Chapter 15
The Flims Rockslide Dam

Andreas von Poschinger

1 The Flims Rockslide Site

The Flims rockslide in the Swiss Alps (Fig. 15.1) is the largest landslide deposit known in the Alps and one of the largest world wide. Its volume has been estimated [16] to be 8 km^3. It covers a surface of about 52 km^2. Also larger volumes have been assumed; 15 km^3 by Heim [6], up to 13 km^3 by Abele [1] and 12 km^3 by Pollet [13]. Its long history of investigations was summarised by Poschinger et al. [16]. Although the huge dimensions impede its study, the deep level of erosion by the Vorderrhein and the Rabiusa rivers has revealed many good outcrops enabling quite easy access and making this site one of the most important for the study of large rockslides. Furthermore, it has not seen important changes in its morphology; Blumenthal [2] pointed out that the surface of the slide mass has been modified very little by erosion. Only along the Vorderrhein valley and its main tributaries has strong incision taken place. In almost all other places the landscape represents that of the early post event state. There was some settling of the freshly deposited masses, but due to its compact structure probably not more than some few meters. Only right along the linear erosion forms of the gorges have some funnel-shaped sinkholes formed. This excellent morphological preservation of the deposits gives many hints to its generation.

In recent years, new impetus has come into the study of the Flims rockslide [17]. Some studies were made for the subsurface investigation for a road tunnel, diverting traffic around the village of Flims. Furthermore, in the last few years several teams of Swiss, French and German scientists have revealed new aspects of the event [14–16, 18, 20]. One important aspect was the dating of the rockslide, thought to be late glacial until then [1, 6, 7, 10], to about 8,200–8,300 ^{14}C yr BP (uncalibrated) by the author [15, 16]. Early Holocene ages are also reported by [5, 8]. This means the slide occurred during a warm climate (Boreal) without any direct glacial influence as a trigger.

A. von Poschinger (✉)
Bavarian Environment Agency, D-80696 München, Germany
e-mail: Andreas.Poschinger@lfu.bayern.de

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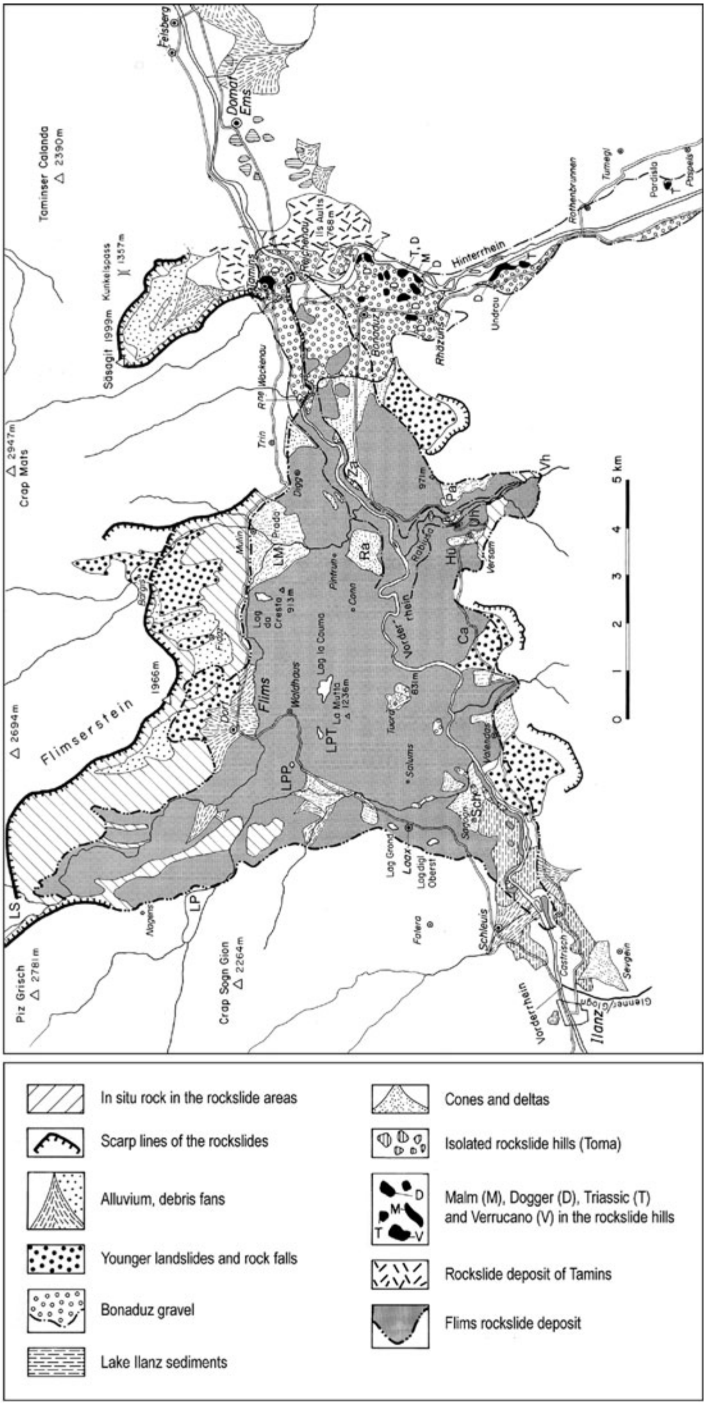
Flimserstein
Flims
Vorderrhein
Hinterrhein
Ilanz
5 km
In situ rock in the rockslide areas
Scarp lines of the rockslides
Alluvium, debris fans
Younger landslides and rock falls
Bonaduz gravel
Lake Ilanz sediments
Cones and deltas
Isolated rockslide hills (Toma)
Malm (M), Dogger (D), Triassic (T) and Verrucano (V) in the rockslide hills
Rockslide deposit of Tamins
Flims rockslide deposit

2 The Rockslide and Its Lakes

2.1 The Rockslide Event

It must be assumed that the rockslide happened "in one great stroke", as already ascertained by Heim [6]. The sedimentary layering of the Jurassic and Cretaceous limestone is parallel to the slope and dipping southward at an angle of about 25–35°. The whole Flimserstein mountain, the source area of the rockslide, is not built up by a simple sequence of strata, but is tectonically shaped by several parallel folds and imbricate thrusts [10]. Within this, the general main structure is striking parallel to the slope. The limestone beds near the sliding surface are separated by fine synsedimentary clay-rich layers, assumed to be responsible for the slope failure. The whole sediment sequence has suffered very low-grade metamorphism.

During the slide event, the moving rock mass did not spread out far to both sides, but kept together its main body. So the movement was "en bloc" and not turbulent or flow-like. Accordingly, the term "sturzstrom", implying according to Heim [7] a flow structure, cannot be applied. Due to the en bloc movement the primary rock structure is still preserved in many places. Nevertheless, the rock is entirely crushed. The degree of fracturing differs from place to place.

The undulating form of the slide surface must have caused a first destruction of the rigid limestone block during the motion. Also the existence of steps, higher than 50 m, within the slide surface must have been responsible for further internal destruction of the sliding mass. The maximum deformation however happened during the impact of the rock mass with the opposite slope, a fact that recently has been described by Pollet [13]. Hence, the resulting facies differs according to the local stress situation attained during the event.

In many places a small-scale three-dimensional jigsaw has been produced, still preserving the original structure (Fig. 15.2). This general structure is cross-cut, more or less densely, by deformation planes and zones. Along these zones the limestone has been crushed to fine gouge. In some places these planes are sub-parallel to the former sedimentary layering as indicated by Pollet [13]. It seems that even more important are ramp-like deformation planes, cross-cutting the bedding and mostly dipping northward.

Only the upper portions of the rockslide mass show the typical facies of a rockslide, i.e. a chaotic blocky material with finer grained matrix and with reduced compactness. Pollet [13] and Wassmer et al. [20] called it "granular facies". This facies is attributed to the lack of confinement of the material and by the

Fig. 15.1 Site map (previous page) and legend. In the map the following sites are indicated by letters: Ca, Carnifels; Hü, Hüschera; Pa, Parstogn; Ra, Ransun; Sch, Schiedberg; Uh, Unterhof; Vh, Vorderhof; Za, Zault. The lakes are: LM, Lag Mulin; LP, Lag Plaun; LPP, Lag Prau Pulta; LPT, Lag Prau Tuleritg; LS, Lag Segnes Sut

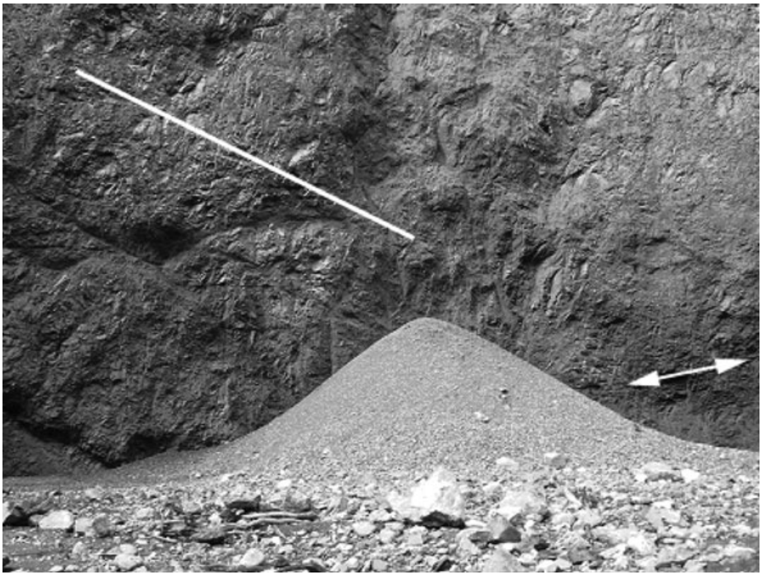

Fig. 15.2 Rockslide material in "three-dimensional jigsaw-facies" in the Rabiusa gorge. The direction of movement was from *right* to *left*. At the *right* margin sub-horizontal former bedding is visible (parallel to the *white arrow*). Important deformation plains cross-cut it and follows upward ramps (*white line*)

disintegration of the top of the sliding mass. Also an effect of relaxation following the preceding shock wave is probable. The thickness of this facies is quite variable; in the outcrops in the frontal part it rarely exceeds 10 m.

The coarse grained facies is clearly distinguished from the compacted, dense rockslide masses and especially from the "jigsaw-facies". The latter shows a broad spectrum of the degree of crushing with all transitions.

With few exceptions the slide mass has not been cemented and so cannot strictly be called a "breccia". The rare exceptions are either matrix-supported breccias or grain-supported breccias. Real matrix-supported breccias occur within the internal shear zones. Rockslide fragments up to some centimetres are embedded within the finest detrital rockslide material. They are to be found mainly at the front and at the bottom of the slide mass. Grain-supported breccias are found on top of the slide mass. They can be rather coarse and not only include rockslide components, but sometimes also fluvial well-rounded pebbles. Their cementation is due to post-event processes.

The upper coarse grained facies has very high permeability and due to its high content of unconsolidated fines, it is easy to erode on the surface, as well as by subsurface erosion in the underground. More complicated is the estimation of the stability of the "jigsaw-facies". In any degree of fracturing it is completely dissected by dense joints. The permeability of this facies may be restricted by two facts. First, the gouge along the deformation planes is very fine and may act as an aquitard. Secondly, the particles have a close "grain to grain" contact with exactly fitting boundaries, deposited under pressure. So, the space between the particles is restricted. Nevertheless, under water pressure, the jigsaw-facies is, due to its high degree of fracturing, quite permeable. But it is very important, as also pointed out by Davies and McSaveney [4], that the special structure impedes significant internal erosion. This material is not easy to erode and especially for subsurface water there is almost no possibility to transport significant amounts of solids.

2.2 The Lakes

2.2.1 Lake Ilanz

The Flims rockslide dammed two large lakes and several small lateral ponds [9]. The biggest lake was that of Ilanz. The maximum level of that lake is a crucial point of discussion. A level of about 820 m a.s.l. is demonstrated by lake sediments (Fig. 15.3), morphological traces and by delta sediments (Fig. 15.4). This evidence marks the level at which the lake existed for some time. As the floodplain sediments also reach to that level, a first breach must have affected a higher level and the lake must have been dammed at that higher level for only a short time without leaving any clear traces. The exact position of that maximum lake level has not been established

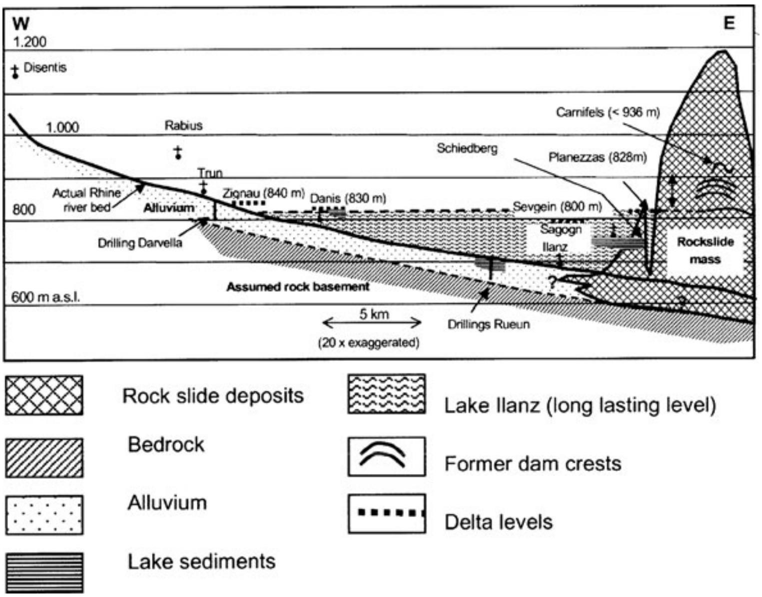

Fig. 15.3 Section along Lake Ilanz. The distribution of rockslide material under the Rhine river bed is assumed only. The maximum lake level did not exceed the Carnifels pass at 936 m a.s.l. and probably reached 870 to 900 m only. The attribution of the Zignau delta to Lake Ilanz is in doubt

Fig. 15.4 Sediments of Lake Ilanz near Schiedberg. The clearly and regularly layered silts and sands show a horizontal bedding surface. The origin of the bedding might have been seasonal changes, but, also, repeated single heavy rain events

and can only be assumed. It is evident that it was significantly higher than 820 m a.s.l., because the large flood plain must have been created by a large amount of water. It also obvious that the lake level did not exceed 936 m a.s.l. At that elevation, a morphological depression on the right bank near Carnifels – Erlacresta (Figs. 15.1 and 15.5) shows clearly that no important overflow has ever taken place. So, the

Fig. 15.5 Delta sediments of the Laaxerbach at Planezzas south of Laax with topset and foreset beds. The top of the foreset beds has an elevation of about 820 m

maximum lake level was somewhere between 820 and 936 m a.s.l. with a higher probability in the range of 850–920 m. For levels lower than 850 m probably the amount of water to be released was too small to create the large flood plain. As the lake surface approached the level of 936 m the risk of seepage and a breach in that area increased. As no signs of such processes are visible, the level probably did not get close to the level of 936 m.

Between 820 and 936 m a.s.l. along the flanks of the slopes only indistinct traces can be found, but cannot be attributed without doubt to either the Lake Ilanz phase or to earlier, late glacial processes. The lack of any clear morphological hints or of sediments higher than 820 m indicates that the first breach occurred very soon after the rockslide event, probably in connection with the first overtopping.

The filling of the lake up to 820 m, considering the figures for the current mean discharge of the Vorderrhein and the rough volume taken from the 1:25,000 topographic map is calculated to take about 13 months [16]. For a further filling up to 870 or even to 920 m, neglecting seepage and in contrast to older estimates indicated by Poschinger et al. [16], a filling time of 2–3 years can be assumed.

The dimensions for Lake Ilanz for the different levels can be roughly estimated from the 1:25,000 topographic map. At the level of 820 m it had a length of about 23 km and a volume of about 1.5 km^3. Assuming a level of 870 m the length is 25 km. At 900 m a.s.l., the length is 27 km and the volume about 2.8 km^3. The surface area of the lake varies with the different water levels between 24 and 33 km^2. These rough figures are to be checked by DTM/GIS calculations in the near future.

In the literature there has been much speculation about the persistence of Lake Ilanz and especially about its break out. The typical lake sediments beneath the present Vorderrhein river-bed near Rueun, about 5 km west of Ilanz that are right in the centre of the Lake Ilanz basin, have a thickness of about 20 m. But also on the shoulders of the valley, near the documented lake level of about 820 m a.s.l., important outcrops of lake sediments are preserved. One site, with about 18 m of well-bedded lake sediments, is located near the Schiedberg ruin, south of the village of Sagogn (Figs. 15.1, 15.3 and 15.5). The layering is almost horizontal and indicates that these sediments are not only lateral remnants of a partial filling, but that the basin was perhaps even completely filled by those sediments.

Thus, the lake must have persisted at this level for many years. The origin of the varve-like layers is not clear. It may be due to yearly seasonal changes but it also can be due to episodic sediment inputs following heavy rainfall events in the catchment. Taking a mean thickness of each layer of about 2 cm, the sequence at Schiedberg consists of about 900 layers. This may indicate a duration of about 900 years. Even in the case of rainfall induced layers it suggests a period of sedimentation of several hundreds of years. And these figures refer only to the 18 m of sedimentation at Schiedberg, not for the probable filling of the whole lake, comprising more than 100 m.

Taking the large volume of the basin filled by sediments, a time span of 1,000 or more years is reasonable. As already mentioned above, these sediments are the only evidence of the longer lasting lake level at 820 m. An important flood after a breach at a higher level is documented by the morphology of the flood plain, described later on.

2.2.2 Lake Versam

Lake Versam and Lake Ilanz were dammed by the same event but filled and drained independently. The smaller Lake Versam was dammed to a level of about 870–880 m a.s.l. and had a length of about 5 km (Fig. 15.6). The steep gradient of the Rabiusa river and the steepness of its slopes are responsible for the comparatively small volume of the basin. As the Rabiusa valley has been strongly eroded, no assumption about the previous volume of the basin is possible. Lake sediments are found near Versam-Unterhof (Fig. 15.1) at an elevation of 860 m and at Parstogn at 870 m a.s.l. On the right bank a slightly inclined shoulder is visible, climbing southward up to about 900 m near Vorderhof. This shoulder is interpreted to be the former delta level. Furthermore, well-bedded laminated silty lake sediments that can be attributed to Lake Versam are found at the footpath from Parstogn down to the Rabiusa bridge at 850 m a.s.l. The lake level did not exceed the elevation of 908 m, because the morphological pass leading to the depression of Hüschera (Fig. 15.1) did not experience any major discharge. According to the gravel and sand layers found at Parstogn, Lake Versam was filled up completely with sediments before the incision of the gorge started.

2.2.3 Small Lakes

Several small lakes were created due to lateral damming by the rockslide mass (Fig. 15.1). Lac Grond and Lac digl Oberst still exist, Lac Plaun, Lac Segnes Sut and Lac Mulin have since been filled up with sediments. The basin of Hüschera near Versam was drained through the permeable rockslide mass and was not filled by

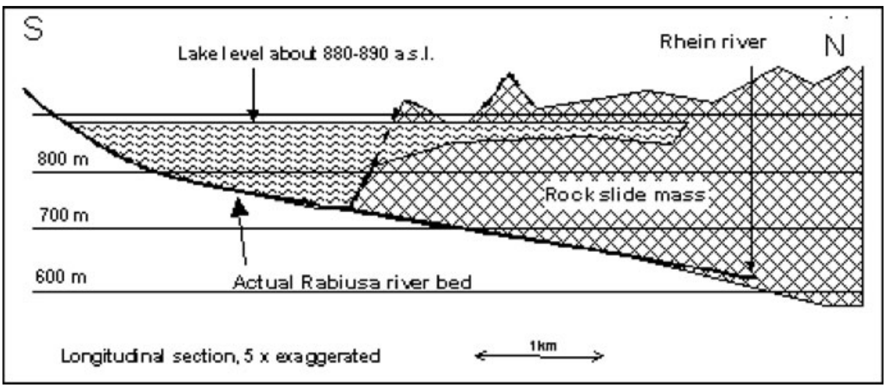

Fig. 15.6 Section along Lake Versam. The steep gradient of the Rabiusa river and the narrow valley are responsible for a relatively small basin

water immediately after the rockslide event. Due to subsequent debris flows of fine-grained sediments from the neighbouring Bündnerschiefer slopes, the basin became less permeable and then for a certain time bonded a small lake [16].

Also on top of the rockslide mass some lakes were created (Fig. 15.1). Lac Prau Pulta, Lag Prau Tuleritg, Lag la Cauma and Lag la Cresta are lakes or ponds with a very sophisticated hydrology. Analysis of the lake sediments in those lakes by Deplazes et al. [5] showed a younger age that did not contradict the radiocarbon dating of the rockslide mentioned above.

2.3 Reconstruction of the Events

2.3.1 Outbreak of Lake Ilanz

Several earlier authors [e.g. 16] assumed a complete and instantaneous break of the Ilanz dam with catastrophic circumstances. All refer to the huge inclined eroded floodway, stretching over more than 6 km from Ransun to Zault (Fig. 15.7), further on to Reichenau, and finally disappearing under younger sediments at Domat-Ems. The surface of the floodway has a strikingly constant inclination of about 2–2.5° (4%). Only the uppermost part at Ransun is flatter, indicating that in that part erosion of the barrier was prevalent. The floodway spread out laterally up to more than 1 km. The volume of the debris eroded is hard to estimate, because its thickness is only known in few outcrops and borings. Very roughly it is assumed to be about $30–50 \times 10^6$ m^3.

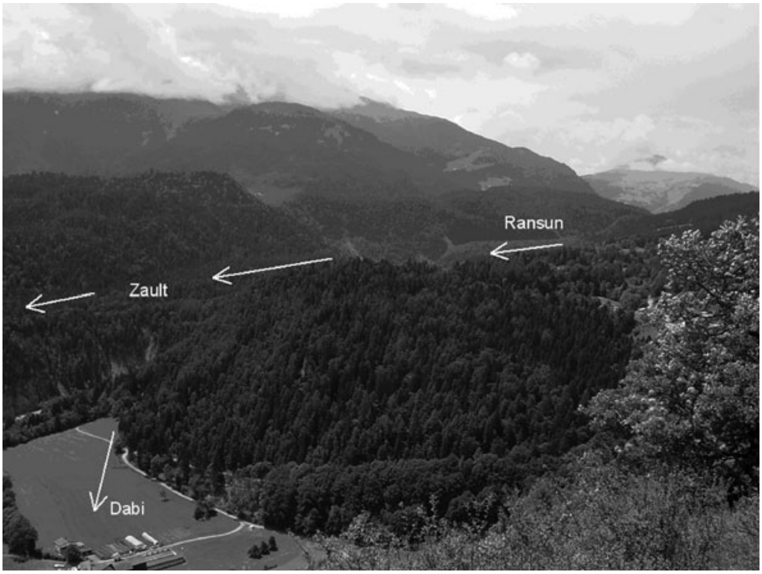

Fig. 15.7 View from Trin towards SW over the rockslide deposits (forested hills in the centre) to the Ilanz floodway (*arrows*) of Ransun (Ra), Zault and Dabi (see Fig. 15.1)

Fig. 15.8 Sediments of the Ilanz outbreak flood at Zault showing clear layering. The fragments consist of angular rockslide material (limestone). In some layers the particles have the size of coarse gravel, in some they consist of sand or even silt only. Around the single large block no disturbance of the bedding is apparent

In several erosion gullies the vertical structure of the flood deposits is well exposed (Fig. 15.8). The rockslide deposits are covered by gravel sediments that have been bulldozed by the rockslide from their former situation in the valley floor to an elevated position [14, 15, 16]. Accordingly, they are part of the rockslide event, forming together with the rockslide debris an undulating surface. This relief was filled up by outbreak sediments. NW of Zault the sedimentation of the flood starts with a typical debris flow deposit, dominated by coarse, slightly rounded blocks. These blocks are concentrated in several layers, separated by finer material. This blocky sediment is about 15 m in thickness. Above it, gradually finer sediments (medium gravel size) occur, showing a layering (Fig. 15.8). The sequence of the layered gravel attains about 10 m in thickness, each single layer about 5–15 cm. All constituents are angular fragments of the rockslide. Some layers contain only sand or even silt. At first sight, the layered gravel indicates a low energy environment. However, single large blocks within these layers (Fig. 15.8) led to questions of origin. Manville (personal communication, 2004) has suggested that, a “hyperconcentrated flow”, as described in Pierson and Costa [12], might be the origin for this sediment. A giant flood as assumed to have happened could have induced such a process of transport. Its deposition was the last phase of the flood event. The layered gravel beds with few boulders are parallel to the surface of the inclined floodway. After this sedimentation, the floodway was incised by fluvial erosion.

As no clear evidence for the maximum lake level (> 820 m) can be found, it must be assumed not to have existed for a very long time. Probably the first overtopping was responsible for the break. This might explain the observations of Wessels [21] in the sediments of Lake Constance, 80 km from Flims downstream in the Rhine river. He found two anomalies in the regular layering of the sediments, separated by several layers of normal sedimentation. Schneider et al. [19] attribute these anomalies to the outbreak of Lake Tamins/Bonaduz (first anomaly) and Lake Ilanz (second anomaly). According to the findings reported above it is more realistic to link these two layers to the Flims rockslide with the generation of the Bonaduz gravel (first anomaly) and to the outbreak of Lake Ilanz (second anomaly). They could also can have been generated by subaquatical slides, e.g. induced by earthquakes.

Uncertainty also prevails about the structure of the former rockslide barrier. Probably the break started in the surficial coarse upper facies. It must be assumed that subsurface erosion as a consequence of heavy seepage within this facies played an important role in the first failure. The main part of the dam was built up by the dense three-dimensional jigsaw facies that is evidently more resistant. Erosion also has cut into this facies, but with the breach duration getting longer and longer, and discharge reducing with the lowering lake surface, the breaching must have come to a stop.

Obviously the remaining barrier was stable until the remaining basin was filled, at least to a great part, with sediments. From then, the sediment load at the barrier increased and erosion became more active again. The further downcutting of the gorge from 820 m to the Vorderrhein level of 610 m, an additional 210 m, has not produced any important flood sediments. This indicates that it progressed slowly. The terraces observed indicate that the erosion happened in several steps. Abele [1] differentiated only three different levels of terraces. My own field investigations showed that at least 5 levels can be mapped.

2.3.2 The Flims/Tamins Relation

The Flims rockslide is closely related to its neighbour, the Tamins rockslide (Fig. 15.9). With a volume indicated by Abele [1] of "only" about 1–1.6 km^3 it always stood in the shadow of its big brother, the Flims slide. The interpretation of the succession of the events is important for the understanding of the mechanisms. Unfortunately, there is until now no radiocarbon dating for the Tamins slide. Preliminary results of recent surface exposure dating on ^{36}Cl done by Ivy-Ochs (personal communication) indicate an age close to that of Flims. The range would be less than $\pm$ 1,000 years.

Several observations favour the assumption that the Tamins slide is older than the Flims event (Fig. 15.10):

(a) The Bonaduz gravels, a very special sediment assumed to have been formed by fluidisation by the impact of a great Fims rockslide onto the alluvium [e.g. 11, 15], have straight contact to the Tamins deposits. The surface of the Tamins

Fig. 15.9 The Tamins rockslide deposits, seen from the Toma hills of Domat-Ems (looking towards West). The slide mass forms a straight barrier across the Rhine valley. A distinct breach (*white line*), caused by the outbreak of Lake Bonaduz, was partly filled later by the outbreak sediments of Lake Ilanz. The inclined flood plain in the centre of the photo has a direct extension to that of Zault. Within the breach in the background the Flims deposits are visible

rockslide block masses shows about 10–20 cm of a well-cemented breccia. This hard crust is smoothened, polished and deeply scratched. Even if this surface is similar to a glacial-polished one, and it has been interpreted as such by some authors [e.g. 16], the direction of the surface gouges is inconsistent with a glacial origin. Furthermore no other glacial influence is evident. Instead, a polishing by the fluidized Bonaduz gravel during its transport is possible.

The contact between the Flims deposits and the Bonaduz graves is not sharp. In many places the rockslide masses and the gravel are mixed and interfingered. So, obviously the Bonaduz gravel were mobilized by the Flims masses and hit against the already existing Tamins deposits.

(b) The Bonaduz gravels are almost only found upstream of the Tamins rockslide barrier and far up the Hinterrhein valley (Fig. 15.1). If they were generated by the Tamins slide they should be found downstream as well. In the case of generation by the Flims slide, an already existing barrier at Tamins would have been the perfect barrier responsible for diversion of the debris up the Hinterrhein valley (Figs. 15.1 and 15.10/3).

(c) The flood sediments of the outbreak of Lake Ilanz are incised into the Bonaduz gravel. Accordingly, the flood event is younger than the Bonaduz gravel (Fig. 15.10/5).

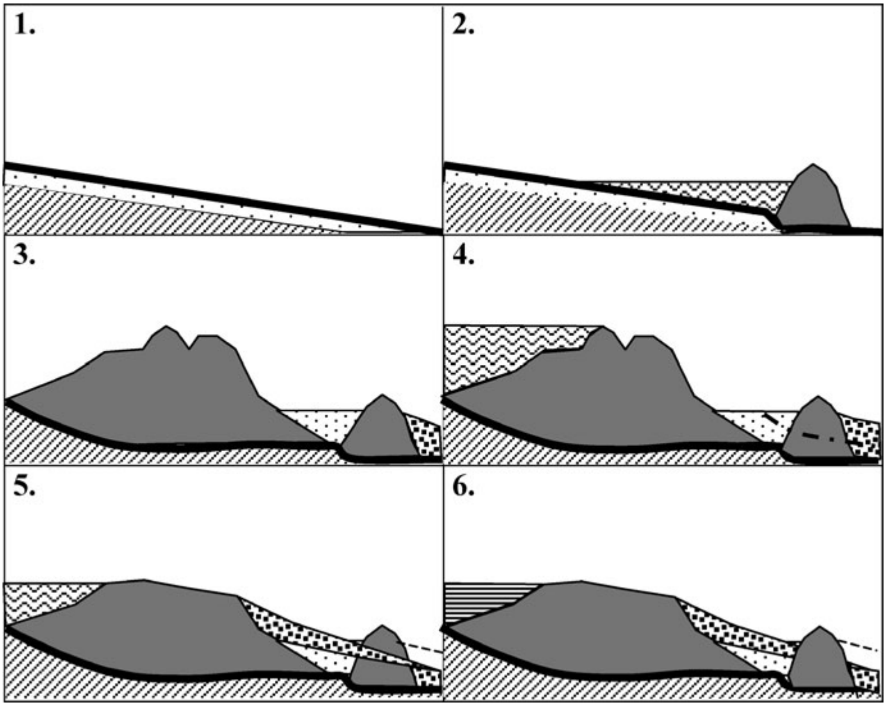

Fig. 15.10 Sketch of the development of the Flims site: 1. Original state of the Vorderrhein river with alluvial sediments; 2. Deposition of the Tamins rockslide and damming of lake Bonaduz; 3. Deposition of Flims rockslide and mobilisation of alluvial sediments (= Bonaduz gravel), drainage of Lake Bonaduz with flood sediments downstream of the Tamins deposits; 4. Partial or even complete filling of Lake Ilanz, erosion in Tamins deposits; 5. Break of Flims barrier down to 820 m, flood sediments crossing the breach in Tamins deposits; 6. Filling of Lake Ilanz with sediments before further erosion to the present river bed

(d) The astonishingly straight and evenly inclined floodway of the Flims dam crosses the Tamins barrier without any disturbance. This indicates that not only the Tamins barrier existed during the flood event, but also the breach in it (Fig. 15.9). Lake Bonaduz, dammed by the Tamins barrier, had already drained through this breach. Remnants of a second flood sediment are to be found in an erosional terrace at the village of Felsberg-Altdorf (Figs. 15.1 and 15.10/3). They have a clearly higher elevated position with respect to the Flims flood sediments and have no extension upstream of the Tamins barrier. So, they are attributed by the author to the Tamins breach event.

All of these observations are an indication for an older age for the Tamins rockslide in relation to the Flims event.

3 Conclusions

Even if many of the observations mentioned above still have to be verified by further investigations, some general conclusions are possible. The Flims rockslide dam had favourable conditions for its stability. The length of the barrier (in downstream flow direction) favours a low hydrologic gradient. The jigsaw structure of some of the debris is relatively stable and prevents subsurface erosion. Nevertheless, the rockslide was followed by an important flood event. The lake level went down by probably less than 100 m, for only about 20–30% of its total height. However, the volume of water, released by the breach, in excess of 1 km^3 was responsible for a catastrophic flood wave that travelled 80 km downstream to Lake Constance.

The example of the Flims rockslide shows that not only the total breach of the rockslide dam may cause great flood disasters. Looking also to other rockslides in the Alps it is obviously not the exception to have a first breaching of the topmost part of the dam. Also the Köfels rockslide has experienced a similar history [3]. Abele [1] enumerates several others (e.g. Col de la Madeleine, Ehrwald, Totalp and In der Wöhr). All dam engineers are aware that due to the often exponentially increasing surface of the lake, the topmost meters of a reservoir have the highest hydrologic and so also economic potential. In the same way, in the case of a break of a natural dam, they have the highest catastrophic potential. Accordingly, measures to prevent an overtopping, and to reduce the lake level for only few meters, might increase the stability of rockslide dams significantly, and decrease the corresponding hazard.

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