next advancing (Würm) ice-stream. A continuity of a valley bottom existed between the northern Enns Valley and the southern tributaries (120 ka). Note that we assume an older age for the Ramsau Conglomerate because the ^{14}C-date is at the limit of the method. An age of 31 ka would, therefore, not change the model but timing.

6. The last glacial maximum (~22 ka) caused new valley overdeepening. The bedrock lay at an assumed elevation of ca. 595 m (Fig. 7F).
7. Strong sedimentation documented the retreat of the glacier; the Holocene valley infill reached a minimum thickness between 120 and 130 m (Fig. 7G).

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REFERENCES

Becker, L.P., 1981. Zur Kenntnis der spätglazialen Entwicklung des mittleren Mandlingtales Stmk./Salzbg.). Mitteilungen des naturwissenschaftlichen Vereins für Steiermark 11, 31–37.

Becker, L.P., 1987. Die quartären Talfüllungen im Raume Schladming. Tagungsband der Arbeitstagung der geologischen Bundesanstalt 1987 Blatt 127 Schladming, 124–133.

Bishop, P., 2007. Long-term landscape evolution: linking tectonics and surface processes. Earth Surface Processes and Landforms, doi: 10.1002/esp.1493.

Brocard, G.Y., van der Beek, P.A., Bourlès, D.L., Siame, L.L. and Mugnier J.-L., 2003. Long-term fluvial incision rates and postglacial river relaxation time in the French Western Alps from ^{10}Be dating of alluvial terraces with assessment of inheritance, soil development and wind ablation effects. Earth and Planetary Science Letters 209, 197–214.

Burbank, D.W. and Anderson, R.S., 2001. Tectonic Geomorphology. Blackwell Science, Oxford, 252 pp.

Cloetingh, S. and Ziegler, P.A., 2007. Tectonic Models for the Evolution of Sedimentary Basins. In: Schubert, G. (ed.), Treatise on Geophysics. V. 6. TOGP 00109, 112 pp.

Digitaler Atlas Steiermark, 2008. http://www.gis.steiermark.at accessed on 24-09-2008, 18-10-2008.

Dunkl, I., Kuhlemann, J., Reinecker, J. and Frisch, W., 2005. Cenozoic relief evolution of the Eastern Alps – constraints from apatite fission track age-provenance of Neogene intramontane sediments. Austrian Journal of Earth Sciences 98, 92–105.

England, Ph. and Molnar, P., 1990. Surface uplift, uplift of rocks, and exhumation of rocks. Geology 18, 1173–1177.

Frisch, W., Kuhlemann, J., Dunkl, I. and Brügel, A., 1998. Palinspastic reconstruction and topographic evolution of the Eastern Alps during late Tertiary tectonic extrusion. Tectonophysics 297, 1–15.

Frisch, W., Székely, B., Kuhlemann, J. and Dunkl, I., 2000a. Geomorphological evolution of the Eastern Alps in response to Miocene tectonics. Z. Geomorph. N. F., 44 (1), 103–138.

Frisch, W., Dunkl, I. and Kuhlemann, J., 2000b. Post-collisional orogen-parallel large-scale extension in the Eastern Alps. Tectonophysics 327, 239–265.

Frisch, W., Kuhlemann, J., Dunkl, I. and Székely, B., 2001. The Dachstein paleosurface and the Augenstein Formation in the Northern Calcareous Alps – a mosaic stone in the geomorphological evolution of the Eastern Alps. International Journal of Earth Sciences 90, 500–518.

Frisch, W., Kuhlemann, J., Dunkl, I., Székely, B., Vennemann, T. and Rettenbacher, A., 2002. Dachstein-Altfläche, Augenstein-Formation und Höhlenentwicklung – die Geschichte der letzten 35 Millionen Jahre in den zentralen Nördlichen Kalkalpen. Die Höhle 53/1.

Gudmundsson, G.H., 1994. An order-of-magnitude estimate of the current uplift-rates in Switzerland caused by the Würm Alpine deglaciation. Eclogae Geologicae Helvetiae 87, 545-557.

Habbe, K.A., 1993. Permafrost in Glaciofluvial Sediments of the Late Pleniglacial of the Last Glaciation and Some Conclusions to Draw. Zeitschrift für Geomorphologie, Supplement Band 92, 97–111.

Hejl, E., 1997. ´Cold spots` during the Cenozoic evolution of the Eastern Alps: thermochronological interpretation of apatite fission-track data. Tectonophysics 272, 159–173.

Hejl, E., 1998. Über die känozoische Abkühlung und Denudation der Zentralalpen östlich der Hohen Tauern – eine Apatit-Spaltspurenanalyse. Mitteilungen der Österreichischen Geologischen Gesellschaft 89, 179–199.

Hoffmann, T. and Schrott, L., 2002. Modelling sediment thickness and rockwall retreat in an Alpine valley using 2D-seismic refraction (Reintal, Bavarian Alps). Zeitschrift für Geomorphologie, Supplement Band 127, 153–173.

Husen van, D., 1968. Ein Beitrag zur Talgeschichte des Ennstales im Quartär. Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Wien 18, 249-286.

Husen van D., 1981. Geologisch-sedimentologische Aspekte im Quartär von Österreich. Mitteilungen der Österreichischen Geologischen Gesellschaft 74/75, 197–230.

Husen van, D., 1987. Zur Entwicklung des oberen Ennstales im Pleistozän. Tagungsband der Arbeitstagung der geologischen Bundesanstalt 1987 Blatt 127 Schladming, 86–93.

Husen van, D., 2000. Geological Processes during the Quaternary. Mitteilungen der Österreichischen Geologischen Gesellschaft 92, 135–156.

Keil, M., 2008. Evolution of an Alpine fault-controlled longitudinal valley – the Upper Enns Valley (Austria). Ph.D. Thesis, Dept. Geography and Geology, University of Salzburg, Austria.

Keller, E.A. and Pinter, N., 1999. Active Tectonics – Earthquakes, Uplift, and Landscape. New Jersey, pp. 338.

Köck, G., Borsdorf, A., Weber, F., Piller, W. and Schmidt, R., 2000. Auszüge aus dem Grundsatzpapier des Österreichischen Nationalkomitees Alpenforschung der ÖAW. 7 S.

Kuhlemann, J., Frisch, W., Dunkl, I. and Székely, B., 2001a. Quantifying tectonic versus erosive denudation by the sediment budget: Miocene core complexes of the Alps. Tectonophysics 330, 1–23.

Kuhlemann, J., Frisch, W., Dunkl, I., Székely, B. and Spiegel, C., 2001b. Miocene shifts of the drainage divide in the Alps and their foreland basin. Geomorphologie 45, 239–265.

Leeder, M., 1999. Sedimentology and Sedimentary Basins. From Turbulence to Tectonics. Blackwell Science, Oxford, 592 pp.

Lenhardt, W.A., Freudenthaler, Ch., Lippitsch, R. and Fiegweil, E., 2007. Focal-depth distributions in the Austrian Eastern Alps based on macroseismic data. Austrian Journal of Earth Sciences 100, 66–79.

Mandl, G. W. and Matura, A., 1995. Geologische Karte der Republik Österreich 1 : 50.000, Blatt 127. Schladming. Geologische Bundesanstalt, Wien.

Neubauer, F., 1988. Bau und Entwicklungsgeschichte des Rennfeld-Mugel- und des Gleinalmkristallins (Ostalpen). Abh. Geologische Bundesanstalt 42, 1–137.

Neubauer, F., 2007. Formation of an intra-orogenic transtensional basin: the Neogene Wagrain basin in the Eastern Alps. 8th Workshop on Alpine Geological Studies (Davos / Switzerland, October 10– 12, 2007) Abstract Volume, p. 54.

Norton, K.P., von Blanckenburg, F., Schlunegger, F., Schwab, M. and Kubik, P.W., 2007. Cosmogenic nuclide-based investigation of spatial erosion and hillslope channel coupling in the transient foreland of the Swiss Alps. Geomorphology 95, 474– 486.

Ouimet, W.B., Whipple, K.X., Crosby, B.T., Johnson, J.P. and Schildgen, T.F., 2008. Epigenetic gorges in fluvial landscapes. Earth Surface Processes and Landforms, doi: 10.1002/esp.1650.

Penck, A. and Brückner, E., 1909. Alpen im Eiszeitalter – Die Eiszeiten in den nördlichen Ostalpen. Leipzig, 393 S.

Pinter, N. and Brandon, M.T., 1997. How erosion builds mountains. Scientific American 276, 74–79.

Pinter, N., 2005. Applications of tectonic geomorphology for deciphering active deformation in the Pannonian Basin, Hungary. Occasional Papers of the Geological Institute of Hungary 204, 25–51.

Ratschbacher, L., Frisch, W., Neubauer, F., Schmid, S.M. and Neugebauer, J., 1989. Extension in compressional orogenic belts: the Eastern Alps. Geology 17, 404–407.

Ratschbacher, L., Frisch, W., Linzer, G. and Merle, O., 1991. Lateral extrusion in the Eastern Alps, part 2: Structural analysis. Tectonics 10, 257–271.

Reinecker, J. and Lenhardt, W.A., 1999. Present-day stress field and deformation in eastern Austria. International Journal of Earth Sciences 88, 532–550.

Reinecker, J., 2000. Stress and deformation: Miocene to present-day tectonics in the Eastern Alps. Tübinger Geowissenschaftliche Arbeiten (TGA) Reihe A: Geologie, Paläontologie, Stratigraphie, pp. 128.

Reitner, J.M. and van Husen, D., 2007. Overdeepened valleys in the Eastern Alps: Why are they still interesting? Geophysical Research Abstracts, Vol. 9, 03833.

Ruess, D. and Höggerl, N., 2002. Bestimmung rezenter Höhen- und Schwereänderungen in Österreich. PANGEO Austria 2002 (Salzburg, Austria, June 28–30, 2002) Programm und Kurzfassungen, p. 151.

Sachsenhofer, R. F., 1988. Zur Inkohlung des Ennstaltertiärs. Sitzungsberichte Österreichische Akademie der Wissenschaften, Mathematisch-Naturwissenschaftliche Klasse Abteilung I 197, 333–342.

Schlunegger, F. and Schneider, H., 2005. Relief-juvenation and topographic length scales in a fluvial drainage basin, Napf area, Central Switzerland. Geomorphology 69, 102–117.

Schmid, Chr., Suette, G. and Weber, F., 2005. Erste Ergebnisse refexionsseismischer Messungen im Ennstal zwischen Liezen und Weng (Steiermark). Jahrbuch der Geologischen Bundesanstalt 145, 107–114.

Schmid, Chr., Weber, F. and Schön, J., 2007. Seismic velocity problems in glacial overdeepened alpine valleys. Geophysical Research Abstracts 9, 06435.

Schrott, L., Niederheide, A., Hankammer, M., Hufschmidt, G. and Dikau, R., 2002. Sediment storage in a mountain catchment: geomorphic coupling and temporal variability (Reintal, Bavarian Alps, Germany). Zeitschrift für Geomorphologie, Supplement Band, 127, 175–196.

Seebacher, R., 2006. Aktuelle Forschungen in der Südwand – Dachsteinloch. Die Höhle, 1–4/2006, 76–89.

Spaun, G., 1964. Das Quartär im Ennstal zwischen Hieflau und Altenmarkt. Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten in Wien 14, 149–184.

Székely, B. (2001). On the surface of the Eastern Alps - a DEM study. Tübinger Geowissenschaftliche Arbeiten Reihe A, 60, 1–157.

Székely, B., Reinecker, J., Dunkl, I., Frisch, W. and Kuhlemann, J., 2002. Neotectonic movements and their geomorphic response as reflected in surface parameters and stress patterns in the Eastern Alps. EGU Stephan Mueller Special Publication Series, 3, 149–166.

Székely, B., Frisch, W., Kuhlemann, J., Danišik, M. and Dunkl, I., 2007. Glaciation cycles, sediment production, isostasy, and fluvial reponse: are the valleys in the Eastern Alps deep enough? Geophysical Research Abstracts, Vol. 9, 08789.

TRANSALP Working Group, 2002. First deep seismic reflection images of the Eastern Alps reveal giant crustal wedges and transcrustal ramps. Geophysical Research Letters, 29, 10, 1452.

Wang, X. and Neubauer, F., 1998. Orogen-parallel strike-slip faults bordering metamorphic core complexes: the Salzach-Enns fault zone in the Eastern Alps, Austria. Journal of Structural Geology 20, 799–818.

Weber, L. and Weiss, A., 1983. Bergbaugeschichte und Geologie der österreichischen Braunkohlenvorkommen. Archiv für Lagerstättenforschung der Geologischen Bundesanstalt (Wien) 4, 1–317.

Weiss, A., 2007. Zur Geschichte des Kohlenbergbaus bei Schladming. Kulturzeitschrift aus Österreichs Mitte 28, 6–10.

Zötl, J., 1960. Der politische Bezirk Liezen als Landschaft und Lebensraum. Graz, (Leykam) 112 pp.

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