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Discussions

Geophysical evidence of consecutive evolution of Tamins rockslide and lake formation, Flims rockslide, and Bonaduz push wave gravels with embedded Toma hills

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Abstract. Rockslides and rock avalanches are amongst the most destructive natural hazards in the alpine environment. The Flims rockslide is the largest known rock-slope failure in the Alps, which provides excellent outcrops and has fascinated researchers since the early 20th century. The postulated impact of the Flims rockslide on (Paleo-) Lake Bonaduz caused intensely fluidized rock material, which formed the so-called Bonaduz Gravel and Toma hills, probably accompanied by a catastrophic impact wave. So far, this hypothesized sequence of events is based only on sedimentological and geomorphic analyses. We present electrical resistivity tomography (ERT) profiles which we correlated with the sedimentological information obtained from dill logs. Our study provides new insights into the distribution, thickness, and internal structure of the Bonaduz Gravel, the Toma and Cresta hills, as well as other flood deposits around the Ils Aults where we studied the sediment to a depth of up to 160 m. There is new field evidence that the Bonaduz Gravel formed an onlap onto the Ils Aults and is thus the stratigraphically younger unit. The Toma/Cresta hills consist of blocky cores with an agglomeration of smaller mixed sediments, which drift and override the Toma/Cresta core, causing their smoothly shaped top. We consider simultaneous transport of the Cresta within the Bonaduz Gravel, yet a slightly slower movement at the front due to a bulldozing effect. This study contributes to an improved understanding of i) the complex stratigraphical context of the Tamins and Flims deposits, ii) water-rich entrainment in rock avalanches, and iii) the genesis and transport of outburst-flood deposits, in particular of Toma hills.

1 Introduction

The Flims rockslide deposit is located in the Vorderrhein River valley, Eastern Switzerland. With its deposits comprising a volume of 10-12 km³ and covering an area of ~52 km² (Heim, 1932; Abele, 1974; Poschinger, 2006), the Flims rockslide is the largest known Alpine rock-slope failure. Along a major thrust fault, the U-shaped W-E directed Rhine valley tectonically separates the Triassic to Cretaceous sedimentary rocks of the Helvetic nappes to the north from metasedimentary rocks of the Penninic nappes to the south (Pfiffner et al., 2002). The Flims rockslide detached from the northern valley flank (Figure 1) and mainly comprises Jurassic limestone from the Quinten-Kalk formation. The rockslide partially transformed into a rock avalanche during its descent, which increased its runout distance (Pollet and Schneider, 2004; Schneider et al., 2004; Aaron et al., 2020). In the following, we simply refer to the Flims rock-slope failure as a rockslide. The deposits had originally been thought to be of a lateglacial age. Based on radiocarbon and cosmogenic nuclide dating, however, the Flims rockslide was dated to a mean age of ~9000 yrs cal BP (Poschinger and Haas, 1997; Schneider et al., 2004; Deplazes et al., 2007; Ivy-Ochs et al., 2009).

The stratigraphical relationship to the neighbouring Tamins rockslide, however, is still a matter of debate. The local stratigraphy and morphology provide evidence that the Tamins rockslide had dammed a paleolake, Lake Bonaduz, which the Flims rockslide presumably impacted (Poschinger et al., 2006; Calhoun and Clague, 2018; Poschinger and Kippel, 2009; Calhoun et al., 2015). Upon impact into Lake Bonaduz and into the sedimentary valley fill (Scheller, 1970; Calhoun and Clague, 2018), the Flims rockslide brought a volume of several 100 mio. m³ of sediment into suspension, evoked by the immense energy input of a push wave. The resulting hyperconcentrated mass flow (Calhoun and Clague, 2018) transported slabs of the impacting rock mass on top and was deposited as Bonaduz Gravel, a characteristic graded but unstratified sediment (Figure 2) that forms a plain between the Flims and Tamins rockslide deposits (Fig. 1; Poschinger et al., 2006; Poschinger and Kippel, 2009; Poschinger and Ruegg, 2012; Pavoni, 1968). Embedded in this plain, the rock slabs were deposited as Toma, i.e. isolated cone- to pyramid- or roof-shaped hills composed of Helvetic bedrock material (Abele, 1974).

In the European Alps, Toma are also known from the rock avalanches at Tschirgant (Dufresne et al., 2016), Eibsee (Ostermann and Prager, 2016), Fernpass (Prager et al., 2006), and Obernberg valley (Ostermann et al., 2012). Deciphering the internal structure of the Toma/Cresta and of the Bonaduz Gravel is assumed a key to understanding the complex emplacement of rock-avalanche material after water-rich entrainment (Poschinger et al., 2006).

The present study addresses the following aspects and brings them in a chronological order of 4 phases: (i) geological events related to the Flims and Tamins rockslides (Phase 1 and 2), (ii) the evolution of the above described characteristic landforms of the Toma/Cresta and the deposit of the Bonaduz Gravel (Phase 3), and (iii) the formation of outburst-flood deposits after rockslide-dam failure (Phase 4). With geoelectrical measurements and data from outcrops as well as publicly available drill logs, we provide insights into the Toma and Bonaduz Gravel up to ~160 m depth, and give a more detailed view on the stratigraphic relationships around the Tamins and Flims rockslide deposits.

2 Methods

Five ERT surveys were conducted in the area around the Tamins rockslide deposit (Fig. 1). We investigated the Bonaduz plain, its contact to the Ils Aults, and two Toma hills – one to the West of Ils Aults (Cresta Bot Dagatg) and one to the East of Ils Aults (Tuma Padrusa). For the ERT measurements, an ABEM SAS 1000 Terrameter and four 100-m and four 200-m-long electric cables with an electrode spacing of 5 m and 10 m, respectively, were used. Roll alongs, the stepwise allocation of cables from the back to the front of a transect, allowed an increased penetration depth over an extended distance covered with one individual transect (e.g. Profile P1 in Figure 3a with one roll along yielding 1000 m profile length). A combination of

Wenner and Schlumberger arrays was chosen to determine both vertical and horizontal resistivity changes. The local topography along the profiles was measured with an inclinometer. The sub-surface resistivity was modeled with RES2Dinv (ver. 3.5) and the determined topography was included in the models. The results were then interpreted based on our field observations in outcrops of the Toma and Bonaduz Gravel close to the profiles. Furthermore, we correlated the ERT models with sedimentological data from drill logs (Kanton Graubünden, 2022). These logs provide basic sedimentological information and interpretations. We reevaluated these drilling results considering the findings in the ERT surveys and in the light of the most recent hypotheses about the Flims and Tamins rockslides. Eventually, we combined 11 drill logs and the four ERT profiles into a schematic cross-sectional overview of the local stratigraphy around the Tamins rockslide deposit (Fig. 4).

3 Results and Interpretation

Profile P1 (Figure 3a) shows a NW-SE oriented transect modelled from two surveys. One survey was conducted in a 500 m five-cable roll along with 5 m electrode spacing, the second survey was conducted in an 800 m long four-cable survey with 10 m electrode spacing. The resistivity data of both transects were combined in order to provide a high spatial resolution in the upper 50-80 m below the surface and a high penetration depth of up to ~160 m. The overall error of the resulting model is 4.9 %. The similarity in the MinMax-models displays this small model variance well (Fig. S1). It should be noted that a gas pipeline crosses perpendicular to the transect at meter 430 and unknown depth. Two main resistivity units can be distinguished. First, in the resistivity model mixed sediments are detected down to 50–60 m penetration depth, indicated in yellow and light blue colour. The sediments of this resistivity unit are well accessible in the gravel pit of Reichenau. A matrix-supported gravel unit with sandy to silty matrix is exposed in the pit. Overall, the unit is normally graded and unstratified, and partially covered by sand and silt beds (Fig. 2b,c). The Reichenau pit represents the type locality of the Bonaduz Gravel and here the unit is ~60 m thick. We interpret these mixed sediments in the acquired model as the Bonaduz Gravel, as the obtained resistivity and depth correlate well with the outcrop. In the middle of the transect, a crossing gas pipeline causes a model artefact. The resistivity patterns to both sides of the artefact appear to match and exemplify the onlap of the Bonaduz Gravel onto the rise of the Ils Aults that is visible at meter 400-450. The Ils Aults is regarded as part of the Tamins rockslide deposit (e.g. Calhoun and Clague, 2018) and is formed by coarse to blocky rock material, which causes the high resistivity values in the second unit, marked with red colour. A finer grained sediment cover on top of the Ils Aults is indicated by mid-range resistivity values in yellow colour.

The Cresta Bot Dagatg was investigated in two transects. Profile P2 (Figure 3b) was obtained from a W-E oriented transect across Bot Dagatg, which is the rise between meter 740 and 840 with an elevation of 690 m a.s.l. The survey reaches a maximum penetration depth of ~160 m on a transect length of 1000 m. The overall error of the resistivity model is 4.9 % (MinMax models in Fig. S1). At meters 390 and 740, power supply lines cross perpendicular to the transect and cause artefacts. Profile P3 (Figure 3c) was obtained from a N-S oriented transect and shows a cross-cut section to Profile P2. This transect is 400 m long with a maximum penetration depth of ~60 m. The overall error of the resistivity model is 5.9 % and shows the highest uncertainties at locations with rapid changes in resistivity (Fig. S1). In both models, the transition from low resistivity values (blue) to high values (red) occurs within a narrow zone. This quick transition in resistivity indicates a distinct change in material composition. We interpret these transition zones to indicate a sharp contact between the blocky core material of the Cresta, and the surrounding Bonaduz Gravel as well as other sedimentary valley fill. In profile P2, the Bonaduz Gravel visibly laps onto the rise of Bot Dagatg from meter 240 to 320. We therefore suggest that the Cresta was transported within the finer-grained hyperconcentrated flow, as proposed by Calhoun and Clague (2018), and slightly overrun by the surrounding slurry after its halt, forming an onlap.

Profile P4 (Figure 3d) was obtained in a 300 m-long W-E oriented survey that crossed Tuma Padrusa. This survey reaches a maximum penetration depth of 60 m. The overall model error is 2.8 %. In the center of the Toma, coarse, blocky material is indicated by high resistivity values. The Toma is covered by a thin layer of mixed sediment, which seems to have overrun the coarse, coherent material in the center, similar to Bot Dagatg. The onlapping and overrunning material probably decelerated during the uphill movement and was partially deposited “on the ramp”. We interpret the narrow transition zone from high to low resistivity values at ~30-40 m penetration depth as the base of the Toma above preexisting sedimentary valley fill.

4 Discussion

The ERT surveys conducted in the present study elucidate the formation and the stratigraphic relation of the Bonaduz Gravel and the Cresta/Toma hills.

4.1 Characteristics of the Bonaduz Gravel and implications for the Tamins-Flims-Timeline

Based on the information obtained from the ERT survey displayed in Profile P1 (Fig. 3a), the Bonaduz Gravel has a mean thickness of ~ 50-70 m at its type locality around Bonaduz. This measurement correlates well with the earlier sedimentological and geomorphological analyses by Calhoun et al. (2015) yielding up to 75 m, and Calhoun and Clague (2018) stating a thickness of 65 m.

The ERT profile P1 (Fig. 3a) further show onlaps of the Bonaduz Gravel onto the Ils Aults deposits. In the stratigraphical context, this onlap implies that the Ils Aults, considered as Tamins deposit, must have been formed before the Bonaduz Gravel and further corroborate the hypotheses (Scheller, 1970; Abele, 1991; Poschinger et al., 2006) that (i) the Tamins rockslide occurred before the Flims rockslide, (ii) the Tamins deposits formed a dam and probably created Lake Bonaduz, and (iii) the Flims rockslide impacted Paleolake Bonaduz, thereby triggering a hyperconcentrated mass flow with gravel in suspension (Calhoun and Clague, 2018), known as Bonaduz Gravel.

4.2 Characteristics of the Cresta/Toma

The two investigated Toma hills Bot Dagatg and Tuma Padrusa, situated to the West and the East of Ils Aults, show more or less the same composition. Based on the model results presented in Profiles P2–4 (Figure 3b-d), we conclude that they most probably consist of large blocks of crushed and shattered rockslide material. This observation is consistent with the early results of Arbenz and Staub (1910) and Calhoun et al. (2015), who investigated outcrops on several Toma hills.

However, the surrounding sediment of these two Toma hills and the contacts therewith are different. The ERT models P2 and P3 (Fig. 3b,c) show that Bot Dagatg is framed by Bonaduz Gravel with an onlap on the southern flank. On the far side of the Tamins deposit, Tuma Padrusa is framed by less blocky, but still coarse-grained material. The surrounding sediment also shows onlaps, but clearly has a different composition compared to the Bonaduz Gravel on the western side of Ils Aults. Probably, Tuma Padrusa resides in remobilized rockslide material and admixed Bonaduz Gravel, a mixture that was formed during the failure of the dam that the Tamins deposit once formed (Calhoun and Clague, 2018). Both studied hills overlie the indiscernible and unaltered sedimentary valley fill at unknown depth (Fig. 4).

Furthermore, for Tuma Padrusa the ERT model indicates a mean thickness of ~30-40 m. Compared to an elevation difference of ~15m between the surrounding plain and the Toma surface in this section, the “root” of the Toma lies 2-3 times deeper.

4.4 Toma transport and stratigraphy

Concerning the formation and stratigraphical position of the Toma/Cresta hills, our results affirm the hypothesis of a simultaneous transport within a highly fluidized mass movement. As suggested by Poschinger and Kippel (2009) andCalhoun and Clague (2018), it is plausible that pieces of the Flims rockslide were transported by a hyperconcentrated flow (Bonaduz Gravel), which itself was caused by the rockslide. Our investigation showed that Bot Dagatg is mainly composed of an isolated rock slab that is embedded in and onlapped by the Bonaduz Gravel, which supports this theory of their synchronous formation and deposition. Likewise, the blocky core of Tuma Padrusa was most probably transported within the sediment that it is embedded in.

Similar observations of Toma transport within highly fluidized mass movements were reported from the Fernpass site (Prager et al., 2006) and analogue models (Paguican et al., 2014). Prager et al. (2006) interpreted the onlapping sediments as post-rockslide fluvial clasts. In the Flims context, we suggest a syn-depositional or late-depositional emplacement of the onlapping unit, clearly linked in time to the main event and the Bonaduz Gravel. We postulate that the coarse centre of a Toma/Cresta comes to stop first due to strong internal cohesive forces and resulting high friction to the surrounding sediment, so that the finer grained slurry can overtop in flow direction, forming an onlap. It is possible that the Toma core is slightly moved and maybe rotated during the overflow of and interaction with the finer sediment (Dufresne and Geertsema, 2020). Still, it remains unclear, whether the top deposits revealed in the outcrops and the ERT models could also have been deposited during later outburst floods of Lake Ilanz (Schneider et al., 2004; Poschinger et al., 2006).

4.4 Other Toma origin?

Concerning the Toma around Domat/Ems on the far side of Ils Aults, Calhoun and Clague (2018) hypothesize that these are pieces of the Tamins rockslide deposit, which was torn apart during a catastrophic dam breakage. Our ERT results of Tuma Padrusa (Fig. 3d) substantiate the possibility that the rock slab was transported eastwards, indicated by the onlap and the overrunning sediment coming from West. Unfortunately, the internal structure and content of the Toma/Cresta do not allow for a clear separation between Flims origin and remobilized Tamins material. But it is interesting to note that we observe very coarse rock material at the front and also in the back of the Toma. This fact might give a hint of a subsurficial connection to neighbouring Toma in the close vicinity, and would support the theory of the torn apart Tamins deposits, but here is need for more field research.

5 Conclusion

The onlap of the Bonaduz Gravel onto the Ils Aults constitutes novel field evidence in the debate about the timeline of geological events around Flims (Fig. 5). The following hypotheses are supported by this evidence: (i) the Tamins rockslide (Phase 1) occurred before the Flims rockslide (Phase 2), (ii) the Tamins deposits formed a dam and probably created Paleolake Bonaduz (Phase 1), and (iii) the Flims rockslide impacted Lake Bonaduz (Phase 2), thereby triggering a push wave and a hyperconcentrated mass flow with gravel in suspension. The Bonaduz gravel event layer between the Flims and Tamins deposits has an average thickness of ~50-70 m.

The stratigraphic position of the Toma/Cresta hills is related to the Flims rockslide (Phase 2) and the Bonaduz Gravel (Phase 3). Some of the hills could also be related to the previous Tamins rockslide (Phase 1). The internal structure shows a core of coherent, blocky rock material, embedded in a fragmented rock mass. During the transport, an agglomeration of mixed sediments with smaller grain size (gravel-sand-mixture) drifts and overrides the Toma core, building an onlap in flow direction and causes a smoothened surface. The Toma transport is regarded as simultaneous for the coherent rock slabs in the Toma core, whereas the onlapping and overriding slurry is assumed to be emplaced rather late-depositional, since the deep-rooted Toma core has already stopped due to internal cohesion and frictional forces opposing the movement. Afterwards, outburst-flood deposits covered parts of the Bonaduz plain (Phase 4).

This study provides other scientists with a better understanding of the complex history of sedimentation and erosion in the Flims area, and further contributes to the process understanding of sediment transport after water-rich entrainment in rock avalanches.

Author contribution

SK and MK designed the experiments and SK and MS carried them out. SK and MS performed the simulations. SK prepared the manuscript with contributions from all co-authors.

Competing interests

One of the (co-)authors is a member of the editorial board of Earth Surface Dynamics.

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Data availability

Additional ERT profiles (MinMax plots) are published as a supplementary Fig. S1 online along with the article.

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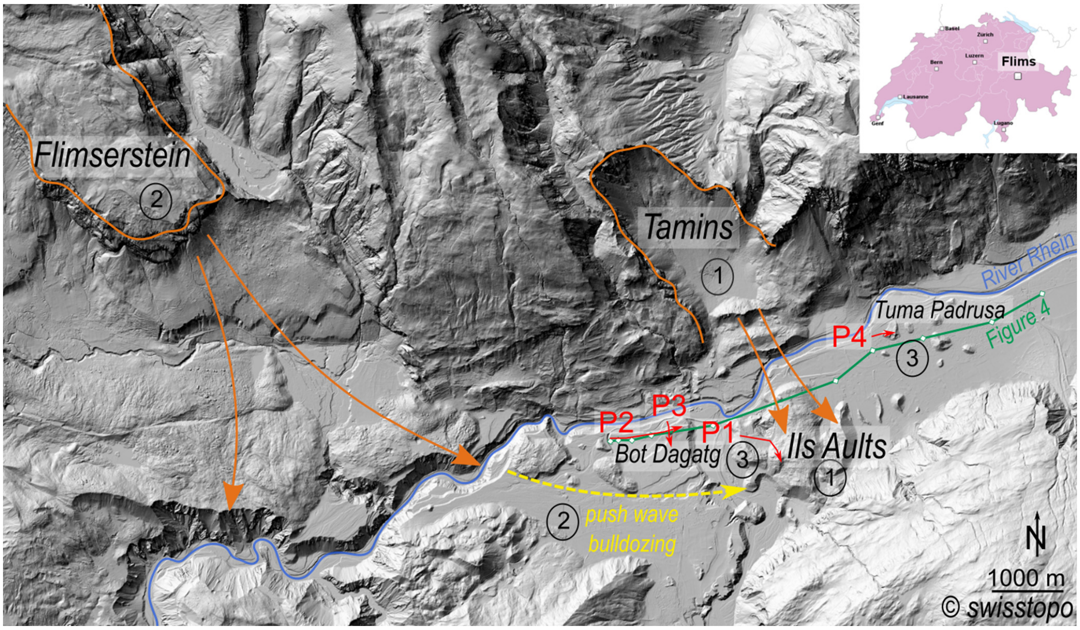

Figure 1: Overview of the Vorderrhein River valley depicting the Flimserstein, where the Flims rockslide detached from, the scarp of the Tamins rockslide, the Ils Aults consisting of Tamins deposits, and Cresta and Toma hills (e.g. Bot Dagatg and Tuma Padrusa). The ERT profiles P1-P4 are marked with red colour. The green profile links drilling sites (white markers) and is shown in Fig. 4. High-resolution DEM: © swisstopo.

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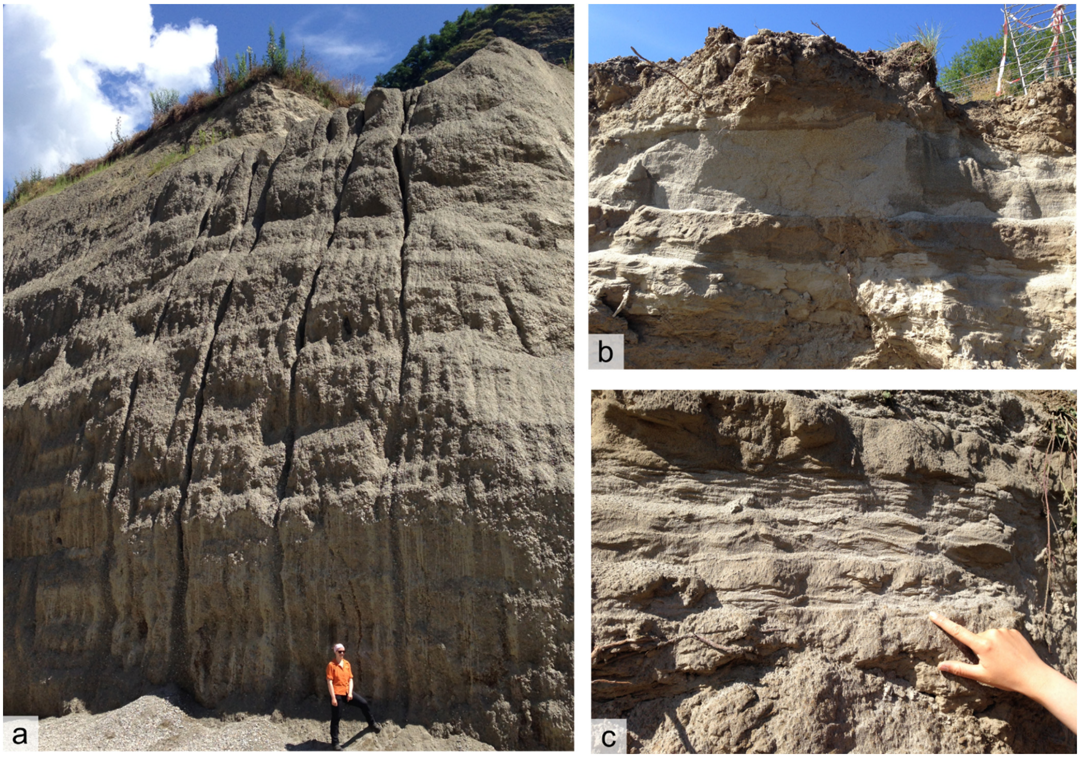
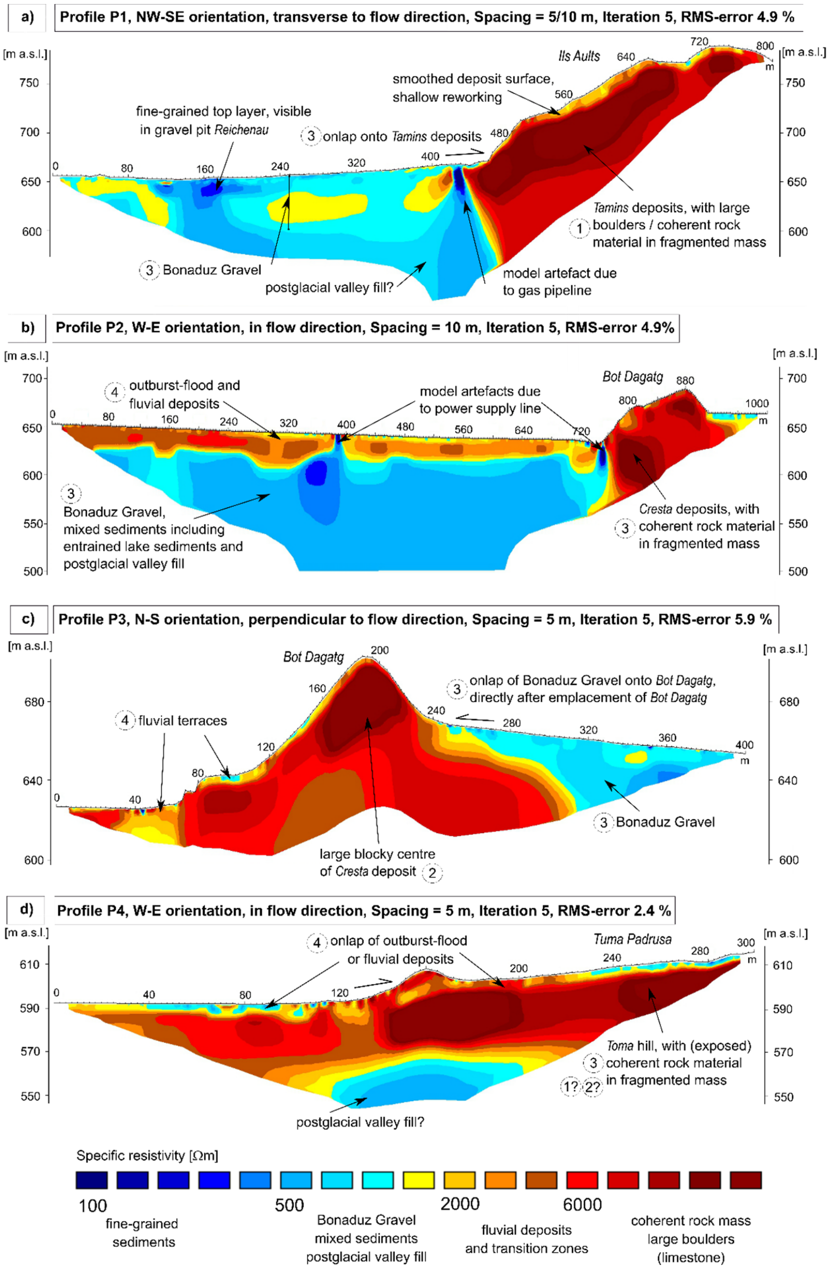


Figure 2: Outcrops of Bonaduz Gravel. a) Unstratified, normally graded gravel deposits with fine-grained matrix and vertical Pavoni pipes in gravel pit near Domleschg. b) and c) Stratified sands and silts at the top of the Bonaduz type locality at the gravel pit in Reichenau. Photo courtesy: M. Krautblatter.



a) Profile P1, NW-SE orientation, transverse to flow direction, Spacing = 5/10 m, Iteration 5, RMS-error 4.9 %

b) Profile P2, W-E orientation, in flow direction, Spacing = 10 m, Iteration 5, RMS-error 4.9%

c) Profile P3, N-S orientation, perpendicular to flow direction, Spacing = 5 m, Iteration 5, RMS-error 5.9 %

d) Profile P4, W-E orientation, in flow direction, Spacing = 5 m, Iteration 5, RMS-error 2.4 %

Figure 3: ERT profiles P1-P4 indicating a) ~60 m thick Bonaduz Gravel (Phase 3) onlapping onto Ils Aults (Phase 1), b) Cresta Bot Dagatg transported within Bonaduz Gravel (Phase 3), covered with some outburst-flood and/or fluvial deposits (Phase 4), c) onlapping Bonaduz Gravel onto the Cresta Bot Dagatg, and d) Tuma Padrusa containing large slabs of (exposed) coherent rock material in a fragmented rock mass.

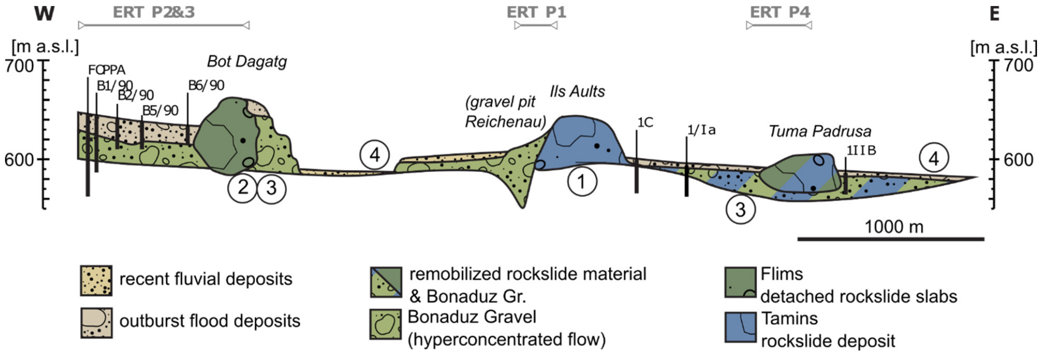


Figure 4: Schematic cross section derived from the presented ERT surveys (indicated in grey). Drilling data supported the interpretation to the depth.

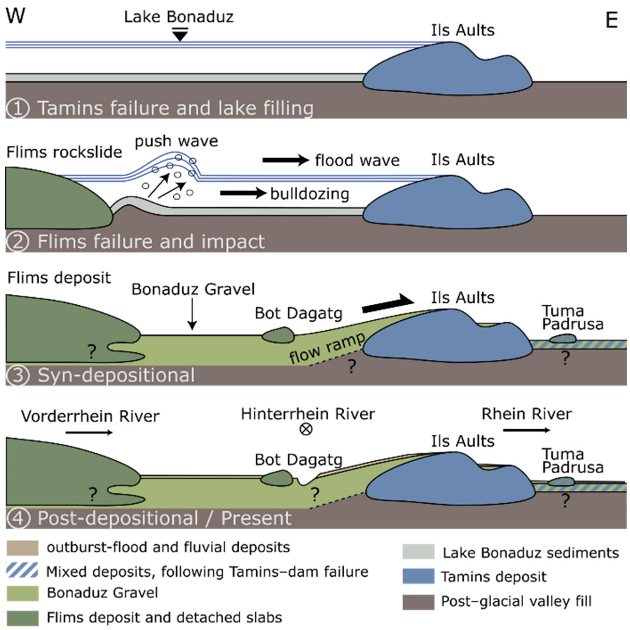


Figure 5: Timeline of geological events displaying the following hypotheses: Phase 1) Lake Bonaduz dammed by the Ils Aults after Tamins rockslide; Phase 2) push wave and bulldozing after impact of Flims rockslide; Phase 3) simultaneous formation of Bonaduz Gravel, transporting Cresta, and possibly also Toma hills; Phase 4) Outburst-flood and recent fluvial deposits partially cover the Bonaduz plain. Schematic sketch without scale.

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