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Rockslide movement supported by the mobilization of groundwater-saturated valley floor sediments

by

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with 9 figures

Summary. If a rockslide reaches the bottom of a valley, it can mobilize the groundwater-saturated valley fill.

Thus, it produces a fluid mixture of water, silt, sand and gravel, which in turn supports the movement of the rockslide masses. Such a combined movement of a rockslide mass riding on water-saturated material can increase both run-out distance and spreading. As in the course of this process the water-saturated material tends to extend horizontally, longitudinal and transversal tension faults and fissures may occur in the rockslide mass. As a consequence, the surface of the rockslide deposits is characterized by pull-apart ridges and depressions. Beyond the outward fringe of the continuous cover of rockslide material valley sediments reminding a debris flow can adjoin, which may contain isolated parts of the rockslide deposits, to be regarded as a continuation of the mass movement.

Zusammenfassung. *Die wechselseitige Abhängigkeit zwischen Bergstürzen und den durch sie mobilisierten wassergesättigten Talfüllungen.* – Erreicht ein Bergsturz den Talboden, so kann er dort die grundwassergesättigten fluvialen Sedimente verdrängen und mobilisieren. Auf dem dabei entstehenden Wasser-Schluff-Sand-Kies-Gemisch können die Trümmer weitergetragen werden, so daß sie eine große Fahrbahnlänge und Streuungsrate erreichen. Da sich das Feststoff-Wasser-Gemisch murartig ausbreitet, kommt es auf den darauf lagernden Trümmermassen zu Zerrungsbewegungen und damit zu longitudinalen und transversalen Abschiebungen und Spalten. Die Oberfläche der Bergsturzmassen ist daher durch Rücken und Tiefenzonen gekennzeichnet. Außerhalb des Randes der geschlossenen Bergsturz-Ablagerungen können in solchen Fällen mächtige murartige ungeschichtete Schotter- und Sandmassen anschließen, die mittransportiertes Bergsturzmaterial in isolierten Einschlüssen enthalten und als Fortsetzung der Gesamtbewegung aufzufassen sind.

Résumé. *Interaction entre les grands éboulements et les sédiments fluviaux mobilisés au fond des vallées.* – En glissant contre le fond d'une vallée, un grand éboulement peut déplacer et mobiliser les sédiments fluviaux qui sont impregnées par les eaux souterraines. Ainsi se produit un mélange entre des graviers, du sable, du limon et de l'eau, qui peut entraîner les débris de l'éboulement. De cette manière les débris atteignent une longue distance de transport et une grande dispersion. Parce que le mélange d'eau et de matériau solide s'étand comme une coulée de boue et de pierres, la couche des débris secs sur leur dos est forcée de s'adapter en formant des faillies de tension et des crevasses. A cause de ces mouvements la surface des dépôts des glissements de roches est caracterisé par des crêtes et des dépressions. En dehors de la couche cohérente de débris le mouvement peut continuer comme une coulée de boue et de pierres, qui à son tour peut entraîner des paques isolés de débris. formant ainsi une extension du mouvement général de l'éboulement.

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1 *Introduction*

If we want to delimit the danger area of imminent rockslides it is important to determine their expected volume and overall height (i. e. the difference of height between the highest point of the head scarp and the lowest point of the deposition area). It is mainly these two factors which influence the overall length (i. e. the maximal distance between the upper rim of the head scarp and the most distant point of the deposition area measured along the path of the mass movement). As a general rule, a large mass results in a more economic motion than a smaller one (in other terms: it requires less overall hight to cover a given overall length).

This well-known size effect (HEIM 1932) can be demonstrated in the Alps (ABELE 1974, fig. 39 and 42). It is surprising, however, that certain rockslides run out definitely farther than could be expected from predictions based on the size effect (SCHEIDEGGER 1973; 235). To quote an example: according to the mentioned prediction the Almtal slide (see below, 2.2) should have an overall coefficient of friction f = 0.198, while in reality f = 0.11 is observed (ABELE 1974; 46, fig. 42); in other terms: the total length covered excedes the predicted one by 80 percent! In the present study one of the possible reasons of such outstanding behaviour is considered, namely the fact that such rockslides often run out on water-saturated material of valley floors. Therefore the question arises as to whether there is a special type of mechanism which allows the rockslide masses to travel that far on valley floors. The examples discussed hereafter demonstrate the plausibility of the idea, that rockslides can mobilize groundwater-saturated valley fill and that in turn this fluid mixture of water, silt, sand, and gravel supports the movement of rockslide masses. The first to mention such a possibility was PAVONI (1968) in his interpretation of the Bonaduz Gravels (see below, 2.1). This view escaped the notice of most geoscientists, even of those who were concerned with rockslides. The author discussed the possibility of such a water-lubricated mobilization (ABELE 1974; 137f), and later he assumed this type of mass movement at the rockslide of Flims (see below, 2.1) and the Alm valley (see below, 2.2; ABELE 1984: 173, 1990 and 1991). Since the Tschirgant rockslide (see below, 2.3) was also found to have interacted with valley bottom sediments (PATZELT & POSCHER 1993), we see that this type of movement has a more general importance.

The mentioned mechanism probably works as follows: when moving over a water-saturated valley fill (which may be gravel as well as finer material), a rockslide mass exerts, by mere gravitation and, if any, also by centrifugal force, a compressive effect upon the fill. The rapidity of motion prevents the pore water from escaping unpressurized and forces it to support part of the rockslide's weight, thus acting as a lubricant. The effectiveness of this highly dynamic process depends on the balance between pressurizing and escape of water, and a crucial condition is sufficient compressibility (by elasticity, crushing, or grain displacement) of the solid material involved. The analogy to pressurized lubricants in technical bearings is striking. In addition, this mechanism might locally be enhanced by vaporization of water owing to frictional heat (as proposed by GOGUEL 1978).

In the following chapters some landslides, most of them in the Alps, are mentioned wich may be not so known. We add, therefore, some basic remarks and data about all of them, mostly after ABELE 1974 (see also fig. 1):

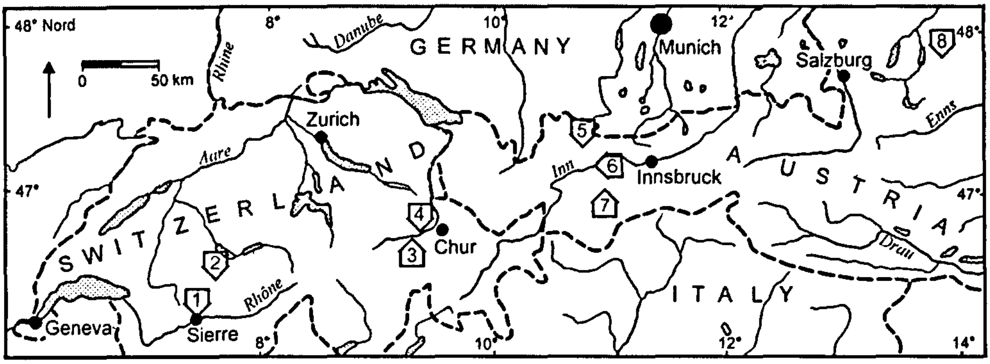

Fig. 1. Location of mentioned landslides.

Alm valley (Almtal) rockslide *(Austrian Alps)*
Situation: see below, 2.2.
Rock: Triassic limestone (Dachsteinkalk).
Area: 7.5 km^2.
Volume: 0.3 km^3.
Overall Slope (Fahrböschung according to HEIM 1932): 6°
Age: Late-glacial, as indicated by moraines of a later on advanced local glacier upon the rockslide deposits.

Fernpass rockslide *(Austrian Alps)*
Situation: Having originated from the western side, the rockslide masses splitted in the valley into two parts, one moving to north east, the other one moving more or less to the south, and established the Fernpass, an important pass for the traffic crossing the Northern Calcareous Alps.
Rock: Predominantly triassic dolomite (Hauptdolomit).
Area: 15 km^2.
Volume: More than 1 km^3.
Overall Slope (Fahrböschung): Northern part: 7°, southern part 5°.
Age: Owing to morainic material covering the rockslide deposits in places, the author supposed formerly a late-glacial age. Now he takes into consideration, that this rockslide could be of holocene age (see below, 2.1.4.2).

Flims rockslide *(Swiss Alps)*
Situation: see below 2.1.
Rock: Predominantly jurassic limestone (Malm).
Area: Around 50 km^2.
Volume: at least 9 km^3. By far the largest rockslide in the Alps.
Overall Slope (Fahrböschung): 4°.
Age: Probably late-glacial due to moraines of later on advanced local glaciers partially covering the rockslide deposits.

Kandertal rockslide *(Swiss Alps)*
Situation: The rockslide, in moving down to the north near Kandersteg, dammed at first the mouth of the Öschinental, a rightside tributary valley of the Kander valley, then followed the main valley to the north.
Rock: Cretaceous limestone.
Area: 6.8 km^2.
Volume: About 0.9 km^3.
Overall Slope (Fahrböschung): $< 10°$.
Age: Late-glacial, as suggested by moraines of a local glacier advanced into the scarp area later on.

Köfels rockslide (*Austrian Alps)*
Situation: The rockslide moved to the west across the Ötztal. Its masses dammed this main valley (former lake of Längenfeld) and blocked a rightside tributary valley (Horlachtal). Large parts of the rockslide deposits have remained more or less intact and, in places, have the appearance of bedrock. This slide became internationally known because of findings of fused rock generated by the slide upon the sliding planes (frictionite). There is still remaining a discussion if this fused rock couldn't result of the impact of a meteorite.
Rock: Of the mentioned landslides it is the only one consisting of crystalline rock, predominantly granitic gneiss.
Area: At least 12 km^2.
Volume: At least 2.1 km^3. By far the largest rockslide in the crystalline parts of the Alps.
Overall Slope (Fahrböschung): About 7° (as far as overall length is known).
Age: Evidently holocene. Radiocarbon date (wood at the base) 8710 ± 150 BP.

Pandemonium Creek rockslide (*Canada*, EVANS et al. 1989)
Situation: Southern Coast Mountains, British Columbia. Originating on a cirque headwall the masses slid down to the north to the Pandemonium Creek, following that valley to the east until the main valley (South Atnarko River), then still turning to the south.
Rock: Gneissic quartz diorite.
Area: About 0.8 km^2.
Volume: 0.005 km^3.
Overall Slope (Fahrböschung): 11° (as far as overall length is known).
Age: Occurred in 1959.

Rockslide of Sierre (Swiss Alps)
Situation: The rockslide masses slid down from the north into the Rhone valley near Sierre (Siders), then splitting into two parts: the smaller one moved upstream to the east, the larger one moved to the west.
Rock: Cretaceous limestone.
Area: 28 km^2.
Volume: More than 2 km^3.
Overall Slope (Fahrböschung): 6°.
Age: The rockslide deposits came, probably, in contact with late-glacial ice.

Tamins-Säsagit rockslide *(Swiss Alps)*
Situation: See 2.1.
Rock: Jurassic limestone (Malm).
Area: More than 17 km^2.
Volume: 1.6 km^3.
Overall Slope (Fahrböschung): $<$ 8° (as far as overall length is known).
Age: Probably late-glacial (see 2.1.4.2).

Tschirgant rockslide *(Austrian Alps)*
Situation: See 2.3.
Rock: Predominantly triassic dolomite (Wettersteindolomit).
Area: 13.2 km^2.
Volume: About 0.2 km^3.
Overall Slope (Fahrböschung): 9° (as far as overall length is known).
Age: Evidently holocene. Radiocarbon dated: 2900 BP.

2 *The interaction of rockslides with the mobilized water-saturated valley fill*

2.1 *The rockslide of Flims and the Bonaduz-Gravels* (figs. 2, 3)

2.1.1 *The situation*

The lowest parts of both the Vorderrhein and Hinterrhein valleys (Grisons, Switzerland) and their confluence area are covered with the huge deposits of the rockslides of Flims (originating from the Segnas valley and representing the largest event of the Alps) and of Tamins-Säsagit. In contact with these deposits there are the so-called "Bonaduz Gravels", originally "Bonaduzer Stauschotter", that means: gravels deposited behind a barrier (GSELL 1917/18, OBERHOLZER 1933, NABHOLZ 1954, 1967, 1975, 1987, REMENYIK 1959, PAVONI 1968, SCHELLER 1970, ABELE 1970a, b, 1974, 1991).

The Bonaduz Gravels are up to more than 50 m thick sediments with well developed graded bedding of coarse gravel in the lower parts and fine material on top. In the confluence area of the Vorderrhein and Hinterrhein rivers these sediments, very similar to those of a wet debris flow, build up fluvial terraces. In both valleys they can be observed as far as 12 km upstream: at some outcrops in the deep gorge of the river Vorderrhein through the Flims rockslide deposits, and, preserved as small terrace remnants only, in the Hinterrhein valley. Below the confluence of the two rivers the unstratified material of the Bonaduz Gravels can be traced only as far as the Tamins-Säsagit rockslide barrier (see also SCHELLER 1970: 83). Thereby, the nearly horizontal surface of the Bonaduz Gravels lies about 50 m above the valley floor sediments at the western slope of the barrier.

2.1.2 *Some hypotheses on the Bonaduz Gravels*

Many hypotheses are existing about the genesis of the Bonaduz Gravels. The original name "Bonaduzer Stauschotter" (dammed gravels) shows, that it was generally accepted, that the rockslide deposits of Ils Aults and of Crest Aulta are of the same unit as those of the area around Tamins, and that this barrier of rockslide masses dammed formerly the river Rhine, furthermore, that this was also the barrier influencing the deposition of the Bonaduz Gravels.

The most interesting hypothesis is that of PAVONI (1968). He was the first to interpret these sediments as the material of a wet debris flow moving upstream the Hinterrhein and to attribute them to the mobilization of fluvial sediments by the Tamins-Säsagit rockslide.

Formerly the author (ABELE 1974: 140) explained the Bonaduz Gravels as flood sediments of the outburst of a lake dammed up by the Flims rockslide around Ilanz. These sediments should be, therefore, younger than the Flims rockslide. He agreed with PAVONI (1968) that de deposition of these gravels was directed upstream in the Hinterrhein valley, and he could find evidence for that direction (see 2.1.3). But when originating from a lake outburst through the Flims rockslide barrier the flood must have been diverted to the south into the Hinterrhein valley by the Tamins-Säsagit-rockslide barrier.

Later, considering the following observed facts, the author came to a similar result as PAVONI (1968), though suggesting a different answer to the question, which landslide mobilized the Bonaduz Gravels.

2.1.3 *Sedimentpetrographical indicators*

The author (Abele 1970a: 124) found components of Punteglias Granite in an outcrop of the Bonaduz Gravels near Unterrealta, Hinterrhein valley, originating from the Vorderrhein valley. Scheller (1970: 82) confirmed these findings and added some other findings of Punteglias Ganite components in the Bonaduz Gravels of the Hinterrhein Valley.

On the other hand there are no Hinterrhein components (e.g. Verruccano) in the mobilized valley fill of the Vorderrhein gorge, as the author (Abele 1974: 136) found out completing a statement of Scheller (1970: 82), that concerned the Rabiusa gorge near Versam.

As the described mobilized fluvial sediments in both the Hinterrhein and Vorderrhein valleys are of the same type, and, therefore, belonging to the Bonaduz Gravels, such a distribution of components could only be produced by an event in the Vorderrhein valley, and not by the Tamins-Säsagit rockslide (as Pavoni, 1968, supposed), which slid down below the confluence of the two rivers and would, therefore, have accumulated the components of both valleys in both valleys.

In the Rabiusa gorge (southern tributary valley of the Vorderrhein valley) a big portion of the Bonaduz Gravels consists exclusively of local material (Bünden Schists) of the Rabiusa catchment area (Safien valley). This is a striking argument against the author's (Abele 1974) former hypothesis, that the Bonaduz Gravels are flood sediments of the outburst of a lake around Ilanz lake (see 2.1.2). The author agrees now, therefore, with Pavoni (1968) that the Bonaduz Gravels were mobilized by a rockslide, though, as will be shown in the following paragraphs, rather by the event of Flims (Abele 1984, 1990 and 1991) than by that of Tamins-Säsagit.

2.1.4 *Stratigraphical indications*

2.1.4.1 *Stratigraphical position of the Bonaduz Gravels*

In the Vorderrhein gorge there is a conspicuous interfingering of the Bonaduz Gravels with the Flims rockslide deposits, particularly south of Sagogn (fig. 2, no. 1), east of the railway station of Trin (fig. 2, no. 3) and near Versam in the (tributary) Rabiusa gorge (fig. 2, no. 2). It is, therefore, evident that it was the Flims rockslide, which mobilized the Bonaduz Gravels.

In spite of the tremendous impact of the Flims rockslide, the rounded pebbles of the Bonaduz Gravels interfingering with the highly fractured material of the Flims rockslide, have not been fractured at all. This can be explained by a high mobility and, therefore, by a considerable water content of the valley fill.

The Bonaduz Gravels were accumulated on the upstream slope of the Tamins-Säsagit rockslide deposits (at Ils Aults, fig. 2, no. 4), not interfingering with these rockslide deposits. Thus, the Flims rockslide must have mobilized the Bonaduz Gravels, when the Tamins-Säsagit rockslide mass had already dammed the river Rhine.

2.1.4.2 *Glacial deposits in contact with the landslides*

Figure 2 shows morainic material of the Vorderrhein glacier upon the deposits of both the Flims and Tamins-Säsagit rockslides, and morainic material of local glaciers upon the Flims rockslide deposits. But no morainic material could be found upon the Bonaduz Gravel terraces.

In attributing the mobilization of the Bonaduz Gravels to the Flims rockslide (see 2.1.4.1) we can, therefore, exclude the old idea of a late-glacial advance of the Vorderrhein glacier across the Flims rockslide deposits (and consequently across the attributed Bonaduz Gravel terraces) until Chur. Such an advance was assumed (Chur Advance, W. Staub 1910, R. Staub 1938, Hantke 1980) because the southern part of the Flims rockslide deposits are covered in many places by morainic material of the Vorderrhein glacier with its well rounded crystalline boulders.

The glacial sediments etc. covering a part of the surface of the evidently post-glacial Köfels rockslide deposits (fig. 1) prove, that an older sediment cover can be transported on the back of a big rockslide (Heuberger 1966, 1984, 1994). The evidently post-glacial Tschirgant rockslide (see below, 2.3) has also, in places, a cover of older glacial (late-glacial) deposits (Heuberger 1966, Patzelt & Poscher 1993). The cover of deposits of the late-glacial Inn glacier upon the Fernpass rockslide was also transported by the rockslide itself into the present position as Abele (1994) could demonstrate. Conclusion: The morainic material of the Vorderrhein glacier upon the southern part of the Flims rockslide deposits cannot be explained, therefore, free of doubts as an evidence, that the Flims rockslide deposits were, later on, overridden by the late-glacial Vorderrhein glacier.

In the western part of the Flims rockslide deposits we cannot exclude that the cover of glacial material was accumulated directly by the Vorderrhein glacier. The missing of Bonaduz Gravels west of Sagogn (fig. 2, no. 1) could be explained by later glacial erosion (but also by fluvial erosion).

The local morainic material upon the northern parts of the Flims rockslide deposits seems to have been accumulated directly by local glaciers from the north. Because of further rockslides the Segnas glacier accumulated rockslide material at the very big moraine south of Flims (compare Gsell 1917/18). This is the strongest argument for a late-glacial age of the Flims rockslide.

It may be asked whether the well rounded crystalline material upon the Tamins-Säsagit rockslide deposits attained its present position by rockslide transport or by a Rhine glacier advancing after the Tamins-Säsagit rockslide and before the Flims rockslide. Furthermore the question remains whether the striae on big blocks of the Tamins-Säsagit rockslide barrier were shaped by this possibly advancing Rhine glacier or by the flow, which accumulated the Bonaduz Gravels.

2.1.5 *Some remarks on the distribution and sedimentation of the Bonaduz Gravels*

In the Vorderrhein gorge through the Flims rockslide deposits, the mobilized valley floor sediments cannot be found in the central parts of the Flims rockslide but only near its fringes:

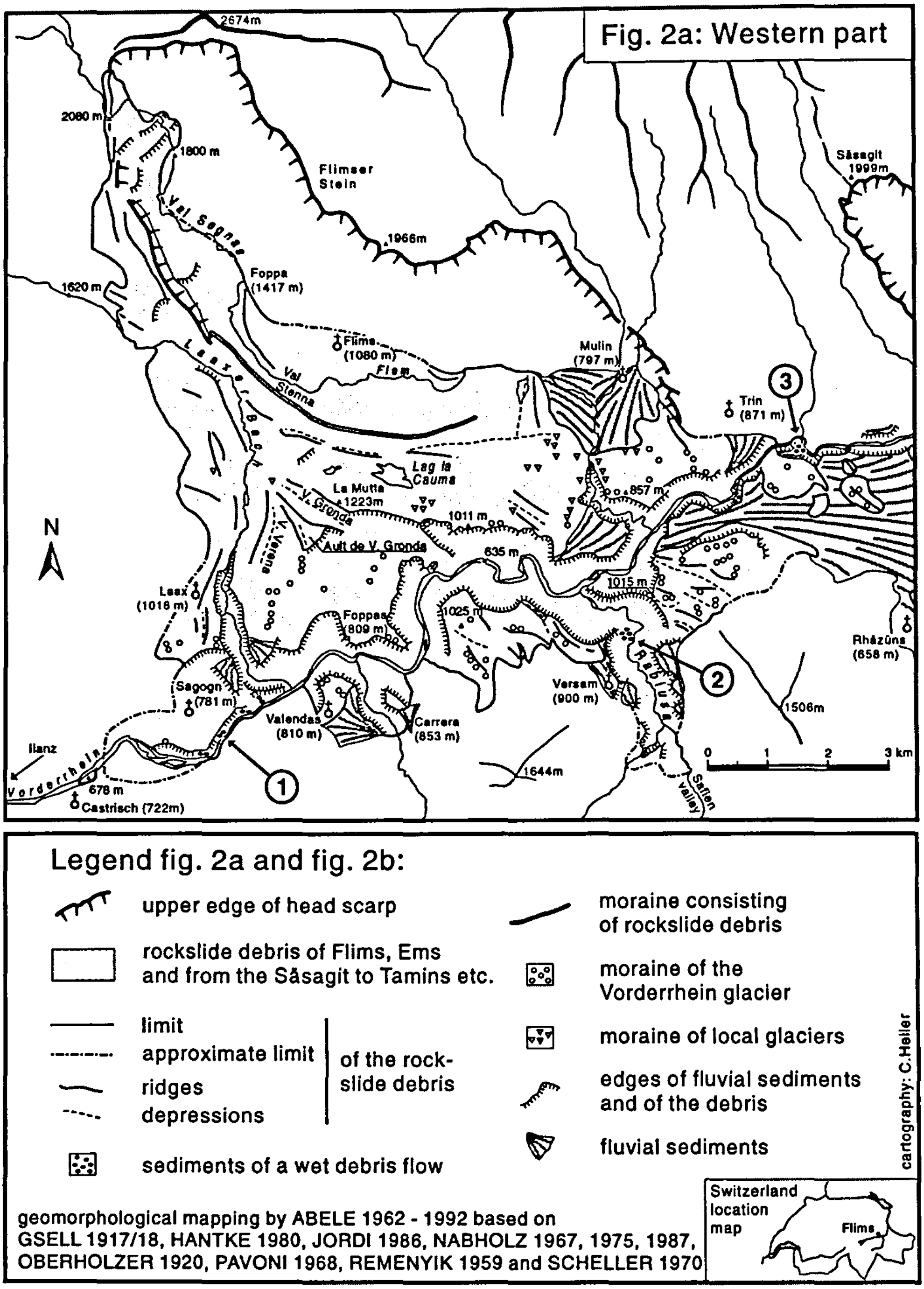
Fig. 2a: Western part
2674m
2080 m
1800 m
Flimser
Stein
Val Segnas
1966m
Foppa
(1417 m)
1620 m
Flims
(1080 m)
Flem
Val
Stenna
Laaxer Bach
Mulin
(797 m)
Trin
(871 m)
Sâsagit
1999m
Lag la
Cauma
La Mutta
1223m
V. Grondа
1011 m
857 m
635 m
Ault de V. Gronda
V. Verlena
Laax
(1016 m)
Foppa
(809 m)
1025 m
1015 m
Rhäzüns
(658 m)
Sagogn
(781 m)
Valendas
(810 m)
Carrera
(853 m)
Versam
(900 m)
Rabiusa
1506m
Ilanz
Vorderrhein
678 m
Castrisch (722m)
1644m
Safien
Valley
0 1 2 3 km
N
Legend fig. 2a and fig. 2b:
upper edge of head scarp
rockslide debris of Flims, Ems
and from the Sâsagit to Tamins etc.
limit
approximate limit
ridges
depressions
of the rock-
slide debris
sediments of a wet debris flow
moraine consisting
of rockslide debris
moraine of the
Vorderrhein glacier
moraine of local glaciers
edges of fluvial sediments
and of the debris
fluvial sediments
cartography: C.Heller
geomorphological mapping by ABELE 1962 - 1992 based on
GSELL 1917/18, HANTKE 1980, JORDI 1986, NABHOLZ 1967, 1975, 1987,
OBERHOLZER 1920, PAVONI 1968, REMENYIK 1959 and SCHELLER 1970
Switzerland
location
map
Flims

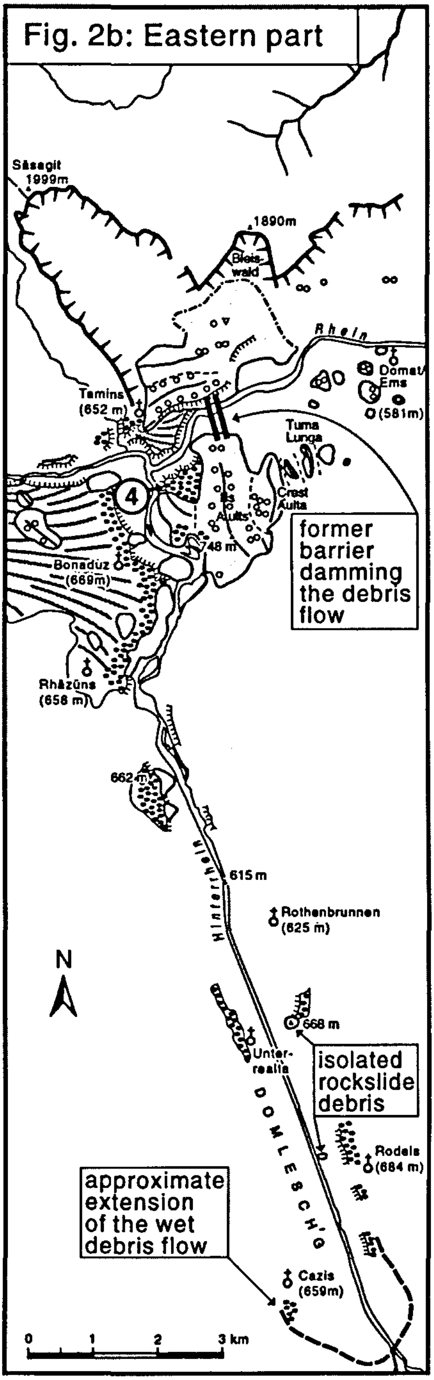

Fig. 2. The rockslide of Flims and the debris flow mobilized by it.

- on the opposite side of the landslide in the Vorderrhein valley in the Rabiusa gorge near Versam just in front of an elevation of the bedrock at the Rabiusa bridge (fig. 2, no. 2),
- in the upstream and downstream parts of the gorge (fig. 2, no. 1 and 3).

Interpretation: The displacement of the mobilized valley fill was especially great at the foot of the steep descent, i. e. where the rockslide mass hit the valley floor. After having crossed the Vorderrhein valley and collided with the opposit slope, the rockslide masses diverged from their original direction spreading upstream and downstream. The movement of these lateral rockslide tongues seems to have been supported by the mobilized valley fill at their basis.

Regarding the fact that the Flims rockslide has sent such big mobilized valley fill masses down the Vorderrhein valley and up the Hinterrhein valley, it is surprising that west of Sagogn (fig. 2, no. 1) no Bonaduz Gravels could be found upstream the Vorderrhein.

In the northern part of the Hinterrhein valley the terraces of the Bonaduz Gravels consist predominantly of rockslide material. To the south the rockslide deposits are not coherent but only isolated complexes which were included in the mobilized valley fill. In this valley the grain size of the Bonaduz Gravels decreases upstream to the south. For short distances this was already observed by PAVONI (1968: 495).

These observed facts in the Hinterrhein valley

- confirm the conclusion (see 2.1.3) that the debris flow was directed from the Vorderrhein – Hinterrhein confluence to the south, that means upstream into the Hinterrhein valley (see already PAVONI 1968, SCHELLER 1970, ABELE 1970a, b),
- may explain the result of mapping, that the Bonaduz Gravel terraces are surprisingly much wider in the north (between Rothenbrunnen and Rhäzüns), where the Hinterrhein valley is considerably narrower than in the south, due to the higher resistance of the landslide deposits in comparison with the flow sediments dominating more in the south,
- is, therefore, in accordance with the observed situation, that southward in the broader valley part of Domleschg only few and comparatively small rockslide deposits can be found, and that there are preserved only very small remnants of the Bonaduz Gravel terraces on both sides of the valley (Unterrealta, Rodels, Cazis; SCHELLER 1970),
- let, therefore, assume, that in the Domleschg the less resistant Bonaduz Gravels gave the river Hinterrhein a better chance to erode the Bonaduz Gravels as an originally coherent sediment cover, and that only the isolated rockslide masses were more resistant, now forming elevations which protrude from the actually flat valley floor until Rodels, 10 km south of the Vorderrhein/Hinterrhein confluence (SCHELLER 1970).

These reflexions and observed facts lead to the conclusion, that the mobilized valley fill was responsible for the transport of the rockslide masses to their extremely remote present position. This helps to explain the extremely great distance of these southern-most remnants of landslide deposits from the head scarp in their isolated position aside from the original direction of the landslide.

This explanation is in accordance with PAVONI's (1968) hypothesis except for his assumption that the Tamins-Säsagit rockslide mobilized the valley fill. Maybe the Tamins-Säsagit landlisde also mobilized fluvial sediments of the Hinterrhein valley on a smaller scale, but the now visible Bonaduz Gravels came from the Flims rockslide (ABELE 1984, 1990 and 1991), as shown sedimentpetrographically (2.1.3) and stratigraphically (2.1.4.1).

The unexpected turn of the movement of the Bonaduz Gravels from east (downstream the river Vorderrhein) to south (upstream the river Hinterrhein) as well as the absence of the Bonaduz Gravels east of the Tamins-Säsagit rockslide barrier lead to the conclusion, that the flow movement of the Bonaduz Gravels was stopped by the Tamins-Säsagit rockslide barrier across the Rhine valley, still not so broadly eroded by the river Rhine as today, so that the flow was diverted into the wide Hinterrhein valley floor of Domleschg. That the Tamins-Säsagit-rockslide barrier has delimited the deposition of the Bonaduz Gravels, was up to now generally accepted (see 2.1.1, 2.1.2).

2.1.6 *Geomorphological remarks*

Fig. 3 shows, in a cross section of the Flims rockslide, a remarkable depression of the surface just above the bottom of the Vorderrhein valley. South of La Mutta the surface drops abruptly and with a steep slope into this broad depression. This is, morphologically, surprising because rockslide deposits reach, usually, their greatest thick-

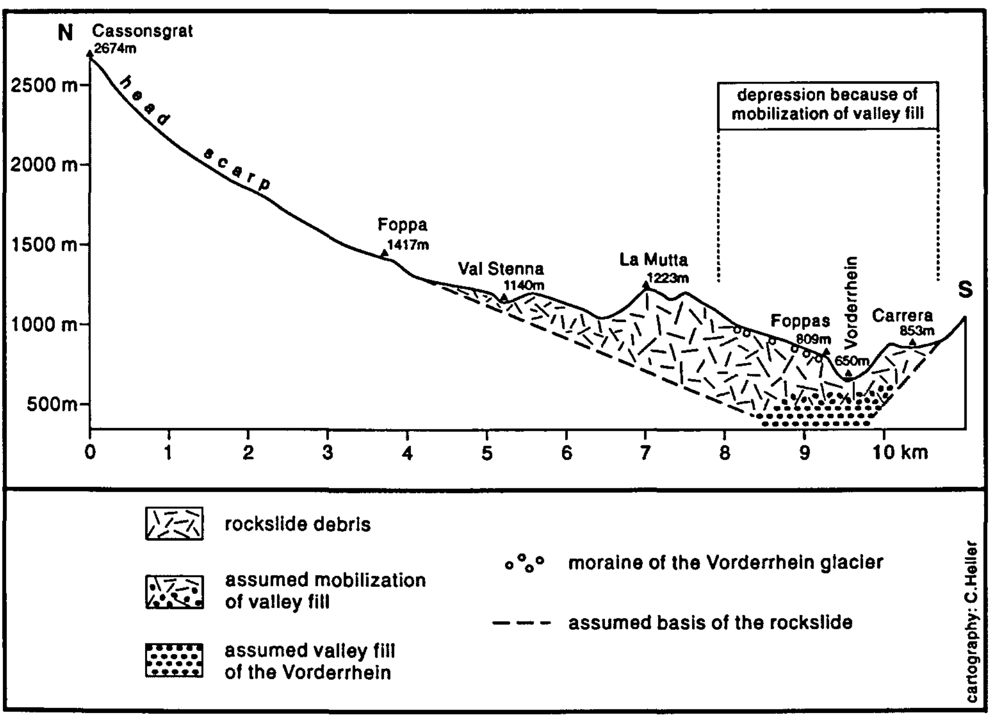

Fig. 3. Longitudinal profile across the Flims rockslide.

ness when colliding with the opposite slope. The big depression is considered to be due to the loss of material by the diverging of the moving masses in two rockslide tongues upstream and downstream on the back of the mobilized valley fill. Another explanation is possible, if the Vorderrhein glacier really covered later on the southwestern part of the rockslide deposits (see above, 2.1.4.2). It could have entered and shaped this now thorugh-like depression, whose original form was, however, probably due to the rockslide mechanics.

Upon the rockslide deposits south of the river Vorderrhein (fig. 2) there can be observed some depressions and even cracks, but also ridges. The author interprets them as pull-apart structures developed by the "riding" of the rockslide masses on top of the Bonaduz gravels following the spreading motion of the compressed, more or less fluid material below. Similar pull-apart structures at the Tamins-Säsagit rockslide deposits south of the river Rhine (Ils Aults, Crest Aulta, Tuma Lunga) and at the rockslide of Sierre (fig. 1) at Pfinwald, Géronde and some hills southwest of Sierre may also have been favoured by a mobilization and spreading of the underlaying water-saturated valley fill.

In the western part of the Flims rockslide deposits the ridges and depression of La Mutta (fig. 2) and west of it (Vald Cronda, Ault de Val Gronda, Val Verena and, north east of Laax, Spunda d'Uletsch) are also interpreted as longitudinal pull-apart structures of the rockslide (first direction). The ridges west of the Laaxer Bach probably are lateral ridges of the rockslide.

2.1.7 *Supposed sequence of the events* (completed by results of the author's earlier publications, particularly ABELE 1974)

1. Tamins-Säsagit (-Bleiswald?) rockslide damming the Rhine valley. A mobilization of the groundwater-saturated valley fill (according to PAVONI 1968) was possible, but corresponding sediments are not known.

The question of a late-glacial advance of the Rhine glacier into this area after the Tamins-Säsagit rockslide but before the Flims rockslide, is still open (see 2.1.4.2).

2. Rockslide of Flims, mobilizing the groundwater-saturated fluvial sediments of the Vorderrhein valley. Their flow influenced the movement of the rockslide masses and their morphology. It moved downstream to the east, then was diverted to the south by the Tamins-Säsagit rockslide barrier and thus travelled another 12 km upstream into the Hinterrhein valley, to be finally deposited as Bonaduz Gravels.

3. Readvance of late-glacial glaciers (see 2.1.4.2). Local glaciers from the north overrode the northern part of the Flims rockslide deposits. If the Vorderrhein glacier also reached the Flims rockslide deposits, the ice could only have covered their western part.

4. Retreat of the glaciers and formation of the large lake of Ilanz dammed by the Flims rockslide deposits. Accumulation of the deltas of the Glogn river at Ilanz and of the Laaxer Bach, accumulation of the big alluvial fan at the outlet of the lake.

5. Fluvial dissection of the deposits of both the Tamins-Säsagit and Flims rockslides, erosion of the Bonaduz Gravels.

6. Subsequent rockslides. The largest one formed the lateral ridges and transversal steps along the western side of the Flims headscarp area west of the river Flem, diverting, with its southernmost part (longitudinal ridge west of Flims), the Flem

river to the west, so that it was forced to erode the gorge of Val Stenna (fig. 2, 3) into the big late-glacial moraine of the Segnas glacier.

2.2 *The rockslide and mobilized fluvial sediments in the Alm valley*

Figures 4 and 5 show, in the Almtal (northern part of Totes Gebirge, Upper Austria), one of the longest rockslides of the Alps, discribed e.g. by the author (ABELE 1970a, 1974, 1984) and VAN HUSEN (1990). Following the bended valley of the Stranegg-Bach and covering its bottom, the rockslide masses formed a slender tongue damming up the main valley with the Alm lake.

South of the Öd lakes in the upper part there are two end moraines relatively dating the rockslide. The outer morainic ridge was interpreted by the author (1970; 1974: 98) to be a rockslide moraine. That means, that the rockslide, in the background of the valley, covered a small late-glacial glacier which shaped, after the rockslide, an end moraine. The inner and fresher shaped morainic ridge indicates, that a readvancing late-glacial glacier overrode the uppermost part of the rockslide deposits.

The coherent tongue of the Almtal rockslide ends about 15 km from the head scarp. In front of it, the valley is filled by a terrace of gravel, sand and silt of a 10 m thick deposit reminding a debris flow, nearly without stratification but with a gradation of coarse material in the lower and finer material in the higher parts. In these sediments are included, conspicuously, isolated and strongly fractured rockslide deposits even until the end of the terrace, shown in the small section of fig. 5 and much more impressive in a long section of the big Vielhaber gravel pit (VAN HUSEN 1990) close to Fischerau. These isolated pieces of rockslide deposits must, therefore, have been transported in the flow, and we may assume that this mass movement in turn was mobilized by the rockslide itself. The water of the melted ice of the overridden glacier must have supported this mobilizing of the valley fill. It can easily be imagined that even parts of the coherent rockslide tongue rode on top of the mobilized valley fill. Thereby the tongue was stretched to one of the longest in the Alps, thus attaining its surprisingly great travel distance.

VAN HUSEN (1990) came to about the same explanation. He will soon publish his results.

2.3 *The Tschirgant rockslide* (fig. 6)

The Tschirgant rockslide (Tyrol, Austria) having originated on the steep northern slope of the Inn valley, crossed this valley (boundary between the Northern Calcareous Alps and the crystalline Central Alps) and penetrated into the mouth of the tributary Ötz valley. There the debris of its triassic Wetterstein dolomite had ample space to spread. It even collided with the opposite slopes of both sides of the entry into the Ötz valley, forming lateral and frontal ridges (ridges south of Ötztal Station and on the slope between Roppen and Sautens). Radiocarbon dates of burried wood (picea) in the rockslide deposits near Sautens, and of burried soil remnants at the base of the rockslide deposits near Ambach (fig. 6, no. 3) led PATZELT & POSCHER (1993: 209, 212, 213) to the conclusion, that the Tschirgant rockslide must have happened at about 2900 years BP.

During its descent to the valley floor de debris incorporated, besides morainic

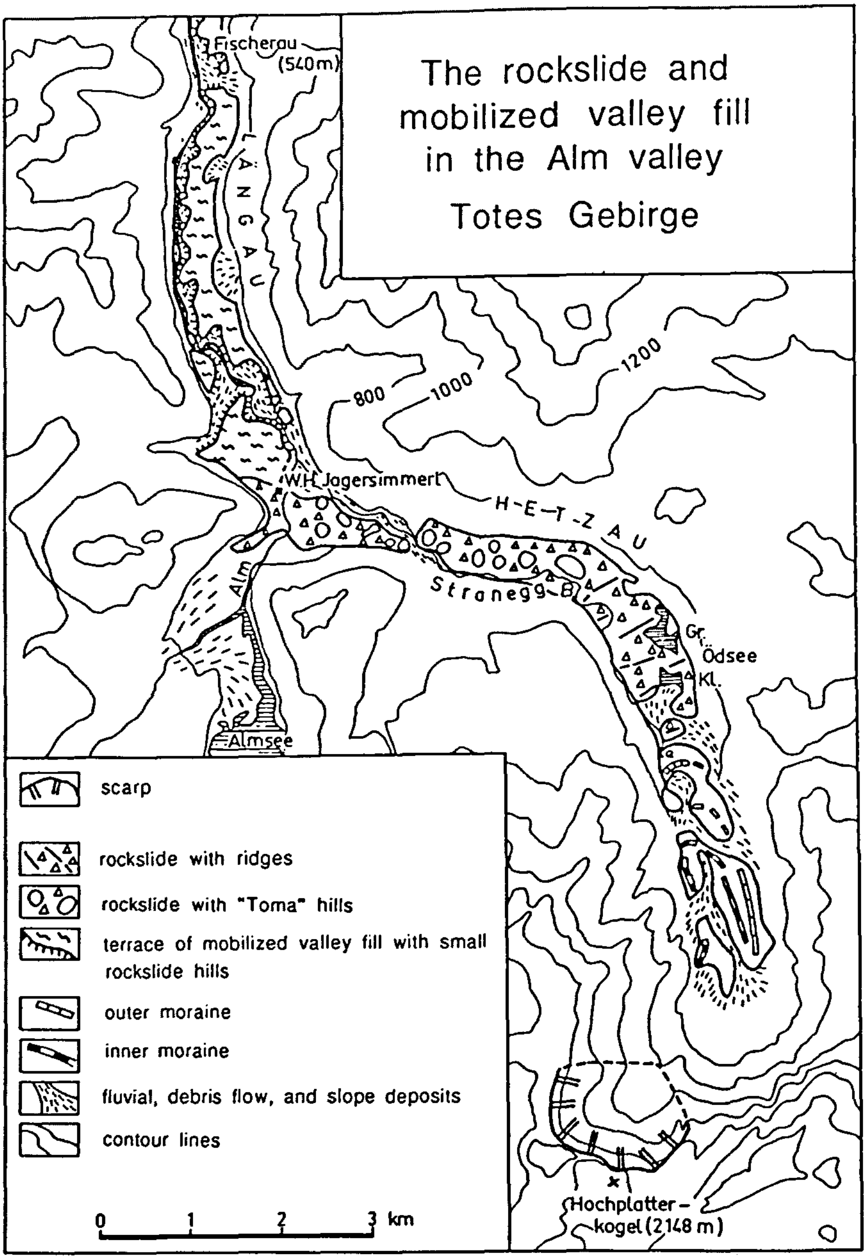

Fig. 4. Alm valley, Totes Gebirge: Rockslide and mobilized valley fill (after ABELE 1984).

material of the late-glacial valley glaciers, sediments of the Inn river and transported them towards Sautens in the Ötz valley (PATZELT & POSCHER 1993). This can be clearly seen in the outcrops along the Ötztaler Ache gorge, which has been cut into the rockslide deposits. At several places (fig. 6, no. 1 and 2) there is a close interfingering of unstratified Inn (!) valley bottom sediments (gravel, sand, and silt) with the

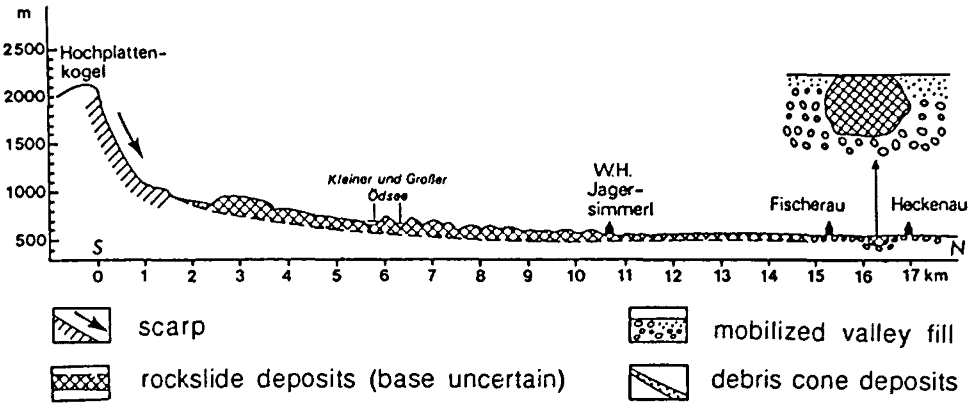

Fig. 5. Section Alm valley, rockslide and mobilized valley fill (after ABELE 1974).

rockslide debris (PATZELT & POSCHER 1993). The fluvial material seems to have been injected from below into crevasses which opened during the debris movement. The water-saturated valley fill may have been pressed upward by the overburden of rockslide debris material. In some of the crevasses there is a gradation of predominantly coarse components in the lower and exclusively fine components in the higher parts. This effect is clearly visible in figs. 7 and 8. Such a gradation could be only brought forth if there was a high content of water in the mixture of gravel, sand, and silt. According to an oral information from T. H. ERISMANN, the observed gradation is strigent for the case of pebbles and sand driven upwards by a vertical flow of water. The gradation must have been brought about during the formation of the crevasses and in the course of simultaneous injection from below.

The just mentioned basal crevasses in the rockslide debris with the injected filling of the mobilized valley bottom sediments can be interpreted as pull-apart structures comparable with the typical pull-apart structures (ridges and a multitude of depressions) on the surface (fig. 6, and schematicly shown in fig. 9).

Apparently, it was the Tschirgant rockslide itself which mobilized the groundwater-saturated Inn river sediments at the foot of its steep descent from the Tschirgant mountain. This mobilization in turn must have contributed to the wide spreading of the debris, so that its comparatively thin blanket covers a large area of the valley bottom. It is, therefore, not surprising that the Tschirgant rockslide's spreading ratio (i. e. the ratio of scar area to depositions area) is one of the highest in the Alps, namely 1:7.3, as compared with an average of 1:2.39 resulting from 31 alpine events presented in one of the author's previous studies (ABELE 1974, Fig. 44).

An outcrop near Ambach (fig. 6, no. 3) shows the combined deposits of landslides debris and mobilized fluvial sediments covering stratified Ötztaler Ache sediments topped by burried soil remnants (PATZELT & POSCHER 1993: 213). The preservation of the stratification of these fluvial Ötz valley sediments and the soil remnants on top seems to be due to the fact, that the rockslide debris here moved on a former fluvial terrace, whose material was not groundwater-saturated. Moreover, the locality is situated at the distal part of the rockslide, where the velocity and momentum of the debris should already have been reduced.

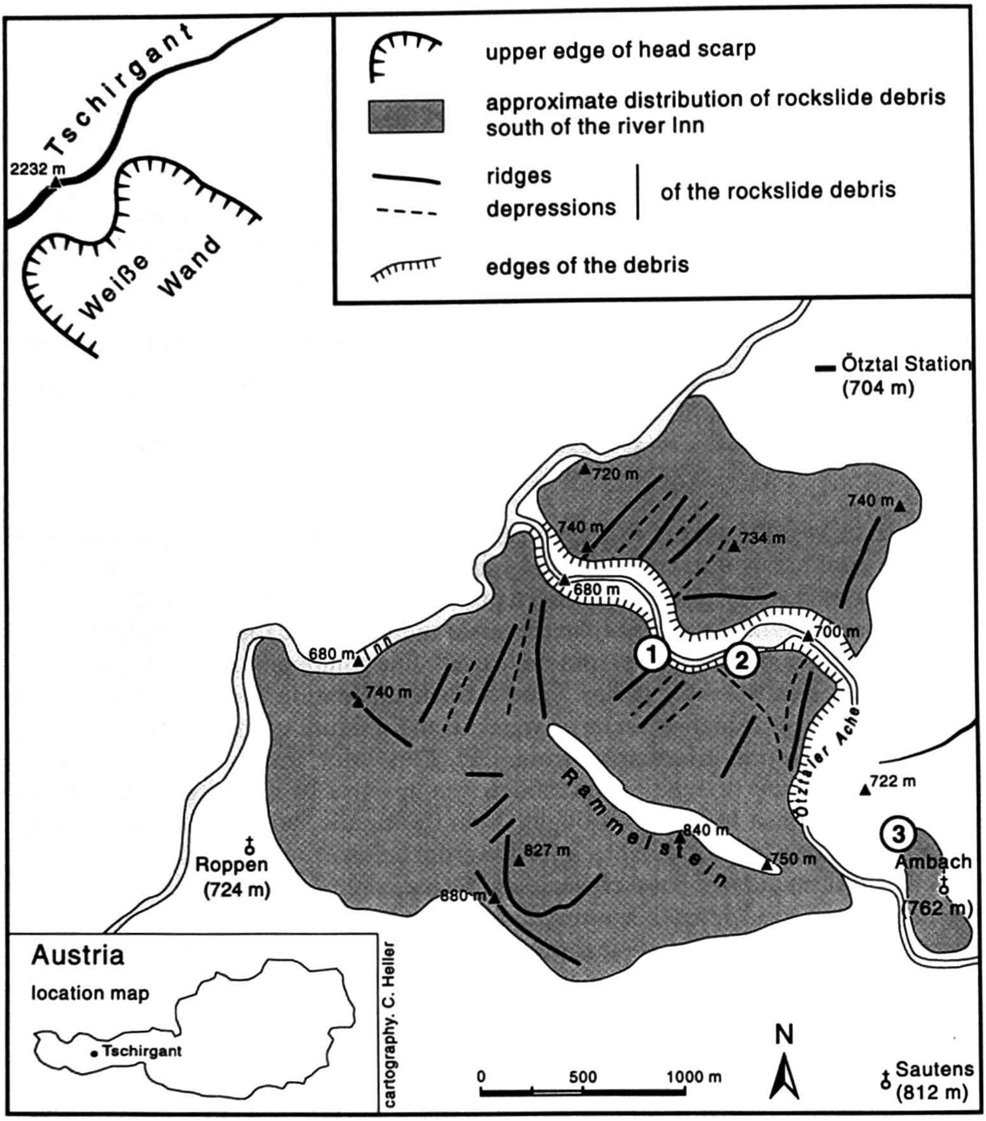

Fig. 6. Tschirgant rockslide.

3 *Conclusion*

When overrunning water-saturated material of a valley floor, the mass of a rockslide may ride on top of this partially liquid material, the latter acting as lubricant and thus resulting in an increased run-out distance. In addition, the bottommost elements may in their turn be saturated with water, thus taking part in a quasi-liquid motion and being mixed with the valley fill. These complex mass movements tend to consist of three sections: in the proximal section (i. e. the part near the head scarp) the rockslide

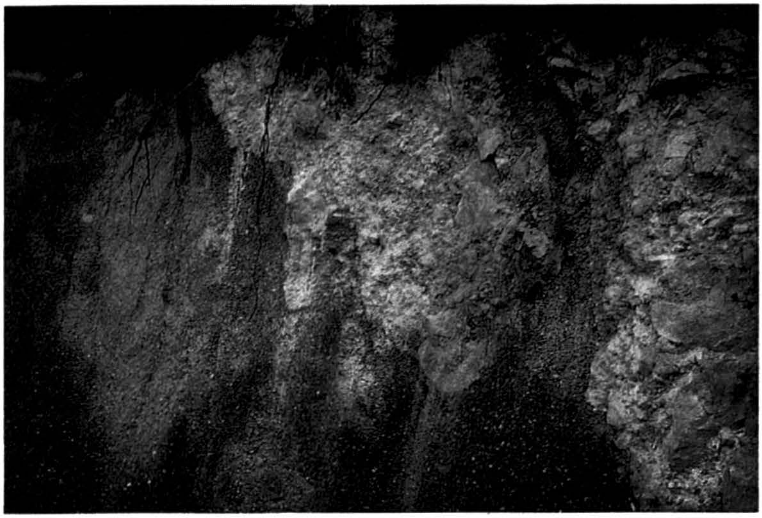

Fig. 7. Basis of the Tschirgant rockslide at the Ötztaler Ache (see fig. 6, no. 1): Close interfingering of rockslide material on top and unstratified but graded fluvial sediments of the river Inn (!) below.

Fig. 8. Basis of the Tschirgant rockslide at the Ötztaler Ache (see fig. 6, no. 2): Close interfingering of rockslide deposits on top and unstratified but graded fluvial sediments of the river Inn (!) below.

debris displaces the water-saturated valley fill (schematic profile, fig. 9, left part). In the central section a coherent cover of rockslide material rides on the mobilized valley fill (fig. 9, central part). The distal section begins beyond the outward fringe of this continuous cover, where the movement can be continued exclusively by a wet debris flow, which may contain isolated parts of the rockslide masses (fig. 9, right part).

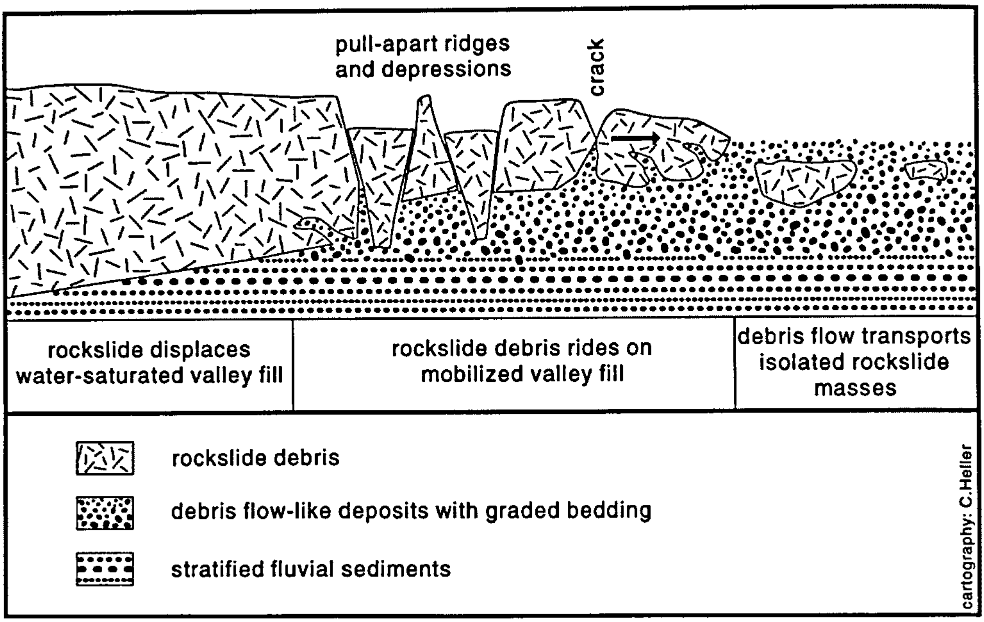

Fig. 9. Movement of rockslide debris on mobilized groundwater-saturated valley fill (schematic profile).

In the central section the rockslide moves through a *kind of lubrication*; but in contrast to the self-lubrication by rock fusion as a consequence of frictional heat (Erismann 1979) or other phenomena (Goguel 1978), this mechanically induced flow is not confined to a very thin layer but comprises a comparatively thick mobile mixture of gravel, sand, silt, and water.

If we take into account that many rockslides glide down to valley floors, we may well presume that quite often the mobilization of groundwater-saturated sediments may enable the rockslide masses to spread, while they are becoming thinner at the same time. Thus, a high *spreading ratio* is attained.

If the valleys are narrower, the mobile mass of rockslide and valley fill material has to adapt itself to the relief. Therefore, there is less lateral extension but more elongation, and the spreading ratios are more moderate. By such a channelling the long rockslide tongue in the Alm valley seems to have been brought forth. The rockslide tongues in the Kander valley and at Sierre as well as those north and south of the Fernpass (see fig. 1) and in the Pandemonium Creek valley (Evans et al. 1989; see below), also may have attained their great length by water-lubricated mobilization of the valley fill.

The mobilized material does not only consist of the sediments of the main river, but also of the alluvial fan deposits of the tributary rivers (Rabiusa from Safien valley, south of the Flims rockslide (fig. 2, see above, 2.1.3), and probably Navisense from the Val d'Anniviers, south of the Sierre rockslide).

The fundamental difference between an essencially solid upper and a more or less fluid lower layer of the combined movement of rockslides and debris flows leads to characteristic *forms on the surface* of this complex of mass movement: When compressed by a rockslide, the water-saturated valley fill tends to extend, which leads to longitudinal and transversal tension faults as well as disruption fissures in the rockslide mass riding on top. As a consequence, the surface of the rockslide debris is characterized by ridges and depressions (fig. 9). The crack-like depressions (on the rockslide debris of e. g. Sierre, Flims, the Fernpass, and the Tschirgant) could have been formed by the collapse of cavities, which were formed by the pull-apart movement of the debris.

It will be observed that, by exception of one, exclusively large events (volume $> 0.2\,km^3$) have been mentioned and listed. This may be a hint to a massive compression of the valley fill being required to generate the supporting pore water pressure according to the above-mentioned mechanism. However, also small rockslides probably function on the same basis if their debris are laterally confined by a sufficiently narrow valley. A striking example is the Pandemonium Creek slide in Canada (Evans et al. 1989).

The question has been raised, whether there is a special type of rockslide mechanism by which we can explain the extremely great travel distances of some rockslides on the valley floors. After regarding the complex mass movements of Flims, the Alm valley, and the Tschirgant (with side-looks at other events), we see that there really is one. It is the *combined movement of rockslides riding on water-satureated valley fill.* In case of an *imminent mass movement*, it is, therefore, important to take into account the *possibility of a dramatical increase of the overall length.*

It must be pointed out, however, that the mere existence of gravel or sand etc. in a valley fill does by no means warrant a particularly long run-out: various additional conditions – in first instance sufficient saturation with water – have to be fulfilled to start the mechanism. And the quantitative approach to the prediction of the expected reach may become a field for future research.

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