Geophysical evidence of massive hyperconcentrated Bonaduz push waves with embedded Toma hills exerted by the Flims rockslide

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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 Lake Bonaduz caused intensely
10   fluidized rock material, which formed the Bonaduz Formation 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 outcrops and drill logs. Here, geophysical evidence on a meter and decameter scale complements prior outcrop and sample intervals with much smaller representativeness. Our study provides new insights into the distribution, thickness, and internal
15   structure of the Bonaduz Formation, and the Toma 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 geophysical evidence that the Bonaduz Formation formed an onlap onto the Ils Aults and is thus the stratigraphically younger unit. The Toma hills consist of blocky cores with an agglomeration of smaller mixed sediments, which drift and override the Toma core, causing their smoothly shaped top. We consider simultaneous transport of the Toma hills within the Bonaduz Formation, yet a slightly slower movement at the front due to a bulldozing
20   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 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
25   the largest known catastrophic 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 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

30   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 (Fig. 1), however, is still a matter of debate. The local

35   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; Poschinger and Kippel, 2009; Calhoun et al., 2015; Calhoun and Clague, 2018). 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 push waves. The resulting hyperconcentrated mass flow (Calhoun and Clague, 2018) transported slabs of the

40   impacting rock mass on top and was deposited as Bonaduz Formation (Wyss and Wiederkehr, 2017), a characteristic graded but unstratified sediment with rip-up clasts of silt- and sandstones and rock avalanche material (Fig. 2a-c) that forms a plain between the Flims and Tamins rockslide deposits (Fig. 1; Pavoni, 1968; Poschinger et al., 2006; Poschinger and Kippel, 2009; Poschinger and Ruegg, 2012). Embedded in this plain, the rock slabs were deposited as Toma (Fig. 1 and Fig. 2d-f), i.e. isolated cone- to pyramid- or roof-shaped hills composed of Helvetic bedrock material (Abele, 1974). Around the Ils Aults, there are

45   three different terms for these hills. According to Arbenz and Staub (1910), the long hills situated in the Bonaduz plain are called 'Cresta', whereas the round or cone-shaped hills containing rockslide material are called 'Toma' around Ems, and 'Put' around Bonaduz (see Fig. 1 for locations). Piperoff (1897) and Arbenz and Staub (1910) interpreted the caps on top of the hills initially as moraine deposits, but only few outcrops were known. Henceforth, we refer to all these morphologically variable hills as 'Toma'.

50   In the European Alps, Toma also occur at the rock avalanches at Fernpass (Prager et al., 2006), Almtal (Van Husen et al., 2007), Obernberg valley (Ostermann et al., 2012), Eibsee (Ostermann and Prager, 2016), and Lago di Braies (Ostermann et al., 2020). Deciphering the internal structure of the Toma and of the Bonaduz Formation 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

55   related to the Flims and Tamins rockslides (Phase 1 and 2), (ii) the evolution of the above described characteristic landforms of the Toma hills and the deposit of the Bonaduz Formation (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 Formation up to ~160 m depth, and give a more detailed view on the stratigraphic relationships around the Tamins and Flims rockslide deposits (Fig. 3).

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 (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 Fig. 4a 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 Formation 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. 5).

3 Results and Interpretation

Profile P1 (Fig. 4a) 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 (Fig. 1). 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 Formation and here the unit is ~60 m thick. We interpret these mixed sediments in the acquired model as the Bonaduz Formation, 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 geometry of a wedge. As such, this location is interpreted as the onlap of the Bonaduz Formation 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.

Bot Dagatg was investigated in two transects. Profile P2 (Fig. 4b) 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 (Fig. 4c) 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 Toma hill, and the surrounding Bonaduz Formation as well as other sedimentary valley fill. In profile P2, the Bonaduz Formation visibly laps onto the rise of Bot Dagatg from meter 240 to 320. We therefore suggest that the Toma hill 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 (Fig. 4d) 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 Formation and the Toma hills.

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

Based on the information obtained from the ERT survey displayed in Profile P1 (Fig. 4a), the Bonaduz Formation 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. 4a) further show onlaps of the Bonaduz Formation 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 Formation 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 Lake Bonaduz, thereby triggering a hyperconcentrated mass flow with gravel in suspension (Calhoun and Clague, 2018), known as Bonaduz Formation. Similar results of mobilized substratum and water-rich entrainment after a rockslide impacting a lake are shown by Knapp et al. (2021) at the Eibsee rock avalanche.

4.2 Characteristics of the Toma

The two investigated Toma hills Bot Dagatg and Tuma Padrusa, situated to the West and the East of Ils Aults, consist of limestone. Bot Dagatg is composed of Cretaceous limestone, Tuma Padrusa of Jurassic limestone (Quinten and Tros limestone). In the ERT profiles, they show more or less the same granular composition. Based on the model results presented in Profiles P2–4 (Fig. 4b-d), we conclude that they most probably consist of large blocks of crushed and shattered rockslide material with capping gravels and fines. These observations are consistent with earlier results of, e.g., Arbenz and Staub (1910), Nabholz (1975) and Calhoun et al. (2015; outcrop picture of Tuma Padrusa in Fig. 155.4 therein).

However, the surrounding sediment of these two Toma hills and the contacts therewith are different. The ERT models P2 and P3 (Fig. 4b,c) show that Bot Dagatg is framed by Bonaduz Formation 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 Formation on the western side of Ils Aults. Probably, Tuma Padrusa resides in remobilized rockslide material and admixed Bonaduz Formation, 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. 5).

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 hills, our results affirm the hypothesis of a simultaneous transport within a highly fluidized mass movement. As suggested by Poschinger and Kippel (2009) and Calhoun and Clague (2018), it is plausible that pieces of the Flims rockslide were transported by a hyperconcentrated flow (Bonaduz Formation), 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 Formation, 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 Formation. We postulate that the coarse centre of a Toma hill

155 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. 4d) 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 Tuma Padrusa do not allow for
165 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 Tuma Padrusa. 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

170 The onlap of the Bonaduz Formation onto the Ils Aults constitutes novel field evidence in the debate about the timeline of geological events around Flims (Fig. 6). 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 Lake Bonaduz (Phase 1), and (iii) the Flims rockslide impacted Lake Bonaduz (Phase 2), thereby triggering push waves and a hyperconcentrated mass flow with gravel in suspension. The Bonaduz Formation between the Flims and Tamins deposits has
175 an average thickness of ~50-70 m.

The stratigraphic position of the Toma hills is related to the Flims rockslide (Phase 2) and the Bonaduz Formation (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
180 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 and fluvial 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.

Data availability

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

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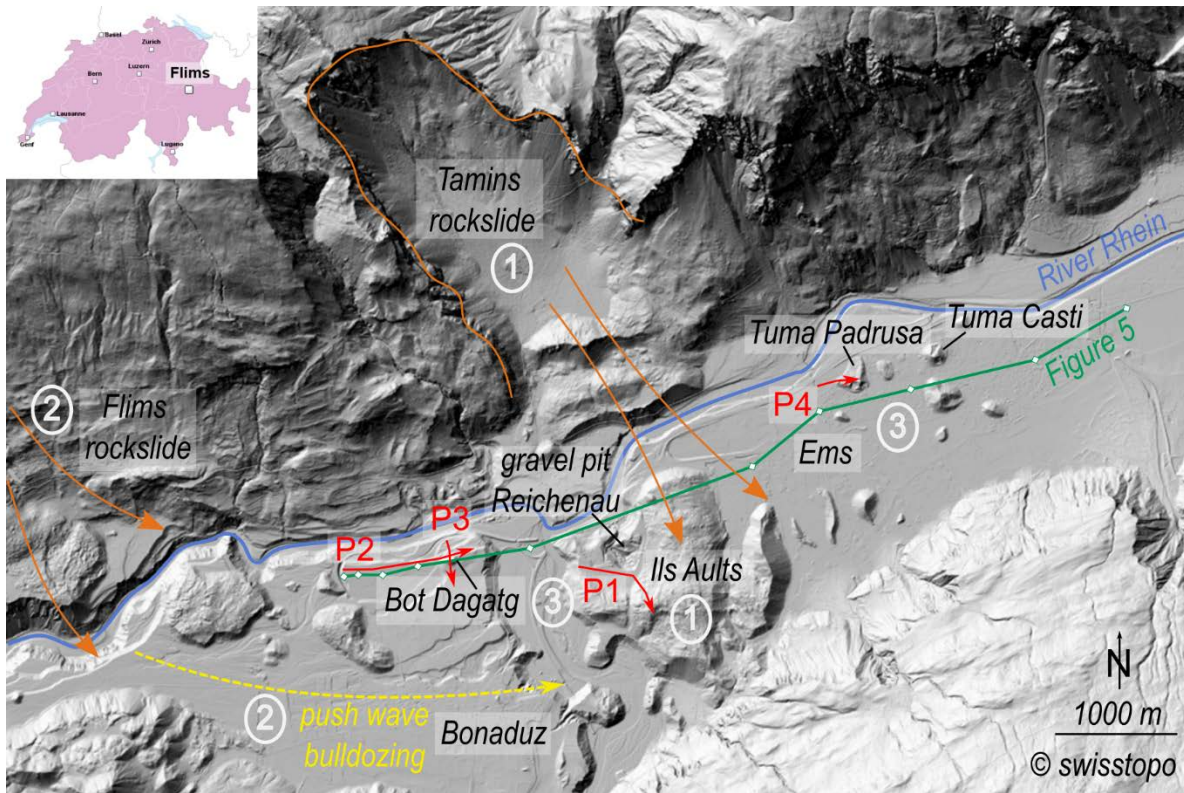
Figure 1: Overview of the study area in the Rhein River valleys depicting the scarp of the Tamins rockslide, the Ils Aults consisting of Tamins deposits, parts of the impact zone of the Flims rockslide and Toma hills (e.g. Bot Dagatg, Tuma Padrusa and Tuma Casti). The ERT profiles P1-P4 (Fig. 4) are marked with red colour. The green profile links drilling sites (white markers) and is shown in Fig. 5. The circled numbers correspond with the evolution phases. High-resolution DEM: © swisstopo.

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Figure 2: Sedimentological field evidence of Bonaduz Formation and Toma hills used for ERT interpretation. a) Unstratified, normally graded gravel deposits with fine-grained matrix and vertical Pavoni pipes in gravel pit near Pardisla. b) Stratified sands and silts at the top of the Bonaduz type locality at the gravel pit in Reichenau. c) Large clasts within and on top of Bonaduz Formation. d) Outcrop with large rock slabs in Toma hill near Pardisla. e) Shattered rockslide material with fine-grained matrix at Tuma Casti (see Fig. 1 for location). f) ERT-profile P2 investigating Bot Dagatg rolls over several drilling sites, e.g. 'B5/90'. Photo courtesy: M. Krautblatter.

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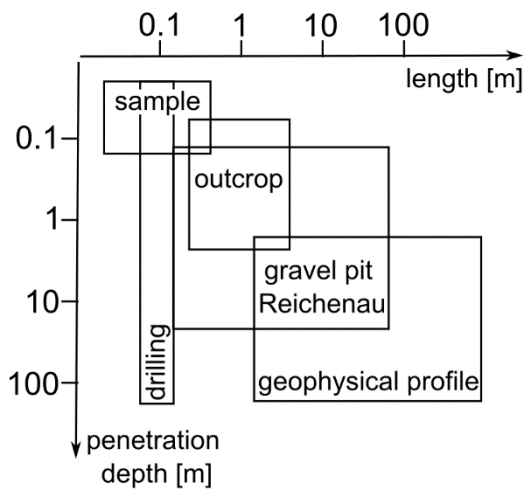
Figure 3: Schematic plot highlighting the novelty of the geophysical results in the framework of a complementary method application.

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

NW — SE

[m a.s.l.]

Ils Aults

fine-grained top layer, visible in gravel pit *Reichenau*

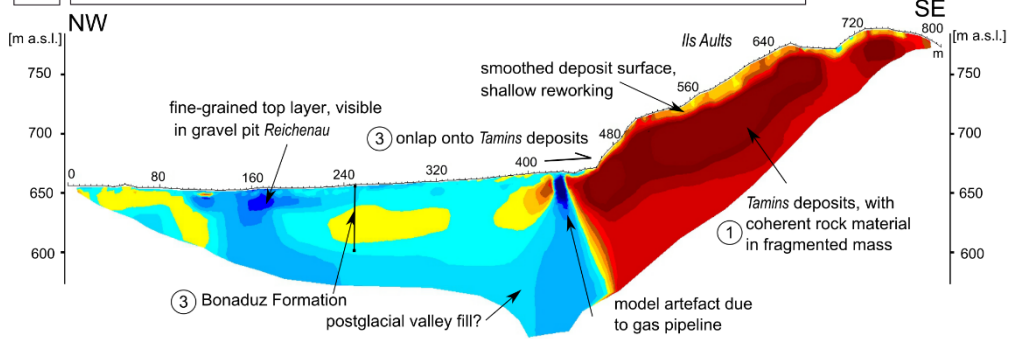
③ onlap onto *Tamins* deposits

smoothed deposit surface, shallow reworking

Tamins deposits, with coherent rock material in fragmented mass ①

③ Bonaduz Formation

postglacial valley fill?

model artefact due to gas pipeline

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

W — E

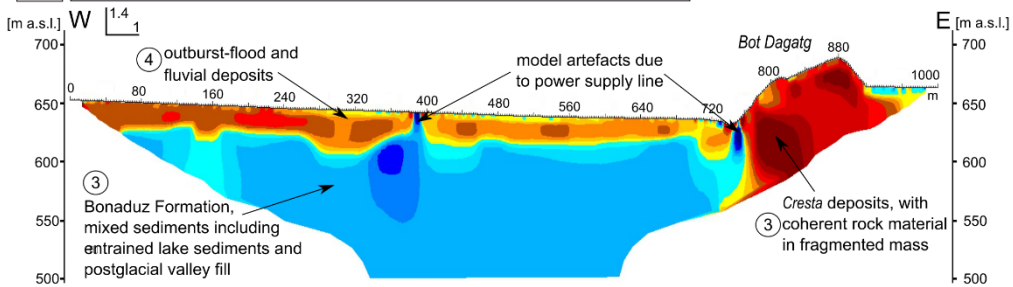
[m a.s.l.]

④ outburst-flood and fluvial deposits

model artefacts due to power supply line

Bot Dagatg

③ Bonaduz Formation, mixed sediments including entrained lake sediments and postglacial valley fill

Cresta deposits, with coherent rock material in fragmented mass ③

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

N — S

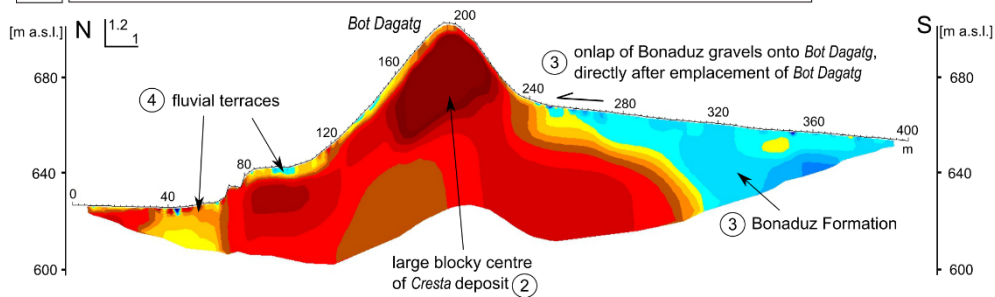
[m a.s.l.]

Bot Dagatg

④ fluvial terraces

③ onlap of Bonaduz gravels onto *Bot Dagatg*, directly after emplacement of *Bot Dagatg*

③ Bonaduz Formation

large blocky centre of *Cresta* deposit ②

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

W — E

[m a.s.l.]

④ onlap of outburst-flood or fluvial deposits

Tuma Padrusa

Toma hill, with coherent rock material in fragmented mass ③
①? ②?

postglacial valley fill?

Specific resistivity [Ωm]

100 — fine-grained sediments

500 — Bonaduz Formation mixed sediments postglacial valley fill

2000 — fluvial deposits and transition zones

6000 — coherent rock mass large boulders (limestone)

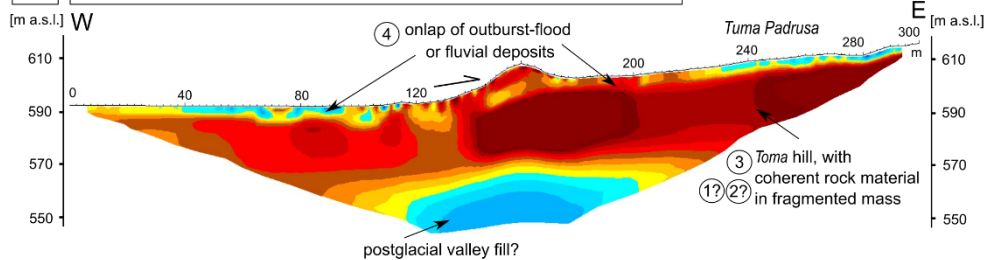
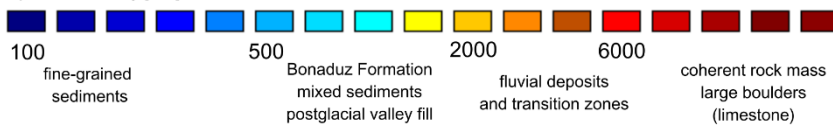



Figure 4: ERT profiles P1-P4 indicating a) ~60 m thick Bonaduz Formation (Phase 3) onlapping onto Ils Aults (Phase 1), b) Bot Dagatg transported within Bonaduz Formation (Phase 3), covered with some outburst-flood and/or fluvial deposits (Phase 4), c) onlapping Bonaduz Formationl onto Bot Dagatg, and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

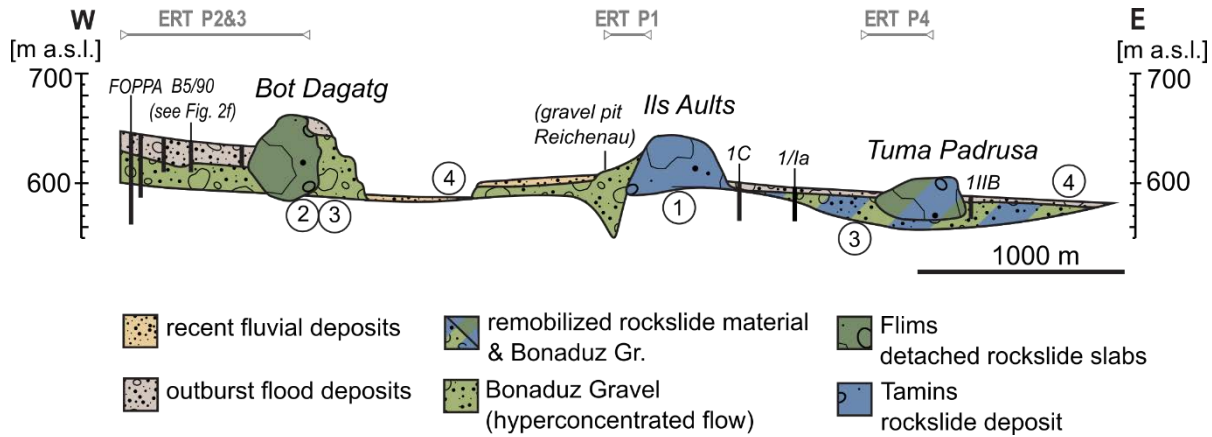



Figure 5: Schematic cross section interpreted from the presented ERT surveys (indicated in grey). Drilling data indicated by black bars supported the interpretation to the depth. The projection of ERT-profile P1 leads to a V-shaped body in the cross section. The circled numbers correspond with the evolution phases 1-4.

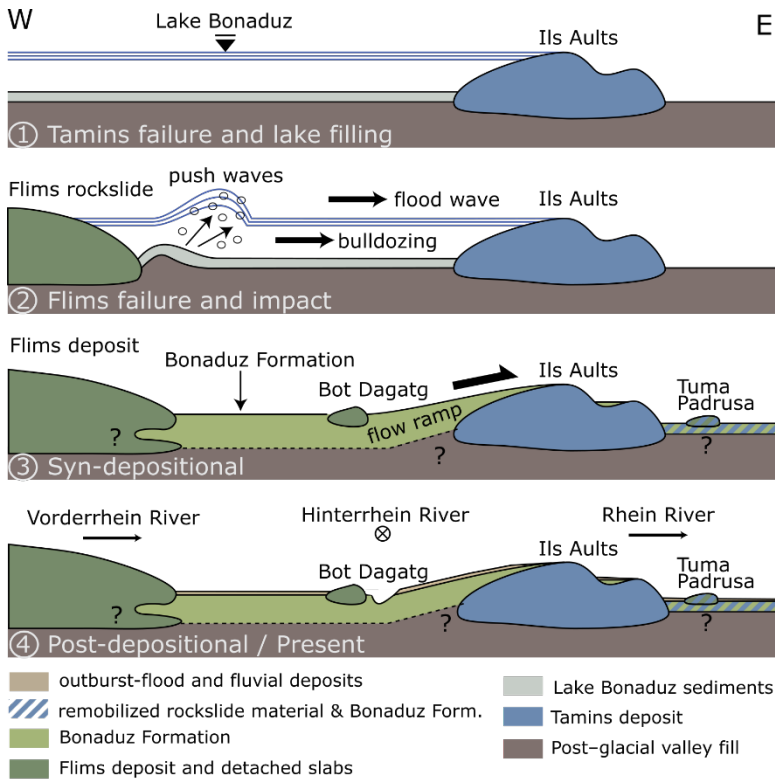



Figure 6: Timeline of geological events displaying the following hypotheses: Phase 1) Lake Bonaduz dammed by the Ils Aults after Tamins rockslide; Phase 2) push waves and bulldozing after impact of Flims rockslide; Phase 3) simultaneous evolution of Bonaduz

Formation, transporting Toma hills; Phase 4) outburst-flood and recent fluvial deposits partially cover the Bonaduz plain. Schematic
230 **sketch without scale.**

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