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MECHANISM AND AGE OF LATE GLACIAL LANDSLIDES IN THE CALCAREOUS ALPS; THE ALMTAL, UPPER AUSTRIA

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ABSTRACT

In conjunction with detailed geological mapping around the Alm and Straneggtal, in Upper Austria, the landslide deposits have been restudied. Along the southern flank of Meisenberg, coarse angular debris with boulders up to ca. 5m^3 size occur. These are composed only of bright Dachsteinkalk sitting as erratic material on the dark-grey limestone of the Gutenstein Formation. The coarse grain size and its distribution only above the trim line of the Last Glacial Maximum (LGM) indicates that this material was deposited in a large-scale rock avalanche. This was derived from the northern rim of the Totes Gebirge and travelled north, spreading out over the glacier and finally reaching the flank of the Meisenberg, some 6km away. Similar deposits at Jh. Miraberg are also remnants of this debris blanket, deposited when the glacier finally melted away. The Hintere Hetzau cirque and the Staneggtal show a conspicuously hummocky topography, covered with huge blocks of Dachsteinkalk. The hummocks consist of densely packed matrix-supported angular debris of Dachsteinkalk and Hauptdolomit, deposited by a huge landslide (ca. 450 million m^3. This was derived from the Büchsenkar and formed a sturzstrom filling the whole Straneggtal. The conspicuous ridges north and south of Drackhütte are surge ridges (Fleckberg) and wave-like ridges created by the dynamics of the sturzstrom. On reaching the Almtal, the sturtzstrom probably entered a shallow lake and was transformed into a suspension that was pushed forward by subsequent incoming material. This suspension flow created a terrace body as far north as the Grünau basin. Sedimentary structures indicate that this occurred in a single short event. Lumps of still dry and densely packed landslide material floated in and above the suspension, forming small hills on the surface of the terrace. Larger lumps of still stratified sandy-gravelly river sediments indicate transport in a frozen state indicating wintertime or early spring conditions.

^{36}Cl surface exposure dating indicates that the avalanches occurred at the end of the LGM, probably shortly before the glaciers started their final melting. The boulders at Meisenberg were deposited around 19,000 years ago. The younger main event, at Straneggtal, took place at the end of the Oldest Dryas, after melting of the Gschnitz stadial glaciers; the most representative age of boulder deposition is 15,600 ± 1100 years.

Im Zuge der geologischen Detailkartierung um das Alm- und Straneggtal wurden auch die seit Abele (1969) als Bergsturzablagerungen eingestuften Lockersedimente neu bearbeitet.

An der Südflanke des Meisenbergs findet sich monomikter, grober, eckiger Schutt ohne Feinanteile aus hellem Dachsteinkalk über dunklen grauen Kalken der Gutenstein-Formation. Seine Verbreitung oberhalb der Höhe der ehemaligen Eisbedeckung (LGM) weist den Schutt als Ablagerung einer Felslawine aus. Sie hat sich offensichtlich aus den Steilwänden am Nordrand des Toten Gebirges gelöst und über die Gletscheroberfläche letztlich 6 km bis zum Meisenberg ausgebreitet. Ähnliche Ablagerungen beim Jh. Miraberg sind wohl Reste dieser Schuttdecke, die beim Niederschmelzen des Gletschers liegen geblieben sind.

Der Karraum der Hinteren Hetzau und das Straneggtal weisen eine auffällige hügelige Oberfläche auf, die mit riesigen Dachsteinkalkblöcken bedeckt ist. Der Talboden wird von feinstoffreichem, dicht gelagertem Schutt aus Dachsteinkalk und Hauptdolomit aufgebaut. Er ist die Ablagerung eines Bergsturzes (ca. 450 Mil. m^3), der sich aus dem Büchsenkar gelöst, und dessen Sturzstrom das Kar und das Straneggtal gänzlich erfüllt hat. Die markanten Wälle um die Drackhütte sind Brandungswälle (Fleckberg) oder durch die Fließbewegung entstandene Querwälle.

Der Sturzstrom ergoss sich im Almtal offensichtlich in einen flachen See, wodurch die kompakten Sedimente aufgeschwemmt wurden und eine Suspension entstand. Diese bildete - durch die nachdrängenden Massen verdrängt - eine Mure, die das Tal bis zum Becken von Grünau mit einer Terrasse erfüllte. Entsprechend dem Sedimentaufbau war die Bildung des Terrassenkörpers ein kurzes Ereignis. Auffällige Formen sind kleine Hügel auf der Oberfläche der Terrasse, die von noch kompakten Sturzstromsedimenten aufgebaut werden. Diese schwimmen wie Knödel in der Suppe in den aufgeschwemmten Materialien der Suspension. Eine genauere Datierung über die grobe geologische Einstufung hinaus war durch ^{36}Cl surface exposure dating am Ende des LGM knapp vor dem Beginn des Abschmelzens des Eises. Die ^{36}Cl-Konzentration zeigt, dass die Blöcke am Meisenberg vor etwa 19.000 Jahren abgelagert wurden. Das jüngere Hauptereignis fand am Ende der Ältesten Dryas nach dem Abschmelzen des Gschnitz Gletschers vor dem Bölling statt. Die Blöcke wurden vor 15.600 ±1100 Jahren abgelagert.

1. INTRODUCTION

The Alm valley, a straight S-N oriented tributary of the Traun river, starts at the northern rim of the Totes Gebirge, from two deeply incised cirques, the 'In der Röll' (Almsee tributary) and the Hintere Hetzau - Straneggbach (Fig.1). Between Grünau and Jagersimmerl, a remarkable terrace with many isolated hills, and, in particular, a hummocky topography along the Straneggbach were for a long time interpreted as till and other glacial deposits (Penck & Brückner 1909, Geyer & Abel 1918, Prey 1956). Abele (1969) was the first to interpret these as deposits from a large landslide with a detachment area at the Büchsenkar. Later 1974 he included a slightly modified view into his comprehensive presentation of the landslides in the Alps. In 1997 he interpreted the terrace along the Almtal as part of the landslide formed by mobilized groundwater-saturated valley floor sediments. More recently, Weidinger (2003) included additional detachment areas. Mapping and detailed sedimentological observations revealed some important data for reconstructing a younger main event with different mechanisms (van Husen 1995). Further investigations, documented here, revealed that an older, smaller event, occurred, as well as details about the detachment area and course of the event. Exposure dating has also been used on the abundant big blocks, using cosmogenic ^{36}Cl, to better constrain the age of the landslides.

2. GEOLOGICAL SETTING

The landslides developed within two nappes of the Calcareous Alps. In the south, along the Straneggbach, the Totengebirgs Nappe, comprising Dachsteinkalk (>1000 m thick) and Hauptdolomit, forms a huge plateau. The landslide material was derived from this unit, above sandy-shaly Lunzer Schichten and Wettersteindolomit (Fig.2). In the north, along the Alm valley, the landslide developed within the Höllengebirgs Decke, which is here exclusively formed of Hauptdolomit and Plattenkalk (Egger and van Husen 2007). North of the more than 1000 m high and essentially vertical wall of the northern plateau rim, the valleys were accompanied by forested smooth but steep flanks in the dolostones (Fig.1).

During the all the glciations, the Almtal and its tributaries were heavily glaciated. During the last glaciation (Würm) the well-documented Almtal glacier was fed by ice from the plateau, filling the two cirques below the north rim. From here, supported by heavy precipitation from northwesterly winds and the exposition to the North, a thick valley glacier in the Almtal extended to about 4 km north of Grünau. Around Jagersimmerl, the glacier surface was at an altitude of 1000 m. From the steeper branch in the Straneggbach, ice discharge also occurred over two divides, into the catchment area of the river Steyrling to the East (Fig.1+3).

Beside the ice-marginal terraces and terminal moraines, which allow the glacier at the LGM to be reconstructed, lodgement till has also been rarely preserved. In contrast to the landslide deposits, the grain size distribution in this highly compacted and cohesive till contains ca. 10% clay and 30 - 40% silt. Striated and polished boulders are frequent (Egger and van Husen 2007).

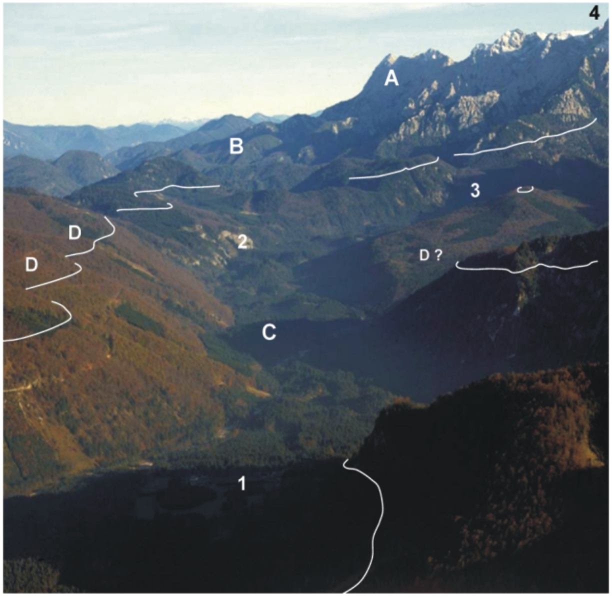

FIGURE 1: View from Almtal to SE over Straneggbach. In the background the North Rim of Totes Gebirge formed by Dachsteinkalk (A). The dolomite topography (B) in the foreground. Along the Straneggbach the hilly topography of the sturzstrom deposits (C). Solid lines are marking the elevation of the glacier during LGM. 1 Jagersimmerl, 2 Ödseen, 3 Drackhütte, 4 Zwillingskogel.

As a result of the glaciations, the Alm and Straneggbach valleys became U-shaped, with steep walls and deeply eroded bedrock on the valley bottom, probably overdeepened in some areas. A borehole at Heckenau showed 112m of unconsolidated Quaternary sediment below the valley floor (Hamilton 1989). In the Hintere Hetzau cirque, ice cover lasted during the LGM up to the end of the Gschnitz stadial, at around 16,000 BP (Ivy-Ochs et al. 2006a) creating oversteepened walls, especially on the western flank. Later on, although for only a short time, a small ice field existed at In der Wildnis, fed mainly by snow and ice avalanches (Fig 3 A).

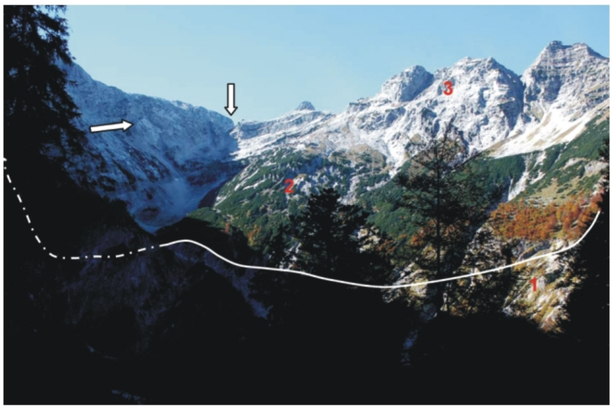

FIGURE 2: Detachment area Büchsenkar. Dotted line marks approximately lower boundary of the moved wedge like pile. Arrows mark slickensides and the fault. 1 Ramsaudolomit, 2 Hauptdolomit, 3 Dachsteinkalk. Solid white line marks the lower edge of the pile, dotted hidden behind rocks in the foreground.

3. Methods

Mapping: Detailed mapping and morphological analysis led to a comprehensive geological map 1:50,000 of the whole area (Egger and van Husen 2007), showing all of the features of the landslides (Fig. 3 A).

Sediment analysis: Repeated determinations of roundness and lithology of the deposits on the terrace in the Almtal (Heckenau gravel pit) were done to differentiate between material coming from the landslide or from the older valley fill of the Almtal. Grain size distribution (Fig. 5) was carried out on sturzstrom (in the sense of A. Heim 1932 cf Hsü 1978) sediments for comparison with similar deposits at Flims (Pollet and Schneider 2004).

Pollen analysis: Investigations of sandy-clayey silt clasts embedded in gravels at Heckenau gravel pit indicate that they are barren of pollen.

^{36}Cl surface exposure dating: The abundant large limestone boulders (>5 m^3) allowed 14 samples to be obtained from 3 different places at Meisenberg, Polster, and Habernau (Fig. 3 A) to determine the age.

4. Field evidence

4.1 Detachment area

The Hintere Hetzau cirque is surrounded by essentially vertical walls both to the east (Zwillingskogel) and the south (Schermberg). Only to the west does the mountain crest step back some hundreds of metres where, at the Büchsenkar a wide niche below the crest, developed, about 200 - 300 m above the valley bottom (Fig.2). This morphology motivated Abele (1969) to propose that the landslide detachment lay in the niche. Here, below the Hochplattkogel–Pyramidenkogel crest, the thick-bedded Dachsteinkalk dips 30° to the ESE and is underlain by Hauptdolomit and sandy-shaly Lunzer Schichten. The southern edge of the Büchsenkar is bordered by a wall showing some slickensides (Fig. 2). This wall develops along a W-E striking fault which merges to the east into the Lahngang fault system, which cuts SW-NE through the limestone plateau of Totes Gebirge.

A different situation occurs to the south and east, where narrow niches in the upper parts of the walls at Kreuz-Zwillingskogel and Schermberg appear. More recently, Weidinger (2003) suggested that these niches are the landslide source area. However, the Dachsteinkalk dips horizontally or slightly to the east, into the wall, at these places and hence a rock mass could only be released by joints. In addition, the Hauptdolomit at these places appears in only a thin layer below the niches, in the lower part of the wall.

4.2 Meisenberg (Jh. Miraberg)

On the south-facing slopes of Meisenberg and Rabenstein (Fig.3) two areas are covered with coarse debris, bearing blocks up to 20 m^3. Without exception, the debris comprises bright Dachsteinkalk, markedly different to the in-situ dark grey underlying material of the Gutenstein Formation. The debris is angular and without any striations. Also, fine-grained debris (sand and silt), which would be necessary if the deposit were to be thought of as glacial in origin, is generally lacking. Between both places, a short moraine ridge indicates an ice mar-gin at the elevation of the lower edge of the debris (Fig. 3A). The debris field at Meisenberg stretches 80 m upslope.

South of Jh. Miraberg an extended block field composed only of angular coarse debris and blocks up to some cubic meters covers the till blanket. This has a strong resemblance with the deposits at Meisenberg.

4.3 Straneggtal

The whole valley bottom along the Straneggbach shows a landscape characterized by steep hills and deep depressions, and large limestone blocks. Only along the creeks are these features absent, having been eroded away. Small outcrops and some larger gravel pits reveal the material and structures the landscape is made of.

All these exposures show angular debris within a fine-grained matrix. The material is mostly matrix-supported, predominantly consisting of pulverized bright limeston (Fig.4); only near the surface can a grain-supported fabric be recognized. The grain size distribution of the cataclastic matrix (< 2 mm) shows a conspicuous bimodal particle distribution with maxima around 0.008 mm and 0.06 mm (Fig.5).

Some of the larger clasts or small blocks are fractured but are not or are only partially disaggregated. The grain size of the material is up to 5 - 10 cm; only a few reach 20 - 30 cm in diameter. Large blocks, especially the bigger ones (from 1 up to 100 m^3), only appear at the surface on the hilltops and on the slopes down to the bottom of the depressions. In the southernmost region, at Hintere Hetzau, these blocks cover almost the entire surface. Down valley, they become fewer and around Jagersimmerl they appear as single blocks or in groups of 2-3.

Nowhere has layering or an orientation of the larger clasts been recognized in the outcrops. At rare sites within the bright white limestone, dark grey dolostone occurs as separate streak-like bodies (Fig.6+7). Both materials were matrix-supported in the same way. The boundaries are sharp and without any shearing or mixing of the two lithologies (Fig.8). Here the fragmentation obviously occurred without intensive mixing or shearing, thus, rather surprisingly, these dolostone streaks have been preserved. Apart from these, only larger clasts of dolostone are embedded within the limestone-dominated deposits.

In the lower E-W stretching section of the sturzstrom, the surface is dominated by hills and depressions with a chaotic distribution. This continues as far as Auerbach and Schwarzenbrunn, divided only by the plough-like slope of SW Jagersimmerl. At Schwarzenbrunn, the landslide deposits are covered by the alluvial fan of the Weißeneggbach, as a result of which only the highest sturzstrom hills can still be seen. South of the bend around the Ödseen and as far as Drackhütte, the sturzstrom hills have a preferred orientation, with straight ridges transverse to the valley train (Fig.3). The inter-

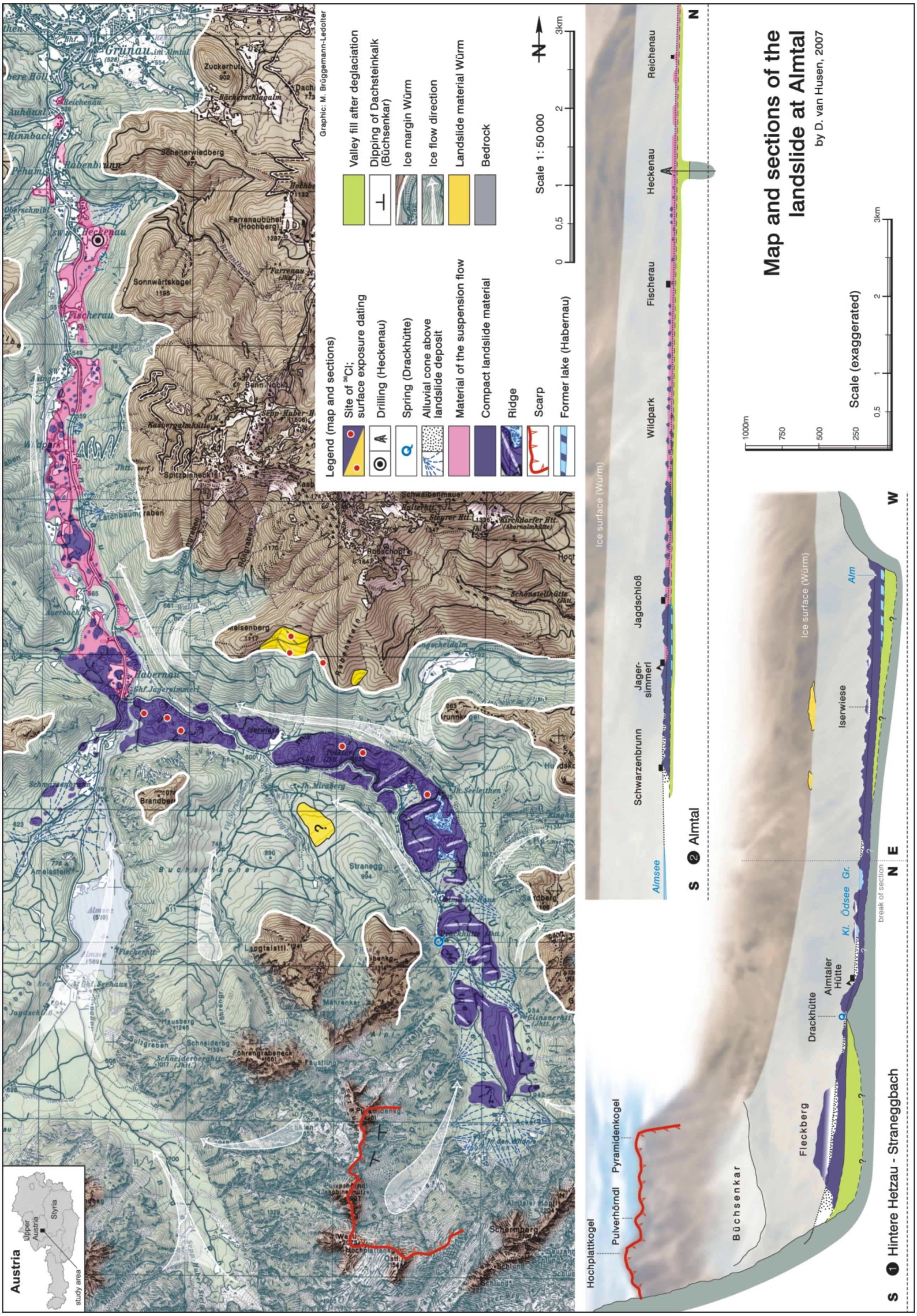

FIGURE 3: Map of the landslide deposits along Straneggtal and Almtal and sections along these valleys.

vening depressions are filled with younger gravels of the Straneggbach (e.g. Almtaler Haus). The ridge at Drackhütte, which is well marked and the highest one, probably sits on top of a bedrock threshold indicated by the permanent spring of the Straneggbach. This may be the glacial threshold at the northern end of the Hintere Hetzau cirque forcing the groundwater fed by precipitation and karst water to overflow (Fig.3, sections). South of Drackhütte, the valley bottom is occupied by smaller transverse ridges and alluvial fan deposits from temporary creeks.

The N-S striking ridge at Fleckberg, on the eastern flank of the Hintere Hetzau cirque, is a remarkable landform (Fig. 3 A). The ridge, which rises 100 to 120 m above the valley bottom, and 30 m above the slope to the east, is densely covered by big blocks of Dachsteinkalk. This is in contrast to the slope to the east, which is covered only by dolostone debris without any blocks of Dachsteinkalk. To the south, it shows a steep slope rising high above the alluvial cones In der Wildnis almost in the middle of the cirque (Fig. 3 A). Initially, this was inter-preted as surge ridge (Brandungswall; Abele 1969) and later as a landslide moraine (Abele 1974) or a moraine (Weidinger 2003).

Figure 4: Compact limestone material of the sturzstrom deposits. See fig. 5 for grain size distribution.

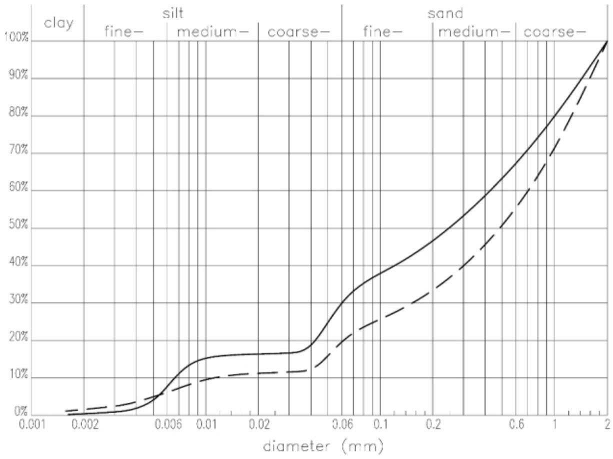

Figure 5: Typical grain size distributions of the sturzstrom deposits. (Solid line ca. 10 m below the surface, dotted line near the surface.)

4.4 Almtal North of Jagersimmerl

Completely different features appear along the Almtal north of Jagersimmerl. On either side of the valley at Habernau, landslide material, with hills and big blocks, has been preserved. In the middle of the valley, around Jagersimmerl, a flat terrace between the hills starts and develops over the whole valley bottom around Auerbach (Fig.3). This terrace, lying ca. 10 m above the Alm River, is overtopped by many small hills, several meters high (Fig.9). Only north of Jagdschloß is there an area with a similar morphology as southeast of Jagersimmerl. The individual hills, which become both smaller and lower down the valley, have been traced as far as Heckenau. From there on, until the mouth of Almtal into the basin of Grünau, the remnants of the terrace do not have such hills. Their distribution is somewhat reminiscent of the thread of the maximum velocity of a river (Fig.3). Outcrops reveal that the hills are made of the same compact matrix-supported material as the sturzstrom deposits along Straneggbach. Remarkably, no big blocks have been found on the slopes of the hills. Only in the area north of Jagdschloß are some of them still preserved.

For many years, the internal structure and sediments could be examined in two gravel pits (Auinger, Heckenau). Consequently, detailed observations as the digging proceeded gave a comprehensive 3-D view of the sedimentary archictecture. The terrace consists predominantly of angular bright limestone (Dachsteinkalk) gravel, with clasts averaging 2-10 cm in diameter, with a low content of sand. The clasts are essentially angular, with only the edges slightly smoothed. Apart from this, an average of about 5 %, in some parts rising up to 10-15 %, of the components are more or less rounded gravels of all the various carbonates from the whole river Alm catchment area. The deposits have an astonishingly low bulk density due to a high content of voids and a low content of sand and silt. The components are often coated with white silt, which also partly fills some of the voids. The deposits show no layering or preferred clast orientation, although a slight fining upwards occurs at the main valley. In the widening of the valley at Heckenau, a horizontal fining to the east was clearly recognizable. Within the gravel deposits, lumps of landslide material are floating. It is the same material as can be found at Straneggtal and. around Jagersimmerl; (Fig. 10+ 11). The compact landslide material always shows a sharp border to the surrounding gravel with such a low bulk density (Fig.12). Grooves and notches indicate that during transport these lumps were eroded and broken into pieces (Fig.11). During this the loss of the big limestone blocks, travelling at the former surface of the sturzstrom also occurred, probably by rotation of the lumps. Detailed observations of the lumps in the Heckenau gravel pit showed they varied in size from ca. 20 cm to 5-6 m and were found throughout the whole deposit. Larger ones near the top of the deposits form the small hills on the terrace surface. The decreasing in average size and height of these hills from south to north also indicates the effects of erosion during transportation. In addition to these lumps, entrained clasts of compact sandy-clayey silt and varved clayey silt that are only partly contorted, as well as lumps of river gravel with their original layering (Fig.13+14) were found throughout the Heckenau gravel pit. The sandy-clayey silt clasts are barren of pollen Remnants of the terrace along the Almtal and its extraordinary sediment have been traced to ca. 10 m above the level of the river Alm and, at its mouth into the Grünau basin, as a thin layer in a borehole 6 m below the present-day level (personal communication W. Jaritz). This fits well with a former outcrop in the Heckenau gravel pit, where these materials were accumulated on top of the older valley fill (Hamilton 1989) some meters below the actual river level of the Alm (Fig.3, B).

5. Interpretation

5.1 Detachment area

The volume and bedding orientation of the niche at Büchsenkar indicate that this is more likely to be the detachment area. Along the W-E fault and the bedding planes, a wedge-like pile of Dachsteinkalk and underlying Hauptdolomit was very easily released, forming the younger main landslide. Along with the white Dachsteinkalk, the darker grey Hauptdolomit appears in the landslide material down valley. Obviously, significant portions of the underlying Hauptdolomit would have been pulled down and become part of the landslide material. This would also indicate that the Büchsenkar is the source area.

The smaller niches to the east may have served as the source region for the older rock avalanche.

5.2 Meisenberg (Jh. Miraberg)

The sediments here were apparently deposited from a rock avalanche that spread out onto the surface of the glacier along the length of the of Straneggbach valley. The source area of the material is the highest mountains around the Hintere Hetzau cirque, since the avalanche mate-rial consist only of Dachsteinkalk. The avalanche spread out on the surface of the southern, steeper part of the glacier (Fig 3) over a maximum distance of 6 km.

The rock avalanche of Sherman Glacier, Alaska, triggered by the great earthquake in 1964 (M. J. McSaveney 1978) serves as a good example for the extent and volume of such an avalanche. This covered the whole width of the glacier with a several meters thick blanket of debris and extended for ca. 5 km, also climbing up bedrock slopes at the glacier margins by some tens of meters. The 30 million m^3 of debris material deposited is not needed to form the Hintere Hetzau avalanche because along the narrower Alpine glacier there is evidence of such material only south of Jh. Miraberg (Fig.3), where a block field on top of till may be a remnant of this rock avalanche. Therefore, 15 - 20 million m^3 of Dachsteinkalk may have been enough to form the avalanche.

5.3 Straneggtal

The Straneggbach valley fill fits very well into the picture of sturzstrom deposits seen in other landslides. The deposits (in the sense of A. Heim 1932; cf. Hsü 1978) moved as a granular flow in some parts, without intensive mixing. The structure of all the sturzstrom sediments can be characterized as chaotic and without any fabric, as described by Pollet & Schneider 2004 for the uppermost and distal parts of the Flims landslide, with no overburden. The sturzstrom, which has an average thickness of about 100 m along the Straneggbach (Fig. 3B), also moved under these conditions.

The shape of the clasts and their grain size are are also very similar. A similar distribution was found in the landslide deposits at Flims, with a strong maximum at 0.03 mm and a weaker one at 0.6 mm (Pollet and Schneider 2004). The stronger

Figure 6: Streaks of dark dolomite material within the bright limestone material.

Figure 7: Detail of mixing of dolomite (1) and limestone (2) material in the streaks.

Figure 8: Sharp boundary between crushed and highly compacted dolomite (1) and limestone (2) material.

maximum at Flims corresponds to the average size of calcite crystals in the marmorean limestone (Pollet & Schneider 2004). The smaller grain size maxima in the Straggebach sturzstrom may be due to the very fine-grained Dachsteinkalk and the smaller amount of grains < 0.6 mm (90% there, 65% here) to the overburden.

Rock comminution may have taken place in this area by 'dynamic fragmentation' (McSaveney and Davis 2002); this is believed to be part of the reason for the long runout of the Straneggbach landslide. However, the rapid transformation of pore water (at least 5%) to steam may also have helped to reduce friction, especially in combination with the simultaneous production of a large volume of very fine particles. From 50 l of water, ca. 60 m^3 of steam can be produced, creating, under such circumstances, a steam explosion (pers. comm. Dr. M. Bichler TU Wien) which penetrated the sturzstrom material whilst it was moving.

The N-S trending ridge at Fleckberg, in combination with the transverse ridge at Drackhütte, and similar features to the south, has previously been interpreted as a terminal moraine of a Late Glacial period glacier with different extents (Abele 1974,Weidinger 2003). These ridges, however, are orientated at 90° to the main valley wall at Fleckberg and its continuation to the north. A moraine interpretation implies that rock avalanches time and again delivered material to form moraine ridges over a longer period. For the main wall, some big blocks east of the wall on the slope should be expected if the main landslide broke down onto a glacier occupying the valley bottom, instead of filling an empty cirque before moving down valley. Thus, the high N-S striking Fleckberg ridge should be interpreted as a surge ridge, and the lower transverse ones as wave-like ridges of the main event.

Figure 9: Approximately 3m high hill formed by sturzstrom deposits at the surface of the terrace along the river Alm, east of Auinger.

5.4 Almtal North of Jagersimmerl

Measurements indicate that the terrace body along the river Alm has an average thickness of ca. 15 m and accumulated at a slightly lower level of the river system after deglaciation compared to the modern one. The immediately subsequent incision and the lack of lateral erosion of the Alm and its tributaries preserved the original terrace surface (Fig.3).

All the sedimentary structures observed indicate that the material forming the terrace body was accumulated in a single event and was transported as a suspension. Very likely, this suspension was created when the distal parts of the landslide were mixed with water on entering a shallow lake at Habernau. That a suspension formed was also due to the high content of fine-grained debris. The lake was probably dammed up by an alluvial cone around Auerbach. The suspension, pushed by the landslide mass behind, flowed down-valley, transporting lumps of non-soaked landslide material like "dumplings in a soup". The entrained clasts of compact sandy silt and varved silt, and, in particular lumps of river gravel with their original layering, give a strong indication that the landslide happened during winter time ore early in the spring.

6. Discussion.

6.1 Mechanical reasons and triggering

The geological situation (sediment sequence, bedding orientation, fault geometry and over-steepened topography) at the north rim of the limestone plateau (Geyer 1918) held the key that made the landslides possible. The mechanical properties of the thin layer of Lunzer Schichten, intercalated between the dolomites, may have played a major role during the release of the landslide. These sandy-shales, in comparison to the overlying Hauptdolimit and Dachsteinkalk, are a weak, essentially ductile material at the base of the more massive and stronger carbonates and probably contributed to the initiation of the landslide (Poisel and Eppensteiner 1989), with the plasticity of the clayey base leading to brittle deformation and instability of the carbonates. During the collapse of the Hauptdolomit at the toe, the bedding planes in the Dachsteinkalk allowed downslope movements of the whole wedge-like pile, which was also mechanically separated from the plateau by the fault in the south (Fig. 2).

Apart from these mechanical factors, the trigger causing the collapse is unknown. There are two likely possibilities. Within the Calcareous Alps - even if rarely - earthquakes occur along the major faults. For example, on 29.1.1967, an earthquake of intensity 6 - 7 happened with an epicentre at Molln, 30 km east of the Alm valley. A comparable event may have triggered the landslide.

The other reason may be a meteorological one, since the landslide apparently took place during wintertime. Warm air along with rainfall at higher elevations may have induced a strong melting of snow and thus a rapid filling of joints and karst cavities with meltwater. During such a situation, the deeply incised valleys were often still occupied by cold air. In such a situation, the sandy-shaly Lunzer Schichten in combination with the still frozen surface, are dammed the discharge, inducing a rapid filling of joints and karst cavities with water. Thus, the increasing weight and hydrostatic pressure may have been the trigger. In this context, it is interesting that at the lowest part of the niche today, a karst spring appears after strong precipitation, fed from solution cavities along the faults.

6.2 Volume of the younger landslide

No indication is available for the former surface morphology of the detachment block prior to movement. Thus the volume displaced can only be estimated from the deposits preserved (Fig.3). Although the present day surface of the sturzstrom can be recognized very well, estimates of the thickness and configuration of the bedrock or older valley fill are very rare, allowing only a rough calculation.

After deglaciation at Hintere Hetzau, the older valley fill was very likely in accordance with the glacial threshold at Drackhütte (Fig. 3 B). Consequently the landslide material up-valley from Drackhütte has a thickness of about 100 m and a volume of ca. 130 million m^3.

Along the course of the Straneggtal, the average thickness of the sturzstrom deposits on top of the bedrock or the tills is ca. 70 - 80 m, considering both hills and depressions. The existence of the two Ödseen and the constant water discharge along the Straneggbach may indicate that the sole of the landslide is more or less at the same elevation as the creek. Only east of Jagersimmerl, Habernau and Schwarzenbrunn was the depth of the sole controlled by the level of the postglacial valley fill along the river Alm to approximately 5 - 10 m below the present-day surface Accordingly, the volume of the sturzstrom deposits down-valley from Drackhütte is estimated to be ca. 270 - 300 million m^3.

Further, the material forming the terrace must be included in the calculation. Using an average thickness of ca. 15 m and taking into account the low degree of compaction, resulting from formation from a suspension in comparison to the compact landslide material, a very rough estimate is 30 million m^3. Thus, a volume of about 450 million m^3 for the whole event is likely. The difference compared to the estimation of 300 million m^3 by Abele (1974) is based on the addition of the deposits at Hintere Hetzau and Almtal. Abele (1974) thought that the cirque was filled by a glacier and that the terrace material along the river Alm consisted of an activate, water-saturated gravel of the riverbed. However, the 90 - 95 % content of landslide material shows that it must also be added to the landslide volume.

6.3 Course and evolution of the two landslides

The older landslide occurred within the time span when the Almtal glacier and its tributaries had their maximum thicknesses (indicated by moraines and ice marginal terraces). The landslide was probably a great rock avalanche transporting coarse debris with many blocks but less fine-grained material. Due to the small quantity of material, little grinding occurred and therefore very little fine-grained limestone debris was produced. The avalanche spread out over the glacier surface and two tongues extended a maximum of 6 km, to the slope of the Meisenberg. The source area for the rock masses must lie in the highest mountains in the south (Schermberg, Almtaler Kopf, Kreuz-Zwillingskogel) because the material is entirely Dachsteinkalk. If the block field south of Jh. Miraberg is a remnant of this older event, then the source area has instead to lie more to the west, around Pyramidenkogel. However, the great distance travelled in relation to the amount of debris suggests a break-away area high above the glacier surface. The avalanche may have moved as a thin blanket of debris similar to that at the Sherman glacier in 1964 (McSaveney

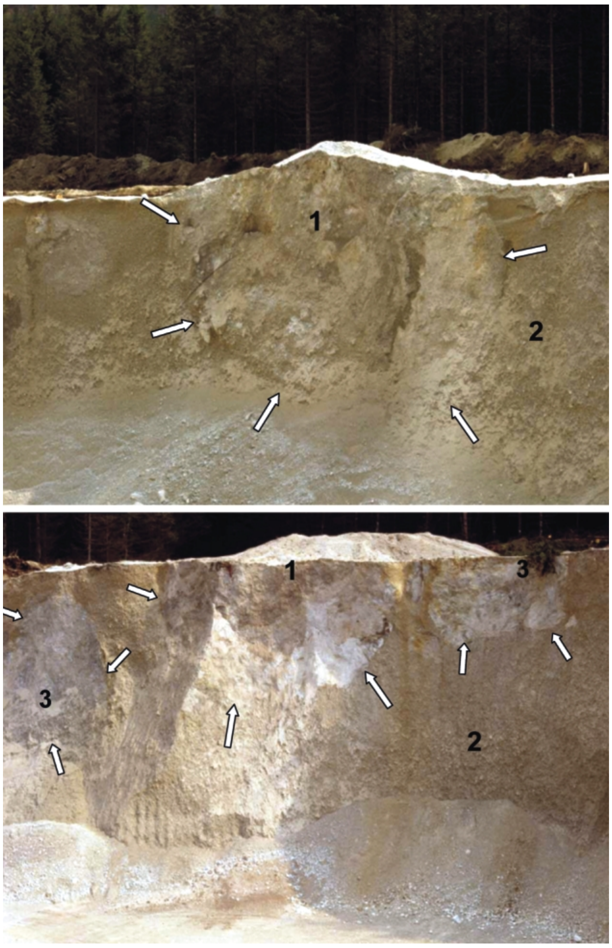

Figure 10 + 11: Both photos show the wall at the Heckenau gravel pit with larger lumps of sturzstrom material (1) near the top of the suspension flow material (2). Both were overtopping the terrace surface by 1 - 1.5m. Smaller lumps (3) are likely broken away from the greater unit in the middle.

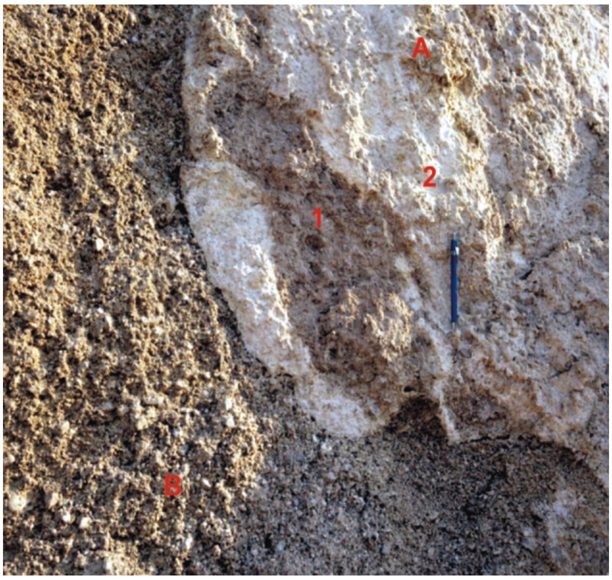

Figure 12: Detail of compact sturzstrom material (A) - with a mixture of dolomite (1) and limestone (2) floating in the deposits of the suspension flow (B) with its typically low bulk density. Note the sharp boundary.

1978) but probably as a straight and not very broadly fanned tongue, because no deposits are preserved on the gentle slopes around the glacier, except at Meisenberg (Fig. 3 A).

The younger main event was a large landslide that moved approximately 450 million m^3 of rock. The appearance of streaks of dolostone in the distal parts of the sturzstrom (in Straneggtal close to Almtal) indicates that the landslide probably started with a short gliding along slip planes directly on top of the sandy-shaly Lunzer Schichten. Therefore, the Hauptdolomit played a bigger role at the beginning of the mass movement. By falling down the ca. 400 m high precipice to the cirque bottom, the rock masses formed the sturzstrom.

The transverse ridges south of Drackhütte were probably formed at the end of the event. They are overtopped by the dominant, straight, S-N striking surge ridge at Fleckberg. This formed when the landslide was deflected by ca. 30°, after striking the lower part of the slope to the east. The abrupt and steep slope at the south of the ridge, and the spur-like continuation more towards the middle of the valley bottom, point to the existence of a small ice field in the area of Ackergraben-In der Wildnis during the event (Fig. 3 A). Otherwise, this whole area would have been filled up with landslide material.

Figure 13: Clast of stratified gravels within the fine grained upper part of the suspension flow deposits. The gravels must have been transported under frozen conditions.

After filling up the Hintere Hetzau cirque, the sturzstrom was deposited over the whole Straneggbach valley down to the Almtal. After surmounting the glacial threshold at Drackhütte, it moved as a granular flow. Due to its moderate thickness (ca. 80 m) and absence of overburden, the deposits are a chaotic facies (terminology of Pollet & Schneider 2004) because there are no large rafts where the original structure is preserved, as at Flims. The reason for the long runout, in spite of the modest thickness, may have been due to dynamic fragmentation (Mc Saveney and Davis 2002) and the internal production of steam (see section 4.3). The sturzstrom first moved (Gr. and Kl. Ödsee) like big waves, forming the transverse ridges; after the bend to the west, only the irregular hill topography along the lower part of Straneggbach formed.

On reaching the Almtal, the sturzstrom was divided into two tongues by the plough-like slope SW of Jagersimmerl. The south-heading one spread out into the mouth of Weißeneggbach; a subsequent alluvial fan from this creek covered the sturzstrom and blocked the Almtal, forming the modern Almsee (Fig.3).

The other tongue flowed to the northwest and must have entered a shallow lake. As a result, a large amount of landslide material was soaked and transformed into a suspension. This was pushed forward by the still incoming sturzstrom and started to flow down valley like a wave, also carrying fragments of non-soaked compact landslide material. A mobilisation of watersaturated gravel from the valley bottom, as Abele (1997) suggested, only occurred on a limited scale, shown by 5-10 % of rounded gravel in the deposits. The reason for this small amount of remobilized gravel, in contrast to the opinion of Abele (1997), may be due to the minor amount of landslide material and consequently energy at the end of the sturzstrom, as it hit the valley floor at the Almtal. In contrast to this scenario at Flims, where the valley fill was mobilized on a grand scale (Bonaduzer Schotter), because the main mass of the landslide (some km^3) hit the pre existing valley floor (Abele 1997).

Thus the proper landslide moved from a break-away rim at an elevation of 2000-2200 m to about 10 km down valley. The landslide may be characterized by a fahrböschungswinkel (Heim 1932, cf. Hsü 1978) of ca. 12°. This angle is around the lowest recorded in landslides with volumes in the order of some 100 million m^3 (Abele 1974), probably due to the very regular path of the Straneggbach valley. Including the deposits along the Almtal would reduce this angle to an astonishingly low value of 6° (Abele 1974). Considering the different transport mechanisms, these should not be added to the landslide, although they were triggered and fed by it.

7. DATING THE EVENTS.

7.1 GEOLOGICAL EVIDENCE

Geological constraints only allow an approximate age to be determined. The older event may have occurred at any time around the climax of the LGM ca. 25,000 to ca. 20,000 cal BP, when the glacier had its maximum thickness. After the onset of glacier down melting, the ava-lanche would not have been able to reach the slope of Meisenberg at the elevations observed.

The younger main event was classified by Abele (1969, 1974) to the early Late Glacial time, since he thought that the Hintere Hetzau was then still occupied by a glacier. In comparison to the nearby Trauntal (van Husen 1977, 2000), this would suggest a position in the Gschnitz Stadial within the Oldest Dryas, at ca. 16,000 cal BP (Ivy-Ochs et al. 2006a). However, the existence of only a small ice field below the high walls suggests a position more likely within Older Dryas, at ca. 14,000 cal BP. This was the last colder period in which some of the glaciers at the north rim of the plateaus reached the valley bottoms (van Husen 2000). Therefore, geological constraints indicate a time between the end of Oldest and the Older Dryas.

7.2 ^{36}CL SURFACE EXPOSURE DATING

The only possibility to determine the age of the two landslides is with surface exposure dating with cosmogenic nuclides, as no organic material for radiocarbon analysis was found entrained within the landslide deposits. Large limestone boulders are abundant, thus we employ ^{36}Cl. ^{10}Be is the most commonly used cosmogenic radionuclide but it requires the presence of quartz. Fourteen samples were taken from boulder surfaces at three different sites: Meisenberg, Polster and Habernau. As discussed in detail above, boulders at the Meisenberg site were deposited during the older landslide, while the latter two sites are deposits of the younger, main event. All sampled boulders were more than 2 m in diameter and were embedded in the landslide deposits. Because of the coverage of boulders tops by soil, leaf litter and vegetation (including trees) some boulders were sampled on their sides (see shielding corrections in Table 2). We focused on rough weathered surfaces to avoid spalled surfaces, which is never-the-less difficult to rule out.

FIGURE 14: Clast of stratified gravels within coarse suspension flow deposits. Clasts of unconsolidated claey silt (1).

Cl was extracted from the limestone samples (major element compositions shown in Table 1) using standard procedures (Ivy-Ochs et al. 2004). Both total rock Cl and ^{36}Cl (Table 2) were determined using accelerator mass spectrometry (AMS) (Synal et al. 1997). To calculate surface exposure ages we have used a production rate of 54 ± 3.5 ^{36}Cl atoms*g Ca-1*yr-1 with a muon contribution of 9.6% (Stone et al. 1996; 1998). For the samples whose major element compositions were not determined (Meisinger 3, 4; Polster 1, 3; Habernau 5, 6), we used a mean value based on the compositions for the other boulders from the same site. In any case, the critical parameter is the Ca concentration which varies little between the different rocks analyzed here. We have followed the procedures of Liu et al. (1994) and Phillips et al. (2001) to calculate the contribution of production due to capture of thermal and epithermal neutrons by ^{35}Cl. Production through the low-energy neutron pathway ranges from 5 to 15 % in these rocks. Uranium and thorium concentrations were below the detection limit of the ICP-MS, so that no correction for subsurface, non-cos-

weight %	Meisenberg 1	Meisenberg 2a	Polster 2	Habernau 1	Habernau 2	Habernau 3
SiO_2	0,99	0,50	0,33	0,24	0,26	0,29
Al_2O_3	0,21	0,05	0,05	0,06	0,04	0,04
Fe_2O_3total	0,15	0,16	0,08	0,05	0,10	0,09
MnO	0,00	0,00	0,00	0,00	0,00	0,00
MgO	0,57	0,59	0,60	2,11	1,28	0,63
CaO	54,73	54,72	54,55	52,86	54,12	54,76
Na_2O	0,02	0,02	0,02	0,03	0,02	0,02
K_2O	0,05	0,03	0,01	0,02	0,01	0,01
TiO_2	0,02	0,02	0,00	0,00	0,00	0,00
P_2O_5	0,00	0,00	0,00	0,00	0,00	0,00
total	56,74	56,09	55,64	55,37	55,83	55,84

TABLE 1: Major elements (weight percent oxides).

Sample No.	Latitude	Elev. (m asl)	Thick. (cm)	Site, setting	Total shield topo. and dip	Cl in rock (ppm)	^{36}Cl atoms*g^{-1} rock	AMS Meas. Error (%)	Exposure age (years)
Meisenberg 1	47,786	1050	4	older landslide on valley flank	0,857	72,2	9.28 x 10^5	3,0	18,800 ± 900
Meisenberg 2a		1050	2	older landslide on valley flank	0,945	60,0	8.21 x 10^5	5,0	15,700 ± 900
Meisenberg 3		1080	3	older landslide on valley flank	0,724	43,8	7.10 x 10^5	5,1	17,900 ± 1500
Meisenberg 4		1040	5	older landslide on valley flank	0,672	66,5	4.27 x 10^5	3,7	11,200 ± 1000
Polster 1	47,775	640	2	Alm Valley landslide	0,549	33,1	2.44 x 10^5	4,0	11,500 ± 700
Polster 2		660	4	Alm Valley landslide	0,614	35,4	2.13 x 10^5	5,0	8600 ± 600
Polster 3		630	2,5	Alm Valley landslide	0,810	17,5	3.29 x 10^5	2,7	10,800 ± 600
Habernau 1	47,782	590	2	Alm Valley landslide	0,715	54,5	2.69 x 10^5	2,6	10,000 ± 900
Habernau 2		580	3	Alm Valley landslide	0,491	22,7	2.68 x 10^5	3,5	15,200 ± 800
Habernau 3		580	4	Alm Valley landslide	0,714	17,1	2.58 x 10^5	7,5	10,000 ± 900
Habernau 5		580	2	Alm Valley landslide	0,490	61,7	2.43 x 10^5	3,9	13,200 ± 700
Habernau 6		580	4	Alm Valley landslide	0,661	35,5	3.71 x 10^5	4,5	15,600 ± 1100

Table 2: Site information, rock total Cl, AMS-measured ^{36}Cl concentrations and calculated surface exposure ages.

mogenic production of ^{36}Cl was required (Fabryka-Martin 1988). Production rates were scaled to the latitude (geographic) and altitude of the sites after Stone (2000). Age uncertainties include AMS measurement errors and uncertainties on shielding corrections based on ± 5 degree on the dip determination. We have not included errors in the production rates or their scaling to the site which are considered to be less than 15% (Gosse & Phillips 2001).

The exposure ages of the four boulders from the Meisenberg site (Fig. 3 A) are 11,200 ± 1000, 15,700 ± 900, 17,900 ± 1500, and 18,800 ± 900 years. As describeed in detail above, their position on the flank of the Straneggbach valley indicates that the valley must have been filled with ice when the landslide occurred. Therefore the two oldest ages, 17,900 ± 1500 and 18,800 ± 900 years, are a good approximation of when this landslide took place. These ages are in good agreement with estimates from other Alpine regions for the onset of down wasting of ice at the end of the LGM (van Husen 2000, Ivy-Ochs et al. 2006b).

The boulders sampled at the Polster and Habernau sites are located atop the hummocky topography of the younger main valley-filling Almtal landslide. Based on field relationships both sites are expected to stem from a single large catastrophic landslide. ^{36}Cl exposure ages from eight boulders at Polster and Habernau range in age from 8600 ± 600 to 15,600 ± 1100 years. In light of the evidence presented above (for example entrained clasts that are barren of pollen) which points to a pre-Bølling age for the landslide, we conclude that the two oldest ages, 15,200 ± 800 and 15,600 ± 1100 years, most closely represent the true age of the landslide. The spread in exposure ages must be due to post-depositional effects such as exhumation, significant shielding by soil and vegetation, or spalling of large slabs off the boulder surfaces.

8. Conclusions

As in many valleys in the Alps (Abele 1974) the development of the valley floor in the Almtal was strongly influenced by large landslides. There it represents a good example how, after the down melting of the valley glacier such an event took place due to the mechanical properties of the rocks of the Triassic lithological sequence.

The formation of the sturzstrom, as well as of the subsequent suspension flow, was strongly controlled by the configuration of the valley floor after deglaciation.

Despite the great extent of the deposits (sturzstrom ca. 9.5 km, suspension flow ca. 7 km) the event happened in a very short time. An estimation of about 70 m/sec (~ 250 km/h) may be correct for the average velocity of a sturzstrom of approximately 450 mill. m^3 and a valley gradient like that at Straneggbach.(Heim 1936, Plafker and Erickson 1978). Accepting these values indicates that the landslide itself lasted only about 2.5 minutes.

The transformation of the head of the sturzstrom into a suspension flow occurred simultaneously with the end of this event. The velocity of the suspension flow, with its high water content, may be estimated at 10 - 15 m/sec (36 - 54 km/h; Costa 1984, Hungr et al. 2001). Thus, the suspension flow may have reached the Grünau basin to the north within ca. 10 minutes.

Thus a maximum time span of 15 - 20 minutes for forming the spectacular landscape along the Straneggtal and the Alm river seems most likely.

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