LiDAR and geomorphic characterisation of landslide-induced liquefaction deposits in the eastern Swiss Alps

by

Nancy Carlson Calhoun

B.Sc., Colorado College, 2007

Thesis Submitted In Partial Fulfillment of the
Requirements for the Degree of
Master of Science

in the
Department of Earth Sciences
Faculty of Science

SIMON FRASER UNIVERSITY

Fall 2015

Approval

Name: **Nancy Calhoun**

Degree: **Master of Science**

Title of Thesis: ***LiDAR and geomorphic characterisation of landslide-induced liquefaction deposits in the eastern Swiss Alps***

Examining Committee: **Chair:** Dr. Gwenn Flowers
Associate Professor

Dr. John Clague
Senior Supervisor
Professor

Dr. Doug Stead
Supervisor
Professor

Dr. Marco Giardino
Supervisor
Professor, University of Torino

Dr. Marten Geertsema
External Examiner
Adjunct Professor, UNBC

Date Defended/Approved: December 8, 2015

Abstract

The Flims rockslide, located in the eastern Swiss Alps, is the largest postglacial landslide in Europe. About 9400 years ago, 10-12 km^3 of limestone detached from the north wall of the Vorderrhein River valley and rapidly fragmented, impacting and liquefying approximately 1 km^3 valley-fill sediments. A slurry of liquefied sediment, the “Bonaduz gravel”, traveled 16 km downvalley and up the Hinterrhein valley, carrying huge fragments of rockslide debris (tumas). The sheet of liquefied sediments is >60 m thick and fines upward from cobble gravel at the base to sand at the top. Another large, slightly older rockslide (Tamins rockslide) blocked the Vorderrhein River and impounded a lake into which the Flims rockslide fell, increasing the mobility of the Bonaduz flow and affecting its flow path. I used field observations and a LiDAR-based DEM to map the Bonaduz gravel and infer its mechanism of emplacement.

Keywords: Flims rockslide; hyperconcentrated flow; liquefaction; LiDAR; DEM

Dedication

I dedicate my thesis to my family and friends, and the canton of Graübünden.

In particular, I dedicate my thesis to my grandmother Nancy Howard Sitterson who dedicated her life to the support of higher education. She supported me and encouraged me to pursue earth science and graduate school.

Acknowledgements

Support from GeoNatHaz, John J. Clague, the Flims team – in particular, the ever-dedicated Andreas von Poschinger, Marco Giardino, Diego Masera, Giochino Roberti, Hazel Wong and Luigi Perotti. I thank the University of Torino-Earth Sciences department for allowing me to process my sediment samples in their facilities. Thank you to fellow “Clagueites” – Nick Roberts, Corinne Griffing, Marty Zaleski, Jared Fath, Stephen Newman and Andrea Wolter – for helpful discussions and assistance over the years. I also thank the staff of the Department of Earth Sciences at Simon Fraser University for supporting me in my pursuit of my graduate degree.

Table of Contents

List of Tables

List of Figures

Photograph Credits

All photographs are the author’s unless otherwise noted.

Chapter 1.

Introduction

The Flims rockslide, the largest postglacial subaerial landslide in Europe, fell onto the floor of the Vorderrhein River valley in the heart of the Swiss Alps in the early Holocene (Figure 1.1). Although the rockslide has been studied for more than 120 years, many of its aspects are still not fully understood and have been the subject of controversy. In particular, the origin of the so-called “tumas” (toma hills), consisting of rockslide debris, and the unusual “Bonaduz gravel”, which underlies many elevated, steep-sided terraces along the Hinterrhein and Vorderrhein rivers, have been long debated. The neighbouring Tamins rockslide, which played an integral, although not well understood role in the early Holocene events in the Vorderrhein valley, has also puzzled researchers.

The Flims rockslide is about 8-12 km^3 in volume and covers an area of 52 km^2 (Poschinger et al., 2006). Its source is Triassic, Jurassic, and Cretaceous limestone, dolomite, and shale of the Helvetic nappe (Ivy-Ochs et al., 2009). Alexander Moritzi, a local Swiss naturalist, first identified the landslide in 1841, and in 1883 the famous Swiss geologist Albert Heim conducted the first detailed study of the deposit and scarp (Poschinger et al., 2006). He commented on the emplacement mechanism of the landslide, estimated its volume, and made the first map of the deposit. He also identified unusual sediments downstream of the rockslide mass, which later became known as the Bonaduz gravel, after the town of Bonaduz where they are best preserved and exposed. Since Heim’s time, many different ideas about their origin and mode of emplacement have been proposed.

The Flims rockslide happened about 9400 years ago, based on radiocarbon ages on wood in the landslide debris and in lacustrine sediments deposited in two lakes on top of the rockslide, and on cosmogenic nuclide ages and pollen analysis (Poschinger et al., 2006; Deplazes et al., 2007; Ivy-Ochs et al., 2009). Albert Heim first proposed that the rockslide occurred after deglaciation. This was further supported over 100 years later by G. Abele, who argued that the rockslide occurred a few thousand years after deglaciation (Poschinger et al., 2006; Abele,1997).

The Tamins rockslide, which is located 5.5 km downvalley of the Flims rockslide in the Vorderrhein valley, has an estimated volume of 1.5 km^3 and covers an area of 17 km^2 (Abele, 1997). It too is postglacial in age, but is older than the Flims rockslide (Poschinger and Kippel, 2009). Although it has received much less attention than the much larger Flims rockslide, it played a key role in the events outlined in my thesis.

My research adds to the large body of work that has been done on the Flims and Tamins rockslides, most recently summarized by Poschinger et al. (2006). I focus on the Bonaduz gravel – its distribution, characteristics, emplacement, and its relation to the tumas and the Flims and Tamins rockslides. My research questions are: How was the Bonaduz gravel transported? How did it acquire its unusual sedimentary characteristics? What is the relationship between the Bonaduz gravel and the Flims and Tamins rockslides? And what is the relationship between the Bonaduz gravel and the tumas? To answer these questions, I studied natural and quarry exposures of Bonaduz gravel, performed an analysis of LiDAR imagery, and completed an exhaustive literature review of similar deposits and landforms in other areas.

In the remainder of this chapter, I describe the study area and summarize the geology and the glacial history of the upper Rhine valley. I also provide an overview of pertinent previous research.

1.1. Study area

In the study area, the eastern Swiss Alps have up to 2200 m of local relief and are dominated by east-west-trending mountain ranges and glaciated U-shaped valleys (Figure 1.1). The Rhine River valley marks a major tectonic boundary controlled by the Chur fault, discussed in section 1.2 (Pfiffner et al., 2002). The Flimserstein – a 500-m-high cliff parallel to the Vorderrhein – is part of the headscarp of the Flims rockslide (Figure 1.2) and one of the peaks in the Calanda massif.

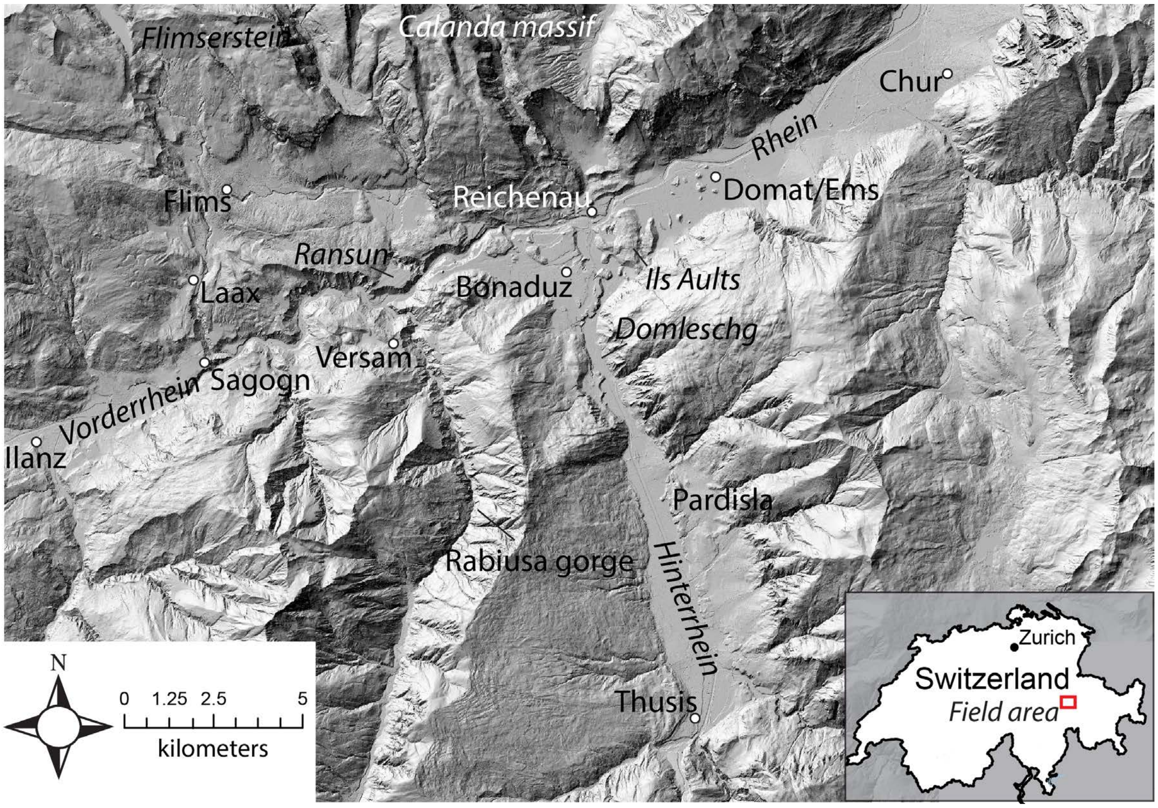


Figure 1.1. Hillshade map of the study area near the confluence of the Vorderrhein and Hinterrhein rivers.

The Rhine River watershed is 185,260 km^2 in size and includes parts of nine countries (Uehlinger et al., 2009). My field area is centered around the confluence area of the Vorderrhein River (the uppermost reach of the Rhine) and the Hinterrhein, its largest tributary. The area above the confluence, including the Hinterrhein watershed, has an area of 6155 km^2, more than 50% of which is forest land, ~20% is cropland, and ~7% is grassland. In the Pliocene, the Rhine River flowed into the Rhone River, but Pleistocene glaciations altered its watershed (Uehlinger et al. 2009) and today it flows directly to the North Sea in the Netherlands. Prior to construction of flood protective structures, the Vorderrhein River was probably braided (Uehlinger et al., 2009).

The Hinterrhein River flows 30 km east from Paradies Glacier before turning northward to enter a narrow bedrock gorge. It then enters a much wider valley at the town of Thusis and flows 15 km in a straight, dyked channel and another 4 km in an unconfined channel to its confluence with the Vorderrhein River at Reichenau. It too was probably braided before being confined to a dyked channel (Uehlinger et al., 2009).

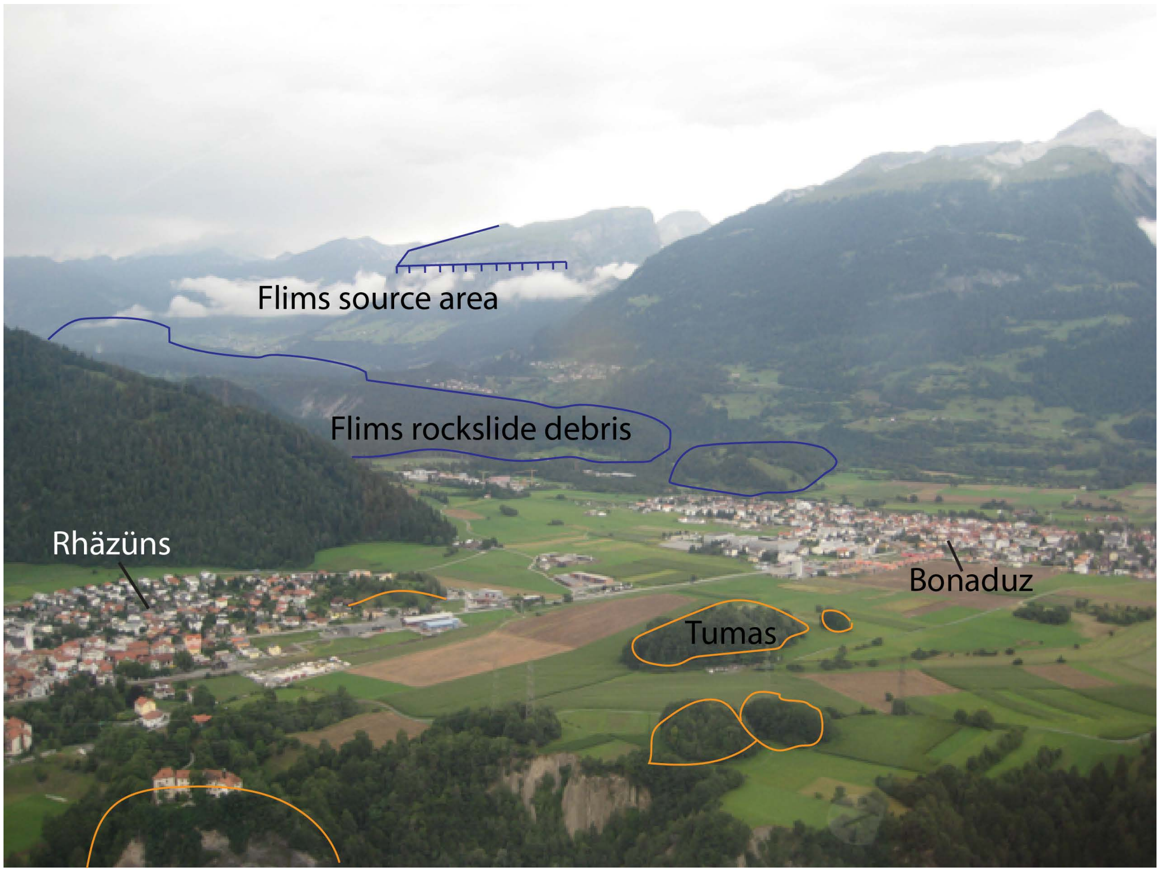


Figure 1.2. View to the northwest of the study area near the confluence of the Vorderrhein and Hinterrhein rivers (the latter is out of the frame to the immediate right). The Bonaduz plain is in the middle ground and the Flims rockslide source area in the background in the clouds. The partially forested cliff at the bottom left is formed in Bonaduz gravel.

The natural vegetation is zoned with elevation: sparsely vegetated Alpine rock fields and alpine grasslands above 2000 m asl, transitioning to dwarf shrublands and fir forests between 1200 and 2000 m asl, and a full mixed forest of fir, spruce, beech, ash, and sycamore below 1200 m asl (Uehlinger et al., 2009). The climate is strongly seasonal, with cold wet winters at high altitudes and moderately rainy, warm summers in valley bottoms. Temperature and precipitation differ markedly with elevation. Mean annual precipitation in the watershed is 1920 mm and mean annual temperature on valley floors is 10ºC (Uehlinger et al., 2009).

The study area has been inhabited for thousands of years (Terberger and Street, 2002). The Flims rockslide occurred during the Mesolithic period, prior to beginning of the Neolithic period about 6400 years ago, when agriculture and domestication became widespread in Europe (Bramanti et al., 2009). Alpine valleys were probably populated soon after glacial retreat (Terberger and Street, 2002), and it is likely that the Vorderrhein valley in the vicinity of the Flims rockslide was inhabited when the rockslide happened.

1.2. Tectonic and geologic setting

The eastern Swiss Alps comprise an orogenic wedge of marine sedimentary rocks that were uplifted, folded, and faulted during the Cretaceous and Cenozoic when the Adriatic plate collided with the European plate to the north (Figure 1.3; Pfiffner et al., 2002). The Helvetic nappes, which in the study area lie north of the Vorderrhein River, represent the former shelf and slope areas of the European plate margin (Pfiffner et al., 2002). The Penninic nappes consist of metamorphosed sedimentary rocks that originated in more distant oceanic troughs, basins, and on a micro-continent (Pfiffner et al., 2002). The Penninic nappe exposed south of the Vorderrhein River in the study area is termed the Bündnerschiefer and comprises Jurassic and early Cretaceous schist, phyllite, limestone, sandstone, and shale, with some ultrabasic intrusions (Funk et al., 1987). The crystalline basement of the Aar and Gotthard massif is exposed in the headwaters of the Vorderrhein River in the vicinity of Gotthard Pass (Pfiffner et al., 2002).

Deformation that produced the eastern Swiss Alps spanned the period from the late Eocene to the Miocene. The Rhine valley follows the Chur fault, which is the boundary between the Penninic nappe to the south and the Helvetic nappe to the north (Figure 1.3; Pfiffner et al., 2002).

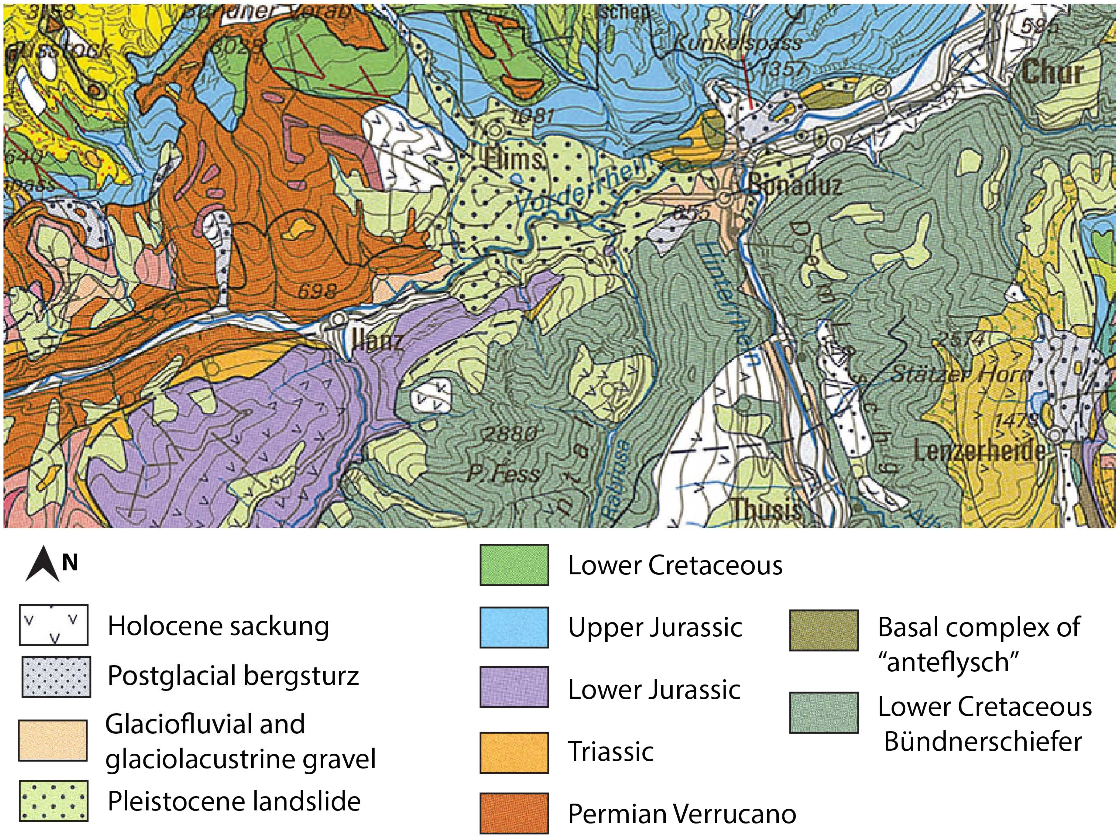


Figure 1.3. Geologic map of the Flims area (SwissTopo, Federal Office of Topography, 2007).

The Glarus thrust crops out above the Vorderrhein River valley, within the uppermost units of the Helvetic sequence exposed in the headscarp of the Flims landslide (Figure 1.4). It accommodated approximately 30-40 km of northward thrusting that placed the basal Verrucano unit of the Helvetic nappe on top of a series of complexly folded and faulted flysch units (Herwegh et al., 2008). The Verrucano unit is underlain successively by Cretaceous sedimentary rocks and by imbricate-thrusted, Upper Jurassic limestone (Pfiffner, 1993).

The Flims and Tamins rockslides have sources within the Helvetic nappe. The main unit involved in both landslides is the late Jurassic Quinten limestone, which is strongly foliated and decapitated by the overlying Glarus thrust (Herwegh et al., 2008). The Quinten limestone is clayey and siliceous; a fold in this unit daylights in the source slope of the Flims rockslide (Kippel, 2002; Pollet et al., 2005).

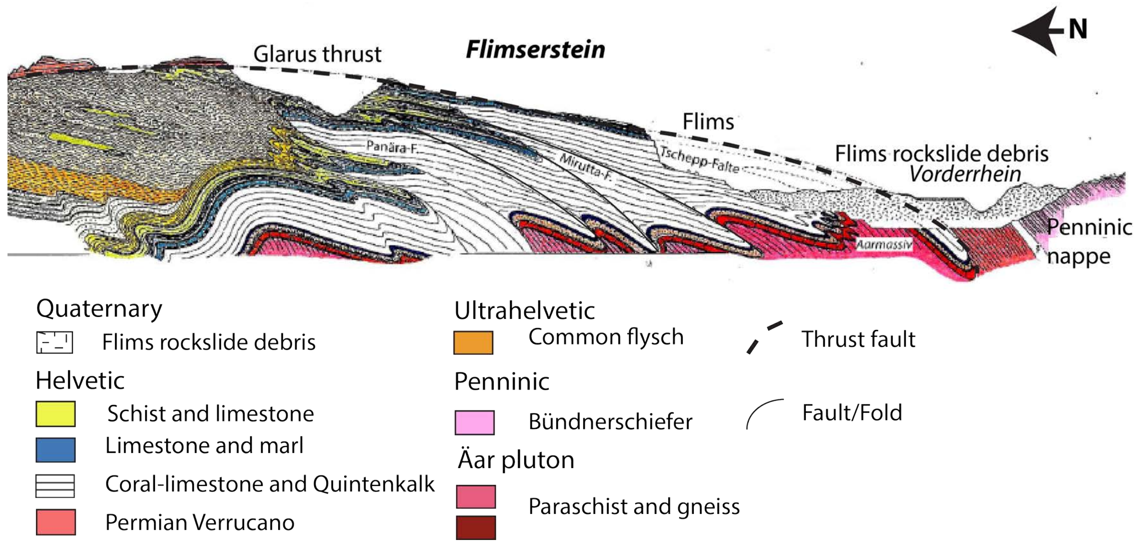


Figure 1.4. Geologic cross-section across the Flimserstein (Oberholzer, 1933; modified by Caprez, 2002). The Glarus thrust separates the Permian Verrucano unit from Jurassic and Cretaceous limestones.

A unit that occurs in the source area of the Tamins rockslide, but not the source area of the Flims rockslide, is the ‘Tamins crystalline’ or ‘Tamins Verrucano’ unit – a green chlorite-rich schist of igneous origin. It is found at the core of a fold in the source area of the Tamins rockslide; the axial plane of the fold dips to the north (Oberholzer, 1933; *in* Kippel, 2002).

Bedding planes in the carbonate units involved in the Flims and Tamins rockslides dip parallel to the slopes that failed. The structural control of these landslides is similar to that of several other large carbonate rockslides, including Saidmarreh in the Zagros fold-and-thrust belt in Iran (Harrison and Falcon, 1937; Roberts and Evans, 2013), and the 1963 Vaiont landslide in Jurassic and Cretaceous limestones in the northeastern Italian Alps (Genevois and Ghirotti, 2005). The Saidmarreh, Vaiont and Flims rockslides are all carbonate, dip-slope failures.

1.3. Pleistocene glaciation

Repeated glaciation during the Pleistocene Epoch conditioned the Vorderrhein valley slopes for the Flims and Tamins rockslides by overdeepening the valley bottom and steepening the valley sides (Nabholz, 1954; Pollet and Schneider, 2004). Alpine valleys, including the Vorderrhein and Hinterrhein, were filled with glacier ice during the last glaciation, which corresponds to Marine Isotope Stage 2. This glaciation has been dated to between about 38,000 and 18,000 years ago; by the latter date, about 80% of the ice had disappeared from the Alps (Ivy-Ochs et al., 2006; Preusser et al., 2011). At the maximum of the last glaciation, all but the highest peaks in the study area were covered by ice, and the glacier in the Rhine valley terminated 12 km northwest of Zurich (Preusser et al., 2011). Several Late-Glacial readvances have been documented in the eastern Swiss Alps and likely affected the Flims and Tamins slopes (Ivy-Ochs et al., 2008; Preusser et al., 2011). The Flims rockslide postdates the Younger Dryas readvance (Egesen readvance) by 3000 years (Poschinger and Haas, 1997; Ivy-Ochs et al., 2008) and occurred under a relatively warm, humid climate during the Preboreal to Boreal period.

Till is locally present on the surface of the Flims rockslide deposit, but is thought to have been 'piggybacked' on top of the slide into the valley (Abele, 1997). There is no evidence of glacial scour, plucking, or other erosional processes on the surfaces of the Flims or Tamins rockslide deposits (Poschinger and Haas, 1997), and radiocarbon ages place the Flims rockslide firmly within postglacial time.

1.4. Previous research on the Flims and Tamins rockslides

Poschinger et al. (2006) provide a review of past research on the Flims rockslide, which dates back to 1841. I did not have access to many of the oldest German publications, although I made efforts to translate many papers and reports written in German. Therefore, my historical literature review relies heavily on Poschinger et al. (2006) and on discussions with Andreas von Poschinger.

1.4.1. The Flims rockslide, Bonaduz gravel, and tumas

Since Albert Heim's initial field mapping of the Flims rockslide in the 1880s, researchers have argued about his suggestion that the rockslide involved *en bloc* movement in 'one great stroke'. The slide mass retains source-area bedding planes and very large blocks, and its internal structure and geomorphic features indicate that it occurred as one main event. The main body of the rockslide struck the opposite valley wall of the Vorderrhein, while tongues of debris traveled up and down the valley. The possibility of multiple events is now discounted (Heim, 1932; Abele, 1997; Poschinger and Haas, 1997; Pollet et al., 2005; Poschinger et al., 2006).

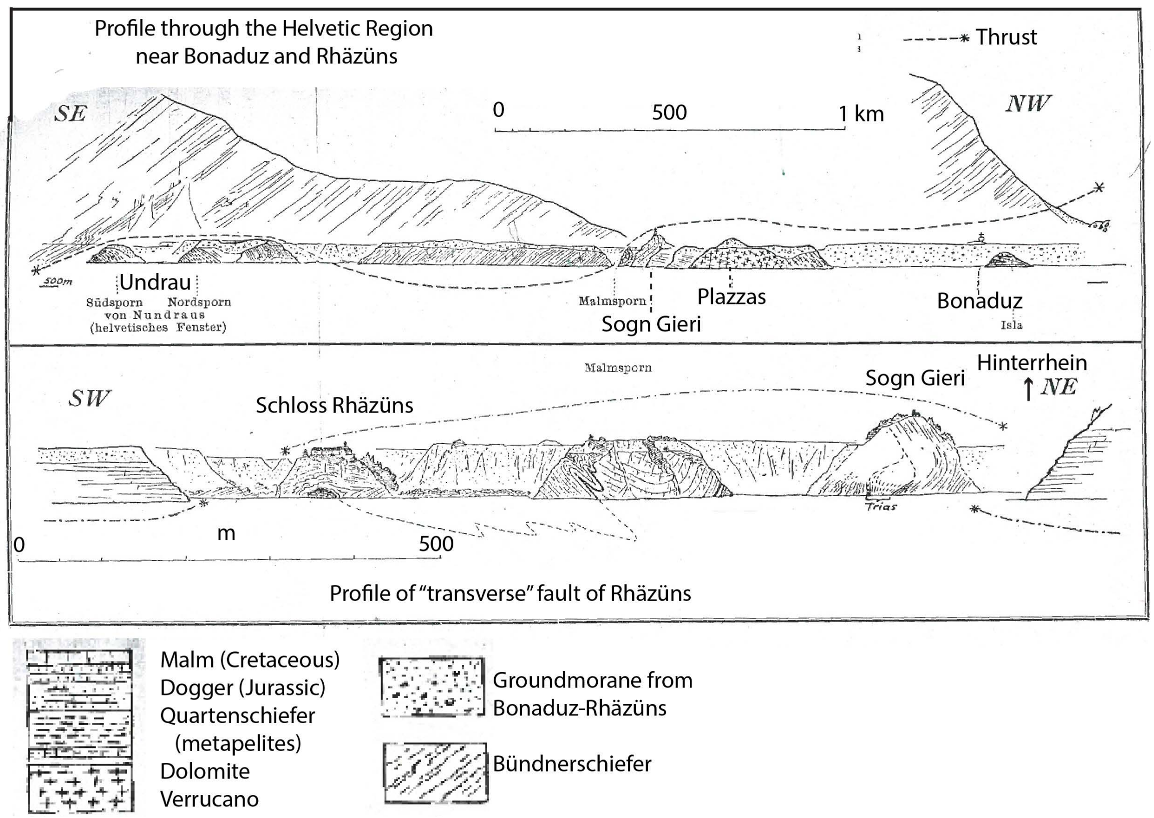


Figure 1.5. Geologic cross-section of the Rhine valley at the confluence of the Vorderrhein and Hinterrhein rivers (Arbenz and Staub, 1910). The dashed lines connect the folded tumas to the northern Helvetic terrane a few kilometres to the north.

In the late nineteenth century, G. Hartung and A. Rothpletz, among others, thought the Flims rockslide was *in-situ* crushed Helvetic bedrock (Poschinger et al., 2006). What are now known as tumas perplexed early workers, as crushed Helvetic rock was found within these isolated hills both downvalley of the main body of the landslide and far up the Hinterrhein valley (Figure 1.5; Arbenz and Staub, 1910). The tumas in the Vorderrhein valley are separated from the Flims landslide by the Tamins rockslide. Previous explanations for these features include young tectonic crushing, exhumation of tectonic windows, and glacial transport of debris cones. For example, an early geologic profile by Arbenz and Staub (1910) shows thrust faults connecting *in situ* bedrock outcrops of Helvetic rocks (tumas) seen along the Hinterrhein and surrounded by 'groundmorane' (Bonaduz gravel) (Figure 1.5).

Nabholz (1954) argued that the crushed Helvetic rocks of the Hinterrhein valley many kilometres south of the Helvetic-Penninic tectonic contact are transported rockslide debris. He thought that their source was the Tamins rockslide, due to their proximity to most of the tumas to the north. He further suggested that the blocks of landslide debris might have been transported on remnant, late Pleistocene glacier ice (Nabholz, 1954).

Shortly after Nabholz published his research, Remenyik (1959) provided evidence of different dip directions within the Helvetic rocks of the tumas in the Hinterrhein valley. Internal fractures, faults, and blocks with different orientations were inconsistent with the argument of Arbenz and Staub (1910) that the hills are *in situ* bedrock outcrops (Figure 1.5). Remenyik (1959) concluded that the hills of Sogn Gieri, Plazzas, and Isla Spur must have been produced by one "bergsturz", or landslide event.

Seismic and electrical surveys conducted on the tumas and Helvetic rocks in the vicinity of the Tamins rockslide led Scheller (1970) to conclude that they are "parts of the debris zone of prehistoric landslide with an origin…. north of Tamins". This work supports Nabholz's and Remenyik's claims that the tumas are 'rootless' masses of rockslide debris and not *in situ* bedrock outcrops. The seismic reflection data revealed the shallow bases of the tumas and an extensive sediment fill up to several hundred metres thick in the valley below them (Scheller, 1970).

Turning now to the Bonaduz gravel, Albert Heim considered this unit to be 'true till' (Poschinger et al., 2006). In contrast, Nabholz (1954) postulated that the Bonaduz gravel accumulated behind the Tamins rockslide when it blocked the Vorderrhein River, and Abele (1974) considered it to be outburst flood deposits from Lake Ilanz, the lake impounded behind the Flims rockslide.

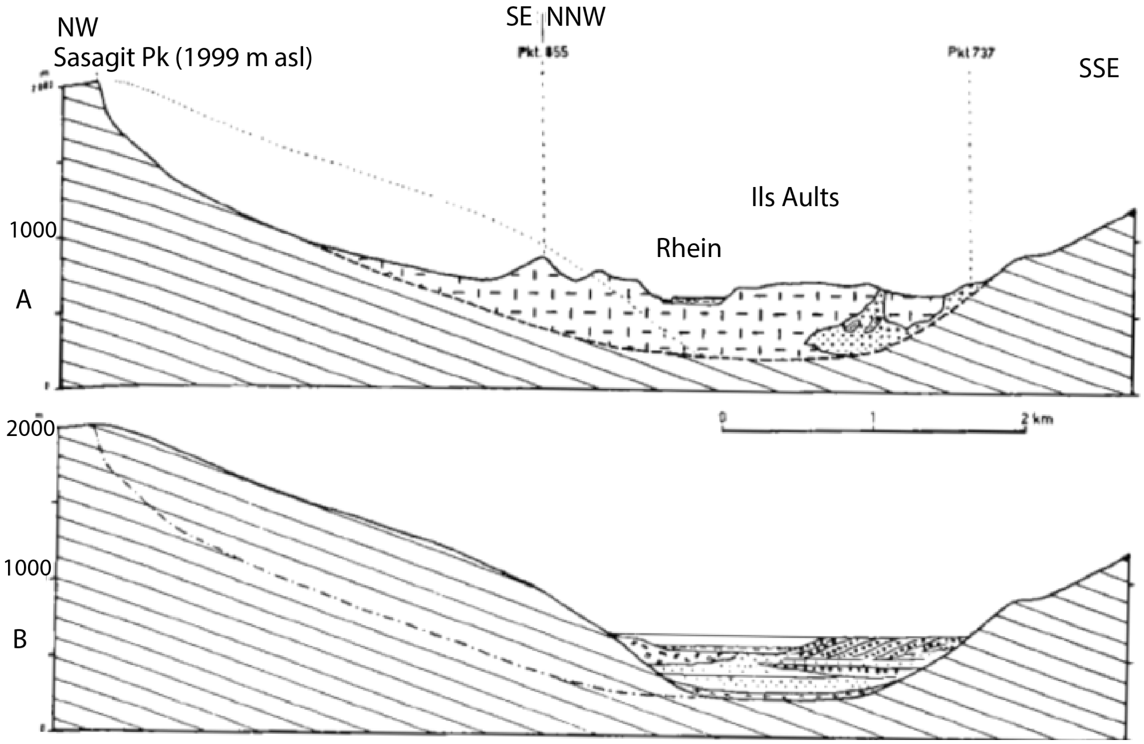


Figure 1.6. Schematic cross-section across the Vorderrhein valley from the headscarp of the Tamins rockslide at Sasagit Peak on the left to the opposite valley wall south-southeast of Ils Aults (Pavoni, 1968). Top: Mobilized fluvial and deltaic sediments (dotted pattern) beneath and adjacent to Tamins rockslide debris (pattern with orthogonal dashes). B) Pre-landslide slope and valley-fill sediments (Pavoni, 1968).

Pavoni (1968) provided the first detailed description of the Bonaduz gravel and offered a new hypothesis for its origin. He noted several characteristics of this ‘alluvium’ that are inconsistent with it being a fluvial deposit: reverse grading through the entire deposit, from coarse gravel at the base to sand at the top; a lack of stratification; very poor sorting, with individual outcrops ranging from gravel to silt; maximum grain size in the coarse gravel fraction; and steeply inclined narrow ‘tubes’ of gravel lacking sand and silt, which later became known as ‘Pavoni pipes’.

Building on the observations of Nabholz (1954) and Remenyik (1959), Pavoni (1968) interpreted the Bonaduz gravel to be ‘Gesteinsbreisediment’ or ‘rock slurry sediment’ (Figure 1.6). He argued that the slurry transported tumas away from the Tamins rockslide in a relatively intact state. He also showed that some of the Bonaduz gravel traveled up to 13 km from its source. He postulated the following sequence of events: 1) retreat of valley glaciers; 2) accumulation of unconsolidated gravel, sand, and lacustrine silt in the valley; 3) two separate landslides (now known as the single Tamins rockslide); and 4) pushing of valley-fill sediments (Bonaduz gravel) as “snow in front of a shovel”, causing a flow of the Bonaduz gravel both down the Vorderrhein valley and up the Hinterrhein valley and rafting large masses of rockslide debris (tumas) with it. Pavoni’s paper profoundly changed thinking about the mechanisms and order of postglacial events in the Vorderrhein and Hinterrhein valleys.

Abele (1997) described key exposures where Bonaduz gravel and Flims landslide debris interfinger and concluded that it was the Flims rockslide, not the Tamins rockslide, that mobilized the Bonaduz gravel. He also noted the presence of clasts of Punteglias granite within the Bonaduz gravel in the Hinterrhein valley; this granite is present only in the Vorderrhein valley upstream of the Flims rockslide. This observation led Abele to conclude that the mobilized valley fill must have originated from Vorderrhein valley-fill sediments and traveled up the Hinterrhein valley.

The mobilized valley fill is partly responsible for the current form of the Flims landslide surface. Abele (1997) hypothesized that the split of the rockslide mass into tongues that moved up and down the Vorderrhein valley and the abrupt steep fronts of the slide mass are the result of the mobilized and laterally flowing basal Bonaduz sediments.

Following the important work of Pavoni and Abele, little work was conducted on the Bonaduz gravel until Andreas von Poschinger began to study remaining unsolved problems in the 1990s. With a student from ETH-Zurich, von Poschinger documented in detail the sedimentary characteristics and distribution of the Bonaduz gravel (Poschinger and Kippel, 2009). They built on Pavoni’s concept of a ‘rock slurry’, arguing that the Bonaduz gravel is a large mass of valley-fill glaciofluvial and glaciolacustrine sediments that was fluidized upon impact of the Flims rockslide on the Vorderrhein valley floor. The instantaneous spike in pore water pressure resulting from the impact caused the granular sediment to liquefy and flow in a laminar manner (Poschinger and Kippel, 2009). A lake, perhaps dammed behind the Tamins rockslide, may have been present in the valley near the point of impact of the Flims rockslide.

Poschinger and Kippel (2009) also proposed that the tumas at Domat and Chur, downvalley from the Tamins rockslide, were transported on Bonaduz gravel during the Flims event. Poschinger and Ruegg (2012) identified several exposures of Bonaduz gravel within the town of Chur, the first such definitive identification of the unit east of the Tamins rockslide. Hills in Chur had previously been thought to have been emplaced by local landslides, but Poschinger and Ruegg (2012) argued that they too are far-travelled masses of rockslide debris. The Chur tumas are associated with Bonaduz gravel and consist of brecciated or blocky Helvetic limestone, dolomite, and mica schist. Poschinger and Ruegg (2012) argued that the limestone and dolomite have a Helvetic source, likely the Flims or Tamins rockslides, and the mica schist might have a Bündnerschiefer source.

Historic maps indicate that there were once 11 tumas in and near Chur (Figure 1.7; Poschinger and Ruegg, 2012). Seven of the 11 hills were removed for building materials and other reasons; only four remain today.

Recent detailed investigations of the Flims rockslide have provided information on the internal structure and transport mechanisms of the failed rock mass (Schneider et al., 1999; Pollet, 2004; Pollet and Schneider, 2004; Pollet et al., 2005; Poschinger et al., 2006). Pollet et al. (2005) propose a ‘slab-on-slab’ model of movement of the Flims rockslide involves dynamic disintegration and movement along pre-existing bedding planes. The ‘slab-on-slab’ model presumes that displacement occurred on centimetre- to metre-scale bedding planes within the limestone source rocks, as well as along transverse oblique joints. As a result, slabs delaminated and moved atop one another, and the rock mass was intensively fractured and crushed during transport (Pollet et al., 2005). The model supposes that the upper ‘slabs’ moved more rapidly and in advance of the lower ‘slabs’, a point that is both contentious and not supported in Pollet et al. (2005).

The impact of the rockslide on the opposing valley wall may be, in part, responsible for the *in situ* shattered blocks and pervasive jigsaw-fit texture (Schneider et al., 1999, 2004; Pollet et al., 2005; Poschinger et al., 2006). The debris was crushed to a fine powder along fractures, with minimal movement of the broken blocks of rock relative to each other. Most of the kinetic energy of this enormous mass of landslide debris was absorbed by the south wall of the Vorderrhein valley, preventing the spreading that is characteristic of rock avalanches such as the Blackhawk rock avalanche in California (Shreve, 1959) and the Saidmarreh rock avalanche in Iran (Harrison and Falcon, 1937; Roberts and Evans, 2013). However, the debris did spread up and down the Vorderrhein with little topographic constraint (Pollet et al., 2005).

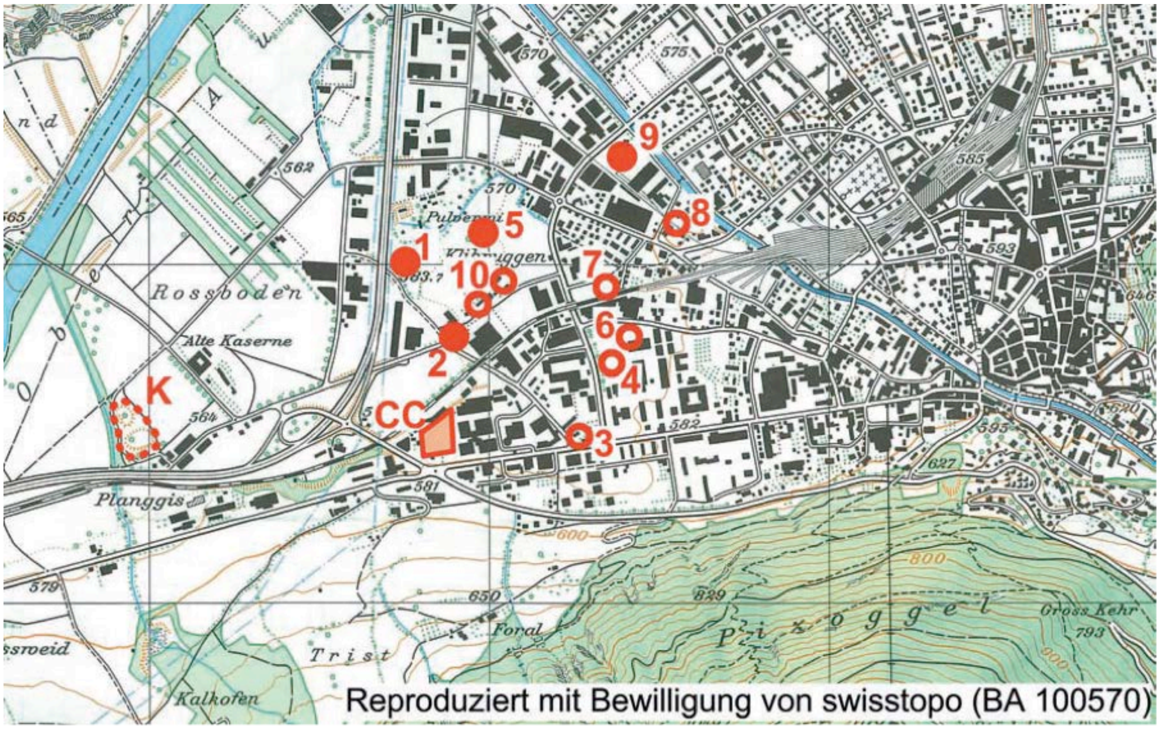


Figure 1.7. Tumas in the city of Chur (Poschinger and Ruegg, 2012). Closed circles are existing tumas and open circles are former tumas removed for building materials and other reasons.

1.4.2. The Tamins rockslide

The Tamins rockslide, although much smaller than the Flims rockslide, is a significant feature in the landscape. The deposit is hummocky and hilly, and forms a cross-valley barrier directly downstream of the confluence of the Vorderrhein and Hinterrhein rivers. It results from *en bloc* movement, with preservation of primary bedding in large blocks of debris (Abele, 1994). Abele (1997) estimated the volume of the rockslide to be 1.6 km^3 and the deposit to cover an area of more than 17 km^2. The landslide is sourced in the same rocks as the Flims landslide – Mesozoic limestone of the Helvetic nappe. The Tamins rockslide, however, also involved Tamins schist

(Section 1.2), which is notably absent up-valley in the source area of the Flims rockslide (Poschinger et al., 2006).

The Tamins rockslide has not been dated but is thought to be older than the Flims rockslide (Abele, 1997; Kippel, 2002; Poschinger et al., 2006). Poschinger and Kippel (2009) reported Bonaduz gravel overlying the Tamins deposit in the Vorderrhein-Hinterrhein confluence area.

The barrier formed by the Tamins rockslide deposit caused the Bonaduz gravel slurry to split into two tongues, one of which flowed up the Hinterrhein valley and the other overtopped and breached the Tamins barrier and flowed down the Alpenrhein valley. There are many tumas downvalley of the Tamins rockslide with minor associated gravel of Bonaduz affinity, but there are no Bonaduz gravel terraces or plains, such as exist upstream of the Tamins rockslide (Poschinger and Ruegg, 2012), with the exception of a terrace with two tumas in Felsberg and a recently identified terrace near Chur (A. von Poschinger, personal communication, 2015).

The lithological similarity of the Flims and Tamins rockslide deposits makes it difficult to determine the source of some of the tumas (see Chapter 3). Were they derived from the Flims rockslide deposit, transported atop the Bonaduz gravel, and carried past the Tamins rockslide deposit? Or are they pieces of the Tamins rockslide deposit that were entrained and transported by the Bonaduz gravel slurry?

1.4.3. Timing of postglacial events in the Vorderrhein valley

The presence of till and erratics on the surface of the Flims rockslide deposit led to debate about the age of that landslide. Heim (1883, *in* Poschinger et al., 2006) reasoned, based on this evidence, that the event was late-glacial. Nabholz (1954) argued that the landslide was caused by glacial debuttressing when ice left the valley. Subsequently, researchers applied absolute dating methods and showed that the landslide occurred long after deglaciation.

The first radiocarbon ages on the Flims rockslide were obtained on samples of wood recovered from gravel overlain by distal rockslide debris in the Rabiusa gorge, near the town of Versam (Poschinger and Haas, 1997). The ages, which range from

8015 ± 215 to 8790 + 85 ^{14}C yrs BP, are maxima for the age of the landslide and indicate that it occurred more than 3000 years after the valley was deglaciated.

Deplazes et al. (2007) cored sediments in two small lakes situated in depressions on the Flims rockslide deposit. Wood and leaf fragments recovered near the base of the lacustrine sequence yielded radiocarbon ages between 7900 ± 120 and 8540 ± 65 ^{14}C yrs BP.

Ivy-Ochs et al. (2009) obtained ^{36}Cl and ^{10}Be surface exposure ages on 16 blocks and other surfaces associated with the Flims rockslide. They also dated the basal sliding surface of the Flims rockslide near the top of the headscarp and several very large boulders on hills at the top of the Flims rockslide debris sheet. The exposure ages range from 4900 ± 250 yr to 15,440 ± 1480 yr. Several of the bedrock surface ages were discarded due to uncertainties in corrections for snow cover and vegetation. Some of the boulder ages were also discarded because they differed so much from ages obtained on nearby boulders; the argument was that the boulders with the anomalous ages might have rolled or toppled. The unweighted mean of the remaining seven sample ages is 8900 +/- 700 yr.

The age of the Tamins rockslide is less certain. No material associated with the landslide and suitable for radiocarbon dating has yet been found and no surface exposures ages have been published. The landslide, however, is postglacial because the deposit has not been overridden by glaciers and has not been rafted downvalley from the source scarp. Poschinger and Kippel (2009) reported an exposure within the quarry at Reichenau that showed Tamins rockslide debris underlying Bonaduz gravel. This evidence implies that the Bonaduz gravel and, by inference, the Flims rockslide are younger than the Tamins rockslide. This inference is consistent with evidence that the Bonaduz gravel slurry was partially deflected 90° up the Hinterrhein valley by the Tamins rockslide barrier.

Chapter 2.

Bonaduz gravel

2.1. Introduction

The Flims rockslide, located in the eastern Swiss Alps, is the largest postglacial terrestrial landslide in Europe. About 9400 years ago, 10-12 km^3 of Cretaceous and Jurassic limestone detached from the north wall of the Vorderrhein River valley. The rock mass rapidly fragmented and, upon impact with the valley floor, liquefied approximately 1 km^3 of late-glacial and postglacial sediments (Pavoni, 1968; Deplazes et al., 2007; Poschinger and Kippel, 2009). A slurry of liquefied sediment traveled down the Vorderrhein valley; part of the flow was deflected by debris of the older Tamins rockslide and traveled 16 km up the valley of the Hinterrhein River, its largest tributary. Huge fragments of rockslide material, referred to as 'tumas', were rafted up to 11 km on the liquefied slurry. The sheet of liquefied sediment deposited by this mass flow is termed the 'Bonaduz gravel'; it is locally more than 60 m thick and fines upward from cobble gravel at the base to sand at the top.

The Flims rockslide and surrounding environment have been studied for more than 150 years. My research is based on field study and interpretation of new LiDAR imagery provided by SwissTOPO, with a focus on the tumas, Bonaduz gravel, and the flanks and toe of the Tamins rockslide. It builds on previous work and hypotheses by a series of eminent Swiss geologists, starting with Albert Heim in the late nineteenth century.

The study region is located in the Rhine River valley near the confluence of the Vorderrhein and Hinterrhein rivers (Figure 2.1). Both the Vorderrhein and Hinterrhein valleys are glacially overdeepened and bordered by steep slopes. The Vorderrhein River follows the Chur fault, a tectonic suture between the southern Penninic and northern Helvetic nappes (Pfiffner, 1993). Up to 500 m of Quaternary sediments lie beneath the valley floor (Pfiffner et al., 1997). Early Holocene rockslides, mass flows, and outburst floods from landslide-dammed lakes have left a strong geomorphic imprint on the valley floor. The early Holocene surface was incised by the Vorderrhein and Hinterrhein rivers. Following human settlement, these rivers were trained and no longer are natural systems.

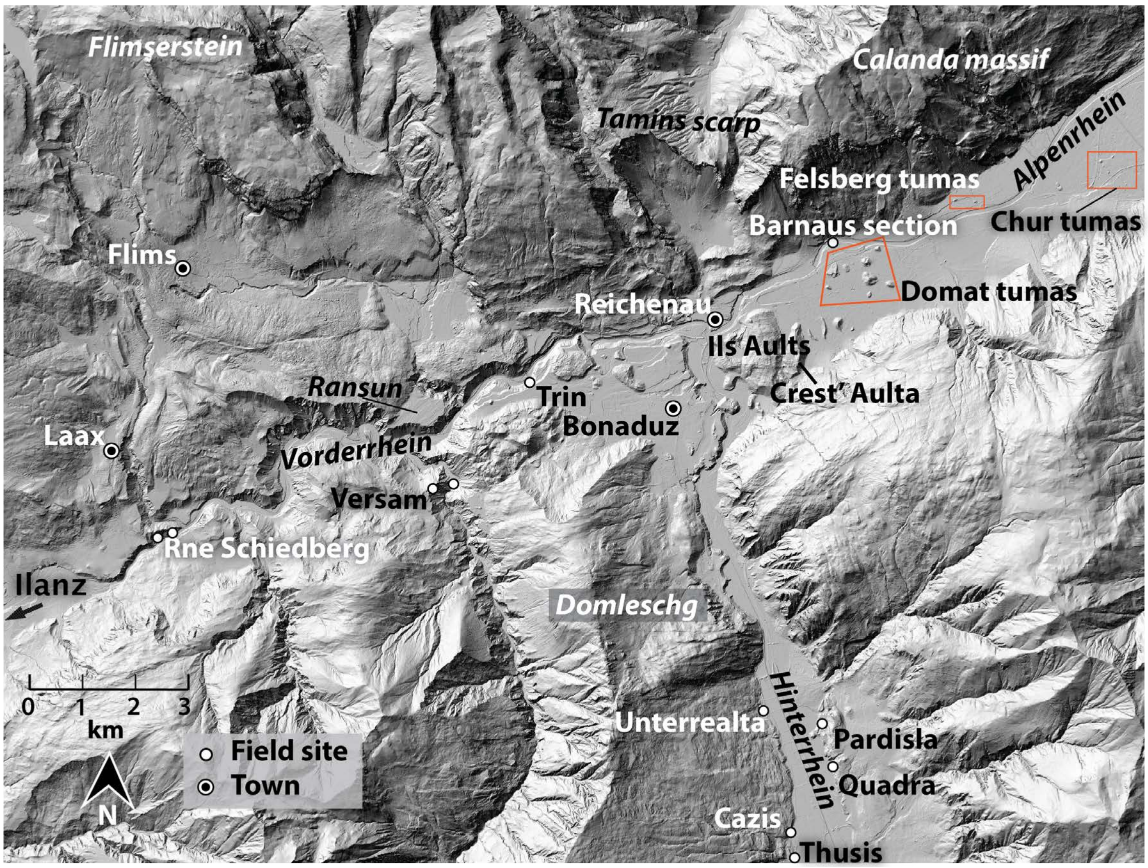


Figure 2.1. Hillshade map and overview of the study area, showing towns and some of the field sites.

The geomorphology of the study area is dominated by the deposits of the Tamins and Flims rockslides and the Bonaduz gravel sheet. The Flims rockslide deposit covers an area of about 46 km^2 and has an undulatory to ridged surface form. The Bonaduz gravel deposit is a gently undulating plain at the confluence of the Hinterrhein and Vorderrhein rivers. The Tamins rockslide deposit straddles the valley and is hummocky with some ridges; it forms a cross-valley obstruction with a narrow valley through which the Alpenrhein River flows. Terraces formed of Bonaduz gravel also occur along the sides of the Hinterrhein valley to near the town of Thusis. The Bonaduz flow overrode and possibly breached the hummocky deposit of the Tamins rockslide (2-2.6 km^3). It rafted tumas downvalley of Tamins and against the upvalley margin of the rockslide deposit.

In this chapter, I document the geomorphology and three-dimensional form of the Bonaduz gravel. I also describe the sedimentology of the unit at key exposures and discuss the relations of the mass flow to the Tamins and Flims rockslides. My objective is to infer the genesis and transport and depositional histories of this remarkable unit.

2.2. Methods

I acquired a digital map of the Vorderrhein and Hinterrhein valleys, including the areas of the Flims and Tamins rockslides and Bonaduz plain, from SwissTOPO. The map was produced from 2-m-resolution LiDAR imagery and reveals previously unrecognized geomorphic features related to the two landslides and the Bonaduz event. I present stratigraphic and sedimentological descriptions of field sites, geomorphic interpretations based on analysis of hillshade digital elevation models (DEMs), and particle-size data.

I determined the location of each of my 25 field sites with a hand-held GPS. I defined stratigraphic units based on lithology and sedimentary structures. Elevations of units were determined using a laser rangefinder and SwissTOPO data. I used the Wentworth classification for grain size terms (Wentworth, 1922). I collected 20 samples of Bonaduz gravel for particle-size analysis and analyzed them following protocols in the *Standard Practice for Wet Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants* prepared by the American Society for Testing and Materials (Appendix A). Particle-size distributions were truncated at 40 mm and 0.07 mm.

I acquired the LiDAR imagery from the SwissTOPO office and used Global Mapper for three-dimensional visualization and basic spatial measurements. Hillshade maps were prepared in ArcMap.

I prepared a geomorphic map of the area in the vicinity of the Vorderrhein-Hinterrhein confluence (Figure 2.2). Features include tumas; Flims and Tamins rockslide deposits; the Bonaduz gravel plain and terraces; Lake Ilanz flood deposits, channels, and terraces; and terraces of the Alpenrhein and its tributaries.

2.3. Results

2.3.1. Geomorphology

Flims rockslide

Albert Heim in 1878 was the first to provide a detailed description of the huge, crushed rock mass in the Vorderrhein valley near Flims. He concluded that the mass had come down in a single enormous 'stroke' (Heim, 1883). Due to the giant dimensions of the slide mass, many later researchers could not accept this audacious theory and offered the alternative hypothesis that it is in-situ bedrock (see Poschinger et al., 2006 for a summary of the controversial discussions). Today, it is accepted that the rock mass detached from the Flimserstein, a nearly 400-m-high cliff in Helvetic limestones. The bedding planes dip at an angle of 20-30º towards the valley floor, making such an enormous failure possible. Using a Digital Elevation Model (DEM), Caprez (2008) calculated the volume of the remaining rockslide mass to be about 8.6-9.3 km^3. He also estimated the volume of the material eroded along the Rhein gorge after the event to be 1.5 km^3, giving a total volume of the failure of about 10-11 km^3. Erratic boulders and even some patches of till are present on top of the rockslide mass, which led some researchers to infer a pre- or syn-glacial age for the event. Absolute dating by the radiocarbon method, however, has shown that the rockslide occurred during the postglacial period, about 9600 years ago (Poschinger and Haas, 1997, Deplazes et al., 2007). The erratics and patchy till atop the slide mass obviously had been transported, as on horseback, from their former positions high on the slopes to where they are found today. New findings indicate that some Quaternary sediments not only lie on top of, but also within, the rockslide mass. They must have been squeezed into fissures in the rockslide mass under very high pressure.

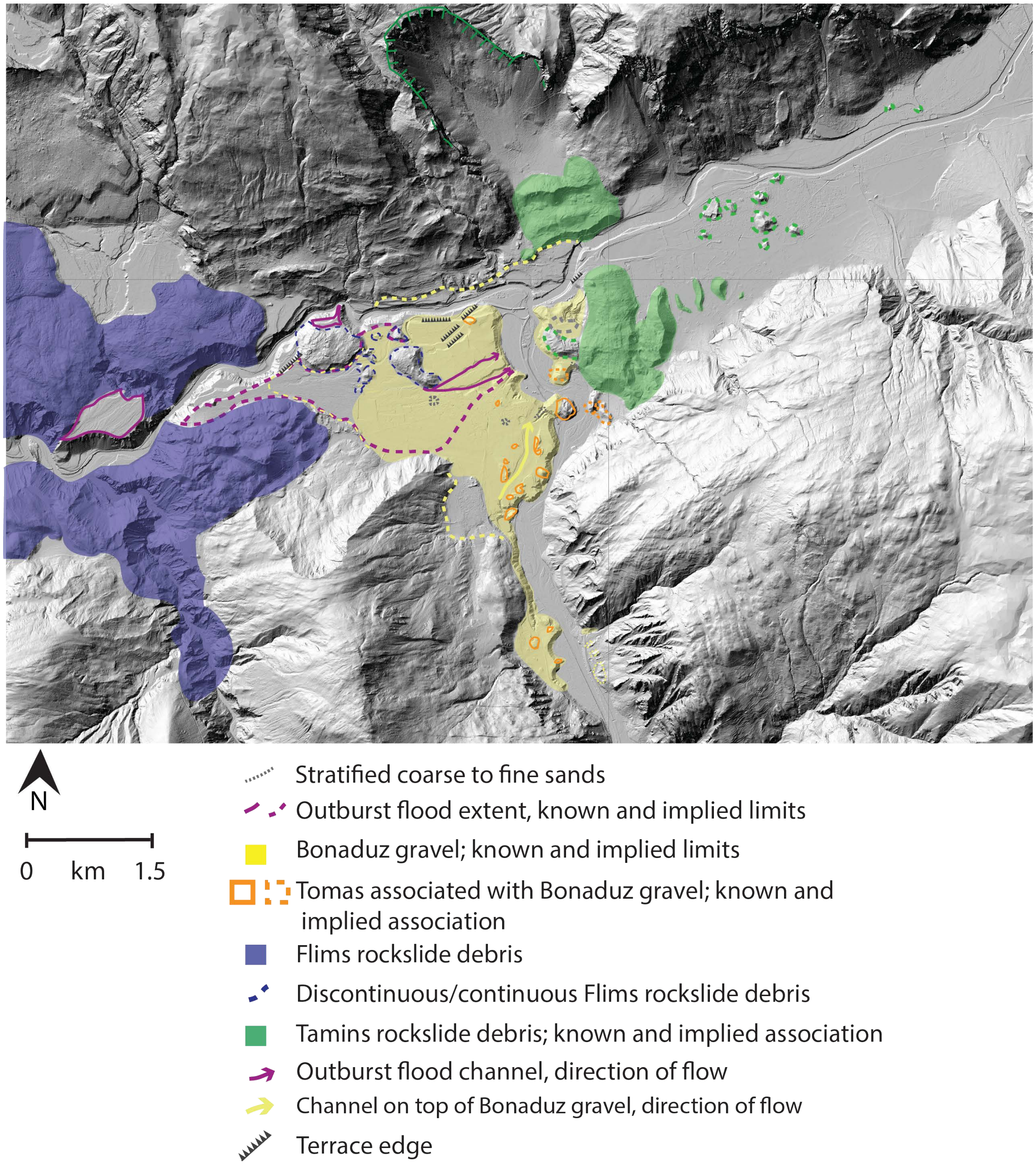


Figure 2.2. Map showing the main sediment units and geomorphic features discussed in the text.

The full extent of the Flims deposit is not easy to determine. On the west, a line from Laax to the Sagogn golf course only marks the surface outcrops. From boreholes, Flims rockslide material is known to extend much farther to the west, beyond Ilanz, but in that area it is buried under younger sediments. The eastern boundary is even more difficult to delineate. The rockslide mass is continuous between Sagogn and Trin, but to the east it comprises a series of hills surrounded by younger sediments. It is not known if the hills of Bot Danisch and Bot Tschavir are connected to the main rockslide body underground or if they are tumas – isolated hills of rockslide material (dashed blue outlines in Figure 2.2). These hills, however, are clearly Flims rockslide material. Farther east, towards Bonaduz and Rhäzüns, the tumas decrease in size and a connection to the Flims event is less evident. It might also be possible that these are remnants of the Tamins rockslide, remobilised and transported by the Flims-Bonaduz event (see below).

Figure 2.3. Photographs of Flims rockslide debris. The left photo was taken within the 'Ruin Aulta' – Vorderrhein river gorge, which is developed entirely within pulverized rockslide debris (photo Hazel Wong). The right photo shows a closer view of typical crushed Flims rockslide debris.

The rockslide material is extremely crushed and shattered (Figure 2.3). Some parts are a chaotic loose assemblage of blocks set in a more-or-less fine matrix. Other parts reveal the intact, former sedimentary bedding, but nevertheless are crushed to centimetre- or millimetre-size and have the form of a three-dimensional jigsaw puzzle (Figure 2.3, right photograph). The material stands in vertical faces many tens of metres high, possibly due to cementation resulting from mixing of finely crushed limestone with groundwater. The debris is compact and resistant to digging. One of the most accessible places to view the debris is along the road from Bonaduz to Versam (parking between the two tunnels).

The trigger for the detachment of such an enormous volume of rock is unknown; we can only speculate. Failure was possibly triggered by an earthquake, either a tectonic one or one induced by another large rockslide, for example the Tamins rockslide. The Chur fault, along which the Vorderrhein and Alpenrhein rivers run, is thought to be active, and surface uplift rates in the field area are 0.8-1.4 mm/yr (Persaud and Pfiffner, 2004). In either case, the Flims rockslide itself certainly caused a severe earthquake (see section 3.1.3).

Another explanation might be climate change. The event happened during the Boreal period, the first warmer and wetter period after the last glaciation (Gruner, 2006). A loss of permafrost at higher elevations may have changed the karst-hydrological regime, perhaps producing exceptional water pressures within the bedrock mass or increasing stresses in rock fractures or along bedding planes (Gruber and Haeberli, 2007).

Vorderrhein valley between Flims and Ilanz

The blockage of the Vorderrhein River and its tributaries by the rockslide mass gave rise to several lakes. The city of Ilanz is located in the basin of the largest of these former lakes, so-called 'Lake Ilanz'. Evidence for this lake can be seen in delta sediments exposed in a quarry 1 km east of Ilanz and in the gorge of the Laaxerbach south of Laax. Silty, well bedded lake-bottom sediments are exposed southeast of Sagogn and are visible from the road between Ilanz to Versam on the opposite slope. Similar fine sediments have also been found in boreholes under younger Rhein alluvium in Ilanz and farther west. All these sediments are below 820 m asl, indicating a long-lived lake at this level, with a volume of about 1.5 km^3 and a length of about 23 km, up to the location of the village of Darvella. Most likely, however, this was not the maximum level of the lake because downvalley outburst sediments indicate that the water was dammed higher up, probably to an elevation of about 900-920 m asl. At that time, the lake had a lake volume of 3 km³ and a length of 29 km, reaching to the location of the village of Rabius (Poschinger, 2006). After an unknown length of time, the upper part of the dam breached, presumably shortly after the first overflow and the lake lowered to the 820-m level. The then-lower lake may have persisted for some hundreds of years before emptying by stepwise erosion of the Vorderrhein River to its present position. Eroded remnants of the dam are visible today in the inclined plane of Ransun (Figure 2.4) and can be seen from a viewpoint on the opposite side of the river, 200 m west of the parking area between the two tunnels on the road from Versam to Bonaduz.

Figure 2.4. Photographs of Ransun: the box in the left photograph is located at 805 m, located at the left edge of the orange line in the right photograph. The orange box outlines a bouldery deposit atop Flims rockslide debris (photo by Hazel Wong). The right photo shows the erosional plain of Ransun dipping to the east (right). The plain is underlain by grey Flims rockslide debris, visible above the river (photo by John J. Clague).

Between Sagogn and Bonaduz, the Vorderrhein River flows in a 300-m deep, steep-walled gorge (Ruin Aulta) cut into Flims rockslide debris. The river has not yet eroded to the bottom of the rockslide debris. The surrounding Flims rockslide debris is hilly and hummocky, with lateral and transverse ridges. This terrain is mostly forested with lakes perched atop the rockslide mass.

Bonaduz plain

Bonaduz gravel underlies the gently rolling surface of the Bonaduz plain, which differs little in elevation (654-660 m asl; Figure 2.5 and 2.6). In the Hinterrhein valley, Bonaduz gravel extends up to 664 m asl at the Rodels and Paradisla quarries, and to

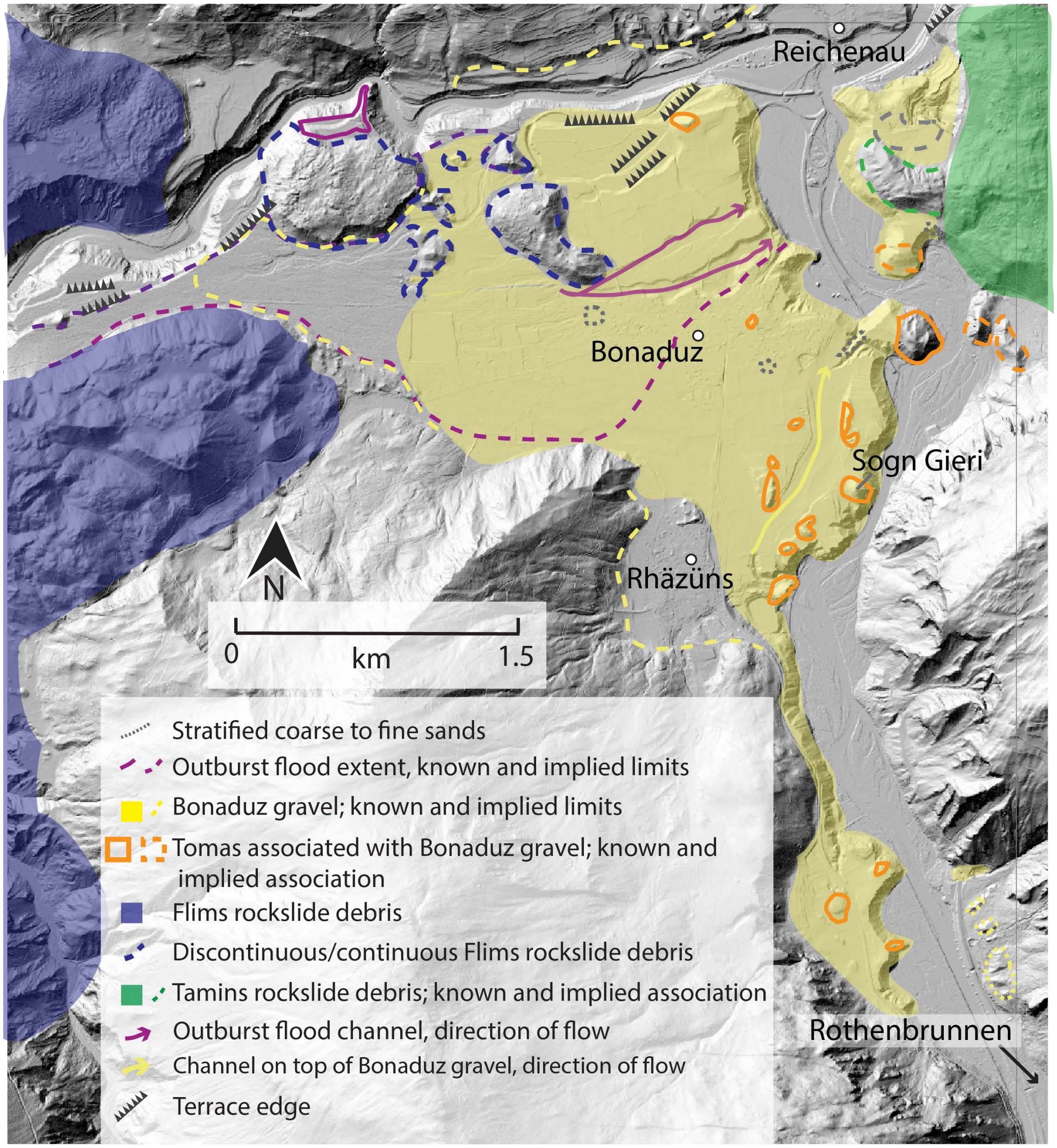


Figure 2.5. Geomorphic map of the deposits produced by the Tamins and Flims rockslide events.

740 m asl at Thusis. The elevation of the base of the Bonaduz gravel is unknown, although the unit is at least 65 m thick beneath the Bonaduz plain. There are boreholes in both the Hinterrhein and Vorderrhein valleys, but the data are not in the public domain. Furthermore, it is difficult to distinguish the Bonaduz gravel from underlying fluvial gravel in borehole logs, because the former is resedimented fluvial gravel.

Bonaduz gravel stands in near-vertical cliffs along the Hinterrhein River and in quarries (Figure 2.7 and 2.8). Isolated forested tumas extend above the surface of the Bonaduz plain (Figure 2.8) and are easily recognized in the LiDAR imagery.

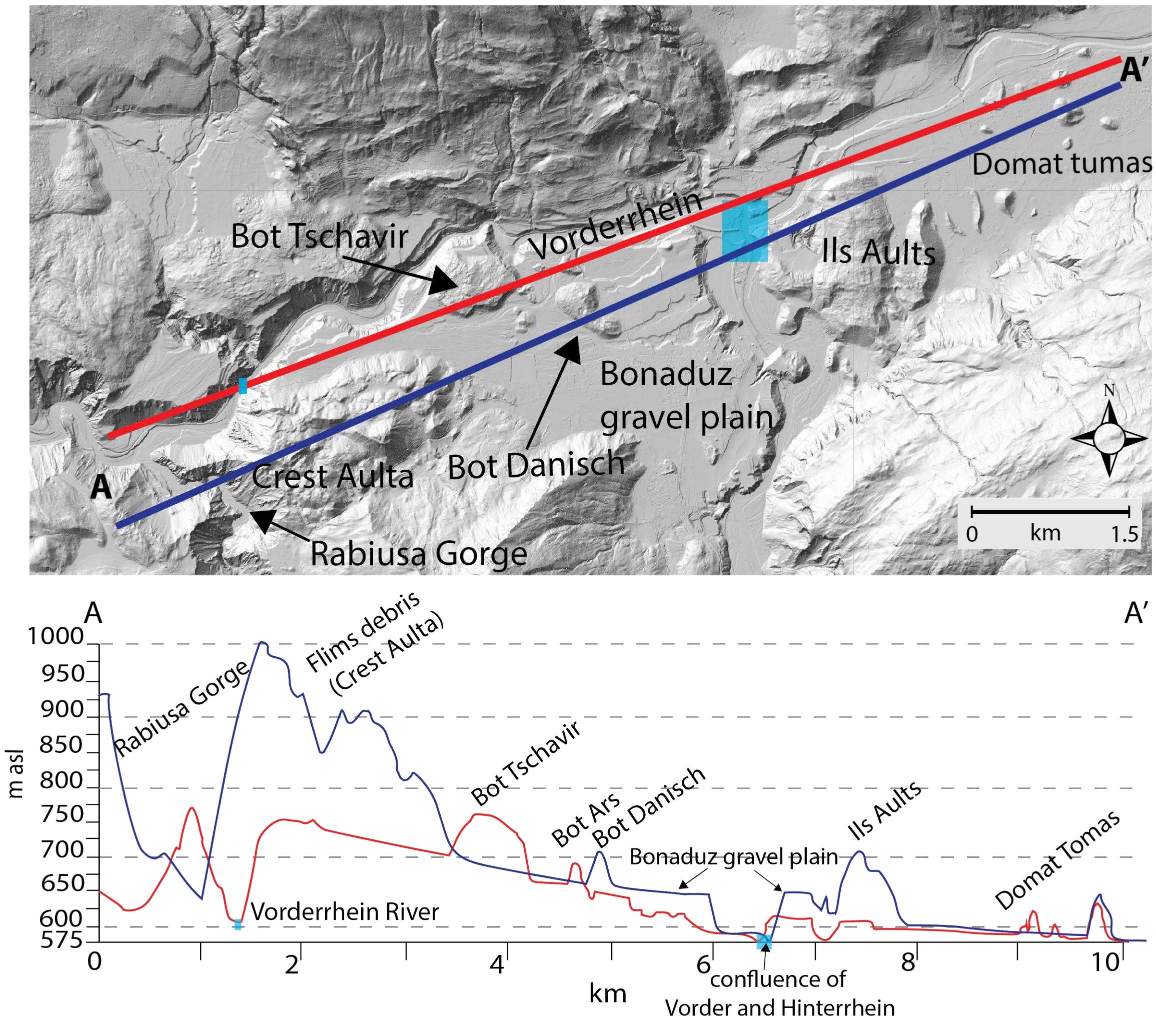


Figure 2.6 Hillshade image and two down-valley profiles, one (red) along the axis of the Vorderrhein River and another crossing Crest' Aulta, Bot Danisch, and Ils Aults (blue). The light blue rectangles show the present positions of rivers. Vertical exaggeration = 7x.

After the Bonaduz mass flow came to rest, the Hinterrhein River trenched the Bonaduz plain. At the time of its emplacement, it would have filled the valley at the confluence of the two rivers to 60 m above present base level. As it incised the Bonaduz gravel, the river encountered resistant tumas embedded within the Bonaduz gravel between Rothenbrunnen and Reichenau.

Directly east of Rhäzüns, for instance, the Hinterrhein takes a circuitous route around the tumas pictured in Figure 2.8. Near the medieval church of Sogn Gieri, one can see the crushed Helvetic rock core of a tuma with Bonaduz gravel on both sides. Channels cut by the Lake Ilanz outburst floods also flow around tumas on the Bonaduz plain. The boundaries between tumas and Bonaduz gravel are accentuated by agricultural practices. The former are wooded hills that rise above plowed fields of Bonaduz gravel. In the Hinterrhein River valley, the Bonaduz gravel forms gently undulating terraces close to the valley wall.

Figure 2.7. Photos of Bonaduz gravel. Left: A typical exposure of Bonaduz gravel along the Hinterrhein River at the edge of the Bonaduz plain (person at the top centre of the photo provides scale). Right: Bonaduz gravel in the Pardisla quarry. The gravel is dominantly of pebble size and contains faint Pavoni pipes. Standard-field book for scale. (Left photo by John J. Clague; right photo by Hazel Wong.)

The land surface near Bonaduz and south of Reichenau was affected by catastrophic outburst floods from Lake Ilanz. The surface of the Bonaduz Plain slopes uniformly 3.5 km to the east from the toe of the Flims rockslide towards the confluence of the Vorderrhein and Hinterrhein rivers. Figure 2.6 shows the Bonaduz Plain in cross-sectional view; the plain is also shown in Figure 2.5. This sloping surface is underlain by an apron of boulder gravel and diamicton deposited by the outburst floods from Lake Ilanz. These deposits overlie the Bonaduz gravel. Broad shallow channels are incised into the apron and probably record flows during the later stages of the outburst sequence.

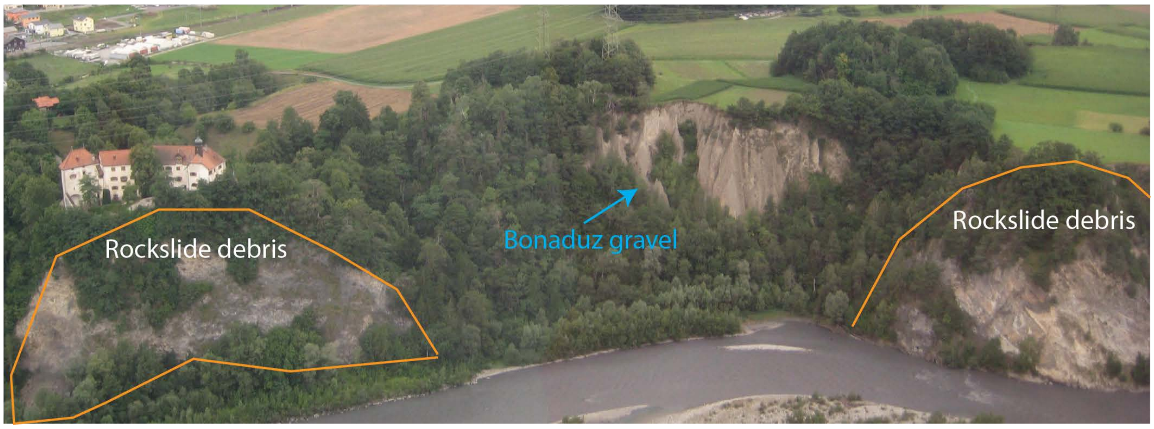


Figure 2.8. Oblique aerial view of the southeast edge of the Bonaduz plain. Two tumas are outlined in orange. Bonaduz gravel is found on both sides of the tumas and underlies the field in the background. The wooded hills at the top of the photo are also tumas. The vertical distance from the Hinterrhein River in the foreground to the surface of the Bonaduz plain is ~65 m. The tops of the tumas are 20 m higher than the surrounding plain. The town of Rhäzüns lies to the left of the frame of the photo.

Tamins rockslide

The Tamins rockslide left a deposit on the floor of the Rhein valley at Reichenau. The source area of the rockslide is a deep, amphitheatre-shaped bowl in Late Jurassic limestone of the Helvetic nappe system (Figure 1.3 and 2.9). The bowl is crowned by the 2000-m high summit of Sennenstein. About 2 km^3 of rock are missing from this amphitheatre. In the literature, this rockslide has also been named after the village of Reichenau, the Säsagit mountain, or the Kunkels pass above the bowl (Poschinger et al., 2006).

A south-sloping plain separates the headscarp of the Tamins rockslide from the outcropping rockslide mass to the south. This plain was formed by infilling of a depression at the trailing edge of the rockslide mass by debris flow deposits that are younger than the rockslide. A peat bog on this plain marks a former small lake. The plain is bordered on the south by an east-trending ridge (Rascheu) (Figure 2.9). Farther south is a second ridge (Cartschitscha) that is parallel to the first. Both ridges are slide blocks emplaced at the trailing edge of the Flims rockslide. The more northerly ridge is up to 100 m high and 1 km long; the southern ridge has less relief.

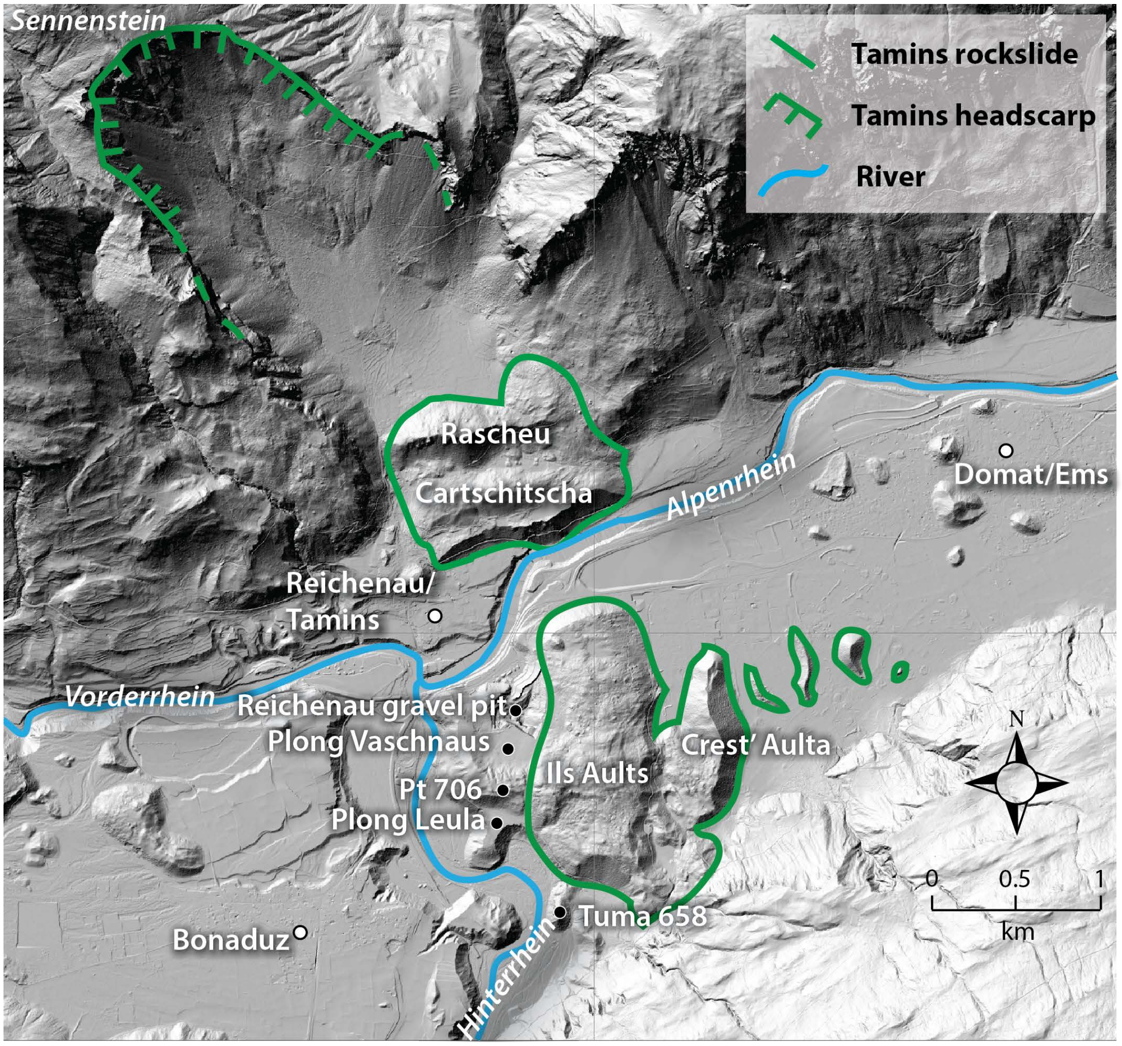


Figure 2.9. The headscarp and deposit of the Tamins rockslide (green) (modified from Poschinger et al., 2015).

Alpenrhein River has eroded a 400-500-m-wide and approximately 100-m-deep valley in the Tamins rockslide mass. On the north side of the river, the Tamins rockslide mass is clearly visible as crushed and blocky Helvetic limestone similar to the Flims rockslide debris. Nested within this valley are downriver-sloping terraces underlain by mass flow deposits of the Flims rockslide and the Lake Ilanz outburst events.

The main part of the Tamins rockslide mass lies south of the Alpenrhein River. It extends for almost 2 km across the Rhein valley and forms the hills of Ils Aults and Crest' Aulta (Figure 2.9). The surface of the debris sheet in this area is undulating and blocky, and reaches up to 170 m above the Alpenrhein River. Bonaduz gravel more than 60 m thick is inset into the rockslide debris near Reichenau and is also exposed at the western margin of the debris sheet beneath a terrace capped by Hinterrhein fluvial gravel. The east edge of Ils Aults is abrupt (Figure 2.6) and is flanked by several narrow steep ridges, including Crest' Aulta and the diminutive ridges to the east. These ridges are cored by Tamins rockslide debris.

The main Tamins rockslide mass reaches the bedrock slope of Bündnershiefer on the south valley wall (Plong Urtgiclera). Its west margin is a steep smooth slope bordered by Tuma 658, Plong Leula and Tuma 706 (Figure 2.9), all of which are cored by rockslide debris. Low open meadows lacking hummocks or blocks separate Ils Aults from the tumas to the southwest and southeast. These meadows are 40-120 m lower than the nearest high points of Ils Aults.

Alpenrhein valley between Flims and Chur

Alpenrhein River terraces are much lower downstream of the Tamins rockslide deposit than upstream (580 m vs. 615-635 m; Figure 2.6). The river is inset 4-12 m into the valley floor in the Domat/Ems area, and this low terrace is underlain by Alpenrhein River deposits that are younger than the Bonaduz gravel. Many tumas extend above the terrace level in Domat/Ems (Figure 2.2) and as far east as Chur. Two tumas are present in the village of Felsberg, associated with a 5-m-high terrace (Figure 2.2).

Three large fans enter the Alpenrhein valley from the south between Tamins and Chur, including the fan on which Chur itself lies. The north wall of the valley is underlain by dip-slope carbonate rocks, which are the source of several historical and prehistoric rockfalls and rockslides, including a devastating rockfall event 2 km east of the town of Flims in 1939. The Alpenrhein River turns abruptly north downstream of the town of Chur, 9 km northeast of the Tamins rockslide deposit.

Hinterrhein Valley

The Hinterrhein River enters the Alpenrhein valley at a right angle. Just before entering the valley, the river flows through a narrow bedrock gorge that constricts the river for 1.5 km. High terraces on both sides of the Hinterrhein River within the gorge are underlain by Bonaduz gravel; the west terrace is the more prominent and continuous of the two (Figure 2.5).

Farther south, the gorge broadens to a 2-3-km wide, flat valley (the Domleschg). From Rothenbrunnen to Thusis, the Hinterrhein River is confined by dykes in a narrow, straight channel. The west side of the valley flanked by steep bedrock slopes. The eastern valley wall is less steep and several fans extend onto the valley floor, overlying the Bonaduz gravel terraces. There is no equivalent of the Bonaduz gravel plain in the Hinterrhein valley, but there are several low rolling Bonaduz gravel terraces nested close to the bedrock walls of the valley. There are two small tumas in this reach: one flanks the Paradisla quarry and the other is near the center of the valley, ~2 km south of the Paradisla quarry near the Quadra field site.

2.3.2. Bonaduz and Bonaduz-like gravels

The massive Flims rockslide crossed the Vorderrhein River valley at high speed and slammed into the opposite valley wall. The impact raised pore water pressures within alluvial sediments, liquefying them and sending a huge mass flow, which we refer to as the ‘Bonaduz mass flow’, down the valley.

Abele (1997) estimated that about 1 km^3 of valley-fill material was mobilized by the impact of the rockslide on the Vorderrhein valley floor. The Bonaduz mass flow, which was probably more than 100 m thick, encountered the barrier formed by the Tamins rockslide and split into the two masses, one of which turned 90° and flowed 15 km up the Hinterrhein valley, rafting huge blocks of rockslide material with it. The other overtopped and possibly burst through the barrier of the Tamins rockslide and continued east down the Rhein valley beyond Chur.

Bonaduz gravel stands in near-vertical cliff faces. In all exposures, the Bonaduz gravel unit fines upward from cobble gravel at the base to granule-rich sand and silt at the top. The pebbles and cobbles are rounded, yet are separated by a silt-rich matrix. Although the gravel fines upward, rip-up clasts of stratified silt up to several metres across occur throughout the deposit. Typical Bonaduz gravel is poorly sorted, with a constant proportion of fine sediment below 0.7 mm. There is no discernible orientation of clasts in the unit. Clast lithologies include carbonates, mica schist, vein quartz, and rare gneiss and granitoid and metavolcanic rocks. All of these lithologies are found in Vorderrhein valley sediments.

The Bonaduz gravel plain and most of the terraces underlain by Bonaduz gravel within the Hinterrhein valley have elevations of about 660 m. However, what I interpret to be fine Bonaduz gravel extends up to ~743 m asl near Thusis at the extreme limit of the Bonaduz mass flow, and the Ruine Schiedberg exposure of Bonaduz gravel, which is in contact with the west margin of the Flims rockslide deposit lies between 710 m and 740 m asl.

Poschinger and Kippel (2009) identified two Bonaduz gravel lithofacies: one the typical fining-upward, silty-sandy cobble to granule gravel, and the other a diamicton with a chaotic orientation of cobbles and boulders admixed with finer gravel and sand, without sorting or grading. The latter lithofacies lacks Pavoni pipes and rip-up clasts. Poschinger and Kippel (2009) concluded that the diamicton is immature Bonaduz gravel that more closely resembles the original valley-fill sediment but also liquefied and flowed during the Flims rockslide. I also hypothesize in Chapter 3 that some of the diamicton represents the leading edge or traction carpet on which the Bonaduz mass flow moved.

I describe in more detail the diamicton lithofacies, which I refer to as 'proto-Bonaduz gravel', later in this chapter at the Ruine Schiedberg section, in the east wall of the Reichenau quarry, in Versam gorge, near Trin station, and at the base of the Unterrealta quarry. The contact between the diamicton lithofacies and typical Bonaduz gravel is commonly wavy to irregular, in places sharp and in other places gradational.

Pavoni pipes

Pavoni pipes, named for the Swiss geologist who first hypothesized that the Bonaduz gravel sheet is a mass flow deposit, are vertical to subvertical streaks lacking fine sand and silt that are ubiquitous throughout the Bonaduz gravel (Figure 2.10). There is a relation between clast size and the length and width of Pavoni pipes (Kippel,

Figure 2.10. Pavoni pipes in Bonaduz gravel at the Reichenau quarry. A) Pipes in the lowest exposed gravels. B) A single pipe showing the absence of silt and sand within the gravel, and steeply dipping stones. C) Pipe with granule-size particles. D) Pipes near the top of the quarry dominated by coarse sand-size particles.

2002). Pavoni pipes in the lower, coarsest part of the Bonaduz gravel unit range from 60 cm to 2 m in length and from 5 to 20 cm in width. Pebbles and cobbles within the pipes are commonly steeply inclined. Near the top of the Bonaduz gravel, where clasts are granule-size, Pavoni pipes are more closely spaced and are 5 to 15 cm long and 0.5 to 5 cm wide.

The pipes mark the paths of pore water that moved upward through the Bonaduz gravel mass as it consolidated immediately after coming to rest. They are not obviously connected to one another. An implication of these elutriation features is that large amounts of water were involved in the Bonaduz mass flow. As discussed in Chapter 3, similar features are generated in laboratory mass flows with moderate particle-to-fluid concentrations (25-55% solid concentrations; Druitt, 1995).

2.3.3. Stratigraphic sections

Figure 2.11 shows the locations of field sites where I documented stratigraphy, with the exception of the Ruine Schiedberg site, shown in Figure 2.1.

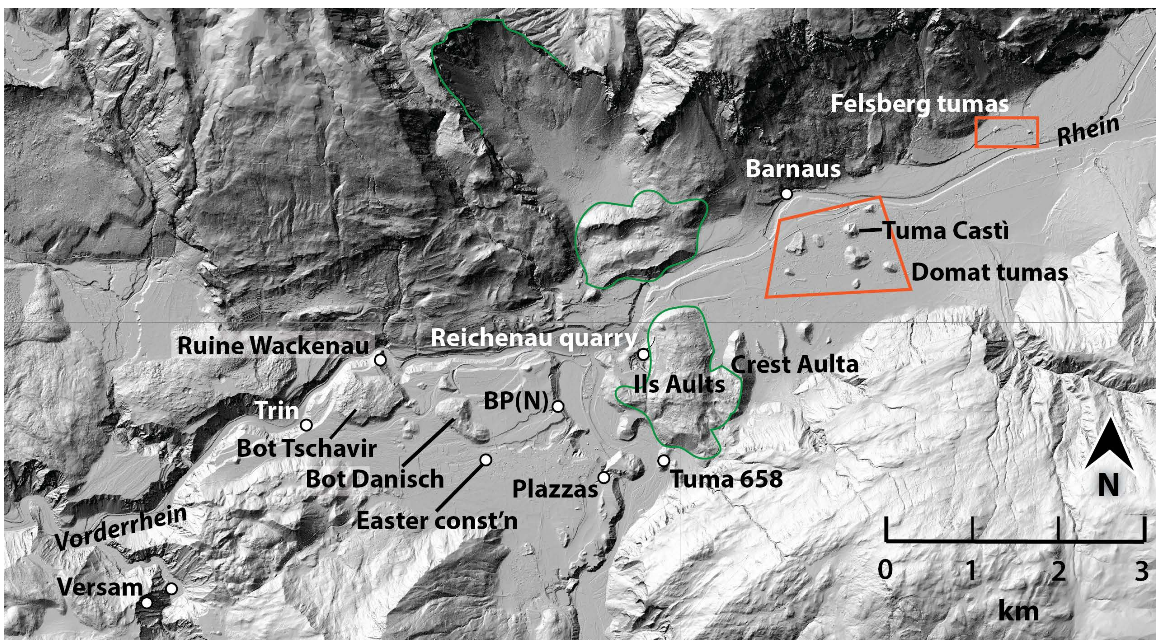


Figure 2.11. Hillshade map of the area near the confluence of Vorderrhein and Hinterrhein rivers, showing field sites.

Ruine Schiedberg

At several sites within and at the margins of the Flims rockslide deposit, liquefied valley-fill sediments are in contact with Flims rockslide debris.

Two of these sites are Ruine Schiedberg and Schiedberg east (Figure 2.12 and 2.13), located near the west margin of the landslide deposit in an exposure that extends up to 100 m above the Vorderrhein River. Fluidized gravel is abruptly bordered along a near-vertical contact by Flims rockslide debris in the Schiedberg east exposure (Figure 2.13), and clasts of rockslide debris are included in the lowermost unit in the Ruine Schiedberg exposure (Figure 2.12).

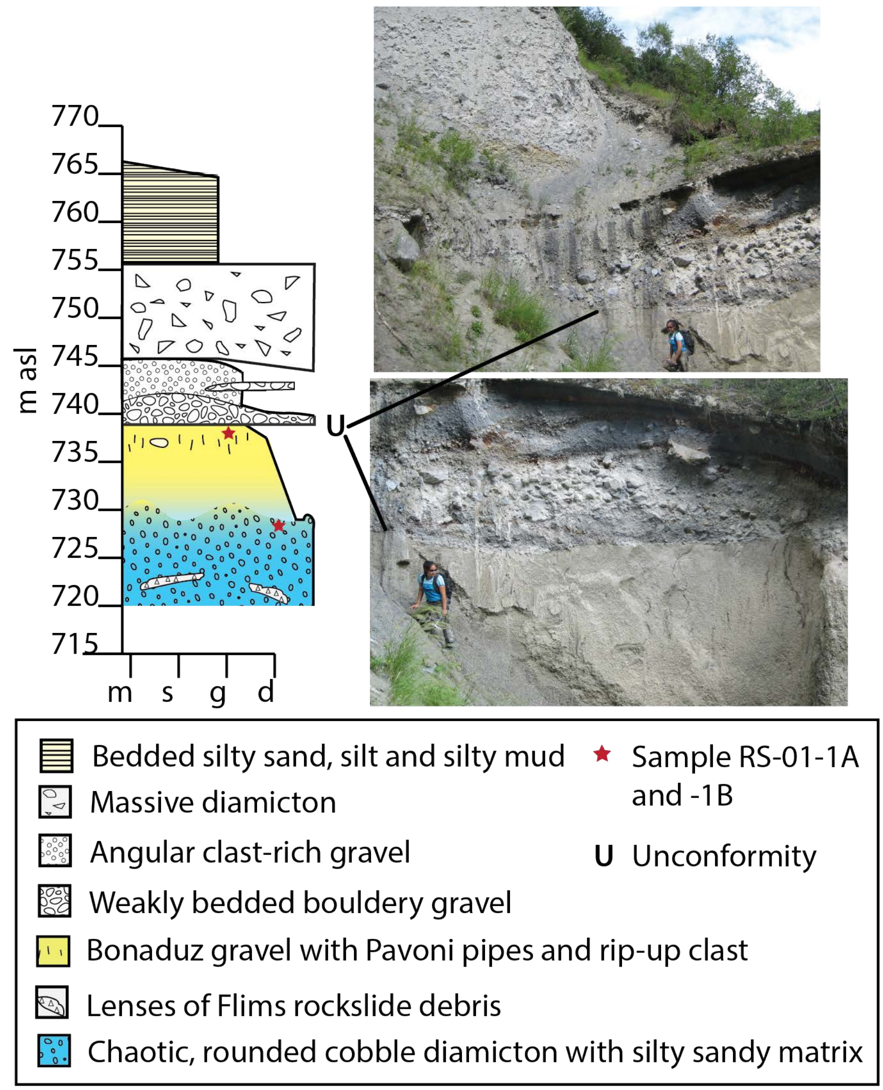


Figure 2.12. Stratigraphy of Ruine Schiedberg section. Particle-size data are presented in Appendix A.

In the Ruine Schiedberg section, the diamicton grades upward into classic

Bonaduz gravel – a silty sandy gravel containing laminated silt rip-up clasts and Pavoni pipes (Figure 2.12). Up to 10 cm of laminated fine sand and silt are present locally at the top of the section. The gravel and capping sand and silt, in turn, are overlain across an erosional upper contact by weakly stratified, clast-supported gravel with subrounded to angular Helvetic limestone clasts ranging in size from pebbles to blocks up to 1 m across. Discontinuous beds range from 20 cm to ~2 m thick. The lowest 2 m of the gravel contain boulder-sized angular clasts, whereas the uppermost 2 m are dominantly pebble-size gravel. The beds dip up to 15° to the south (i.e. towards the river). Some large angular clasts are bordered by silt matrix, which is locally laminated. The gravel unit is locally capped by 10 cm of laminated sand and silt with a cemented upper contact dipping to the south. Above this unit is about 10 m of massive matrix-supported diamicton containing a mix of rounded to angular clasts up to 50 cm across. The diamicton, in turn, is sharply overlain by horizontally bedded and laminated silty sand and silt.

In an exposure about 300 m northeast of Ruine Schiedberg, a ca. 10-m-thick unit of Bonaduz gravel is in near-vertical contact with pulverized rockslide debris (Figure 2.13). The gravel gradually fines upward from cobble- to pebble-size, which is characteristic of Bonaduz gravel. Tabular cobbles and pebbles dip steeply along the contact between the gravel and the rockslide debris. Rockslide debris adjacent to the gravel contains scattered rounded stones.

Chaotic proto-Bonaduz diamicton with rounded to angular stones up to cobble-size is exposed at the base of the Schiedberg East section. Lenses of crushed Helvetic limestone rockslide debris up to several metres thick occur within the diamicton.

Higher in the section, above a covered portion of the slope, is a matrix-supported stony silt and an overlying stratified silt unit. The stony silt contains angular limestone fragments ranging from granules to large pebbles and a rip-up clast of highly deformed, laminated to bedded sandy silt. The overlying sandy silt unit, which can be traced for 30 m along the width of the exposure, contains rare rounded pebbles and has a loaded upper contact with flames up to 2 m high (Figure 2.13). Laminations within the sandy silt unit are locally faulted and folded. The sandy silt unit is conformably, but sharply

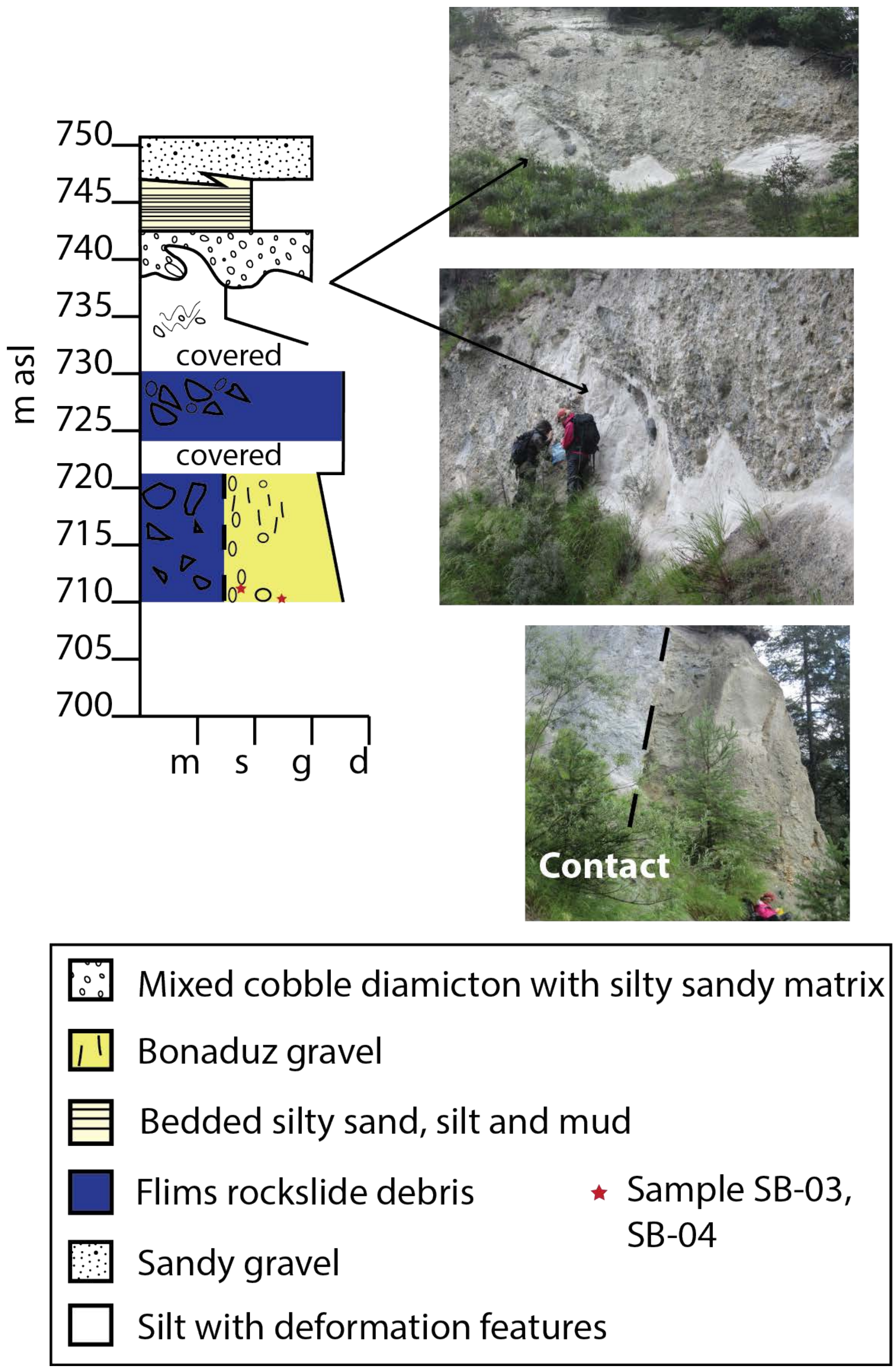


Figure 2.13. Stratigraphy of Schiedberg East section (photos John J. Clague). Particle-size data are presented in Appendix A.

overlain by about 4 m of poorly sorted, nearly massive, sandy pebble-cobble gravel with a mix of subangular to rounded clasts. Although the gravel fines upward, it lacks the typical structure of classic Bonaduz gravel. It is sharply overlain by 3 m of horizontally stratified silt and sand, which interfinger near the top of the section with 2 m of sandy gravel.

Trin Station

Classic Bonaduz gravel crops out in two pillars within Flims rockslide debris in an

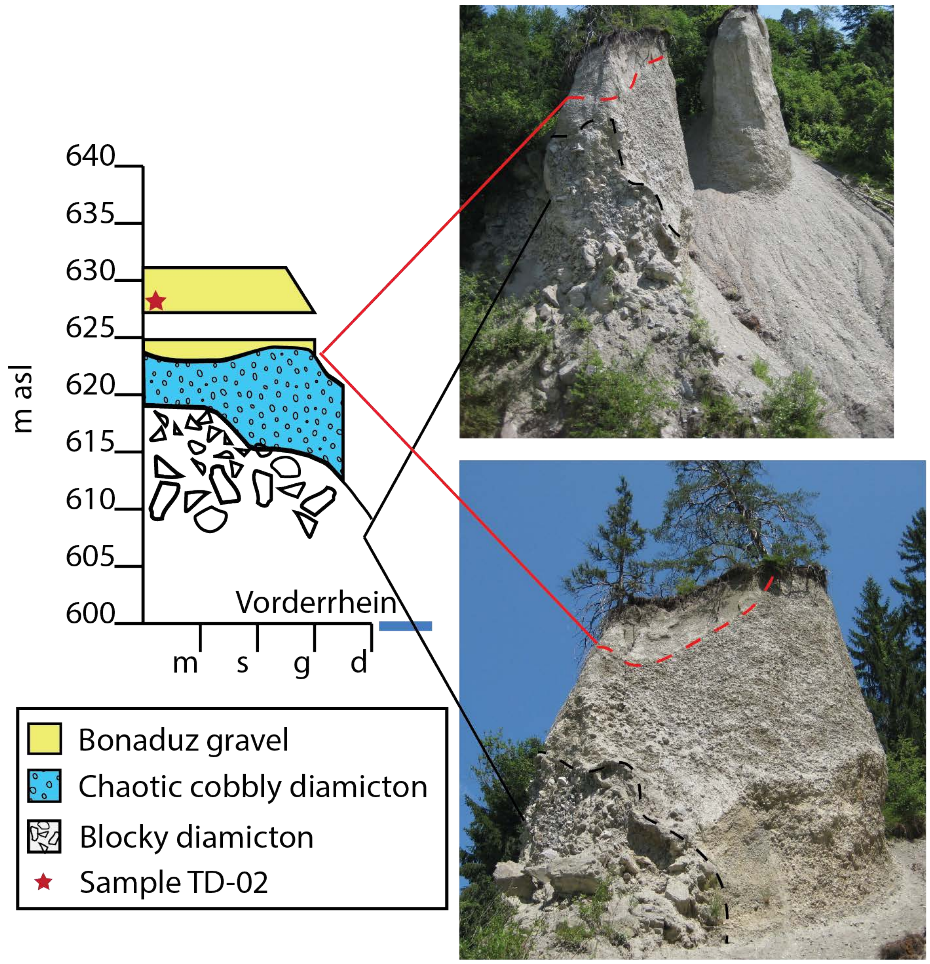


Figure 2.14. Stratigraphy of Trin Station section on the south side of the Vorderrhein River. Blocky rockslide debris at the base of the exposure is overlain across a wavy, irregular surface by cobbly diamicton. The uppermost sediments are classical fining-upwards Bonaduz gravel. Pulverized Flims rockslide debris is present both upstream and downstream of these spires.

exposure along the Vorderrhein River opposite the Trin train station (Figure 2.14). Rockslide debris at the base of the exposure comprises angular particles of Helvetic limestone ranging in size from clay to blocks up to 2 m across (Figure 2.14). The rockslide debris is overlain across a locally steep, undulatory contact by 3-10 m of massive diamicton that grades upward from clast- to matrix-supported and has a silt-sand matrix. Stones within the diamicton are subrounded to rounded, heterolithic, and dominantly pebble to cobble-size. Many tabular stones along the steep contact with the rockslide debris are near-vertical. The contact is strongly cemented, with ~5 cm of fine material separating the rockslide debris and aligned stones in the diamicton.

The proto-Bonaduz gravel unit described above grades over a short distance into a 10-m-thick, body of classic Bonaduz gravel – upward-fining pebble gravel with a sandy silty matrix and Pavoni pipes. Stones are aligned parallel to the 5-8-cm-wide contact between the diamicton and Bonaduz gravel.

Versam Gorge

Rabiusa Creek flows into the Vorderrhein River along a deep valley (Versam Gorge) incised several hundred metres into Flims rockslide debris. I examined and logged an exposure 14 m high and 25 m wide approximately 800 m upstream from the confluence of Rabiusa Creek and the Vorderrhein River (Figure 2.15, bottom). The section is located a few metres above the level of the stream along the south-facing slope named ‘Steinbruch’ on the *Reichenau* 1:25,000 topographic map. The section exposes matrix-supported cobble gravel with rounded to subrounded, chaotically oriented clasts up to 25-30 cm across in near-vertical contact with Flims rockslide debris. Pebbles and cobbles dip steeply at the contact between the two units.

About 20 m above this outcrop is a small exposure of cobble gravel (middle section in Figure 2.15), bordered along a sharp, near-vertical contact by rockslide debris. The lateral and lower boundaries of the gravel are obscured by colluvium. Above the cobble gravel is thick rockslide debris, forming the wall of the gorge.

I found another exposure of poorly sorted gravel an additional 220 m higher in Versam Gorge (elevation ~900 m; top section, Figure 2.15). This outcrop is the highest occurrence of rounded cobbles and pebbles that I found in contact with Flims rockslide debris. The exposure is approximately 15 m high and at least 6 m wide. Weakly stratified, poorly sorted, cobble- rich gravel with scattered boulders up to 1 m across

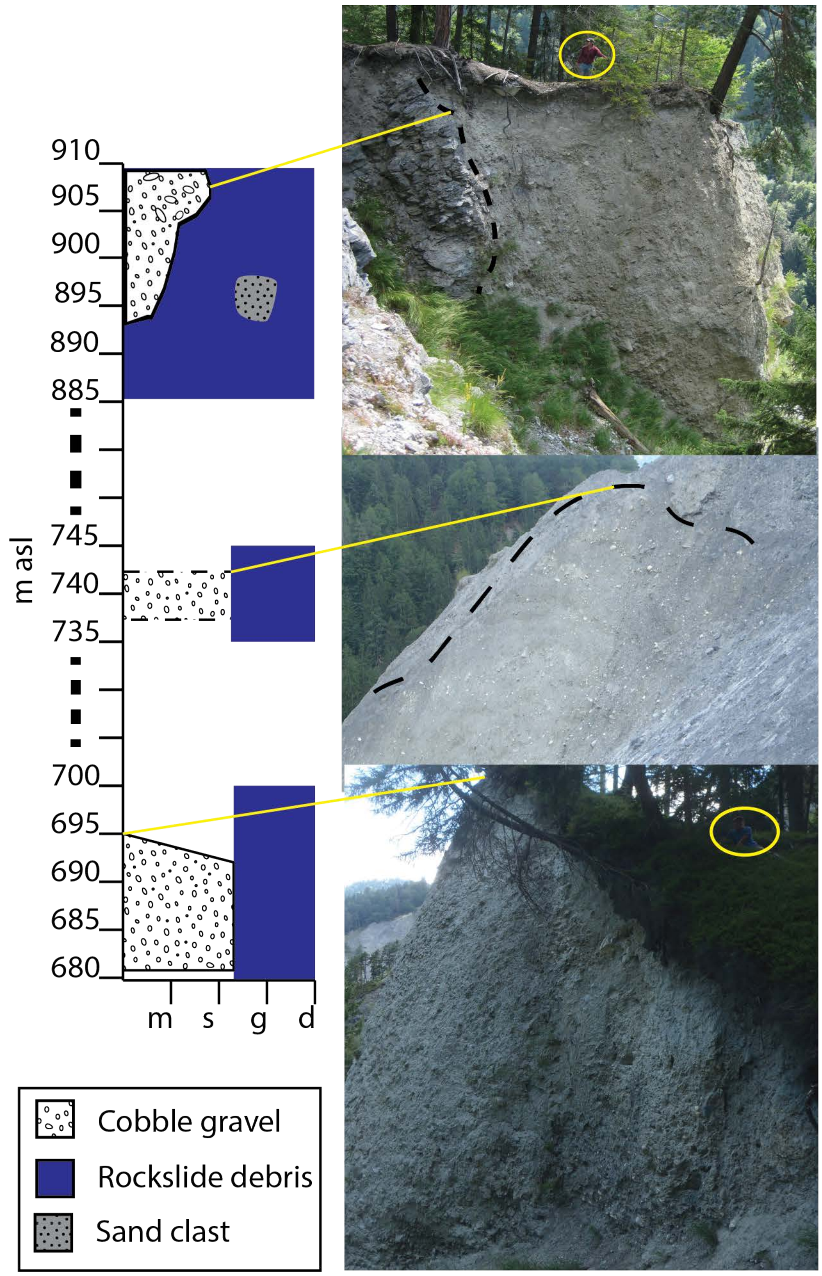


Figure 2.15. Stratigraphy of the Versam Gorge sections. The three sections are separated laterally and vertically. In each section, cobble gravel abuts thick Flims rockslide debris. The yellow ovals highlight a person for scale. The dashed lines in the photos delineate contacts; the two horizontal dashed lines in the middle sketch show the elevation range of the exposed gravel.

and a sand-silt matrix abuts Flims rockslide debris along a near-vertical contact. Cobbles near the contact dip steeply parallel to it. The gravel contains a large clast or lens of sand 3 m across. Unlike classic Bonaduz gravel, this sediment is not vertically graded. The rockslide debris consists of angular limestone particles ranging in size from coarse sand to blocks metres across.

Reichenau quarry

One of the best exposures of Bonaduz gravel at the time I was doing my field work is the Reichenau gravel pit, just south of the town of Tamins (Figure 2.11). The gravel pit exposed about 65 m of gravel in three walls oriented at angles of nearly 90° with respect to one another (Figure 2.16).

Figure 2.16. Reichenau quarry exposing Bonaduz gravel in near-vertical faces; view to the south (photo John J. Clague). Tamins rockslide debris underlies the forested area at the top of the photo. The yellow oval highlights a person standing in the quarry.

The base of the Bonaduz gravel unit lies an unknown distance below the base of the pit (elevation 595 m). The unit gradually fines upward from massive cobble gravel with a maximum clast size of about 12 cm at the base of the quarry to granule gravel near the top (Figure 2.17 and Figure 2.18). Other than fining upward, the sediment is massive – it comprises rounded stones set in a matrix of silt and very fine to fine sand. The sand content ranges from 25 to 85% of the sediment, increasing upward (Figure

2.18). Silt and clay consistently constitute 8-16% of the sediment, from the lowest samples to the highest ones (Figure 2.18).

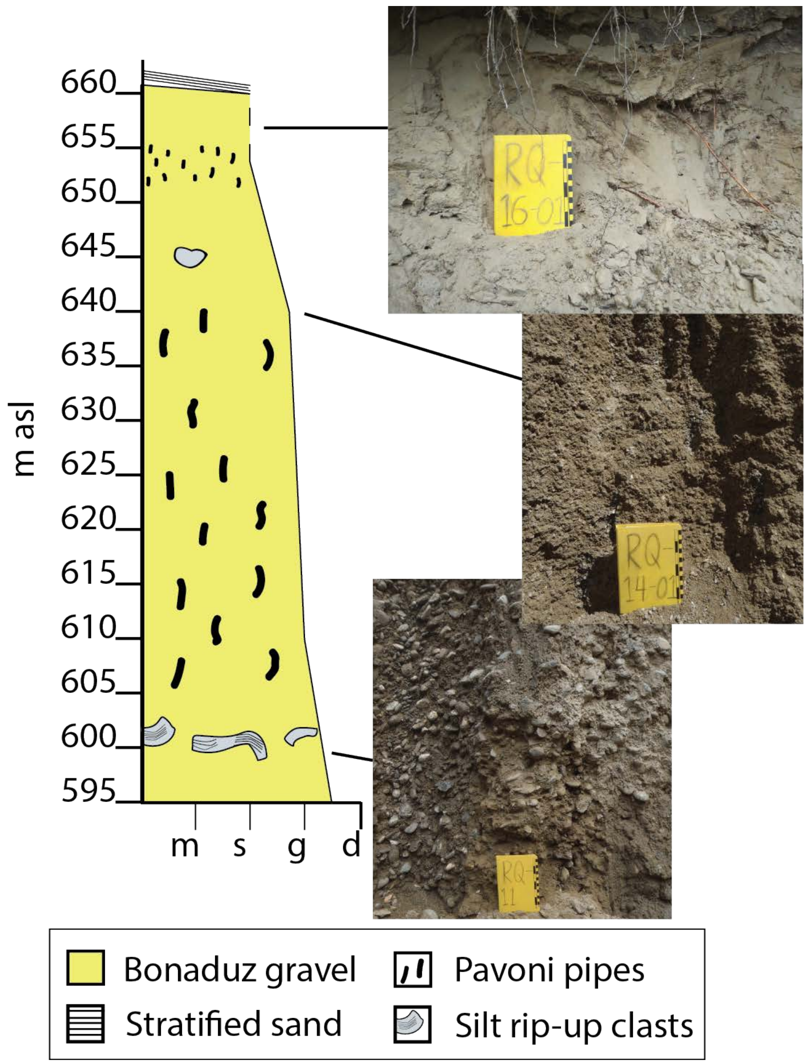


Figure 2.17. Stratigraphy of sediments exposed in the Reichenau quarry and representative photos of the lower, middle, and upper parts of the section.

Rip-up clasts of laminated lacustrine clayey silt up to 5 m in length are scattered throughout the Bonaduz gravel in the quarry. The largest rip-up clasts are folded, indicating that they were still soft when entrained into the Bonaduz flow. One large rip-up clast is bent and torn into three pieces (Figure 2.19).

In the east wall of the quarry, nearest the edge of Tamins landslide deposit, a >30-m-wide, ~15-m-high tongue of coarse cobble-boulder gravel and diamicton intertongues with finer Bonaduz gravel (Figure 2.20). Small boulders are up to 20-30 cm across and subrounded to well-rounded (see Appendix 1, Figure A.13). The coarse tongue of sediment also contains scattered subrounded to angular boulders up to about 1.5 m across. The contact between the two facies is gradational, suggesting some mixing during transport.

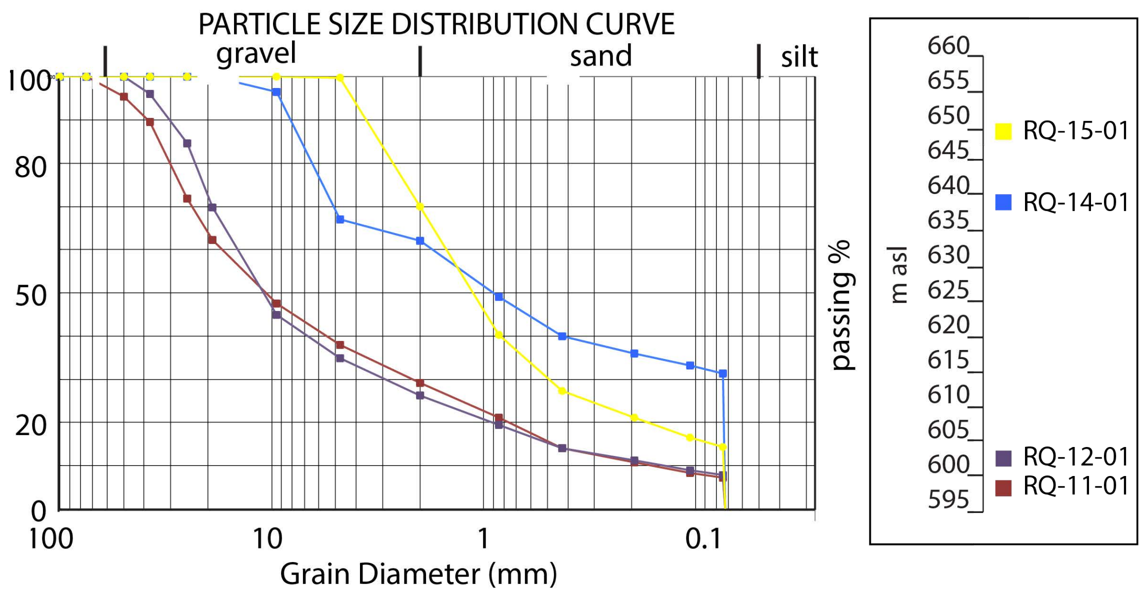


Figure 2.18. Particle-size distributions of six samples of Bonaduz gravel collected at the Reichenau quarry (distributions truncated at 0.07 mm and about 6 cm). The gravel fines upward.

A ca. 12-cm-wide clastic dyke extends to the top of the Bonaduz gravel in the southwest wall of the quarry. The outermost centimetre of the dyke comprises silt. It is bordered inward by alternating layers of fine to coarse sand oriented parallel to the walls of the dyke. A sample (RQ-14-01 in Figure 2.18) was collected from the clastic dyke for particle-size analysis (see Appendix 1).

Figure 2.19. A) A large rip-up clast, deformed and torn into three pieces, exposed in the Reichenau quarry. B) Internal laminae and thin beds in a silt rip-up clast in the Reichenau quarry; note outsized cobbles at the top of the rip-up clast.

The topmost several metres of Bonaduz gravel in the southwest wall of the Reichenau quarry comprises massive sandy silt without pebbles or cobbles and with no Pavoni pipes. These sediments are capped by up to 3 m of horizontally laminated and thin-bedded silt and sand that also lack Pavoni pipes and are inset into a broad shallow flat-floored channel at the top of massive silt. Some strata within the channel fill are rippled or have drape lamination.

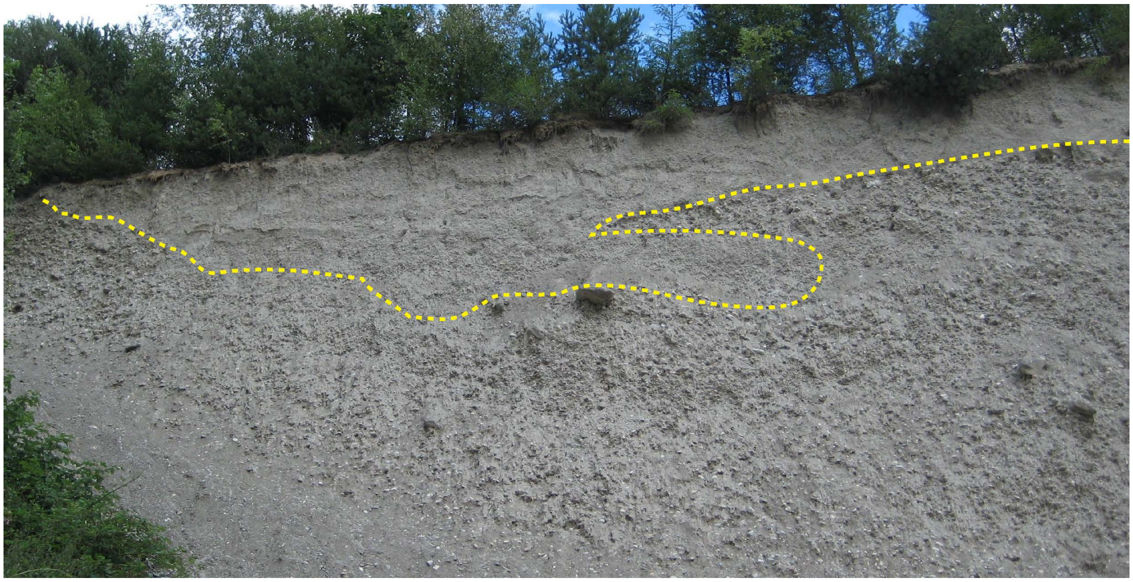


Figure 2.20. East wall of the Reichenau quarry, showing tongue of coarse cobble-boulder gravel (bounded by dotted yellow lines) within the Bonaduz gravel. The outsized clast at the centre of the photo, just below the contact, is approximately 1.5 m across.

Margin of Tamins rockslide on the east side of the Reichenau quarry

A 1-m-deep ditch for a water line extends approximately 150 m from near the east side of the Reichenau quarry at 662 m asl onto the Tamins rockslide deposit to at least 670 m asl. The sediment exposed in the ditch is very poorly sorted, cobble-boulder gravel with some angular Helvetic limestone blocks up to 1.5 m across (Figure 2.21). The large clast size and very poor sorting, as well as the admixed angular limestone blocks, distinguish this unit from the classic Bonaduz gravel in the Reichenau quarry, 40 m to the west and 3-15 m below the end of the ditch. It must overlie Tamins rockslide debris, although the latter is not exposed in the ditch.

Figure 2.21. Very poorly sorted cobble-boulder gravel exposed in a ditch on the gently rising slope directly above the Reichenau quarry. The pipe at the bottom of the ditch is approximately 12 cm in diameter. Note subrounded cobbles and boulders that are much larger than clasts in the nearby quarry.

Hinterrhein valley sites

The Unterrealta quarry is located on the west side of the Hinterrhein valley just upstream of a narrow (~400 m) bedrock bottleneck in the valley (Domleschg). Approximately 17 m of Bonaduz gravel is exposed in the quarry (Figure 2.22). The base of the exposure is a very poorly sorted cobble gravel with ca. 25-30% sand and silt matrix and a maximum clast size of 22 cm. This sediment grades upward into more typical Bonaduz gravel with better sorting, a sandier matrix, and some Pavoni pipes.

Opposite the Unterrealta quarry, at a similar elevation, is the Pardisla quarry. The steep, 25-m-high walls of this quarry expose Bonaduz gravel similar to that in the Reichenau quarry. Silty sandy cobble gravel at the base of the quarry grades upward into silty sandy pebble gravel at the top (Figure 2.22). The matrix content of the sediment is 12%. Multi-metre-long rip-up clasts of laminated clayey silt, which are plastically deformed but intact, are present throughout the gravel. Pavoni pipes are also present, although not as common as in the Reichenau quarry.

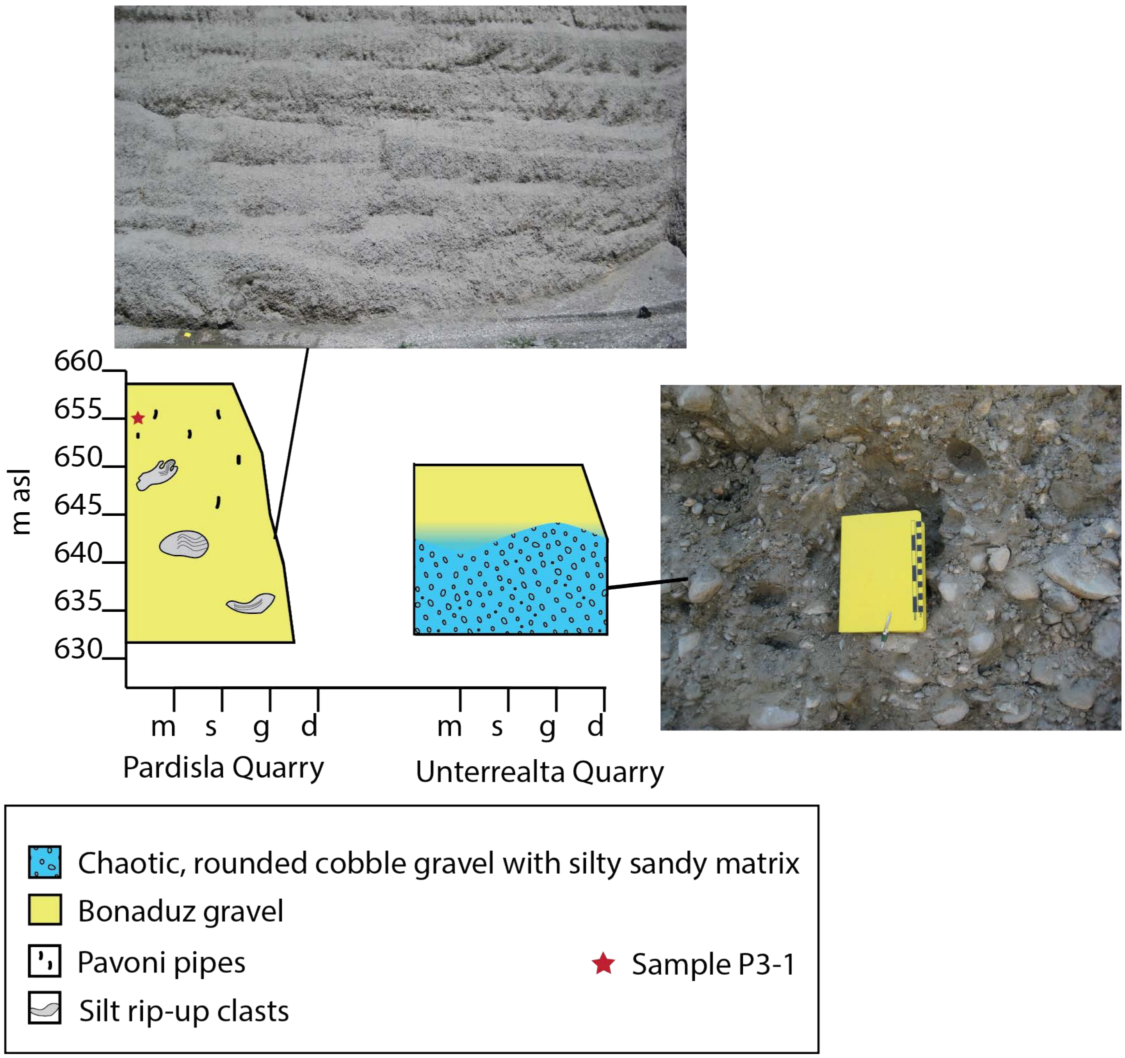


Figure 2.22. Stratigraphy of the Pardisla and Unterrealta quarry sections. A yellow standard field book (provides scale lower left in the upper photo). Particle-size data are presented in Appendix A.

Farther upvalley, near Rodels, a small gravel pit located on a gently rolling surface 30 m above the modern floodplain of the Hinterrhein River exposes a few metres of typical Bonaduz gravel, with a silt rip-up clast similar to those present at other sites (Figure 2.23). This site is 12 km upvalley from the mouth of the Hinterrhein River. Between Thusis and Cazis near the head of the Hinterrhein river valley, a gently rolling terrace on the west side of the valley exposes granule- and pebble-size gravel set in a silt and sand matrix, similar in character to Bonaduz gravel (Figure 2.23). The exposure, however, is limited and I found no silt rip-up clasts or Pavoni pipes within the gravel. The most upvalley of these exposures is 14.5 km from the margin of the Flims rockslide and the most distal occurrence of what I interpret to be Bonaduz gravel.

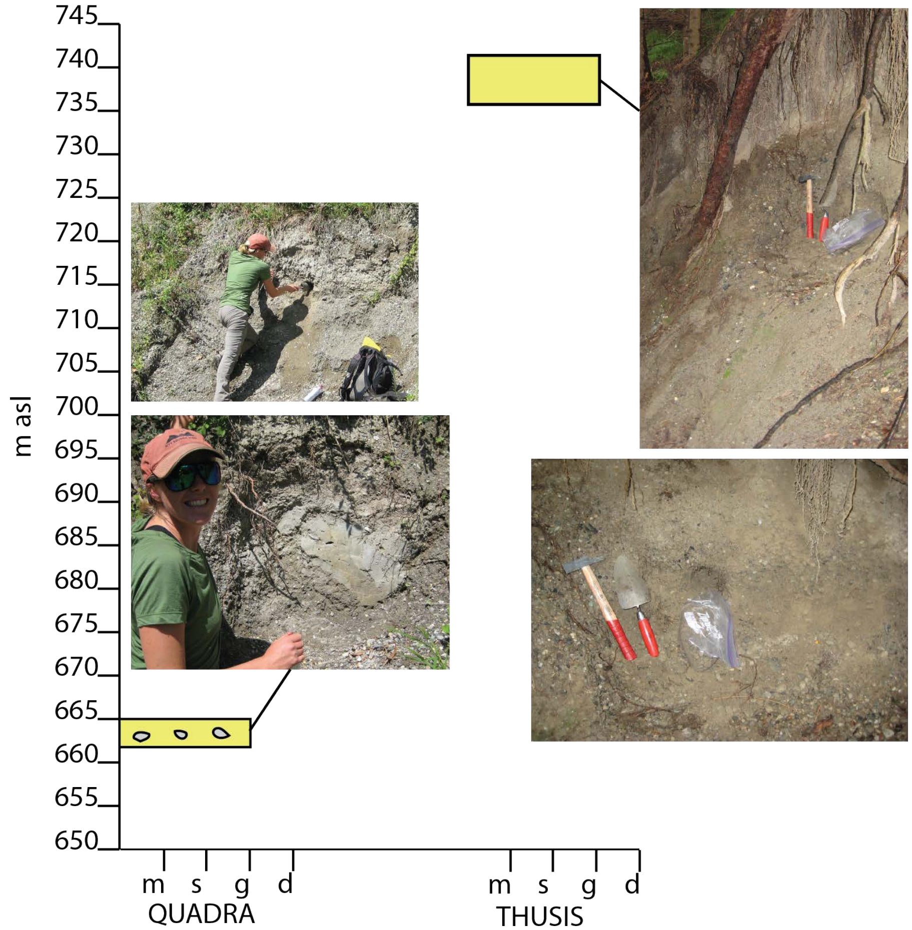


Figure 2.23. Bonaduz gravel in the Hinterrhein valley near Rodels (site name Quadra) and ~2 km farther southwest at Thusis. Rodels and Thusis are the farthest sites from the Vorderrhein valley, and the highest, where I found Bonaduz gravel. (Photos of Quadra section by Mary Calhoun.)

Ils Aults sites

The surface of the Tamins rockslide at Ils Aults on the south side of the Alpenrhein River is dominated by large Helvetic limestone blocks up to many metres across. These blocks are visible in the LiDAR imagery and obvious in the field.

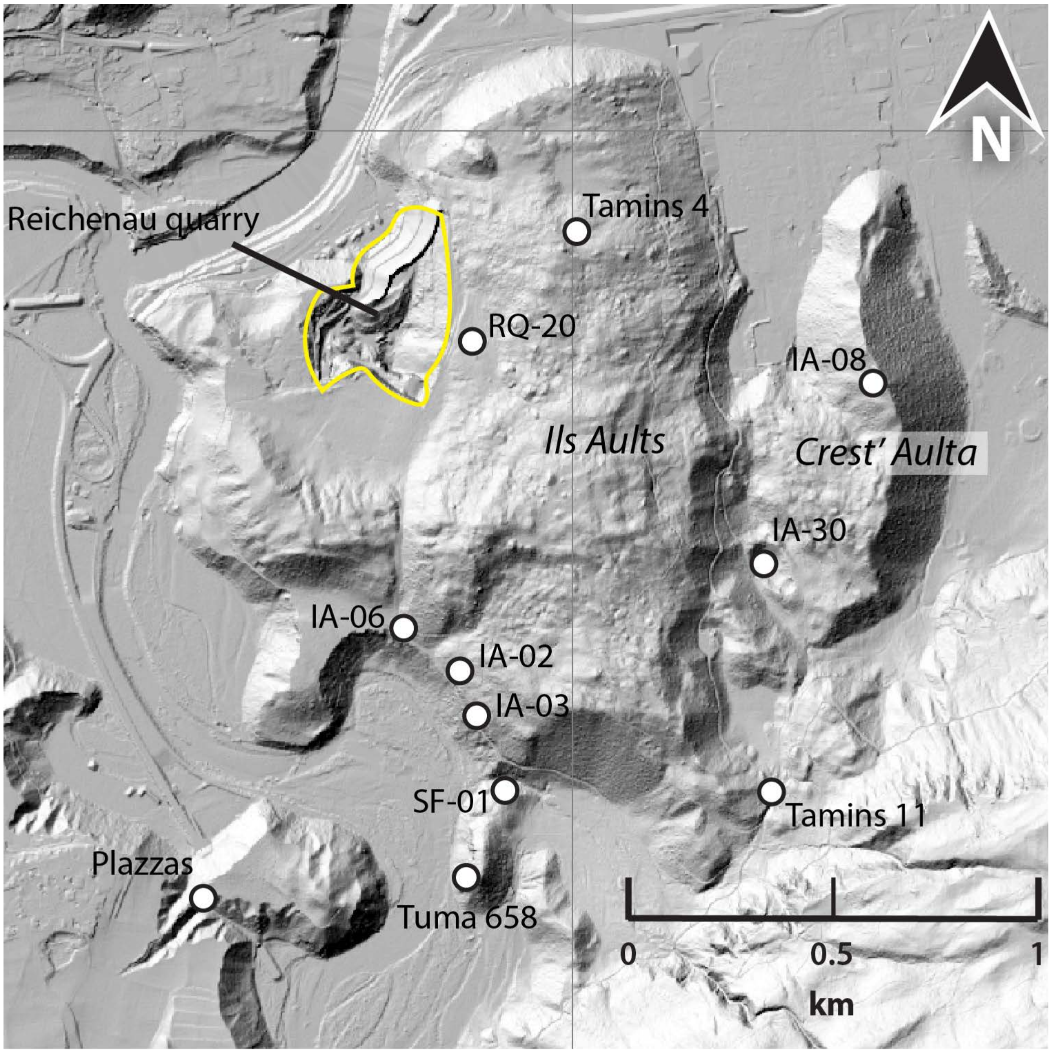


Figure 2.24. Field sites on and around the Tamins rockslide.

The surface of Ils Aults is hilly and irregular, with up to 60 m of relief (Figure 2.24). Its lower northern part, however, has much less relief and is marked by several faint lineations that trend east-west parallel to the Alpenrhein River. Pockets of gravel with rounded pebbles and cobble are present on the surface of the lower, northern part of Ils Aults. In addition, there are two, more conspicuous curved north-trending lineations on eastern Ils Aults, parallel to the eastern margin of rockslide deposit (Figure 2.24). I interpret the latter to be extensional fractures recording incipient disarticulation of the Tamins rockslide mass due to liquefaction of the underlying valley fill.

Several tumas with steep (up to ~70°) sides and narrow crests are present 1-3 km east of Ils Aults. The largest of the tumas, and the one closest to Ils Aults, is Crest' Aulta (Figure 2.24). The east flank of Crest' Aulta is steep and smooth, whereas the southern section of the west flank is hummocky, with several hills and ridges connecting it to the eastern slope of Ils Aults.

Southwestern Ils Aults (IA-02 and IA-03)

A forestry road on the southwest slope of Ils Aults exposes sandy cobble-boulder gravel surrounded and underlain by Tamins rockslide debris. IA-02 is a 1-m-high exposure of poorly sorted, clast-supported, cobble gravel with clasts up to 20 cm across at ~643 m asl. One hundred metres to the south and seven metres lower is site IA-03, where several subrounded mica schist and limestone boulders, one of which is >2.1 m across, occur within rounded cobble gravel.

Northern Ils Aults (Tamins 4)

I dug a 1-m-deep pit on the gently rolling surface of Ils Aults in an area of Helvetic limestone megablocks 8-20 m in length. A poorly sorted, pebble-cobble gravel in the lowest part of the pit (65-100 cm deep) contains subrounded to subangular pebbles and cobbles ranging up to 29 cm in size. The gravel is gradationally overlain by an upward-fining, crudely stratified diamicton with pebbles and small cobbles up to 12 cm in diameter and a silt-sand matrix constituting up to 40% of the sediment.

Road junction (Tamins 11)

A road-cut at 685 m asl on the southeast side of Il Aults exposes 2.75 m of chaotically bedded silt and very fine sand with some pebble zones and clastic dykes consisting of sandy silt. Near-vertical flame structures, steeply dipping laminations, and liquefied zones of silt and very fine sand characterize the exposure. Many elongate and tabular pebbles have steep dips.

Crest' Aulta

I dug a 80-cm-deep pit at the crest of Crest' Aulta (~710 m asl, IA-08, Figure 2.24). Crushed Helvetic rockslide debris is overlain by 15-25 cm of weathered matrix-supported diamicton, with subangular to subrounded pebbles and cobbles. The diamicton is overlain across an undulating sharp contact by 55-65 cm of sandy grey silt containing about 10% subangular pebbles (~10%).

I obtained a 3.5-m-long core with an auger in a closed based at the base of the west flank of Crest' Aulta (IA-30, Figure 2.24). Three metres of horizontally stratified silt and sand is overlain by 50 cm of humified organic soil. Sediment between 100 and 190 cm depth is mainly fine sand, where sediment at 50-100 cm and 190-350 cm depth is dominantly laminated to thin-bedded silt with some fine to medium sand interlayers.

Tuma 658

Several sections on the north and west sides of Tuma 658 provide insight into the relation between the tuma and the Bonaduz mass flow event (Figure 2.25 and Figure 2.26). The northern third of Tuma 658 has a lower, relatively flat surface. This surface is bordered by a higher surface to the south, culminating in an elevation of 658 m asl.

The lower northern section (SF-01, Figure 2.26) is underlain by gravelly and sandy sediments. The lowest 6 m of this section is matrix-supported sandy pebble gravel with rounded to subrounded stones up to 2 cm across. A sand lens was observed in the upper part of the gravel unit. The gravel unit is truncated by a cobble lag, which in turn is overlain by 0.5 m of horizontally laminated and bedded sand; the lower part of the sand unit contains 1-2-cm-thick beds rich in granules. The sand is overlain by 1.5 m of sandy silt, followed by a 5.5-m-thick unit of sand; the latter coarsens upward, but contains alternating layers of very fine and fine sand. A 1-m-thick covered zone is overlain by approximately 5.5 m of clast-supported gravel with rounded to subrounded pebbles.

About 75 m south of section SF-01, the tuma rises in elevation. In a section facing the Hinterrhein River, on the west side of the tuma, gravel is overlain across an erosive irregular contact by polymictic blocky diamicton (top of photo A in Figure 2.25) containing angular to rounded clasts up to 75 cm across in a sand-silt matrix. The diamicton is overlain by 20 cm of horizontally stratified fine sand and, at the northern limit of the exposure by up to 2 m of rounded, pebble-cobble gravel, which extends to the top of the tuma at this location.

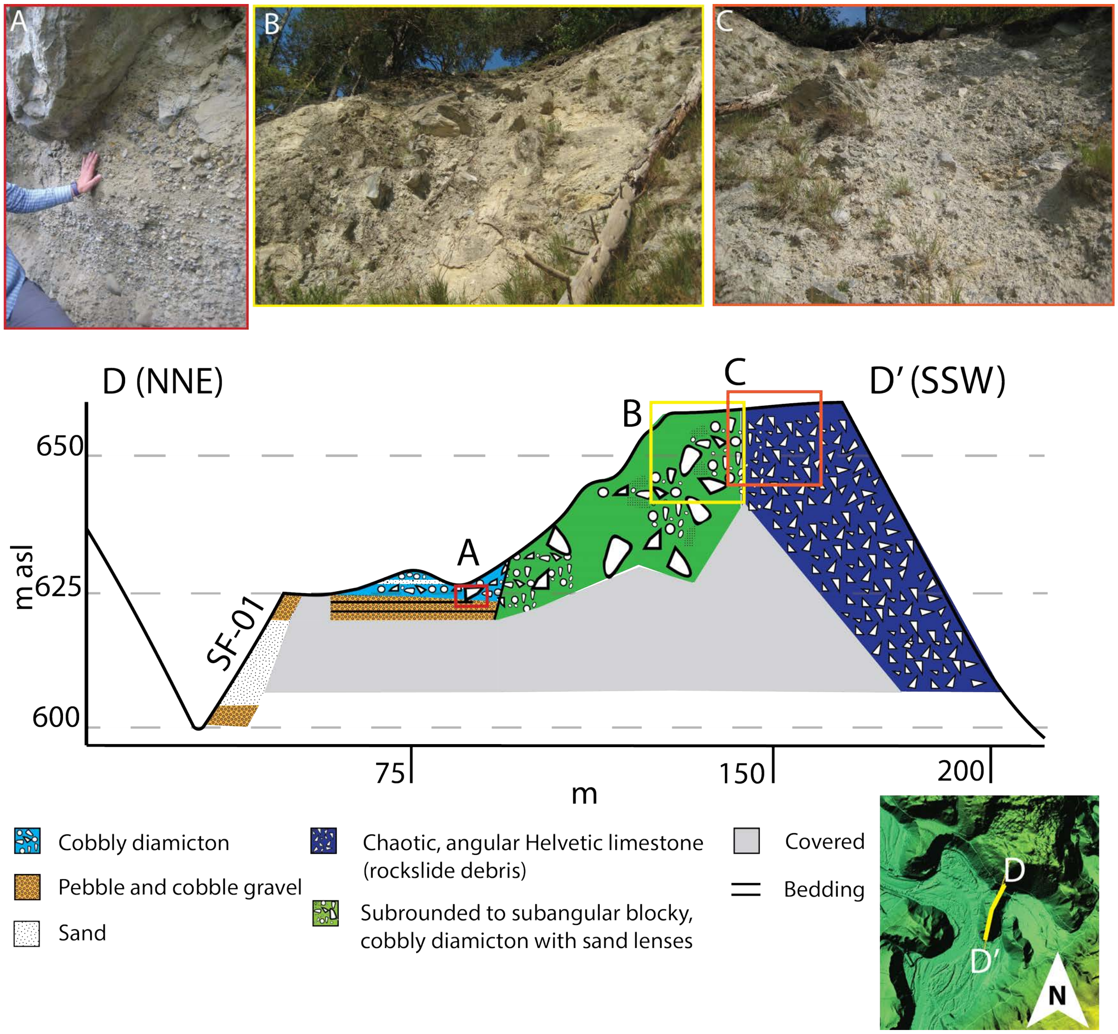


Figure 2.25. NNE-SSW cross-section of Tuma 658 showing inferred geology. Site SF-01 (Figure 2.25) is located on the slope above the creek at the NNE edge of the tuma. The same tree stem is visible in photos B and C. Photo B shows matrix-supported blocky diamicton. The contact between this diamicton and rockslide debris is located to the right of the tree trunk in photo C. Photo A highlights the contact between weakly stratified gravel and diamicton mentioned in the text.

The blocky diamicton unit thickens to the south and the overlying sand and gravel pinch out against it and the rising tuma surface. In the exposure at B in Figure 2.25, it comprises a chaotic mix of rounded cobbles, angular small blocks, and blocks of a conglomerate up to 3.5 m across.

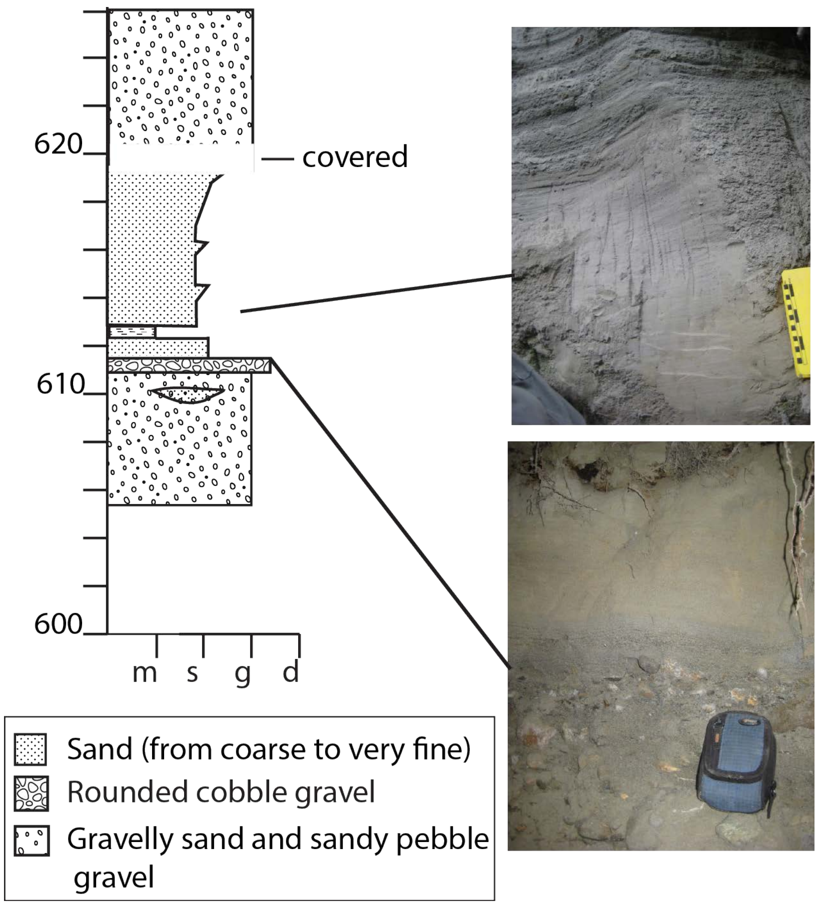


Figure 2.26. Stratigraphy of section SF-01 at the north-northeast side of Tuma 658 (see also Figure 2.25). A 15-cm digital camera case serves as scale in the lower photo.

Still farther to the south, at C in Figure 2.25, the diamicton unit is much coarser, with blocks 2-3 m across and small lenses of sand and pebbles. The diamicton has a near-vertical contact with rockslide debris that forms the core of the southern part of the tuma (Figure 2.25). The contact zone between the two units is 2 m thick and consists of mixed subrounded gravel and angular Helvetic limestone blocks. The rockslide debris consists of angular fragments of Helvetic limestone in a silt-rich matrix (photo C in Figure 2.25).

Barnaus

The north and south banks of the Alpenrhein River about 3 km downstream of the breach in the Tamins rockslide barrier expose sediments attributable to the Bonaduz mass flow and perhaps the outburst floods from Lake Ilanz. The lowest exposed unit in the south bank is a dense matrix-supported diamicton dominated by angular fragments of Helvetic limestone and a silty matrix (Figure 2.27, photo A). The diamicton is weakly stratified; some zones consist nearly entirely of silt and are devoid of clasts. Rare large clasts of limestone are shattered, but still intact, with a jigsaw-type fabric. Distinctive flame-like structures occur within the unit. The maximum exposed thickness of the unit is 1.5 m.

At the downriver (east) end of this exposure, the diamicton unit is in contact with a large mass of Bonaduz gravel (Figure 2.28). This mass may be a rip-up clast of the gravel.

The diamicton is truncated and unconformably overlain by 5 m of clast-supported, poorly sorted, cobble-boulder gravel. A boulder lag marks the contact between the two units. The gravel has weak subhorizontal bedding. Local imbrication of clasts in the gravel indicates deposition by an east-flowing river. The cobble-boulder gravel grades upward into a finer, bedded, pebble-cobble gravel.

A small outcrop of bedrock anchors the section on the north side of the river at Barnaus (Figure 2.27). Above it is up to 1 m of interlensing silt and silty gravel with discontinuous plant-rich horizons. The silt contains scattered angular to rounded pebbles. This unit, in turn, is unconformably overlain by subhorizontally stratified, clast-supported gravel. At the upriver (west) end of the exposure, the clasts are angular to subangular and conspicuously striated. Many of these clasts are >1 m across; the largest is 1.4 m in size. Most all of the clasts are Helvetic limestone, but some are mica schist. This unit fines and becomes better stratified upward and in a downriver (east) direction along the >60-m length of the exposure; in addition, more of the clasts are rounded and subrounded to the east. This unit coincides in elevation with the diamicton unit exposed on the opposite (south) bank of the Alpenrhein River.

Overlying the blocky gravel is a yellow, matrix-supported diamicton with a silt matrix and lenses of cobble gravel (the upper unit in photo A and the middle unit in photo B, Figure 2.27). Most clasts are pebble and cobble-size, but the diamicton also contains

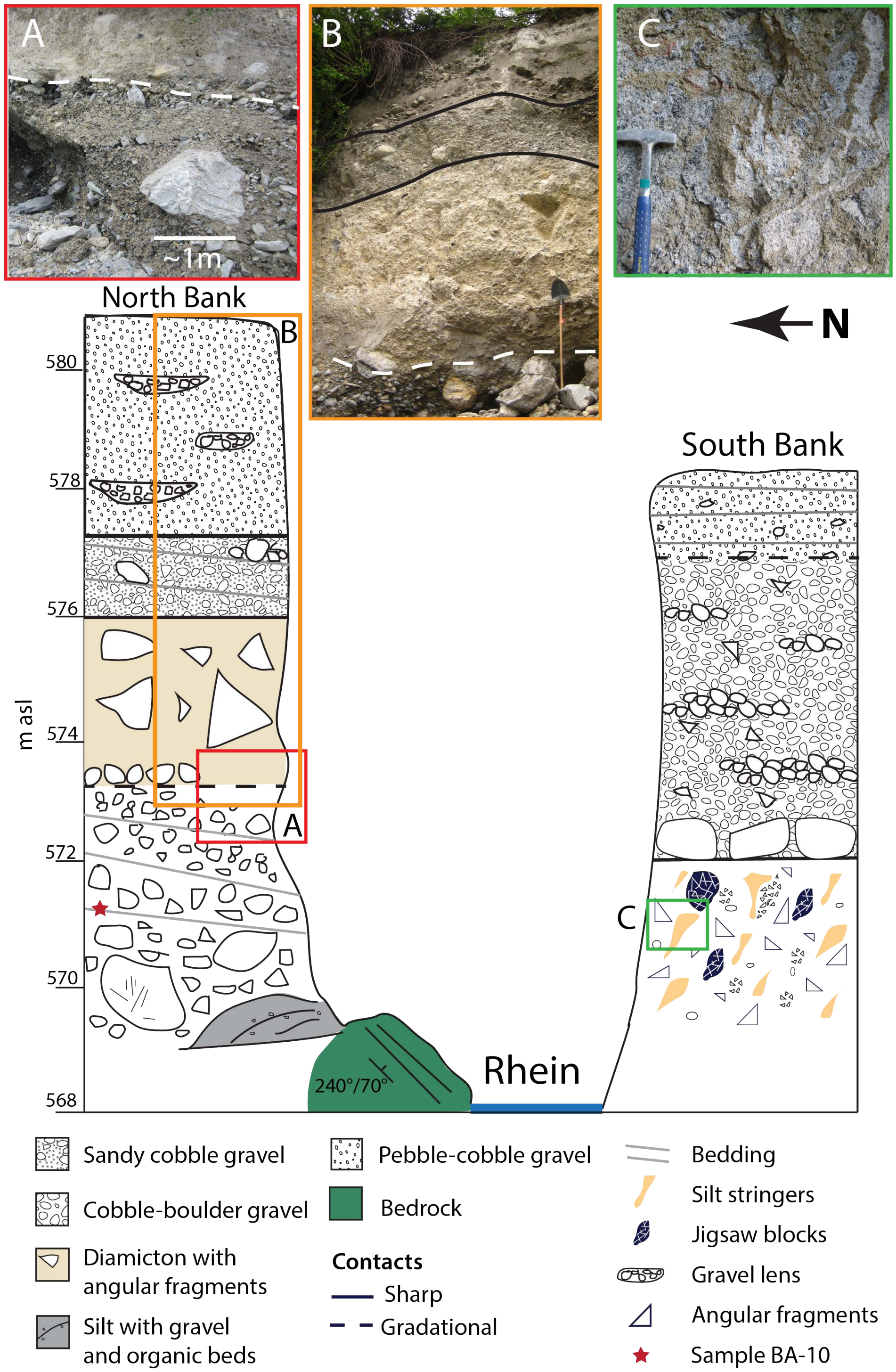


Figure 2.27. Exposures on the south and north sides of Alpenrhein River at Barnaus. Photo A shows the contact between the lower, striated gravel and overlying diamicton at Barnaus North. Photo B shows the upper four units at Barnaus North. Photo C shows the silt stringers and jigsaw Helvetic limestone blocks in the diamicton at the base of the section at Barnaus South. (Photo C by Hazel Wong.)

larger angular to subangular blocks of Helvetic limestone and the Tamins crystalline unit. The diamicton is overlain across an erosional contact by bedded cobble-boulder gravel that grades upward into finer cobble gravel with lenses of gravelly sand. This unit correlates with the gravel unit at Barnaus South.

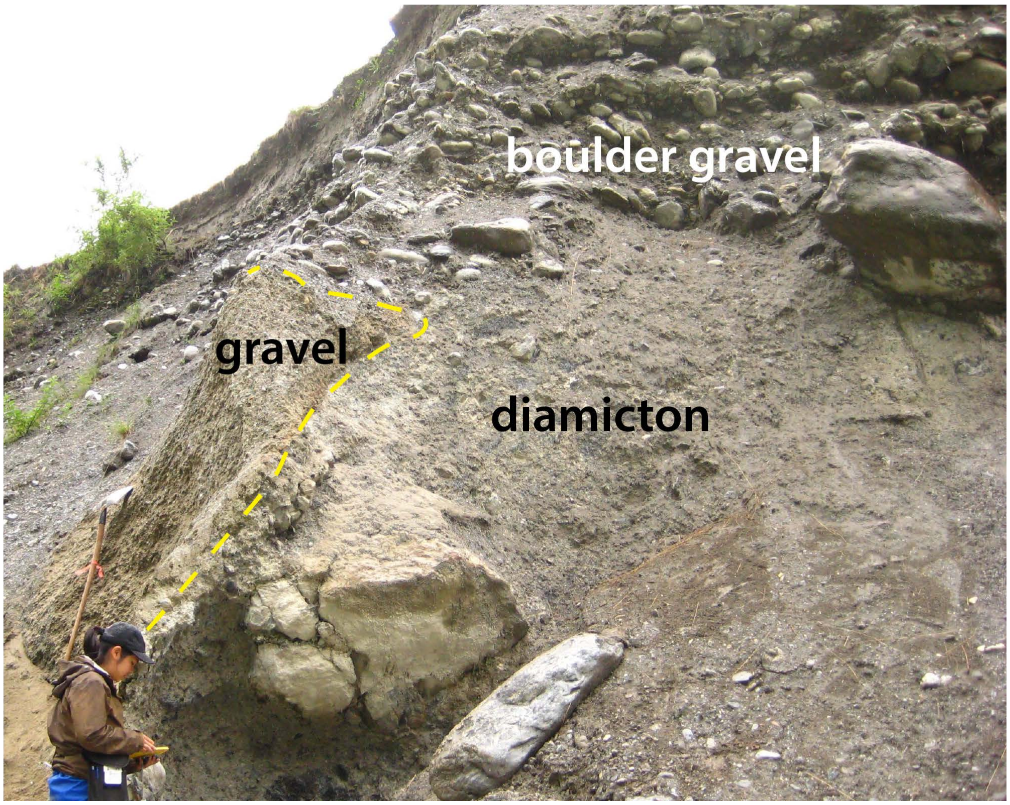


Figure 2.28. A block of Bonaduz gravel bordered along a steep contact by matrix-supported diamicton at the Barnaus South site. Both are unconformably overlain by cobble-boulder gravel.

2.3.4. Late-phase and post-Bonaduz deposits

In this section, I describe a relatively thin sequence of sediments that caps classic Bonaduz gravel and was deposited after the Bonaduz mass flow came to rest.

Plazzas

In a gully incised into the Bonaduz plain near Plazzas (Figure 2.24), Bonaduz gravel is abruptly overlain by a 5-10-cm-thick bed of clast-supported gravel with little

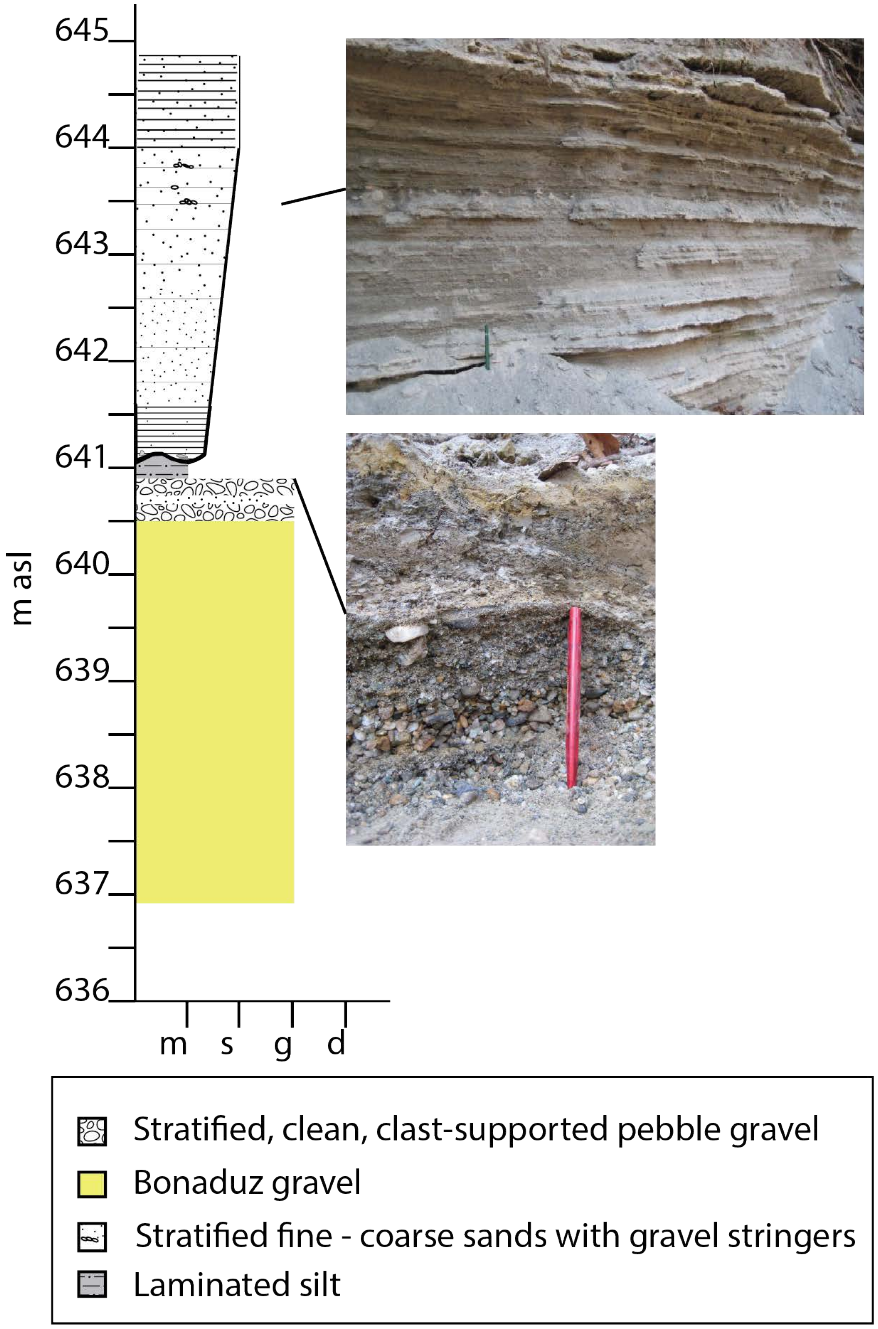


Figure 2.29. The Plazzas section. The upper photo shows planar, stratified sand and minor fine gravel at the top of the section. The lower left photo shows stratified pebble gravel and a capping thin layer of mottled clayey silt overlying Bonaduz gravel (red pen for scale). The lower photo shows interbedded pebble gravel and sand above Bonaduz gravel (30-cm-long shovel for scale).

sand or silt matrix (Figure 2.29). This bed, in turn, is overlain by 40 cm of interlayered coarse and very coarse sand and pebble gravel. A sharp, wavy, cemented contact separates these sediments from 8-12 cm of structureless clayey silt. The upper contact of the clayey silt bed is erosional – rip-up clasts of silt are present within the lowest 10 cm of an overlying bed that coarsens upward from fine sandy silt to stratified fine sand over a vertical distance of 25-30 cm, and then into 3.5 m of stratified medium to very coarse sand with gravel stringers. The total thickness of the sequence above the Bonaduz gravel is 4.5 m.

Bonaduz gravel plain building excavations

Several excavations for building foundations in the town of Bonaduz exposed the uppermost 2-5 m of sediment underlying the Bonaduz plain. In one excavation, which I refer to as the 'Easter construction site' (see Figure 2.11 for location), typical Bonaduz gravel is overlain by 0.5-1.25 m of laminated very fine sand with strata dipping 15° to the northwest (Figure 2.30). Beds of coarse to very coarse sand and fine gravel conformably overlie the laminated sand. Both units are cut by normal faults with centimeter-scale offsets. The upper part of this sandy sequence is overlain across an erosional contact by up to 4 m of clast- to matrix-supported diamicton consisting of a chaotic mixture of boulders and blocks of limestone up to 3.5 m across with a matrix of gravel and sand (Figure 2.30). Rip-ups of sand are present at the base of the diamicton. The diamicton is the deposit of the outburst flood resulting from the partial draining of Lake Ilanz.

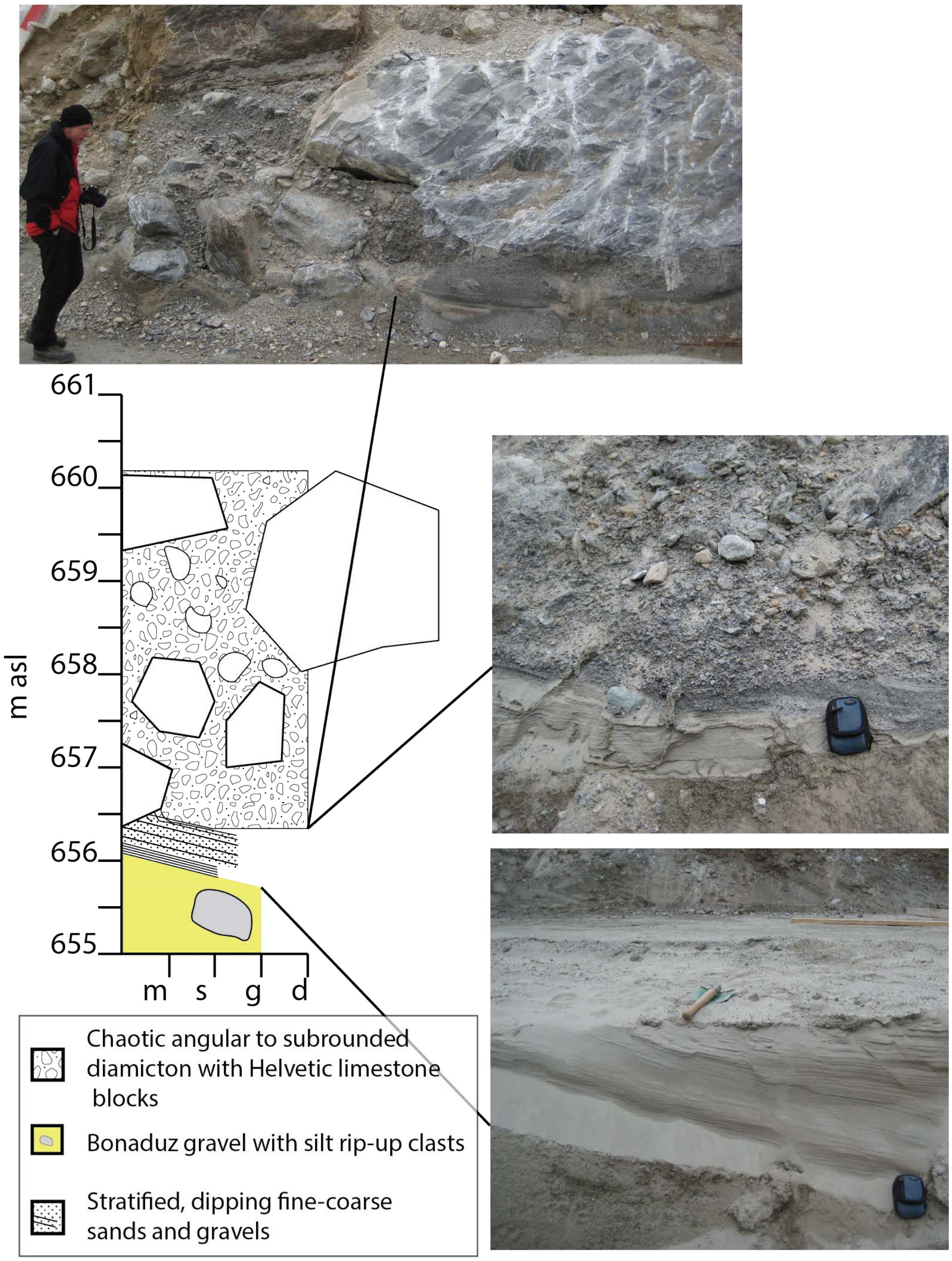


Figure 2.30. Sediments exposed at the Easter construction site in the town of Bonaduz; camera case for scale. Lake Ilanz outburst flood deposits overlie laminated sand and Bonaduz gravel.

East margin of the Bonaduz plain

Bonaduz gravel is capped by 1.5 m of horizontally stratified, clast-supported gravel at the head of a gully incised into the Bonaduz plain north of Bonaduz (site BP(N) in Figure 2.11). The exposure is located at the north end of a shallow, east-northeast-trending channel, highlighted with an arrow in Figure 2.31. The capping gravel unit is horizontally stratified, with stratification emphasized by differences in clast size. The lower and upper parts of the unit are granule-pebble gravel, and the middle part is a bed of cobble-boulder gravel with clasts up to about 1 m in size. The capping gravel overlies >12 m of classic, upward-fining Bonaduz gravel with abundant Pavoni pipes up to about 20 cm wide and rare silt rip-up clasts.

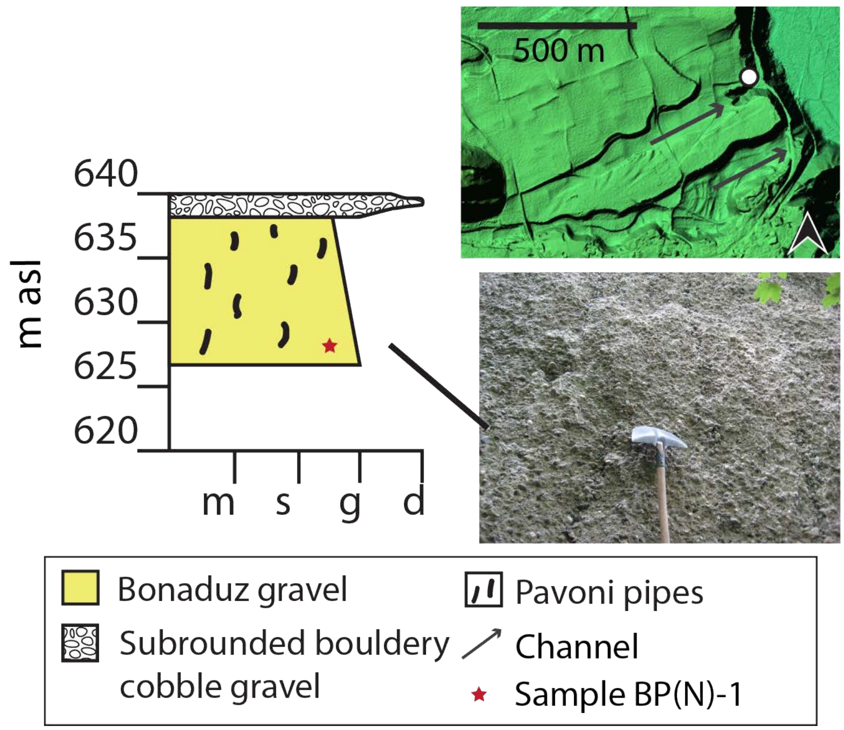


Figure 2.31. Stratigraphy at site BP(N) on the Bonaduz plain. The LiDAR hillshade image at the upper right shows the location of the site (open circle). The hill at the lower left corner of the hillshade image (Bot Danisch) is a tuma consisting of Flims rockslide debris. Two channels eroded by the Lake Ilanz outburst floods wrap around south side of the tuma. The southern channel is lower in elevation (630 m asl) than the northern channel (640 m asl); the northern channel terminates in a 25-m-deep gully at 615 m.

Ils Aults

A terrace nested against the Tamins rockslide on the east side of the Hinterrhein River (site IA-06, Figure 2.24) is underlain by thick Bonaduz gravel capped by a 2-m-

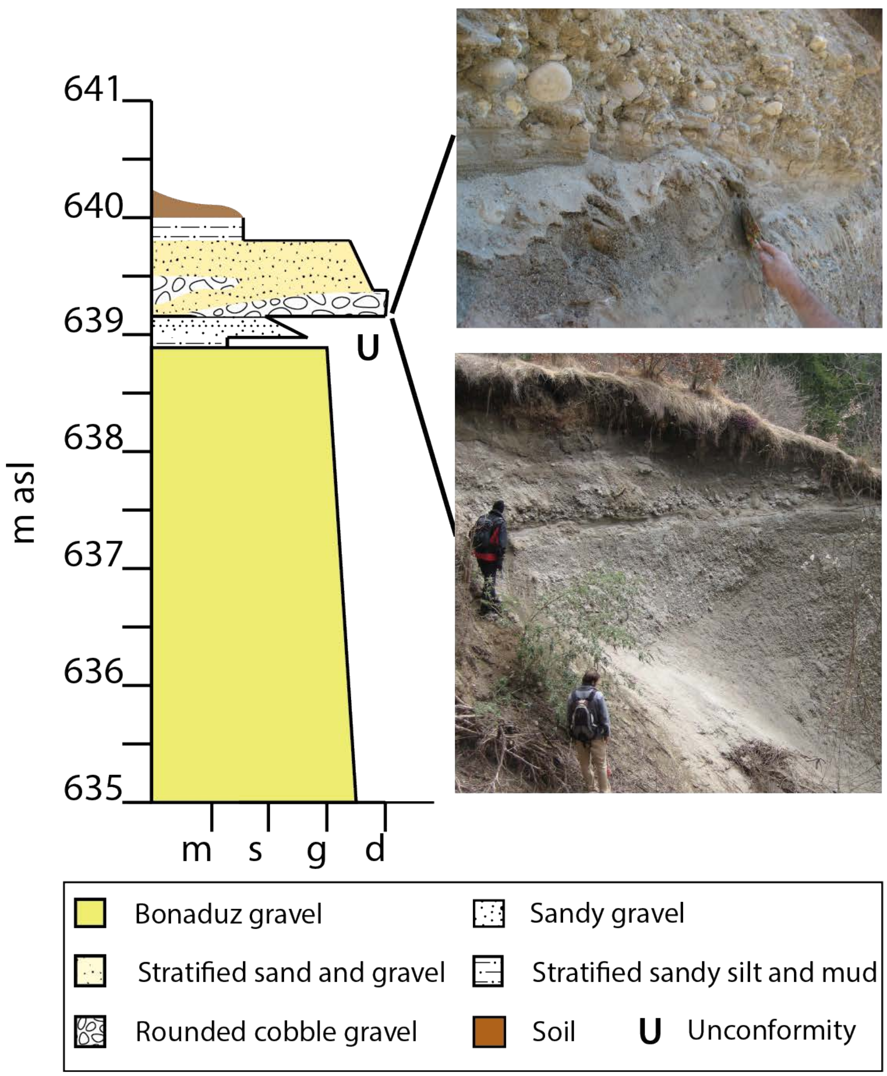


Figure 2.32. Stratigraphy of Ils Aults section IA-06. The two photos show fluvial sand and gravel overlying Bonaduz gravel; the unconformable contact (U) is at the level of the trowel in the upper photo and the shoulders of the higher of the two people in the lower photo.

thick sequence of fluvial sediments comprising, from bottom to top: 30 cm of horizontally stratified fine to coarse sand; 0-25 cm of imbricated, clast-supported, pebble-cobble gravel; and 1 m of stratified pebble gravel grading upward into 60 cm of stony sand and silty sand (Figure 2.32). The capping fluvial sequence was deposited by the Hinterrhein River when it flowed 40 m above its present level shortly after the Bonaduz gravel was deposited.

Ruine Wackenau

A steep erosional slope on the south side of the Vorderrhein River at Ruine Wackenau exposes 25 m of sediment underlying a Lake Ilanz outburst flood terrace (Figure 2.33). The lowest 12 m of the section are large blocks of Helvetic limestone, which I interpret to be Flims rockslide debris. This blocky debris is overlain by subhorizontally stratified gravel, comprising beds of clast-supported, angular to subrounded clasts up to boulder size (Figure 2.33). The lowest bed is the coarsest, with clasts up to 1 m across. The uppermost beds in the section are the finest in the sequence, but are still cobble-rich and contain some boulders.

Figure 2.33. Lake Ilanz outburst flood deposits exposed at Ruine Wackenau above the Vorderrhein River. The dashed line indicates a contact between finer beds above and coarser beds below. For scale, the lookout at the upper left (arrowed) is approximately 1.25 m high.

2.3.5. *Other observations*

Downvalley-dipping terraces are inset into the Tamins rockslide deposit on both the north and south sides of the Alpenrhein River (Figure 2.34). They decline from 630 m asl at the upriver (west) margin of the landslide to 614 m asl at the downriver (east) margin. Rounded heterolithic pebbles, cobbles, and boulders underlie the terraces and cap Tamins rockslide debris.

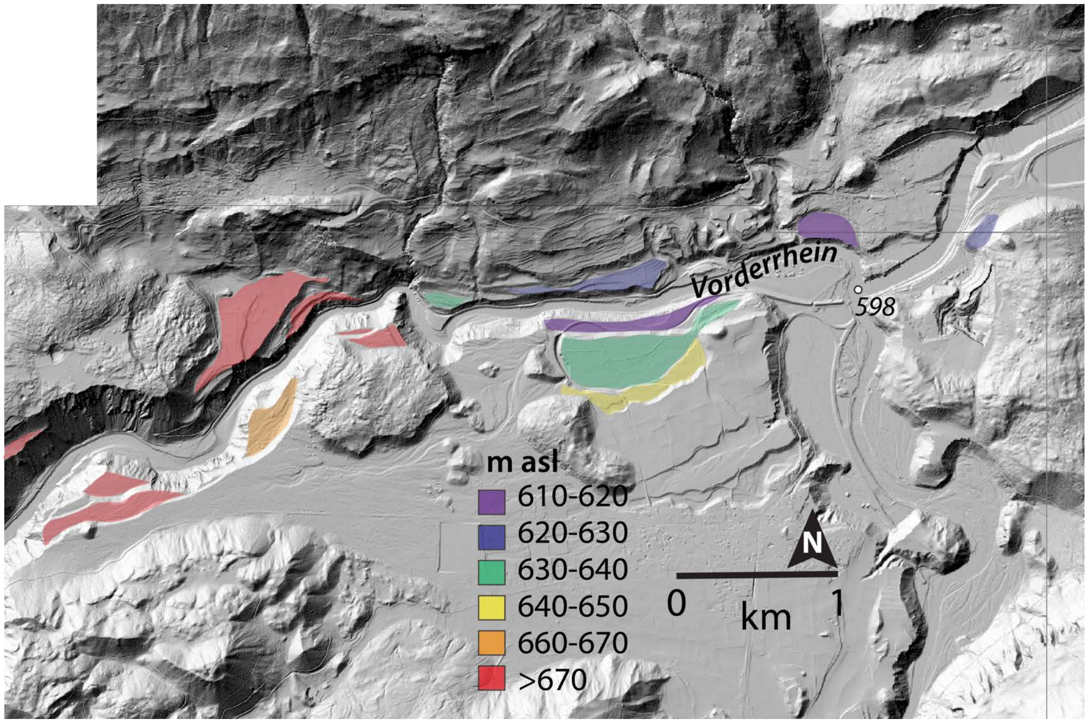


Figure 2.34. Hillshade image showing terraces along the Vorderrhein River. The colour patterns indicate the approximate elevations of the terraces. Most of the terraces are unpaired and some are laterally discontinuous. The terraces slope to the east; the highest surfaces are Lake Ilanz outburst flood paths across the Bonaduz plain.

Masera (2013) mapped the tumas on the Bonaduz plain and in the Domat-Ems area. He noted poorly sorted rounded gravel on and within several of the tumas. Rounded pebbles and cobbles are present, for example, within rockslide debris at Bot Danisch (Figure 2.35).

Exposures along the Hinterrhein River show the relationship between tumas and Bonaduz gravel. At several sites, rockslide debris forming tumas is exposed from the level of Hinterrhein River to the surface of the Bonaduz plain.

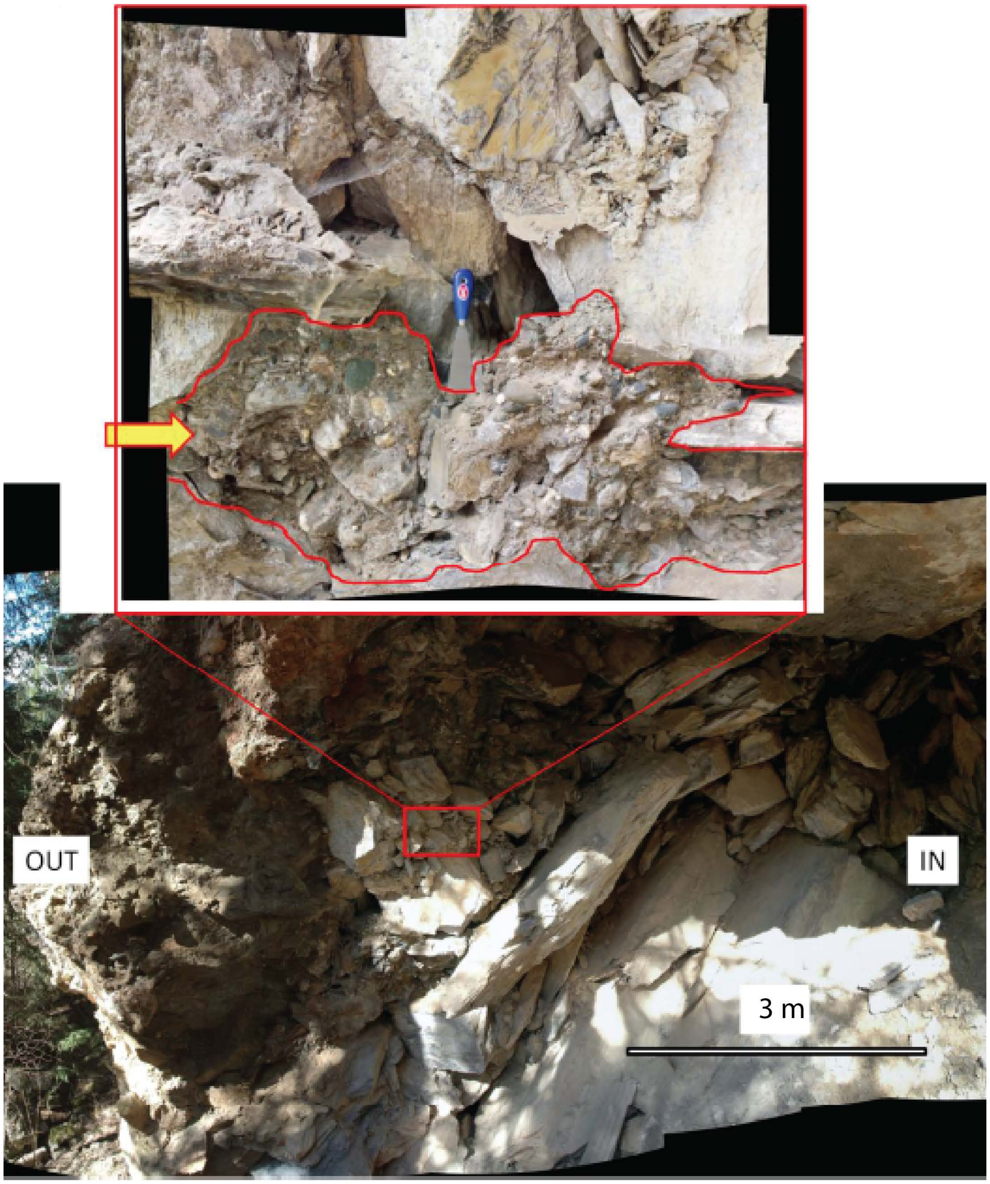


Figure 2.35. Fragmented blocky rockslide debris at Bot Danisch (Figure 2.11). The upper photo shows a zone of mixed angular fragments of limestone and rounded pebbles and cobbles surrounded by larger blocks of limestone. In the lower photo, 'IN' is toward the interior of the tuma; 'OUT' is the edge of the tuma. The lower photo shows the overall blocky debris, with a mass of polymictic rounded gravel a few meters from the edge of the tuma (Masera, 2013).

2.4. Discussion

The genesis of Bonaduz gravel has long been debated. Early researchers considered it to be till or glaciofluvial sediment. In 1968, Nazario Pavoni hypothesized that the Bonaduz gravel was the product of wet gravel slurry mobilized by the impact of the Tamins rockslide. He noted several unique sedimentological features, including dewatering pipes (see below), ubiquitous upward fining, and Helvetic limestone clasts in the Hinterrhein valley, an area where there is only Penninic bedrock. Evidence that the Bonaduz gravel is contemporaneous with the Flims rockslide can be seen at several sites where rounded pebbles and cobbles fill clastic dykes in rockslide debris.

Although the Bonaduz mass flow likely overtopped and breached the Tamins rockslide barrier, there is no terrace equivalent to the Bonaduz plain downvalley of Reichenau. It is likely that Bonaduz mass flow deposits downstream of Reichenau are covered by Rhein River alluvium, probably in part reworked from Bonaduz sediments deposited farther upstream.

2.4.1. Pre-Flims landslide geomorphology

In this section, I reconstruct the geomorphology of the Vorderrhein valley, the likely valley-fill sediments, and depositional environments immediately before the Flims rockslide ~9600 years ago. This reconstruction provides context for understanding the circumstances in which the Bonaduz gravel was produced and deposited. Key to this understanding is the hypothesized existence of Lake Bonaduz upstream of the Tamins rockslide.

The elevations of the base of the Flims and Tamins debris sheets and the Bonaduz gravel are not known, but we do know that the Vorderrhein River has not yet incised completely through any of them. Caprez (2008) produced GIS-based models of pre- and post-Flims landslide morphology, with a focus on the Flims rockslide scarp and detachment area (Figure 2.36). He modeled Vorderrhein valley floor elevations of 500 m and 525 m asl, atop of what is referred to ‘alluvium’ in Figure 2.36, and he assumed that ~6.5 km^3 of Flims rockslide debris struck and covered the valley bottom. He fit a polynomial curve to the pre-Flims land surface to generate rockslide volume estimates;

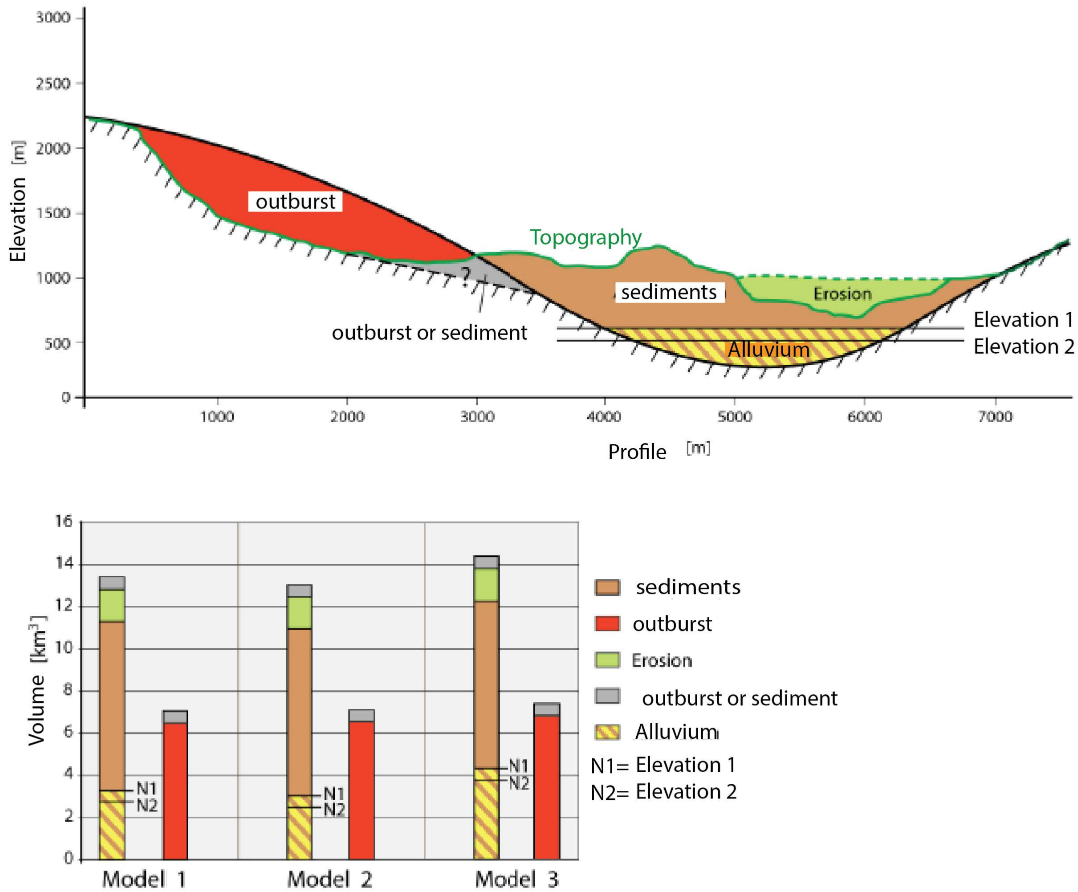


Figure 2.36. North-south cross-section from the Flims detachment surface across Vorderrhein River (Caprez, 2008, his fig. 40; modified only to include English terms). The green line is the modern land surface. The polygon labeled 'outburst' is the detached rockslide mass. The polygon labeled 'sediments' (brown) is present-day rockslide debris. A portion of the rockslide material, coloured green, has been eroded by the Vorderrhein River over the past 9600 years. The grey polygon ('outburst or sediment') is material of uncertain origin (either part of the detached rock mass or rockslide debris). The yellow polygon with diagonal stripes is pre-landslide valley fill. In the volume estimates, the totals presumably include all fill above the basement (black line in upper profile). Caprez (2008) considered three different scenarios (Models 1, 2, and 3), based on three different rockslide volumes paired with two different pre-Flims valley floor elevations (N1 and N2).

he also estimated the volume of Flims rockslide debris eroded by the Vorderrhein River and its tributaries since the landslide. The implication is that Vorderrhein and Hinterrhein rivers flowed at lower levels at the time of the Flims and Tamins rockslides (Figure 2.37).

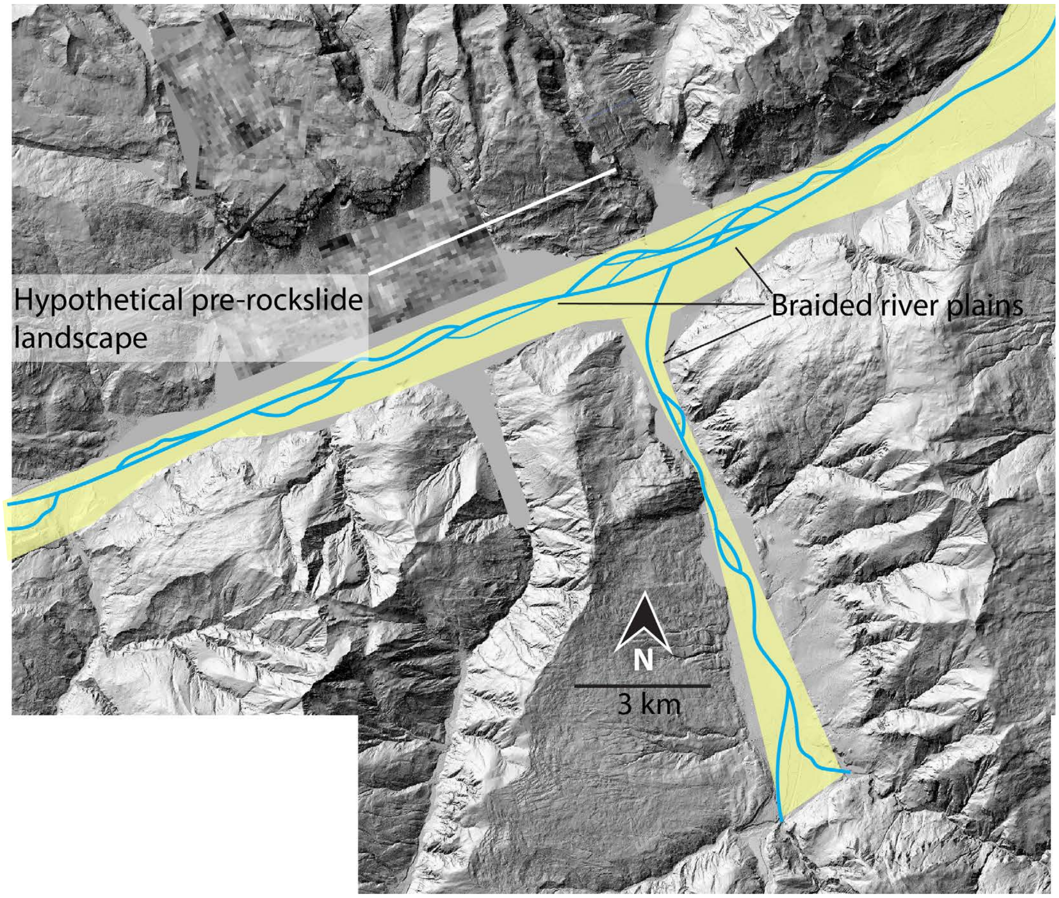


Figure 2.37. Schematic reconstruction of the geomorphology and depositional environment of the Vorderrhein, Hinterrhein, and Alpenrhein river valleys after retreat of the Rhein valley glacier at the end of the Pleistocene, but before the Tamins and Flims rockslides. The elevation at the confluence of Vorderrhein and Hinterrhein rivers was less than 595 m asl.

The Tamins landslide blocked the Vorderrhein River and impounded a lake that extended, not only west up the Vorderrhein valley, but also south up the Hinterrhein Valley (Figure 2.38). I refer to this lake as Lake Bonaduz. Based on the likely pre-Flims configuration of the rockslide barrier, Lake Bonaduz may have been more than 100 m deep at the Tamins barrier and reached upvalley to the site of the Flims rockslide during the early Holocene. The Vorderrhein and Hinterrhein rivers, at that time, would have been building deltas into Lake Bonaduz. I hypothesize that the Vorderrhein River was building a delta into Lake Bonaduz at the Flims impact site (Figure 2.38). The valley-fill sediments at the impact site were likely pebble-cobble fluvial gravels overlying sandy or gravelly delta-slope deposits and perhaps, at depth, Lake Bonaduz lacustrine silt or even late-glacial lacustrine silt.

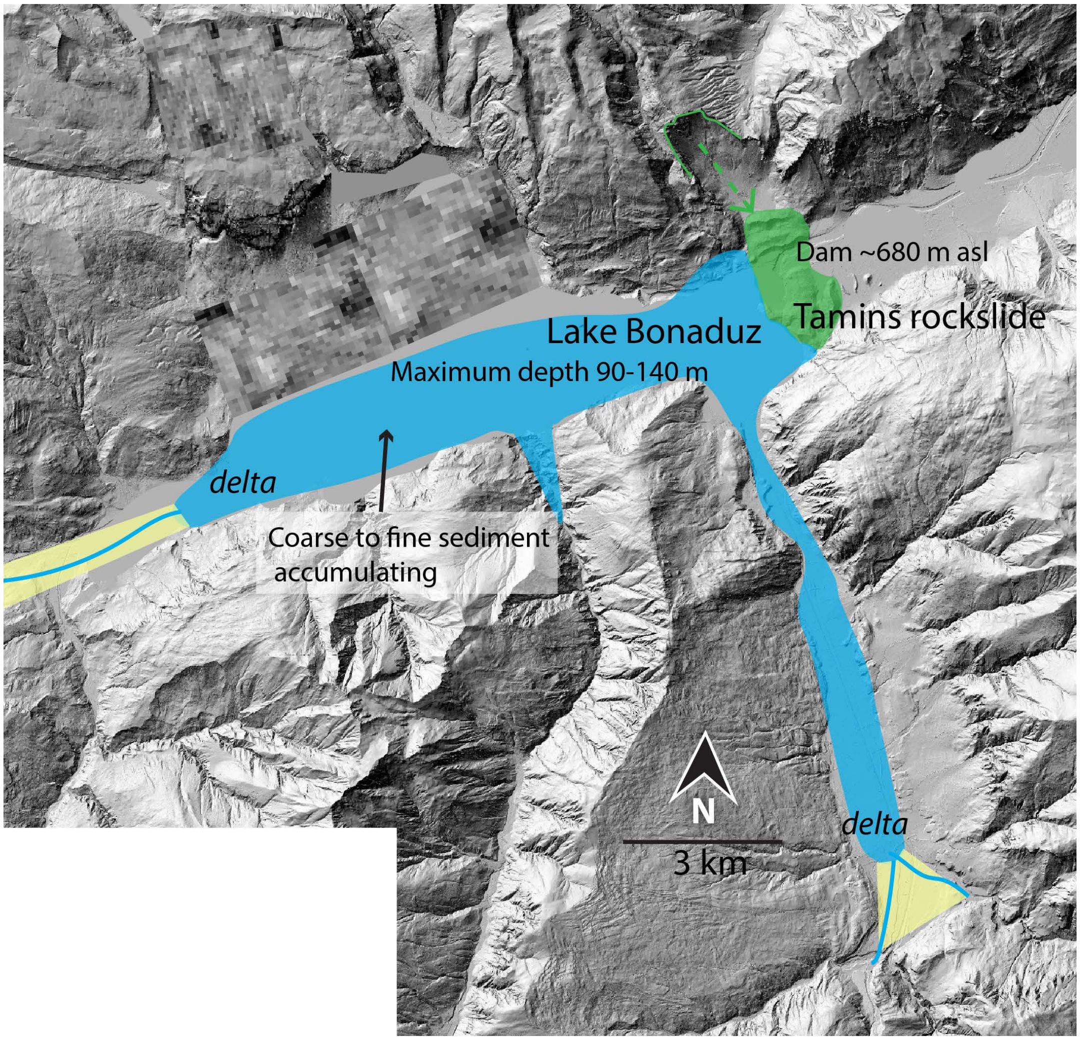


Figure 2.38. Schematic reconstruction of Lake Bonaduz after the Tamins rockslide (green) blocked Vorderrhein valley and formed a barrier at approximately 700 m asl.

2.4.2. The Bonaduz mass flow

The Bonaduz gravel consistently exhibits (1) upward-fining through thicknesses of tens of metres, (2) rip-up clasts of clayey silt, and (3) dewatering Pavoni pipes. In addition, coarser gravel, up to boulder size, occurs as tongues within typical Bonaduz gravel at the Reichenau quarry and just beyond the limit of the typical Bonaduz gravel on the Tamins rockslide on the west side of Ils Aults (Figure 2.21). Poorly sorted coarse gravel is associated with typical Bonaduz gravel at Schiedberg, Trin Station, and, Versam Gorge, all exposures within and at the margins of the Flims rockslide (Figure 2.12, 2.14, and 2.15, respectively). Gravels in the Hinterrhein valley farthest from the Flims rockslide are finer, but otherwise remarkably similar to typical Bonaduz gravel in the Vorderrhein valley, in spite of large differences in transport distance.

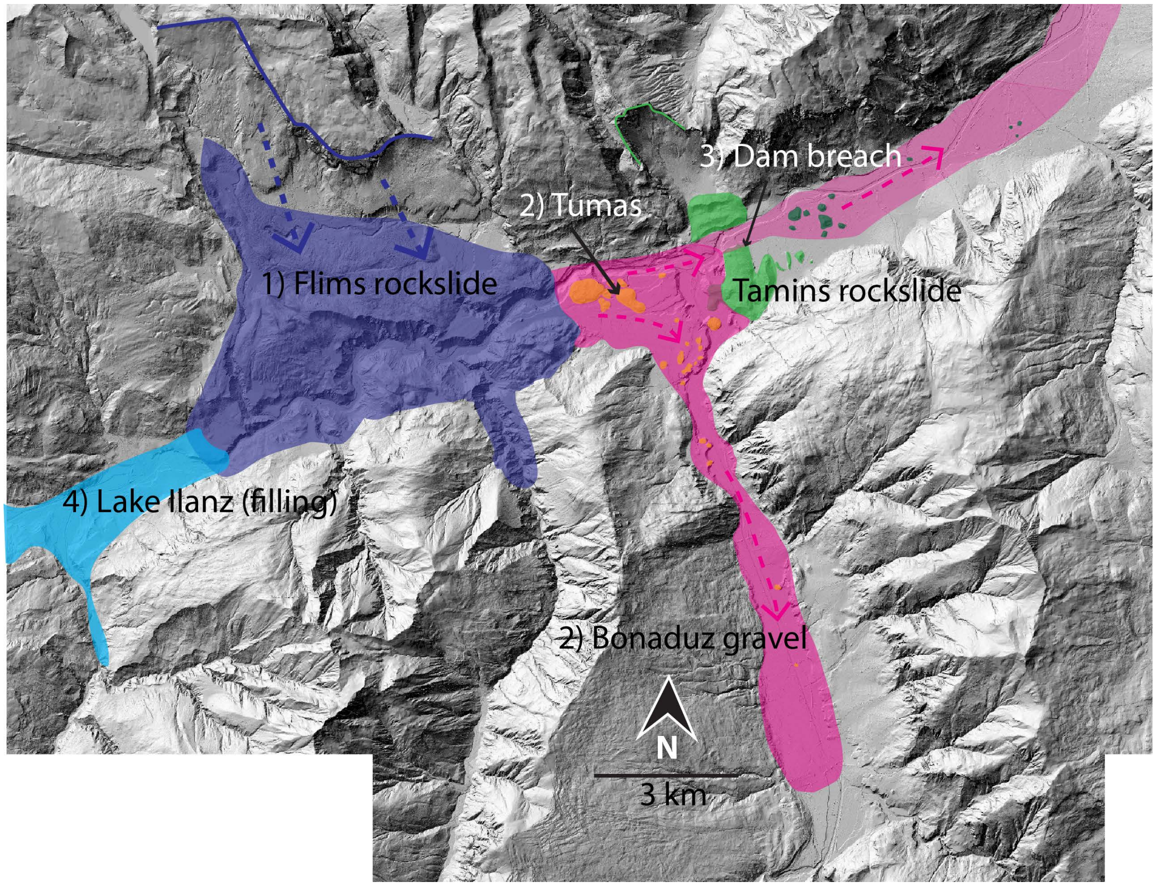


Figure 2.39. Sequence of events following the Flims rockslide (event 1, violet). 2) The Bonaduz mass flow (pink) travels up the Hinterrhein valley carrying tumas (orange). It also overtops the Tamins rockslide barrier. 3) Coincidentally with event 2, the Tamins rockslide barrier is breached or partially breached and masses of the rockslide are transported as tumas down the Alpenrhein valley (dark green) on the Bonaduz flow. 4) Lake Ilanz (blue) forms behind the Flims rockslide barrier.

Bonaduz gravel is distributed from the toe of the Flims rockslide to the west side of the Tamins rockslide and throughout the Hinterrhein valley to Thusis (Figure 2.39). It has been identified in an exposure downstream of the Tamins rockslide in the town of

Chur (A. von Poschinger, personal communication, 2015). Poorly sorted silty gravel with affinities to Bonaduz gravel, yet unknown affiliation, are present on the sides and crests of tumas in the Domat/Ems and Chur areas (Poschinger and Ruegg, 2012; Masera, 2013).

Based on the characteristics and distribution of the Bonaduz gravel, I draw some inferences about the nature of the mass flow that deposited the unit. The impact of the Flims rockslide released a huge amount of energy, some of which propagated through the valley-fill sediments as seismic waves. The impact elevated pore pressures in these sediments, causing them to liquefy over a large area and to a great depth within the valley fill. The footprint of this pore-pressure spike and liquefaction is unknown, but disarticulation of the Tamins landslide, manifested by the movement of tumas away from the east margin of Ils Aults (Figure 2.39), raises the possibility that it may have extended downvalley past the Tamins rockslide.

The Tamins landslide was an obstruction to the Bonaduz mass flow. It turned part of the flow almost 90°, such that it traveled through the bedrock gorge of Domleschg and up the Hinterrhein valley to Thusis (Figure 2.39). The remainder of the flow overtopped the northern part of Ils Aults and possibly breached the Tamins barrier where the Alpenrhein flows past Ils Aults. Large bodies of Tamins rockslide material were entrained in the flow and carried downvalley as far as Chur.

The presence of injected Bonaduz gravel within Flims rockslide debris demonstrates that valley-fill material was liquefied by the impact of the landslide on the Vorderrhein valley floor. I interpret the basal diamicton unit at the Schiedberg section (Figure 2.12) to be the product of mixing of fluvial gravel with rockslide debris. The Bonaduz gravel is also reworked valley-fill material.

The distribution and thickness of Bonaduz gravel downvalley of the Flims rockslide and in the Hinterrhein valley indicate that as much as 1 km^3 of valley-fill sediments were liquefied and transported distances of up to 15 km as a mass flow (Abele, 1997). The high silt and sand content and the presence of laminated clayey silt rip-ups indicate that lacustrine sediments were involved, perhaps associated with a glacial lake or Lake Bonaduz. The systematic upward-fining of the unit and its rounded clasts, mainly of granule to cobble size, have implications for the origin of the unit. The mass differentiated vertically over a short period of time and over its short distance of transport within a thick column of rapidly moving sediment. The implication is that the flow was laminar rather than turbulent. Remarkably, however, clayey-silt rip-up clasts are dispersed throughout the gravel and do not decrease noticeably in size upward through the unit. Ubiquitous Pavoni pipes indicate that the flow contained large amounts of water. At the Reichenau quarry, the uppermost sediments consist entirely of silt and very fine sand, likely deposited by the elutriated water that escaped from the underlying coarser sediments. I explore the Bonaduz mass flow in greater detail in Chapter 3.

2.4.3. Tuma distribution and origin

Bonaduz gravel surrounds tumas in several exposures along the Hinterrhein River, implying that these hills of rockslide material moved on or within the Bonaduz mass flow. Pockets of rounded gravel are found within and on the tumas, also implying contemporaneous movement (Figure 2.35; Poschinger and Ruegg, 2012; Masera, 2013). The composition, shapes, and orientations of the tumas tell us something about their source and the manner in which they moved (Masera, 2013).

The hills closest to the Flims rockslide – Bot Danisch and Bot Tschavir – are likely tumas. They have similar shapes to other tumas and are separated at the surface from the nearest unquestionably intact Flims rockslide debris by Bonaduz gravel and Lake Ilanz outburst flood deposits (Figure 2.5). It is possible, however, that Bot Danisch and Bot Tschavir are connected at depth with the Flims debris sheet, in which case they would not be tumas. An exposure of rockslide debris beneath the Zault plain, along Vorderrhein River east of Trin Station, could be part of a subsurface extension of the Flims rockslide to Bot Tschavir, the nearest hill. Bot Danisch is farther away and less likely to be connected to the Flims rockslide.

Small tumas were transported up the Hinterrhein valley with the Bonaduz mass flow. Others may have stranded against the west side of the Tamins landslide. The tumas in Domat/Ems and Chur consist of Helvetic limestone debris and could have a

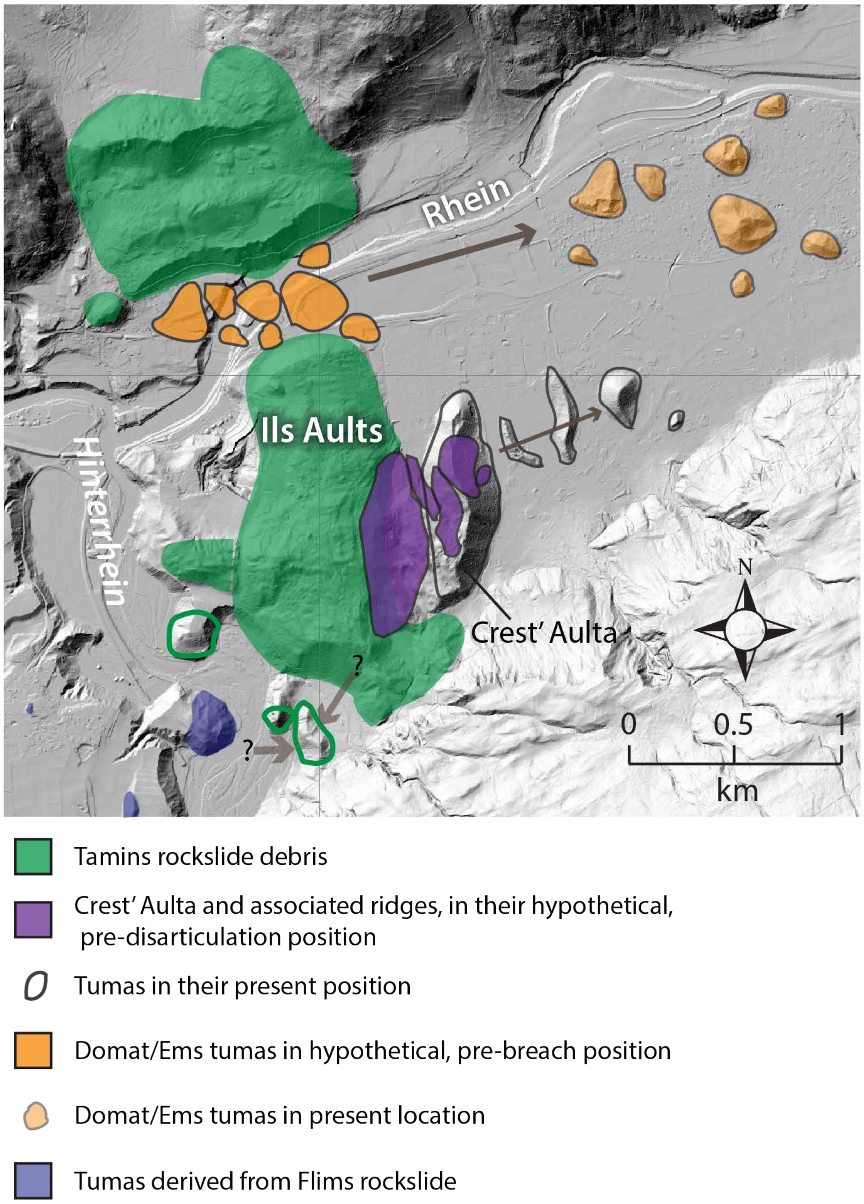


Figure 2.40. Likely sources of tumas east and southwest of the Tamins rockslide; arrows showing their movement paths to positions today.

Flims or Tamins rockslide source. However, their proximity to the Tamins rockslide and the huge breach in the Tamins barrier indicate this landslide is likely the source (Figure 2.40). The tumas just southeast of Ils Aults (e.g. Crest' Aulta) clearly detached and moved away from the Tamins rockslide deposit (Figure 2.41).

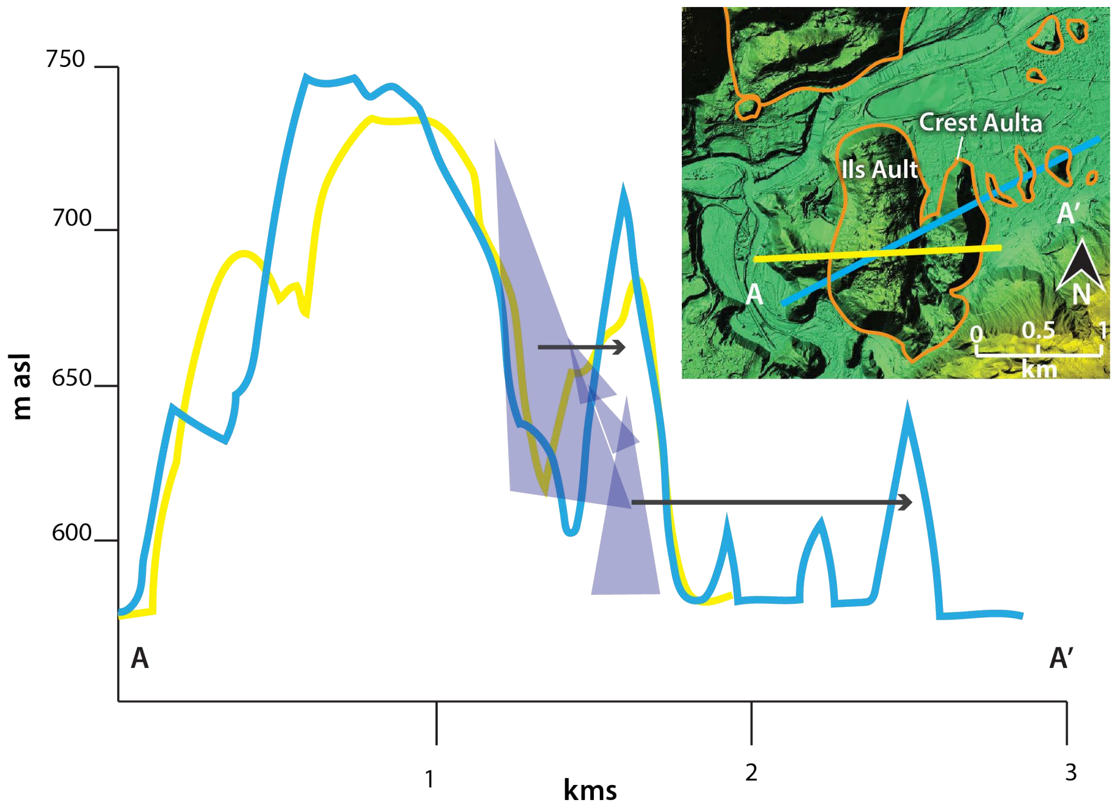


Figure 2.41. Two cross-sections of the Tamins rockslide deposit, one including the small tumas east of Crest' Aulta. Vertical exaggeration = 10x. The purplish gray polygons are restored masses of the Tamins rockslide mass, prior to disarticulation and eastward rafting of Crest' Aulta and tumas to the east. Arrows indicate the assumed direction and amount of movement of the tumas.

The Tamins barrier probably was breached by a combination of disarticulation of the Tamins rockslide mass due to valley-wide liquefaction and impact of the Bonaduz mass flow (Figure 2.41). If the Tamins barrier had remained intact during the Flims rockslide and Bonaduz mass flow, another explanation would be required for the transport of tumas downvalley all the way to Chur. The only other plausible mechanism is the outburst floods from Lake Ilanz, but is unlikely that the draining of the lake, which occurred in several stages (Poschinger, 2006), could have breached the barrier and carried tumas up to 10 km downvalley. Furthermore, extrapolation of the Lake Ilanz outburst flood surface downvalley to Tamins suggests that at least part of the breach existed before the floods happened.

2.4.4. Terminal Bonaduz events

At several places in the Vorderrhein-Hinterrhein confluence area, Bonaduz gravel is overlain by up to 2 m of horizontally stratified to gently inclined sandy silt, sand, and fine gravel. Similar fine sediments were not found on top of Bonaduz gravel in the Hinterrhein valley.

A constraint on the age of these fine-grained sediments is provided by sediments exposed in building excavations in the town of Bonaduz. In one of these excavations, laminated and thin-bedded sand conformably overlies Bonaduz gravel and is overlain by Lake Ilanz outburst flood deposits (Figure 2.30). The sand thus was deposited after the Bonaduz gravel was emplaced but before the Lake Ilanz outburst floods. The first of the Lake Ilanz outburst floods probably happened within years of the Flims rockslide and Bonaduz mass flow. Based on this temporal constraint and the association of the Bonaduz gravel and the horizontally stratified capping sand, I interpret the latter to have been deposited from after-flow of large amounts of water expelled from the Bonaduz gravel and from the Hinterrhein River when it spilled over the Bonaduz plain immediately following the Flims rockslide.

Broad shallow channels eroded into the Bonaduz plain are other evidence of a downvalley flush of sediment-laden water immediately after Bonaduz gravel was deposited (Figure 2.42). The largest of the channels is 125-200 m wide, is bordered by stepped 5-10-m-high sides, and slopes gently towards the Hinterrhein River. The channel floor is gently undulating, suggesting that the Bonaduz gravel beneath it continued to dewater and settled irregularly while the channel carried water. The Plazzas exposure (Figure 2.29) is located near the mouth of this channel, where it terminates at the edge of the Bonaduz plain.

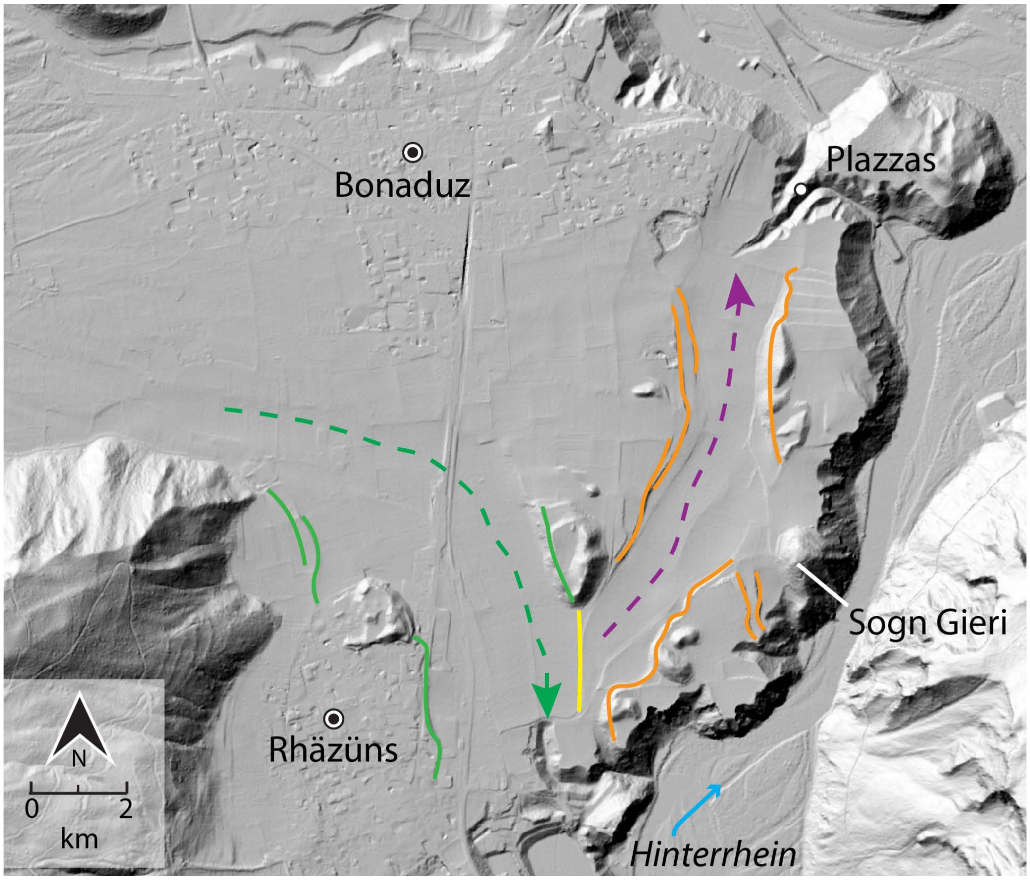


Figure 2.42. Hillshade image of two broad shallow channels on the Bonaduz plain. The dashed green lines delineate a subtle, ~2-4-m-deep channel that is gently inclined to the south. The pink arrow marks a 3-6-m -deep channel dipping to the north-northeast. The orange lines are the edges of terraces bordering the eastern channel. The yellow line marks the divide (~2 m high) between the two channels. Both channels debouch into gullies, one at Plazzas and the other an unnamed gully southeast of Rhäzuns.

One interpretation of the capping sediments at Plazzas is that they record, sequentially, elutriation of the uppermost Bonaduz gravel (fine pebble gravel devoid of matrix), ephemeral ponding of water behind the breached or partially breached Tamins barrier (clayey silt bed), and then a flow of water down the channel (coarsening-upward sequence). Alternatively, the clayey silt layer may represent the fines expelled from the settled Bonaduz gravel.

Large amounts of water are required to carry the flow up the Hinterrhein valley to Thusis. This water was derived in part from rapid dewatering of the Bonaduz gravel

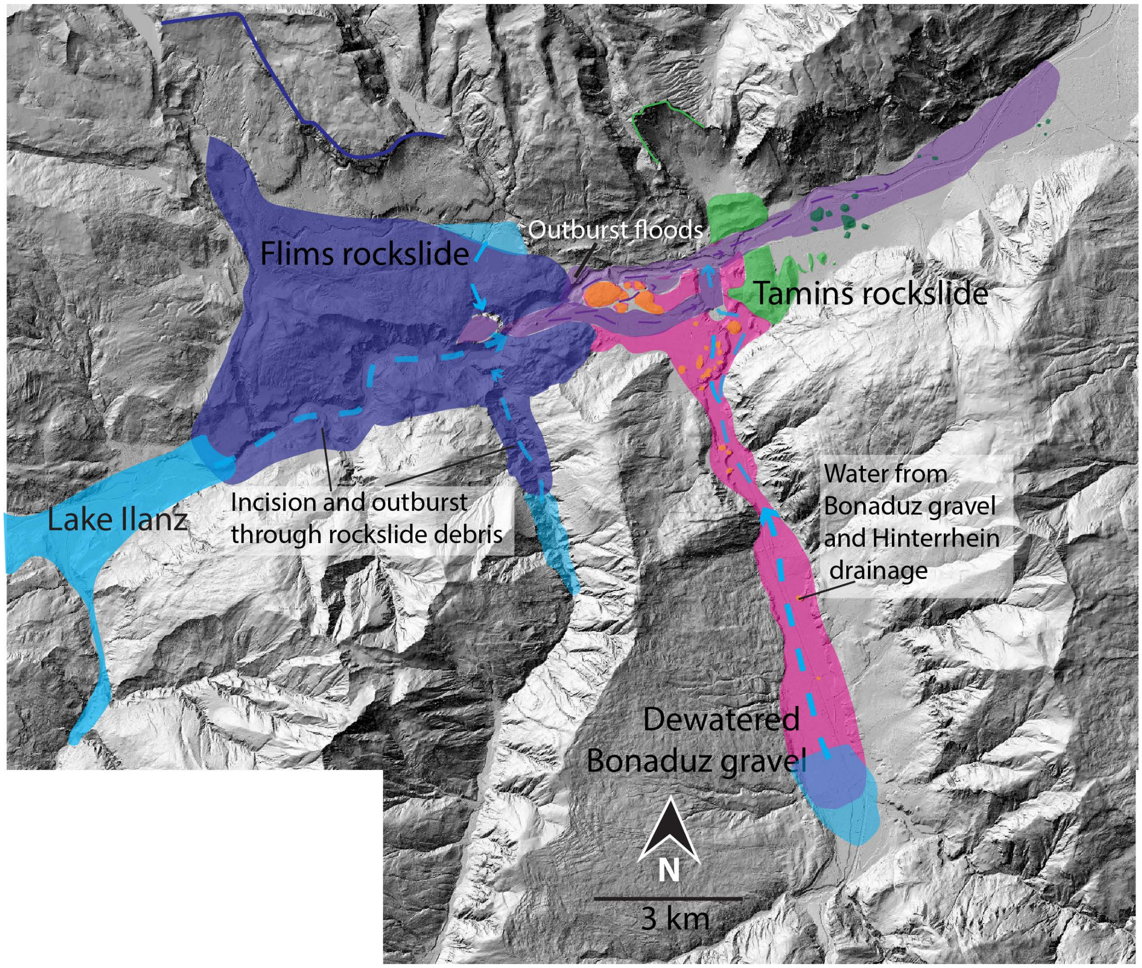


Figure 2.43. Post-Bonaduz flow events. A large volume of water displaced from Lake Bonaduz and augmented by dewatering of the Bonaduz mass flow and Hinterrhein River flow produced a flood out of the Hinterrhein valley. Later, a series of outburst floods from Lake Ilanz pass through and perhaps enlarge the breach in the Tamins rockslide. The earliest flood covered the Bonaduz gravel plain (purple), leaving a blocky deposit; subsequent flood events were channeled along the Vorderrhein River gorge at successively lower elevations, forming terraces.

when it came to rest (Figure 2.43). It is very likely, however, that the waters of Lake Bonaduz were also involved in the mass flow. If, as I argue earlier, a lake existed behind the Tamins rockslide barrier when the Flims rockslide happened, much or all of its waters would have been swept down the Vorderrhein valley and up the Hinterrhein valley, with the Bonaduz gravel either forming a carpet at the base of a water column or lagging behind an initial wave and flood (Figure 2.43). There is some evidence for an extreme amount of water escaping the Hinterrhein valley immediately after the Bonaduz gravel came to rest. An east-trending ridge of rockslide debris lies between Ils Aults on the east and the Reichenau quarry to the north. The north flank of this ridge (but notably not the south flank) is cut by a series of gullies up to 5 m deep that extend from the narrow crest of the ridge at 706 m asl to near the south edge of the Reichenau quarry at 662 m asl. An apron of fans extends northward from the base of the ridge toward the quarry. The fans are underlain by cobble-boulder gravel eroded from the ridge flank. The distal sediments of this apron are exposed at the top of the south wall of the Reichenau quarry. There, a shallow flat-floored channel is filled with stratified sand and minor pebble gravel. Most of the strata are horizontal and structureless, but there are rare climbing ripples and drape lamination in the sand beds. These sediments were deposited by strong flow in standing water. The gullies that head at the ridge crest south of the Reichenau quarry must have been formed by water flowing out of Hinterrhein valley and over the ridge soon after the Bonaduz gravel came to rest. By implication, the water column over the Bonaduz plain was at least 40 m deep when backflow from the Hinterrhein valley reached the Vorderrhein-Hinterrhein confluence area. The large volume of water, at least temporarily, was unable to escape through the Tamins breach and ponded in lowermost Hinterrhein valley.

The Bonaduz plain was rapidly incised soon after the Bonaduz gravel dewatered and the normal base flow of the Hinterrhein River was re-established. Gullies up to 300 m long and 60 m deep extend westward into the plain from the Hinterrhein valley (Figure 2.44). The gullies are relict, having carried no water since the Hinterrhein and Vorderrhein rivers reached their present levels. I surmise that they formed during the immediate aftermath of the Flims landslide by backflow from the Hinterrhein valley and, soon thereafter, from the first outflows from Lake Ilanz.

The large difference in elevation between the Bonaduz plain and the valley floor below the Tamins landslide facilitated rapid erosion of the Bonaduz plain by water leaving the Vorderrhein and Hinterrhein valleys. I interpret the imbricated, clast-supported cobble gravel overlying Bonaduz gravel at site IA-06 at the southwest side of Ils Aults (Figure 2.32 and 2.44) to have been deposited in the channel of Hinterrhein River as it began to incise the Bonaduz plain.

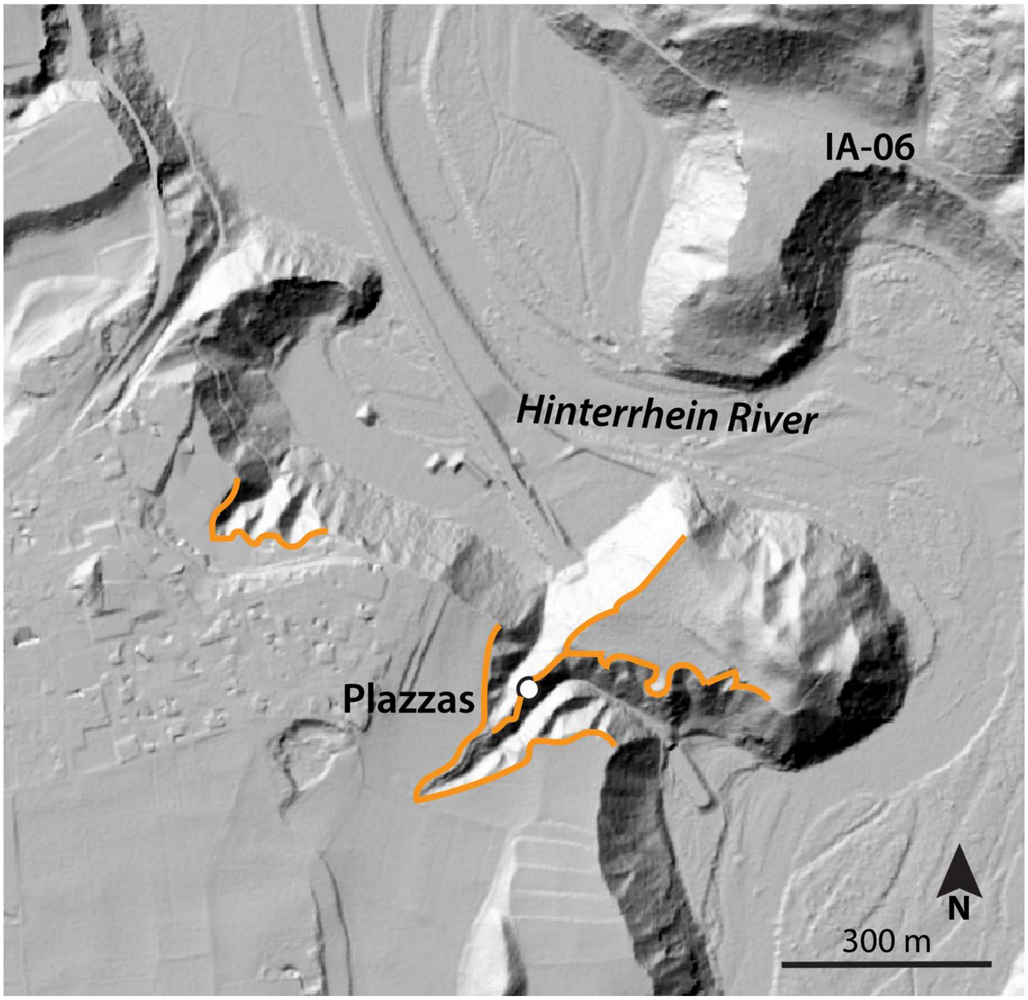


Figure 2.44. Hillshade LiDAR image of the gullies near Plazzas. The gullies (outlined in orange) are steep, narrow, up to 60 m deep.

The blocky diamicton overlying Bonaduz gravel in several construction sites in the town of Bonaduz was deposited by an outburst flood from Lake Ilanz. The deposit has a fan shape with a uniform 2° slope down to the east. Shallow wide channels and terraces are present on the fan surface near hills of rockslide debris, including Bot Danisch and Bot Tschavir (Figure 2.11). The debris deposits of Lake Ilanz outbursts are 60-200 m above the level of the Vorderrhein River to the north. These observations suggest that the first floodwaters from Lake Ilanz crossed the Bonaduz plain shortly after the Flims rockslide and that outburst floods continued after incision of the plain by the Vorderrhein and Hinterrhein rivers had begun. The first flood spilled across the Bonaduz plain, creating the above-mentioned apron, whereas later floods were funnelled into the deepening Vorderrhein valley, where they are associated with a series of terraces (Figure 2.34).

The elevation of the base of the breach in the Tamins rockslide dam created by the Bonaduz mass flow is not exactly known, but was likely about 630 m asl, given that Lake Ilanz outburst flood deposits extend no lower than this elevation just upstream of the Tamins barrier. There are prominent downvalley sloping terraces within the breach at 615 m and 625 m asl, 25 m and 35 m above the level of the modern river. The higher terrace near the Reichenau quarry is underlain by large angular Helvetic limestone blocks capped by a patchy veneer of rounded boulders, cobbles, and pebbles. One or both of these terraces probably record the level of Lake Ilanz floodwaters after the Tamins dam had been breached or partially breached by the Bonaduz mass flow.

2.5. Summary

Several researchers have studied the Bonaduz gravel and offered ideas about its origin. Pavoni (1968) proposed that the unit was emplaced by a 'mud slurry' that he thought resulted from impact of the Tamins rockslide on the Vorderrhein valley floor. Later, Scheller (1972) provided geophysical evidence that the tumas in the Hinterrhein valley between Reichenau and Pardisla quarry are 'rootless' pieces of Flims rockslide debris, not bedrock outcrops. Poschinger and Kippel (2009) furthered our understanding of this enigmatic gravel unit by identifying two lithofacies and documenting their sedimentological characteristics.

I provide additional descriptions of Bonaduz gravel at key sites in the Vorderrhein and Hinterrhein valleys. I integrated stratigraphic and sedimentological information at these sites with geomorphic observations derived from hillshade LiDAR imagery. I describe events spanning the period from the Flims rockslide and Bonaduz gravel emplacement, through late-stage backflow from the Hinterrhein valley and Lake Ilanz outburst floods, to incision of the Bonaduz plain by the Hinterrhein and Vorderrhein rivers. I link these events to sediments and landforms.

The presence of rounded gravel on the northern part of Ils Aults indicates that the Tamins rockslide was partially overtopped by the Bonaduz flow. Tumas also moved east from Ils Aults as a result of valley-wide liquefaction during the Flims rockslide. Sediments beneath the Tamins rockslide mass may have liquefied, contributing to its breach or partial breach by the Bonaduz mass flow.

When the Bonaduz mass flow came to rest, large amounts of water were expelled from the deposit. This water, augmented by water displaced from Lake Bonaduz and by Hinterrhein River flow deposited a layer of sandy silt, sand, and fine gravel in broad shallow channels on the Bonaduz plain. The breach in the Tamins rockslide barrier remained the outlet through which the reorganized Hinterrhein and Vorderrhein rivers flowed.

Following the Bonaduz event, the first Lake Ilanz outburst floods flowed over the Bonaduz gravel plain and around Bot Danisch and Bot Tschavir, depositing an apron of coarse blocky diamicton as a fan atop the plain. Subsequent Lake Ilanz floods flowed in successively lower channels developing on the incised floor of the Vorderrhein valley.

Chapter 3. The Bonaduz gravel mass flow

In this chapter, I summarize pertinent literature on mass flows and discuss the applicability of existing mass flow classifications, and ideas about genesis, transport, and deposition to the Bonaduz gravel. I present relevant field data and geomorphic observations in the area near the confluence of the Hinterrhein and Vorderrhein rivers that bear on these issues. These data and observations provide insights into events and processes immediately after the impact of the Flims rockslide on the Hinterrhein valley floor. In the final section of the chapter, I discuss additional research that might be done to test the ideas I present here.

3.1. Mass flows

Mass flows are a group of mass movements included within all landslide classifications, including the commonly used classification of Varnes (1978), which was updated in 1996 by Cruden and Varnes. The Cruden and Varnes (1996) classification discriminates mass movements according to the dominant material type and movement mechanisms. Material types are bedrock, debris, and earth. ‘Debris’ is loose unsorted material with 20-80% particles larger than 2 mm that forms at Earth’s surface through erosional and depositional processes (Hungr et al., 2001). In comparison, ‘earth’ is unconsolidated sediment with >80% particles smaller than 2 mm (Campbell et al., 1985). In this context, the Bonaduz gravel falls within the ‘debris’ category. Movement types identified by Cruden and Varnes (1996) include falls, topples, slides, and flows. The movement type explored in this chapter is ‘flow,’ defined as “motion involving internal distortion of a moving mass” (Hungr et al., 2001). First, I will define the different flow types and then consider how mass flows initiate and move, exploring several secondary processes.

3.1.1. Definition and classification of mass flow types

Flow-type landslides (Table 3.1) are characterized by fluid motion and generally involve a fluid moving over a rigid or non-deforming bed (Hungr et al., 2001). The presence or absence of water and rheology further differentiate mass flow types (Selby, 1993; Hungr et al., 2001; Hungr, 2005). The following is a review of the classification and terminology used to describe different flow-type mass movements.

Water floods versus debris-rich flows

Hungr et al. (2001, p. 235) state that water-rich mass flows are distinguished by "material type, water content, presence of excess pore-pressure or liquefaction at the source of the landslide, presence of defined recurrent path (channel) and deposition area (fan), velocity, and peak discharge of the event". At one end of the continuum are debris floods, which are channelized flows in which most of the sediment is transported particle-by-particle as bedload. Debris floods themselves lie along a continuum with 'clear-water floods'; this continuum is characterized by differences in the amount of sediment transported at the channel bed or in suspension. Hungr et al. (2001, p. 231) state that a "debris flood is a very rapid, surging flow of water heavily charged with debris in a steep channel".

Water-rich mass flows can also be differentiated on the basis of viscosity as either Newtonian or non-Newtonian. Newtonian fluids react with equal deformation to any given additional stress, meaning that there is a linear relation between shear stress and shear rate. These fluids do not have internal strength that resists flow. In contrast, non-Newtonian fluids show is a non-linear relation between shear stress and shear rate (Varnes, 1978; Campbell, et al., 1985). Non-Newtonian fluids resist shear stress but flow under larger stresses (Bingham fluid); their viscosity decreases with an increase in the velocity gradient (pseudo-plastic), or their viscosity increases with an increase in the velocity gradient (dilatant fluids) (Bagnold, 1954).

At the other end of the mass flow continuum are viscous debris flows, which are internally deforming bodies of water-rich sediment, commonly with abundant fines. Debris flows are channelized on steep slopes, but may escape their channels on lower gradient surfaces such as debris fans. Varnes (1978) states that a “debris flow is a very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel”.

Debris flows may be analogous to Bingham fluids that initially resist flow but then flow under larger shear stresses. However, Iverson (1997) points out that an increase in the content of fines in a sediment-water mixture decreases its apparent strength because the fines “help sustain high pore pressures that reduce frictional resistance and enhance spreading”. Simple Bingham fluid models also do not take into account any grain interactions or the fluid between particles (Iverson, 1997).

Table 3.1. Classification of flow-like landslides (after Hungr et al., 2001).

Material	Water content	Special condition	Velocity	Name
Silt, sand, gravel, debris (talus)	Dry, moist, or saturated	No excess pore pressure; limited volume	Various	Non-liquefied sand (silt, gravel, debris) flow
Silt, sand, debris, Weak rock	Saturated at rupture surface	Liquefiable material, constant water	Extremely rapid	Sand (silt, debris, rock) flow slide
Sensitive clay	At or above liquid limit	Liquefaction *in situ*, constant water content	Extremely rapid	Clay flow slide
Peat	Saturated	Excess pore pressure	Slow to very rapid	Peat flow
Clay or earth	Near plastic limit	Slow movement, plug flow (sliding)	Rapid	Earth flow
Debris	Saturated	Established channel, higher water content	Extremely rapid	Debris flow
Mud	At or above liquid limit	-Fine grained debris flow	Very rapid	Mud flow
Debris	Free water present	Flood	Extremely rapid	Debris flood
Debris	Partly or fully saturated	No established channel, relatively shallow, steep source	Extremely rapid	Debris avalanche
Fragmented rock	Mainly dry	Intact rock at source, large volume	Extremely rapid	Rock avalanche

Flow slides

A ‘flow slide’ is a flow of liquefied sand or silt. Flow slides have a high water content and can travel at high speeds over long distances on gentle slopes (Hungr et al., 2001). The source sediment must have a collapsible structure that enables generation of high pore pressures. A disturbance such as an earthquake can cause the soil structure to collapse and the material to liquefy, but in many cases no trigger is involved. Flow slides commonly occur in deltaic sand and silt, lacustrine and marine silts, and loess (Hungr et al., 2001).

Hyperconcentrated flows

A hyperconcentrated flow, as described by Pierson (2005), is a transitional mass flow between a water flood and a debris flow (Figure 3.1). A flood transitions into a hyperconcentrated flow when particles on the bed begin to move together, *en masse*, and coarse sediment becomes suspended in the flow. Water flood behaviour begins to be affected by sediment when particle concentrations reach about 4% by volume (Pierson, 2005); fine sediment has a greater impact on viscosity than coarse sediment. According to Pierson (2005), a hyperconcentrated flood transitions into a debris flow when rising concentrations of sediment generate a critical yield strength (Figure 3.1). At this yield strength, a 4-mm particle can be suspended indefinitely in the moving flow.

Hyperconcentrated flows are not considered a separate flow type by Hungr et al (2001). Rather, they view hyperconcentrated flows as indistinguishable from debris flows or as a stage in a mass flow event (Hungr et al., 2001, p. 233). Other researchers, however, continue to advocate for the use of this term (Sohn, 1997; Dasgupta, 2003; Pierson, 2005).

Hyperconcentrated flows deposit material through traction carpet accretion and suspension fallout (Pierson, 2005). Most deposits are poorly to very poorly sorted and are either massive or horizontally stratified. Deposits generally fine downstream (Pierson, 2005).

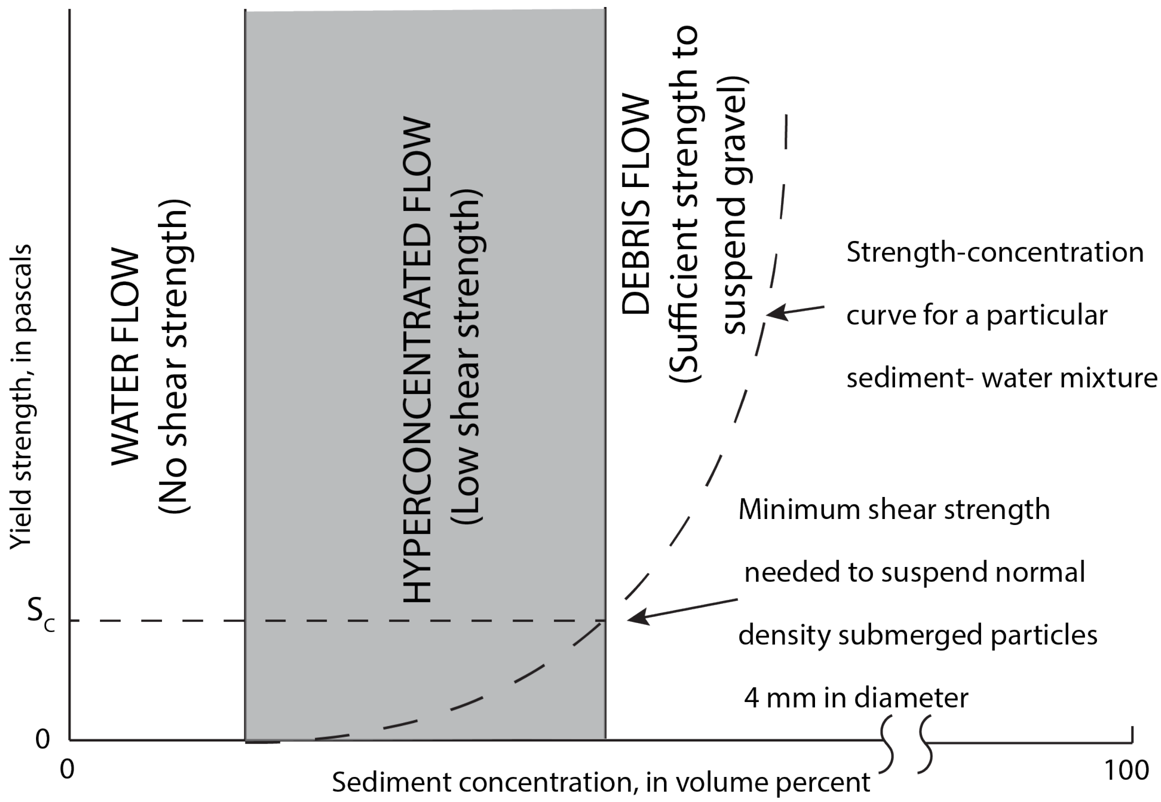


Figure 3.1. The water flood – debris flow continuum expressed in terms of the relation between yield strength of the sediment-water mixture and suspended sediment concentration (modified from Pierson, 2005, his figure 8.1).

Debris flows

A 'debris flow' is a poorly sorted, saturated, sediment flow that travels along a channel (Iverson, 1997). Sediment concentrations can exceed 60% by volume (Pierson, 2005). Debris flows entail a complex mix of viscous fluid mechanisms and forces between particles acting together on the flowing mass (Pierson, 2005). Movement is commonly in surges, with steep coarse fronts followed by finer, more fluid tails. The largest clasts may be concentrated nearer the front, sides, and top of the flow. Several different methods of movement have been proposed and debated: 1) clay cohesion, which allows large clasts to be suspended in the flow (Middleton and Hampton, 1973); 2) buoyancy due to excess pore-water pressure within the body of flow; and 3) dispersive pressures caused by intergranular contact stresses as grains shear past one another (Davies, 1986).

Debris flow deposits also are poorly to very poorly sorted and are either massive or have only weakly developed stratification (Jakob, 2005). Levees and a coarse layer of larger boulders on the surface of the deposit are common features. Debris flows commonly come to rest on fans at the ends of steep channels (Jakob, 2005).

Although there appears to be a mechanistic difference between debris flows and hyperconcentrated flows, they lie along a continuum. A hyperconcentrated flow can 'bulk up' to become a debris flow, and a debris flow can change into a hyperconcentrated flow with the addition of water along its path. Flood deposits commonly exhibit bedding, cross-beds, and many other fluvial features. Debris flow deposits are very poorly sorted and commonly can be classified as matrix- or clast-supported diamictons. These characteristics stem from the viscosity of the flow and dense grain packing that do not allow stratification to develop or mature (Pierson, 2005). Inverse grading, with large clasts near the top of the deposit, may occur due to dispersive pressures forcing larger clasts upward (Nemec and Steele, 1984). Hyperconcentrated flows, on the other hand, exhibit some stratification; the progressive loss of energy facilitates deposition through particle density settling (Pierson, 2005).

Lahars

A 'lahar' is a volcanic-derived debris flow that commonly contains more sediment than water (Vallance, 2005). Lahars can be very large and are the farthest reaching terrestrial mass flows. With their high sediment load and ready access to water, lahars can transition from debris flows to hyperconcentrated flows, or vice versa (Cronin, et al., 2000). Field observations have shown that lahars can travel faster than streamflow, pushing water in front of them and incorporating water along their paths.

Slurry

Another term that has been used in the literature for a viscous mass flow is 'slurry' (Bagnold, 1956). Major (2003b) describes a slurry as a mix of solids and water that can flow without phase separation. A large part of the energy transfer is between particles, not a gravitational response to fluid flow. The particles contribute to motion and are not "passively carried along" (Major, 2003b). Some debris flows resemble slurries; other examples are pumped industrial slurries, for example cement (Major, 2003b). Lowe and Guy (2000) use the term ‘slurry flow’ for subaqueous equivalents of hyperconcentrated flows that are transitional between debris flows and turbidity currents. Slurry flows are characterized by both turbulent and cohesive sediment support (Lowe and Guy, 2000).

Sediment gravity flow

The term ‘sediment gravity flow’ has been applied to flows of sediment or a sediment-fluid mixture under the influence of gravity in a subaqueous environment (Middleton and Hampton, 1973; Dasgupta, 2003). The phenomenon has been inferred mainly from studies of processes operating in submarine canyons and on continental slopes, and on the resulting deposits (Dasgupta, 2003). These processes lie outside the Cruden and Varnes (1996) classification, which is limited to subaerial mass movements. Sediment gravity flows encompass a variety of phenomena, including turbidity currents, grain flows, subaqueous debris flows, fluidized sediment flows, and slurry flows (Figure 3.2; Middleton and Hampton, 1973; Lowe and Guy, 2000).

Turbidity currents

‘Turbidity currents’, defined as subaqueous gravity flows with a particle-fluid ratio less than 50%, sustain themselves on gentle slopes by the turbulence of the flowing medium. Motion, driven by gravity, causes turbulence in a sediment-water mixture, and the density difference with the surrounding fluid causes grains to mix in suspension (Middleton and Hampton, 1973). As energy wanes, the largest grains fall out of suspension, which leads to less and less energetic flow, creating the typical fining-upward sequences seen in turbidity current deposits (Dasgupta, 2003). Typical, repeating sequences of sediments known as Bouma sequences characterize turbidity current deposits. Turbidity currents, like debris flows, commonly involve sequential surges, each of which leaves a coarser bed at the base and an overlying fining-upward sequence deposited as flow energy wanes (Middleton and Hampton, 1973; Dasgupta, 2003).

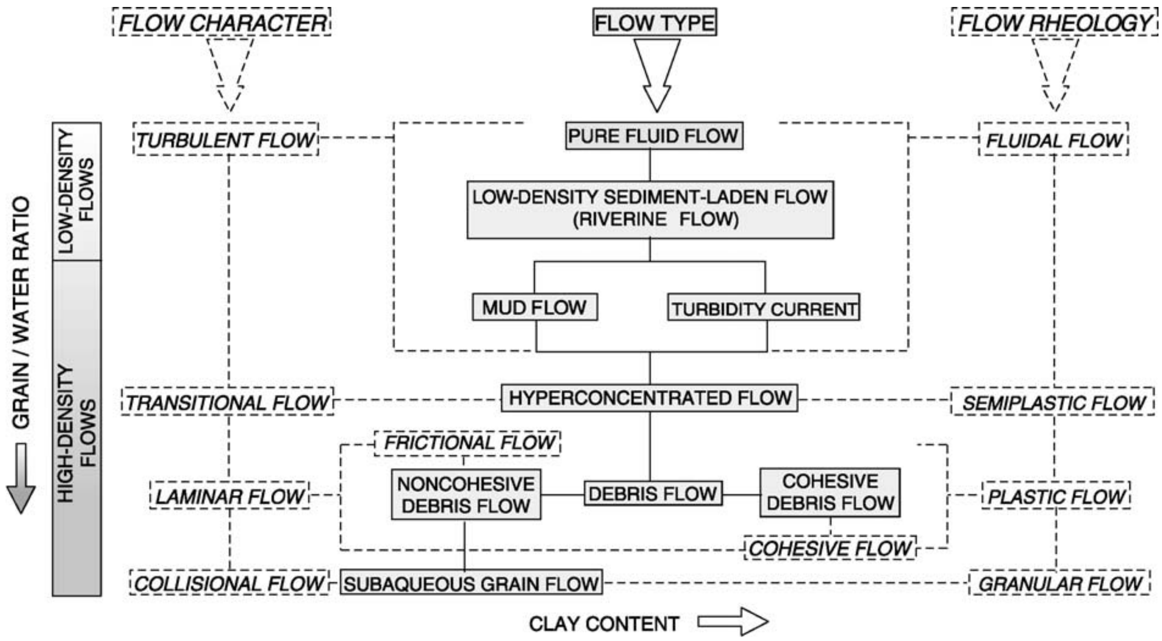


Figure 3.2. Classification of mass flows based on sediment concentration and clay content (Dasgupta, 2003).

Fluidized flows

Fluidized sediment flows happen when fine sediment passes from the solid to the liquid state. There is a sudden loss of strength due to an increase in pore-fluid pressure (‘liquefaction’; Middleton and Hampton, 1973; Dasgupta, 2003). The upward escape of fluid maintains motion, while grains settle under the influence of gravity (Middleton and Hampton, 1973). Middleton and Hampton (1973) argue that fluidized flow mechanisms can operate in tandem with turbulence or dispersive pressures. Lowe (1976) acknowledges that fluidization can initiate a mass movement, but is unlikely to be maintained or be common in most liquefied or sediment gravity flows. Dasgupta (2003) agrees and argues that fluidization is likely transient in nature and that, while it may initiate a flow, it should not be adopted as a distinct flow type.

Grain flows

A ‘grain flow’ is supported by grain-to-grain interactions. Grains shear past one another, causing dilatant dispersive pressures, as proposed by Bagnold (1954). Middleton and Hampton (1973) describe grain flows as cohesionless sediment flows with negligible turbulence. They comment that grain flows might be poorly preserved in the rock record and share sedimentological characteristics of other flows, such as debris flows and turbidity currents.

3.1.2. Flow behaviour

Researches have proposed different phenomena to explain flow behaviour and the deposits found in the rock record. Particle and fluid interaction, particle-on-particle interaction, and forces driving or deterring flow are discussed below with relation to the resulting deposits.

Traction carpets

Fisher (1983) presented the idea of flow transformation, with coarser sediment segregating in the lower part of the flow and finer sediment carried in an overlying less

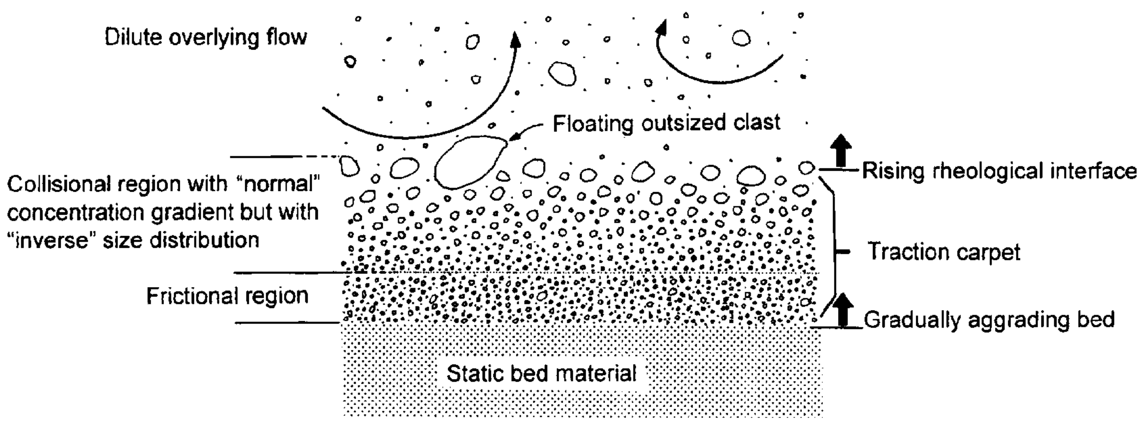


Figure 3.3. Schematic diagram of a hyperconcentrated flow, showing a traction carpet overlain by a zone of turbulent flow (Sohn, 1997).

concentrated part. The lower layer has been referred to as a 'traction carpet', and its existence has been supported in experimental, observational, and sedimentological studies (Postma, 1986; Sohn, 1997; Lowe and Guy, 2000). Traction carpets have a different rheology and velocity than the overlying flow (Sohn, 1997). Particles within the carpet move in unison, rather than individually, as they do in flood flows. Traction carpets develop between the bed and an overlying turbulent flow layer (Figure 3.3; Sohn, 1997). Sohn (1997) presented a conceptual model of such a flow, with a frictional zone marked by aggradation and particle collisions increasing higher in the flow. In the frictional zone, grains are continually in contact with one another (very high particle concentrations, low strain rates). In the overlying collisional zone, large shear stresses exerted by the overlying turbulent flow result in large gradients in grain concentration, active grain collision, and dispersive forces (Figure 3.3). Sohn (1997) argued that the traction carpet initiates when basal sediment concentrations reach 9% by volume during segregation from the overlying, more dilute portion of the flow. At this concentration, collisional grain interactions dictate flow behaviour, as shown experimentally by Bagnold (1956, 1966).

Particle settling

Flow viscosity and rheology dictate particle settling and grading. Particles may move downward in a flow due to gravitational forces. Particle density, shape, and size, flow velocity, and turbulence determine whether or not, and the rate at which, particles settle. Sediment concentration in a mass flow also dictates settling behaviour (Major, 2003a). At low particle concentrations, particles are unimpeded in their downward movement, and particle size and density determine their settling rate. As particle concentrations increase, however, the fluid dynamics of the flow change from Newtonian to non-Newtonian (Pierson, 2005). The increase in particle concentration dampens turbulence (Bagnold, 1966; Sohn, 1997). 'Hindered settling' (Major, 2003a) occurs when the concentration of sediment in the flow strongly influences fluid behaviour, overriding the gravitational effect of particle density, shape, and size.

Based on laboratory experiments with volcanic materials, Druitt (1995) concluded that there are three categories of flow behaviour related to particle concentration. At sediment concentrations of a few percent by volume, particles do not settle according to Stoke's law, which is based on the free fall of particles through a fluid with no grain interactions. At sediment concentrations ranging from 10% to 50%, particles segregate within the flow according to particle size and density. These high sediment concentrations induce changes in fluid density and viscosity, and intergranular displacement of fluid (Major, 2003a). At concentrations higher than 50%, particle

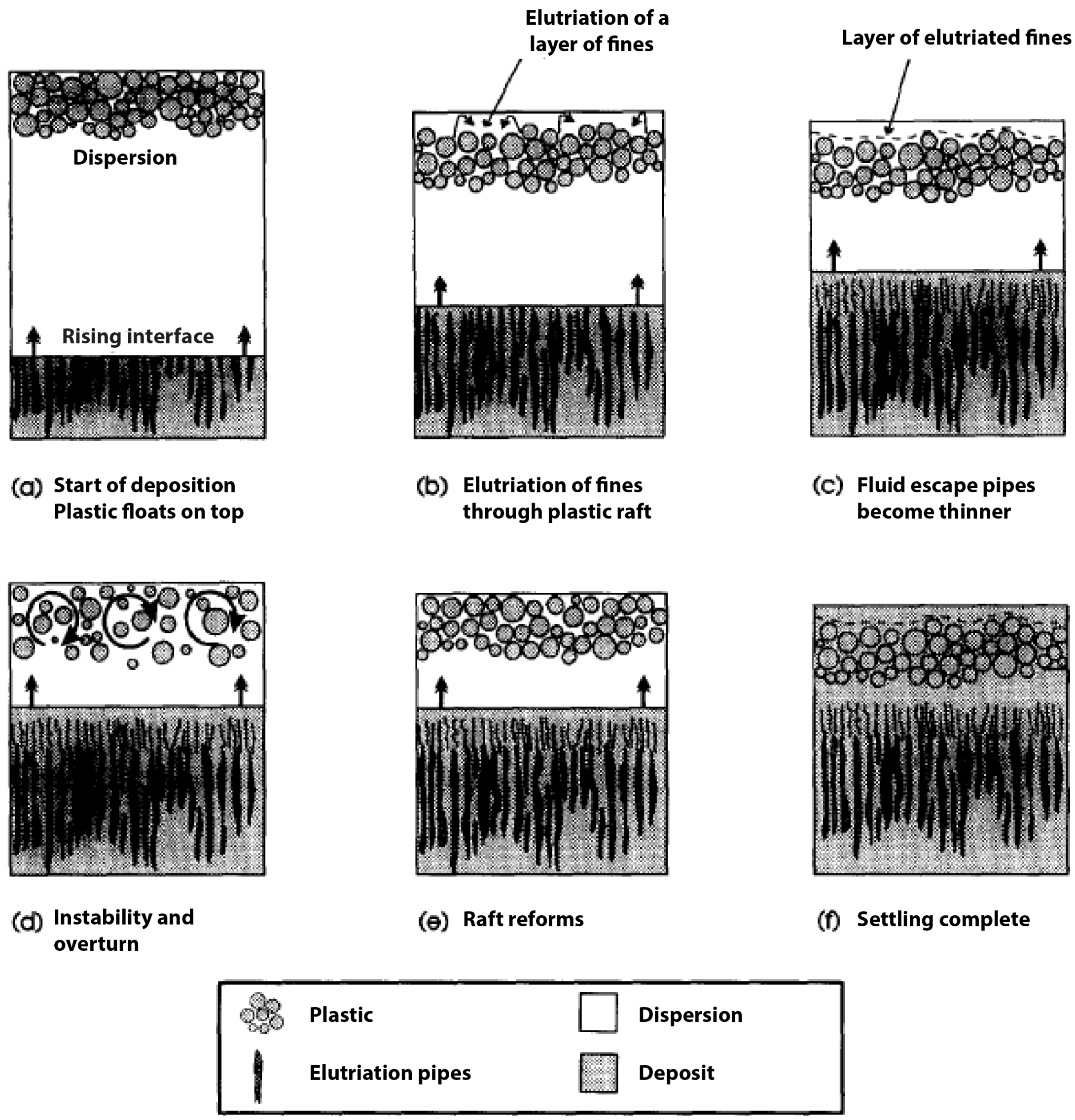


Figure 3.4. Schematic diagram showing successive stages in the formation of elutriation pipes during settling of a flow with 45% sediment (Druitt, 1995). The sediment mix comprises silicon carbide particle sizes ranging from 5.5 µm to 1000 µm and larger plastic grains. Excluding the plastic grains, the deposit is normally graded.

contacts suppress segregation by size and density, deposition occurs *en masse*, and the resulting deposit is massive, lacking internal structure. Particle segregation thus occurs mainly at intermediate sediment concentrations, and the resulting deposit is commonly normally graded. Fluid flow around the falling particles facilitates upward movement of finer particles, which are deposited later. Separation by size and density is most effective in suspensions with large differences in particle size. In his laboratory experiments, Druitt (1995) observed elutriation pipe formation and expansion (Figure 3.4). Strong upwelling of water and fine particles due to settling of coarser particles and expulsion of intergranular water produced vertical zones of elutriated, well-sorted sediment. Elutriation pipes also formed while the deposit aggraded in flows with particle concentrations between 25% and 55%, with strong discharge of fluid above each pipe. At a sediment concentration of 60%, elutriation pipes nucleated throughout the sediment, lengthening and widening with time.

Lowe (1976) proposed equations for estimating the viscosity and rheology of subaqueous sediment gravity flows based on the work of Bagnold (1966) and experimental data, although he did not consider traction movement at the base of the flows. I used his equations to calculate rough estimates for the Reynolds number of the Bonaduz mass flow:

$$R_f = \frac{\rho_f H U_{max}}{\mu_f}$$

$$\text{where } R_f = \text{flow Reynold's number}; \rho_f = \text{density of flow } \left(\frac{g}{cm^3}\right);\ H = \text{Hydraulic radius of flow} = \frac{2A}{P} (\text{cross sectional area} = A; \text{wetted perimeter} = P);\ U_{max} = \text{Max flow velocity } \left(\frac{m}{s}\right);\ \mu_f = \text{viscosity of solid and fluid mixture } \left(\frac{g}{cm \cdot s}\right)$$

(Equation 7 from Lowe (1976))

Estimates for Bonaduz gravel:

$$\rho_f\text{: } \rho_{water} = 1.0 \left(\frac{g}{cm^3}\right) \text{ and } \rho_{limestone} = 2.6 \left(\frac{g}{cm^3}\right), \rho_f = 1.6 \text{ to } 2.0 \left(\frac{g}{cm^3}\right);\ H = \frac{2(0.25\ km^2)}{2.7} km = 0.18;\ \mu_f = \text{Very broad approximation} = 0.005 \text{ to } 0.8 \left(\frac{g}{cm \cdot s}\right);\ U_{max} = 4 \text{ to} > 10 \left(\frac{m}{s}\right);$$

$$R_f = [576 - 720]$$

My estimate of the Reynolds number for the Bonaduz gravel is near the laminar-turbulent boundary of 500 (Lowe, 1976). Above this number, a flow is turbulent. My estimate is, at best, approximate, given uncertainties in key variables, especially density and velocity. Perhaps the Bonaduz mass flow was both turbulent and transitional to laminar flow behaviour.

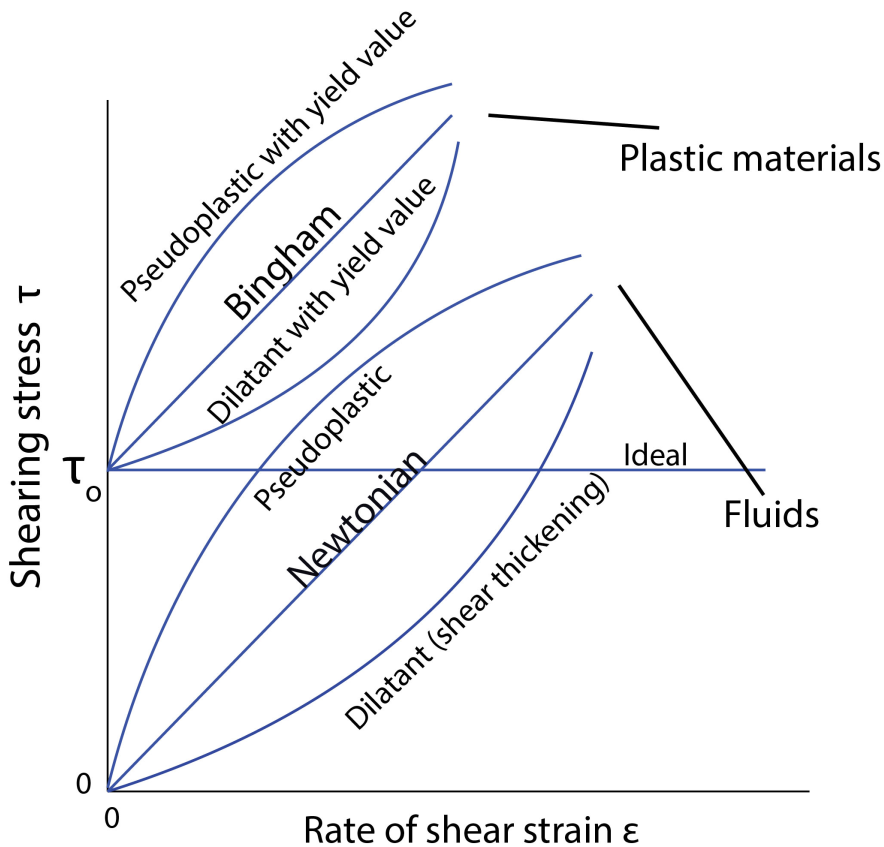


Figure 3.5. Idealized behavior of fluids and plastic materials (Selby, 1993). Plastic materials have a yield stress, which, once surpassed, deform at a linear or exponential rate.

Flow behaviour

Davies (1986) proposed that debris flows move as a dilatant plastic, which is material that behaves as a solid below a threshold stress, but deforms proportionally to the amount of stress applied above this threshold. Dilatancy refers to two separate processes: rheological dilatancy and volumetric dilatancy. In the case of rheological dilatancy, viscosity increases with an increase in shear stress; volumetric dilatancy occurs when a fluid increases in volume under shear as a result of dispersive pressure (Lowe, 1976).

Once yield stress exceeds a critical value in a Bingham plastic material, the space between grains expands, causing the volume of the material to increase and allowing grains to shear past one another (Figure 3.5; Bagnold, 1954). Debris flows are able to support very large particles if dispersive stresses are large.

3.1.3 Liquefaction

"Fluidization demands that fluid be forced upward through the grain-mass until the downward-acting immersed particle weight is balanced by the fluid drag" (Allen, 1982, p. 294). A continuous influx of fluid is essential (Allen, 1982; Dasgupta, 2003). Once in motion, the flow behaves as liquidized sediment. Upward fluid movement within a mass flow occurs as particles settle (Major, 2003a). Fluidization of a mass of sediment the size, depth, and extent of the Bonaduz gravel appears to require the presence of an external body of water, specifically a lake.

Liquefaction occurs when pore water pressure in granular sediment rapidly increases and becomes equal to the total normal stress. The effective stress drops to zero, grains within the sediment lose frictional contact with one another, and the shear strength of the material approaches zero. This internal loss of strength allows the material to behave like a liquid. Liquefaction is commonly associated with loose fine sand and silt, a high water table or the presence of water within the sediment, and low compaction (Ferrer and de Vallejo, 2011, p. 106). Liquefaction is caused by disturbance of the sediment, for example earthquake-generated ground motions, mass movements, or rapid and substantial aggradation.

Liquefaction induced by earthquakes

Obermeier et al. (2005) reviewed the characteristics of sediments that are prone to liquefaction and the earthquake magnitude and ground motions necessary to liquefy them. They concluded that a minimum magnitude of 5.5 is required to liquefy sediments. They also reviewed instances of liquefaction of gravel and gravelly sand, and found that earthquake magnitudes of ~7.0-7.5 and peak accelerations of 0.4-0.5 *g* are required where pore water cannot easily escape (i.e., where gravel is capped by less permeable fine sediments). Based on observations from the 2008 Wenchuan (China) earthquake, Cao et al. (2011) concluded that, without a fine-grained cap, gravel might not even liquefy at high (0.5-1.0 g) ground accelerations.

A well-known example of liquefaction on a large scale is that caused by the 1811-1812 New Madrid earthquakes in the east-central United States (Obermeier, 1989). Cyclic seismic ground motions induced liquefaction in water-saturated alluvial sediments over an area 40-60 km wide and ~180 km long. Liquefaction during the earthquakes was manifested by irregular settlement of the ground surface, fissuring of the ground, eruption of watery sand and silt (‘sand blows’), and lateral spreading towards river channels. The total volume of silt and sand that liquefied is unknown, but thousands of sand blows formed during the earthquakes.

The following examples show that water-saturated gravel can, in some cases, liquefy. Bezerra et al. (2005) documented large fluidization and elutriation features, including dikes, pillars, and pockets within Quaternary alluvial gravels in Rio Grande do Norte and Ceará states in northeast Brazil. The dikes, pillars, and pockets form a composite structure: dikes are the upper part of the structure and intrude other sediments; the pillars are intermediate, elutriated subvertical features; and the pockets are bowl-shaped forms with concentrations of coarse grains from which fine sediments have been elutriated. These features range from several centimetres to 4 m in width and height. Bezerra et al. (2005) concluded that strong earthquake ground motions likely liquefied the gravels and created the composite elutriation structures through expulsion of water and reorganization of the sediment structure. Yegian et al. (1994) documented liquefaction of gravels due to the **M**~6.8 earthquake in Armenia in 1988. In this case, freely draining gravel did not liquefy under peak ground accelerations of 0.5–1.0 *g*, whereas saturated gravel with an impermeable cap readily liquefied, causing large-scale deformation and lateral spreading. Cao et al. (2011) documented more than 100 instances of liquefaction of gravelly sand during the 2008 Wenchuan earthquake (**M**7.9). Liquefaction occurred over a broad gravel plain and produced fissures, sand boils, and small-scale lateral spreading.

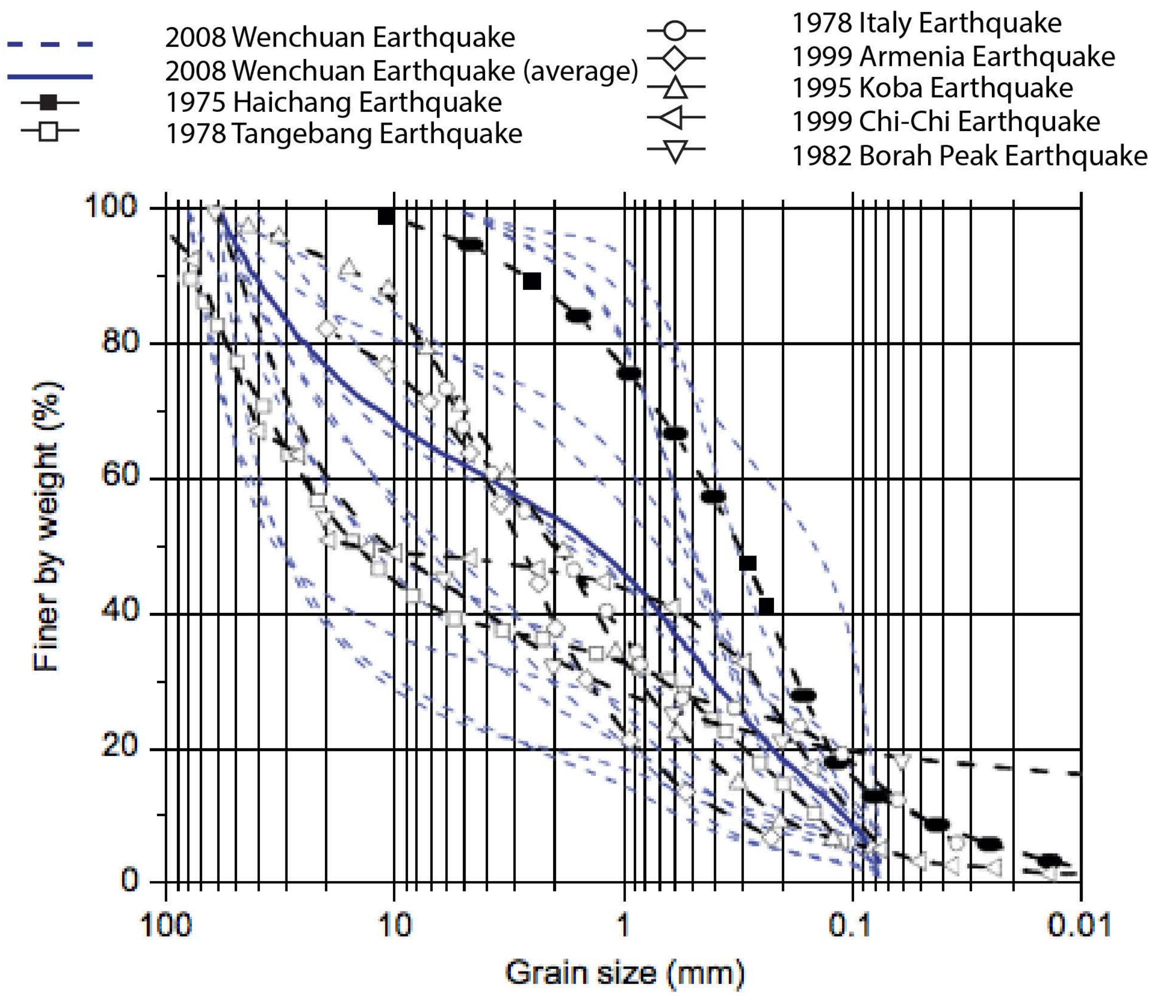


Figure 3.6. Cumulative grain-size curves of gravels that liquefied during historic earthquakes around the world (Cao et al., 2011). The coarsest Wenchuan (2008) samples have a particle-size distribution similar to that of the Bonaduz ‘chaotic cobble’ facies.

Cao et al. (2011) compared different particle sizes in sediments liquefied during many historic earthquakes (Figure 3.6). Several samples of sediment liquefied during the Wenchuan (2008), Borah Peak (1982), and Chi Chi (1999) earthquakes have 50% or more gravel coarser than 10 mm, similar to samples of basal Bonaduz gravel. The Chi Chi earthquake example does not have as much sand as typical Bonaduz gravel. The coarsest Wenchuan (2008) samples are similar to coarse Bonaduz gravel (sample SB-03 in Figure A.8 of Appendix 1, and sample RQ-20 in Figure A.13 in Appendix 1). The three examples cited above provide evidence for widespread liquefaction of coarse sediments, but none of them generated a mass flow analogous, even on a small scale, to the Bonaduz flow.

Liquefaction induced by landslides

Very large landslides produce huge amounts of energy, and their impacts induce ground motions similar to those generated by earthquakes. These forces have been estimated from seismometer records (Ekström and Stark, 2013; Moretti et al., 2015). Kanamori (1984), for example estimated an energy release of 10^{13} N from the 1980 Mount St. Helens debris avalanche, which had a volume of 2.5 km^3. Ekström and Stark (2013) estimated local ground motions from seismic traces of 29 large landslides that have happened over the past 32 years. Many of the landslides produced long wavelength seismic energy equivalent to a $M_{SW} > 5$ tectonic earthquake. Ekström and Stark (2013) established scalable relations between these events, creating a log-scale model relating surface wave magnitude and force (N) (Figure 3.7). Extrapolating from their curve, the energy generated by the impact of the Flims rockslide on the floor of the Vorderrhein valley (>5x10^{12} N) would be equivalent to a M_{sw} 6.0 or larger earthquake. Likely, there was a prolonged energy release by the Flims rockslide, from the initial detachment of the rock mass, through subsequent motion and fragmentation, to the impact of the rock mass on the valley floor and opposing steep valley wall and the cessation of movement. The period of the signal probably spanned more than 200 seconds (Figure 3.7F). The Flims rockslide, however, is about three times larger than the largest landslide in Ekström and Stark's (2013) database, limiting the applicability of the relations shown in Figure 3.7.

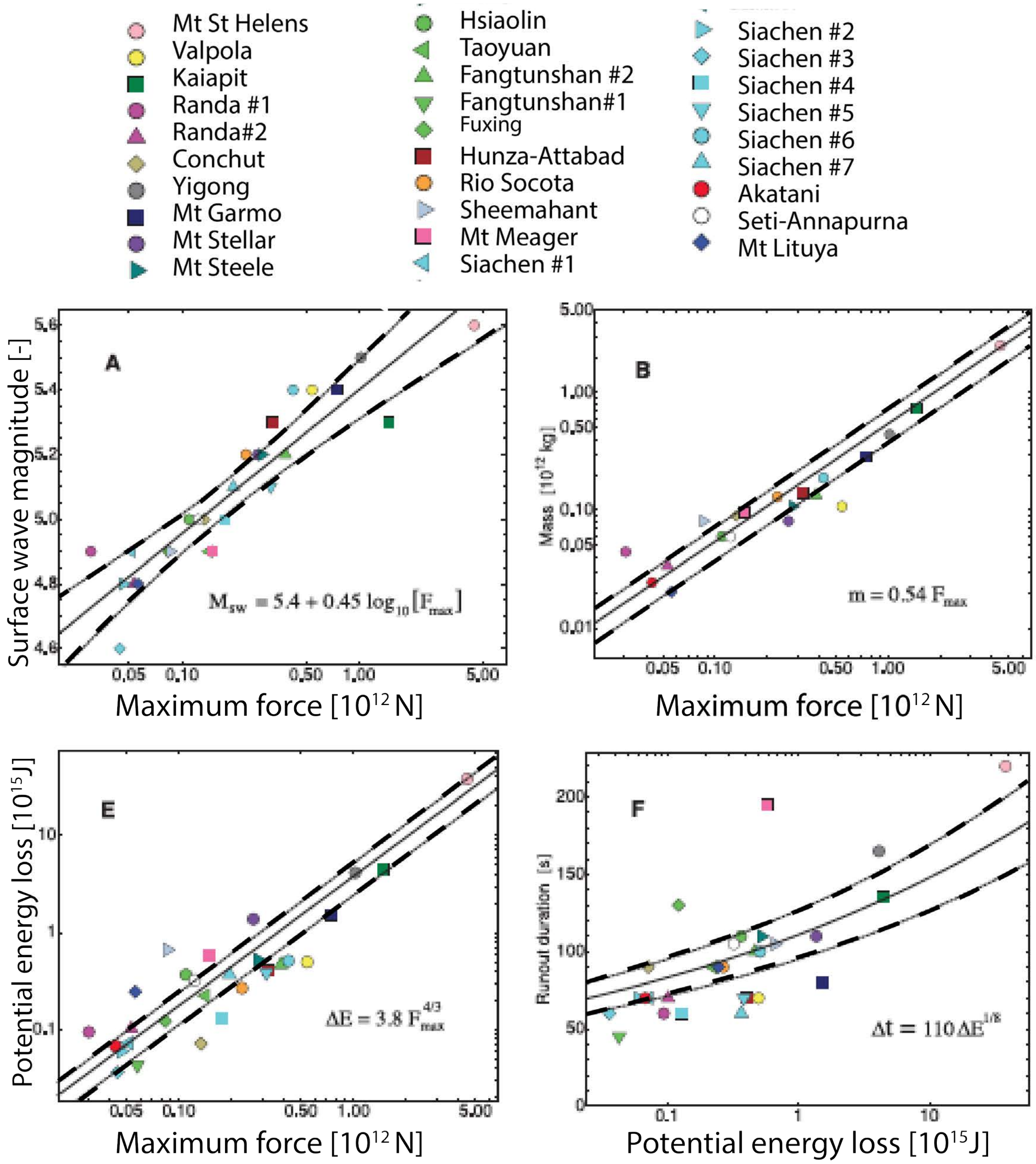


Figure 3.7. Relationships proposed by Ekström and Stark (2013) for force and energy generated by 29 historic landslides based on seismic traces: maximum force (F_{max}) versus A) long-period surface-wave magnitude, B) mass, and E) potential energy loss. F) Run-out duration versus potential energy loss. Best-fit lines are solid; dashed lines are 3 sigma limits. The Flims rockslide is three times larger than the largest landslide in the dataset (Mt. St. Helens 1980) implying that the latter would lie beyond the limits of these graphs.

Landslide interaction with its substrate

Many examples of substrate liquefaction induced by overriding landslides have been reported in the literature (Heuberger et al., 1984; Abele, 1994, 1997; Hungr and Evans, 2004; Hewitt et al., 2008; Prager et al., 2012; Dufresne et al., 2015). 'Splash

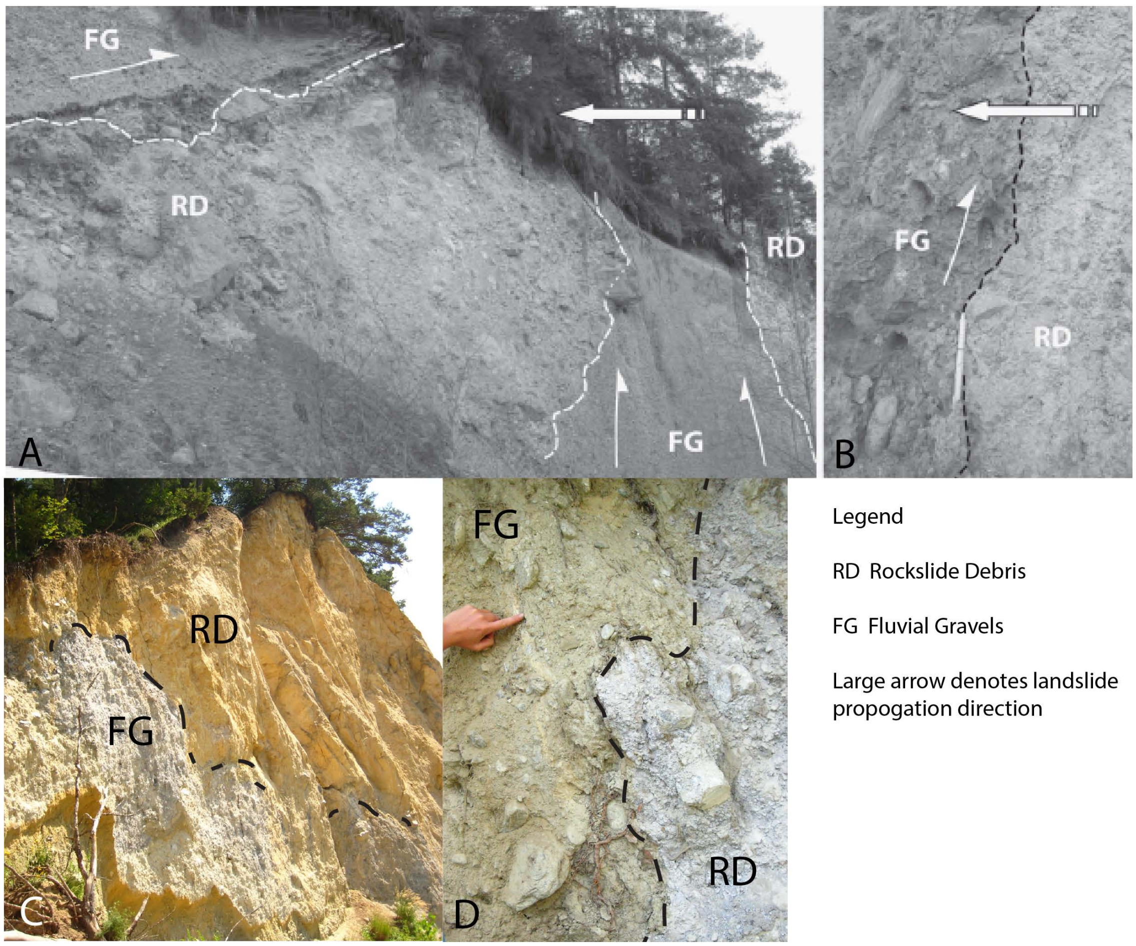


Figure 3.8. Liquefaction and deformation induced by the Tschirgant landslide, Tyrol, Austria. A) and B) Half arrows denote thrusting of fluvial gravel over rockslide debris and intrusion of fluvial gravel into the debris mass (Prager et al., 2012). C) and D) Dashed lines delineate contacts between rockslide debris and fluvial gravel.

zones' of fine-grained sediment beyond the margin of landslides have been described at Frank, Alberta (Cruden and Hungr, 1986), and in the eastern Fraser River valley, British Columbia (Orwin et al., 2004). At Tschirgant, in Tyrol, Austria, alluvial deposits derived from the valley floor were thrust over and injected into the base of a prehistoric rockslide mass (Figure 3.8; Prager et al., 2012; Dufresne et al., 2015). The contact between rockslide debris and alluvium is sharp and highly contorted, described as being "dynamically mingled with complex sedimentary structures" (Prager et al., 2012). These examples are similar to the complex contacts between rockslide debris and well-rounded gravels at Trin Station, Ruine Schiedberg, and Versam Gorge.

Liquefaction of slope material and subsequent entrainment by debris flows also have been hypothesized by Sassa (1988), Sassa and Lee (1996), and Sassa and Wang, (2005). These authors, and earlier Bhandari and Hutchinson (1971), argued that undrained loading of substrate materials is a mechanism for liquefaction. Undrained loading occurs when saturated materials experience a rapid increase in pore pressure due to loading without time for the pore water to escape.

The Bonaduz gravel differs from the above examples in that much, or nearly all, of it was derived from liquefaction beyond the margin of the Flims rockslide, and the liquefied sediment traveled up to 15 km or more beyond the margin of the rockslide. Nevertheless, the examples given above provide a basis for understanding the interaction between the Flims rockslide and the Bonaduz gravel.

3.1.4. Water waves generated by landslides

A possible secondary effect of the Flims rockslide is an impact displacement wave in hypothetical Lake Bonaduz. The impact may have not only liquefied valley-fill sediment, but also displaced water ahead of the Bonaduz mass flow.

Based on studies of large landslides into Lituya Bay and Disenchantment Bay, Alaska, Slingerland and Voight (1979) discussed four types of landslide-triggered displacement waves: oscillatory, transitional, solitary, and bore waves. Oscillatory waves are periodic in the direction of travel with water particles moving in a closed elliptical pattern. Solitary waves are single waves with a constant velocity, a dominantly translational motion, and low dispersion; the water surface is entirely above mean water level. Bore waves are forward-moving, steep, turbulent waves; the water level at and behind the wave front is the same (Slingerland and Voight 1979). Bore waves attenuate rapidly with distance traveled.

The most important factors that control the type of wave generated by a landslide are the velocity and thickness of the impacting mass and the water depth at the impact site. A minimum thickness of 350 m of Flims rockslide material impacted the Vorderrhein valley floor; this is the minimum thickness of debris lodged against the opposite valley wall. The minimum depth of Lake Bonaduz can be constrained by the height of the Tamins rockslide dam and the current elevation of Vorderrhein River. The spillway of the Tamins dam was likely about 675 m asl and the current elevation of Vorderrhein River at the impact site is 585 m asl, yielding a theoretical minimum water depth of about 90 m. The Flims rockslide is several orders of magnitude larger than the Alaska rockslides cited by Slingerland and Voight (1979). The velocity of the Flims rockslide is unknown, but almost certainly was very high, based on the internal fragmentation, fall height, and the volume of the failed rock mass. Based on the large size and velocity of the Flims rockslide and the relatively small body of water that it entered, the Flims rockslide probably created a bore type wave with a steep turbulent front that rapidly attenuated away from the impact site. A bore type wave is more likely than a solitary wave due to the large volume of Flims rockslide debris compared to the much smaller water volume in Lake Bonaduz (Slingerland and Voight, 1979).

Based on the examples given by Slingerland and Voight (1979), water waves reach much higher on nearby valley walls than the landslides themselves. In the case of the Flims rockslide, a wave, likely a bore-type wave, may have traveled in front of the Bonaduz mass flow both up the Hinterrhein valley and down the Alpenrhein valley. Both from field and laboratory evidence, Slingerland and Voight (1979) point out that reflection, refraction, and diffraction of these waves along their paths greatly reduce their heights and travel distances. A wave generated by the Flims rockslide would have reflected and diffracted both on the southern Vorderrhein valley wall and on entering the Hinterrhein valley.

The highest exposure of Bonaduz gravel is near the town of Thusis, 15 km from the toe of the Flims rockslide. Perhaps the wave reached this limit beyond the more viscous, sediment-rich Bonaduz mass flow. In this hypothetical scenario, this leading wave may have deposited the gravel at ~740 m asl near Thusis, which is 80 m higher than the typical exposures of Bonaduz gravel. This gravel lacks Pavoni pipes and the grading typical of classical Bonaduz gravel, implying a different transport or depositional mechanism. Lake Bonaduz may have extended far into the Hinterrhein valley, allowing wave propagation far into this reach (lake extent in Figure 2.38, wave production in Figure 2.39 and wave extent in Figure 2.43).

3.2. The Bonaduz mass flow

The Bonaduz gravel does not fit comfortably into existing mass movement classifications, which incorporate only slope-specific processes (Hungr et al., 2001; Table 3.1). These classifications are not applicable to the liquefaction and transport of huge masses of sediment on valley floors with little to no slope, much less opposing slopes.

As I have shown in my discussion of mass flow terminology and classifications, many terms have been applied to mass flows based on inferences and assumptions about dynamic processes that govern their behaviour. The key factors that serve to discriminate different flow types are flow rheology, particle concentrations, and flow path (Dasgupta, 2003; Figure 3.2). Unfortunately, it is difficult to infer these factors from geomorphic and sedimentological characteristics alone. Such is the case with the Bonaduz gravel.

In the next section, I discuss the flow type that the Bonaduz gravel most closely aligns with. Available information that constrains my interpretation includes the three-dimensional distribution of the Bonaduz gravel and its sedimentological characteristics, including lithology and sedimentary structures. Aspects that are not observable, but can be reasonably estimated or inferred, include the velocity and depth of the flow, water content, and the characteristics of the source sediments.

3.2.1. Classification of the Bonaduz mass flow

Key characteristics of unit

The widespread distribution and unusual sedimentological characteristics of the Bonaduz gravel demonstrate that it was emplaced by a mass flow. That this flow was sediment-charged and water-rich is shown by: 1) the relatively uniform elevation of the gravel surface, 2) the suspended lacustrine rip-up clasts, 3) the ubiquitous upward-fining of the unit, 4) its high silt content, 5) clasts that are consistently well rounded and not shattered, and 6) fluidized injections of gravel and diamicton high in Flims debris sheet. The distribution of the Bonaduz gravel shows that the flow moved as a valley-wide sheet unconfined by a channel and that it both overtopped and was deflected by obstructions such as the Tamins rockslide mass. The flow was sufficiently viscous to detach and transport tumas many kilometres from the Flims and Tamins rockslide deposits.

As I suggested previously, the Flims rockslide very likely entered Lake Bonaduz and displaced hundreds of thousands of cubic metres of water. The Bonaduz gravel filled the floor of the Lake Bonaduz basin with gravel mobilized from the upvalley fill.

Bonaduz gravel deposits near the margin of the Flims rockslide may have traveled less than 1 km, but similar deposits reached Thusis and traveled past Chur. The uppermost elevations of the deposit on the Bonaduz plain are consistently between 655 and 667 m asl, but the gravel reaches up to 743 m asl near Thusis. The geometry of the flow may have contributed to its extraordinary travel distance in the Hinterrhein valley. One lobe of the flow was forced through the 525-m-wide gorge between Rhäzüns and Rothenbrunnen, near the mouth of Hinterrhein River. This constriction may have maintained the high fluid pressures in the flow, much like a Venturi tube, jetting it up the valley.

Controls on particle settling

In this section, I explore physical controls on particle settling and grading in mass flows and how they apply to the Bonaduz flow. The Bonaduz mass flow: 1) was largely laminar; 2) was less viscous than typical channelized debris flows; 3) sustained movement over very long distances by maintaining high pore-fluid pressures; 4) moved at a high speed, perhaps >10 m/s; 5) was not driven by gravity (it flowed up the Hinterrhein Valley and thus must have maintained fluidity through a different process); 6) was either sufficiently erosive to incorporate multi-metre-length clasts of lacustrine sediments or the Flims rockslide impact broke-up lacustrine sediments and Bonaduz gravel entrained them; and 7) contained large amounts of interstitial water (Pavoni pipes are ubiquitous). Liquefaction and upward fluid flow are part of the explanation.

The maximum thickness of the flow, although unknown, is greater than 65 m, which is the maximum exposed thickness of Bonaduz gravel. The latter value, however, does not account for the large volume of interstitial water and the pore space between grains required for rapid flow. Based on literature on mass flow water content, the Bonaduz flow likely contained 35-70% water by volume (Iverson, 2005). Clasts within the Bonaduz gravel are not scratched, fractured, or broken, thus grain-to-grain contacts were minimal; the clasts presumably were supported by pore water. Therefore, if 1-1.6 km^3 of sediment were involved in the Bonaduz flow, as suggested by Abele (1997) and Kippel (2002), respectively, the flowing mass contained ~0.350-1.12 km^3 of water.

Additional questions about the Bonaduz flow come to mind. Did the flow entrain additional sediment as it moved downvalley? Was the liquefied body of sediment restricted to the valley floor directly impacted by the Flims rockslide, or did liquefaction and mobilization occur well beyond the margin of the rockslide?

Normal grading of the Bonaduz gravel was produced by rapid particle settling during flow, which is indicative of a hyperconcentrated flow with a moderate concentration of grains (Druitt, 1995; Major, 2003a; Pierson, 2005). As suggested by Sohn (1997) for hyperconcentrated flows in general, the base and leading edge of the Bonaduz mass flow may have had the rheology of a debris flow. Exposures of this hypothesized basal sheet are rare, but do occur at Barnaus and in the drainage ditch extending eastward from the Reichenau quarry onto the Tamins rockslide (Chapter 2). I hypothesize that this basal layer carried an overlying traction carpet (the Bonaduz gravel) and allowed particles to settle through that carpet based on density and size (Sohn, 1997; Vallance, 2005).

The term 'turbidity current' is not applicable to the Bonaduz flow because these flows are turbulent and turbulence would have suppressed particle-size sorting that is so characteristic of Bonaduz gravel. Turbulence would also have destroyed the silt rip-ups that are scattered through the deposit. Based on the literature reviewed earlier in this chapter, the general term 'sediment gravity flow' – a flow that, by definition, is driven by gravity – is not appropriate for the Bonaduz flow, which traveled against the slope up the Hinterrhein valley.

Flow slides involve loose granular material and are characteristic of certain topographic and geological environments. Most flow slides are subaqueous and typically occur at the fronts of marine or lacustrine deltas where sediments can have a loose, collapsive internal structure and high pore-water pressures (Hungr et al., 2001). Flow slides involve liquefaction at their source and are capable of flowing long distances (Hungr et al., 2001). Although it is not clear that flow slides would produce grading, this type of flow is similar to the Bonaduz mass flow in its ability to travel long distances on gentle slopes. Furthermore, like the Bonaduz flow, they are initiated by liquefaction.

3.2.2 Further observations focused on the Tamins landslide and nearby features

Tamins breach

The breach in the Tamins debris sheet through which the Alpenrhein River flows is about 115 m deep, 500 m wide, and 500 m long. Using the 'cut-and-fill tool' in Global Mapper, I calculated that the total volume of rockslide debris missing from the Tamins breach, as well as the exposed volumes of the eight tumas in the Domat-Ems area. My estimate of rockslide material missing from the breach is 22-40 x 10^6 m^3. The estimated volume of exposed tumas is considerably less – 8 ×10^6 m^3, but this estimate does not include the buried portions of the tumas, which lie below alluvium of the Alpenrhein valley. In addition, there are at least 13 tumas farther downvalley, in Felsberg and Chur, that I did not include in my analysis, thus the estimate of 8 x 10^6 m^3 is certainly too low. Furthermore, the breach may have widened or deepened during the 9600 years since the Bonaduz flow, notably during the outburst floods from Lake Ilanz. Given all these considerations, the volume of rockslide debris in the tumas in Domat/Ems, Felsberg, and Chur is consistent with a Tamins source.

An alternative hypothesis is that the Tamins breach formed before the Flims rockslide, and the tumas at Domat/Ems, Felsberg, and Chur are derived from the Flims rockslide deposit and were rafted through the breach by the Bonaduz mass flow. This hypothesis faces several problems. First, it is questionable whether tumas of the size of some of those at Domat/Ems could be rafted through the breach, as large as it is. Second, tumas of definitive Flims origin on the Bonaduz plain decrease in size to the east away from the margin of the landslide and towards the Tamins breach. Those nearest the breach are smaller than the largest tumas at Domat/Ems. Third, Crest' Aulta and the other ridge-like tumas just east of Ils Aults are clearly derived from the Tamins rockslide, and it seems reasonable that the Domat/Ems tumas are similarly sourced. Finally, tumas on the Bonaduz plain are lithologically more heterogeneous than those at Domat/Ems. The former include mica schist, metasandstone, and limestone debris, whereas the latter are exclusively limestone (Remenyik, 1959; Masera, 2013).

The lowermost stratigraphic units at the Barnaus section (Figure 2.27) probably record breaching of the Tamins rockslide dam and the Bonaduz mass flow. The lowest unit on the south side of the Alpenrhein at Barnaus extends to near or below river level (~568 m asl). On the north side, the basal unit overlies thin late Pleistocene sediments and bedrock at the most downstream exposure, ~2 m above river level. Although the basal units on the two sides of the river differ, both have properties of mass flow deposits (see Chapter 2). The unit on the south bank consists mainly of angular fragments of millimetre- to multiple-metre-size Helvetic limestone and some polylithic rounded stones set in a fine-grained matrix. The presence of a large block of Bonaduz gravel within this unit implies that the mass flow was contemporaneous with, or occurred soon after, the Bonaduz mass flow. The unit on the north bank at Barnaus contains angular to subangular striated blocks of Helvetic limestone, implying high emplacement energy. The likely source is the Tamins breach, <1.5 km upstream. I speculate that the Domat/Ems, Felsberg, and Chur tumas were transported on a flow comprising the basal sediment at Barnaus and overlying Bonaduz gravel.

Tumas

The debris sheet of the Tamins rockslide comprises a central, rectangular-shaped body (Ils Aults) that has been eroded by Alpenrhein River and is bordered by

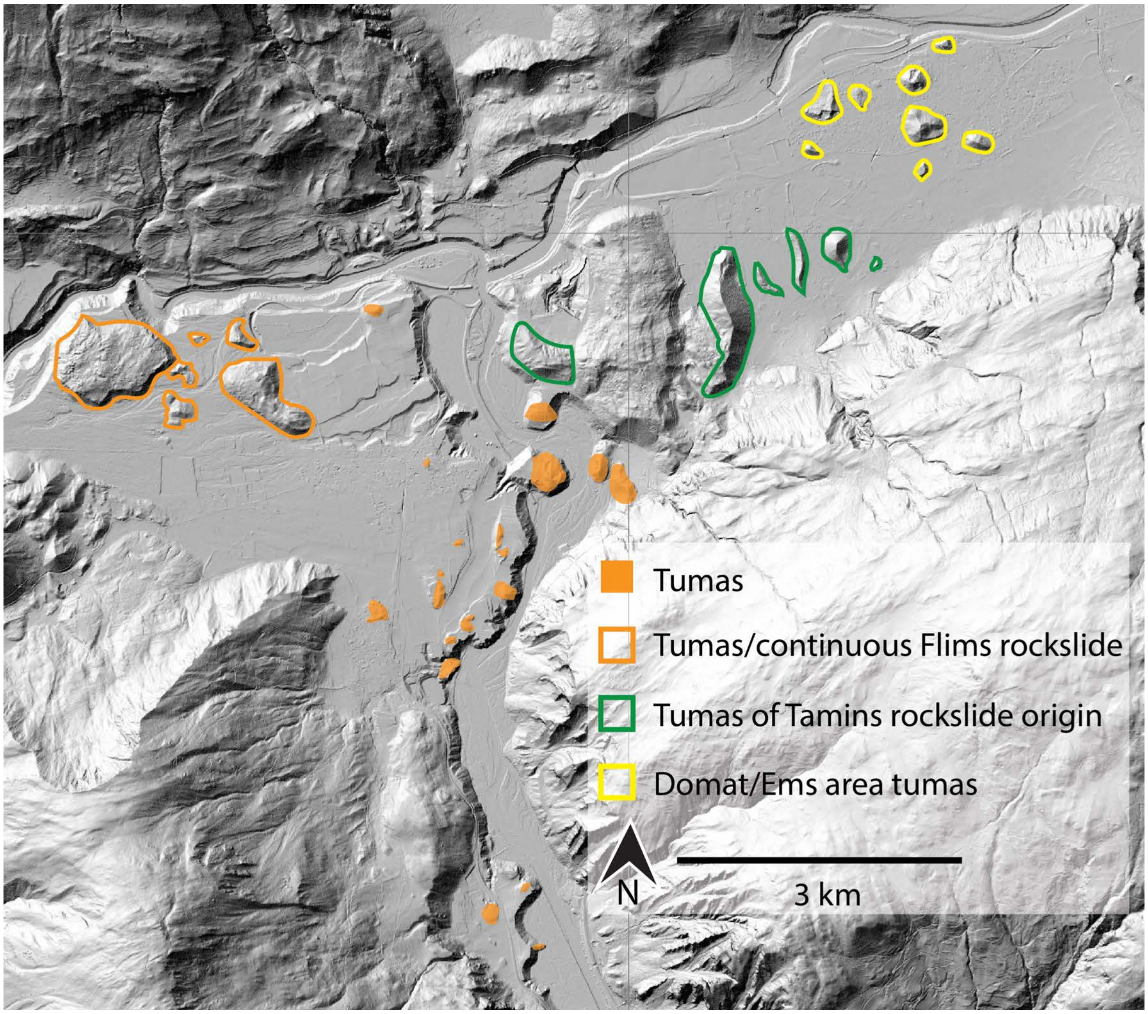


Figure 3.9. Tumas in the Vorderrhein-Hinterrhein confluence area.

steep flanking ridges of rockslide debris (tumas) to the north and south (Figure 3.9). The Domat/Ems cluster consists of eight hills, spread out over an area of 4 km^2, 1-2.5 km downvalley of Ils Aults. Tumas at Felsburg and Chur are much smaller and much farther downvalley, although they too consist of Helvetic limestone debris. Irrespective of size, all of the tumas are aligned along a trajectory extending downvalley from the breach in the Tamins rockslide deposit. I hypothesize that the Tamins breach formed when the lowest portion of the Tamins rockslide deposit detached on the Bonaduz mass flow and was carried downvalley. The eight large tumas became stranded in the Domat/Ems area and smaller tumas continued downvalley as far as Chur.

Bonaduz gravel laps high onto the Tamins rockslide deposit. An east-west cross-section across the deposit shows a 50-m difference in the elevation of the Bonaduz plain and the valley floor below the Tamins barrier (Figure 2.5 and 2.40). The fact that the Tamins debris sheet had such an effect on the Bonaduz mass flow suggests that the rockslide barrier was intact at the moment the Bonaduz flow encountered it.

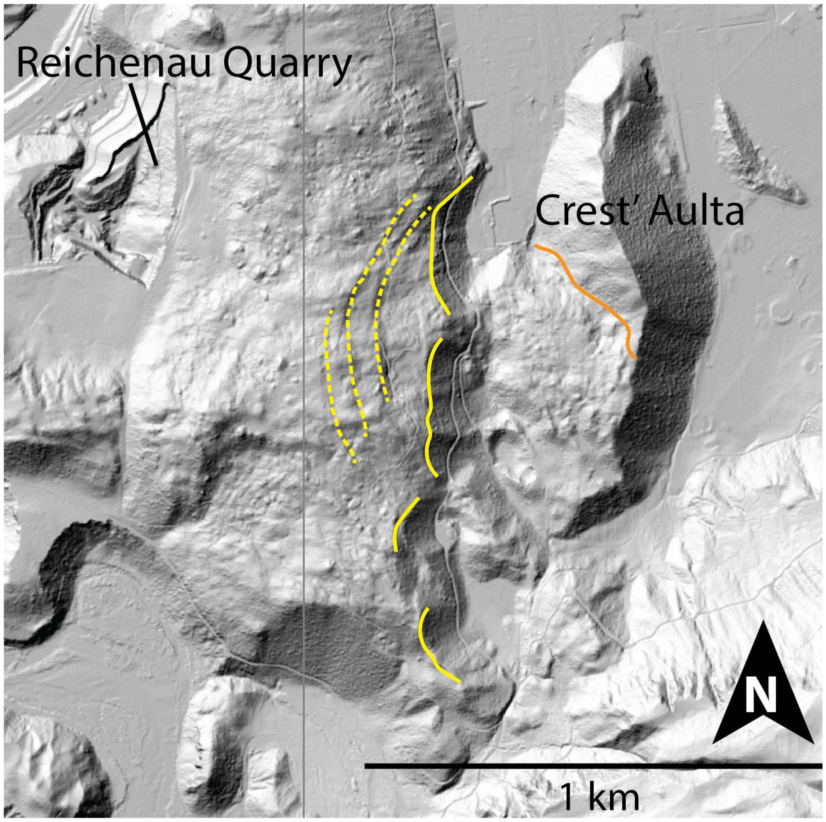


Figure 3.10. Hillshade LiDAR image of Ils Aults, the main body of Tamins rockslide. Solid yellow lines delineate the scalloped eastern edge of Ils Aults. Lineations on Ils Ault are shown by dashed yellow lines. The orange line delineates the boundary between irregular blocky terrain and the smooth steep slope of Crest' Aulta (see text for details).

The narrow steep-sided hills of Helvetic rockslide debris 300-1400 m east of the main body of the Tamins rockslide are tumas that I interpret to be derived from Ils Aults (Figures 2.40, 2.41 and 3.9). These tumas decrease in size to the east, away from Ils Aults. The east and northwest slopes of Crest' Aulta are very steep (up to 55°), but smooth. The southwest slope, however, is gentler, irregular, and blocky, resembling the

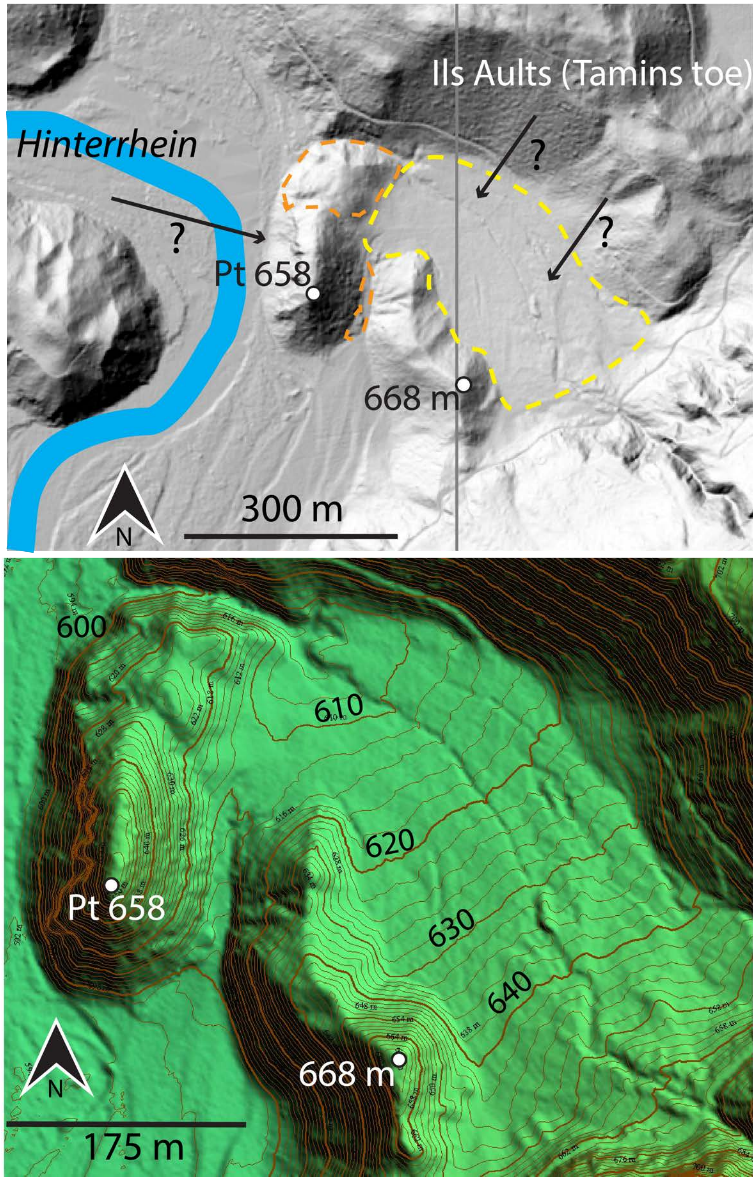


Figure 3.11. Hillshade image of Tuma 658 and the low-lying 'hole' to the east, delineated by the yellow dashed line. The orange dashed line denotes thick sand and gravelley sand. The 'hole' is partially filled with post-Bonaduz debris flow deposits. Its surface is about 40-50 m below the crests of the bordering tumas and >20 m above the level of the Hinterrhein River.

surface of Ils Aults itself (Figure 3.10). Large blocks of angular Helvetic limestone lie on this surface.

A question that arises from these observations is what process moved Crest' Aulta and the eastern smaller ridges? I hypothesize that the impact of the Flims rockslide on the Vorderrhein valley floor liquefied both nearby valley fill and fluvial and perhaps deltaic and lacustrine sediments beneath the Tamins barrier, partially disarticulating the Tamins rockslide mass. Another possible explanation is that the Tamins rockslide itself may have liquefied valley-fill deposits when it struck the valley floor.

Two tumas on the southwest side of Ils Aults, just east of the Hinterrhein River, are enigmatic (Figure 3.11). Did they detach and move away from the Tamins rockslide mass and, if so, did this happen during the Flims rockslide or the Tamins rockslide? Or are the tumas derived from the Flims rockslide? In either case, why is the low-lying, nearly closed depression bordered by the two tumas (Figure 3.11) not filled with Bonaduz gravel, as might be expected given that thick Bonaduz gravel underlies both the Bonaduz plain to the immediate west and a terrace just to the north? If the Bonaduz gravel did fill the depression, how was it subsequently removed? If, on the other hand, the ridges moved away from Ils Aults after the Bonaduz flow, what was the driving mechanism?

Exposures of one of the tumas (Tuma 658) along the Hinterrhein River bear on these questions (Figure 2.25 and Figure 2.26; pages 51-53). The exposures reveal a core of Helvetic limestone rockslide debris abutting very coarse diamicton with large blocks of cemented gravel.

The stratigraphic sections shown in Figure 2.25 and Figure 2.26 indicate the presence of fluvial gravel on top of sand beneath the north shoulder of Tuma 658. The gravel, however, is much higher than the floor of the depression to the south, which is problematic (Figure 3.11). It is difficult to explain these sediments unless one of two conditions is met: 1) similar sediments also filled the depression but have since been removed by erosion; 2) the depression did not exist when the fluvial gravel and underlying sand were deposited. If we accept the former explanation, it is odd that all traces of the former sediment infill in the depression have been removed by erosion. Could the small stream crossing the debris fan have evacuated all sediment from the depression? The latter case, however, is equally problematic in that it requires that

Tuma 668 and possibly Tuma 658 detached from Ils Aults and moved toward the Hinterrhein valley after the Bonaduz event. Sand and fluvial gravel are also exposed between Tuma 658 and Tuma 668 m directly to the southeast, although at a lower elevation than on the north flank of Tumas 658.

Backflow from Hinterrhein valley

A few hundred metres north of Tuma 658 is another tuma (Pt. 706 m on Reichenau SwissTopo quadrangle map). It abuts Ils Aults, but is oriented nearly orthogonal to it (Figure 3.12). Angular to subangular blocks of chlorite-mica schist are exposed on the west slope of the tuma, and I noted scattered blocks of limestone. Up to 60 cm of poorly sorted gravel with rounded pebbles and cobbles are present locally on the crest of the tuma. To the north and south, the tuma is bordered by terraces underlain by thick Bonaduz gravel. The north flank of Tuma 706 is incised by several steep gullies up to 5 m deep that head at the crest of the tuma and terminate on fans that extend out onto and cover the Bonaduz gravel terrace directly south of the Reichenau Quarry. No similar gullies or fans are present on the south flank of the tuma. The fans are underlain by angular to subangular blocks of limestone and rounded and subrounded heterolithic pebbles and cobbles. Sediments likely underlying the distal edge of the fans are exposed in the south wall of the Reichenau quarry. They comprise horizontally bedded sand with some climbing ripples and drape lamination, and minor fine gravel.

The gullies and fans must postdate the Bonaduz gravel, although likely not by much. Although the crest of the tuma is nearly 50 m above the level of the Bonaduz plain, it appears to have been overtopped by a strong flow that eroded the gullies and formed the fans at the base of the tuma to the north. Only the Bonaduz event is capable of doing this work. Tuma 706 itself may have been overtopped by the leading edge of the Bonaduz mass flow, given that there is rounded gravel at its crest. Alternatively, or perhaps in tandem, the tuma was overtopped by a displacement wave from Lake Bonaduz. The gullies, however, trend northward, counter to the direction of presumed overtopping by the Bonaduz mass flow. Another hypothesis, more consistent with this trend, is that the tuma was overtopped by backflow of the huge amounts of water that carried the Bonaduz mass flow up the Hinterrhein valley to Thusis. Large amounts of

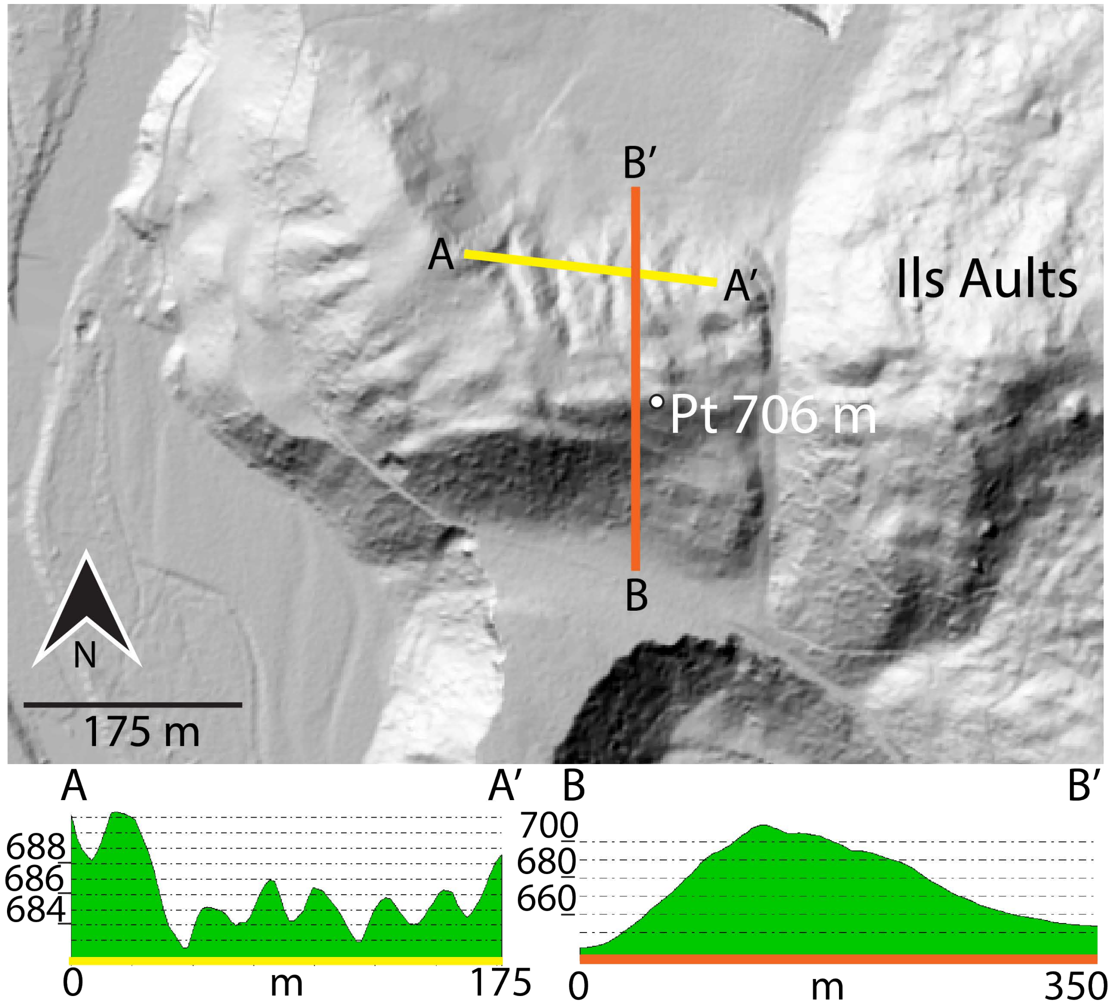


Figure 3.12. Hillshade LiDAR image of Hill 706 and topographic cross-sections across the gullies on its north side (yellow line) and across the tuma (orange line). Vertical exaggeration in both cross-sections = 6.

water would have moved up the Hinterrhein valley as part of the Bonaduz flow, and backflow would have been augmented by the waters in the south arm of Lake Bonaduz, normal base flow of the Hinterrhein River, and by dewatering of the Bonaduz gravel itself and normal base flow of the Hinterrhein River.

3.2.4. Future research

Many questions about the early Holocene events in the confluence area of the Hinterrhein and Vorderrhein river valleys remain, and these questions could be answered with additional research. The greatest limitation of my research is the sparse subsurface data available to me. The elevations of the base of the Flims and Tamins rockslide deposits are unknown, as is the base of the Bonaduz gravel. The thickness of Bonaduz gravel in the Hinterrhein valley is also unknown, and there is little information on the stratigraphy of the valley fill in the Alpenrhein valley east of Tamins. Several large tumas on the Bonaduz plain may be continuous at depth with the Flims rockslide deposit or, alternatively, may be disconnected and rootless. Seismic reflection, refraction, or resistivity surveys might reveal the base of the landslide deposits, Bonaduz gravel, and the tumas, and the boundaries between them. Acquisition and study of existing borehole data would further help delimit these boundaries. Collection and logging of new cores in critical areas, preferably using vibrasonic techniques, are also desirable.

Numerical simulations of the Flims rockslide and Bonaduz mass flow could also be enlightening, if complex. Sudden failure of 10 km^3 of rock, followed by its impact on the floor of a steep-walled valley filled with alluvium, outwash, and fine-grained lake sediments, which in turn induced liquefaction and a mass flow on a grand scale might lend itself to multi-faceted 3-D computer modeling. Some computer models, such as DAN-3D, rely on ‘turbulence’ as a variable. As I have shown in Chapter 3, we have a broad estimate of turbulence within the Bonaduz gravel mass flow, as well as ranges of estimates for viscosity, depth and water content. Relating the Bonaduz flow to other flows based on differences in scale, density, viscosity, water-sediment ratios, and velocity might provide an improved understanding of the event, even if they are constrained by approximations of the physical variables. The observational dataset provided by this and earlier studies could be the building block for such simulations.

Chapter 4. Conclusions

The Flims rockslide, located in the eastern Swiss Alps, is the largest postglacial landslide in Europe. About 9400 years ago, 10-12 km^3 of Cretaceous limestone detached from the north wall of the Vorderrhein River valley. The rock mass rapidly fragmented and, upon impact with the valley floor, liquefied approximately 1 km^3 of late-glacial and postglacial sediments. A slurry of liquefied sediment traveled down the Vorderrhein valley and 16 km up the valley of the Hinterrhein River, its largest tributary. Huge fragments of rockslide material (tumas), up to 280 m across and 55 m high, were rafted up to 11 km on the liquefied slurry. The deposit of this mass flow, referred to as the “Bonaduz gravel”, is locally >60 m thick and fines upward from cobble gravel at the base to sand at the top.

Chapter 1 of this thesis summarizes previous research on the Flims and Tamins rockslides, as well as the Bonaduz gravel mass flow. For much of the past 140 years, researchers debated the origin of the Bonaduz gravel unit. Some hypothesized that the gravel was fluvial, lacustrine, or glacial in origin. Building on the work of Abele (1997) and Kippel and Poschinger (2009), I conclude, with evidence presented in Chapter 2, that the Bonaduz gravel is the result of a mass flow of liquefied sediment.

I described stratigraphic sections and created geomorphic maps using field data and LiDAR-imagery. I present a hypothesized series of events in the early Holocene in the confluence area of the Vorderrhein and Hinterrhein rivers, where there is geomorphic and sedimentological evidence that the Tamins rockslide is older than the Flims rockslide.

I conclude that after the Bonaduz mass flow came to resst and dewatered, sands were deposited on top of the Bonaduz gravel before it was incised by the Hinterrhein River, stranding the Bonaduz gravel plain. Lake Ilanz outburst flood deposits overly both the Bonaduz gravel and stratified sands atop the Bonaduz gravel. The initial Lake Ilanz outburst flood traveled across the Bonaduz gravel, depositing an apron of diamicton and gravel. Later floods were confined, at lower elevations, within the present-day Vorderrhein River gorge.

I hypothesize that liquefaction induced by the Flims rockslide fragmented the Tamins rockslide mass and rafted tumas down the Vorderrhein valley. Based on (1) erosional terraces within the Tamins rockslide dam breach, (2) Lake Ilanz outburst flood sediments overlying the Bonaduz gravel, (3) rounded gravel on the surface of the Tamins rockslide deposit, and (4) the position and shape of the Domat/Ems area tumas, I conclude that the Tamins rockslide dam was breached or partially breached by the Flims rockslide and Bonaduz mass flow. The Bonaduz flow overrode Tamins rockslide debris and likely carried the Domat/Ems, Felsberg and Chur tumas with it.

I considered the applicability of existing landslide classifications to the Bonaduz mass flow event and hypothesize an emplacement mechanism for the Bonaduz gravel. The Bonaduz flow was likely a laminar hyperconcentrated flow with a high water content. It was able to move over low-angle slopes for long distances. However, the Bonaduz mass flow is orders of magnitude larger than all hyperconcentated flows described in the literature.

Ekström and Stark (2013) used seismic data from historic landslides to infer their maximum force, runout duration, and potential energy loss. They demonstrated that the landslide impacts create seismic energy. Extrapolating their data, I hypothesize that the Flims rockslide created an earthquake larger than **M**5.5 that strongly shook the Vorderrhein valley-fill sediments. The sudden impact of the Flims rockslide on the Vorderrhein valley floor sharply elevated pore pressures within the valley-fill sediments, creating an undrained load that liquefied the sediments over a large area..

References

Abele, G. (1974). Bergstürze in den Alpen: ihre Verbreitung, Morphologie und Folgeerscheinungen [Rockslides in the Alps: Their Distribution, Morphology and Sequence]. *Wissenschaftliche Alpenvereinshefte*, Munich (25), 1-243.

Abele, G. (1994). Large rockslides: Their causes and movement on internal sliding planes. *Mountain Research and Development,* 14(4), 315-320*.*

Abele, G. (1997). Rockslide movement supported by the mobilization of groundwater-saturated valley floor sediments. *Zeitscrift für Geomorphology*, 41(1), 1-20.

Allen, J. (1982). *Sedimentary Structures: Their Character and Physical Basis, Volume II*. Amsterdam: Elsevier.

Arbenz, P. and Staub, W. (1910). Die Wurzelregion der helvetischen Decken im Hinterrheingebiet und die Überschiebung der Bündnerschiefer südlich von Bonaduz [The root region of the Helvetic nappe in the Hinterrhein area and the thrust of the Bündnerschiefer south of Bonaduz]. Verhanglungen der Naturforschenden Gesellschaft in Zürich [Negotiations of the Natural History Society], 55, 23-62.

Bagnold, R. (1954). Experiments of a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. *Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences*, 225(A), 49-63.

Bagnold, R. (1956). The flow of cohesionless grains in fluids. *Proceedings of the Royal Society,* 249(964), 235-297.

Bagnold, R.A. (1966). *An Approach to the Sediment Transport Problem from General Physics*. U.S. Geological Survey Professional Paper 422-1.

Bezerra, F., Fonseca, V., Vita-Finzi, C., Lima-Filbo, F. and Saadi, A. (2005). Liquefaction-induced structures in Quaternary alluvial gravels and gravelly sediments, NE Brazil. *Engineering Geology*, 76, 191-208.

Bramanti, B. Thomas, M.G., Haak, W., Unterlaender, M., Jores, P., Tambets, K., Antanaitis-Jacobs, I., Haidle, M.N., Jankauskas, R., Kind, C-J., Lueth, F. Terberger, T., Hiller, J., Matsumura, S., Forster, P. and Burger, J. (2009). Genetic discontinuity between local hunter-gatherers and Central Europe's first farmers. *Science,* 326, 137-140.

Campbell, R., Varnes, D., Fleming, R., Hampton, M., Prior, D., Sangrey, D., Nichols, D. and Brabb, E. (1985). *Feasibility of a Nationwide Program for the Identificiation and Delineation of Hazards from Mud Flows and Other Landslides. Chapter A. Landslide Classification for Identification of Mud Flows and Other Landslides:* U.S. Geological Survey Open-file Report 85-276A.

Cao, Z., Youd, T., and Yuan, X. (2011). Gravelly soils that liquefied during 2008 Wenchuan, China earthquake, Ms=8.0. *Soil Dynamics and Earthquake Engineering*, 31, 1132-1143.

Caprez, J. (2008). *Das Flimser Berstruzereignis; 3D-Gelanderekonstruktionen und Volumenberchnungen milt Hilfe von GIS [The Flims Rockslide: 3D-Land Reconstruction and Volume with Help from GIS].* Diploma thesis, University of Zurich, Zurich, Switzerland.

Church, M.A. and Kellerhals, R. (1978). On the statistics of grain size variation along a gravel river. *Canadian Journal of Earth Sciences,* 15(7), 1151-1160.

Church, M.A., McLean, D.G. and Wolcott, J.F. (1987). River bed gravels: Sampling and analysis. In Thorne, C., Bathurst, J. and Hey, R. (eds.), *Sediment Transport in Gravel-Bed Rivers.* New York: John Wiley and Sons, 43-88.

Cronin, S., Lecointre, J.A., Palmer, A.S. and Neall, V.E. (2000). Transformation, internal stratification and depositional processes within a channelized, multi-peaked lahar flow, *New Zealand Journal of Geology and Geophysics*, 43(1), 117-128.

Cruden, D. and Hungr, O. (1986). The debris of the Frank Slide and theories of rockslide-avalanche mobility. *Canadian Journal of Earth Sciences*, 23(3), 425-432.

Cruden, D. and Varnes, D. (1996). Landslide types and processes. In Turner, A.K. and Schuster, R.L. (eds.), *Landslide Investigation and Mitigation*. U.S. National Research Council, Transportation Research Board Special Report 247, Washington, DC, 36-75.

Dasgupta, P. (2003). Sediment gravity flow - The conceptual problems. *Earth Science Reviews*, 62, 265-281.

Davies, T. (1986). Large debris flows: A macro-viscous phenomenon. *Acta Mechanica*, 63, 161-178.

Deplazes, G., Anselmatti, F. and Hajdas, I. (2007). Lake sediments deposited on the Flims rockslide mass: The key to date the largest mass movement of the Alps. *Terra Nova,* 19(4), 252-258.

Druitt, T. (1995). Settling behaviour of concentrated dispersions and other volcanological applications. *Journal of Volcanology and Geothermal Research,* 65, 27-39.

Dufresne, A., Prager, C. and Bösmeier, A. (2015). Insights into rock avalanche emplacement processes from detailed morpholithological studies of the Tschirgant deposit (Tyrol, Austria). *Earth Surface Processes and Landforms*. Doi: 10.1002/esp.3847.

Ekström, G. and Stark, C. (2013). Simple scaling of catastrophic landslide dynamics. *Science,* 339 (6126), 1416-1419.

Ferrer, M. and de Vallejo, L.I.G. (2011). *Geological Engineering.* CRC Press, Taylor & Francis Group, London, UK.

Fisher, R. (1983). Flow transformations in sediment gravity flows. *Geology*, 11, 273-274.

Funk, H., Oberhänsli, Pfiffner, O.A., Schmid, S. and Wildi, W. (1987). The evolution of the northern margin of Tethys in eastern Switzerland. *Episodes*, 10(2), 102-106.

Genevois, R. and Ghirotti, M. (2005). The 1963 Vaiont Landslide. *Giornale di Geologia Applicata*, 1, 41-52.

Gruber, S. and Haeberli, W. (2007). Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *Journal of Geophysical Research*, 112, F02S18.

Gruner, U. (2006). Klima in den Alpen – gibt es Zusammenhänge? [Climate in the Alps: are there relationships?] *Separatdruck aus Bulltein für angewandte Geologie, [Offprint of Bulletin of Applied Geology],* 11(2), 25-34.

Harrison, J.V. and Falcon, N.L. (1937). The Saidmarreh Landslip, south-west Iran. *The Geographical Journal*, 89(1), 42-47.

Heim, A. (1883). Der alte Bergsturz von Flims. [The old landslide of Flims]. *Jahrbuch des Schweizer Alpenclubs [Yearbook of the Swiss Alpine Club],* 18, 295-309.

Heim, A. (1932). *Bergsturz und Menschenleben [Landslides and Peoples Lives].* Zurich: Verhanglungen der Naturforschenden Gesellschaft 218.

Heim, A. (1932) *Landslides and Human Lives* (translated by Nigel Skermer). Bitech Publishing, Vancouver, BC. (Original work published 1932.)

Herwegh, M., Hürzeler, J., Pfiffner, O.A., Schmid, S., Abart, R. and Ebert, A. (2008). The Glarus thrust: Excursion guide and report of a field trip of the Swiss Tectonic Studies Group (Swiss Geological Society, 14-16.09.2006). *Swiss Journal of Geoscience*, 101, 323-340.

Heuberger, H., Masch, L., Preuss, E. and Schröcker, A. (1984). Quaternary landslides and rock fusion in central Nepal and in the Tyrolean Alps. *Mountain Research and Development,* 4(4), 345-362.

Hewitt, K., Clague, J. and Orwin, J. (2008). Legacies of catastrophic rock slop failures in mountain landscapes. *Earth Science Reviews*, 87, 1-38.

Hungr, O. (2005). Classification and terminology. In Jakob, M. and Hungr, M. (eds.), *Debris Flow Hazards and Related Phenomena*. Berlin, Heidelberg: Springer, 9-23.

Hungr , O. and Evans, S. (2004). Entrainment of debris in rock avalanches: An analysis of a long run-out mechanism. *Geological Society of America Bulletin*, 116(9/10), 1240-1252.

Hungr, O., Evans, S., Bovis, M. and Hutchinson, J. (2001). A review of the classification of landslides of the flow type. *Environmental and Engineering Geoscience*, 7(3), 221-238.

Hutchinson, J. and Bhandari, R. (1971). Undrained loading, a fundamental mechanism of mudflows and other mass movements. *Géotechnique*, 21(4), 353-358.

Iverson, R. (1997). The physics of debris flows. *Reviews of Geophysic*s, 35(3), 245-296.

Iverson, R. (2005). Debris flow mechanics*.* In Jakob, M. and Hungr, O. (eds.), *Debris-flow Hazards and Related Phenomena.* Berlin, Heidelberg: Springer, 105-134.

Ivy-Ochs, S., Kerschner, H., Kubik, P. and Schlüchter, C. (2006). Glacier response in the European Alps to Heinrich Event 1 cooling: The Gschnitz stadial. *Journal of Quaternary Science,* 21(2), 115-130.

Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W. and Schluchter, C. (2008). Chronology of the last glacial cycle in the European Alps. *Journal of Quaternary Science,* 23(6-7), 559-573.

Ivy-Ochs, S., Poschinger, A.V., Synal, H.-A. and Maisch, M. (2009). Surface exposure dating of the Flims landslide, Graubünden, Switzerland. *Geomorphology,* 103(1), 104-112.

Jakob, M. (2005). Debris-flow hazard analysis. In Jakob, M. and Hungr, M. (eds.), *Debris Flow Hazards and Related Phenomena*. Berlin, Heidelberg: Springer, 411-443.

Kanamori, H., Given, J. and Lay, T. (1984). Analysis of seismic body waves excited by the Mount St. Helens eruption of May 18, 1980. *Journal of Geophysical Research*, 89(B3), 1856-1866.

Kippel, Th. (2002). *Die Kiese in der Bonaduzer Fazies.* Diploma thesis, ETH Zurich, Zurich, Switzerland.

Lowe, D. (1976). Subaqueous liquefied and fluidized sediment flows and their deposits. *Sedimentology,* 23*,* 285-308.

Lowe, D. and Guy, M. (2000). Slurry-flow deposits in the Britannia Formation (Lower Cretaceous), North Sea: A new perspective on the turbidity current and debris flow problem. *Sedimentology*, 47, 31-70.

Major, J. (2003a). Hindered settling. In Middleton, V., Church, M., Coniglio, M., Hardie, L. and Longstaffe, F. (eds.), *Encyclopedia of Sediments and Sedimentary Rocks.* Dordrecht, Netherlands: Kluwer Academic, 358-360.

Major, J. (2003b). Slurry. In Middleton, V., Church, M., Coniglio, M., Hardie, L. and Longstaffe, F. (eds.), *Encyclopedia of Sediments and Sedimentary Rocks.* Dordrecht, Netherlands: Kluwer Academic, 674-675.

Masera, D. (2013). *Geomorphology and Geomatics for the Study of Landforms and Deposits Related to the Flims and Tamins Landslides (Rhein Valley, Switzerland).* Master's thesis, University of Torino, Torino, Italy.

Middleton, G. and Hampton, M. (1973). Sediment gravity flows: Mechanics of flow and deposition. In *Turbidites and Deep Water Sedimentation.* Society for Sedimentary Geology, Pacific Section, Short Course Notes, 38 pp.

Moretti, L., Allstadt, K., Mangney, A., Capdeville, Y., Stutzmann, E. and Bouchut, F. (2015). Numerical modeling of the Mount Meager landslide constrained by its force history derived from seismic data. *Journal of Geophysical Research - Solid Earth*, 120(4), 2579-2599.

Nabholz, W.K. (1954). Neue Beobachtungen im Bergsturzgebiet Südlich Reichenau-Tamins (Graubünden). [New observations in the landslide area south of Reichenau-Tamins (Graubünden)]. *Verhandlungen der Natuforschenden Gesellschaft in Basel*, 65(1), 67-81.

Nemec, W. and Steele, R.J. (1984). Alluvial and coastal conglomerates: Their significant features and some comments on gravelly mass-flow deposits. In Koster, E.H. and Steel, R.J. (eds.), *Sedimentology of Gravels and Conglomerates*. Canadian Society of Petroleum Geologists, Memoir 10, 1-31.

Oberholzer, J. (1933). *Geologie der Glarneralpen [Geology of the Glarner Alps], Beitraege zur geologischen Karte der Schweiz. [Contributions to the Geological Map of Switzerland],* Swiss Geological Commission, Neue Folge [New Episode] 28.

Obermeier, S. (1989). *The New Madrid earthquakes – An Engineering-geologic Interpretation of Relict Liquefaction Features*. U.S. Geological Survey Professional Paper 1336-B, 1-114.

Obermeier, S., Olson, S. and Green, R. (2005). Field occurrences of liquefaction-induced features: A primer for engineering geologic analysis of paleoseismic shaking. *Engineering Geology,* 76, 209-234.

Orwin, J., Clague, J. and Gerath, R. (2004). The Cheam rock avalanche, Fraser Valley, British Columbia, Canada. *Landslides*, 4, 289-298.

Pavoni, N. (1968). Uber die Entstehung der Kiesmassen in Bergsturzgebiet von Bonaduz-Reichenau (Graubünden). *Eclogae Geologicae Helvetiae*, 61(2), 494-500.

Persaud, M. and Pfiffner, O.A. (2004). Active deformation in the eastern Swiss Alps: Post-glacial faults, seismicity and surface uplift. *Tectonophysics*, 385, 59-84.

Pfiffner, O.A. (1993). The structure of the Helvetic nappes and its relation to the mechanical stratigraphy. *Journal of Structural Geology*, 15(3-5), 511-521.

Pfiffner, O.A., Lehner, P. Heitzmann, P., Mueller, S. and Steck, A. (eds). (1997). *Deep Structure of the Swiss Alps: Results from NRP 20.* Basel, Switzerland: Birkhauser.

Pfiffner, O.A., Schlunegger, F. and Buiter, S.J.H. (2002). The Swiss Alps and their peripheral foreland basin: Stratigraphic response to deep crustal processes. *Tectonics,* 21(2), 1-15.

Pierson, T. (2005). Hyperconcentrated flow – Transitional process between water flow and debris flow. In Jakob, M. and Hungr, M. (eds.), *Debris Flow Hazards and Related Phenomena*. Berlin, Heidelberg: Springer, 159-203.

Pollet, N. (2004). Significance of source areas and deposits in the analysis of high-speed rock movements: Alpine examples*. Bulletin of Engineering Geology and the Environment*, 63, 353-365.

Pollet, N. and Schneider, J.-L.M. (2004). Dynamic disintegration processes accompanying transport of the Holocene Flims sturzstrom (Swiss Alps). *Earth and Planetary Science Letters,* 221, 433-448.

Pollet, N., Cojean, R., Couture, R., Schneider, J. -L., Strom, A.L., Voirin, C. and Wassmer, P. (2005). A slab-on-slab model for the Flims rockslide (Swiss Alps). *Canadian Geotechnical Journal*, 42, 587-600.

Poschinger, A.v. (2006). The stability of the Flims rockslide dam. *Italian Journal of Engineering Geology and Environment, Special Issue*, 1, 87-90.

Poschinger, A.v. and Haas, U. (1997). Der Flimser Bergsturz doch ein Warmzeitliches Ereignis? [The Flims Landslide, after all a warm-temporal event?] *Bulletin for Applied Geology*, 2(1), 35.

Poschinger A.v. and Kippel, Th. (2009). Alluvial deposits liquefied by the Flims rockslide. *Geomorphology,* 103(1), 50-56.

Poschinger, A.v. and Ruegg, T. (2012). Die Churer Tomahügel, ein besonderes Zeugnis der Landschaftsgenese [The Chur toma hills, a special evidence of the landscape genesis]. *Jahresbericht Naturforschung Gesellschaft Graubünden [Annual Report of the Nature Research Society of Graubünden]*, 117, 93-100.

Poschinger, A.v., Wassmer, P. and Maisch, M. (2006). The Flims Rockslide; History of interpretation and new insights. In Evans, S., Scarascia Mugnozza, G., Strom, G. and Hermanns, R. (eds.), *Landslides from Massive Rock Slope Failure.* NATO Science Series IV, Earth and Environmental Sciences IV, 49, 329-356.

Postma, G. (1986). Classification for sediment gravity-flow deposits based on flow conditions during sedimentation. *Geology*, 114, 291-294.

Prager, C., Zangerl, C. and Kerschner, H. (2012). Sedimentology and mechanics of major rock avalanches: Implications from (pre-) historic Sturzstrom deposits (Tyrolean Alps, Austria). In Eberhardt, E., Froese, C., Turner, K. and Leroueil, S. (eds.), *Landslides and Engineered Slopes: Protecting Society through Improved Understanding,* Proceedings of the 11th International Symposium on Landslides, Banff, AB. Boca Raton, FL: CRC Press, 895-900.

Preusser, F., Graf, H.R., Keller, O., Krayss, E. and Schlüchter, C. (2011). Quaternary glaciation history of northern Switzerland. *Quaternary Science Journal,* 60(2-3), 282-305.

Remenyik, T. (1959). Geologische Untersuchungen der Bergsturzlandschaft zwischen Chur und Rodels [Geological investigations in the landslide area between Chur and Rodels]. *Eclogae Geologicae Helvetiae*, 52(1), 177-235.

Roberts, N. and Evans, S. (2013). The gigantic Seymareh (Saidmarreh) rock avalanche, Zagros Fold-Thrust Belt Iran. *Journal of the Geological Society, London*, 170, 685-700.

Sassa, K. (1988). Special lecture: Geotechnical model of the motion of landslides. In Bonnard, A. (ed.), *Proceedings of the 5th International Symposium on Landslides, Vol. 1, Landslides.* Rotterdam, Netherlands: A.A. Balkema, 37-55.

Sassa, J. and Lee, K. (1996). A study on the apparent friction angle mobilized during the undrained loading in long run-out landslides. *Bulletin of Disaster Prevention Resource Institute*, Kyoto University, 45(4), no. 393.

Sassa, K. and Wang, G. (2005). Mechanism of landslide-triggered debris flows: Liquefaction phenomena due to the undrained loading of torrent deposits. In Jakob, M. and Hungr, O (eds.), *Debris-flow Hazards and Related Phenomena.* Heidelberg: Springer, 82-104.

Scheller, E. (1970). Geophysikalisch Untersuchungen zum Problem des Taminser Bergsturzes (Dissertation Abstract). *Eidgenossischen Techniscehn Hochschule Zurich,* #4560.

Schneider, J-L., Pollet, N., Chapron, E., Wessels, M. and Wassmer, P. (2004). Signature of Rhine Valley sturzstrom dam failures in Holocene sediments of Lake Constance, Germany. *Sedimentary Geology,* 169, 75-91.

Schneider, J-L., Wassmer, P. and Ledésert, B. (1999). La fabrique interne des depots du sturzstrom de Flims (Alpes suisses): Caractierstiques et implications sur les mecanismes de transport [The fabric of the sturzstrom of Flims (Swiss Alps): Characteristics and implications on the transport mechanisms]. *Earth and Planetary Sciences,* 328(9), 607-613.

Selby, M.J. (1993). *Hillslope Processes and Materials.* Oxford: Oxford University Press.

Shreve, R. (1959). *Geology and Mechanics of the Blackhawk Landslide, Lucerne Valley, California*. Ph.D. thesis, California Institute of Technology, Pasadena, CA.

Slingerland, R. and Voight, B. (1979). Occurrences, properties, and predictive models of landslide-generated water waves. In Voight, B. (ed.), *Developments in Geotechnical Engineering 14B: Rockslides and Avalanches.* Amsterdam: Elsevier Publishing, 317-400.

Sohn, Y. (1997). On traction-carpet sedimentation. *Journal of Sedimentary Research*, 67(3), 502-509.

SwissTOPO, Federal Office of Topography, Swiss Confederation, [http://www.swisstopo.admin.ch/internet/swisstopo/en/home/products/height/swissALTI3D.html]. Accessed September 23, 2015.

Terberger, T. and Street, M. (2002). Hiatus or continuity? New results for the question of pleniglacial settlement in Central Europe. *Antiquity*, 76, 691-698.

Uehlinger, U., Wantzen, K., Leuven, R. and Arndt, H. (2009). The Rhine River Basin. In Tockner, K., Uehlinger, U. and Robinson, C. (eds.), *Rivers of Europe.* London: Academic Press, 199-245.

Vallance, J. (2005). Volcanic debris flows. In Jakob, M. and Hungr, M. (eds.), *Debris Flow Hazards and Related Phenomena*. Berlin, Heidelberg: Springer, 247-274.

Varnes, D.J. (1978). Slope movement types and processes. In Schuster, R. and Krizek, R. (eds.), *Landslides: Analysis and Control.* U.S. National Academy of Sciences, Transportation and Road Research Board, Special Report 176, 11-33.

Wentworth, C. (1922). A scale of grade and class terms for clastic sediments. *The Journal of Geology*, 30(5), 377-392.

Yegian, M., Ghargraman, V. and Harutinunyan, R. (1994). Liquefaction and embankment failure case histories, 1988 Armenia Earthquake. *ASCE Journal of Geotechnical Engineering,* 120(3), 581-596.

Appendix A.

Field sites

The following figures include most of my field sites. I also made observations between sites, however these figures only show all sites mentioned in the text and used to make the geomorphic map.

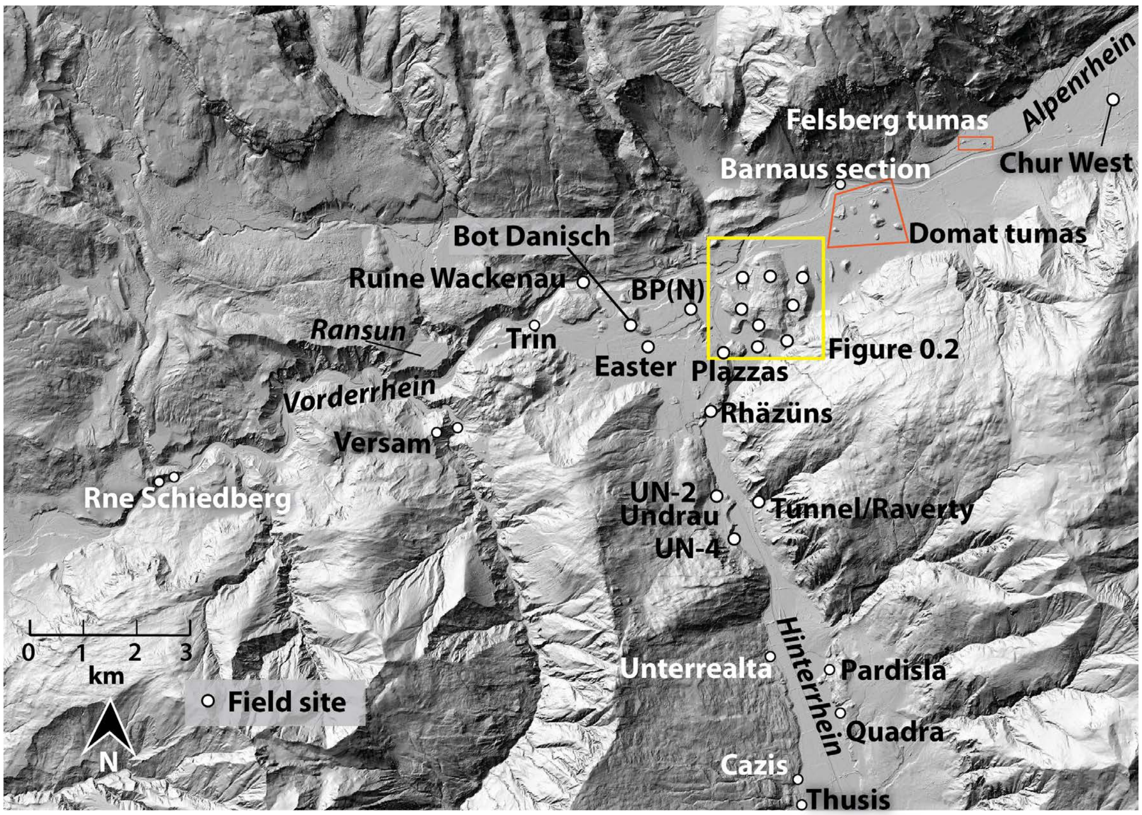


Figure A.1 Field site locations.

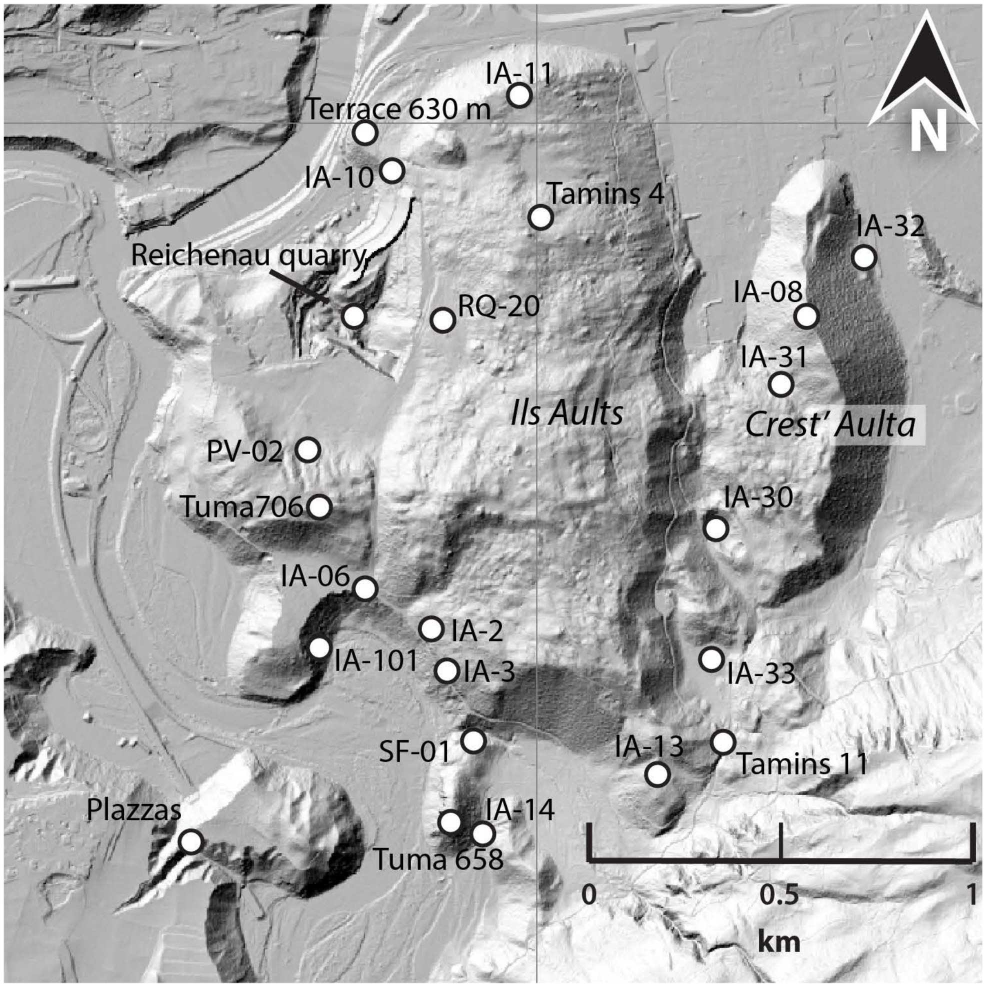


Figure A.2 Field sites in and around Ils Aults.

Particle-size data

I used ASTM guidelines D 2217-85, D 421-85, and D 422-63 to perform wet-sieve and hydrometer analyses of samples in the HydroGeoLab of the Department of Earth Sciences at the University of Torino.

A limitation in sampling gravels for particle-size analysis is taking a large enough sample to accurately characterize the sediment (Church and Kellerhals, 1978; Church et al., 1987). The samples were as large as I could reasonably transport; the largest samples were those with the largest clasts. Commonly, samples of gravel were >2500 g and up to 5000 g of the total weight of the sample. Church et al. (1987) suggest that the largest single particle in a sample should not exceed 0.1% (and 1% in very large clast samples). I did not achieve this standard in samples with large clasts, however the data provided useful information on proportions of fine gravel, sand, and silt in the samples. I would not, however, be able to use these data for modeling purposes.

Table A.1. Locations and description of particle-size samples.

Sample site and number	Elevation (m asl)	Description
BA-10-01	572	Matrix material from lowermost unit, north bank of Alpenrhein at Barnaus
UN-04-01	624	Bonaduz gravel, Undrau
UN-04-02	652	Silt clast within typical Bonaduz gravel, Undrau
BP(N)-1	628	Bonaduz gravel, on east edge of Bonaduz plain
P3-1	655	Bonaduz gravel, Pardisla quarry
SB-03	710	Cobble gravel below Bonaduz gravel near vertical contact with Flims rockslide debris, Ruine Schiedberg east
SB-04	712	Bonaduz gravel near contact with Flims rockslide debris, Ruine Schiedberg east
RS-01-1A	738	Bonaduz gravel near upper contact of Bonaduz gravel with overlying diamicton at Ruine Schiedberg
RS-01-1B	728	Chaotic diamicton 10 m below Bonaduz gravel at Ruine Schiedberg
TD-02-01	627	Bonaduz gravel, Trin-Digg
RQ-20	625	Tongue of gravel along east wall of Reichenau quarry.

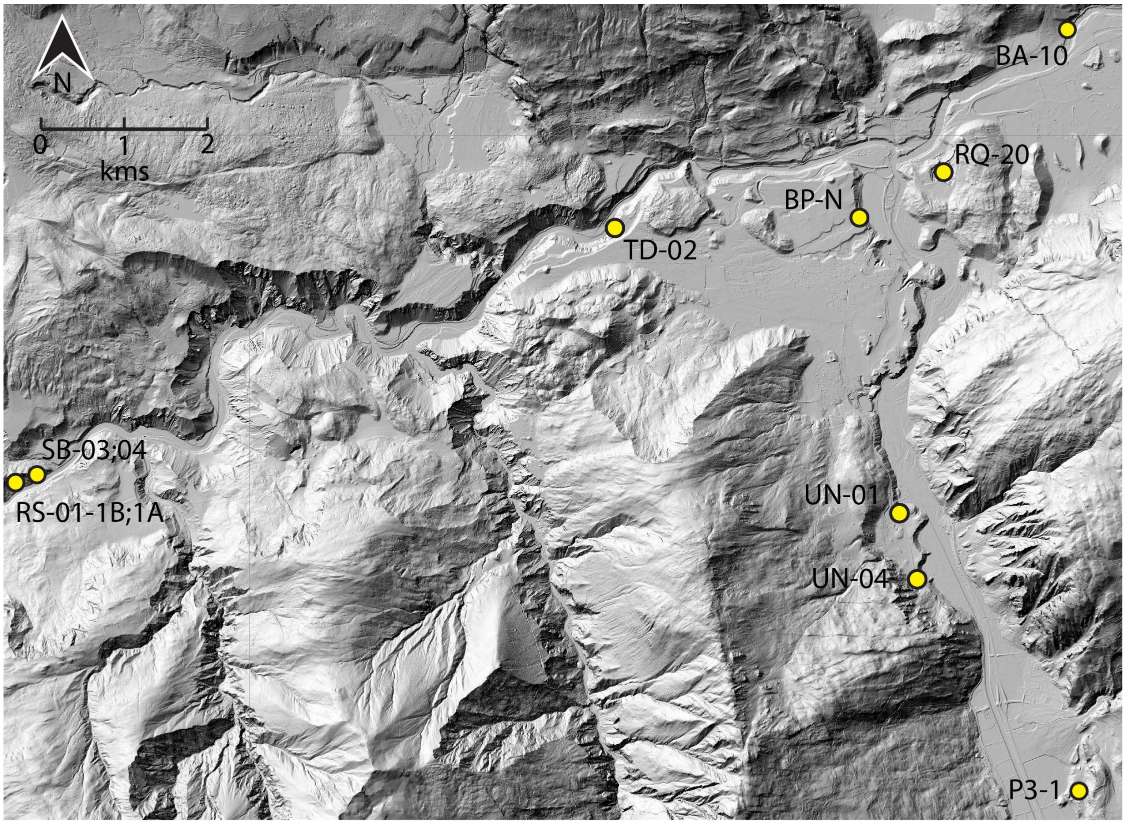


Figure A.3 Locations of sites at which particle-size samples were collected.

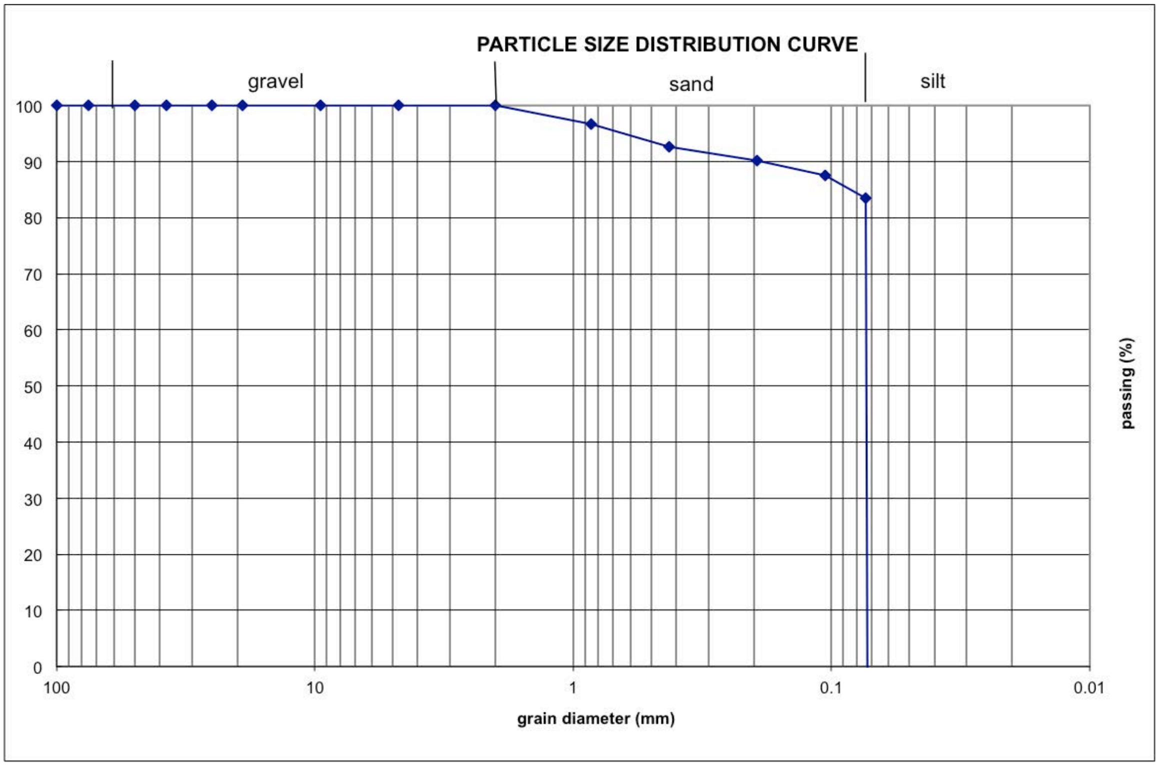


Figure A.4 Cumulative particle-size curve for sample BA-10-01.

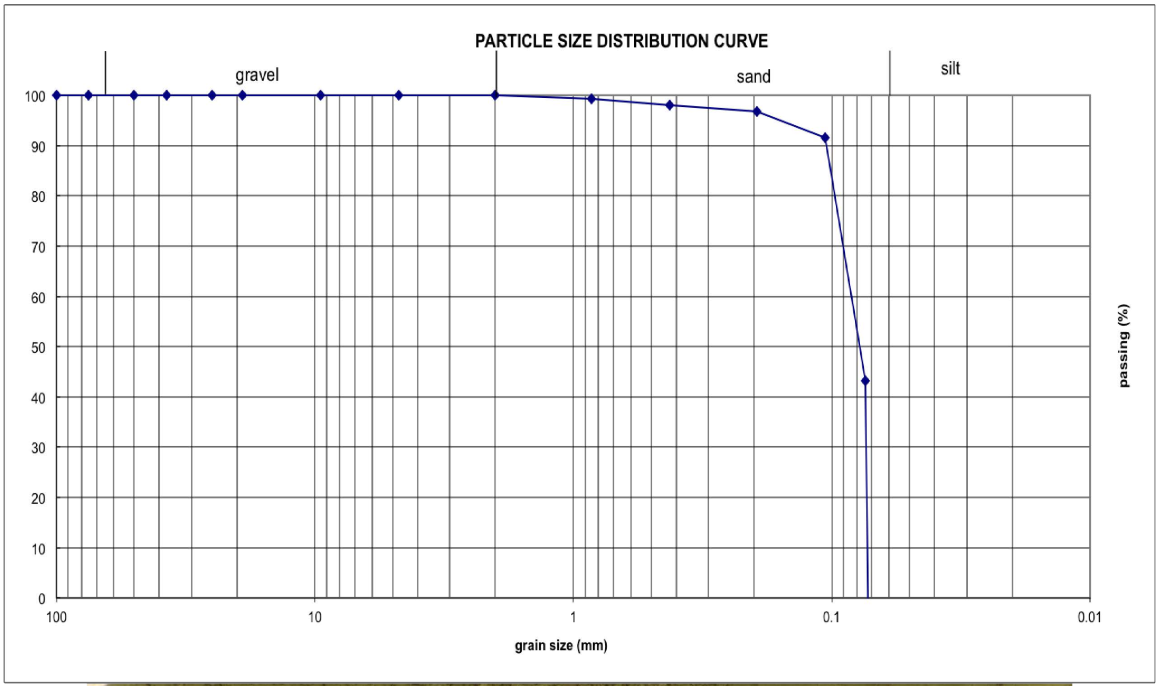
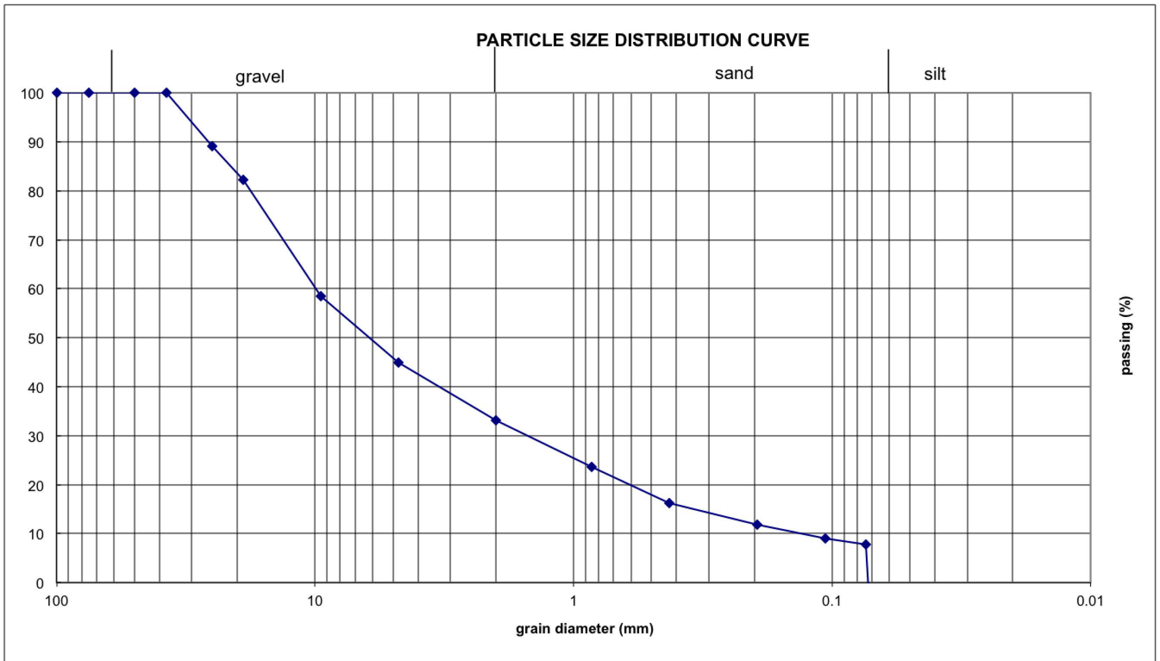


Figure A.5 Cumulative particle-size curve for sample UN-04-02. Photo shows a deformed silt clast within typical Bonaduz gravel at Undrau.



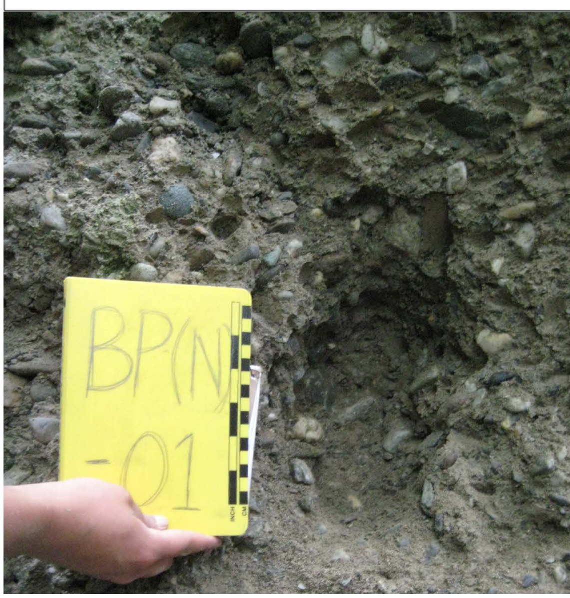


Figure A.6. Cumulative particle-size curve for sample BP(N)-01. The sample was colllected from the base of typical Bonaduz gravel, exposed at the eastern edge of the Bonaduz plain near the confluence of the Hinterrhein and Vorderrhein rivers.

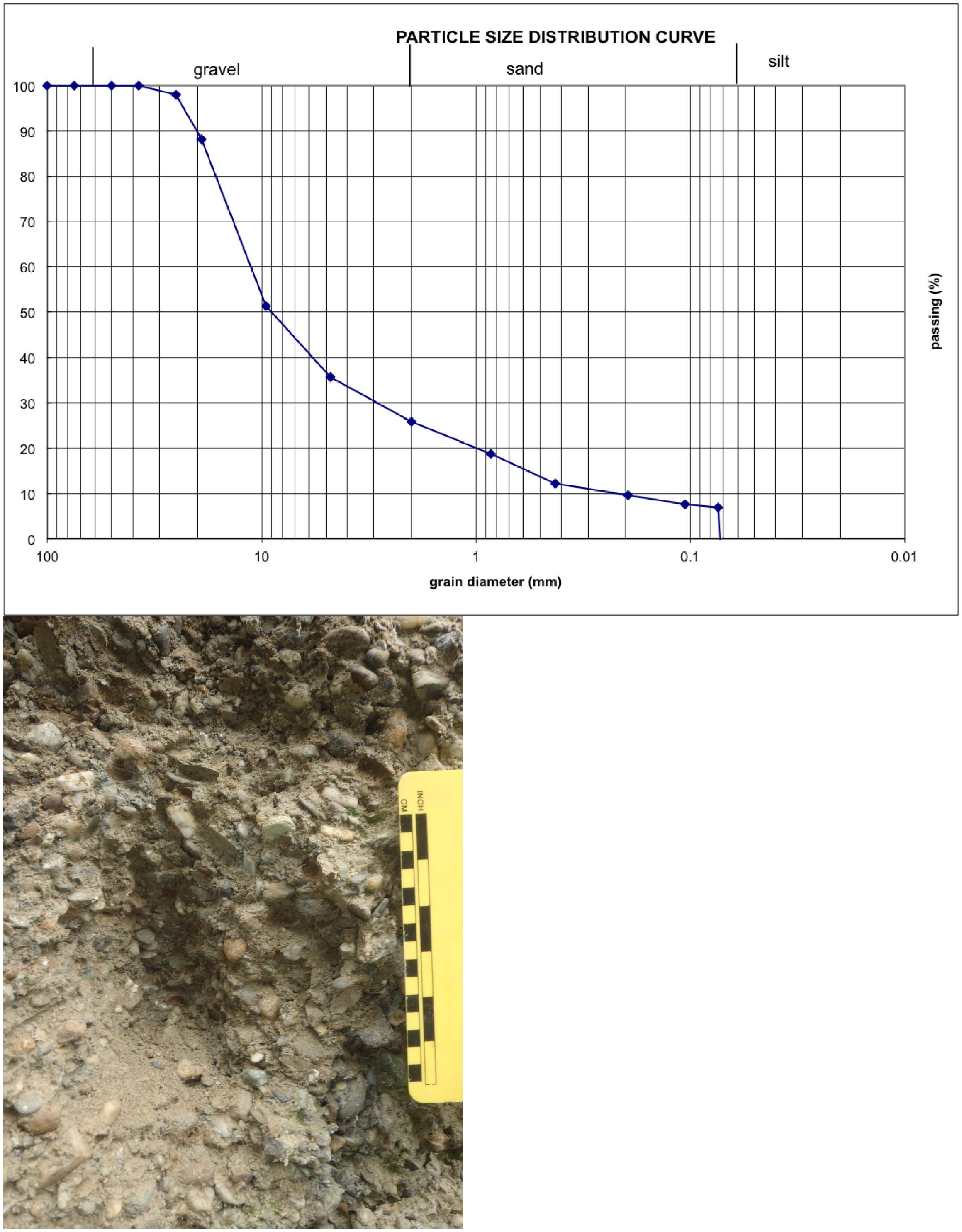


Figure A.7. Cumulative particle-size curve for sample UN-01-01. The sample was collected from typical Bonaduz gravel near the large tuma of mica schist in Undrau.

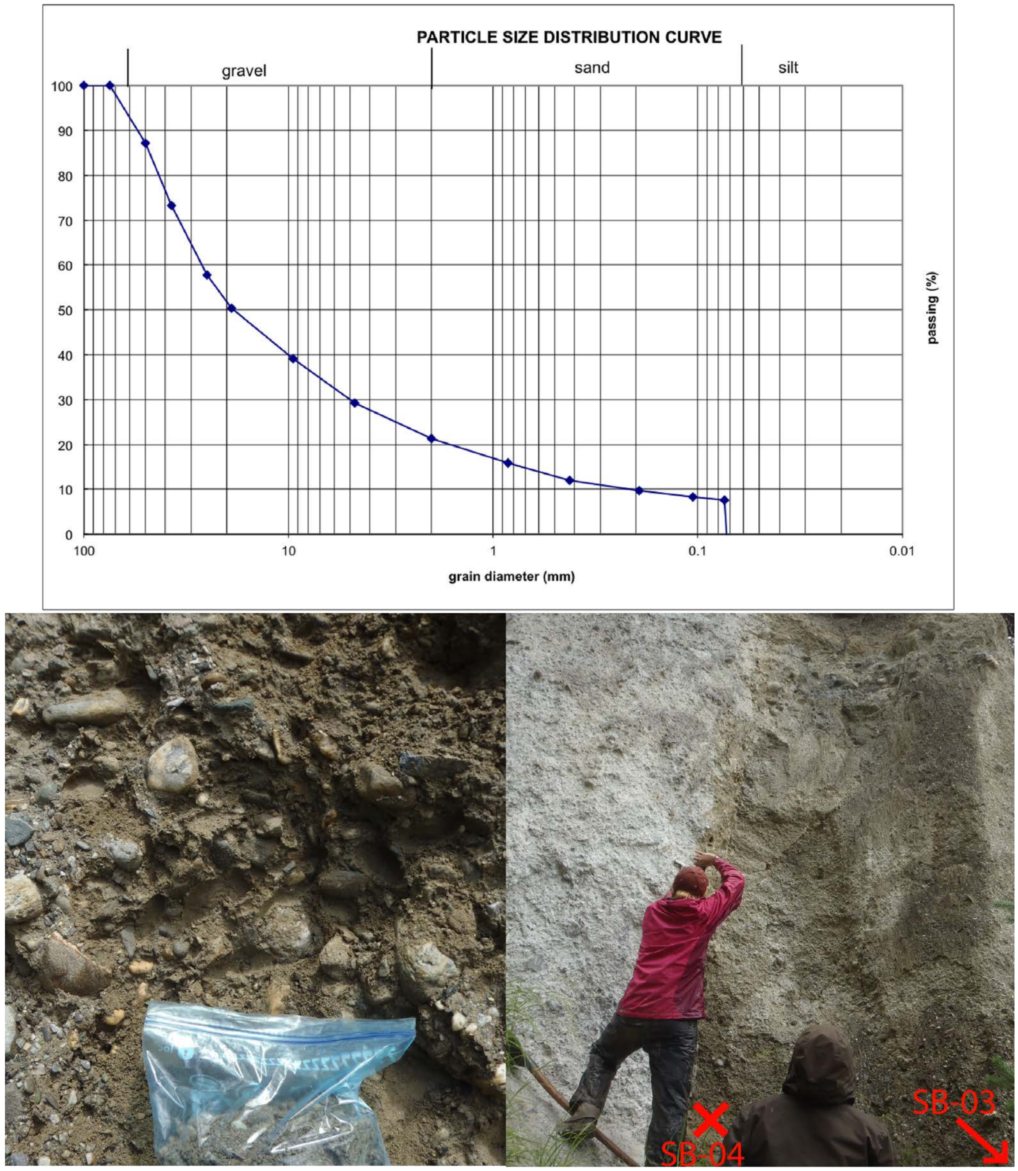


Figure A.8. Cumulative particle-size curve for sample SB-03. The sample was collected from the lowest exposure of typical Bonaduz gravel near a vertical contact between rockslide debris and Bonaduz gravel. This sample contained chaotic cobbles, likely larger than can be represented through standard particle-size analysis. However, the curve does illustrate the distribution of pebble- and finer-size sediment.

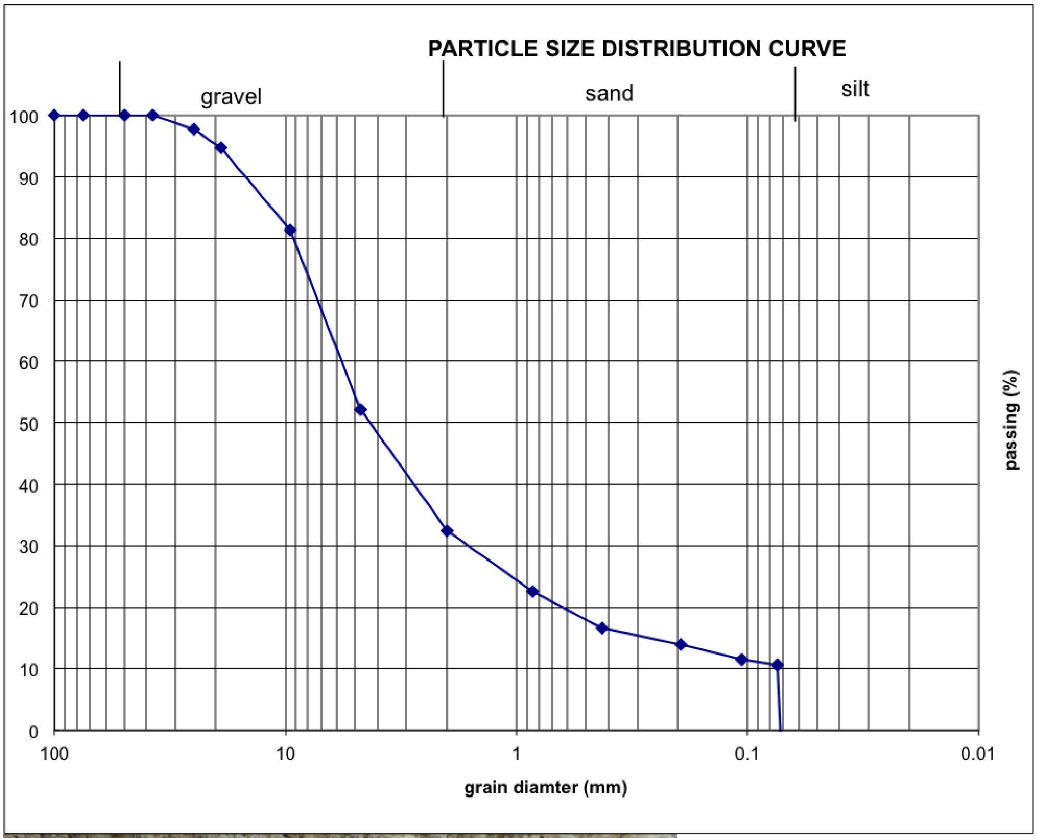


Figure A.9. Cumulative particle-size curve for sample SB-04. The sample was collected from Bonaduz gravel within 0.5 m of the vertical contact between rockslide debris and typical Bonaduz gravel (see Figure A.8).

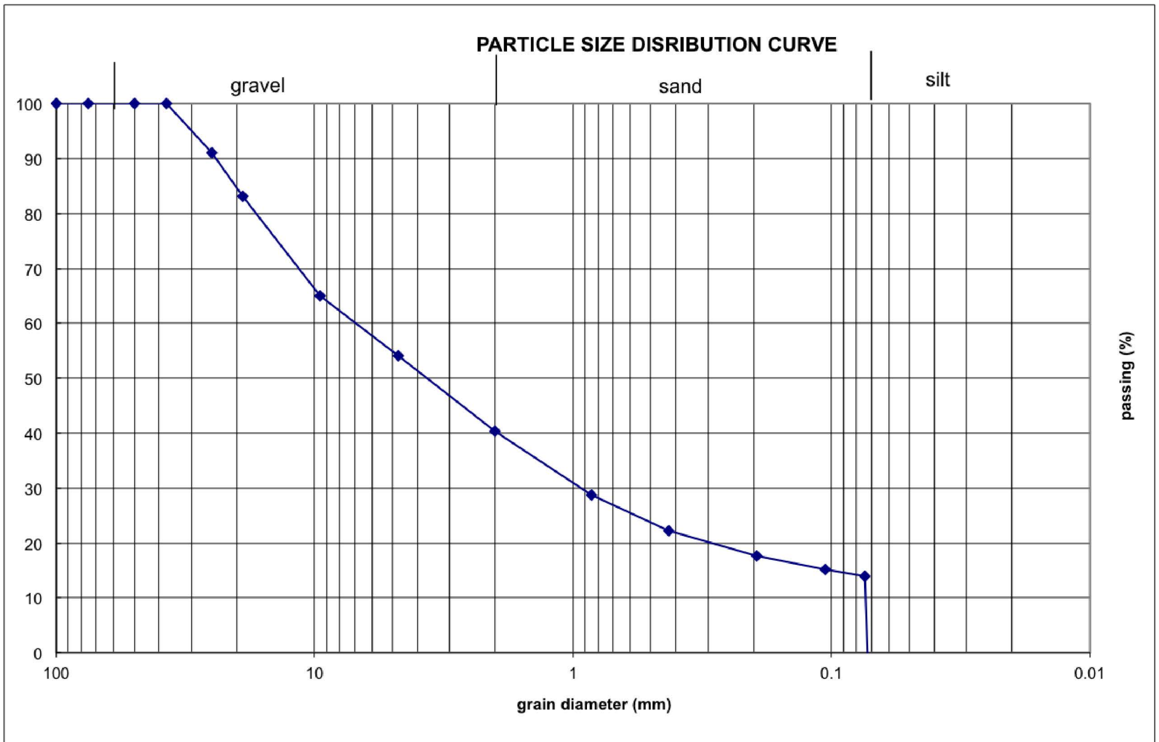


Figure A.10. Cumulative particle-size curve for sample RS-01-1A. The sample was collected from chaotic cobble gravel below typical Bonaduz gravel.

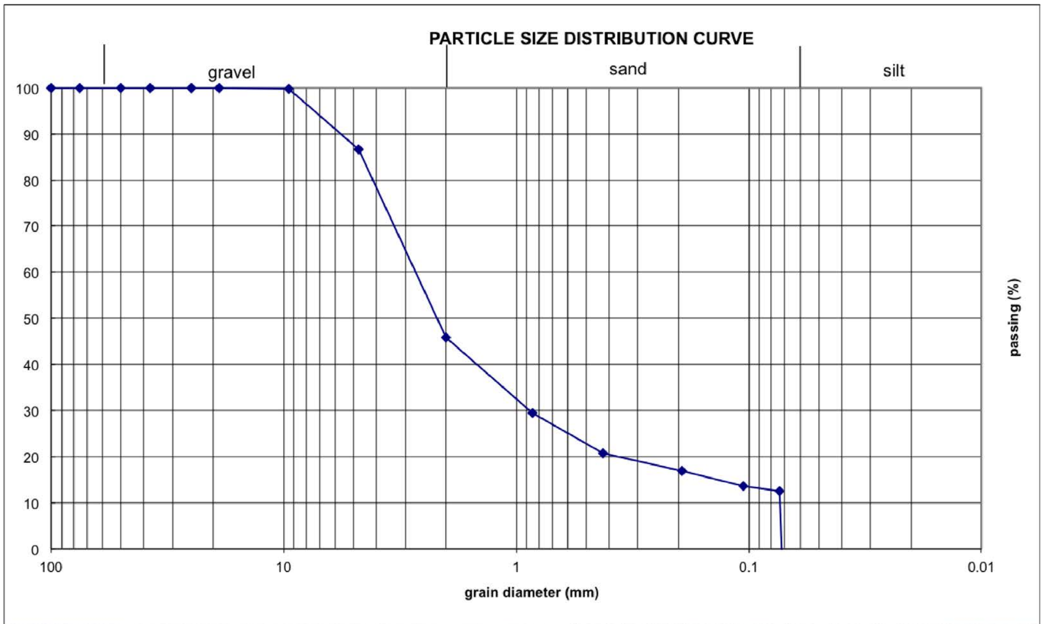


Figure A.11. Cumulative particle-size curve for sample RS-01-1B. The sample was collected from typical Bonaduz gravel 40 cm below the upper contact with overlying diamicton.

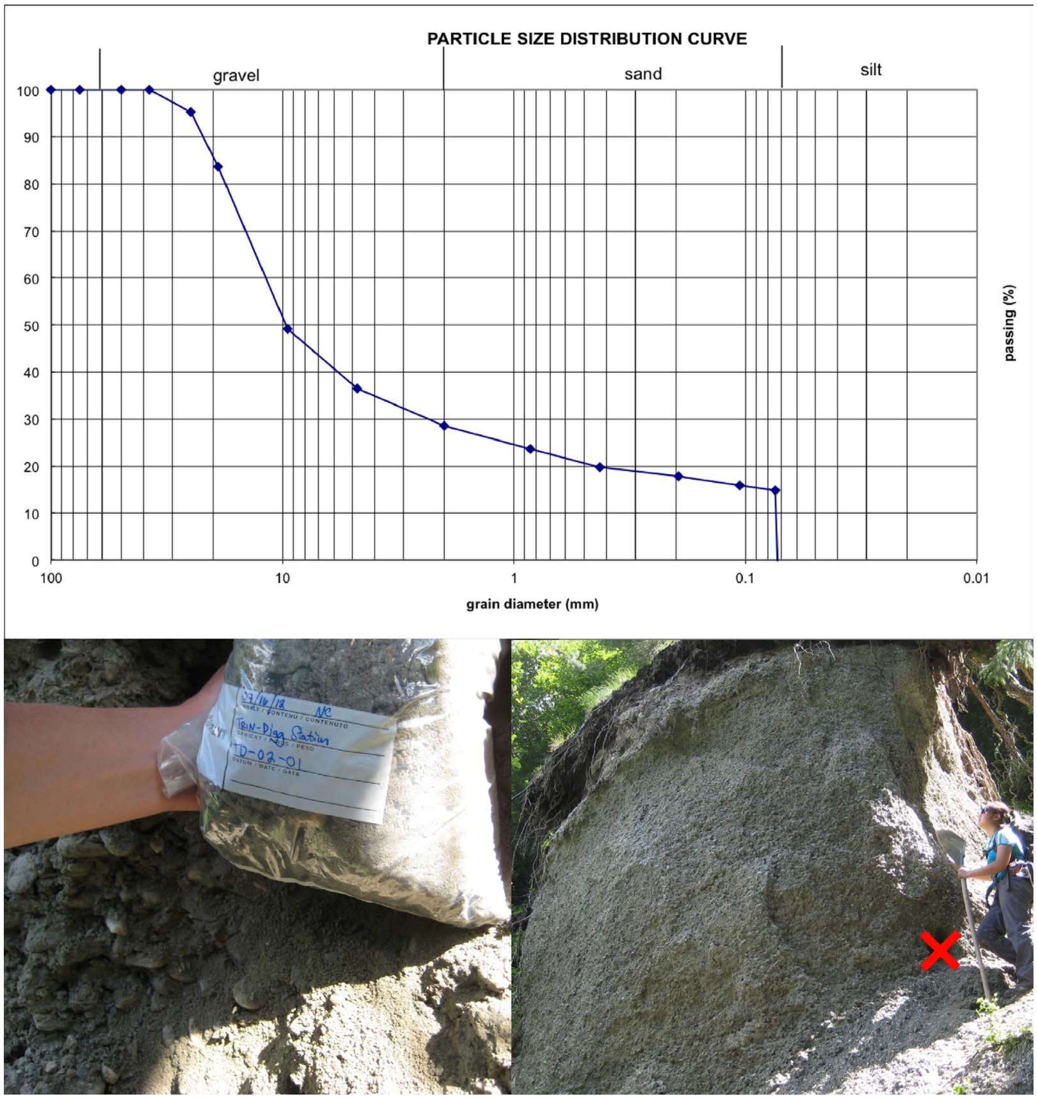


Figure A.12. Cumulative particle-size curve for sample TD-02-01. The sample was collected from typical Bonaduz gravel at the highest exposure at Trin-Digg.

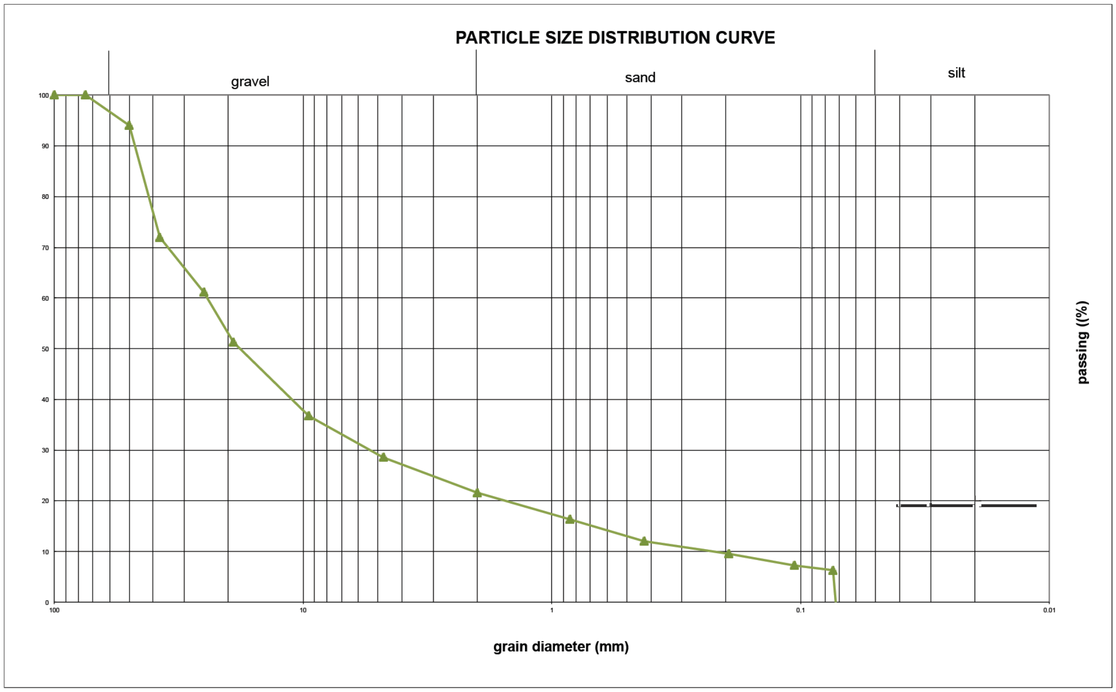


Figure A.13 Cumulative particle-size curve for sample RQ-20. The sample was collected from a tongue of coarse sediment in the east wall of the Reichenau quarry (see Figure 2.19).