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An analogue Toma Hill formation model for the Tyrolian Fernpass rockslide

Abstract The Fernpass rockslide occurred about 4100 years ago and is one of the largest rock slope failures in the Alps, the run-out area being characterized by a hummocky surface with Toma Hills that were formed after the rockslide event. These hills, characterized by a cone-like shape with a flattened top, are typical for many rockslides, and the name “Toma” is derived from local dialects in Switzerland and Tyrol, Austria. So far, five hypotheses have been proposed for the formation of Toma Hills, the two relating to glacial activity being outdated meanwhile. These hypotheses cannot explain all features observed on site. Therefore, to investigate one of these hypotheses, a qualitative laboratory-scale analogue groundwater flow model with the size $1.5 \times 1 \times 0.8$ m was used to investigate the contribution of internal erosion by suffosion to forming Toma Hills. From the model, hydrogeological calculations of Darcy velocity and hydraulic conductivity were determined to help understand the present study. The average hydraulic gradient of the experiments was close to that in reality. Hydraulic conductivities in the five experiments were comparable to the calculated field hydraulic conductivity (Bialas and Seelheim equations). A limnokrene like one south-west of Biberwier developed in all experiments. Development of lateral and transversal cracks, water-filled lateral depressions of the material in the model and discharge of finer material implicated that internal erosion is a substantial contribution to the Toma Hill formation. Based on the experimental results, we deduce that Toma Hill formation took between 140 and 580 years.

Keywords Fernpass rockslide · Toma Hill formation · Hummocky morphology · Internal erosion by suffosion · Analogue model · Tyrol

Introduction and background

Gravitational movement of large, dry and loose material is a typical erosional process in mountainous areas as the Alps (Abele 1974; Ampferer 1904; Baltzer 1874/75; Heim 1932). Such occasions are often alluded to as dry rockslides (rock slide), rockfalls (rock falls) or rock topples (Cruden and Varnes 1996; Erismann and Abele 2013; Imre et al. 2010; Sassa et al. 2007). The Alps are the setting for several small and large rockslides, and the rockslide occurrence in this region has attracted a wide research attention focusing on the causes of the rockslides, triggering mechanisms, climatic influences and the formation of Toma Hills (e.g. Abele 1964, 1991, 1994; Ampferer 1941; Erismann and Abele 2013; Gruner 2006; Leuchs 1921; Matznetter 1956; Penck 1882; von Poschinger 2011; von Poschinger et al. 2006). However, only a few researches centre explicitly on Toma Hills (Brunner 1962; Imre et al. 2010; Wolkersdorfer 1991; Wolkersdorfer et al. 2017). This study focuses on the Fernpass rockslide and associated Toma Hills, which can be found in the Northern Calcareous Alps between the Lechtal Mountains in the West and the Mieminger Mountains in the East (Fig. 1). We describe the qualitative study of Toma Hills using an analogue (physical) laboratory-scale model to

understand their formation mechanism. First results of this study have already been published in Wolkersdorfer et al. (2017), but will be substantially extended here.

Toma Hills are morphological structures formed during or after some rockslides, and one cannot recognize any system in their arrangement within the hummocky morphology of the rockslide deposit. Their name “Toma” originates from local language in Austria and Switzerland (Penck and Brückner 1901), which in turn derives from Latin *tumus* or *tumulus* (Staub 1910). Abele (1974) defined them morphologically as “isolated cone-, pyramid- or roof-shaped eminences consisting mainly of landslide material with more or less smooth slopes of constant gradient” and explicitly excluded a genetic explanation. Staub (1910) adds that the Toma landscape is partly a result of fluvial processes and he describes cases where he sees Toma Hills clearly resulting from fluvial erosion. Yet, Nussbaum (1934) points out that “Toma” also occurs “where a cutting and meandering river is missing”. In many cases, the Toma Hills consist of an outer covering with loose material and a core with harder or less fractured material, which was already noticed by the earliest authors (Sererhard 1742 [1872, 1994]). One exception, described in the literature, is the Bindschedler-Bühl near Chur, which consisted only of loose, unconsolidated material (Brunner 1962). Internally, the material can consist of both loosened and fractured rockslide material and moraines as well as crystalline erratica. Toma Hills are usually imbedded in a complex, hummocky morphology, but not all the hummocks in such a morphology can be classified as Toma Hills. In this, our distinction between hummocks and Toma Hills s.s. differs from other authors. Typically, the Toma Hills at the Fernpass rockslide occur where the valley widens which gave rise to the hypothesis presented later in this paper (Fig. 3), and a characteristic already described by Much (1871) who even reflects the hills’ natural genesis.

Factors that normally influence the occurrence of a rockslide typically include the slope angle, slope stability, water content of the rocks, erosion, weathering, overloading, gravity and the geological setting. Some of the abovementioned variables also control the geometry of the failure surface and its advancement both in space and time (Crosta and Clague 2009). Since the earliest studies of alpine rockslides, various models and hypotheses have been displayed to clarify the areas of substantial slope failure, activating processes, rates and sorts of development, time of event, their geometry and their effects including, for instance, effects on structure and expanded disintegration (Abele 1964; Imre et al. 2010). Especially Imre et al. (2010) and Meili et al. (2013) conducted and published results of laboratory experiments of the Toma formation resulting from physical processes causing fragmentation of the sturzstrom (rock avalanche) debris. Other than in the model described in this paper, water did not play a role in their hypothesis of Toma Hill formation.

Pouliquen et al. (1997) and recently Valderrama et al. (2018) conducted analogue models to study fingering that might occur at rockslides. In none of the experiments described in these papers, indication for the formation of Toma Hill-like structures was

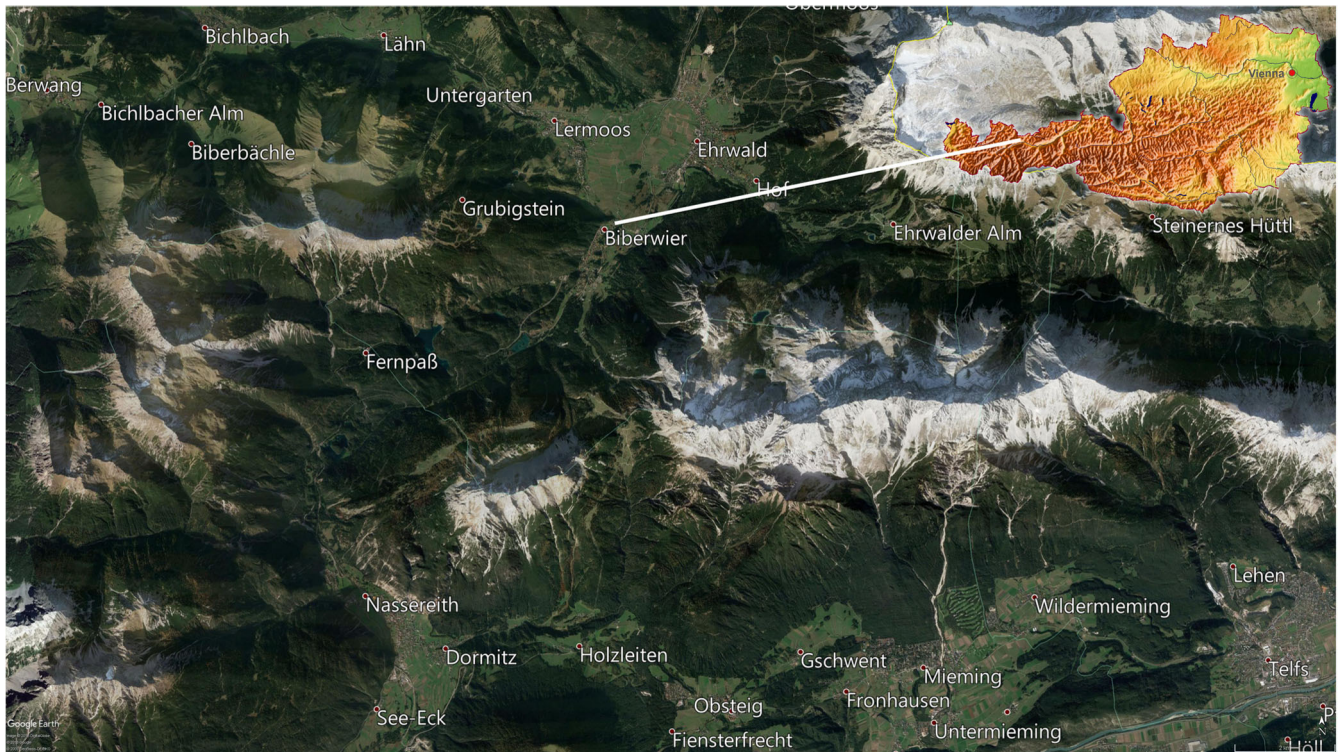


Fig. 1 Overview of the study area. The Fernpass rockslide is slightly left of the centre of the map and morphologically ranges from Biberwier in the NE to See-Eck in the SW (© Google Earth, Wikipedia)

encountered. Instead, their experiments explained ridges, which are not evident at the Fernpass rockslide, though Dufresne and Davies (2009) list them in their Table 1, referring to Abele (1964). Shea and de Vries (2008) studied the difference between the development of ridged or hummocky surfaces with numerous laboratory experiments. They found that “the analogue model demonstrated that collapses composed of initially heterogeneous materials [...] tend to generate hummocky surfaces”, while “dominantly fine grained and homogeneous granular material slides” caused dominantly ridged structures. None of their results specifically explains the formation of Toma Hill-like structures.

Numerical models were conducted by Gramiger et al. (2016) to study the runout of two rockslides in the Swiss Bernese Alps. Though hummocky surfaces appear in the nature and in the model, none of them can be considered Toma Hills and their model, consequently, cannot be used to understand the Toma Hill formation in more detail.

Stepri (2003) conducted small-scale laboratory experiments of internal erosion (suffosion) in the context of seepage flow to pumping wells and defined small particles as being smaller than 75 μm . Based on her results, she developed a model for the erosion and transport of these fine particles and came up with a relationship between the hydraulic gradient and the time needed to erode 95% of her fine material. She finally used her results to numerically model the erosion and seepage flow to wells resulting in settlement values from these processes.

Internal erosion was also investigated in laboratory experiments by Chang and Zhang (2011) as a function of stress, and they noticed that fine material is first eroded in the uppermost part of the sediment and that the hydraulic conductivity increases while finer particles are

eroded. Cui et al. (2017) investigated erosion of slopes in an analogue model and found that fine particles ($\leq 2 \text{ mm}$) are transported within the sediment in a smaller column and not on a larger one on the slope surface. According to their findings, soil composition and structure is important for the transport of fine material.

A more general review and discussion of the internal instability processes that occur in loose rock material has been given by Fannin and Slangen (2014), who present a summary of studies conducted to understand erosion of earth dams. In these engineering studies, internal erosion processes are a substantial threat to dam stability (Vazquez Borrigan 2014).

There are several cases of dry rockslides or rock falls, where the separation of the fragments occurs even when the vertical drop of the material is comparably narrow. These rockslides might become sturzstroms as the movement controlling inter-granular coefficient of friction might become less. Sturzstroms are rockslides of extended volume compelling run-out which show concentrated discontinuity of blocks of rock because of the collision of rocks during the rock debris movement (Heim 1932; Hermanns 2013; Imre et al. 2010; Prager et al. 2006b). Though a number of causes will contribute to a rockslide, there is one, which ultimately triggers the movement of material in most cases: fluvial erosion as the dominant process because it is linear, regressive and connected with convergent valley streams (Abele 1994). The Fernpass rockslide material and area are dominated by chemical sedimentary rocks, stream channels and groundwater flow within the debris. Therefore, it may be possible that carbonate rocks in the area may have been fractured along bedding planes, and because of the presence of streams, fluvial erosion may have played a role in triggering the Fernpass rockslide (Mostler 2013; Penck 1882).

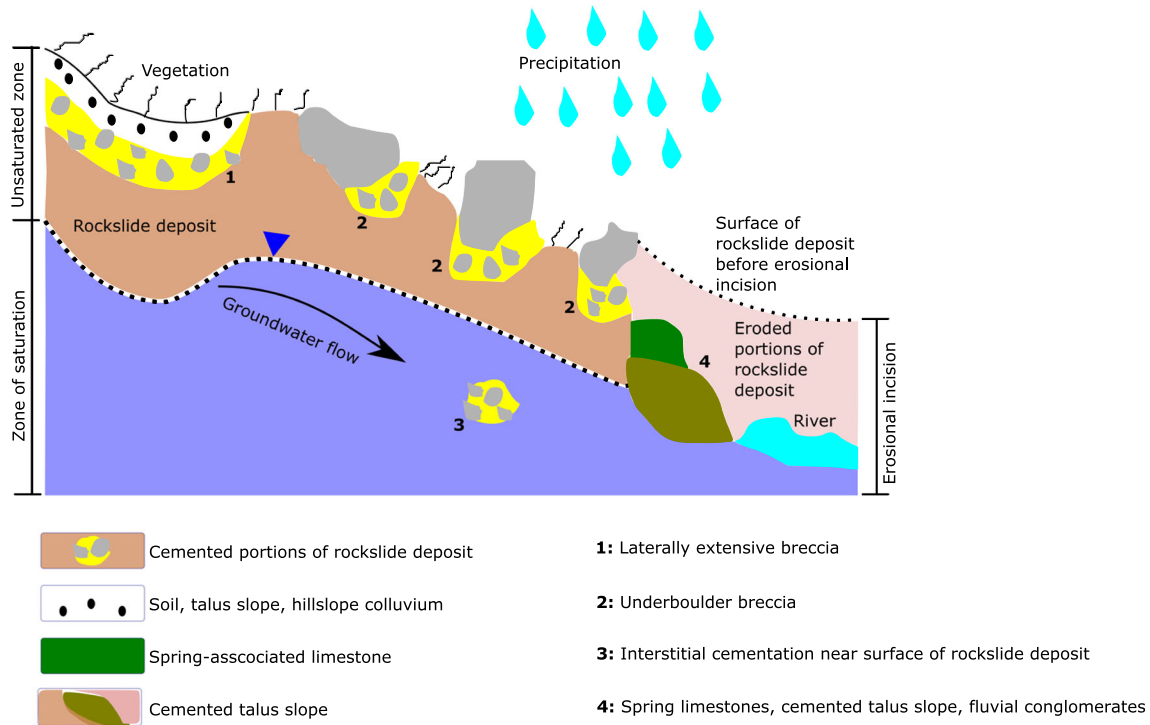


Fig. 2 Diagenetic features associated with carbonate-lithic rockslide deposits. Not to scale (after Sanders et al. 2010)

Some rockslides can travel a long way from the source of the initial fall. The debris and rock fragments from rockslides can range from tiny grains to boulders, and some boulders tend to break up into smaller pieces as the slide moves down slope and large pieces collide with each other (Prager and Zangerl 2005). A hummocky morphology, which on first sight seems to be similar to the Toma Hill landscape, also formed in conjunction with the debris avalanches of the Iriga volcano, Philippines (Capra 2011), and Reiser et al. (2010) pointed out that sometimes even moraines might be confused with Toma Hills. Yet, the movement of the Fernpass rockslide and several other rockslides have proven to be unusual and maybe the explicit reason for confusion of the formation of Toma Hills.

During the movement of rockslide deposits, processes such as lithification and diagenesis take place (Fig. 2). The Fernpass sturzstrom contains solid rocks, such as conglomerates, which may have formed when sediments compacted under pressure (lithification), and they (sediments and/or sedimentary rocks) changed during and after lithification (diagenesis) (Sanders et al. 2010).

Problem statement and definitions

The formation of Toma Hills has proven to be an ongoing discussion with multiple hypotheses behind it. They were even thought to be terminal moraines of a local glacier (e.g. Mojsisovics 1871), and, actually, such a confusion cannot be held against earlier

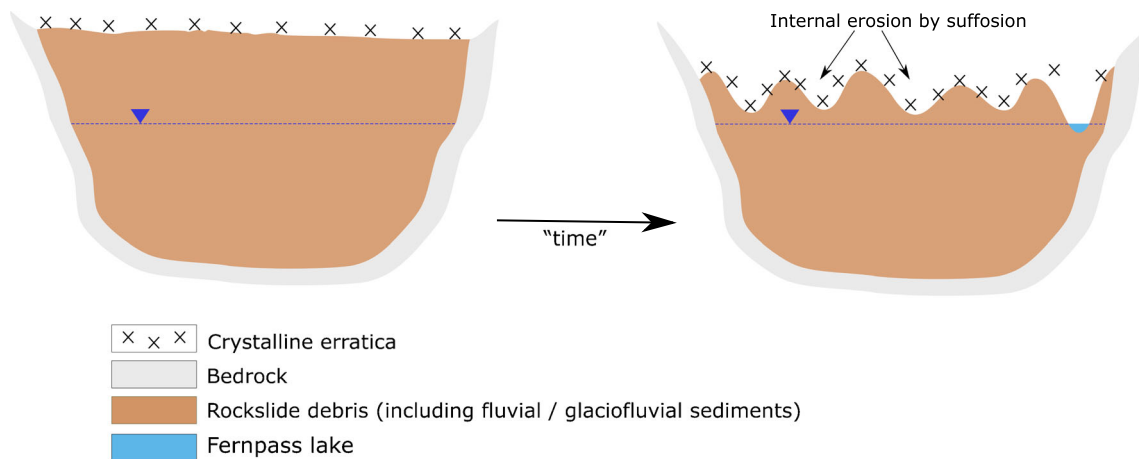


Fig. 3 Simplified conceptual model of the processes involved in Toma Hill formation (not to scale). Left: shortly after the rock fall, right: after internal erosion occurred. Till and different sturzstrom deposits are not explicitly shown



Fig. 4 Eroded Fernpass rockslide debris; width of scale 15 cm

researchers as there are indeed similarities (Reiser et al. 2010). Several hypotheses have been proposed so far: one of the first hypotheses was that Toma Hills are formed as a result of dead ice melting, and another one saw the Toma Hills formed in conjunction with the transportation of rockslide material on a still existing glacier. They were then followed by another hypothesis which is based on the karstification process. The area surrounding the Fernpass is characterized mainly by chemically sedimentary rocks, from dolostones to bituminous dolostones and gypsum, and therefore, this hypothesis is based on these types of rocks. The recent hypothesis is that the hills were formed by transportation of rockslide material on liquefied, water-saturated sediments. The concept that was used is that of inertial entrainment friction to support this hypothesis. However, the hypothesis proposed in this paper sees the Toma Hill formation in the context of internal erosion by suffosion, which will be investigated and discussed hereafter strictly in the view of Toma Hill formation (Fig. 3).

Different groundwater velocities were exploited in our analogue experiments to identify if it is possible for groundwater to erode, transport and deposit different grain sizes resulting in an overprint of the rock debris, ultimately resulting in the formation of Toma Hills. As a matter of course, the analogue model—like any

model—is an oversimplification of the reality (Box 1979), but was designed to mirror the initial stage of the rockslide after the main sturzstrom came to a provisional rest. Preferential flow paths, as they might exist in various locations within the sturzstrom as outlined in Schuch (1981), might not be exactly mirrored by the small-scale analogue model. In addition, the analogue model discussed here is not taking into consideration precipitation, snow or surface runoff. Though the Fernpass rockslide with all the lakes, hummocks and Toma Hills can be considered a small drainage basin, the principles first described in detail by Tóth (1963) about the various groundwater flows in small drainage basins will not be considered in the analogue model.

During hydrogeological mapping and field investigations around Biberwier, in the northern branch of the Fernpass rockslide, the second author had noticed some characteristics, some of which had already been described by previous researchers mentioned in the introduction: (1) in some smaller valleys between Toma Hills, flowing groundwater can be heard “gurgling” occasionally and (2) the angles of the hill flanks correspond to the natural fill angles of the respective material of which the hills are formed. Consequently, the formation of Toma Hills will be discussed here in the context of mass loss due to erosion and the accompanied internal instability of the rock debris (“sediment”).

The characteristics of the Fernpass rockslide’s internal structure are dominated by both, fragmentation and a varying block-size separation with grain shapes ranging from sub angular to well-rounded (Fig. 4) and a decrease of block sizes from proximal to distal (Abele 1974; Prager et al. 2006a). This further implies that material making up Toma Hills is of unconsolidated and unsorted debris with strongly varying grain sizes (Prager et al. 2009a; Prager et al. 2009b). It raises questions such as how fast groundwater is and was flowing through the rockslide debris and what groundwater velocity is required to erode, transport and deposit certain fragment sizes of the debris. Therefore, the time it takes for groundwater to move through the medium, the groundwater velocity and hydraulic conductivity of the material were crucial factors during the analogue laboratory study.

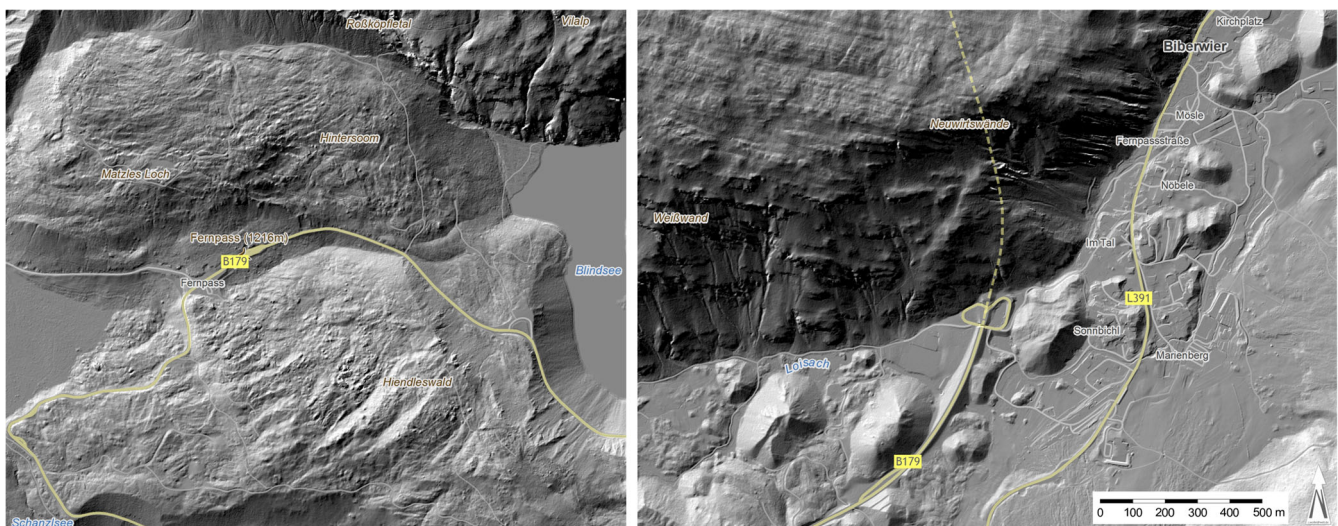


Fig. 5 Comparison of hummocky surface (left) and Toma Hill characterized surface (right) morphology at the Fernpass. © Tiris Lidar data 2019



Fig. 6 Overview of the Fernpass rockslide near Biberwier (in the right of the image). (1) Rockslide source area, (2) Fernpass lakes, (3) northern branch of the rockslide also indicated with an arrow, with, (4) selected Toma Hills. Direction of view to the south-west

As indicated in the introduction, this study distinguishes between hummocks and Toma Hills s.s. (Fig. 5). On first sight, both look very similar, but a hummocky surface does not necessarily show the pyramid-like features observed in a Toma Hill

morphology (see “Introduction” for a description of Toma Hill features). In general, a hummocky rockslide morphology, like the one in figure 9.15 of Deline et al. (2015) or on top of the Heinleswald of the Fernpass rockslide, does not imply that these

Table 1 Characteristic physico-chemical parameters of surface and groundwater from the northern branch of the Fernpass rockslide (Wolkersdorfer, unpublished data; Vegter 1996). Last column represents Pretoria tap water. The mean of the pH has been calculated from the H^+ activities

	<i>n</i>	Minimum	Maximum	Mean	Std. deviation	Vegter (1996)
Temp. (°C)	122	4.4	28.0	8.3	2.9	–
pH (–)	119	6.9	8.5	7.9	0.3	–
el. cond. (µS/cm)	122	169	546	346	66	–
Redox SHE (mV)	117	140	688	385	88	–
O ₂ (mg/L)	108	0.80	24.40	10.74	2.82	–
O ₂ (%)	111	4.1	235.0	100.7	25.0	–
Total Hardness (°dH)	29	5.0	16.7	9.4	2.0	12
<i>k_B</i> value (mmol/L)	24	0.00	0.29	0.06	0.08	–
<i>k_A</i> value (mmol/L)	38	1.79	5.95	3.31	0.70	4
Ca (mg/L)	31	28	69	44	10	43
Mg (mg/L)	31	6.4	24	15.5	3.1	31
Na (mg/L)	31	0.17	10.0	4.0	2.5	8
Sr (mg/L)	31	0.0	5.0	1.7	1.4	–
K (mg/L)	31	0.12	1.20	0.61	0.19	–
Ba (µg/L)	31	2.8	51.3	14.8	9.4	–
Li (µg/L)	31	0.29	3.0	1.2	0.6	–
Sb (µg/L)	31	0.01	2.31	0.25	0.41	–
HCO ₃ [–] (mg/L)	31	109	363	206	45	121
SO ₄ ^{2–} (mg/L)	31	11	40	24	5	8
Cl [–] (mg/L)	31	0.4	17	7.7	3.9	20
NO ₃ [–] (mg/L)	31	0.5	2.7	1.5	0.4	8
F [–] (mg/L)	31	0.1	0.9	0.4	0.1	–
CaO/MgO	–	–	–	2.38	–	1.16

hummocks have the same genesis as the Toma Hills. To ensure that there is no confusion between hummocks, which can have variable genesis, and Toma Hills *s.s.*, this paper will deviate from the ambiguous usage in other publications (Dufresne 2014; Dufresne et al. 2015; Paguican et al. 2014). While this applies for the terminology, it does not apply for the explanations provided in the before mentioned papers.

Relating to internal erosion processes caused by flow or seepage of groundwater, the international terminology can be considered inconsistent. For the same phenomenon, authors are using “suffusion”, “suffosion” or other terms more or less interchangeably, which might be confusing for readers. Fannin and Slangen (2014) go one step further and point out that this “lack of clarity arising from use of the same term to describe these two distinct phenomena is an impediment to scientific progress”. They define that *suffusion* entails mass loss, decreased hydraulic conductivity and no volume loss, while *suffosion* entails mass and volume loss and a change in hydraulic conductivity. As described above, the Toma Hill formation is discussed here in the context of mass and volume loss, and therefore, the term *suffosion* describes the phenomena more precisely than *suffusion*.

Study area and geological setting

The Fernpass rockslide and related Toma Hills (Fig. 6) are located in the Northern Calcareous Alps, between Nassereith and Biberwier, about 42 km west-northwest of Tyrol’s capital Innsbruck, Austria (Fig. 1). Geologically, the Fernpass area is mainly characterized by shallow-marine dolostones of the Norian Hauptdolomit (Upper Triassic) and the bituminous Upper Norian Seefeld Formation which makes up the younger successions of the monotonous Hauptdolomit (Prager et al. 2009b; Schmid et al.

2004). In addition, the area contains metamorphosed crystalline rocks such as marble, quartzite and amphibolite on top and within the rockslide material, called crystalline *erratica*. Today, the Fernpass high is the water divide between the river Inn in the south and the Isar in the north.

The rockslide has been dated by three independent radiometric methods, ^{14}C -, ^{36}Cl - and $^{230}\text{Th}/^{234}\text{U}$ -dating, on which samples were collected at different places on the southern branch of the rockslide. The ^{14}C -dating method yielded a minimum age of 4100 ± 1300 a and a $^{230}\text{Th}/^{234}\text{U}$ -dating method produced age of about 4150 ± 100 a (Prager et al. 2008, 2009a), which is older than the 2255 ± 60 a ^{14}C -age reported by Abele (1991) for a pine tree deposited in lacustrine material of the Kälbertal. Rockslide material makes up Toma Hills, but it does not mean they are in their current form the same age as the rockslide. Actually, they might be younger because it takes time for the Hills to form after the initial rockslide.

The rockslide originated from the Afrigall cirque and an elevation of approximately 2100–2300 müA, showing debris of a volume of about 1 km^3 . The material is more than 350 m thick and split into two channelled sturzstroms with a length of up to 16 km (Abele 1964). One of the sturzstrom branches contains a larger debris volume when compared to the other one. The reason for the two channelled sturzstrom branches is likely to have been caused by gravity and the force of the rockslide on partly liquefied fluvial sediments, as it has been described for example by Carlson Calhoun (2015) relating to the Flims rockslide. Taking all these characteristics into account, the Fernpass rockslide is a real “rock slide” according to the Cruden and Varnes (1996) classification.

One characteristic of the Fernpass rockslide is the convex transverse profile of the debris, which is a result of a relatively

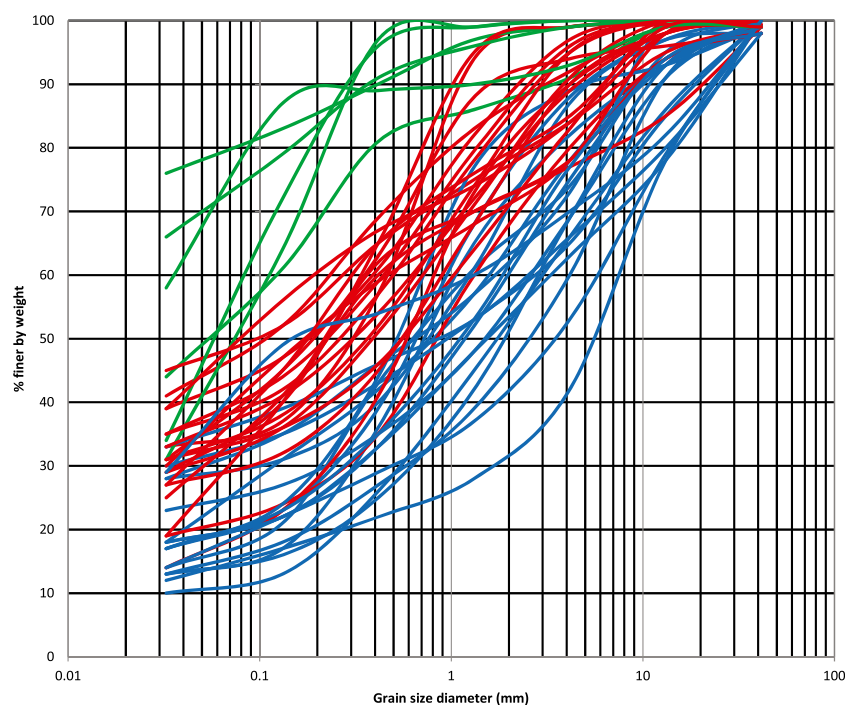


Fig. 7 Sieve curves for the 45 sieve analyses in Schuch (1981). Colours are based on statistical analysis using PCA and hierarchical cluster analysis using three clusters. It was not possible to correlate the clusters with the depositional facies

Table 2 Statistical data of the 45 sieve analyses in Schuch (1981). *Std. Dev.* standard deviation of the population

Material type	Size range (mm)	Median (%)	Average (%)	Min. (%)	Max. (%)	Std. Dev. (%)
Silt	0.002–0.063	29	29	10	76	14
Sand	0.063–0.2	7	10	3	38	8
Sand	0.2–0.63	13	14	2	33	6
Sand	0.63–2	15	16	1	37	9
Gravel	2–6.3	15	14	1	27	7
Gravel	6.3–20	11	12	0	36	9
Gravel	20–63	2	5	0	22	7

small head difference between the Afrigall (source of the rockslide) and Biberwier (Abele 1974). This convex profile gives way to small marginal valleys (“Randtälchen”, sensu Abele 1964) on both sides of the debris, in which small rivulets flow (e.g. Loisch, Dorfbach, Fig. 1). In addition to the morphological feature Toma Hills, the Fernpass rockslide is characterized by morphological, circular depressions which are interpreted as karst dolines (Abele 1964). Mostler (2013) proposed that these dolines are indicative for gypsum karst and consequently the whole Fernpass area is not a rockslide but a result of karstification, a hypothesis already proposed by Penck (1882) and refuted since then. Yet, as Abele (1974) pointed out, the debris of the Vajont Valley rockslide showed doline-like structures caused by either internal erosion or by sagging of the unconsolidated material. These doline-like structures can be seen at the Vajont Valley rockslide front slope in many early images. Comparable sinkhole structures due to internal erosion developed at the Himalayan Upper Hunza rockslide at Attabad (Delaney and Evans 2011). Also Li and Zhou (1999) and Dufresne et al. (2016) showed that sinkholes can result from suffosion or subrosion. It could therefore be, and the analogue model results give a clear indication for this hypothesis, that some (but not all) of the doline-like structures at the Fernpass result from physical erosion rather than chemical erosion. An investigation, such as these described in the vicinity of the Tschirgant rockslide (Dufresne et al. 2016), if some of these structures might be bomb or artillery craters resulting from the April 1945 capture of the Fernpass is still outstanding. At least the doline-like-structure on the access road to the Blindsee would need some further investigation in the future.

Though no comprehensive published investigation of the Fernpass’ hydrogeology exists, the Tyrolian geodata system TIRIS lists 11 groundwater monitoring stations on the northern and

southern branches. One is dry and the other 10 have a depth to groundwater of 2 to 190 m. As the groundwater monitoring stations with the higher depth to groundwater are close to the Heinleswald at the Fernpass height, where a hummocky surface but no Toma hills exists, they can be excluded from the comparison between natural situation and the analogue model. In the area of the Toma Hills, depth to groundwater ranges between 2 and 10 m. Wolkersdorfer (unpublished) investigated the hydrogeochemistry of the ground and surface water of the Fernpass area.

Methods and materials

Material selection and properties

Using the 45 sieve analyses of the sediments from the northern Fernpass branch, which Schuch (1981) analysed in three boreholes (Fig. 7), a method for composing a synthetic rockslide sediment for the analogue experiment was developed. From the sieve analysis results, the average and median of all sieve analyses were calculated and to exclude outliers, the median values were used for composing the synthetic rockslide material. This proved to be a great simplification of the actual sedimentological composition of a Toma Hill (Table 2), especially because the sieving method used by Schuch (1981) tends to result in smaller size fractions compared to the real situation (pers. comm. H. Mostler 2017). In addition, as the experimental setup should investigate physical and not chemical erosion, an inert material was used.

Based on these results of the 45 sieve analyses, the synthetic material was composed in the laboratory (inert quartzitic material; De Souza Hardware & Brick Depot, Akasia, South Africa) (Table 3), shifting the size fraction range to the coarser side to accounting for the possible bias in the sieve analysis. From the median values of

Table 3 Calculated sediment mass based on the Schuch (1981) data, and real composition of the synthetic rock material used for experiments nos. 3 and 5. No detailed results are available for experiments nos. 1, 2 and 4

Material type	Size range (mm)	Sediment mass (kg %)	Experiment 3 (%)	Experiment 5 (%)	Average (%)
Silt	0.002–0.063	481 31	18	11	15
Sand	0.063–0.2	116 8	24	18	21
Sand	0.2–0.63	215 14	26	16	21
Sand	0.63–2	249 16	3	8	6
Gravel	2–6.3	249 16	21	34	28
Gravel	6.3–20	183 12	4	5	5
Gravel	20–63	34 2	3	7	5

Table 4 Summary of experiments nos. 1 to 5 (see also electronic attachments 1 to 5)

	Exp. 1 (C)	Exp. 2 (D)	Exp. 3 (E)	Exp. 4	Exp. 5A	Exp. 5B
Number of pumps used	2 in day 1; 1 from day 2 onwards	2	2	2	2	2
Inflow (L/min)	1.1 for O ₂ 0.5 for O ₃	1.2 for O ₂ 0.5 for O ₃	0.9 for O ₂ 0.2 for O ₃	0.8 for O ₂ 0.1 for O ₃	0.8 for O ₂ 0.1 for O ₃	0.7 for O ₂ 0.3 for O ₃
Inlets used	I ₁ and I ₃ ; I ₁ was changed for I ₄ and I ₃ for I ₆ on day 1; only I ₄ was used from day 2 onwards	I ₇ and I ₆ ; on day 15, I ₉ was changed for I ₆	I ₇ and I ₉	I ₇ and I ₉	I ₆ and I ₇ ; on day 2, I ₆ was changed for I ₉	I ₇ and I ₆ NaCl tracer test conducted
Outlets used	O ₂ and O ₃	O ₂ and O ₃	O ₂ and O ₃	O ₂ and O ₃	O ₂ and O ₃	O ₂ and O ₃
Duration	30 days	30 days	32 days	30 days	5 days (not finished)	30 days
Average flow at outlet (mL/min)	0.8 for O ₂ 0.3 for O ₃	1.0 for O ₂ 0.4 for O ₃	0.7 for O ₂ 0.1 for O ₃	0.7 for O ₂ 0.2 for O ₃	None → experiment interrupted	0.8 for O ₂ 0.4 for O ₃
Remarks	None	Blue aquarium gravel "acting" as moraine	20-cm-long pipes extending inlets I ₇ and I ₉ from the inside of the tank	Flow started at the very bottom of the tank. Material was compacted	Same setup as Exp. no. 5B; experiment stopped, as wrong material was delivered	20-cm-long pipes used to extend inlets I ₇ and I ₆ from the inside of the tank
Material height (cm)	69	58	55	50	54	55
Hydraulic gradient	0.33	0.17	0.17	0.17	0.17	0.17
Electronic attachment	1	2	3	4	–	5
d_{50}	Not determined	Not determined	0.76 mm	Not determined	Not determined	3.92 mm
Re	–	–	0.14	–	–	0.73

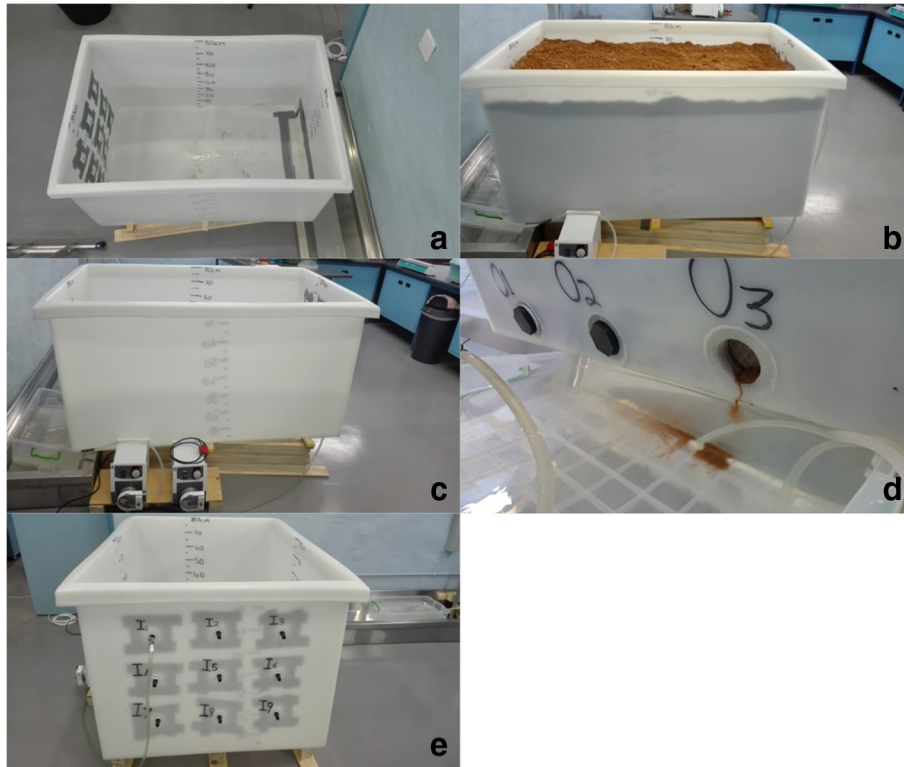


Fig. 8 Full view of the analogue model. **a** Showing the upper view and the inside of the tank on which outlets and inlets are seen from the inside covered with sieve. **b** Tank filled with material. **c** Showing the pumps used during the experiments. **d** Showing the outlets from the outer part of the tank, labelled O_1 to O_3 . **e** Inlets from the outer part of the tank, labelled I_1 to I_9 . Spacing of the marks 10 cm

the sieve analyses, hydraulic conductivities were calculated using the equations of Seelheim and Bialas (Aschenbrenner 1996) and were found to be around 5.0×10^{-4} m/s ($n = 41$) and 1.8×10^{-5} m/s ($n = 16$) respectively.

Several parameters were modified during the five experiments: number of inlets and outlets used, compaction of material and number of pumps used (Table 4). This was necessary for understanding the Toma Hill formation mechanism. As the analogue

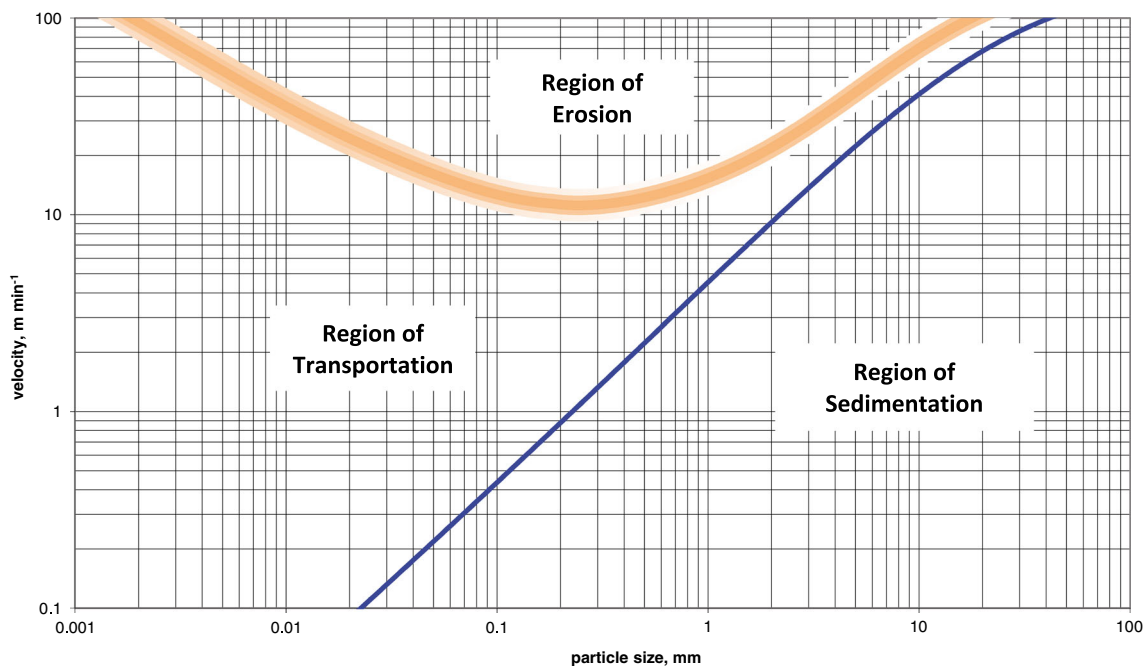


Fig. 9 Simplified Hjulström diagram in m min^{-1} , modified from Hjulström (1935) and Sundborg (1956)

Table 5 Mass of the eroded material of the experiments. Experiment 5A was stopped after some days, as material delivered had a too small grain size

	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5B	Average	St. Dev.
Eroded material (g)	317.02	202.27	158.23	136.80	202.61	203.4	62.3

experiment aimed in understanding the initial Toma Hill formation processes, where the rockslide debris was still uncompacted, the experimental setup also used uncompacted sediment. Only in experiment 4, the sediment was compacted to study potential differences in the Toma Hill formation as a function of compaction. The changes do not include the type of material since a similar combination of material was used throughout all five experiments.

Experimental design: analogue model

Analogue or physical modelling is commonly used in geological studies when it comes to understanding geological processes and time scales, especially in the context of CCS (carbon capture and storage) and radioactive waste disposal (Higgs et al. 2015; Smellie et al. 1997).

As the Toma Hill formation took a long time to complete, possibly hundreds to thousands of years, the model was chosen such that this process could be studied in the laboratory. Consequently, an analogue groundwater flow model (“physical model”) was designed to understand the contribution of internal erosion by suffusion in the formation of Toma Hills. This approach was chosen as it allows to modify the water movement in such a way that it can be seen how the groundwater within the model travels.

The analogue model comprises of a rectangle $1.50 \times 1.00 \times 0.80$ m polyethylene tank (Pioneer Plastics, Rosslyn, South Africa) with nine inlet points at three different elevations to allow for the adjustment of the hydraulic gradient (labelled I_1 to I_9 at the front of the tank) and three outlet points (labelled O_1 to O_3 at the back of the tank) to force the direction and flow rate. Inlets were used for water inflow and outlets for water and eroded material discharge (Fig. 8). This setup allowed for varying the flow conditions within a large range of conditions.

A 60-L container was placed next to the outlets, used as a reservoir and to collect the eroded, finer material. Peristaltic pumps (Heidolph PD 5006, Schwabach, Germany) were used to circulate water from the reservoir to the chosen inlet point(s), and the pump speed was adjusted until the inflow equalled the outflow volume. The tank was raised 4 cm at the inflow side to provide an initial hydraulic gradient. In all five experiments, an average of 0.98 m^3 of loose (1.52 t, bulk density of 1.56 g/cm^3) or 0.75 m^3 of compacted (1.52 t, bulk density of 2.03 g/cm^3) evenly mixed sand and gravel was used. After completely filling the tank with the material, Ca-Mg- HCO_3 -type (Table 1), Pretoria tap water (Vegter

1996) was passed through the synthetic rockslide material under ambient temperature (15–25 °C) by means of two peristaltic pumps. This water has a composition similar to that of the northern branch of the Fernpass rockslide. Each experiment had a duration of ± 30 days and the flow rate was adjusted between 0.9 and 1.7 L/min with an average hydraulic gradient of 0.2 (median 0.17), identical to the natural hydraulic gradient of 0.2 between the Hiendleswald ($\pm 1300 \text{ müA}$) and Biberwier ($\pm 990 \text{ müA}$). Flow in the experiments was laminar, as the Reynolds numbers ranged between $Re = 0.14$ and $Re = 0.73$ (Table 4).

Tracer test

To evaluate the mean residence times and velocities of the water in the analogue model, two tracer tests with sodium chloride (NaCl, table salt) were conducted. As concentrated salt solutions tend to flow to the bottom of the tank, the smallest possible concentrations for obtaining peaks were used and the tap water allowed to reach ambient temperature. Ten grams (33.3 g/L) and 20 g (66.7 g/L) of NaCl, respectively, were dissolved in 300 mL of tap water and thoroughly stirred on a magnetic stirrer until all the salt was completely dissolved. As the 33.3 g/L solution did not result in an evaluable peak, only the 66.7 mg/L test applied at the end of the tank test no. 5B will be discussed here. All the tracer solution was injected into the injection stream at inlet I_6 within 39 s and the tracer concentration measured at the outlets O_2 and O_3 with the Sommer Messtechnik TQ-S (Austria) electrical conductivity probes and tracer system for 46 h. To evaluate the data, the QTRACER2 software was used (Field 2002).

Additional experimental procedures

The objective of the study was to provide a first approach using an analogue lab-scale model for investigating internal erosion occurring in sediment that build up Toma Hills. The Fernpass rockslide material comprises a mixture of coarse and fine particles, in which it was expected that the fine particles will be eroded by groundwater flow resulting in internal instability of the rockslide debris. In this context, the term “fine material” is used differently than by

Table 6 Hydraulic conductivity for the material on the northern branch of the Fernpass rockslide determined by different methods

Method	k_f (m/s)
Natural material (calculated)	$1.8 \times 10^{-5} - 5.0 \times 10^{-4}$
Synthetic material (calculated)	$8.3 \times 10^{-6} - 2.1 \times 10^{-4}$
From experiment (measured)	$8.7 \times 10^{-6} - 8.0 \times 10^{-5}$
Schuch (1981)	$a \times 10^{-5} - 4.8 \times 10^{-3}$
Wolkersdorfer (unpublished)	$8.1 \times 10^{-7} - 1.1 \times 10^{-6}$

**Fig. 10** Beginning of crack formation and a water-filled lateral depression during experiment number 1. Spacing of the marks 10 cm

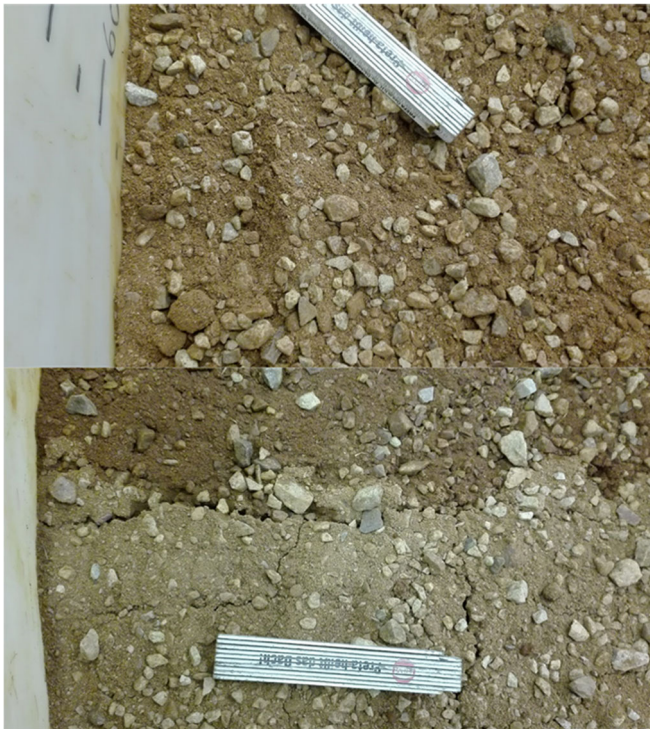


Fig. 11 Formation of isolated hills as cracks crossed during experiment no. 5. Length of scale 20 cm

Sterpi (2003), who conducted experiments about internal erosion. She defined “finer particles” as all particles smaller than 75 µm,



Fig. 12 Limnokrenes in the lab experiment and at the Fernpass near Biberwier. a Limnokrene developing during experiment no. 3 (electronic attachment 6). b Limnokrene near Biberwier (electronic attachment 7)

while this paper considers all material that flows out of the tank as “fine material” with a maximum of 3 mm (experiment no. 4). A similar boundary of 2 mm for eroded fine material was observed by Cui et al. (2017), who conducted experiments on fine particle movement during heavy rainfall.

This experiment’s coarse fraction of the gravel material formed a skeleton texture, and it was observed that internal erosion by suffosion transported the smaller fraction of the sediment. During this process, finer material is detached by the action of seepage flow once the water velocity exceeds a given threshold. It is then transported through the voids within the coarse material and redeposited within the interstitial space of the material itself once the velocity falls below threshold velocity. A process, which, consequently, reduces porosity. This was observed during the experiments when cracks formed in the analogue model, finer material being eroded, and discharge in the outlets O₂ and O₃ reduced during the experiment, implicating a reduction in porosity. A sample of this eroded finer material during experiment nos. 4 and 5B was taken and tested at the laboratory by laser diffraction together with the finer material found in the limnokrene in the Fernpass area near Biberwier.

The following parameters were varied for the analogue modeling of the formation of the Toma Hill: flow, hydraulic gradient and compaction of the material. Precipitation or fluvial processes were not simulated in these experiments, since the tank did not have a drain for running water above ground. The Hjulström diagram (Hjulström 1935; Sundborg 1956) and the grain size distribution of the material eroded from the tank were used to estimate the water velocity within the tank (Fig. 9).

Results and discussion

General features observed during the experiments

Five experiments with various boundary conditions were conducted to test the hypothesis of the Toma Hill formation in the analogue model (electronic attachments 1–5). During all these experiments, it was evident that internal erosion by suffosion has a substantial influence in structural formation of the hills through the formation of cracks, lateral depressions and erosion of finer material.

Internal erosion is a comparably slow process, as groundwater flows comparatively slow through the subsurface. It could be observed that the depth to the water level in the analogue experiments ranged between 1 and 9 cm, compared to the Fernpass area, where it is 2 to 10 m. As all the five experiments ran for 30–32 days with close to natural conditions, only a small amount of material was eroded (on average 136–317 g) (Table 5). This eroded material had a grain size of at most 0.425 mm and on average a d_{50} of 0.373 mm. Since the rockslide occurred, it took the Toma Hills a maximum of 4100 years to develop their current shapes. Therefore, if this process occurred for 4100 years in the lab, with additional precipitation, the morphology of the hills would be clearly seen. With the beforementioned information and utilization of the Hjulström diagram (Hjulström 1935; Sundborg 1956), groundwater velocities of 1–20 m/min can be derived. Using the grain distribution curve, hydraulic conductivities for the synthetic sediment were found to be 2.1×10^{-4} m/s and 8.3×10^{-5} m/s according to Seelheim and Bialas respectively (Aschenbrenner 1996), and these are slightly lower than the median of the natural material

Table 7 Summary of sedimentological parameters of the Biberwier limnokrene material and eroded finer material of experiments nos. 4 and 5B. C_u uniformity coefficient, C_c coefficient of curvature

Sediment	d_{10} (μm)	d_{30} (μm)	d_{50} (μm)	d_{60} (μm)	d_{90} (μm)	C_u	C_c
Limnokrene	421	660	806	970	1584	2.3	1.1
Exp. no. 4	76	240	463	586	1250	7.7	1.3
Exp. no. 5B	53	165	282	350	680	6.6	1.5

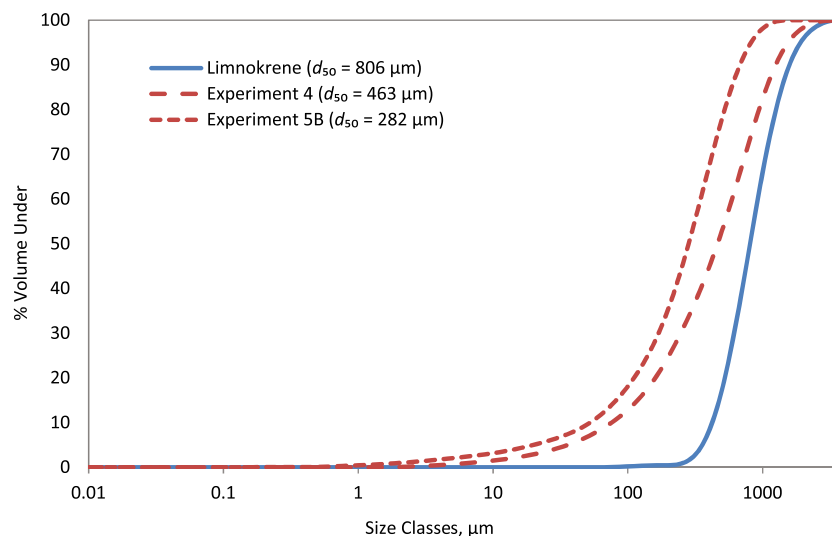
(Table 6). During the experiments, the outflow was measured frequently and the hydraulic gradient was adjusted; therefore, using this together with Darcy's law (Darcy 1856; Hölting and Coldewey 2013), the hydraulic conductivity was found to be around 8.7×10^{-5} to 8.0×10^{-5} m/s. Schuch (1981) found his hydraulic conductivities determined in the laboratory to be around $a \times 10^{-5}$ to 4.8×10^{-5} m/s, which might be substantially lower than the real ones in the field (Table 6). The reason for this maybe that the sieving method of Schuch (1981) results in generally finer sediments than in reality (pers. comm. H. Mostler 2017). Yet, besides these issues, we found a good agreement between the lab results and the morphologic features of the real-world situation.

Lateral and transversal cracks formed in all experiments within few minutes after the water inflow was started. These cracks implicate substantial contribution of internal erosion by suffosion. During the experiment, all the cracks began to widen; for experiment numbers 1 and 5, they widened to a width of about 2 cm and for experiments 2, 3, and 4, about 0.5–1 cm of widening was observed. On the sides of the tank, lateral depressions with a width of about 5–13 cm and a depth just about 2–3 cm developed in all five experiments (Fig. 10). Over time, water began to accumulate in these depressions, and after a couple of days, the water therein would sometimes disappear (by infiltration into the “underground”). This observation is interesting in so far, as it mirrors the formation of the more or less lateral Blindsee and Weißensee lakes in the northern branch of the Fernpass rockslide. It can be assumed that the internal erosion of rockslide material on the flanks of the debris was larger than in the middle, causing a preferential lake formation there.

In experiment no. 4, the material was compacted during tank filling; however, all the features that occurred in the uncompacted experiments developed similarly, i.e. lateral and transversal cracks as well as lateral depressions. This shows that the compaction of the material has no influence on the initial Toma Hill formation. When cracks crossed each other, sometimes isolated “hills” with heights of 1 to 3 cm appeared in those cases, where the material's characteristic slope angles allowed their formation during the experiment (Fig. 11).

Another feature that developed in all the experiments was a limnokrene (sensu Bornhauser 1912; also written limnocrene), which is the emergence of groundwater in a basin, sometimes indicating artesian pressure in the aquifer. In the experiments, these limnokrenes formed on the inlet side, where water was introduced into the tank (Fig. 12). A similar limnokrene exists south-west of Biberwier, about 20 m east of the Pastor Fink Trail. It has the same characteristics as those observed during the experiments, with finer sediments swirling where the groundwater emerges to the surface.

The limnokrene material is one of the many examples where finer material of the Biberwier Fernpass rockslide emerges to surface. According to the results obtained (Table 7), the coefficient of curvature (C_c) is below 3 for all samples and the uniformity coefficient (C_u) for the Biberwier limnokrene material is less than 3, which means that the sediment is well-graded, uniform and has a very narrow particle size range; that of experiment nos. 4 and 5B is greater than 5, indicating a well-graded sediment, which has a wide range particle size distribution (Das and Sobhan 2018; Handy

**Fig. 13** Laser diffraction results for the limnokrene material near Biberwier and experiments nos. 4 and 5B eroded finer material

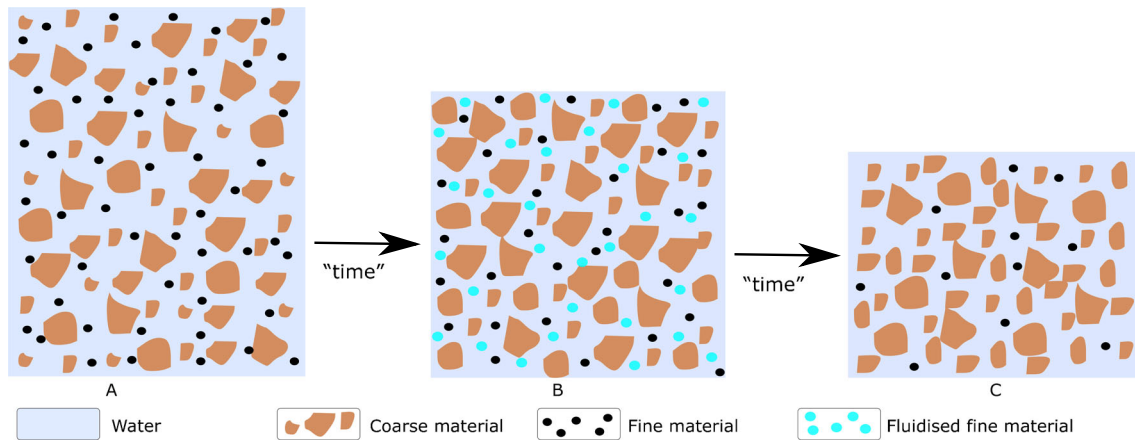


Fig. 14 Suffosion process. a Intact material. b Internal erosion taking place. c Material after full internal erosion occurred. The grains are not connecting with each other in this section to allow for the drawing of compaction

and Spangler 2007; Murthy 2002). The effective size of the materials (d_{10}) indicates how different the materials are even though the initial thought in the field was that they are similar. In addition, the d_{50} of the Biberwier limnokrene is twice as large than the eroded material of the analogue experiment (Fig. 13). The reason for all the above is that the finer material of the Biberwier limnokrene has already been washed out over the course of time, while the eroded material is the freshly eroded sediment of the experimental setup.

Description of the eroded material and lateral depressions of material
 During the experiment, finer material was eroded daily at a varying rate, implying that internal erosion is taking place. At the same time, also the volume of the gravel in the tank reduced by about 0.08–0.2 m³, and therefore, according to the definitions of Fannin and Slangen (2014), internal instability resulting from suffosion occurred. These results are in line with those of the numerical model of Sterpi (2003), who observed both settlement due to internal erosion and the stress on the material.

The process of grain detachment due to seepage flow is controlled by different parameters such as the velocity of the flowing water, hydraulic gradient, porosity, the concentration of fluidized

material and the amount of material that can be eroded (Fig. 14). During each single experiment, the hydraulic gradient was kept constant and inflow speed varied which influenced the change in groundwater flow velocity and ultimately influencing porosity. The amount of finer material being eroded reduced during the continuation of each experiment and lateral depressions developed (Fig. 15), implicating varying flow velocity and porosity of each single experiment.

Flow measurements at the outflow of the tank showed a fast decrease of the outflow during the first day and a constant flow thereafter. During the 30 subsequent days of the experiment, though the sediment in the tank compacted, only a small decrease of the sediment's permeability could be observed.

Tracer test with NaCl

As the evaluation results with QTRACER show, 101% and 88% of the NaCl tracer arrived in experiment no. 5B, which means that the data can be used for evaluation. The Peclet numbers of the two outflows indicate both advective and diffusive flow through the system which can be explained by preferential flow on the sides and the cracks of the tanks and diffusive flow through the sediment material. Mean tracer velocities are around 0.01 m/min and the maximum ones 0.1–6.4 m/min. Using the Hjulström diagram, the higher velocities would be able to erode particles between ± 0.1 and 1 mm in size and transport particles between ± 0.001 and 1 mm, which is in the range of particle sizes measured in the eroded material from the tanks. As the particle sizes in the Biberwier limnokrene are also within that size spectrum, it might be concluded that the groundwater flow velocity might be in a similar range, indicating that the experimental settings can be used to qualitatively describe the features at the Fernpass rockslide.

Conclusions

In the experiments, the hydraulic gradient was close to that of the Fernpass rockslide. Therefore, processes that took place during the experiments can be compared to those in reality. Cracks, lateral depressions, doline-like structures and a limnokrene developed during the five experiments, and this implicates that internal erosion by suffosion substantially contributed in Toma Hill

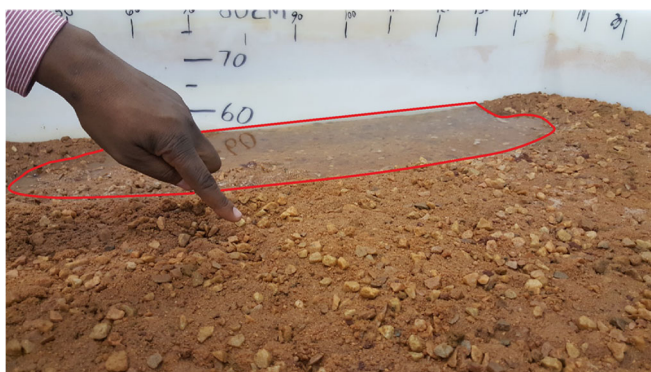


Fig. 15 Development of water-filled lateral depression (framed in red) during experiment number 1. Spacing of the marks 10 cm; finger indicating a dry lateral depression starting to develop

formation. These cracks are likely to be the structural formation of the hills. Lateral depressions developed in all experiments and in most cases, water filled up these depressions and lake-like structures ended up forming. Interestingly, such features are found in the Fernpass area, where, for example, Lake Mittersee, Blindsee and the Weißensee possess similar characteristics as the analogue experiment lakes.

The Fernpass rockslide area is dominated by dolines, and such doline-like structures also developed during the experiments. It was previously said that the dolines of the Fernpass are caused by dissolution of gypsum or limestone; however, these structures can be solely explained by the process of internal erosion such as during the experiments. Lateral and transversal cracks developed in the analogue model and these are also found on the northern branch of the rockslide area.

A limnokrene developed during the experiments which is like the one in the southern part of Biberwier. This shows that groundwater flow follows preferential pathways because of higher hydraulic conductivities, and therefore, this results in the transportation of finer material to the surface. Based on the tracer test results, it can be concluded that the flow velocities of the water in the tank and the groundwater around the limnokrene are between 0.1 and 7 m/min.

In conclusion, the experimental results show that internal erosion by suffosion seems to have contributed substantially to the formation of the Toma Hills and the doline-like structures of the Fernpass rockslide. The development of cracks and depressions during the experiments would also be an explanation for the valley structures encountered between several of the Toma Hills, where groundwater can be heard “gurgling” occasionally. As this is an indication for faster flowing water, it can be considered a result of the internal erosion, going along with an increase of the hydraulic conductivity, experimentally observed by Chang and Zhang (2011). In addition, several springs are occurring on the northern slope of the Fernpass rockslide where finer material is still being eroded (as can be seen in the Biberwier limnokrene), proving that internal erosion is a still ongoing process. This means that steady-state conditions did not fully develop yet, though the erosion capacity (as shown by the decreasing amount of finer material being transported in the tank experiments) will decrease under long-term conditions.

Although the experiment was not quantitative, and the boundary conditions changed since the rockslide occurred, we estimate that the 50–70-m-high Toma Hills were largely formed 140 to 580 years after the rockslide came to its halt. This assumption is based on the 1–3-cm hill formation within 30 experimental days and that surface run-off or other processes did not affect the elevation of the characteristic Toma Hill’s flat top. This time frame coincides with the results of Sterpi (2003) that at a hydraulic gradient of 0.17, about 95% of her fine material are eroded after 200 years, going along with sediment settling. As crystalline erratica still occur often on top and on the Toma Hills’ flanks, surface run-off was very likely not the main contribution to the Toma Hill formation, because these erratica would already have been eroded. Based on the results of Cui et al. (2017), who observed that fine particles are transported in the subsoil during rain events and the observations during our laboratory experiments, we conclude that similar transport processes also occurred in the initial phase of Toma Hill formation. We also conclude that the formation of the Toma Hills is a still ongoing process, as indicated by “gurgling” water and the occurrence of at least one known limnokrene.

Remark

In this paper, we are citing one of the latest monographs about landslides: *Progress in Landslide Science*, edited by Sassa et al. (2007). We are doing that to show that also other nations are heavily involved in this type of research. Yet, it is somehow disappointing that the editors and authors of this 2007 publication are largely ignoring the outstanding work that has been done and still is done relating to rockslides or landslides in Austria, Switzerland, France and Germany. When the first chapter of the book is called “Landslide Science as a New Scientific Discipline”, it is clear evidence that outside the German-speaking world, not much is known about the early pioneers of Penck, Brückner or Abele and the newer work by v. Poschinger, Prager or Imre—just to name some of the most cited authors. Looking to the authors of the 2007 book, this is not astonishing: nearly 60% of them come from Japan, and no single German-speaking author is included. Only one of the papers we are referring to in this paper is cited in Sassa et al. (2007) and no reference to the outstanding Flims or Vajont Valley rockslides is given. This might mainly be due to the language barrier: most of the important early work has been published in German and French and, therefore, might not have been accessible to the authors and editors. In addition, one of the most relevant conferences about Austrian and Swiss rockslides, the “Geoforum Umhausen”, is held in German language only and therefore restricts the spread of knowledge about rockslides. It is therefore an advantage that the international journal *Landslides* was founded in conjunction to the meeting that lead to the publication of Sassa et al. (2007). Let us hope that this journal is heavily used also by the middle European authors in the future.

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