

ORIGINAL PAPER

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The Flims rock avalanche: structure and consequences

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Abstract

The Flims rock avalanche has a gliding surface that cuts down section in a limestone sequence and does not follow a weak horizon. The gliding surface is parallel to bedding and/or to the penetrative Alpine foliation in the limestone that is characterized by a shape-preferred orientation of calcite grains. Predisposition was governed by structural weaknesses in form of sub-vertical fault zones within solid limestone. Faults controlled the orientation of lateral scarps of the rock avalanche. The main body of the rock avalanche behaved as semi-coherent mass, which preserved the original overall structure. The internal deformation occurred by dynamic fragmentation, which was distributed rather heterogeneously. Fragmentation starts by the formation of veins consisting of comminuted limestone. In a later stage crosscutting veins coalesce to form a texture with entirely comminuted limestone (“rock flour”) containing angular shattered fragments of limestone of variable sizes. The involvement of the post-glacial water-saturated substrate contributed to the long-runout of the Flims rock avalanche. The substrate was plowed bulldozer-wise at the front of the rock avalanche and escaped upward through the moving rock avalanche as clastic dikes and blow-out pipes. Bulldozing raised the valley floor in front of the rock avalanche by more than 100 m and, on the margins, entrained pieces of the valley flank and the neighboring, older Tamins rock avalanche deposit. The liquefied substrate breached the Tamins rock avalanche at Reichenau and entrained fragments thereof down the valley. The fragments now form the famous tumas of Domat/Ems, Felsberg and Chur. Lake Ilanz, dammed the by Flims rock avalanche, experienced a first major outburst shortly after its formation.

Keywords: Rock avalanches, Geomorphology, Landscape evolution, Dynamic fragmentation, Long-runout, Natural dam breach, Flims rock avalanche, Tamins rock avalanche, Lake Bonaduz, Lake Ilanz

1 Introduction

Rock avalanches modify landscapes dramatically and almost instantaneously. In mountainous regions the rock avalanche deposits as well as the release areas highlight such abrupt changes. Rock avalanches also tend to create dams that block rivers and lead to the formation of lakes. Overtopping of these dams can lead to catastrophic floods. In the area of the confluence of the Vorderrhein and the Hinterrhein in eastern Switzerland, two large rock avalanches, the Tamins and Flims rock avalanches

display all the issues of such landscape changes including the formation of the Ruinaulta, a major gorge cut into the rock avalanche deposits. The two rock avalanches are located within the Geopark Sardona immediately adjacent to the UNESCO natural heritage site Tectonic Arena Sardona.

Figure 1 shows the geographic setting. The Tamins rock avalanche deposit occupies the area of confluence of Vorder- and Hinterrhein while the deposit of the Flims rock avalanche spreads over a much larger area along the Vorderrhein. A third and minor rock avalanche descended from the Bargis area onto the Flims rock avalanche deposits.

Two large lakes formed in the process: the Tamins rock avalanche barred the Vorder- and Hinterrhein and

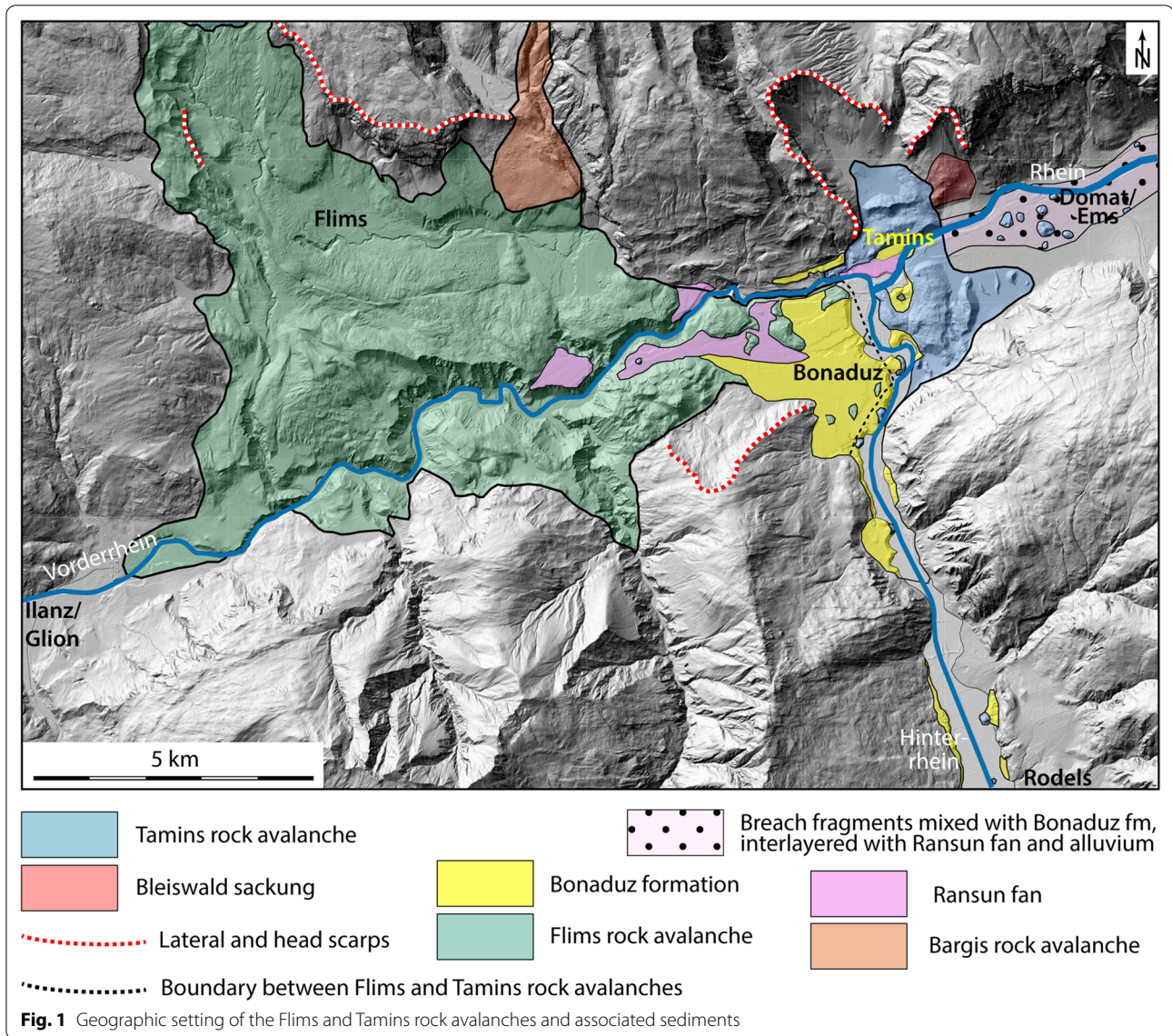
Editorial handling: Wilfried Winkler

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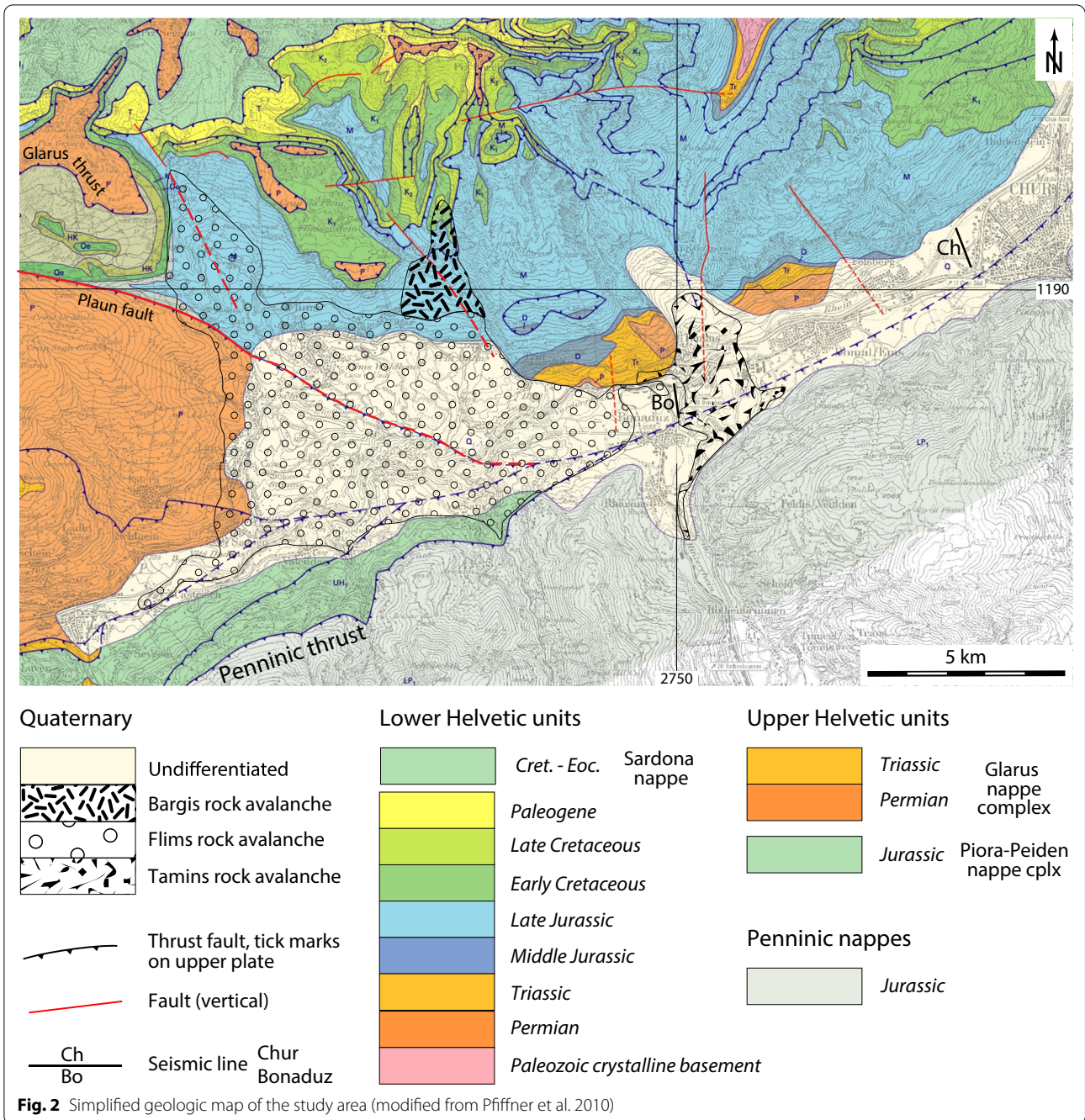


created Lake Bonaduz, the Flims rock avalanche barred the Vorderrhein and created Lake Ilanz. Both lakes extended way upstream as will be discussed later.

1.1 Geological setting

The two rock avalanches involve rocks from the Helvetic nappe system, but the deposits lie on the boundary between the Helvetic and Penninic nappe systems (see Fig. 2). These nappe systems pertain to the passive margin of the European continent, which developed in Jurassic times and was subsequently shortened and metamorphosed in Cenozoic times during the Alpine orogeny. The Helvetic nappe system is subdivided by the famous Glarus thrust into an upper and lower unit. The lower Helvetic units contain a thick Late Jurassic to Early

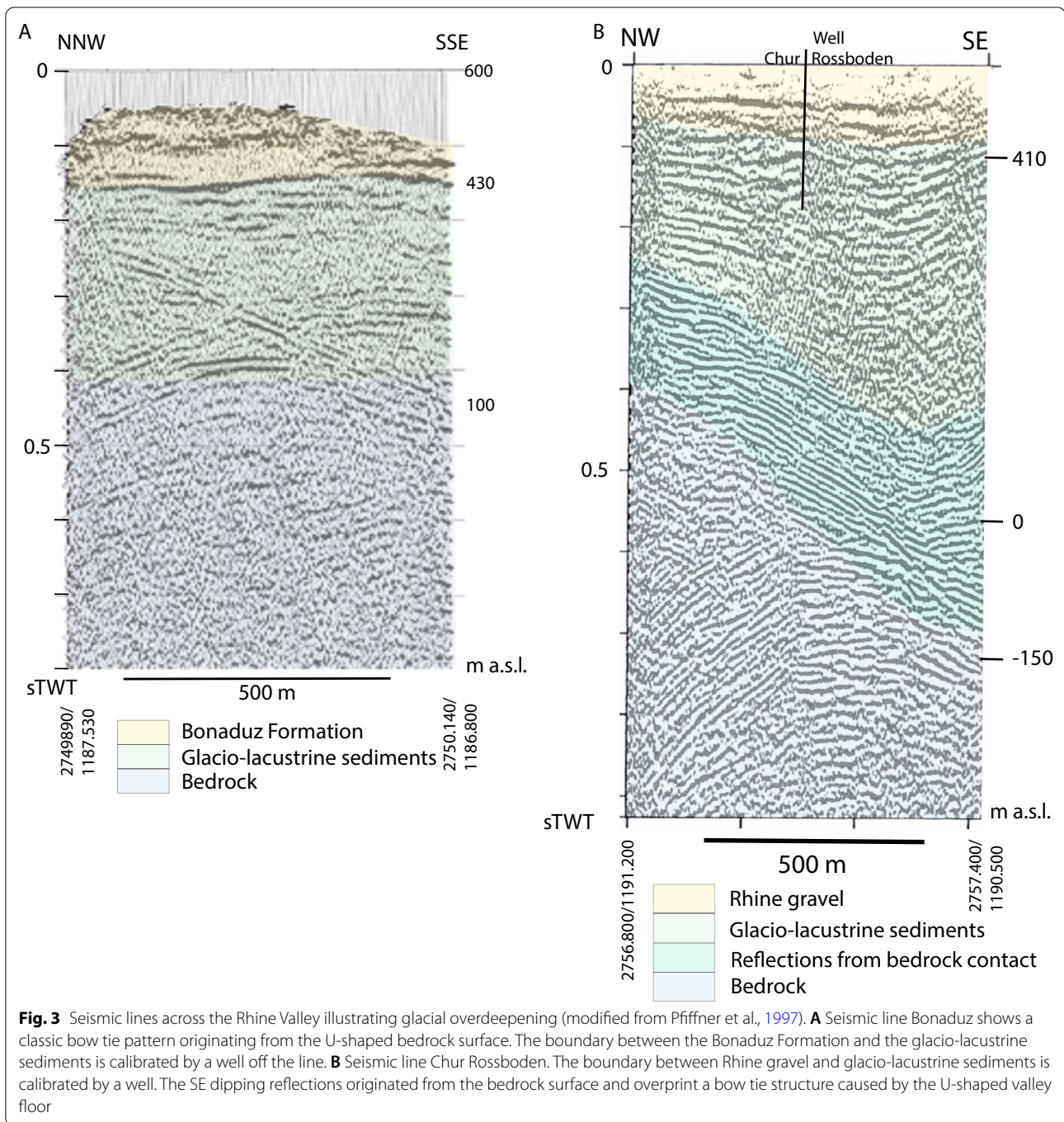
Cretaceous limestone sequence that played a dominant role in the development of the rock avalanches. The massive limestones, namely Quinten and Tros limestone, are nearly 500 m thick and tend to form high cliffs. The upper Helvetic units put Permian clastics (Verrucano group) onto the lower Helvetic limestone; regarding the Flims rock avalanche the upper Helvetic units were almost entirely eroded such that only remnants (klippen) of Verrucano remained. The Piora-Peiden nappe complex of the upper Helvetic units are made of a sandstone-marl-shale sequence, which lithologically resembles much the sedimentary sequence of the overlying Penninic nappe system. It is the boundary between these erodible strata and the more resistant limestone of the lower Helvetic units that controlled riverine and glacial incision and



ultimately the course of the main valley axis along the Vorderrhein and Rhine rivers (see Figs. 1 and 2).

The Quaternary glaciations had a pronounced influence on the morphology of the study area. During the Last Glacial Maximum, LGM, ice covered the entire valley as shown by the highest erratic blocks occurring at roughly 2100 m a.s.l. (Florineth & Schlüchter, 1998; Pfiffner & Wyss, 2023). The glaciers overdeepened the valley such that the bedrock surface is located at about

100 m a.s.l. in the study area (see Fig. 3A and B; Pfiffner et al., 1997, Pfiffner & Wyss, 2023); bedrock is overlain by fine glacio-lacustrine clastics and, above about 420 m a.s.l., by gravel. The glacio-lacustrine clastics evolved from an ancient lake connecting Lake Zürich, Walensee and Lake Constance with a lake level of 405 m a.s.l. (Müller, 1999; Pollet and Schindler, 2004). This lake, together with its sedimentary fill, which reached to about 420 m a.s.l., extended most probably up valley into the area of



the ensuing Flims rock avalanche. As weak substrate it had a serious impact on the long-runout of the rock avalanche.

1.2 History of research

The first description of the Flims rock avalanche dates back to Albert Heim (1883) who provided a detailed account of the rock avalanche deposits and speculated

about the palaeo-topography and gliding surface; he did not recognize the Tamins rock avalanche as a separate event. Hartung (1884) gave a detailed description of local outcrops of the “Flims breccia” and its morphological expression. Several people then analyzed the lithological composition of the hills in the flat valley bottom (called tumas, crest, or bot) and confirmed that the hills are part of rock avalanches (Piperoff, 1897; W. Staub, 1910;

Gsell, 1917; Remenyik, 1959). Very soon researches were investigating the gravel and sand around the village of Bonaduz and discussed the possibility of liquefaction and long-runout. Pavoni (1968) detected desiccation pipes (later called “Pavoni pipes”) and Abele (1970) postulated that a giant mixture of water, gravel and rock avalanche fragments moved way up the Hinterrhein and back; he interpreted that the flood was caused by the outburst of a lake that transported pebbles from the Vorderrhein valley up the Hinterrhein valley. Nabholz (1975) and Kirchen (1993) summarized the state of knowledge at that time. A more detailed account of the early history of research is provided by von Poschinger et al. (2006).

It was only later that dating of the rock avalanches was accomplished and emplacement mechanisms were studied. von Poschinger and Haas (1997) studied pollen in the lake sediments upstream of the Flims rock avalanche and pieces of wood found at the front of the rock avalanche deposits. In both cases they obtained ages of around 9000–8000 B.P., i.e. post-glacial. These ages contradicted the hypothesis of previous workers who thought that glaciers of the waning LGM had overridden the rock avalanche deposits. Later work by radiocarbon dating of lake sediments (Deplazes et al., 2007) and boulder exposure ages by Ivy-Ochs et al. (2009) narrowed down the Holocene age to 9480–9430 B.P., respectively 8900 ± 700 B.P. Nicolussi et al. (2015) recalculated the radiocarbon ages of Deplazes et al. (2007) to 9475–9343 B.P.

Schneider et al. (1999) studied the internal fabric of the Flims rock avalanche and interpreted that layer-parallel slip was important as transport mechanism. Wassmer et al. (2004) extended this work, classified the rock types into a more stratified facies and a more granular facies, and tried to correlate these facies to the subsequent overtopping event. Pollet and Schneider (2004) interpreted the stratified facies to indicate slab-on-slab motion of the rock avalanche and that the chaotic (granular) facies developed from a stratified facies owing to dynamic disintegration of the rock avalanche as it moves. Observations by the author in the course of a mapping project could not confirm these interpretations. Alternative interpretations will be discussed below.

Caprez (2008) presents a thorough analysis of the paleo-topography and the volume of the Flims rock avalanche deposit using polynomial regression and obtained a volume estimate of around 11 km^3 .

Considerable interest was then devoted to the role of the lakes and their sedimentary fill on the emplacement and runout of the rock avalanches. von Poschinger (2005) discusses Lake Ilanz dammed by the Flims rock avalanche; this included the description of an outcrop of bedded fines and an evaluation of the lake level. von Poschinger and Kippel (2009) describe the

Bonaduz Formation, gravel and sand that had accumulated upstream of the Tamins rock avalanche and which were heavily mobilized by the impact of the Flims rock avalanche. Liquefaction of this gravel and sand had been postulated previously by Pavoni (1968) and Abele (1970). Calhoun and Clague (2018) addressed the question of the flow mechanism in the Bonaduz Formation and concluded that the slurry moved as hyperconcentrated flow likely above a carpet that behaved as debris flow. Knapp (2020) explored the impact phenomena using geophysical methods down to a depth of 160 m and concluded that large blocks of rock avalanche debris was transported in the slurry of the Bonaduz Formation; the impact of the Flims rock avalanche into Lake Bonaduz is held responsible for the creation of a flood overtopping the Tamins rock avalanche deposit, a point that was also raised by Scholz (2018).

Volken (2015) and Aaron et al. (2020) applied stability analyses and finite element modeling to assess the triggering mechanism and long-runout of the Flims rock avalanche; they conclude that preconditioning was structurally controlled and that liquefaction augmented run out.

In recent times the two rock avalanches, the lakes they caused by them and the outburst of these lakes were studied in detail by geologic and geomorphic mapping at the scale 1:25,000 (Pfiffner & Wyss, 2023, and work in progress for map sheet Flims). This work helped to elucidate the origin of rock types within the rock avalanches, the internal fabric of the rock avalanche deposits as well as pebble compositions in younger debris flows and thus clarified many aspects of the events discussed here.

The aim of this paper is to analyze the 3-dimensional internal structure of the Flims rock avalanche, the rock fabrics within the deposit, and the processes associated with the impact of rock avalanches on lakes and lake sediments. To this purpose the source area and the deposit were mapped in detail in order to unravel the flow pattern of the rock avalanche. In addition, the overflowing of a rock avalanche dam and the ensuing flooding and incision of the rock avalanche deposit were analyzed in detail. Altogether the paper illustrates how extremely rapid landscape changes can occur.

2 Large-scale structure of the Flims rock avalanche

The Flims rock avalanche, the largest rock avalanche in the Alps, filled the Vorderrhein valley over a surface of around 60 km^2 . The source area is situated above the name-giving village Flims. Four scarps may be differentiated, a frontal scarp, two lateral scarps and the head scarp (see Fig. 4A). The frontal scarp runs in a WSW–ENE direction south of Flimsenstein. It is more or less



parallel to vertical faults recognizable on the top plateau of Flimserstein, which have offsets of 20–30 m.

In the western flank of Flimserstein a lateral scarp oriented in a NNW–SSE direction is parallel to faults and a regional jointing system. The joints are subvertical and perpendicular to the fold axes of the regional fold-and-thrust structures (Pfiffner, 1977). The faults are also subvertical and have minor vertical offsets. Volken (2015) and Aaron et al. (2020) distinguish three major sets of faults of which set 1 striking NNW–SSE is the most important one. These faults are parallel to segments of

the lateral and frontal scarp. The lateral scarp forms two jogs, which are parallel to the frontal scarp. Aaron et al. (2020) give an account of the faults in Flimserstein and conclude that preconditioning of the rock avalanche was structurally controlled.

The source area west of Flimserstein is difficult to assess. A possible lateral scarp can only be seen south of La Crappa (Fig. 4A) because in the region between Segnas Sut and La Crappa the rock avalanche ran up and surmounted the valley flank and a potential lateral scarp. The bedrock west of the lateral scarp is covered

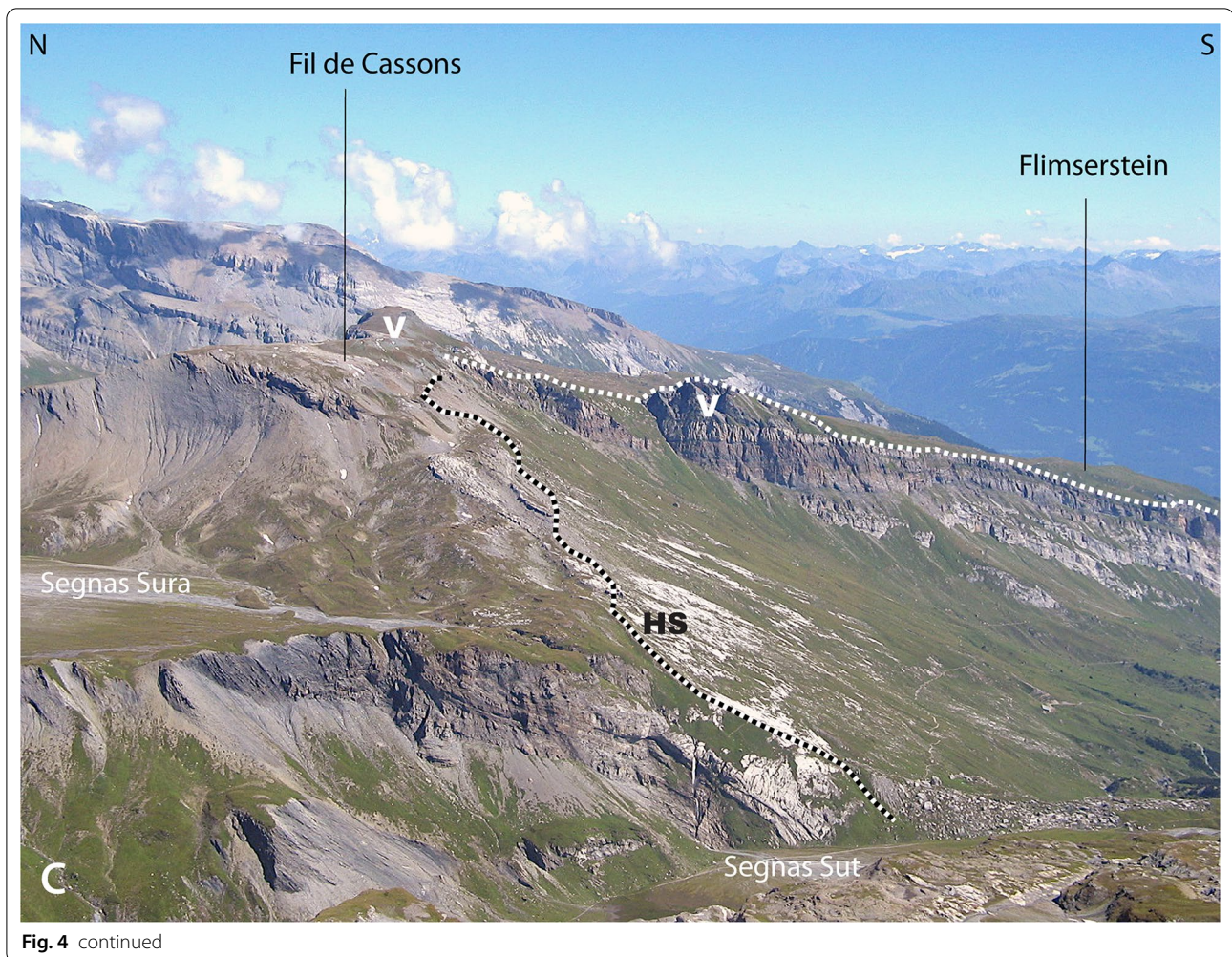


Fig. 4 continued

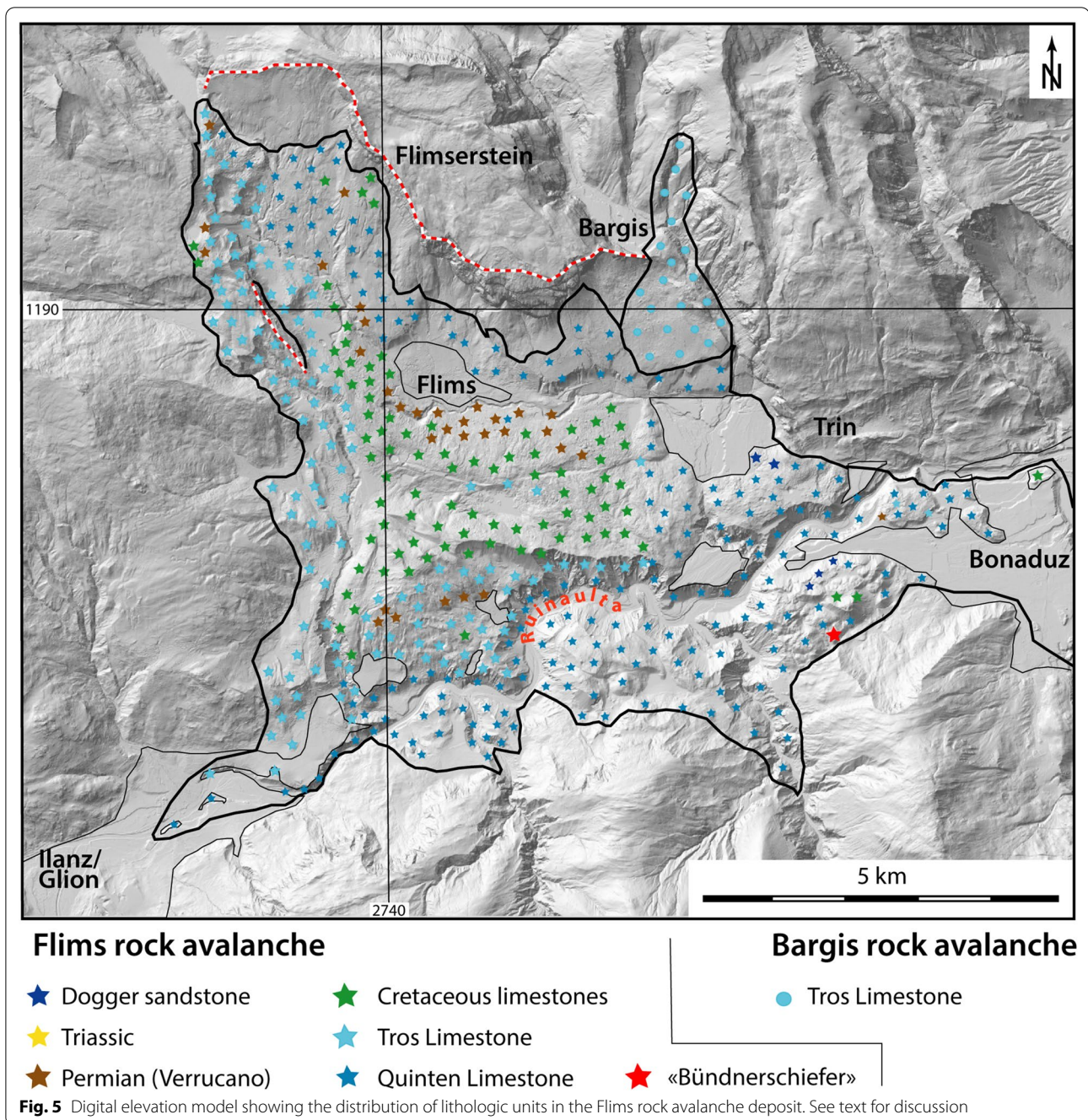
by rock avalanche debris in the forest south of La Crappa. It has to be noted that the valley of Segnas Sut extended farther to the south prior to the mass movement (Caprez, 2008), and it seems that between Segnas Sut and La Crappa only the eastern flank of that valley was involved in the rock avalanche.

The extent and morphology of the rock avalanche deposits can be evaluated and contemplated in the photograph of Fig. 4B. Much of the deposits are covered by forest. The very irregular small-scale topography of the carapace of the rock avalanche precluded its use for grass farming such that a pristine forest was preserved. The larger-scale topography is characterized by rounded hills of variable shape. The most striking feature is a gorge, the Ruinaulta, which the Vorderrhein has cut into the rock avalanche debris. Steep rocky slopes point to rapid incision and ongoing lateral erosion by the river. Regarding the long-runout of the rock avalanche two features are important. In the lower right corner of Fig. 10B the rock avalanche entered into

the narrow valley Safiental, and downstream it reached as far as Bonaduz.

The head scarp between Fil de Cassons and Segnas Sut is illustrated in Fig. 4C. The scarp is the boundary between bedrock in the north and the gliding surface to the south. The entire mountain that once formed the western extension of Flimserstein must have had a considerable slope towards Segnes Sura. The altitude of this collapsed mountain must have reached at least 2800 m a.s.l., with peaks that consisted of Permian volcanoclastics, the so-called “Verrucano”, which is expected at this altitude judging from the regional structure of the Glarus thrust.

In the course of a mapping project of the Geological Atlas of Switzerland 1:25,000 the entire rock avalanche was analyzed regarding the lithologic units making up the deposits. The result is shown in Fig. 5. The stars are colored with regard to the predominant lithologic units encountered. In some instances, the dense vegetation rendered the analysis difficult. Knowing the units from



mapping bedrock in the Flimserstein region helped to identify individual blocks encountered in the dense forest. A similar analysis was performed by Gsell (1917) and produced preliminary results that sparked the interest for a renewed and more detailed analysis. Figure 5 reveals that individual units appear in patches. For example, Cretaceous limestone blocks occupy a girdle west and south of Flims. A girdle of blocks of Tros Limestone outcrops as band next to the Cretaceous blocks to the west and south.

Verrucano blocks appear as patches inside the Cretaceous and the Tros limestones. The Quinten limestone occupies the largest portion on the surface. It forms a band north of Flims immediately beneath the lateral and frontal scarps of Flimserstein as well as the eastern portion of the rock avalanche deposit and the part south of the Vorderrhein. Middle Jurassic sandstone blocks occur in the east, west of Trin and south of the Vorderrhein. Apart from these patches of lithologic units smaller sized

occurrences of Verrucano and Cretaceous limestones are found in the northernmost part, the trailing edge of the rock avalanche deposits. A peculiar new observation is the occurrence of patches of metamorphic marl and sandy limestone (so called «Bündnerschiefer») west of Bonaduz, rocks which were entrained from the southern flank of the valley.

All in all the distribution of the lithologic units in the rock avalanche deposit reflect the original structure of the ancestral Flimsenstein in a remarkable way. This is particularly striking in the area of Ruinaulta (Fig. 5). In the Flimsenstein the cliffs of the frontal and lateral scarp show a stratigraphic succession of Quinten Limestone, Tros Limestone and Cretaceous limestones topped by klippen of Verrucano. The same succession is observed in the rock avalanche deposits going up from the Vorderrhein towards Flims. Similarly the Middle Jurassic sandstones observed in the east of the rock avalanche deposit (west of Bonaduz) may be related to the bedrock outcrops near Trin where these units were present in the subsurface of the ancestral Flimsenstein west of Trin. The Quinten Limestone blocks south of the Vorderrhein represent the leading edge of the rock avalanche that once formed the base of the ancestral Flimsenstein. Thus it seems that the entire rock avalanche moved as a disintegrating mass without turbulent flow, a point that will be discussed later.

2.1 The paleo-topography

The reconstruction of the paleo-topography of the source area and the valley floor is of crucial importance to determine the volume of the rock avalanche and has the potential to provide clues regarding the geometry of the failure of the mountain flank. Caprez (2008) performed a reconstruction using polynomial regression to determine the shape of the valley slopes. He estimated the valley bottom to be only slightly beneath the present-day riverbed. The reconstruction performed by Volken (2015) was a simple projection of the valley flank from the east across the Turnigla valley. Here, a paleo-topography constructed by extrapolating the contour lines from the adjacent areas to the east and the west is presented (see Fig. 6). It shows the former land surface of the source area of the rock avalanche all the way down to the former valley bottom, which is taken to be at around 500 m a.s.l. based on seismic data, i.e. much deeper than anticipated by Caprez (2008). Two paleo-valleys that are shown in Fig. 6 need to be mentioned. They were located at the eastern and western margin of the rock avalanche deposit as already reported by Caprez (2008). In the east it is the Turnigla valley descending from Bargis to Trin Mulin and which represents the downward continuation of a NNW–SSE oriented deep valley extending along the eastern margin

of Flimsenstein. The Flims rock avalanche did not fill this valley. In fact, the eastern margin of the rock avalanche deposit is situated west of the Turnigla gorge. However, a later rock avalanche, the Bargis rock avalanche, crossed the valley at Bargis, dammed the Turnigla River and moved down towards Trin Mulin. Presently the Turnigla River is cutting a gorge into that dam.

A second valley at the western margin of the Flims rock avalanche is to be expected as SSE continuation of Segnas Sut. For both valleys, the paleo-topography at the confluence with the Vorderrhein is ill defined. As mentioned above, a valley bottom at around 500 m a.s.l. can be deduced from extrapolation of reflection seismics Chur and Reichenau/Bonaduz (see Fig. 6B).

Both valleys discussed above actually follow major NNW–SSE striking tectonic faults. The faults are wrench faults, which were activated and active during the nappe forming tectonics of the area. They mark abrupt lateral changes in the internal structure of folds and nappes (see Pfiffner, 1978, 2011; Pfiffner & Wyss, 2023). These faults might have weakened the rocks along the fault trace by fracturing which then controlled the formation of the two valleys.

The pre-failure topography included a ridge higher than 2500 m a.s.l., but barely reaching 3000 m a.s.l. east of Flimsenstein/Cassons. Its southern flank had an average slope of 20°, but could locally have been steeper reaching 30 or even 45°. Altogether the Flims rock avalanche removed a substantial part of the ancestral Flimsenstein. Roughly 50% of that volume is missing in the west, 15% in the south and 35% remained in place.

2.2 The gliding surface

The construction of the sliding surface of the rock avalanche and its continuation into the base of the rock avalanche deposit was done using information from detailed mapping (own work) and from wells that were drilled for the road tunnel in the subsurface of Flims (Report of the Geologengemeinschaft Umfahrung Flims, 2007). Three cross-sections were constructed parallel to the movement direction of the rock avalanche to assess the geometry of the gliding surface (see Fig. 7A). All of them show that the dip of the gliding surface varies considerably. The cross-section in the east displays the source area and the head scarp between Tegia Sura and Fidaz. In this location the scarp shows two shallow dipping segments at Pardatsch and Pinut. Abundant scree accumulated on these to the north of Fidaz and modified the slope towards the angle of repose. The gliding surface has a steep step of 45° south of Fidaz and is shown to level off at 500 m a.s.l. The cross-section located in the center has a segment with a shallow dip of 10° between Foppa and Naraus and steep steps of 30° south of Spalegna and north of the Flem

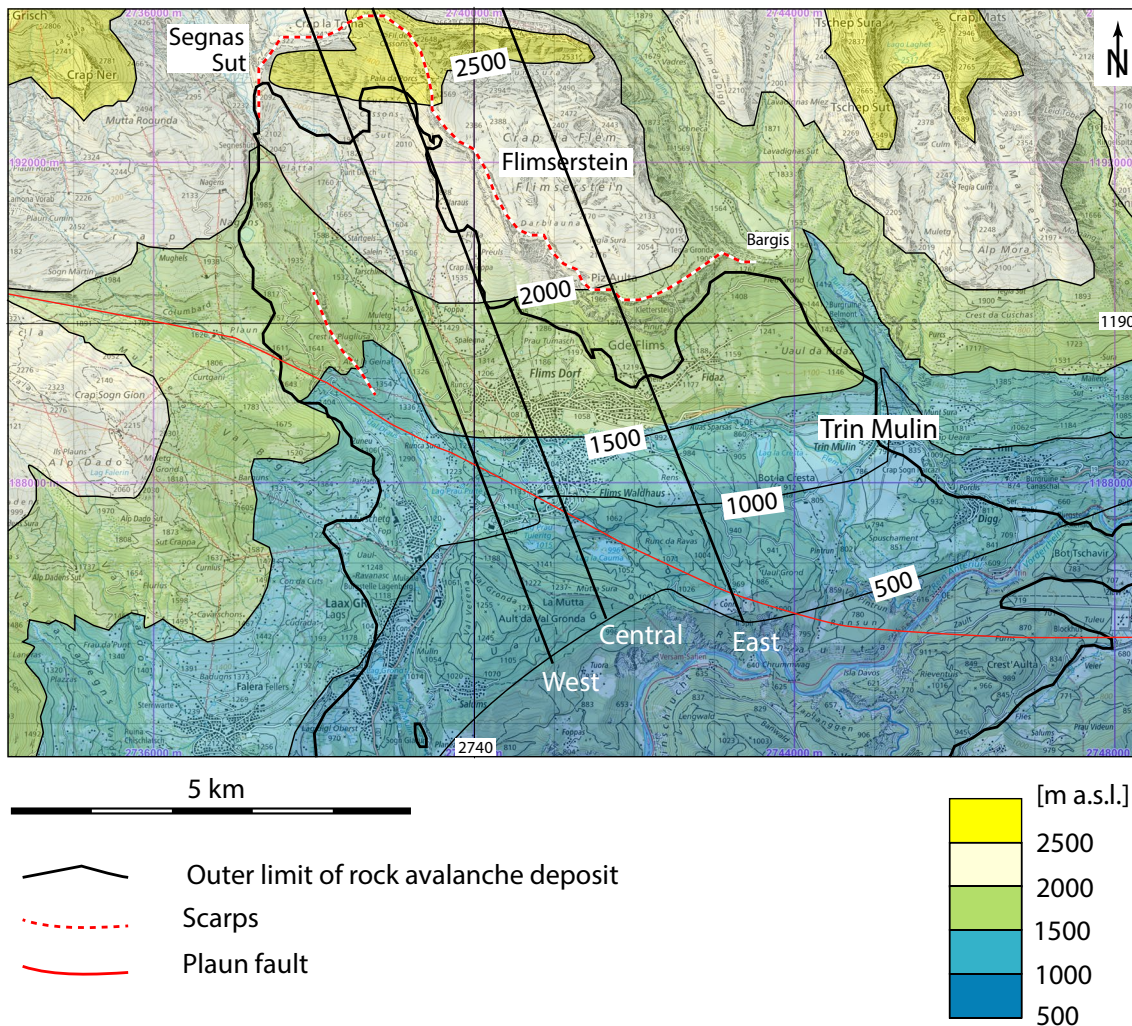


Fig. 6 Palaeo-topography of the source area of the Flims rock avalanche shown as map with topographic contours. West, Central, East: traces of cross-sections shown in Fig. 7A

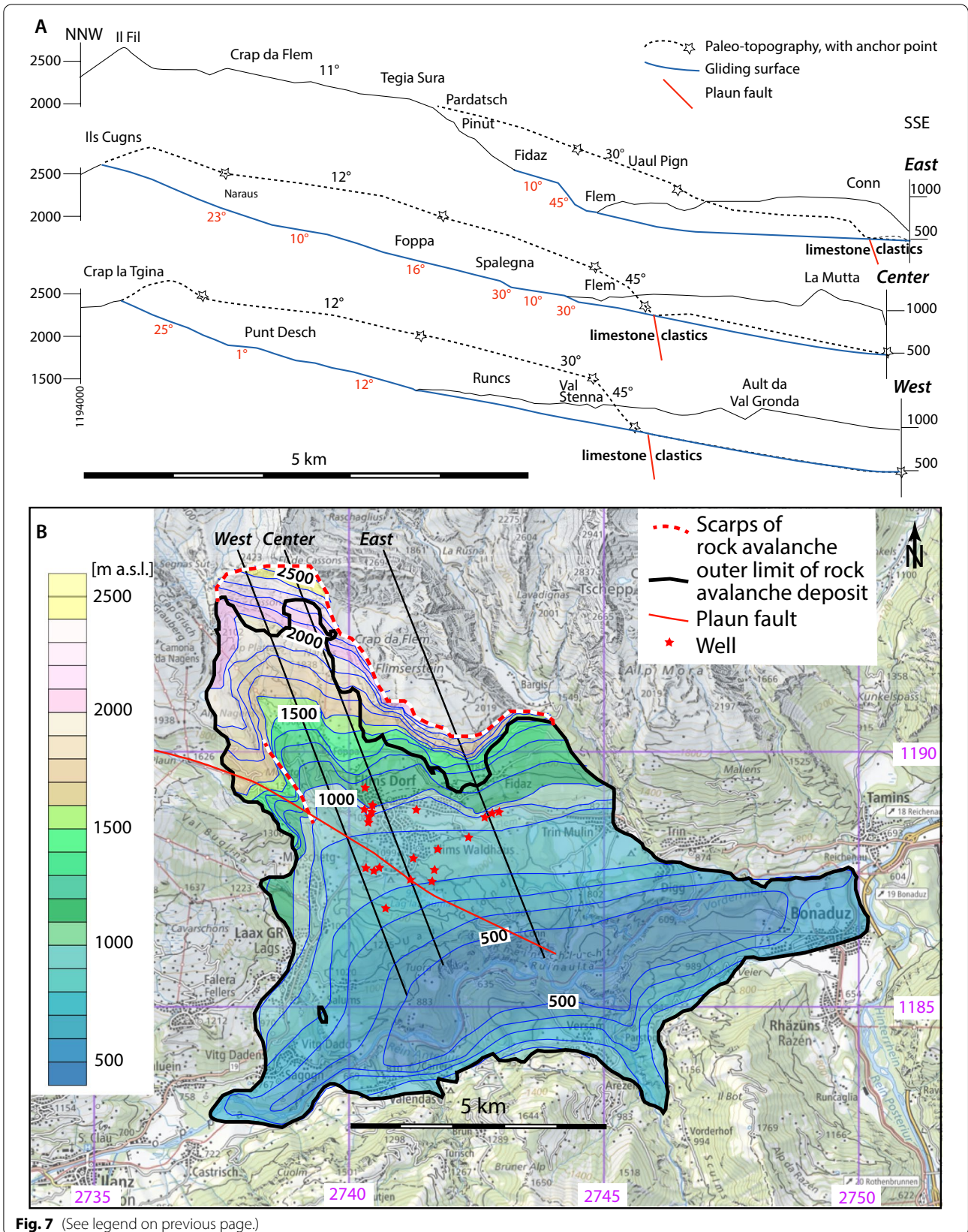
creek. The cross-section in the west finally has a segment with a shallow dip of 1° at Punt Desch. Both the central and western cross-sections indicate a dip of $23\text{--}25^\circ$ south of the head scarp Il Cugns—Crap la Tgina and more shallow dips of $10\text{--}12^\circ$ in the lower reaches, thus suggesting a somewhat concave shape of the sliding surface.

Combining these three cross-sections with field and well data structure contours were constructed to show the 3D-geometry of the gliding surface (see Fig. 7B). As

is evident in Fig. 7B the gliding surface is not an even surface. Namely in the uppermost part it contains steps that run parallel to the lateral escarpments of the rock avalanche (e.g. NNW of Flims Dorf) or across this movement direction (north of and beneath Flims Dorf). The complex pattern west of the western lateral scarp represents the base of the rock avalanche deposit that was overflowing the valley flank. The lower part, i.e. structure contours between 800 and 500 m a.s.l., is ill constrained

(See figure on next page.)

Fig. 7 Gliding surface of the Flims rock avalanche. **A** Cross-sections parallel to the movement direction of the rock avalanche showing the geometry of the gliding surface. The gliding surface is shown in blue and becomes the base of the rock avalanche deposit in the lower part. Red numbers are slope angles. For each cross-section the paleo-topography with anchor points derived from Fig. 12 are given as well. Traces are given in Figs. 6 and 7B. **B** 3D-geometry shown as map with topographic contours. Well locations are given as red stars. The movement direction of the rock avalanche was parallel to the two lateral scarps. East, Center and West denote traces of cross-sections shown in Fig. 7A



by data and is therefore approximated as relatively even surface. The movement direction of the rock avalanche was most probably parallel to the two lateral scarps and the steps parallel to these.

The geological structure of the bedrock in the zone of depletion and the area with thin rock avalanche deposit, i.e. areas located between 2000 to 1000 m a.s.l., is well constrained from geological mapping. Projecting the geological contacts onto the gliding surface it follows that there is no single weak layer as detachment horizon available. In the zone of depletion, the dip angle of bedding is shallower than the gliding surface.

A major fault, the Plaun fault, cuts across the area and intersects all of the three cross-sections of Fig. 7A. This fault separates limestone in the north from clastics in the south. The limestone pertains to the lower Helvetics and tends to form high cliffs as for example at Flimsenstein today. The clastics are part of the Verrucano group. These rocks are more easily eroded than the limestone and tend to form relatively shallow dipping slopes. It is for this reason that the paleo-topographic slope north of the Plaun fault is taken to be steep similar to the situation observed at the locality Plaun to the west of the Flims rock avalanche deposit.

The bedrock in the immediate footwall of the gliding surface doesn't show significant deformation features that could be related to the gliding process. In contrast, the rock avalanche deposits immediately above the gliding surface are highly fractured and brecciated. Along the steep steps within the gliding surface the rocks are heavily fractured with a blocky texture such that it is difficult to decide if one deals with fractured bedrock or with rock avalanche deposit. These steps within the gliding surface have orientations parallel to the head and the lateral scarps. Those parallel to the lateral scarps as well as the lateral scarps themselves suggest that initially the rock avalanche moved towards the SSE.

2.3 Volume

The volume of the rock avalanche deposit is determined from the area of 60 km² it covers. Average thicknesses were calculated for every km², whereby the topographic surface of the rock avalanche deposit was restituted to the original level above the deep incisions post-dating the Flims event. The maximum thickness of the deposit may be estimated at 500 m between Flims and the Vorderrhein assuming that the base is located at around 500 m a.s.l. Thicknesses of around 400 m are estimated for the area between Lag la Cauma and along the Vorderrhein. The total volume amounts to roughly 11.3 km³. This number is only slightly higher than the estimate of 11 km³ presented by Caprez (2008), which is based on polynomial regression. The difference can be attributed

to the assumed elevation of the valley floor prior to the Flims event (500 m a.s.l. this study, 600 to 700 m a.s.l. in Caprez, 2008).

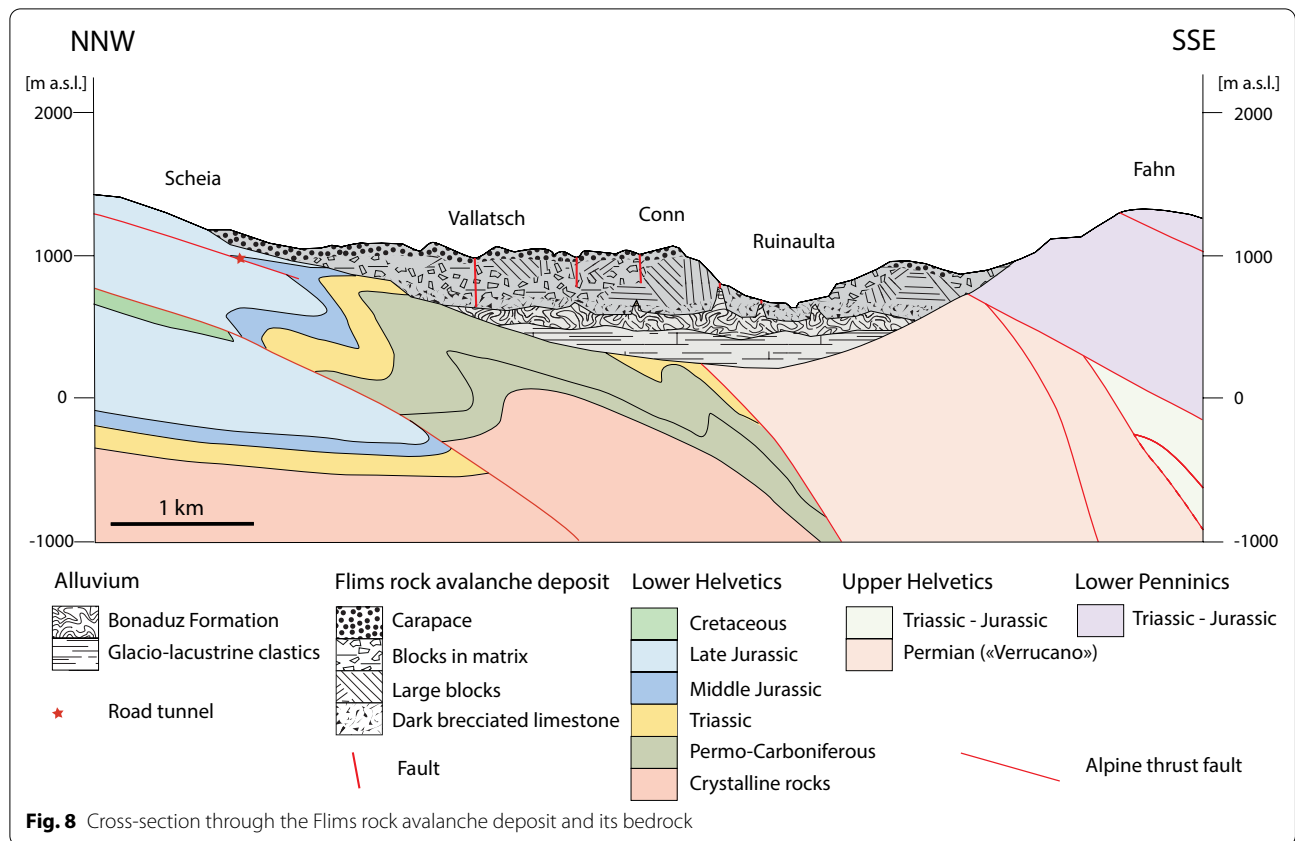
Based on the paleo-topography (Fig. 6) and the gliding surface (Fig. 7A, B) the volume of the source rock was determined as well. The piece of the ancestral Flimsenstein missing in the west has a volume of about 5.5 km³, the piece missing in the south about 4.75 km³, summing up to 10.25 km³. This volume estimate suggests that the volume of the source rock was increased by 10% owing to disintegration and fragmentation into the rock avalanche deposit, a volume increase in concert with the analysis of many rock avalanches by Hungr and Evans (2004).

3 Internal structure of the Flims rock avalanche

The deep incision of the Vorderrhein and its tributaries offers a unique insight into the stratigraphy and internal structure of the Flims rock avalanche. The cross-section shown in Fig. 8 highlights these features. The rock avalanche deposits contain four lithologically distinct units. The lowermost unit is a dark gray brecciated limestone, which outcrops throughout the base of the valley flanks. The middle part consists of gray fractured limestone that appears in two major types that outcrop side by side. One type is made of large compartments of limestone measuring up to 200 m in diameter. The other type is a matrix-supported breccia, which has smaller blocks measuring less than a meter in diameter, embedded in a very fine-grained crushed matrix. The uppermost unit is a carapace of more loosely spaced blocks of limestone. These four units will be discussed in more detail using the photographs shown in Figs. 9 and 10. A 5th unit represented by clastic dykes will be discussed in conjunction with the base of the rock avalanche and the underlying units.

Figure 9A displays the dark gray brecciated limestone near the base of the rock avalanche at the floor of the Ruinaulta gorge at Islaplanggen. Water seeping through the limestone is responsible for the dark color and suggests enhanced permeability near the base of the rock avalanche. This is also indicated by springs originating in this unit as well as ice filled grooves observed in winter-time. A detailed view of the dark gray limestone is given in Fig. 9B. The limestone is heavily fractured and even brecciated, a texture, which is also observed in the overlying gray limestone unit. It must be noted that the contact to the substrate of the rock avalanche is not exposed within the Ruinaulta gorge along the Vorderrhein. However, in the Val da Mulin the base of the rock avalanche is in contact with the underlying bedrock and consists of the same dark gray brecciated limestone mentioned above and shown in Fig. 9A.

The gray fractured limestone in the middle of the rock avalanche deposit makes out about 80% in volume and is



of variable appearance. Figure 9C (left) depicts gray angular blocks in a whitish matrix. The majority of the blocks measure less than 1 m. The matrix consists of comminuted limestone with a grain size ≤ 2 mm. The rock is a matrix-supported breccia and corresponds to a cataclasite. Its texture could be called “block-in-powder”. Locally these cataclasites are cut by faults (Fig. 9C, right), which express themselves by a white cohesionless fault gouge.

Large compartments of gray fractured limestone are shown in Fig. 9D. The one beneath the road shows original bedding in the Quinten Limestone and extends over

more than 200 m. The one above the road contains a folded limestone layer. Such folds are typical for the Quinten Limestone of the source area. They formed in the course of nappe stacking in the Helvetic nappe system, in this case at elevated temperatures of around 300 °C. At close inspection one observes that the folded layer is intensively fragmented with fractures that have no visible offset. The same holds true for all the large compartments and small blocks within the rock avalanche deposit. The folds in Fig. 8D are cut by faults, which offset the light-colored thin layer. These faults developed in

(See figure on next page.)

Fig. 9 Rock avalanche deposit at outcrop. **A** Dark gray brecciated limestone near the base of the Flims rock avalanche deposit at the locality Isplaplangen (coord. 2744250/118350). The photograph taken in winter shows icicles emanating from several point sources within the black limestone. Light colored scree outcrops in steep narrow gullies. **B** Detailed view of dark gray brecciated limestone at the confluence of Rabiusa and Vorderrhein (coord. 2744350/118350). A ca. 10 cm thick breccia layer (double arrows) with centimeter scale components in a fine-grained comminuted white limestone matrix cuts across highly fractured limestone (Quinten Limestone). Fracturing and comminution are also responsible for the occurrence of small pockets of comminuted white limestone within the fractured limestone. All in all the rock fabric is indicative for a cataclasite. **C** Gray fractured limestone cataclasite in the cliff 400 m WSW of the railroad station Versam-Safien (coord. 2742550/1185500). The photograph on the left shows a “block-in-powder” texture with angular blocks in a comminuted limestone matrix. The photograph on the right shows a vertical fault with a white fault gouge (double arrows) consisting of comminuted limestone. Photos A. Pfiffner. **D** Large fragmented compartments in the lower reaches of the Versamertobel (coord. 2745330/1185240). A large compartment with original bedding (arrows) is visible below the road and a large compartment with folds above the road. A sharp contact separates the latter on the left from a cataclasite (cc) with “block-in-powder” texture. Photo courtesy M. Weidmann

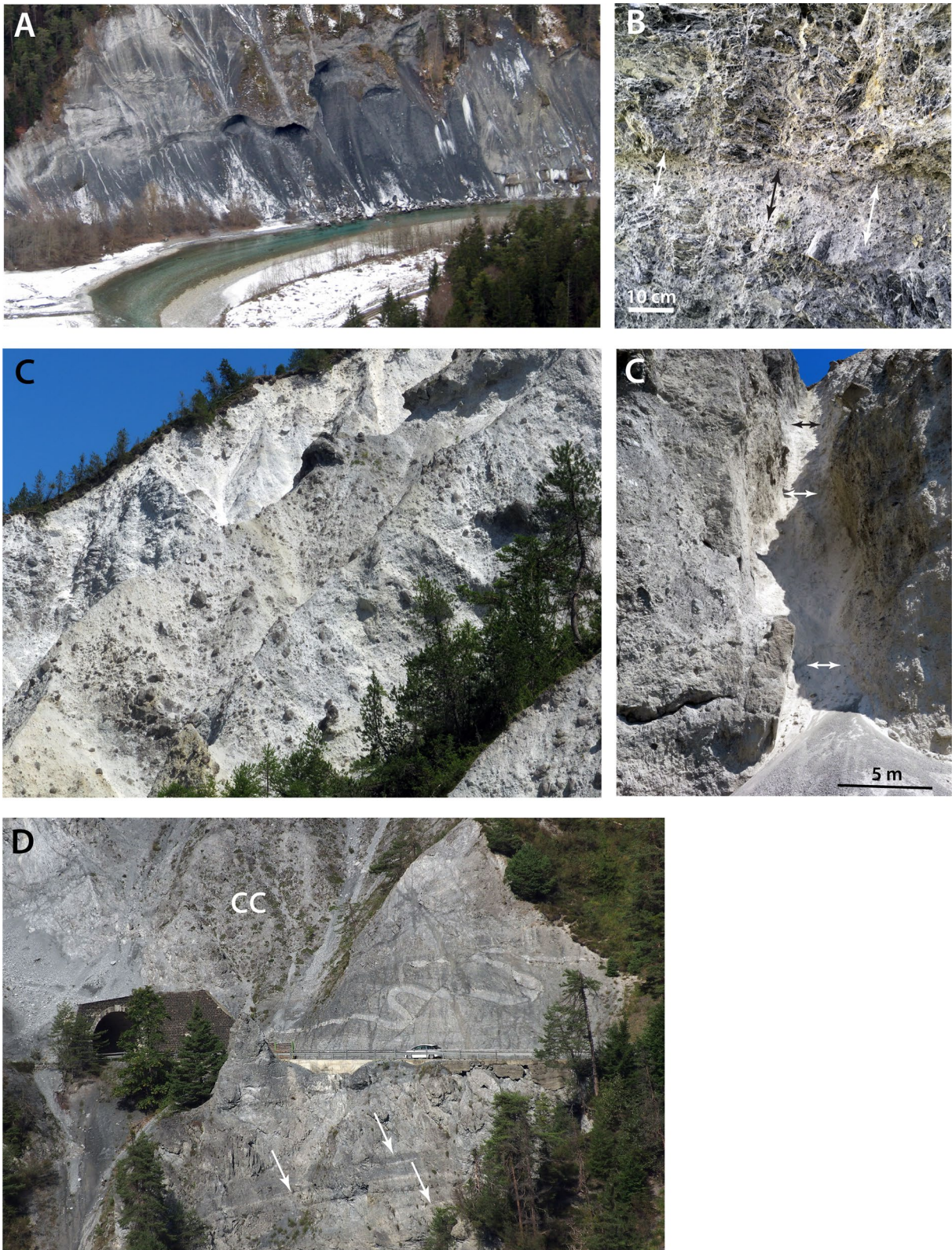


Fig. 9 (See legend on previous page.)

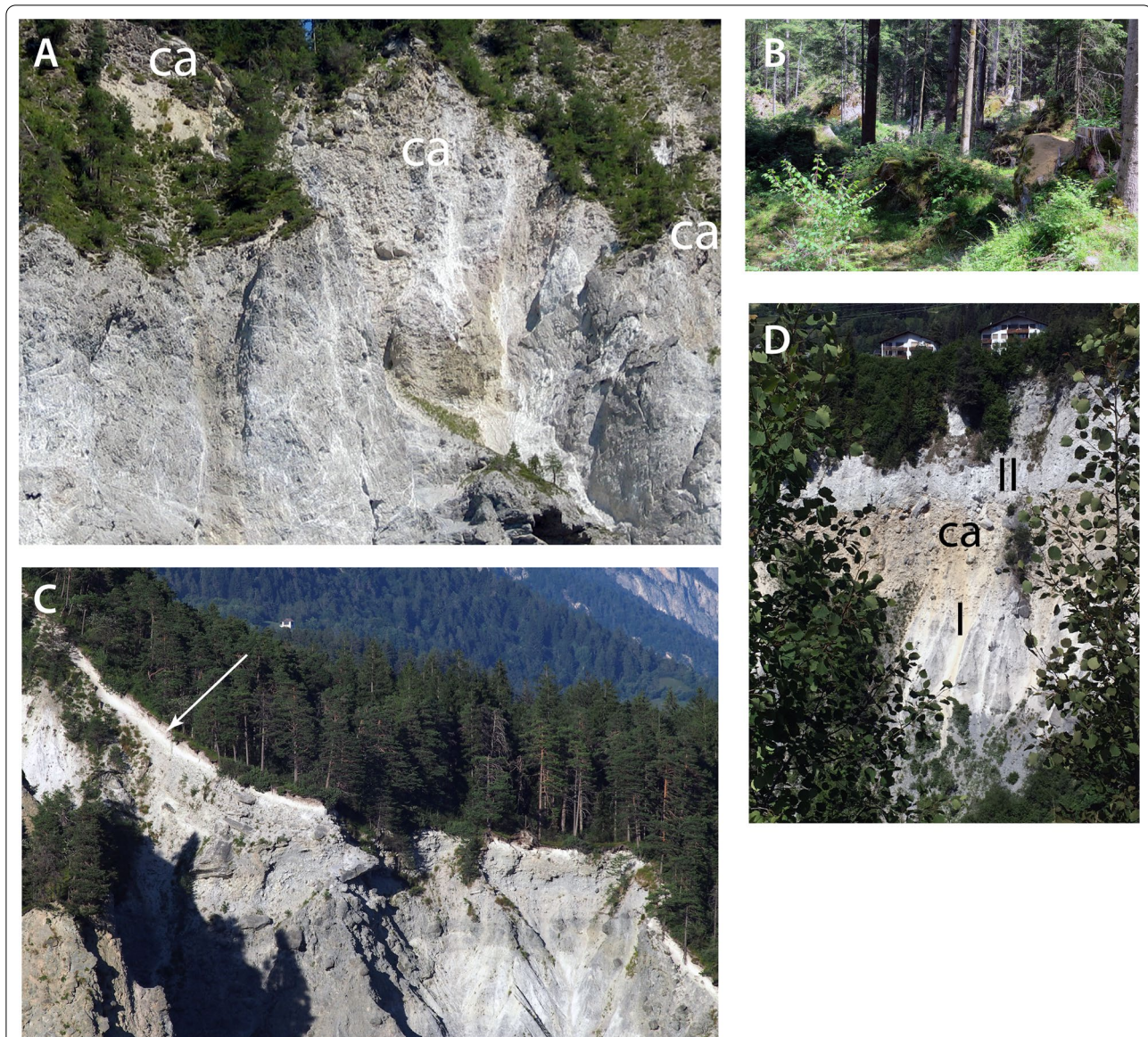


Fig. 10 Rock avalanche deposit. **A** The carapace (ca) in the cliff of Las Ruinas sut Crestaulta 1 km east of railroad station Versam-Safien (coord. 2744000/1186000). Photo A. Pffifner. **B** Carapace blocks in Uaul Zuppau 2 km ESE of Flims Dorf (coord. 2743230/1188000). Photo A. Pffifner. **C** Dust layer (white arrow) above the carapace photographed 1 km ENE of railroad station Versam-Safien at Las Ruinas sut Crestaulta (coord. 2744000/1186000). Photo courtesy M. Weidmann. **D** Two rock avalanche deposits (I and II) on top of each other separated by carapace (ca) as seen in the western flank of Val da Mulin ("Laaxertobel"). View is to the west. See text for discussion. Photo A. Pffifner

the course of the rock avalanche event. A heavily fractured zone immediately beneath the road separates the two compartments. The upper compartment borders a cataclaste with a "block-in-powder" texture, which outcrops above the tunnel.

The uppermost layer of the rock avalanche deposit is pictured in Fig. 10A. The uppermost 20 to 30 m consists of loosely packed blocks that measure one to several meters in diameter. The surface of the outcrop contrasts to the underlying fractured limestone, which

has a smoother outcrop surface. At the surface the loosely packed blocks generate a highly complex micromorphology with small depressions and individual blocks sticking out of the forest floor (see Fig. 10B). The orientation of bedding in these blocks is totally chaotic suggesting that they were free to move (and rotate) close to the surface of the rock avalanche.

At some localities a thin layer of white and very fine-grained sediment may be observed on top of the carapace (see Fig. 10C). The sediment is essentially made of calcite

and is about 1 m thick. It formed most likely from dust settling after the rock avalanche event.

In the flanks bordering the deep gorge of Val da Mulin (“Laaxertobel”) at the western limit of the Flims rock avalanche deposit two events can be recognized. Figure 10D shows the western flank of the gorge looking west to buildings of the village of Laax. Here the carapace nature of the brownish layer in the middle of the cliff and the topmost part of the gray layer above it are clearly evident. The brownish carapace layer may well be Cretaceous limestone (Öhrli Limestone), which is brownish at outcrop. All in all, the outcrop suggests that the avalanche formation occurred in episodes where a proximal compartment was emplaced onto an earlier formed one.

Insight for the internal structure of the rock avalanche deposit can also be gained from the morphologic expression visible on a digital elevation model. Figure 11A displays the area around Flims Dorf and Flims Waldhaus, which is hummocky at kilometer scale as well as on 10 m scale. Four of the depressions are lakes all of which have no superficial water influx. In Lag Prau Pulté the influx from the bottom is important with upwelling visible at the surface. Lag Prau Tuleritg and Lag la Cauma have low levels in winter and are filled by melt water in spring. Lag la Cauma starts to fill only once Lag Prau Tuleritg has reached a certain level. Both lakes have no superficial outlet. Lag la Cresta is also lacking a superficial inlet and has a minor outlet a few meters below the lake level. All these lakes as well as numerous springs point to permeability reminiscent of karst.

Two larger valleys can be made out in Fig. 11A, Vallatsch and Val Gronda. Both represent faults within the rock avalanche deposit. These faults were most probably activated late in the rock avalanche event. The lack of reference points on either side of the faults makes it impossible to determine the relative motion of the two sides and thus the fault types remains unknown. However, it can be speculated that they represent extensional faults activated as the trailing edge of the rock avalanche slowed down relative to the leading edge. In the case of Vallatsch, several closed depressions lacking water are lined up along the valley. These depressions may have formed by soil piping, i.e. collapse after erosion of fine-grained crushed limestone by subsurface flow of water (Bernatek-Jakiel & Poesen, 2018). Subsurface flow of water is evident from the upwelling in Lag Prau Pulté. In this case permeability along the fault might be just as important as karst. Closed depressions lacking water occur also along Val Gronda and the same arguments as for Vallatsch can be put forward. Several lineaments north and west of Conn are most likely faults with small offsets (marked 7 in Fig. 11A). They are sub-parallel and strike NW–SE. All of these faults suggest that the rock

avalanche deposit was a fractured but semi-coherent mass at the time of its formation. To the south of Conn a major erosional scarp extends across much of the rock avalanche deposit. Its eastern part is much sharper and younger and has to do with the incision of the Vorderrhein (see discussion below).

Several peculiar craters with diameters of up to 50 m are observed mainly south of the Vorderrhein between Carrera and Versam (see Fig. 11B) and north of the Vorderrhein near Trin. The craters are up to 15 m deep and lack any sediment at their bottom. The craters are not aligned but rather singular features loosely dispersed in the rock avalanche deposit. They are circular shaped with relatively steep walls. No backfilling can be detected. It is speculated that they represent blow-out pipes that formed when the Flims rock avalanche impacted and liquefied the water-saturated substrate of the valley floor. It is thought that the ensuing high-pressure conditions led to ejection of water and vapor upward through the rock avalanche deposit in somewhat randomly located vertical pipes. A comparable feature has been recognized in the Bonaduz Formation by Pavoni (1968). Similar to the closed basins mentioned above additional soil piping may have increased the depth of the craters. The continuation of these structures at depth cannot be assessed owing to the lack of outcrops.

Faults within the rock avalanche deposit are also related to the liquefaction of the glacio-fluvial sediment of the valley floor upon impact of the rock avalanche. At several places clastic dykes were injected vertically into the rock avalanche deposit. One example is located near the confluence of Flem creek and Vorderrhein in Val Pintrun (see Fig. 12A). The clastic dyke is about 10 m wide and filled with gravel, sand and clay. Clay layers within gravel are vertical, and within gravel components are rounded and have their long axis vertically aligned. The dyke intruded into solid fractured limestone. It is suspected that the clastic dyke intruded into the rock avalanche deposit along an opening created by a vertical fault.

Figure 12B shows two pillars of indurated gravel. As already noted by Calhoun and Clague (2018) the gravel is finig upward. But in the left pillar one clearly recognizes limestone blocks, which are remnants of the wall rock, i.e. rock avalanche deposit. The pillars are situated at an elevation just above the Vorderrhein, but rock avalanche deposits outcrop higher up behind the pillars. It thus seems that the pillars stem from a clastic dyke that did not reach the surface of the rock avalanche deposit. Most of this clastic dyke was worn down by erosion.

The blow-out craters and the clastic dykes are located along the valley axis of the Vorderrhein in the area west of Versam and south of Trin. Seemingly they occupy the area above the central axis of the ancient valley.

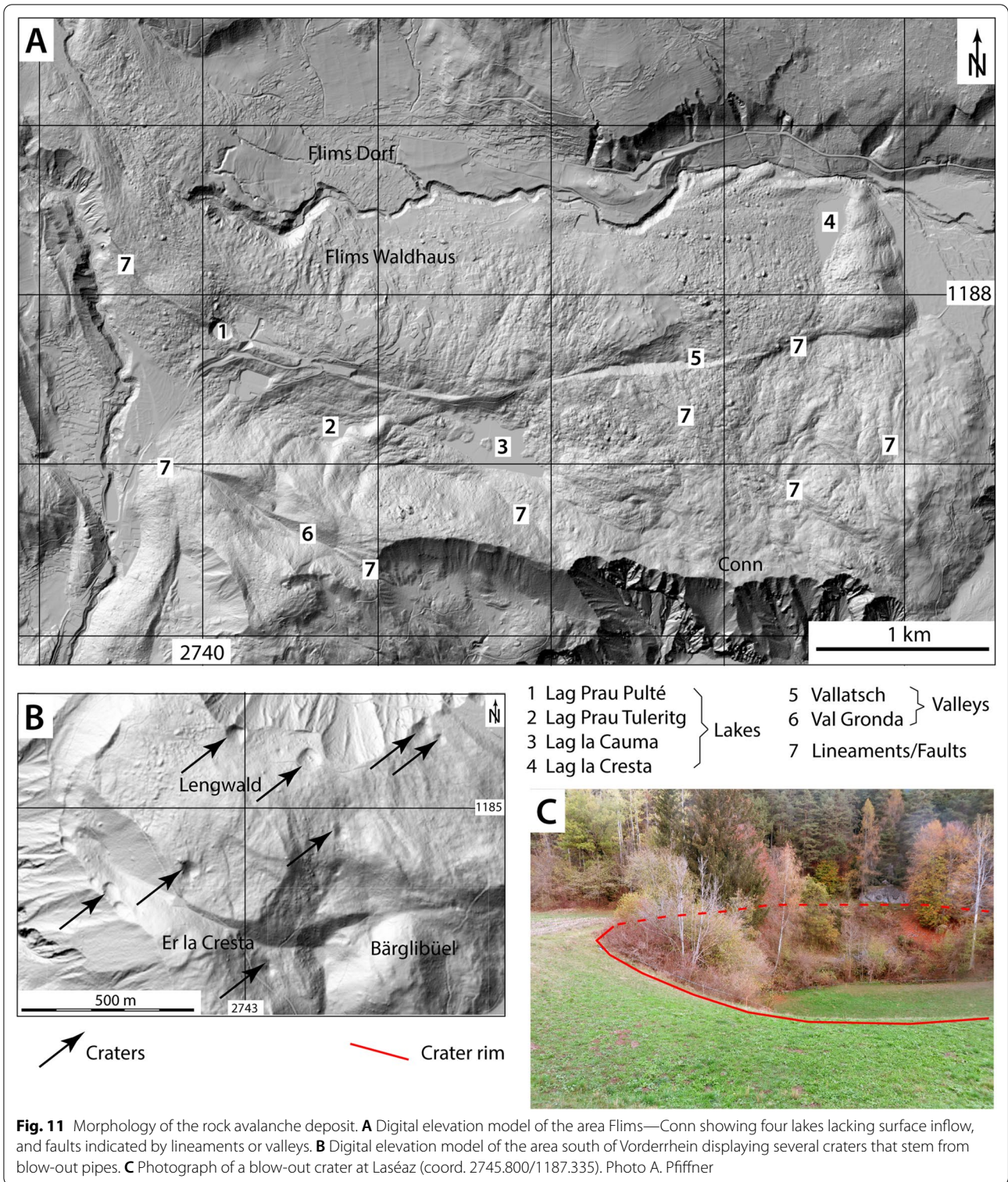


Fig. 11 Morphology of the rock avalanche deposit. **A** Digital elevation model of the area Flims—Conn showing four lakes lacking surface inflow, and faults indicated by lineaments or valleys. **B** Digital elevation model of the area south of Vorderrhein displaying several craters that stem from blow-out pipes. **C** Photograph of a blow-out crater at Laséaz (coord. 2745.800/1187.335). Photo A. Piffner

In the cross-section of Fig. 8 the glacio-fluvial clastic valley fill is shown to be perturbed just beneath the rock avalanche deposit owing to liquefaction by the impact of the rock avalanche. The basal contact of the rock

avalanche deposit is drawn as to have pointed plugs rising into the deposit. The geometry is drawn to show the kinship between plugs, faults and clastic dykes.



Fig. 12 Injection of substrate into the rock avalanche deposit. **A** Clastic dyke in Val Pintrun (coord. 2745380/1186500) displaying vertically layered gravel (gr), sand (sa) and silt (si) between limestone compartments (ls) of the rock avalanche deposit. **B** Two gravel pillars 250 m east of railroad station Trin. The pillar on the left is in vertical contact with rock avalanche deposit

4 The Bonaduz formation

The Bonaduz Formation consists of gravel that lacks depositional structures and shows fining upward grading. Pavoni (1968) and Calhoun and Clague (2018) provide a detailed description of this sediment. The gravel part is topped by sand and in addition it contains fragments of rock avalanche deposits measuring up to several hundreds of meters, as well as rip-up clasts of silt (see von Poschinger & Kippel, 2009).

Regarding the pebble spectra two observations are important: (1) Pebbles of Punteglias granite and Helvetic sediments are described from outcrops in the Hinterrhein valley by Abele (1997) and von Poschinger and Kippel (2009), respectively. (2) In the Reichenau gravel pit, the Bonaduz Formation contains radiolarian chert pebbles (own observation); these can only stem from Austroalpine nappes and must therefore have been transported by the tributaries of the Hinterrhein. Thus, even though the Bonaduz Formation was mobilized and liquefied, pebbles from both source areas were present in the area of confluence of Vorder- and Hinterrhein—similar to the situation that one can observe at present in the river bed at the confluence in Reichenau.

The distribution of the Bonaduz Formation is shown in Fig. 1. The main area is around the village of Bonaduz. The outcrops north of Vorderrhein at Matriel (west of Tamins) witness the later incision by the Vorderrhein. Towards the south, the Bonaduz formation may be traced over a distance of more than 10 km along the Hinterrhein to Rodels and farther to Summaprada (Wyss et al., 2017). The top of the formation at Bonaduz is at 660 m a.s.l., it then rises southward to 720 m a.s.l. at Summaprada. Towards the ENE the Bonaduz Formation may be traced down the Rhine Valley for a long distance. It includes the hills (tumas) around Domat/Ems and extends at least to Chur as discussed in von Poschinger and Ruegg (2012). Towards the west, the Bonaduz Formation is present in clastic dykes on both sides of the Vorderrhein and is reported in geotechnical investigations farther up valley around Ilanz/Glion (Aemisegger, 2018 and 2019).

In the Reichenau gravel pit (located between Bonaduz and Tamins in Fig. 1) an important outcrop was created during mining activity; it exposed Tamins rock avalanche deposit beneath the Bonaduz Formation testifies that the latter is younger. The photographs in Fig. 13 taken in the Reichenau gravel pit summarize the sedimentary fabric of

the Bonaduz formation. Figure 13A illustrates the lack of stratification in the gravel. Figure 13B shows a Pavoni or elutriation pipe, i.e. a vertical pipe where water escaped upward, a proof that the sediment had initially been water saturated. A large rip-up clast of silt within gravel is depicted in Fig. 13C. An even larger rip-up clast is present in Tuma Casté, a hill in Domat/Ems, where it makes out the northern half of this hill and beyond. These clasts bear witness of scouring and mixing during motion of the liquefied slurry.

The composition of the large fragments of rock avalanche deposits in the Bonaduz formation allows us to assess the motion pattern of the Bonaduz formation in map view. While Quinten limestone is abundant in both, the Tamins and the Flims rock avalanche, Cretaceous limestones are clearly attributed to the Flims rock avalanche, and Permian volcanics and Triassic dolostones are unequivocally linked to the Tamins rock avalanche (the Permian clastics in the Flims rock avalanche deposit can easily be distinguished from the volcanics). Based on this it is possible to draw a boundary between Flims derived and Tamins derived fragments (dashed line in Fig. 1). A detailed analysis of the contents of the various hills is given in Piperoff (1897), Staub (1910), Remenyik (1959) and Pfiffner and Wyss (2023). The easternmost fragments attributed to the Flims rock avalanche (Bot Dagatg and Bot Panadisich north of Bonaduz) may be considered as long-runout features. But the contacts at Bot Dagatg are such that the Cretaceous limestones sit on and next to Bonaduz formation suggesting some scouring of the Bonaduz formation by the Flims rock avalanche. The fragments linked to the Tamins rock avalanche have a more complex history. At Plazzas (east of Bonaduz) a large fragment of Permian volcanics is overlain by Bonaduz formation, and southeast of Bonaduz the fragments of Jurassic strata are outcropping within the Bonaduz Formation. The latter is shown in Fig. 13D. Here the fragment to the right consists of a syncline of Jurassic strata, bordering to the left to Bonaduz Formation making a high cliff. The fragment to the left, topped by a castle, is made of Jurassic sediments again and is surrounded by Bonaduz Formation. Fragments that have been carried farther south into the Hinterrhein valley (Domleschg) contain Permian volcanics and Triassic dolostones. The southernmost fragment at Rodels consists of Permian volcanics. It seems most likely that these far travelled fragments were ripped off the

(See figure on next page.)

Fig. 13 Bonaduz Formation at outcrop. **A** Detailed view of gravel within the Bonaduz Formation in the Reichenau gravel pit. Note the lack of any sign of stratification. **B** Pavoni pipe in the Reichenau gravel pit with near vertical elutriation in the Bonaduz Formation. **C** Large rip-up clast of silt within the Bonaduz Formation in the Reichenau gravel pit. **D** The plain with the villages Bonaduz and Rhäzüns corresponds to the top of the Bonaduz Formation. In the foreground two large rock avalanche fragments are exposed along the Hinterrhein. To the right a synformal structure within Jurassic sediments and to the left middle Jurassic sediments. Between the two fragments gravel of the Bonaduz Formation forms a steep cliff. Bo: Bonaduz Formation, Do: middle Jurassic sandstone (Dogger), Ma: upper Jurassic Schilt formation (Malm). Photos A. Pfiffner.

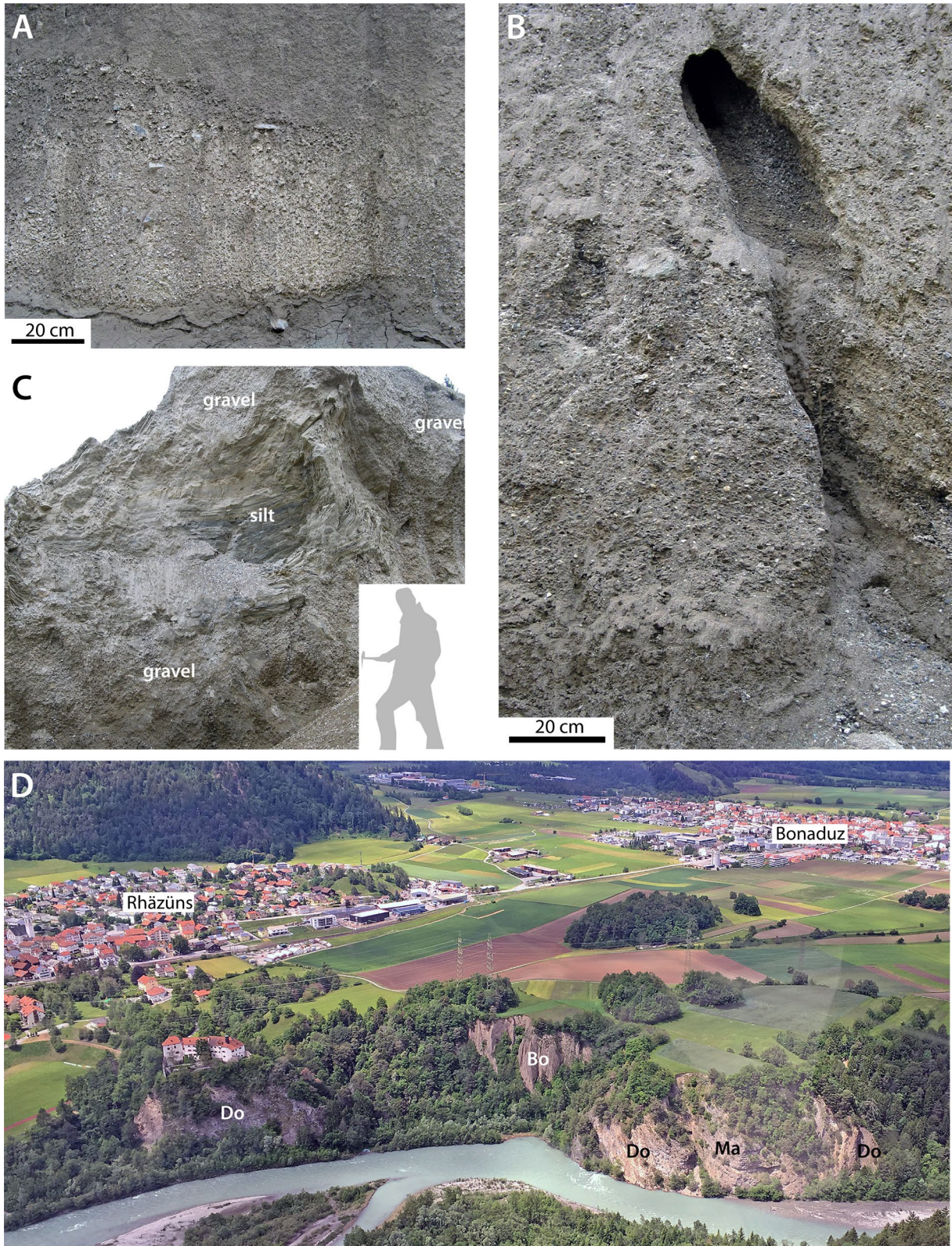


Fig. 13 (See legend on previous page.)

western margin of the Tamins rock avalanche deposit and washed southward with the Bonaduz Formation slurry.

As discussed by Calhoun and Clague (2018) the Bonaduz Formation moved as a mass flow with sufficiently high viscosity as to transport large fragments of rock avalanche deposit over considerable distance. They also argue that the mass flow moved rapidly and that it was not driven by gravity given that it moved to higher elevations towards the south (Summaprada).

The Bonaduz mass flow triggered by the impact of the Flims rock avalanche moved also towards the ridge across the Rhine Valley created by the Tamins rock avalanche, struck this ridge and breached it as already pointed out by von Poschinger (2005) and Calhoun and Clague (2018). The breach is evident in the photograph in Fig. 14A. The mass flow entrained the rock avalanche deposit of the breach and carried it down the valley. Large fragments settled around Domat/Ems (see Fig. 1), in Felsberg and in Chur as hills (tumas). These are depicted in the photograph of Fig. 14B. The composition of these tumas reflects the composition of the Tamins rock avalanche deposit, namely mainly Quinten limestone. Locally, east of Domat/Ems and in Felsberg also Permian and Triassic rocks can be found (Pfiffner & Wyss, 2023). The volume of the breach is estimated at 36 million m³ by extrapolating the ridge shape from Tuma da Zislis across the Rhine. The volume of the entrained fragments is more difficult to estimate. For one the base of the Bonaduz mass flow is nowhere exposed. Well data do not distinguish Bonaduz derived gravel. They do however show that rock avalanche fragments are present beneath the alluvium away from the tumas and that some of the tumas are connected in the subsurface. Assuming that the tumas reach 20 m beneath the topographic surface as suggested by well data, their total volume amounts to about 10 million m³. Assuming that the Bonaduz mass flow extends over the entire surface from the breach to Chur spanning all the tumas, an additional volume of entrained rock avalanche fragments must be considered. If a 10 m thick subsurface continuation over one third of the area is admitted, a volume of 26 million m³ is obtained, balancing the volume of the breach.

On the photograph of Fig. 14B one recognizes large fans that were built by tributaries from the right (south) on the valley floor. These fans are still active but were already present at the time of the Flims event as evidenced by Paleolithic artefacts found on the Plessur fan in Chur (Nielson, 2002). The artefacts are thought

to represent remnants of a resting place of hunters and date to 13,000–10,000 B.P., i.e., they are older than the 9450 B.P. of the Flims rock avalanche. Thus, the rock avalanches as well as the Bonaduz mass flow were both witnessed by Paleolithic hunters.

Finally, it has to be mentioned that as the Bonaduz mass flow crashed into and breaching the ridge of the Tamins rock avalanche, a tsunami went over this ridge leaving behind a thin sediment layer. Such splash zones exist north and south of the Rhine (see Scholz, 2018; Calhoun & Clague, 2018; Scholz, 2018; Pfiffner & Wyss, 2023; Pfiffner et al., in press). The sediment is a diamicton with rounded pebbles of limestone and crystalline rocks embedded in a silty matrix. Outcrops are located in local depressions but also on ridges (see map by Pfiffner & Wyss, 2023, and Pfiffner et al., in press). North of the Rhine, at Rascheu, diamicton can be found up to 780 m a.s.l., that is 100 m higher than the maximum level of Lake Bonaduz (680 m a.s.l.).

5 Lake Ilanz

Lake Ilanz, the lake dammed by the Flims rock avalanche, has been widely discussed in the literature. One of the main issues was the evaluation of the lake level. A review of the ideas is given in von Poschinger (2005). This author outlined the occurrence of lake sediments, namely fines which indicate a lake level at 820 m. a.s.l., but did not rule out a short-lived higher level in the early stages. Nevertheless, he mentioned that the lake level could never have exceeded 935 m a.s.l., i.e. the altitude of the pass of Carnifels between Carrera and Versam (see Fig. 15). This pass is devoid of indications speaking for a water or wind gap. Wassmer et al. (2004) on the other hand interpret that the lake level was at 1150 m a.s.l. They used the presence of terraces with gravel in the Lugnez valley to sustain their interpretation. However, the detailed analysis of Nabholz (1951) clearly revealed that these terraces are Pleistocene glacio-fluvial deposits, i.e. much older.

Several delta deposits shed from the Flims rock avalanche deposit outline the lake level of Lake Ilanz (see Fig. 15). The easternmost is located at Tuora and suggests that the ancestral dam was most likely extending across the Vorderrhein east of Tuora as a continuation of the ridge Lengwald—La Mutta and from here eastward towards Ransun (see Fig. 15). The delta deposits at Tuora, as well as the ones found farther west (e.g. Planezzas in Fig. 15) all are inclined towards the Vorderrhein with the lowermost subhorizontal part at 820 m a.s.l. They

(See figure on next page.)

Fig. 14 **A** Aerial view of the Reichenau breach. White line with tick marks outlines the erosional scarp. Photo ©VBS. **B** Aerial view of the Tuma landscape of Domat/Ems. Note the large fans built up from tributaries on the right (south) that deviate the Rhine to the left. These fans existed already at the time of the Flims events such that the Bonaduz mass flow was also constrained to the left side of the valley floor. Photo R. Homberger, courtesy of F. Isepponi

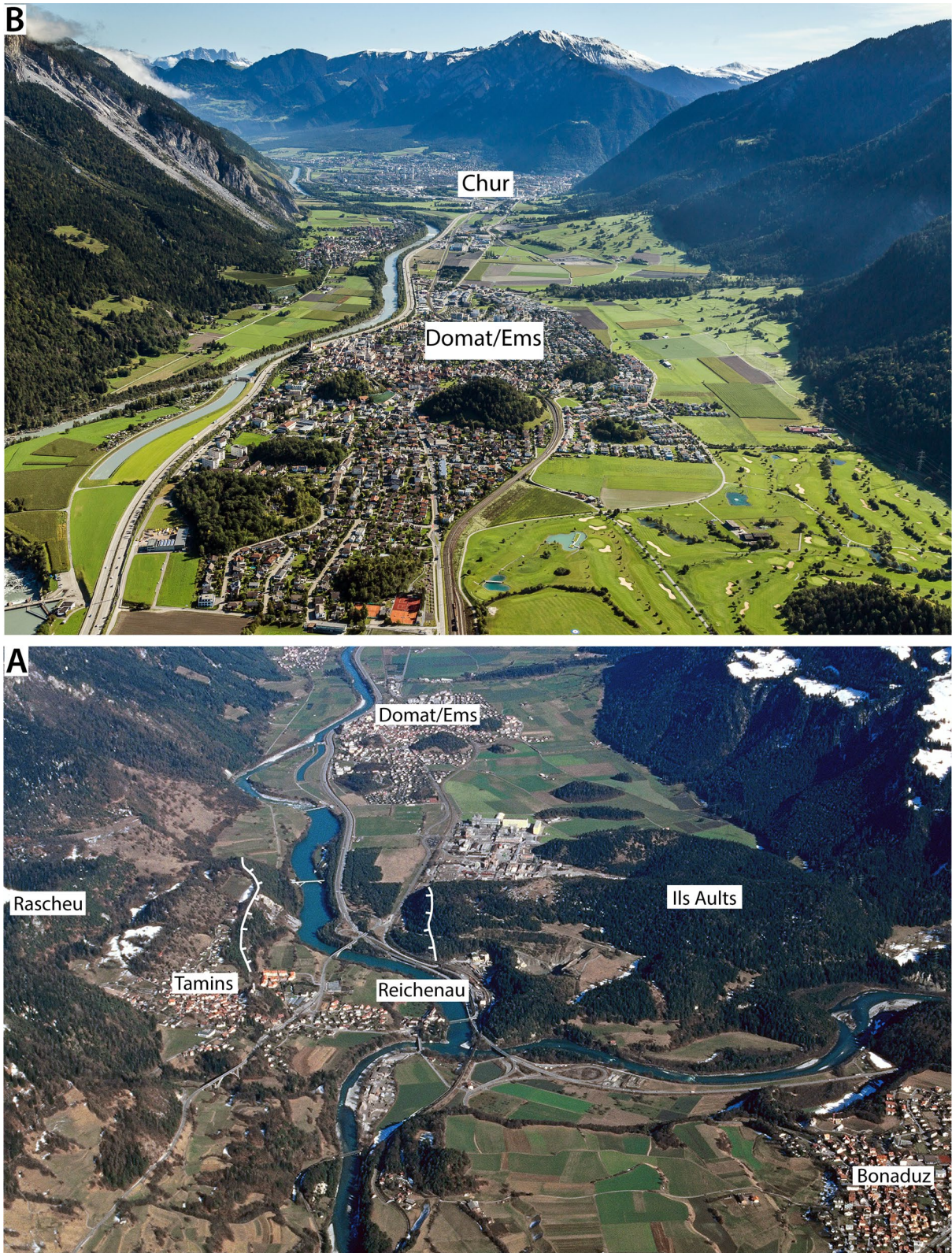
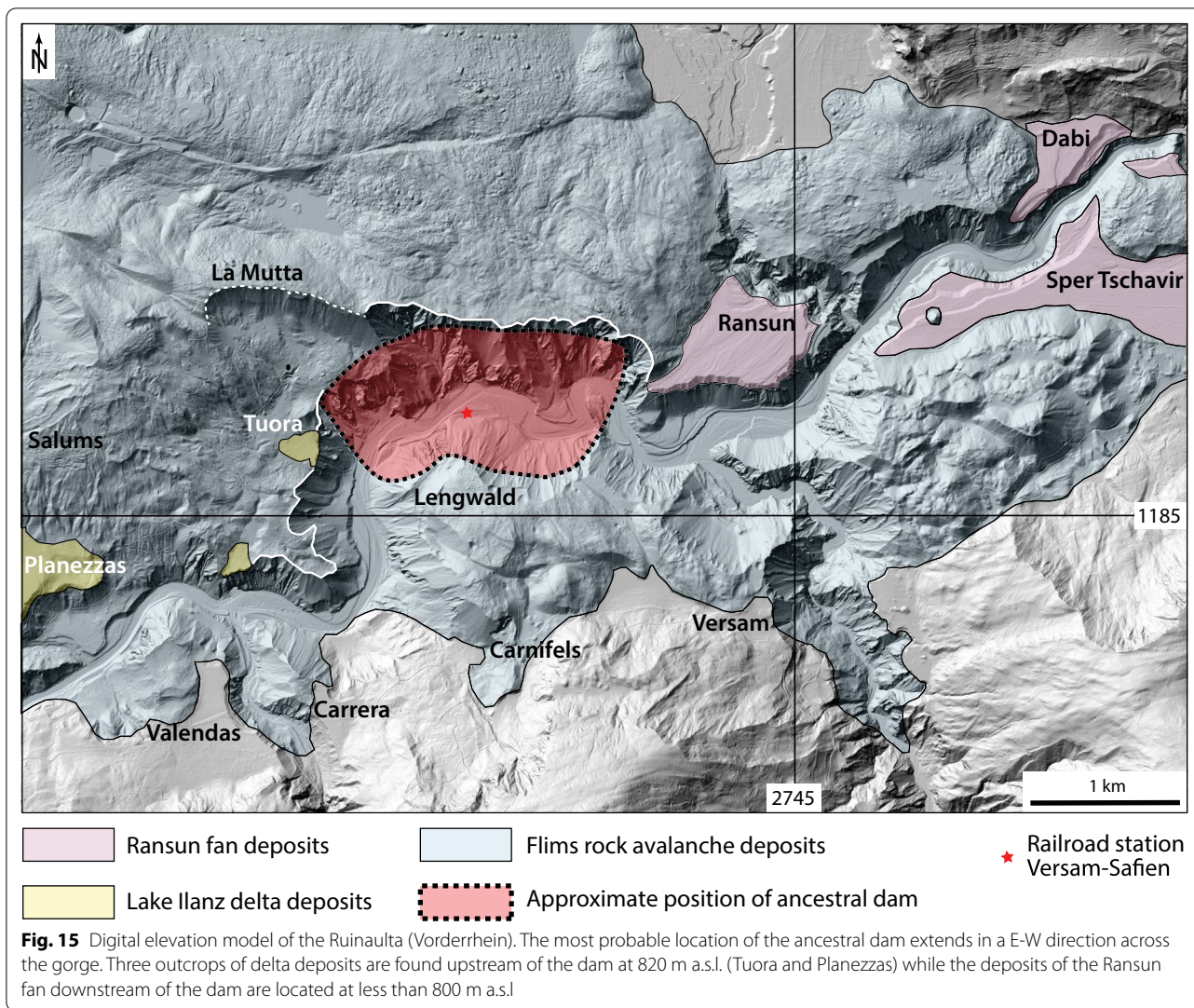


Fig. 14 (See legend on previous page.)



confirm a lake level at 820 m a.s.l. which implies that the lake extended upstream to Zignau (Rein Anterior/Vorderrhein) and Uors (Glon/Glenner).

Figure 16A is a detailed view of the area around Planezzas. Several gullies between Salums and Planezzas Sura are dry today and end at the gentle slope of Planezzas Sura. It is argued that these gullies formed just after the rock avalanche event before vegetation protected the slope from erosion. At the lake level the eroded sediment

was incorporated into a delta. Val da Mulin is cut into this gentle slope by subsequent erosion and exposes horizontally layered clastics of Planezzas (see Fig. 16B). Figure 16C shows the same sediments on the opposite side of Val da Mulin south of Bregl. Here too, horizontal bedding is evident with alternating layers of finer and coarser clastics. Layers of cobble and boulder deposits point to a dynamic regime. The gray color of the outcrop stems from the fact that the clastics consist basically of

(See figure on next page.)

Fig. 16 Delta and lake sediments of Lake Ilanz. **A** Digital elevation model of Planezzas Sura. Gullies end downward at the foot of the slope suggesting that incision ceased once the lake level, resp. the delta at Planezzas was reached. **B** Delta sediments shed into Lake Ilanz at Planezzas east of Val da Mulin. The sediments (white arrows) overly rock avalanche deposits and are about 50 m thick. **C** Delta sediments shed into Lake Ilanz at Sagogn west of Val da Mulin. The sediments are stratified with a layer of boulder-sized clasts on the right. **D** Lake sediments (white arrow) at Ruinas da Starviz south of Sagogn in a cliff bordering the Vorderrhein (coord. 2739420/1183620). The sequence is stratified and includes fine-grained layers. Photos A. Pfiffner

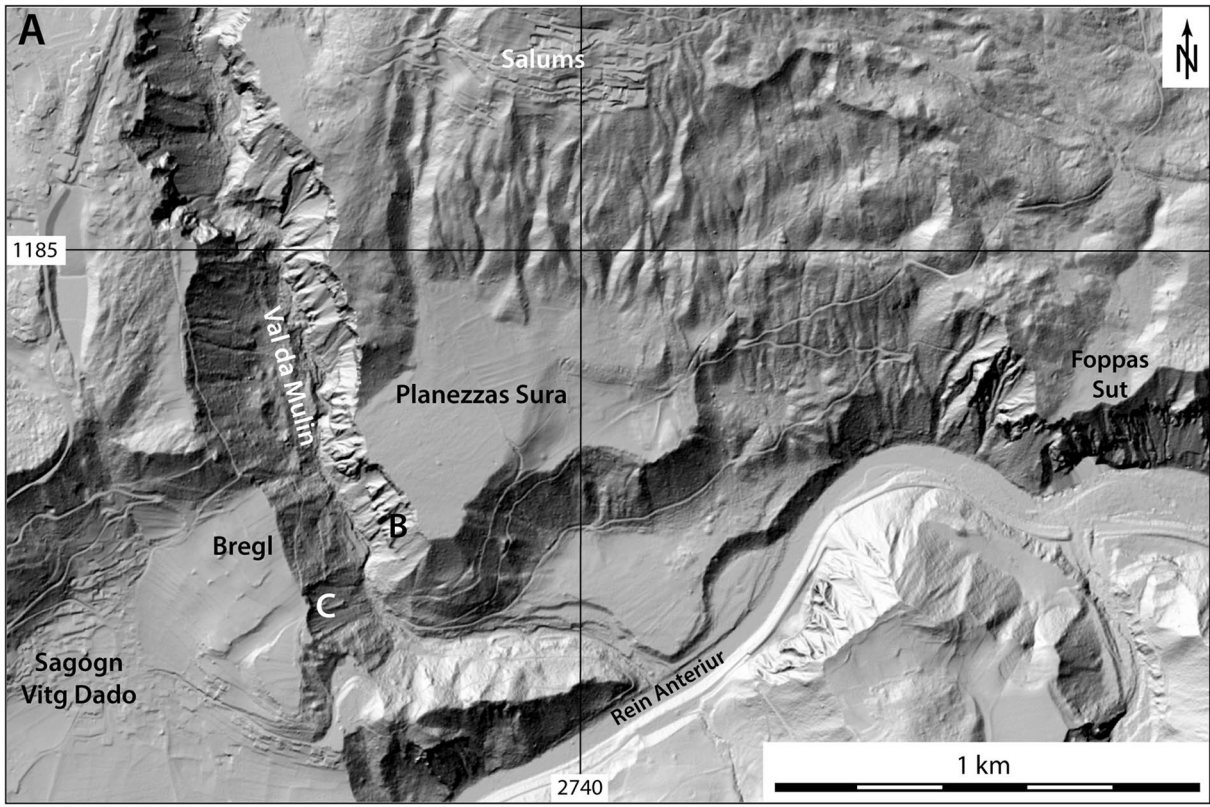


Fig. 16 (See legend on previous page.)

reworked rock avalanche deposits (Quinten and Tros limestone).

Sharp erosional scarps follow the course of the Vorderrhein on either side of the Ruinaulta. North of the presumed dam location a significant change is observed. North of railroad station Versam-Safien the sharp break in topography occurs at 1000 m a.s.l.; it then climbs to 1200 m a.s.l. to La Mutta. At the same time south of La Mutta the topography levels off towards the presumed dam and a sharp break may be followed from here to the west at lower elevation (820 m a.s.l.). It could be put forward that while Lake Ilanz existed, higher erosion rate downstream of the dam widened the gorge and shifted the active erosional scarp outward.

At Ruinas da Starviz (SE of Sagogn Vitg Dado) a very small outcrop of horizontally layered fine clastics are attached to the cliff made of rock avalanche deposit (see Fig. 16D) at 700 m a.s.l. This outcrop suggests that the sediments were laid down on the margin of the rock avalanche deposit (represented by the cliff). Similar sediments are reported from an outcrop 500 m farther to the north at 780–800 m a.s.l. by von Poschinger (2005). There, a 20 m thick succession of finely-layered silt and sand overlies layered coarse-grained clastics, which in turn overlie rock avalanche deposits. The author speculated that this 900fold repetition could possibly represent a time interval of 900 years of varve-sedimentation in Lake Ilanz, or if intermittent heavy rainfalls are included, a shorter time span. Considering the outcrops in the lower reaches of Val da Mulin (Fig. 16B and C) it seems more plausible that these sediments represent the distal part of an alluvial fan emanating from Val da Mulin. From Sagogn westward, the southern limit of the Flims rock avalanche deposits follows more or less the Vorderrhein.

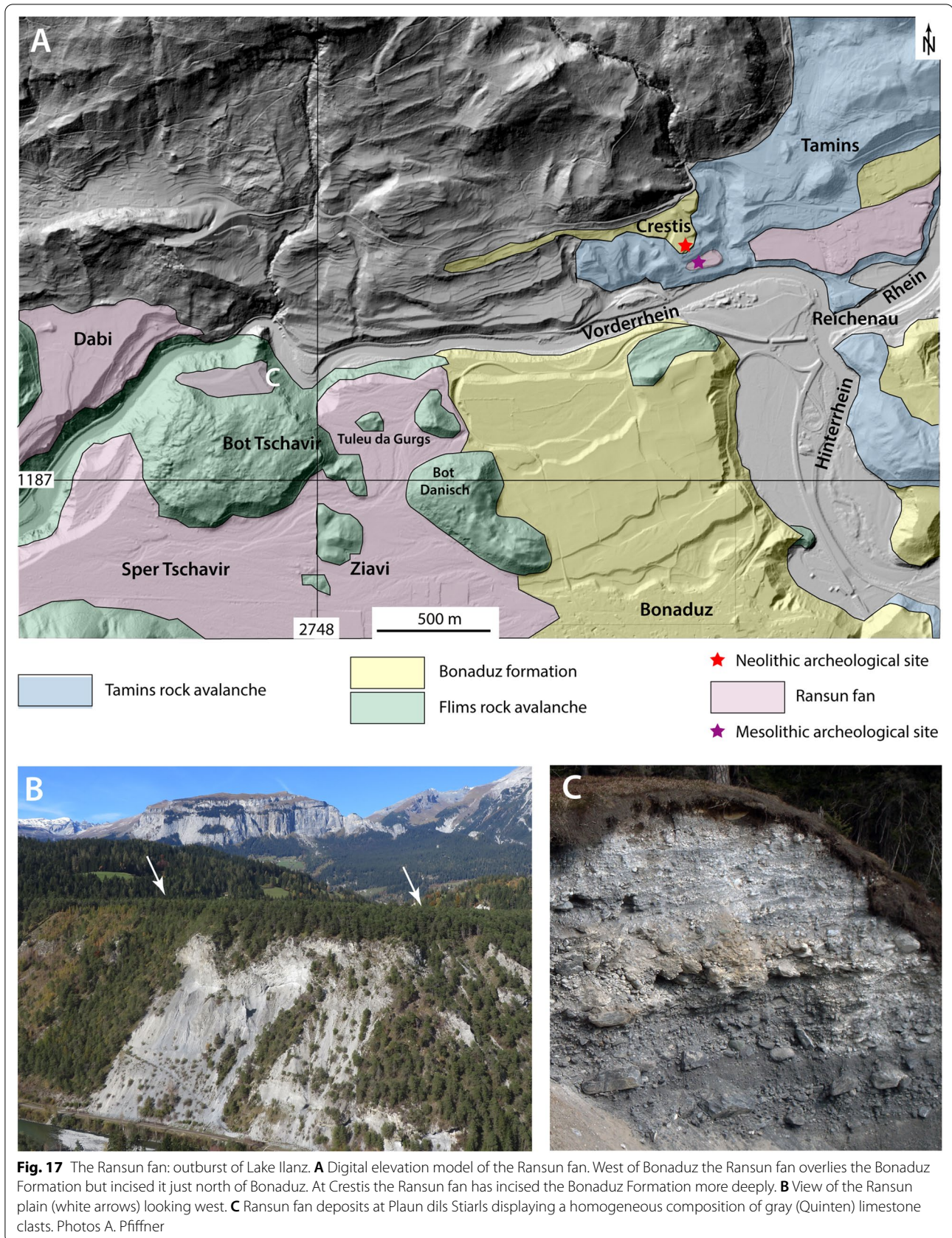
Once the lake was filled, which according to the estimate of von Poschinger (2005) took only one or two years, the dam was overtopped and incision of the natural dam started. Dam breach is complex and depends on the grain-size distribution within the dam and the erodibility of the dam material (Mei et al., 2021). According to Li et al. (2021) dam breaching of natural dams occurs in three stages: (1) Incision with fine particles being moved leading to a notch in the dam crest, (2) Development stage with erosion on the down-stream side of the dam and mobilization of unsorted particles which are deposited in an alluvial fan, and, (3) Failure of the dam with rapid “two-helix flow” erosion deepening and enlarging the breach and resulting in collapse of the slopes. Costa and Schuster (1988) analyzed the longevity of landslide dams and came to the conclusion that 85% of the 93 dams they worked on failed within one year. Dams consisting of large or cohesive particles last longer because of their resistance to erosion to surface water flow and to

pipng and seepage within the dam. In case of Lake Ilanz the dam was composed of a coherent limestone breccia, which now forms high cliffs in the Ruinaulta gorge. The dam therefore can be considered as relatively stable and resistant to breaching.

A large alluvial fan, named Ransun fan, is exposed downstream of the natural dam (Fig. 15). It can be recognized by slightly inclined plains neatly lined up downstream the valley, but dissected by later incision of the Vorderrhein River. The Ransun fan has an average slope of 1.3° from Ransun to Reichenau/Tamins. Remnants of plains occur at the localities Ransun (780 m a.s.l.), Dabi and Sper Tschavir (700 m a.s.l.), Ziavi (680 m a.s.l.), Tuleu da Gurgs (660 m a.s.l.), Mittler Crestis (630 m a.s.l.) and Reichenau/Tamins (610 m a.s.l.) in Fig. 17A. Fossil channels outline the course of debris flows, visible at Ransun (Fig. 15) and around Ziavi (Fig. 17A). From Sper Tschavir to the east, the flow diverted with one branch extending toward Bonaduz and the other towards Tuleu da Gurgs. North of Bonaduz the debris flows incised the Bonaduz formation. The composition of the fan deposits is exclusively (Quinten) limestone, which suggests that this fan was fed solely by the rock avalanche deposit of the dam.

The locality Ransun represents a gently east-dipping wooded planar surface (see Fig. 17B), which is underlain by 10 – 20 m thick coarse-grained clastics with rounded pebbles, cobbles and 2 m large blocks. Despite thick vegetation, fossil channels are omnipresent. The base of the deposits as observed along the erosional scarp is irregularly shaped reflecting erosional processes while the top of the deposits is more planar indicating depositional processes. At the localities Zault (coord. 2745630/1186160) and Plaun dils Stiarls (coord. 2,747,750/1187470) these sediments outcrop on an erosional scarp and show horizontal bedding with cobbles concentrated in individual layers (see also von Poschinger, 2005). The photograph in Fig. 17C shows the outcrop at Plaun dils Stiarls with its homogeneous composition of gray (Quinten) limestone. A most interesting terrace pertaining to the Ransun fan is located at Mittler Crestis near Tamins (coord. 2749700/1187950). Archeological excavations revealed artefacts of Mesolithic age (9500–9000 BP; Seifert, 2013), i.e. ages hardly younger than the age of the Flims rock avalanche (9450 BP). Obviously, Lake Ilanz did not last very long and incision of the natural dam started very soon after the Flims event.

As already outlined by earlier workers (von Poschinger, 2005, Calhoun & Clague 2018) several alluvial terraces at lower level than the Ransun fan can be traced along the Vorderrhein. Candrian (2010) could map four terraces located roughly 5, 10, 20 and 40 m above the Vorderrhein, all of them sloping with 0,3° to the east. At Chrummwag, 1 km east of railroad station Versam-Safien



(coord. 2743750/1185650) an ancestral valley floor is visible about 40 m above the Vorderrhein (see Fig. 18A). The valley fill consists of limestone blocks that stem from a smaller rock avalanche, which blocked and deviated the river to the north. Subsequent incision resulted in the meander the river now follows. The photograph in Fig. 18B shows an alluvial terrace 40 m above the Vorderrhein in the locality Ruina dallas Foppas which is topped by limestone scree. Figure 18C finally displays an alluvial terrace 30 m above the Vorderrhein at Islahalda with rounded pebbles and cobbles of crystalline rocks. The lower terraces were obviously fed by material from farther upstream where crystalline rocks were available.

6 Discussion

6.1 Pre-failure situation and gliding surface

It has long been known that the geologic structure of the source area plays an important role in the triggering of rock avalanches. Important parameters include the mechanical properties of the rocks and pre-existing deformation features like joints or foliations, and the presence of a potential detachment horizon. The Flims rock avalanche developed in predominantly massive limestone on a steep valley flank carved by glaciers. By the time the rock avalanche was mobilized the glaciers had melted away for at least 5000 years. Thus, it is unlikely that a direct link between the disappearance of the support of the ice on the mountain flank and the triggering of the rock avalanche exists. However, the disappearance of the glaciers had an isostatic effect, which initiated faults raising the valley-side compartments relative to mountain-side compartments (Ustaszewski et al., 2008). In addition, substantial temperature fluctuations occurred in the time interval between the LGM and the time of the rock avalanche events (Blümel, 2002). For example, the warm period of the Bölling interstadial was followed by the cold Younger Dryas, which in turn was followed by a longer warm period with ice-free Alps (the so-called Climate Optimum). Both, the Tamins and Flims rock avalanche events occurred in the early phase of this warm period. It can be argued that the preceding temperature changes with freezing and thawing permafrost had fractured and weakened the bedrock. The effect of water percolating in ice-free tension cracks, along joints, foliation planes and bedding planes may affect stability at greater depth (Fischer et al., 2010; Gischig et al., 2011a, b; Kenner & Phillips, 2017). With climate warming at the onset of the Climate Optimum, permafrost became warm and at -1 to 0 °C tensile strength and frictional strength between formerly ice-bound bedrock pieces are greatly reduced (Davies et al., 2001; Haeberli & Hohmann, 2008) leading to destabilizing slopes.

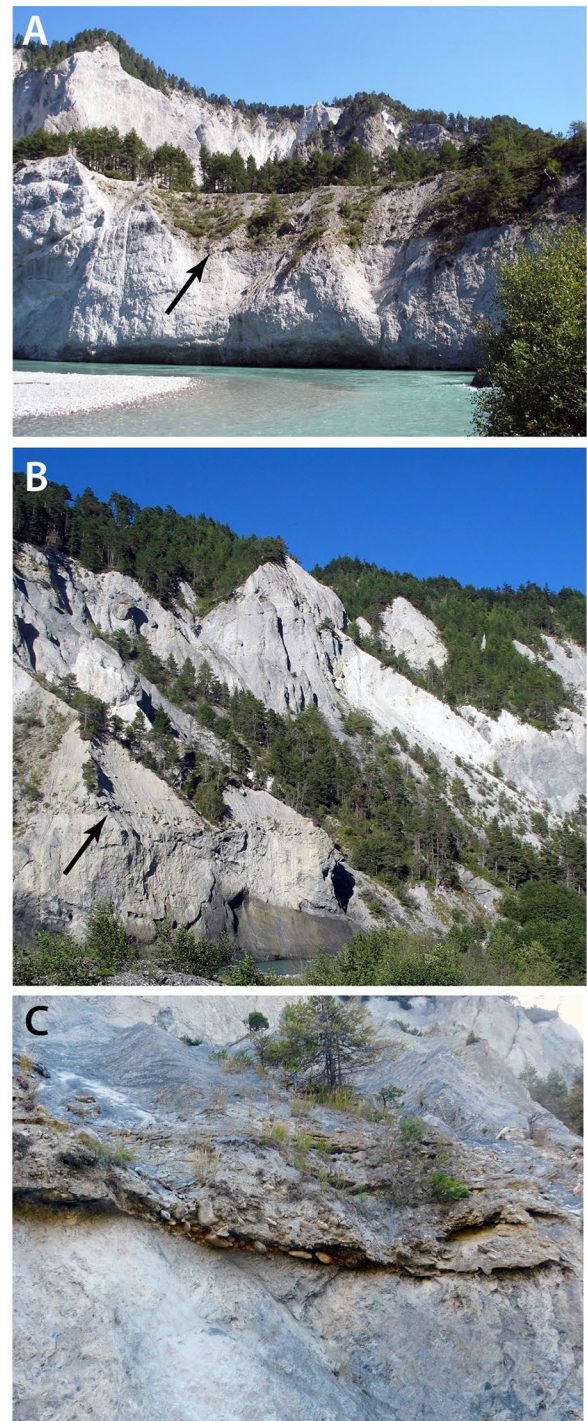


Fig. 18 Incision of the Ruinalta gorge. **A** Ancestral valley floor (black arrow) at Chrummwag located 40 m above the modern Vorderrhein. **B** Ancestral riverbed (black arrow) perched on the cliffs of Ruina dallas Foppas. **C** Ancestral riverbed perched on the cliffs of Islahalda. Pebbles include rounded cobbles of crystalline basement. Photos A. Pfiffner

The paleo-landsurface is interpreted to have a steep slope just north of the Plaun fault where bedrock consists of «Upper Quinten limestone», a poorly bedded massive limestone which tends to form high cliffs throughout the Alps. As discussed by Wolters and Müller (2008) such abrupt slope angle changes give rise to gravity-induced high shear stress concentrations activating a glide surface emanating from the break in slope. The cross-sections showing the paleo-landsurface and the glide surface of the Flims rock avalanche (Fig. 7A) highlight the lateral continuation of the break in slope.

Pre-existing structural weaknesses were likely to have influenced the instability. In the Flims rock avalanche, both lateral scarps follow a fault system. New mapping has revealed that the eastern fault runs along the valley of Bargis down to Trin Mulin, the western from Plaun Segnas Sut down towards Flims. Both faults are parallel to the main regional jointing system (Pfiffner, 1977) and allowed some independent deformation within the nappe pile on either side. As discussed by Volken (2015) and Aaron et al. (2020) the lateral scarp located on the western flank of Flimsenstein is also parallel to the main jointing system and associated faults. Additional vertical fault zones and joints enhanced the effect of percolating water and air venting in destabilizing the rock mass and ultimately controlled the orientation and location of the lateral scarps.

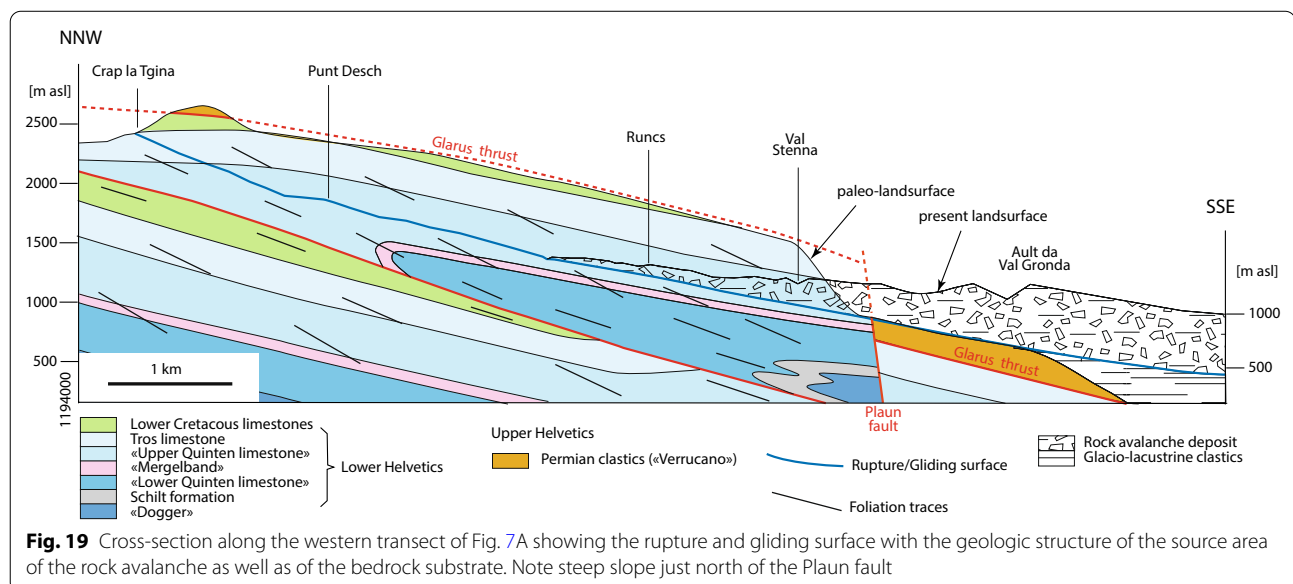
Remains the question if the basal gliding surface of the rock avalanches is also structurally controlled. Recent mapping (Pfiffner & Wyss, 2023, and work in progress) combined with data from the road tunnel in Flims have provided crucial information. The gliding surface is

sub-parallel to bedding in the lower reaches (see Fig. 19) and cuts up section towards the head scarp. The gliding surface has a flat segment near Punt Desch from where it cuts up section to the north. Volken (2015) and Aaron et al. (2020) speculated that the «Mergelband» acted as detachment layer. However, construction of the Flims tunnel accompanied by several boreholes (Geologengesellschaft Umfahrung Flims 2007) and recent mapping revealed that the «Mergelband» is located below the top-bedrock surface beneath the rock avalanche deposit as shown in Fig. 19. Moreover the «Mergelband» is not a marl, but a 20–30 m thick sequence of thin bedded limestone in which 2–5 cm thick limestone beds alternate with 2–3 cm thick slightly argillaceous limestone beds (Pfiffner, 1972a, b).

A penetrative Alpine foliation is present in the limestones above and beneath the gliding surface, which is oriented sub-parallel to the gliding surface and may represent a potential weakening fabric. Flattened calcite grains and occasional sheet silicates oriented parallel to the long axes of the calcite grains define this foliation (see Fig. 20). This anisotropy may have controlled the orientation of fracturing.

The structural level of the gliding surface is possibly controlled by the pre-failure topography (Figs. 7A and 19) and the associated high tensile stresses at the break in slope at the foot of a steep limestone cliff (Savage, 1993; Wolters & Muller, 2008).

As mentioned earlier, the gliding surface contains steps and lateral ramps that are up to 50 m high. The lateral ramps are parallel to the lateral scarps and possibly also structurally controlled. More interesting are the steps



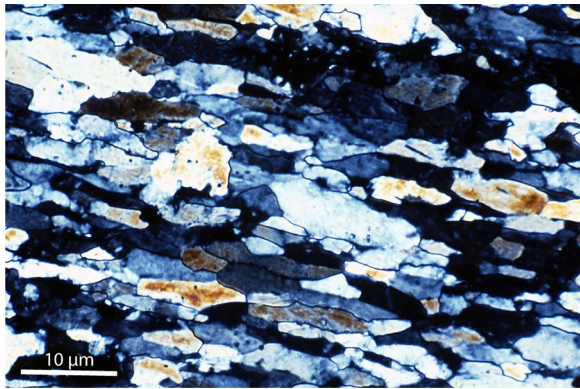


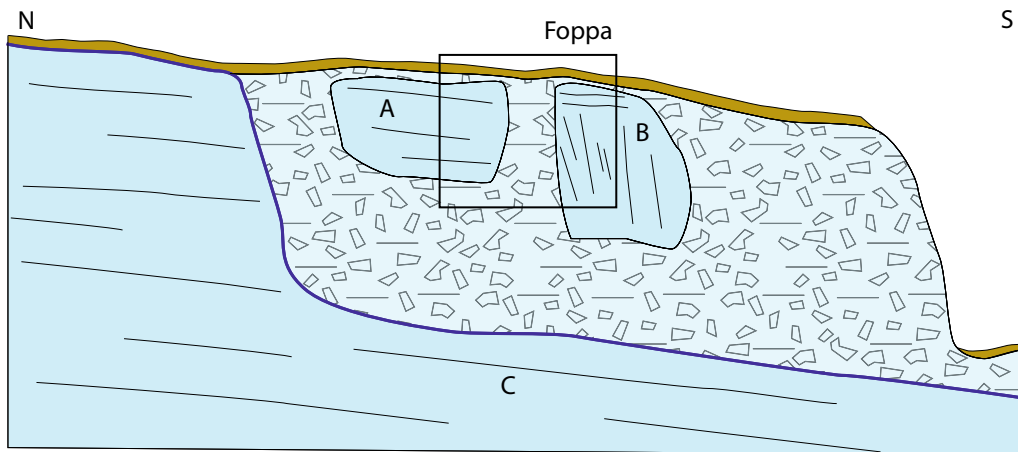
Fig. 20 Thin-section of Quinten limestone showing shape preferred orientation of calcite grains

where the basal gliding surface jumps to a lower level. The limestone forming the step are highly shattered and fragmented into blocks such that one is often not sure whether to consider it part of the rock avalanche or the in situ collapsing substrate. The situation is presented in

Fig. 21 with two blocks swimming in a crushed matrix of the rock avalanche. Block A was detached but remained coherent such that bedding is preserved. Block B is shattered with steeply dipping joints cutting across a more brecciated part. It seems that the blocks were torn away from the bedrock at the step and gradually incorporated into the rock avalanche, reflecting the transition from incipient collapse of the substrate to comminution in the moving rock avalanche.

6.2 Disintegration of rock avalanche deposit

There are two ways to look at the internal structure of a rock avalanche. One is to consider the lithological composition in relation to the source area, the other the deformation state reflecting the mechanical behavior of the rocks. In case of the Flims rock avalanche the lithologies in the rock avalanche deposit show a distribution surprisingly akin to the one in the source area. Flimserstein has a simple structure (see Fig. 19), which most likely also existed in the broken away mass to the south and west: a 600 m thick succession of Late Jurassic limestones, i.e. Quinten and Tros Limestone overlain










-  Soil
-  Rock avalanche deposit
-  «Upper Quinten limestone» (with bedding)
-  A coherent block
-  B shattered block
-  C bedrock
-  gliding surface

Fig. 21 Step in the glide surface west of the cable car station Foppa (coord. 2739420/1190025). The rectangle gives approximate position of photograph. Photo A. Pfiffner

by about 100 m of Early Cretaceous limestones. These in turn are overlain in thrust contact by klippen of Permian volcanoclastics («Verrucano»). The thickness of these volcanoclastics is at most 100 m on Flimserstein but could have been higher in the broken away parts. Mapping the lithologies in the rock avalanche (Gsell, 1917/18 and own work) reveals that the lower part exposed in the gorge of Ruinaulta is exclusively Quinten Limestone at the base of the cliffs and Tros Limestone in their upper part. The forested area above the cliffs contains Cretaceous limestones and locally «Verrucano» (Fig. 5). Although the thick forest in this area conceals a lot of information, Cretaceous limestones and «Verrucano» blocks outcrop in distinct areas. Only the boundary between areas with blocks of Tros limestone and Cretaceous limestones is sometimes difficult to trace because of some mixing. It thus follows again that the rock avalanche moved as a more or less coherent (internally broken) mass with no sign of turbulent flow.

Regarding the deformation state within the rock avalanche deposit, the observation is in concert with rock avalanches world wide: a carapace at the top of a fragmented body and a basal mixed zone (see e.g. McSaveney et al., 2006, Strom, 2006; Dufresne et al., 2016b or Zhang et al., 2019). The distinction between differently fragmented body parts is unlike the Tschirgant rock avalanche (Dufresne et al. 2016a) simpler in the Flims rock avalanche due to its homogeneous composition. This structural distinction is shown in the cross-section of Fig. 8. The blocky layer of the carapace travels along passively (Strom, 2006) but individual blocks, which can escape upward in the rock avalanche, are free to rotate. This is supported by the observation that these blocks display chaotic orientations of bedding and foliation.

As Strom (2006) and Zhang et al. (2019) discuss, the body of rock avalanches beneath the carapace is highly shattered and thus has a lower strength facilitating flow. Dynamic fragmentation comminutes the rocks and leads to the formation of matrix-supported breccias (McSaveney et al. 2006). This process permits granular flow to happen and is according to these authors a prerequisite for a rock avalanche to spread.

As discussed earlier, fragmentation within the Flims rock avalanche deposit is inhomogeneous. Large compartments 200–300 m in diameter float within a highly fragmented and comminuted matrix and are obviously able to travel as semi-coherent compartments, semi-coherent meaning that they contain original bedding structure but are heavily jointed (see Fig. 22). The outcrops above Isla Davos (coord. 2745000/1185600) contain large compartments within the rock avalanche, which retained the original stratification in the Quinten limestone. The outcrop 300 m east of Isla Davos shows a

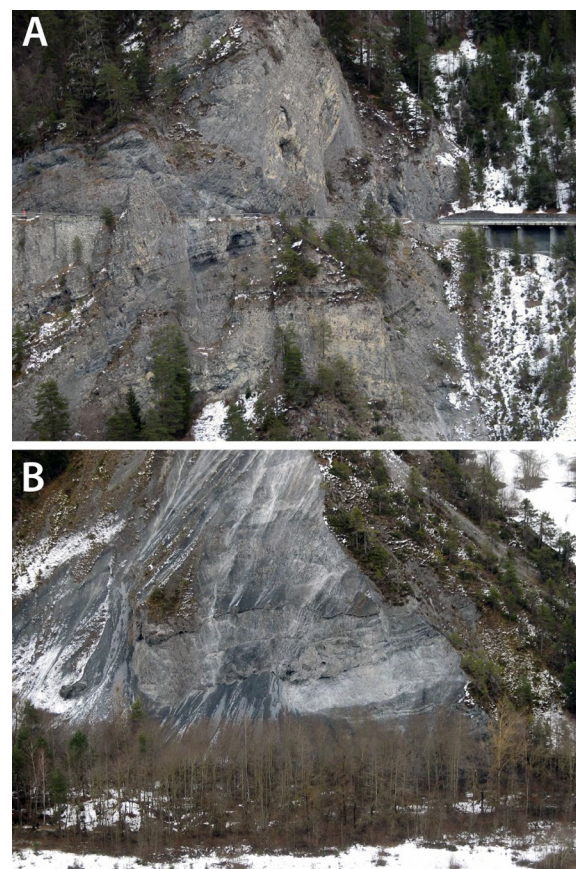


Fig. 22 Large compartments in the outcrops in the flank above Isla Davos. **A** Bedding in a tilted block. Bedding gets steeper as one goes into the flank. **B** An isolated block with visible stratification is floating in comminuted limestone. Photos A. Pfiffner

tilted compartment with a diameter of 200 m (Fig. 22A). In the outcrop 300 m SW of Isla Davos a slightly tilted compartment is embedded in a cataclastic limestone, which develops scree slopes (Fig. 22B). The compartment contains a 15 m thick light layer, which might represent a dolomitic passage within the limestone. Dolomitic passages are typical for the «Upper Quinten limestone» (Pfiffner, 1972b). As discussed earlier, the Flims rock avalanche deposit is also cut by km-sized faults (see Fig. 9C and 11A) that express themselves morphologically.

The comminuted matrix corresponds to a cataclastic resp. matrix-supported breccia with a “block-in-powder” texture (see Fig. 9C). The process of cataclasis is illustrated in the outcrops shown in Fig. 23A, B and C. The outcrop at Isla Casti (coord. 2743300/1185770) is an erosional scarp of the Vorderrhein. In the larger scale view of Fig. 23A a subvertical fault cuts across the brecciated limestone. It is topped by gravel deposited in the course of river incision into the rock avalanche deposit. A 30 cm wide fault gouge made of comminuted limestone

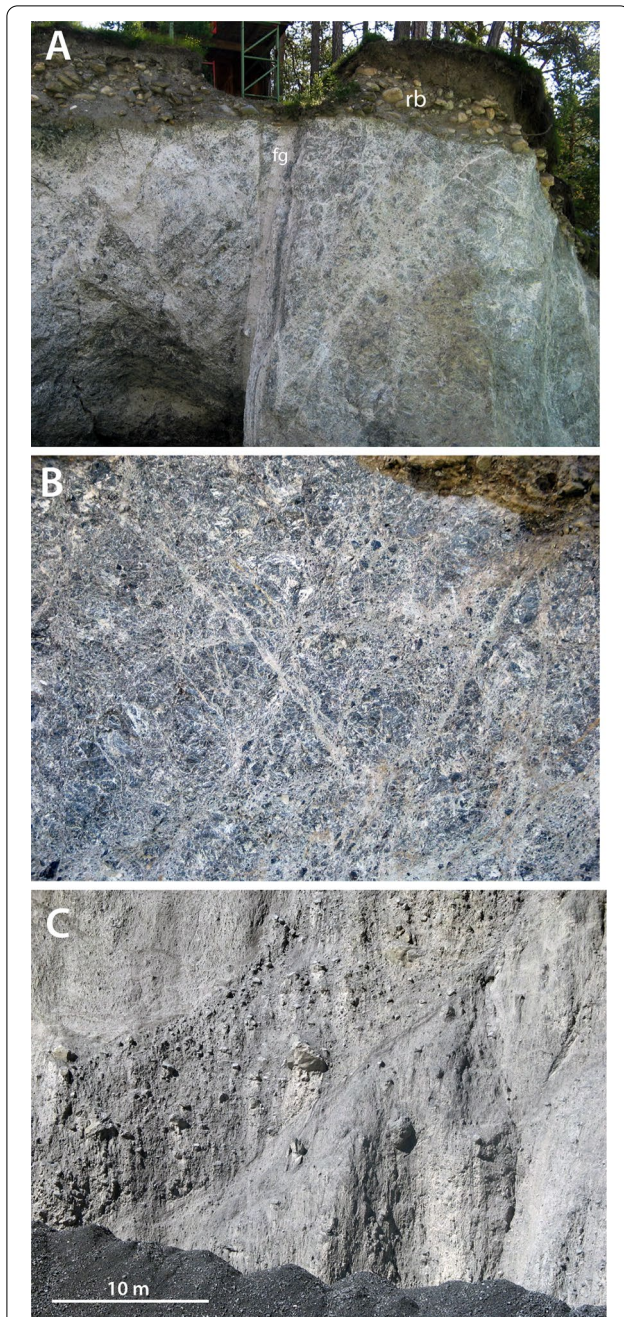


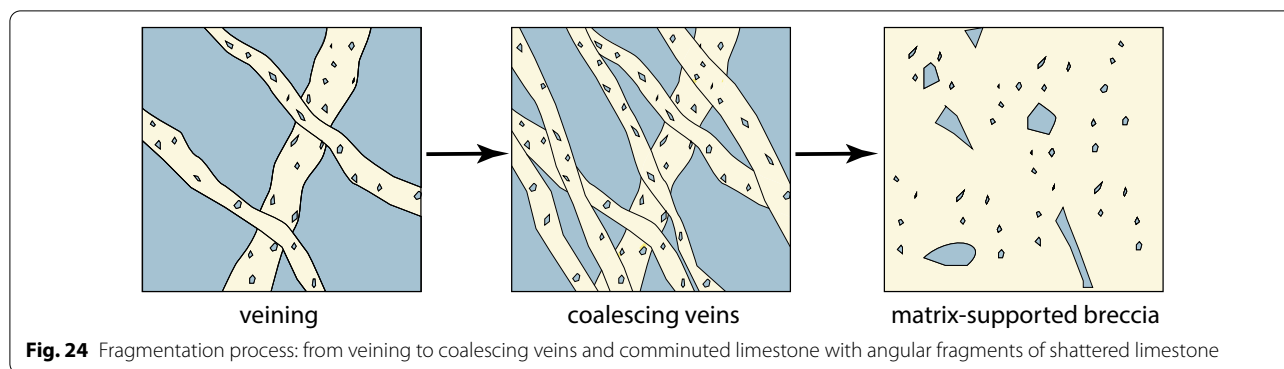
Fig. 23 Fragmentation and comminution of limestone in the rock avalanche deposit **A** Overview of outcrop at Isla Casti. A major fault with a thick gouge (fg) is accompanied by parallel faults and splaying faults with thinner gouge. Top of outcrop is a perched river bed (rb). **B** Detailed view of the outcrop at Isla Casti. Brecciation of Quinten Limestone occurred by multiple generations of veins. Vein filling is light colored and consists of comminuted limestone. **C** Quarry outcrop at Carnifels. A distinct band with larger angular blocks cuts across brecciated limestone. Fault gouge is developed along the contacts. Photos A, Piffner

outlines the fault. Close inspection of the outcrop reveals that thinner fault gouges accompany the major one on either side, and within the brecciated limestone some anastomosing veins are aligned parallel to the fault. This suggests that brecciation and comminution are associated with the fault gradually invading the neighboring limestone. The detailed view in Fig. 23B shows a brecciated dark gray (Quinten) limestone containing several generations of light colored and very fine-grained veins. The veins are either short and straight or long and anastomosing. Vein material is a comminuted very fine-grained limestone powder. In several places, the anastomosing veins become thick and contain small angular fragments of dark gray limestone. This is particularly true for old anastomosing veins, which are cut by younger and thinner veins. All in all, it seems that multiple veining increases the volume of comminuted (crushed) limestone gradually. It is however impossible to interpret the veining sequence in a simple scenario of shearing.

In the quarry Carnifels (coord. 743050/1184240) at the southern border of the Flims rock avalanche a S-dipping fault zone may be observed (see Fig. 23C). A 10 m thick layer containing many limestone blocks up to 2 m in diameter cuts across a body of comminuted limestone containing fewer and smaller limestone blocks. A thin fault gouge of comminuted limestone marks the contact on either side of the layer. This outcrop suggests that comminution and faulting at km scale occurred simultaneously in successive steps.

Schneider et al. (1999) and Pollet and Schneider (2004) who studied microstructures in the Flims rock avalanche claim that major discontinuities of 10 cm thickness constituted of comminuted rock developed from bedding planes; they are supposedly sub-horizontal and accompanied by limestone fragments bound by joints and displaced in a book-shelf manner. The present study could not confirm this interpretation.

Summing up it seems that the Flims rock avalanche was disintegrated internally as it moved. Disintegration occurred at all scales including km-scale planar faults, preservation of large semi-coherent compartments and pervasive comminution throughout the body of the rock avalanche. The planar faults within the rock avalanche debris cannot be correlated to pre-existing faults in the source area; on the other hand, a reactivation of faults or heavy jointing in the the source area cannot be ruled out. The process of fragmentation is illustrated in Fig. 24. In a first stage comminution occurs along fractures cutting across the limestone and results in veins made of comminuted limestone powder. As deformation continues multiple cross-cutting veins appear. At the intersections of veins pieces of limestone embedded in comminuted limestone powder persist. Ongoing deformation then



results in bodies of comminuted limestone powder containing smaller or larger angular fragments of limestone. Local stress conditions within the moving rock avalanche determine to which stage fragmentation develops, leaving high-grade and low-grade fragmented volumes side by side.

The basal zone of the Flims rock avalanche is not exposed in direct contact with the water saturated gravel of the former valley floor. However, the dark brecciated limestone outcropping in direct contact with the bedrock in Val da Mulin is identical to the lowermost dark colored brecciated limestone shown in Fig. 9A and B; more importantly, it does not differ in texture from the overlying gray brecciated limestone. Weatening by percolating water is responsible for its dark color and points to enhanced permeability at the base of the rock avalanche deposit. At several locations the dark limestone is offset by faults, which suggests that the higher permeability was attained in early stages of motion and disintegration of the rock avalanche.

Given that injections of silt, sand and gravel are observed in the lower part of the Ruinaulta gorge, a complex basal zone with mixture of rock avalanche deposit and substrate is to be expected (as shown in the cross-section of Fig. 8 and in Fig. 25).

6.3 Long-runout

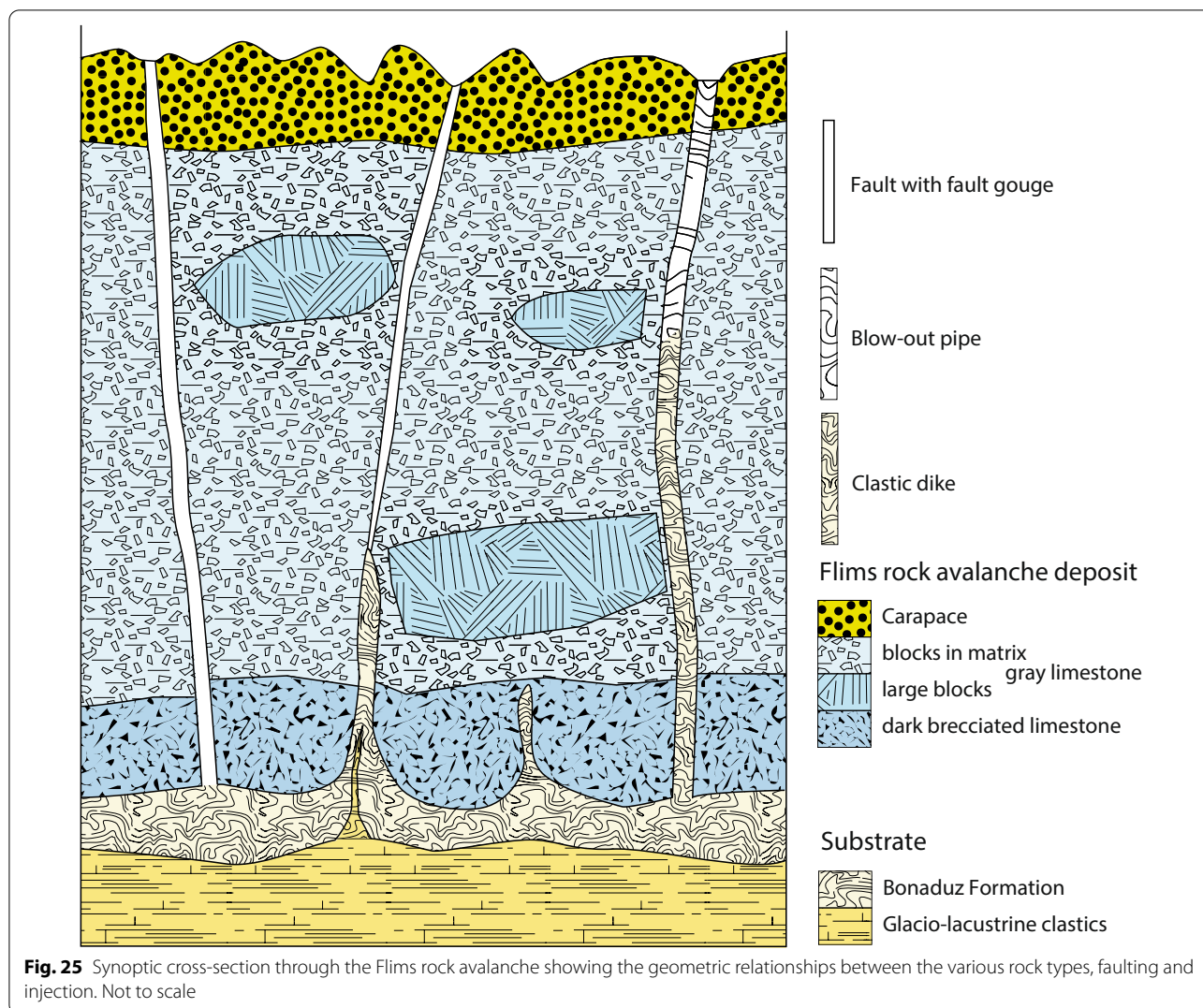
The problem of how to explain the long-runout of rock avalanches has been addressed by many scientists proposing a variety of mechanisms. Davies and McSaveney (2012) give a summary of this conundrum. Explanations put forward include for example air-layer lubrication, fluidization by extruding air, dust dispersion, steam from frictional heating, gaseous pore pressure or melting of rock (see Davies & McSaveney, 2012 for references). Additional explanations (op. cit.) invoke high vibration or pressure wave propagation as well as loading of saturated substrates and mechanical fluidization.

The authors conclude that from an energetic point of view dynamic rock fragmentation is the most suitable process to explain long-runout. In particular they emphasize the effectiveness of the release of elastic energy of breaking grains. Apart from this, they note that fragmentation is universal in long-runout rock avalanches. Considering the Flims rock avalanche fragmentation is in fact ubiquitous.

Abele (1997) and Calhoun and Clague (2018) consider that liquefaction of the substrate consisting of water saturated glacio-lacustrine and fluvial sediment played an important role for explaining the long-runout of the Flims rock avalanche. Liquefaction may be enhanced by entrainment of substrate pieces as Hungr and Evans (2004) have shown for the Eagle slide and the Momash River slide in British Columbia (Canada). Zeng et al. (2021) observed entrainment and injection of liquefied substrate from the Nixu rock avalanche in southern Tibet. In this case the rock avalanche moved on a basal shear zone and bulldozed and gradually overran the substrate at the front of the rock avalanche. The entrained substrate was subsequently liquefied and injected upward into the rock avalanche. Similarly, in case of the Tschirgant rock avalanche Dufresne et al. (2016a) report that the substrate was intricately involved in the internal deformation processes.

Aaron and McDougall (2019) studied the phenomenon of long-runout of rock avalanches as function of the substrate. They concluded that saturated substrate correlates with longer runouts in comparison to bedrock substrate. Their data are shown in Fig. 26, which is complemented with the H/L ratios of the Tamins and Flims rock avalanches. The Flims rock avalanche with a H/L ratio of 0.18 plots way beneath the rock avalanches with bedrock and unsaturated substrate, in the field of saturated substrate.

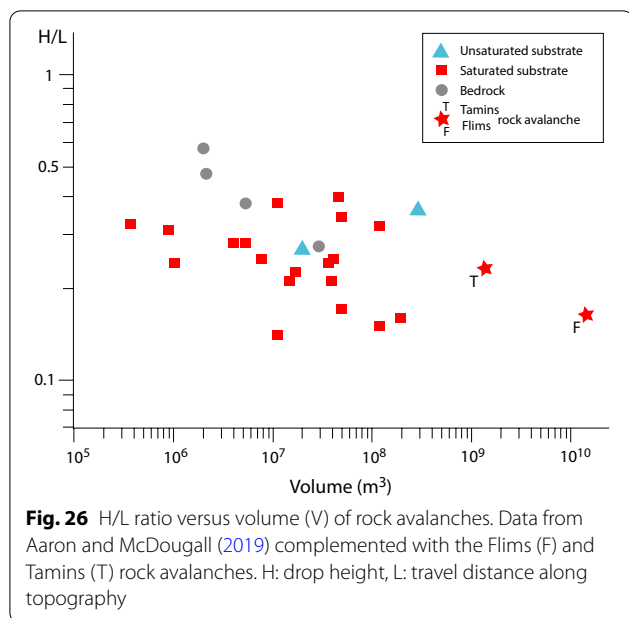
For the Flims rock avalanche there are several observations that need to be considered regarding long-runout. First of all, there are several places where the rock



avalanche deposit is in steep contact with the Bonaduz Formation (north of Bonaduz at Bot Dagatz and east of Sagogn near Ruina Schiedberg). In addition, and maybe more importantly, the hills west of Bonaduz at the front of the rock avalanche are locally covered with Bonaduz Formation suggesting bulldozing; and the hills south of Crest’Aulta west of Bonaduz at the lateral limit of the rock avalanche (coord. 2746150/1185100) contain slate and sandstone (see Fig. 5) that have been scraped off from the southern valley flank (Penninic nappes).

The mobilization of the substrate manifests itself by the clastic dikes injected into the Flims rock avalanche (Fig. 12A and 24) and the blowout pipes (Fig. 11B and 24). The presence of lacustrine silt within the clastic dikes indicates that this mobilization was deep reaching. Bulldozing at the front of the rock avalanche near Bonaduz raised the ancestral valley floor from 500 to 650 m a.s.l. and produced the Bonaduz Formation with

its somewhat chaotic content of fragments of rock avalanche deposits and lacustrine rip up clasts (Figs. 13C and D). Calhoun and Clague (2018) studied this deposit in detail and concluded that it moved as a hyperconcentrated flow. This mass movement carried rock avalanche fragments some 10 km up the Hinterrhein valley to Rodels (Fig. 1) and breached the Tamins rock avalanche deposit at Reichenau entraining fragments of this deposit 10 km down the valley to Domat/Ems and Chur (Fig. 14). Mapping the lithologies of the entrained rock avalanche fragments north and south of Bonaduz it is possible to differentiate between Flims and Tamins derived rock avalanche fragments (Cretaceous, resp. Permian and Triassic lithologies). Thus, it was possible to draw a line of contact passing east of Bonaduz in a N–S direction. Important to note is that the farthest travelled blocks (Rodels in Fig. 1) are derived from the Tamins rock avalanche.



6.4 Shortlived lake

The Flims rock avalanche dammed the Vorderrhein resulting in Lake Ilanz, which reached way upstream the main valley. Considering the mean annual discharges of the Vorderrhein and its main tributary Glenner, von Poschinger et al. (2006) estimated that this lake was filled within 13 months up to the level of 820 m a.s.l. The ensuing erosion processes by overtopping could have involved three phases (Li et al. 2021): uniform bed erosion leading to a spillway and increasing outflow, backward erosion on the dam with increased outflow and enlargement of the spillway, and, finally, erosion of the outflow channel and rapid increase of discharge. The incipient stage with static overflow in natural dams is strongly influenced by the nature of the lithological composition of the dam (Mei et al., 2021). Fine-grained material is removed first and quickly. In case of the Flims rock avalanche the top of the dam contained large blocks of the carapace, which would likely have slowed down the formation of a spillway. Overflow occurred across a hummocky landscape with closed basins that may have collected and preserved the fine-grained material. Because of erosion along the breach the initial courses of the spillways can only be guessed at but were likely curved around small-scale hummocks. Costa and Schuster (1988) and Fan et al. (2020) report that most historic natural dams breached within less than a year. For Lake Ilanz there is evidence for outbursts and incision in the form of debris flow deposits. These occur on terraces of diminishing altitude downstream of the dam (Calhoun & Clague, 2018). The uppermost debris flow deposits pertain to the Ransun fan (Pfiffner & Wyss, 2023) and consist of gray limestone

exclusively. This material can be derived from the Flims rock avalanche solely. At the locality Crestis west of Tamins archeological excavations yielded artefacts from within this fan. They are of late Mesolithic age and indicate fan activity 9500–9000 years ago. The apex of the Ransun fan is at 800 m a.s.l., i.e. about 20 m lower than the lake level which suggests that the Ransun fan is the first outburst of Lake Ilanz. This leaves a time interval of less than 480 years, and possibly only a few years for the existence of this lake. The Ransun fan can be followed over at least 10 km downstream to Domat/Ems. But the flood may correlate to a singularity in the lake deposits of Lake Constance located 80 km farther downstream (Schaller et al., 2022). These authors correlate a double-turbidite with the Flims rock avalanche (the Reichenau breach) and a overlying turbidite with the outburst of Lake Ilanz (Ransun fan).

The younger incision history indicated by the various river beds perched on the flanks of the Ruinaulta gorge and terraces that have not been dated yet.

There are two major tributaries of the Vorderrhein within the Flims rock avalanche upstream of the dam: Ual da Mulin east of Sagogn and Carrerabach between Valendas and Carrera. Both of them incised their delta that they had shed into Lake Ilanz once the dam was breached. This incision must have occurred rapidly: 120 and 100 m in 9000 years, resp. 133 and 111 mm/a and is still going on. According to an eye witness (Pfarrer Candrian) the erosional scarp of Ual da Mulin retreated up to 50 m between 1843 and 1880 (Heim 1883).

7 Conclusions

Structural weaknesses in the rock mass were an important factor in the predisposition of the Flims rock avalanche. They include pre-existing faults as well as regional joint systems that controlled the geometry of the lateral scarps.

The gliding surface is rather irregular. It cuts down the stratigraphy from the head scarp and contains several steps and lateral ramps. It does not follow a single weak layer. A parallelism to an Alpine foliation and bedding in the limestone is locally present and may have influenced the development of the gliding surface. The gliding surface possibly emanated at a break in slope of the paleo-topography.

The 3-dimensional repartition of the lithologies within the rock avalanche strongly resembles the one of the source area. The rock avalanche moved in large parts as a semi-coherent mass and lacks indications for turbulent flow.

The internal deformation of the limestone within the rock avalanche occurred by dynamic fragmentation and is rather heterogeneously distributed within the rock

avalanche body. It includes the translation of 100 m sized compartments within a flowing fragmented matrix; the compartments are shattered but not fragmented. Fragmentation seems to start by veining and evolves as cross-cutting veins coalesce and result in larger volumes of entirely comminuted limestone powder, which contains angular fragments of only shattered limestone.

The long-runout of the Flims rock avalanche is associated with a thorough involvement of the saturated substrate by bulldozing and entrainment of liquefied substrate and fragments of the older Tamins rock avalanche, and ripping off pieces of the valley flank to the south.

The liquefied substrate escaped upward into the rock avalanche as clastic dikes and blow-out pipes. These features are observed along the axis of the (ancient) valley where the saturated substrate had a maximum thickness.

Lake Ilanz, dammed by the rock avalanche, was short-lived. Dam breach provoked debris flows which built a fan that extends at least 10 km downstream.

Acknowledgements

Mapping projects of the Swiss Geological Survey gave me the opportunity to have a close look at forests geologists usually avoid. The Institute of Geological Sciences of the University of Bern provided research infrastructure. I thank Roland Wyss for many discussions and collaboration in the map project. Collaboration and discussion with the ETH group, Susan Ivy-Ochs, Zhasmin Mussina, Olivia Steinemann-Kronig, Naki Agçar and Jordan Aaron on the Tamins rock avalanche greatly deepened my understanding of rock avalanches. Thanks go to Markus Weidmann for providing photographs of critical outcrops and to Andreas von Poschinger for stimulating discussions. Comments by reviewers and the handling editor Wilfried Winkler improved the manuscript.

Author contributions

The author has designed the study, acquired and interpreted the data and drafted the work. The author read and approved the final manuscript.

Funding

The author was funded for field work by swisstopo/Landesgeologie.

Availability of data and materials

All data generated or analysed during this study are included in this published article. More detailed information will be available once the Geological Atlas 1:25'000 Map sheets 1195 Reichenau and 1194 Flims are published.

Declarations

Competing interests

The author declares that he has no competing interests.

Received: 17 June 2022 Accepted: 2 November 2022

Published online: 28 November 2022

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