Mass-Movements in Cold and Polar Climates

Þorsteinn Saemundsson, Costanza Morino, Susan J Conway

► To cite this version:

Þorsteinn Saemundsson, Costanza Morino, Susan J Conway. Mass-Movements in Cold and Polar Climates. Reference Module in Earth Systems and Environmental Sciences, Elsevier, 2021, 10.1016/B978-0-12-818234-5.00117-6 . hal-03356287

HAL Id: hal-03356287

<https://hal.science/hal-03356287>

Submitted on 27 Sep 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Mass-Movements in Cold and Polar Climates

Þorsteinn Sæmundsson^{1,2}

Costanza Morino³

Susan J. Conway⁴

1. Department of Geography and Tourism, University of Iceland, Askja, Sturlugata 7, 101 Reykjavík, Iceland

2. Institute of Earth Sciences, University of Iceland, Askja, Sturlugata 7, 101 Reykjavík, Iceland

3. Laboratoire Environnements, Dynamiques et Territoires de la Montagne UMR-CNRS 5204, Université Savoie Mont Blanc, Chambéry, France

4. Laboratoire de Planétologie et Géodynamique de Nantes UMR-CNRS 6112, Université de Nantes, France

14 **Abstract**

15 Mass-movements in cold and Polar climates often involve permafrost and ice and
16 hence these two phenomena are recurring themes throughout this chapter. We
17 consider specifically mass movements in glacial, periglacial and paraglacial settings.
18 For each environmental setting we describe the types of mass movement that have
19 been documented in the literature, describing the current research foci and remaining
20 challenges. We specifically highlight that mass-movements in cold and Polar climates
21 are particularly sensitive to climate change, because of the involvement of permafrost
22 and ice in their triggering and dynamics and therefore we may anticipate an increasing
23 frequency and increased hazard from these phenomena in the future in response to
24 unprecedented rates of environmental change.

25

26 **Keywords:** Rapid mass movements, active-layer-detachment slides, retrogressive-
27 thaw slumps, debris flows, rock/debris falls, rock/debris slides, rock/debris avalanches,
28 deep seated gravitational slope deformation (DSGDS), slush flows, ice-flows, snow-
29 avalanches, permafrost, glacial environments, periglacial environments, paraglacial
30 environments,

1. Introduction

Mass movement refers to the processes of downslope movement of rock, debris and soil under the influence of gravity (Crozier, 2002; Hutchinson, 1968). Mass wasting, mass movement, slope movement or slope failure are commonly used as synonyms. Another commonly used term for discrete slope movements is “landslides” (Crozier, 1989), and these movements are set apart from processes of subsidence and creep that usually lack discrete failure boundaries. Mass movements are generally divided into slow and rapid mass movements. Slow mass movements evolve over extended periods of time from months to decades or longer, such as deep-seated gravitational slope deformations (e.g., Dramis and Sorriso-Valvo, 1995). They also include phenomena like solifluction, a process that originates from the action of freeze-thaw cycles that induce downslope displacement in general at a rate of at most 1 m/year of soils in cold environments, where vegetation is lacking or sparse (e.g., Andersson, 1906; Ballantyne and Harris, 1994; Washburn, 1980). In contrast, rapid mass movements usually refer to high-magnitude, low-frequency processes that can be extremely fast moving (up to the scale of 5 m/s; Hungr, 2007).

Mass movements are classified in a number of ways, for example, according to the type of material, the type of movement, the volume of displaced material, and the extent of the material’s spreading area (Cruden and Varnes, 1996; Hungr et al., 2014; Varnes, 1978). Varnes (1978) developed a classification system for slope movements, based on five possible types of movement (fall, topple, slide, spread and flow) and on the type of material (rock, debris and earth). In Varnes' (1978) classification, slow processes such as subsidence, creeping and solifluction are not accounted for, and are considered by other authors (Sidle and Ochiai, 2006). Here, we adopt the updated Varnes landslide classification from Hungr et al. (2014), where the most significant

changes from the initial Varnes' version are: i) the use of textural classes to replace the term "earth", which has no standard definition in either geological or geotechnical material description schemes; ii) the reintroduction of "ice" as type of material, because many destructive mass movements on mountain slopes contain varying proportions of ice; iii) the introduction of slow mass movements under the movement type of "slope deformation".

This chapter will specifically describe and discuss mass movements in cold and polar environments. We divide this chapter into three sections which consider the following geomorphological and environmental settings: glacial, periglacial and paraglacial. Glacial environments are those where the accumulation of ice and snow is favoured to such an extent that bodies of ice accumulate on hillslopes or even flat ground and then flow *en masse* (glaciers or ice caps).

Periglacial environments are those where 1) the process of ground-freezing and thawing is dominant (Tricart, 1956); 2) permafrost - defined as soil or rock with a temperature below 0°C continuously for >1 year (Dobinski, 2011; French, 2007; Muller, 1945; Péwé and Brown, 1973; Subcommittee, 1988; Washburn, 1980) - is present.

Paraglacial environments are non-glacial and landforms in this type of environments are formed during and after the deglaciation (Slaymaker, 2004; Church and Ryder, 1972). The paraglacial processes in non-glacial environments are though directly influenced by glaciation (Church and Ryder 1972).

In each section we will describe the types of mass movement that have been documented in each environment, describing their general geomorphic characteristics, behaviour/dynamics, and triggering factors. We will highlight remaining open research questions, or key areas of active research. Finally we discuss the role of climate change in modulating the hazard posed by the mass movements in these three environments.

2. Rapid Mass Movements in glacial environments

Mountainous cold and polar environments form steep-slope environments conducive to mass failures and to the presence of glaciers, hence it is not surprising that the two phenomena interact. There are four broad configurations of this interaction:

- Landslides can fall on top of glaciers without entraining a significant portion of the glacier itself so called “supra-glacial landslides”.
- Landslides can fall on top of glaciers and in so doing entrain a significant portion of the glacier ice, resulting in rock-ice avalanches.
- Glaciers themselves can fail catastrophically resulting in ice avalanches. Such ice avalanches can themselves entrain debris resulting in rock-ice avalanches.
- Glaciers can advance over and remobilise landside deposits (e.g., **Burki et al., 2009**; Cook et al., 2013). Although glaciers could be considered as a type of mass movement, they are specifically discussed in the “Cryospheric Geomorphology” volume of this encyclopedia, and hence this remobilisation will not be detailed further in this chapter. However, this type of reworking is important in the context of supraglacial landslide deposits and will be briefly mentioned in that context.

In the following sections we will discuss first supra-glacial landslides, then ice and rock-ice avalanches.

2.1 Supra-glacial landslides

Spectacular examples of large-scale rock avalanches falling onto glaciers are documented in the literature, mainly from the United States (Post 1965, Shreve 1966,

Dufresne et al. 2019, Crandell & Fahnestock 1965), the Himalayas (Hewitt 1988, 2009a) and the New Zealand (Chinn et al. 1992). The main characteristic of such rock avalanches is the exceptionally long distances reached by the deposits over the ice surface. Several large-scale mass movements which have fallen onto glaciers during recent decades have been described and an international dataset with fall height, runout and volume has been developed (e.g. Schneider et al. 2011, Deline et al. 2015a).

Landslides falling onto glaciers have deposits that differ from their counterparts that fall onto other terrain types due to the interaction with the ice. Most notably, their runout can be a lot greater than other landslides (e.g., Evans and Clague, 1994; Pirulli, 2009; Sosio et al., 2012). They tend to spread out, forming sheets of debris, which cover large areas (Figure 1; e.g., Delaney and Evans, 2014). Tongue-shaped, multi-lobed margins (Dufresne et al., 2019; Shreve, 1966; Shugar and Clague, 2011) and longitudinal furrows/ridges/bands (e.g., Dufresne and Davies, 2009) are other characteristics associated with these landslide deposits (Figure 1). A greater fragmentation of the rockmass is observed compared to non-glacial slides (Delaney and Evans, 2014). These observations are linked to the fact that the falling debris moves over a low-friction surface. Details on how the ice and snow incorporated in the landslide affect the physical processes which determine the landslide's motion are complex and debated (Pudasaini and Krautblatter, 2014; Schneider et al., 2011; Sosio et al., 2012). It should also be noted that not all mass wasting onto glaciers causes excessive runouts or distinctive deposits (e.g., Deline, 2009).

Similar to landslides in general, the triggers for such landslides are linked to a wide variety of factors, including seismic events (Shreve, 1966) and rockwall permafrost degradation (Coe et al., 2018), but of particular interest is the potential link with glacial retreat (see below).

Figure 1: Examples of supraglacial rock avalanches. (a) On February 16, 2014 a rock avalanche detached from Mount La Perouse in Glacier Bay National Park, Alaska, USA. Relief from head scarp to toe is about 1770 m. Photo taken on March 6, 2014 by Marten Geertsema. (b) The Morsárjökull rock avalanche in Iceland, which occurred on 20th March 2007. Width of the deposit is ~350 m and the relief from head scarp to toe is ~640 m. Photo taken in July 2007 by Matthew Roberts.

Snowmelt is often one of the triggers of the ground-saturation that leads to landslides (e.g., Moreiras et al., 2012), but the influence of the incorporation of snow itself into the body of landslides is less-well studied. Yamasaki et al. (2014) found that the incorporation and propagation over deep snow alone can increase the mobility of a landslide. Dufresne et al. (2019) reported that that passive sliding on snow atop of a glacier caused the Lamplugh rock avalanche to slide “silently”, or aseismically. This mechanism has been inferred to be the origin of many “silent” supraglacial landslides

not detected by seismometers but instead in optical remote sensing (Smith et al., 2020).

The attempt to understand the dynamics of these landslides is partly driven by a need to understand the long runout of these landslides, as this can pose hazard to downslope communities and infrastructure, particularly if the landslide debris falls into the sea or terminal lake (e.g., Dufresne et al., 2018 a,b; Hubbard et al., 2005).

Understanding the magnitude-frequency of this type of landslide is important for understanding their role in landscape evolution at geological timescales, yet this is remarkably hard to quantify as deposits are usually unrecognisable in the landscape due to glacial reworking (e.g., Schleier et al., 2015). Debris that falls in the accumulation zone can be hidden by snowfall then rapidly sequestered into glaciers on the order of months (e.g., Dunning et al., 2015; Smith et al., 2020). Hence, deposits that fall on the ablation zone are transported down-glacier and contribute to the glacial deposits which are reworked beyond recognition at geological timescales. Some success has been obtained by monitoring seismic signals (e.g., Ekstrom and Stark, 2013), but this only gives a snapshot of the situation at the present day. These landslides are on the continuum in our understanding of the role of mass movements in landscape evolution during glacial retreat (see Section 4 on mass movements in Paraglacial environments) and it is still an open question as to whether paraglacial or supraglacial mass movements play a greater role in shaping what we recognise today as the typical post-glacial landscape.

These landslides also play a role in conditioning the behaviour of glaciers and have therefore been studied by glaciologists in order to understand glacial response to changing climate and the sedimentary deposits (e.g., Reznichenko et al., 2011). Debris in the ablation zone can alter glacial dynamics by shutting off ablation (e.g., D'Agata and Zanutta, 2007), or accelerating it. Debris can accelerate the glacier

motion (e.g., Shulmeister et al., 2009) and provoke surging behaviour (e.g., Hewitt, 2009a). Equally, thick isolating debris can decelerate, or stall glacial movement. Supraglacial debris inputs by landslides can confound attempts to use moraines as markers of glacial advances/retreats and therefore limit their use as climate markers. This is because they confuse the sedimentary record via the introduction of significant lags between temperature changes and recorded “events”. The dynamic interplay between debris and ice within the glacial system is an active area of research and the role of mass movements in this interplay is yet another piece to add to the puzzle. The key drivers motivating research in this field are: understanding glacial meltwater generation for its contribution to sea level change, hydroelectricity generation and as a resource for potable water. Generation of glacial meltwater and sediment can also generate hazardous process-linkages and pose significant risk to infrastructure and habitation.

2.2 Ice, Rock-ice and ice-rock avalanches

2.2.1 Snow, ice avalanches and slushflows

Snow and ice avalanches are a common type of rapid mass movement in cold and polar environments and are a critical driver of alpine glacial accumulation (e.g., Price et al., 2019). They take many forms because they can incorporate materials with a wide range of material properties (powder snow, sintered snow, ice, liquid water, rocks, debris, mud...) in varying proportions and can include phase changes e.g. from ice to water. From a geomorphology point of view many of these mass movements are transient as they do not supply significant sediment volume. Avalanche debris cones and strewn boulders are landscape elements that indicate the dominance of avalanches in downslope sediment transport (Figure 2b,c; e.g., Decaulne and

200 Sæmundsson, 2010; Jomelli and Francou, 2000; Luckman, 1992). Research into snow
201 avalanches is mainly driven by a desire to understand the risk and design engineering
202 solutions to mitigate it.

203
204 *Figure 2: Examples of slush flow and avalanche deposits. (a) Freshly deposited*
205 *slushflow from the Mt. Bleikkollubólstindur above the farm Hof in SE, Iceland. Photo*
206 *taken by Brynja Kristjánsdóttir 2021. (b) Aerial view of two chutes in the Hólsádalur*

valley, northern Iceland, which host frequent snow avalanches whose deposits are found on the opposite side of the stream in the valley. The viewpoint of panel c is noted on the figure. Credit Loftmyndir ehf. (c) Field view of avalanche deposits within which pebbles from the stream below are found. A person is standing atop the deposits for scale. Photo taken by Þorsteinn Sæmundsson 2016.

Slush flows are mass movements that behave like debris flows (described fully in Section 3), but contain a significant amount of snow or ice (e.g., André, 1990; Decaulne and Sæmundsson, 2006; Elder and Kattelman, 1993; Gude and Scherer, 1995; Hétu et al., 2017; Larocque et al., 2001; Nyberg, 1989; Pérez-Guillén et al., 2019). They are characterised by levees and lobate tongues (Figure 2a) and have a longer runout than dry avalanches. They are capable of transporting clasts up to metres in size, although some slush flows contain only snow and are usually called “slush avalanches” or “wet avalanches” (Figure 2a; e.g., Bartelt et al., 2012; Eckerstorfer and Christiansen, 2012). Slush flows are triggered in a similar way to debris flows, by saturation of the sliding mass by snowmelt or precipitation. There has not yet been any research that permits the distinction of slush flow and debris flow deposits in the sedimentary record meaning their impact on the landscape at geologic timescales is broadly unknown. Slush flows are generally studied alongside snow avalanches or debris flows and form part of a spectrum of processes that can pose hazard to populations and infrastructure in steep mountainous environments.

2.2.3 Ice, ice-rock and rock-ice avalanches

Mass movements in glacial areas can originate from the glaciers themselves, the hillslopes, or both. Once initiated these mass movements can further interact with

downslope debris, snow, ice or rock causing complex events that can be hard to classify uniquely (e.g., Petrakov et al., 2008).

There have been three recent well-reported cases where large portions of glaciers detached to form rapid mass movements (Evans et al., 2009a; Falaschi et al., 2019; Gilbert et al., 2018; Kääb et al., 2018; Tian et al., 2017). For example, the collapse of two nearby glaciers in the Aru range in Tibet was widely reported in the media because of the remarkable visibility in satellite images (Figure 3a). However, these mass movements leave very little geomorphological evidence in the landscape, because their main constituent is ice which is rapidly ablated in the relatively warm locations where the deposits are laid down. Hence, the frequency of such failures in the geologic record is unknown. The limitation to a handful of present-day cases means that, although these types of failure pose considerable risk, there are many open questions as to how they are triggered.

Figure 3: (a) Pléiades 3D rendering of the two glacier collapses in the Aru Mountains, Tibet with kind permission of Etienne Berthier at the CNRS. The fan in the foreground is ~ 2 km across. Image credit CNES Pléiades, Airbus Defence and Space. (b, c and d) Mt. Kazbek in Southern Russia before and after a hanging glacier collapsed from the slope of Mt. Dzhimarai-Khokh onto the Kolka Glacier which

triggered an avalanche of ice and debris that went over the Maili Glacier terminus then slid more than 24 km burying villages in North Ossetia on 20th September 2002. (b, c) False-colour images from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) aboard NASA's Terra satellite. The deep reds show vegetated land surfaces, grey areas are bare rock, and white shows ice-cover. (d) True colour image from the Advanced Land Imager instrument on the EO-1 spacecraft. Images available from <https://earthobservatory.nasa.gov>

Landscape change does occur where glaciers and rock detach together, or rock avalanches impact and incorporate glaciers or rock glaciers (Evans et al., 2009b; Haeberli et al., 2004; Schneider et al., 2011). Triggering of these large, complex events has been attributed to thermal perturbations from both climate and geothermal origins (Huggel, 2009; Huggel et al., 2012). These events occur on the flanks of volcanoes as well as in in uplifted mountain areas. They have no specific geomorphic signature and can display the attributes generally associated with rock avalanches (Figure 3b-d), debris avalanches, debris flows and supraglacial landslides, with their defining characteristic being their large mobility. The large-scale of these events and their mobility means they are both rare, but can be extremely hazardous (Evans et al., 2009b; Iribarren Anaconda et al., 2015). The deposits of ancient rock-ice avalanches are reported in the literature, but only when the role of the ice is thought to have played a minimal effect on the resulting geomorphology (Robinson et al., 2014). It is unclear how important such large mass movements are in long-term landscape evolution, because their sedimentary signal is hard to detangle from other mass movements with which they share morphologic properties. The main research challenge lies in dissecting the dominant processes within the evolution of the mass movement to understand the mobility and potential hazard of such flows. Predicting where and when

such huge movements might occur remains the major challenge, as it does for rock avalanches in general.

3. Mass Movements in periglacial environments

Periglacial environments are sensitive to rapid changes in local climate, snow cover, topography, incoming radiation, ground and soil characteristics, which influence the variability of ground thermal regimes at local scale (e.g., Harris and Pedersen, 1998; Harris *et al.*, 2009; Thomas *et al.*, 2009; Hasler *et al.*, 2015). As average temperatures continue to rise, permafrost and permafrost ice are expected to degrade (Biskaborn *et al.*, 2019; Blunden and Arndt, 2020; Christiansen *et al.*, 2010; Gislås *et al.*, 2017; Harris *et al.*, 2009; Romanovsky *et al.*, 2010; Slater and Lawrence, 2013), particularly at high latitudes, where average yearly temperatures are increasing at faster rates than global averages (Alexeev and Jackson, 2013; Blunden and Arndt, 2020; Masson-Delmotte *et al.*, 2006; Screen *et al.*, 2012).

In the last decades, mass movements have been studied in relation to degrading permafrost conditions (Ashastina *et al.*, 2017; Blais-Stevens *et al.*, 2015; Fischer *et al.*, 2006; Gruber and Haeberli, 2007; Haeberli *et al.*, 2017a; Huscroft *et al.*, 2003; Patton *et al.*, 2019a; Ravanel *et al.*, 2017). Mass movements are particularly common under periglacial conditions, as freeze-thaw weathering causes deterioration of rock, sediments and soils (e.g., Dobinski, 2011; Harris *et al.*, 2001). Frost action promotes mechanical fragmentation of rocks (Matsuoka and Murton, 2008; Prick, 2003), with resulting loose material available for transport (Van Vliet-Lanoë and Fox, 2018). Degrading-permafrost conditions reduce slope stability, as reaching -1.5°C - 0°C or melting temperatures causes reduction in ground shear strength, loss of ice/rock interlocking, increase in the hydraulic permeability, and ice segregation (Davies *et al.*,

2001; Draebing et al., 2017; Draebing and Krautblatter, 2019; Gruber and Haeberli, 2007; Krautblatter et al., 2013a; Matsuoka and Murton, 2008; Murton et al., 2006).

Different types of mass movements can occur in terrains affected by permafrost, which in high-latitude lowland permafrost regions is classified into zones based on its geographic extent and continuity. Permafrost is defined continuous where frozen ground is present at 90-100% localities, while it is defined discontinuous where units of frozen ground (50-90%) are separated by unfrozen areas. Sporadic and isolated permafrost is restricted to limited areas, covering respectively 10-50% and 0-10% of the terrain considered as permafrost (e.g., Black, 1954; French, 2007; Péwé, 1983). Permafrost is also present at lower latitudes at high elevation, it is called mountain permafrost, and it is characterised by an extreme spatial variability (Gruber and Haeberli, 2007; Haeberli et al., 2011; Péwé, 1983; Stearns, 1966). Mass movements in periglacial environments can be distinctive of a particular class of permafrost or ubiquitous in various permafrost terrains, and we will specifically discuss: active-layer-detachment slides, retrogressive-thaw slumps, debris flows, rock/debris falls, rock/debris slides, rock/debris avalanches.

3.1 Active-layer-detachment slides

Active-layer-detachment slides are localised slope failures (Figure 4) that are confined to the permafrost active layer in continuous and discontinuous ice-rich permafrost terrains (Leibman, 1995; Lewkowicz, 1990; Lewkowicz et al., 1992; Lewkowicz and Harris, 2005a,b). They fall in the suite of landforms resulting from the process of thawing of ice-rich permafrost or melting of massive ground ice called thermokarst (French, 2007; Kokelj and Jorgenson, 2013). They occur due to a reduction in shear strength resulting from high porewater pressures and low effective

327 strengths, due to rapid thawing of ice lenses at the base of the active layer or in the
328 upper part of permafrost in fine-grained soils with low hydraulic conductivity (French,
329 2007; Lamoureux and Lafrenière, 2009; Lewkowicz, 2007). The movements generally
330 involve shallow (~1 m deep) failures over a thin shear zone or shear plane on very low-
331 angled slopes (Kokelj and Jorgenson, 2013; Lewkowicz and Harris, 2005a). Few direct
332 observations exist of in-action active-layer-detachment slides, and they develop over
333 a period of minutes to several days by a single almost instantaneous sliding movement
334 or by progressive movements of a few metres per hour, reaching runout distances of
335 up to several hundred metres (Lewkowicz, 2007; Lewkowicz and Harris, 2005a).
336 Active-layer-detachment slides usually occur in clusters (Balser et al., 2009; Couture
337 and Riopel, 2008; Lamoureux and Lafrenière, 2009), generally after warm summers,
338 rapid spring thaw, high snowmelt, prolonged summer precipitation, or forest or tundra
339 fires (Gooseff et al., 2009; Lamoureux and Lafrenière, 2009). Active-layer-detachment
340 slides can enhance slope sediment and solute yields in stream systems (Lamoureux
341 and Lafrenière, 2009; Lewkowicz, 2007; Lewkowicz and Kokelj, 2002), impact the
342 patterns of tundra vegetation communities (e.g., Cannone et al., 2010; Frost et al.,
343 2018; Verdonen et al., 2020) and mobilise carbon sequestered in shallow permafrost
344 (e.g., Abbott et al., 2015; Beamish et al., 2014; Turetsky et al., 2019; Woods et al.,
345 2011). An increase in active-layer-detachment slides has been observed also in the
346 western Antarctic Peninsula region, where permafrost has reached degrading
347 temperatures (– 0.4 to – 3.1 °C; because the area has been affected by the greatest
348 degree of warming in the past 50 years (Bockheim et al., 2013; Guglielmin, 2012;
349 Vieira et al., 2008). Research is particularly focussed on the role these mass
350 movements have in releasing carbon contributing to the positive feedback mechanism
351 of the warming climate releasing carbon trapped in continuous permafrost, which goes
352 on to exacerbate future warming and so on. Although areas with continuous permafrost

are sparsely inhabited, these mass movements can pose risk to infrastructure (e.g. Behnia and Blias-Stevens 2018), but also to archaeological investigations (Walls et al. 2020).

Figure 4 - Active-layer detachment slide (perimeter marked with white dashed line), Fosheim Peninsula, Ellesmere Island, Nunavut, Canada. Modified after Lewkowicz, 2007.

3.2 Retrogressive-thaw slumps

Retrogressive-thaw slumps are semi-circular depressions resulting from thawing of ice-rich permafrost terrains (Burn and Friele, 1989; French, 2007; Lantuit and Pollard, 2008). They occur where ice-rich permafrost is exposed to thaw, and are generally triggered by wave action along coasts, undercutting erosion of banks along streams or lakes, or active-layer-detachment slides (Lantuit and Pollard, 2008; Patton et al., 2019b). Thaw slumps cannot be classified as “rapid movements” — they can develop over decades (Lacelle et al., 2010) — but phenomena like falls or flows can transport thawed material from the slump headwall as secondary movements (Lantuit et al., 2012; Murton, 2001). They can cover vast areas, from 0.05 up to 0.8 km², as in the case of the Batagaika mega-thaw-slump (Figure 5), which in the last thirty years has increased its size by three times, reaching an area of 0.78 km² in 2018 (Vadakkedath et al., 2020). Thaw slumps expose ground ice to thaw, modify the landscape, and can erode and transport thawed material to lakes, valley-bottoms or coastal zones (Kokelj et al., 2015; Lafrenière and Lamoureux, 2019; Lantuit et al., 2012; Murton et al., 2017).

Retrogressive thaw slumps are showing an accelerated activity due to global warming in continuous and discontinuous permafrost terrains, from western Canadian Arctic to Siberia (e.g., Ashastina et al., 2017; Jones et al., 2019; Segal et al., 2016). Thousands of retrogressive thaw slumps have formed in the last 30 years due to extreme temperatures in High Arctic (Banks, Island, Canada), and are modelled to rise to over 10,000 per decade by 2075 (Lewkowicz and Way, 2019). Hence, similarly to active-layer detachment slides current research focuses on the impact climate change is having on these mass movements.

Figure 5 - The Batagaika mega-thaw slump in the Chersky Range area, Sakha Republic, Russia. CNES/Airbus Image from Google Earth, 6th October 2019.

3.3 Debris Flows

389 Debris flows are rapid, downslope flows of poorly sorted debris mixed with water
390 (e.g., Iverson, 1997), and are common on the slopes of periglacial environments,
391 including in the European Alps to Iceland (Figure 6), from the Tibetan Plateau to
392 Antarctica (Decaulne and Sæmundsson, 2006b; Morino et al. 2019; Cannone et al.,
393 2006; Oliva and Ruiz-Fernández, 2015; Sattler et al., 2011; Yu et al., 2020). Debris
394 flows can travel over long distances and transport large amounts of material at great
395 speed (Zimmermann and Haeberli, 1992). They are characterised by a central
396 channel, the construction of levees on one or both sides of channel, and a terminal
397 depositional lobe or lobes (e.g., Costa, 1984). Steep slopes, loose materials and wet
398 conditions are favourable for the occurrence of debris flows (Lewin and Warburton,
399 1994). This combination of factors is extremely common in periglacial mountain
400 environments, where climatic warming during the 19th and 20th centuries has
401 indirectly increased the frequency of debris flows (Decaulne and Sæmundsson,
402 2006b; Haeberli et al., 1990; Rebetez et al., 1997; Zimmermann, 1990; Zimmermann
403 and Haeberli, 1992). This increased frequency is not directly linked to the thaw of
404 perennially frozen debris in the source areas (i.e., meltwater producing a source of
405 fluid), but it has been shown that there is a link between the initiation zones and the
406 thickening of the active layer as a reaction to the increase in atmospheric temperatures
407 (Sattler et al., 2011). This has also been observed where the interface between frozen
408 and unfrozen ground seems to control the depth of movement in debris flows (Huscroft
409 et al., 2003). Active-layer failures may result from increased concentration of water
410 above the permafrost table, generating debris flows and mass failures (Kummert et al.,
411 2018; Lugon and Stoffel, 2010; Marcer et al., 2020), particularly in formerly frozen
412 sediment mantled slopes (Davies et al., 2001; Fischer et al., 2013; Haeberli, 2013).
413 Recently deglaciated terrains have an abundance of debris often perched in unstable

positions that are particularly susceptible to remobilisation by debris flows (Ballantyne 2002).

Debris flows often pose hazard to human habitation and infrastructure and the main challenge lies in developing tools to effectively predict where and when they will be triggered in addition to understanding their runout. On one hand this requires, a deeper understanding of the physical mechanisms where significant effort is being put into focussed monitoring and developing sophisticated physics-based models. And on the other hand it also requires the development simple yet effective tools to enable public authorities and other stakeholders to mitigate the hazard posed by debris flows.

Figure 6 - The debris flows above in the Gleiðarhjalli slope above the town of Ísafjörður, Westfjords, Iceland (Decaulne and Sæmundsson, 2006b; Morino et al. 2019).

428

429 **3.4 Rock/debris falls**

430 Rock/debris falls are mass movements on steep slopes (Fig. 7a), rock/debris slides
431 (Fig. 7b) are mass movements that occur along discrete surfaces, and rock/debris
432 avalanches are large-volume ($>1\text{M m}^3$) mass movements that cause fragmentation
433 during rapid transport (Fig. 7c) (Cruden and Varnes, 1996; Hungr et al., 2014). These
434 phenomena are frequent in mountain glacial and periglacial environments, usually in
435 paraglacial settings where glacial over-deepening, stress-release fracturing after
436 removal of glacial ice (Ballantyne, 2002; McColl and Davies, 2013), glacial
437 debuitressing (Blikra et al., 2006; Cossart et al., 2014), degrading permafrost (Clague
438 et al., 2012a; Deline et al., 2015a; Fischer et al., 2006; Gruber and Haeberli, 2007;
439 Krautblatter et al., 2013b; Magnin et al., 2020; Morino et al., 2019; Sæmundsson et
440 al., 2018), and cooling-warming cycles (Draebing, 2020) can all act to destabilise rock
441 walls and debris source areas. These factors can induce changes in the stress field
442 and expose previously insulated surfaces to altered mechanical and thermal erosion
443 (Draebing et al., 2017; Haeberli, 1997; Jia et al., 2015; Krautblatter et al., 2013b;
444 Wegmann et al., 1998), which can consequently favour mass wasting processes. The
445 increase in temperatures in the last decades due to climate change has resulted in
446 increased activity of such rock/debris falls, slides and avalanches; a correlation
447 between exceptional heatwaves and rockfalls (Fig. 7a) has been established (Huggel
448 et al., 2012; Ravanel et al., 2017; Ravanel and Deline, 2008). When permafrost
449 degrades, physical changes also occur in the rock mass and in loose deposits (Allen
450 and Huggel, 2013; Draebing et al., 2017; Gruber and Haeberli, 2007; Harris et al.,
451 2009; Ravanel et al., 2017). After permafrost thaw, the shear strength of rock/debris
452 significantly reduces with warming (minimum factor of safety is between -1.5°C and

0°C) (Davies et al., 2001). Ice segregation and volume expansion subsequent to increased temperatures can lead to failures (Gruber and Haeberli, 2007). Elevated water pressure and reduced frictional strength can result from meltwater or ground-water flow in previously frozen masses (Harris, 2005). Ice-rich permafrost occurs in loose-deposits landforms such as rock glaciers, ice-cored moraines and talus slopes (Dramis et al., 1995; Isaksen et al., 2000; Kenner et al., 2017; Lukas et al., 2005; Monnier and Kinnard, 2015), and its degradation can cause a reduction in cementation, which can lead to the occurrence of falls, slides (Fig. 7b) or avalanches (Fig. 7c; Dramis et al., 1995). Rock and debris falls, slides and avalanches directly attributed to this mechanism have been reported from numerous locations in cold climates around the globe, including Alaska, Canada, European Alps, Greenland, Himalaya, New Zealand, Norway, Russia (Deline, 2009; Evans et al., 2009[a](#),[b](#),[c](#); Fischer and Huggel, 2008; Frauenfelder et al., 2018; Gruber et al., 2017; Huggel et al., 2012, 2005; Magnin et al., 2019; Patton et al., 2019a; Sosio et al., 2008; Svennevig et al., 2019). Much current research is focussed on mitigating the risk from such events and is reliant on understanding and modelling the influence of increasing temperature on the state of the permafrost, the influence of the associated hydrology which finally leads to the destabilisation of rock mass.

Figure 7 - Rapid mass movements caused by permafrost degradation. a. The Tour Ronde rock fall of 27th August 2015, Mont Blanc Massif, France (modified after Ravel et al., 2017); b. The Móafellshyrna debris slide of 20th September 2012, Tröllaskagi peninsula, Iceland (Sæmundsson et al. 2018, Morino et al. 2019); c. The Val Pola rock avalanche of 28th July 1987, Central Alps, Italy (modified after Crosta et al., 2004).

4. Rapid Mass Movements in Paraglacial Environments

Paraglacial environments represent the relatively rapid adjustment from deglaciated landscape to non-glacial conditions (Ballantyne 2002). A wide range of subaerial processes are active in these environments which can be active over different timescales and lead to different rates of landscape change (evolution). Many of these

processes are intimately associated with periglacial environments, already described in Section 3. Periglacial conditions usually only persist for a relatively short period after deglaciation, and here we focus on (large scale) Mass Movements that are not necessarily related to periglacial environmental conditions, yet occur in a paraglacial setting.

Massive rock slope failures are as frequent or more frequent in glaciated basins than in equivalent ice-free mountainous terrain (McSaveney 2002, Geertsema et al. 2006, Hewitt 2009a Deline et al. 2015a). Complex interactions between several factors can affect the occurrence of mass movements according to Pacione (1999); inherent factors (e.g. lithology, rock structure, slope form, topographic relief), preparatory factors (e.g. weathering, de-buttressing, climate change), triggering factors (e.g. earthquake, rainstorm) and factors that may affect mobility (e.g. glacial surface) (Agliardi et al. 2012, Deline et al. 2015b). According to Ballantyne (2002) the response of a rock slope to glacier down wasting has been reported to result in large rock avalanches, large-scale, progressive and slow rock mass deformation, and frequent rock fall events. Slope steepening caused by glacial erosion and unloading or de-buttressing due to glacial retreat often leads to rock slope failures (Agliardi et al. 2012, Holm et al. 2004, Lane et al., 2017, Stoffel & Huggel 2012). Thermal and mechanical alteration can result from cycles of ice loading and unloading and exposition of rock to new thermal regimes due to the glacier retreat (Cody et al., 2020; Coquin et al., 2015; Evans and Clague, 1994; Grämiger et al., 2017; McColl, 2012; McColl and Draebing, 2019; Mercier et al., 2017; Wegmann et al., 1998). Finally, permafrost fluctuations throughout the Holocene is likely a first order control on past and modern rock slope failures (Hilger et al., 2021).

Figure 8 A Deep seated gravitational slope deformation at Forkastningsfjellet in Spitsbergen documented by Kuhn et al. (2019, 2021). (a) Unannotated view towards the blocks that are sliding downslope. (b) Annotated view showing the location of the main sliding surfaces that define the different blocks with white arrows indicating displacement directions. (c) Side-on view of the same slope showing the rotation of the block nearest the coast. Images kindly provided by Reginald Hermanns.

Deep seated gravitational slope deformation (DSGSD, also called "sagging" or "sackung", Figure 8) are one of the adjustment processes which can be detected in

paraglacial setting and can be categorized as mountain slope deformation of steep, high mountain slopes, manifested by scarps and cracks, but lacking a defined rupture surface and slow movement rates (Hungr et al., 2014). DSGSD are large mass movements with long duration slow motion processes that can experience irregular rates of activity characterized by periods of rapid reactivating (Pánek et al. 2013) which often result in high volume and long-runout events (Hewitt et al., 2008; Hewitt, 2009a,b,c; Mege and Bourgeois, 2011; Pánek & Klimeš, 2016; Pedrazzini et al., 2013). The first observations of the geomorphic role and impact of DSGSD dates back to the 1940s, but recent developments in remote sensing, e.g. InSAR have made it easier to detect these slow movements which has led to increasing understanding and recognition of DSGSD (e.g. Ambrosi and Crosta, 2006; Colesanti and Wasowski, 2006; Hilley et al., 2004; Saroli et al., 2005; Teshebaeva et al. 2019).

DSGSD have been observed in various rock types and are generally characterized by discontinuous or poorly defined lateral boundaries (Ambrosi and Crosta, 2006; Varnes et al., 1990). According to Agliardi et al. (2001) diagnostic features of DSGSD can include: “morpho-structures (doubled ridges, scarps, counterscarps, etc.) similar to those observable, at a smaller scale, in cohesive soils landslides; size of the phenomenon comparable to the slope; present day low rate of displacement (mm/y, in alpine and prealpine areas); presence of minor landslides inside the deformed mass and ancient collapses of the lower part of the slope”.

DSGSD are not considered as imminent hazardous phenomena because of their slow movement rate, but a part of the creeping mass can evolve into multiple sequential failures or into fast large catastrophic slope failures such as rockslides and rock avalanche (Agliardi et al. 2012). These large-scale events, even though they are infrequent, can cause hazardous conditions e.g. on glaciers and surrounding areas (e.g. Deline et al. 2015b; Dufresne et al. 2019; Hewitt et al. 2011), in fjord environments

were rock-slope failures can generate tsunamis (Böhme et al. 2011; Kuhn et al. 2019) and in valley systems where large rock-slope failures can dam rivers (Oppikofer et al., 2020; Strom and Korup, 2006).

Many case studies of DSGSD have been described in various settings around the world, but it is difficult to understand their controlling factors due to the variety of geologic and environmental settings in which they occur (Agilardi et al. 2012). They are widespread in orogenic mountain ranges (Ambrosi and Crosta, 2006; Agilardi et al. 2009; 2012; Korup, 2006;), and have been described from the Central-Eastern Alps (Forcella, 1984; Forcella and Orombelli, 1984; Zischinsky, 1966), Norway (Böhme et al. 2013; Oppikofer et al. 2017; Schleier et al. 2016), Spitsbergen (Figure 8) (Kuhn et al. 2019; 2021), Iceland (Coquin et al. 2015; 2019) and other places.

Research challenges, on mass movements in Paraglacial environments and in some extent in Periglacial environments, have during the last decades focused more and more on the hidden hazard which DSGSD can cause to human habitation in these environments. Recent and future developments in remote sensing will without doubt deepen our understanding on the physical mechanisms and triggering factors for DSGSD. These developments will improve our monitoring and hazard analyses.

5. Climate change and hazard of mass movements in cold and polar climates

According to the definition of (Varnes, 1984), landslide hazard is defined as the probability that a landslide event of a certain magnitude occurs within a period of time in a given area. Landslide risk - as any other risk - refers to the expected degree of loss due to a landslide event, and it is the result of the product of the landslide hazard and the vulnerability, with the latter being the degree to which a community, a structure,

a service or an area is likely to be damaged by a hazardous phenomenon (UNDHA, 1992). Mass movements can be extremely dangerous, as they are processes that can severely threaten human life and affect infrastructures (Crozier and Glade, 2005; Geertsema et al., 2009; Haque et al., 2016; Kjekstad and Highland, 2009; Petley, 2012). Slope failures can involve different types of materials and can have a great diversity of velocities and fluid contents, making them hard to understand and produce the appropriate countermeasures.

Even if high level of uncertainty of global-climate predictions and the lack of spatial resolution of the available downscaled projections, there is a strong theoretical basis for increased landslide activity as a result of climate change (Borgatti and Soldati, 2010; Crozier, 2010; Gariano and Guzzetti, 2016; Haque et al., 2019; Wood et al., 2020). There are few studies (Coe, 2020; Coe et al., 2018; Schlögel et al., 2011; Uhlmann et al., 2013) that systematically evaluate and compare the magnitude, frequency, and extent of landslide events in glacial and periglacial environments on the long term (Allen et al., 2011; Bessette-Kirton and Coe, 2020; Hock et al., 2019). Cold environments are particularly sensitive to variations in atmospheric temperatures (Clague et al., 2012b; Huggel et al., 2012) that lead to an enhanced reaction of slopes to glacial retreat and permafrost degradation (e.g., Gruber et al., 2017; Gruber and Haeberli, 2007; Harris et al., 2009; Hock et al., 2019; Kos et al., 2016; Patton et al., 2019a; Schoeneich et al., 2011). As result of climate change, mass movements in cryospheric regions can be triggered by warming periods, freeze-thaw, rapid snowmelt, intense and/or prolonged precipitation (Huggel et al., 2012, 2010; Stoffel and Huggel, 2012). From a hazard perspective, understanding how these factors will impact failures' frequency and magnitude is becoming increasingly important.

In glacial environments, retreat and thinning of glacial ice reduces lateral support of steep rock walls (Ballantyne, 2002). This can generate a reduction in slope stability by

debutressing steep valley walls (Lane et al., 2017), that are impacted by modifications in the stress field and subject to mechanical and thermal alteration, and consequently slope instabilities (Cody et al., 2020; Coquin et al., 2015; Evans and Clague, 1994; Grämiger et al., 2017; McColl, 2012; McColl and Draebing, 2019; Mercier et al., 2017; Wegmann et al., 1998). Failures linked to glacial retreat can range from small-scale rock fall to catastrophic rock/debris avalanches. As glacial environments are highly dynamic because of increasing atmospheric temperatures, the landslide hazard in these regions is more difficult to assess because of the changing zones of instability and initiation (e.g., Evans and Clague, 1988; Geertsema et al., 2006a,b; Kääb et al., 2005). The consequences of landslides in glacial environments can be more unexpected and severe than the events themselves, generating hazardous consequences because of dam-creation (Fan et al., 2020; Oppikofer et al., 2020; Strom and Korup, 2006), or tsunami if they reach the water (Dahl-Jensen et al., 2004; Dai et al., 2020; Dufresne et al., 2018a). A better understanding of changes in slope stability caused by the loss of glacier ice could improve the definition of landslide hazard zones, aiding to protect areas and populations exposed to these hazards (Haeberli et al., 2017b; Hock et al., 2019).

Climate change is causing permafrost degradation at high latitudes and in mountain regions (e.g., Blunden and Arndt, 2020; Slater and Lawrence, 2013), and this is confirmed by local monitoring permafrost studies in the European Alps, Alaska, Canada, Siberia, Iceland, Greenland, northern Europe, the Tibetan Plateau, the Andes and the Antarctic Peninsula (Christiansen et al., 2010; Czekirda et al., 2019; Gislås et al., 2017; Harris et al., 2009; Panda et al., 2014; Pastick et al., 2015; Romanovsky et al., 2010; Westermann et al., 2017; Zou et al., 2017). Among the consequences of permafrost degradation, the most hazardous are mass movements like rock falls, debris flows, rock/debris avalanches (Darrow et al., 2017; Deline et al., 2015a;

Huscroft et al., 2004; Patton et al., 2019a; Schoeneich et al., 2011). Mountains host 12% of the global population (Schild, 2008), and about a quarter of the permafrost on Earth is hosted in mountainous terrains (Gruber, 2012). Therefore, mass movements in periglacial mountain environments pose at direct risk the local population and infrastructure (e.g., Haeberli, 2013; Schoeneich et al., 2011), and can impact local economies and tourism, communication and transport systems and power generation industries (e.g., Arenson and Jakob, 2017; Duvillard et al., 2019; Mourey et al., 2019; Pröbstl-Haider et al., 2016). The unpredictability of the extension and speed of permafrost degradation makes the understanding of landslide processes in mountain periglacial environments even more urgent, in order to predict and mitigate their hazardous consequences.

Due to their magnitude and mobility, rock/ices avalanches are also particularly hazardous in both glacial and periglacial environments (Davies and McSaveney, 2012; Evans and Clague, 1988; Geertsema et al., 2006a, 2006b; Hungr and Evans, 2004). Several examples with volumes ranging up to millions of cubic metres include the rock/ice avalanche from Monte Rosa in the western Italia Alps in 2007 (Fischer et al., 2011), the rock/ice avalanches at Mount Munday in 1997 and at Kendall Glacier in 1999 in British Columbia (Delaney and Evans, 2014; Geertsema et al., 2006a), the 2005 Mt. Steller rock/ice avalanche in Alaska (Huggel et al., 2008), the 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus, with the latter one causing the death of ~140 people (Evans et al., 2009c; Haeberli et al., 2004; Huggel et al., 2005).

Hazard related to mass movements in both glacial and periglacial environments include also catastrophic phenomena such as glacial lake outburst floods (GLOFs). GLOFs are floods that originate from lakes formed behind a landslide dam (Fan et al., 2020; Oppikofer et al., 2020; Strom and Korup, 2006) or dammed by a frontal moraine or glacial ice (Carey et al., 2012; Clague and Evans, 2000; Cook et al., 2016; Haeberli

et al., 2016; Harrison et al., 2018; Hubbard et al., 2005; Richardson and Reynolds, 2000; Veh et al., 2019; Westoby et al., 2014). The lakes can drain catastrophically for several reasons, including mass movements into the lake (Figure 9) (Costa and Schuster, 1988; Korup and Tweed, 2007). Their influence on settlements and infrastructure can be devastating (e.g. Kjartansson 1967; Dahl-Jensen et al., 2004; Stoffel & Huggel, 2012; Dai et al., 2020; Deline et al., 2015b; Dufresne et al., 2018a, b). In regions like the Himalaya, GLOFs have been recognised as the dominant long-term drivers of fluvial erosion and valley evolution (Cook et al., 2018). They are extremely destructive due to their magnitude and unpredictability (Khanal et al., 2015; Mool et al., 2011; Schwanghart et al., 2016; Shrestha et al., 2010). GLOFs' frequency and magnitude are thought to be increasing in response to climate change (Bajracharya and Mool, 2009; Bolch et al., 2011; Dussaillant et al., 2010; Harrison et al., 2018; Lutz et al., 2016). This is due to the fact that outlet glaciers have thinned and retreated from their basins, resulting often in unstable slopes combined with accelerated formation and rapid growth of proglacial lakes (e.g. Guðmundsson et al. 2019; IPCC, 2012).

Figure 9. The Steinsholtstjökull rockslide and the GLOF in the Steinsholtisdalur valley in 1967. The extent of panels d and e are shown as black boxes on panels a-c. (a) Aerial photograph taken in August 1960 (b) Aerial photograph taken in September 1967, eight months after the rock slide. (c) Modern image showing clearly that the headwall of the slide was about 900 m long. (d) Detailed view showing a 100 m long fracture in the Innstíhaus above the Steinsholtstjökull outlet glacier. (e) Same view as in panel d, but using the modern image shown in panel c to illustrate the amount of material mobilised. Aerial images are from the National Land Survey of Iceland.

Landslides and mass movements such as active-layer-detachment slides and thaw slumps in degrading-permafrost terrains can impact on the environments in which they

occur. The physical and ecological structure of hillslopes and fluvial networks can be affected by an increased sediment, nutrients, and soil displacement of mass movements (Abbott and Jones, 2015b; Bowden et al., 2008; Gooseff et al., 2009; Osterkamp et al., 2009; Turetsky et al., 2019; Zongxing et al., 2016). These phenomena can generate disturbance to terrestrial and aquatic ecosystems (Bowden et al., 2008; Callaghan et al., 2011; Cannone et al., 2010; Osterkamp et al., 2009; Racine et al., 2004). An increase in mass movements occurrence in cold and polar terrains due to permafrost thaw because of the warming climate may also accelerate the release to the atmosphere of Pleistocene sequestered carbon (Belshe et al., 2013; Grosse et al., 2011; Masyagina et al., 2019; Pautler et al., 2010; Schuur et al., 2009, 2008; Tarnocai et al., 2009). Thaw-slumps and active-layer-detachment-slides activity in the Arctic has enhanced in the last decades (Jorgenson and Osterkamp, 2005; Luo et al., 2019), generating alterations in the water quality of nearby lakes and streams (Kokelj et al., 2013; Lafrenière and Lamoureux, 2019; Segal et al., 2016), vegetation and soils (Khomutov and Leibman, 2014; Lantuit et al., 2012), and trace gases (Abbott and Jones, 2015).

6. Conclusions

In this chapter, we emphasized the major types of rapid mass movements that reflect the most characteristic expression of rapid down-slope sediment transport in cold and polar environments under glacial, periglacial and paraglacial conditions. Many of these rapid mass wasting processes are not exclusive to the glacial, periglacial and paraglacial domains, but we highlighted that permafrost and ice are the critical agent in their development. We focussed on the specific attributes that distinguish these mass movements from ones in other environments and the

associated specific research challenges. Cryospheric terrains in mountainous and high-latitude environments are the most susceptible to slope stability problems, as warming temperature cause permafrost and ice to degrade. These changes if maintained or worsen can have significant implications for hazard analyses and adaptation strategies in these environmentally sensitive areas of the world.

7. References

- Abbott, B.W., Jones, J.B., 2015. Permafrost collapse alters soil carbon stocks, respiration, CH₄, and N₂O in upland tundra. *Glob. Chang. Biol.* 21, 4570-4587.
- Abbott, B.W., Jones, J.B., Godsey, S.E., Larouche, J.R., Bowden, W.B., 2015. Patterns and persistence of hydrologic carbon and nutrient export from collapsing upland permafrost. *Biogeosciences Discuss.* 12.
- Agliardi, F., Crosta, G. and Zanchi, A. (2001). Structural constraints on deep-seated slope deformation kinematics. *Engineering Geology*, 59, 83-102.
- Agliardi, F., Crosta, G. B., Zanchi, A. and Ravazzi, C. (2009). Onset and timing of deep-seated gravitational slope deformations in the eastern Alps, Italy. *Geomorphology*, 103, 113-129.
- Agliardi, F., Crosta, G.B. and Frattini, P. 2012. Slow rock slope deformations. In: Clague, J.J & Stead, D.(eds). *Landslides Types, Mechanisms and Modeling*, 207-221. Cambridge University Press.
- Alexeev, V.A., Jackson, C.H., 2013. Polar amplification: is atmospheric heat transport important? *Clim. Dyn.* 41, 533-547.
- Allen, S., Huggel, C., 2013. Extremely warm temperatures as a potential cause of recent high mountain rockfall. *Glob. Planet. Change* 107, 59-69.
- Allen, S.K., Cox, S.C., Owens, I.F., 2011. Rock avalanches and other landslides in the central Southern Alps of New Zealand: A regional study considering possible climate change impacts. *Landslides* 8, 33-48. <https://doi.org/10.1007/s10346-010-0222-z>
- Ambrosi, C. and Crosta, G. B. (2006). Large sackung along major tectonic features in the central Italian Alps. *Engineering Geology*, 83, 183-200.
- Andersson, J.G., 1906. Solifluction , a Component of Subaërial Denudation. *J. Geol.* 14, 91-112.
- André, M.-F., 1990. Frequency of debris flows and slush avalanches in Spitsbergen: a tentative evaluation from lichenometry. *Pol. Polar Res.* 11, 345-363.
- Arenson, L.U., Jakob, M., 2017. Permafrost-related geohazards and infrastructure construction in mountainous environments, in: *Oxford Research Encyclopedia of Natural Hazard Science*.
- Ashastina, K., Schirrmeister, L., Fuchs, M., Kienast, F., 2017. Palaeoclimate characteristics in interior Siberia of MIS 6-2: First insights from the Batagay permafrost mega-thaw slump in the Yana Highlands. *Clim. Past* 13, 795-818. <https://doi.org/10.5194/cp-13-795-2017>
- Bajracharya, S.R., Mool, P., 2009. Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Ann. Glaciol.* 50, 81-86.
- Ballantyne, C.K., 2002. Paraglacial geomorphology. *Quat. Sci. Rev.* 21, 1935-2017.
- Ballantyne, C.K., Harris, C., 1994. *The Periglaciation of Great Britain*. Cambridge University Press, Cambridge.
- Balser, A.W., Gooseff, M.N., Jones, J.B., Bowden, W.B., 2009. Thermokarst distribution and relationships to landscape characteristics in the Feniak Lake region, Noatak National Preserve, Alaska.
- Bartelt, P., Glover, J., Feistl, T., Bühler, Y., Buser, O., 2012. Formation of levees and en-echelon shear planes during snow avalanche run-out. *J. Glaciol.* 58, 980-992. <https://doi.org/10.3189/2012JoG11J011>
- Beamish, A., Neil, A., Wagner, I., Scott, N.A., 2014. Short-term impacts of active layer detachments on carbon exchange in a High Arctic ecosystem, Cape Bounty, Nunavut, Canada. *Polar Biol.* 37, 1459-1468.
- Behnia, P., & Blais-Stevens, A. (2018). Landslide susceptibility modelling using the quantitative random

- forest method along the northern portion of the Yukon Alaska Highway Corridor, Canada. *Natural hazards*, 90(3), 1407-1426.
- Belshe, E.F., Schuur, E.A.G., Bolker, B.M., 2013. Tundra ecosystems observed to be CO₂ sources due to differential amplification of the carbon cycle. *Ecol. Lett.* 16, 1307-1315.
- Bessette-Kirton, E.K., Coe, J.A., 2020. A 36-year record of rock avalanches in the Saint Elias Mountains of Alaska, with implications for future hazards. *Front. Earth Sci.* 8, 293.
- Biskaborn, B.K., Smith, S.L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D.A., Schoeneich, P., Romanovsky, V.E., Lewkowicz, A.G., Abramov, A., Allard, M., Boike, J., Cable, W.L., Christiansen, H.H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johannsson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckman, J.P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, A.B.K., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M., Lantuit, H., 2019. Permafrost is warming at a global scale. *Nat. Commun.* 10, 1-11. <https://doi.org/10.1038/s41467-018-08240-4>
- Black, R.F., 1954. Permafrost: a review. *Geol. Soc. Am. Bull.* 65, 839-856.
- Blais-Stevens, A., Geertsema, M., Schwab, J.W., Van Asch, T.W.J., 2015. Complex Landslide Triggered in an Eocene Volcanic-Volcaniclastic Succession along Sutherland River, British Columbia, Canada. *Environ. Eng. Geosci.* 21, 35-45. <https://doi.org/10.2113/gseegeosci.21.1.35>
- Blikra, L.H., Longva, O., Braathen, A., Anda, E., Dehls, J.F., Stalsberg, K., 2006. Rock slope failures in Norwegian fjord areas: examples, spatial distribution and temporal pattern, in: *Landslides from Massive Rock Slope Failure*. Springer, pp. 475-496.
- Blunden, J., Arndt, D.S., 2020. State of the Climate in 2019. *Bull. Am. Meteorol. Soc.* 101, S1-S429.
- Bockheim, J., Vieira, G., Ramos, M., López-Martínez, J., Serrano, E., Guglielmin, M., Wilhelm, K., Nieuwendam, A., 2013. Climate warming and permafrost dynamics in the Antarctic Peninsula region. *Glob. Planet. Change* 100, 215-223.
- Böhme, M., Hermanns, R. L., Oppikofer, T., Fischer, L., Bunkholt, H. S., Eiken, T., Pedrazzini, A., Derron, M.-H., Jaboyedoff, M., and Blikra, L. H., 2013, Analyzing complex rock slope deformation at Stampa, western Norway, by integrating geomorphology, kinematics and numerical modeling: *Engineering Geology*, v. 154, p. 116-130.
- Bolch, T., Pieczonka, T., Benn, D.I., 2011. Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery. *Cryosph.* 5, 349-358.
- Borgatti, L., Soldati, M., 2010. Landslides and climatic change. *Geomorphol. hazards disaster Prev.* 87-95.
- Bowden, W.B., Gooseff, M.N., Balser, A., Green, A., Peterson, B.J., Bradford, J., 2008. Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems. *J. Geophys. Res. Biogeosciences* 113.
- Burki, V., Larsen, E., Fredin, O., Nesje, A., 2009. Glacial remobilization cycles as revealed by lateral moraine sediment, Bødalsbreen glacier foreland, western Norway. *The Holocene* 19, 415-426. <https://doi.org/10.1177/0959683608101391>
- Burn, C.R., Friele, P.A., 1989. Geomorphology, vegetation succession, soil characteristics and permafrost in retrogressive thaw slumps near Mayo, Yukon Territory. *Arctic* 31-40.
- Callaghan, T. V., Tweedie, C.E., Åkerman, J., Andrews, C., Bergstedt, J., Butler, M.G., Christensen, T.R., Cooley, D., Dahlberg, U., Danby, R.K., 2011. Multi-decadal changes in tundra environments and ecosystems: synthesis of the International Polar Year-Back to the Future Project (IPY-BTF). *Ambio* 40, 705.
- Cannone, N., Ellis Evans, J.C., Strachan, R., Guglielmin, M., 2006. Interactions between climate, vegetation and the active layer in soils at two Maritime Antarctic sites. *Antarct. Sci.* 18, 323.
- Cannone, N., Lewkowicz, A.G., Guglielmin, M., 2010. Vegetation colonization of permafrost-related landslides, Ellesmere Island, Canadian High Arctic. *J. Geophys. Res. Biogeosciences* 115.
- Carey, M., Huggel, C., Bury, J., Portocarrero, C., Haeberli, W., 2012. An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. *Clim. Change* 112, 733-767.
- Church, M. & Ryder, J.M. 1972. Paraglacial Sedimentation: A Consideration of Fluvial Processes Conditioned by Glaciation. *Geological Society of America Bulletin*, v. 83, p. 3059-3072, DOI:10.1130/0016-7606(1972)83[3059:PSACOF]2.0.CO;2
- Chinn, T.J. & McSaveney, M.J. 1992: The Mount Cook rock avalanche of 14 December 1991. Institute of Geological and Nuclear Sciences Ltd., New Zealand.
- Christiansen, H.H., Etzelmüller, B., Isaksen, K., Juliussen, H., Farbrøt, H., Humlum, O., Johansson, M., Ingeman-Nielsen, T., Kristensen, L., Hjort, J., 2010. The thermal state of permafrost in the nordic area during the international polar year 2007-2009. *Permafr. Periglac. Process.* 21, 156-181.

- Clague, J.J., Evans, S.G., 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quat. Sci. Rev.* 19, 1763-1783.
- Clague, J.J., Huggel, C., Korup, O., McGuire, B., 2012a. Climate Change and Hazardous Processes in High Mountains. *Rev. la Asoc. Geológica Argentina* 69, 328-338. <https://doi.org/10.5167/uzh-77920>
- Clague, J.J., Huggel, C., Korup, O., McGuire, B., 2012b. Climate change and hazardous processes in high mountains. *Rev. la Asoc. Geol. Argentina* 69, 328-338. <https://doi.org/10.5167/uzh-77920>
- Cody, E., Anderson, B.M., McColl, S.T., Fuller, I.C., Purdie, H.L., 2020. Paraglacial adjustment of sediment slopes during and immediately after glacial debuitressing. *Geomorphology* 371, 107411.
- Coe, J.A., 2020. Bellwether sites for evaluating changes in landslide frequency and magnitude in cryospheric mountainous terrain: a call for systematic, long-term observations to decipher the impact of climate change. *Landslides* 1-19.
- Coe, J.A., Bessette-Kirton, E.K., Geertsema, M., 2018. Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery. *Landslides* 15, 393-407.
- Colesanti, C. and Wasowski, J., 2006. Investigating landslides with spaceborne Synthetic Aperture Radar (SAR) interferometry. *Engineering Geology* 88(3-4): 173-199. <https://doi.org/10.1016/j.enggeo.2006.09.013>.
- Cook, K.L., Andermann, C., Gimbert, F., Adhikari, B.R., Hovius, N., 2018. Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. *Science* (80-.). 362, 53-57.
- Cook, S.J., Kougkoulos, I., Edwards, L.A., Dortch, J., Hoffmann, D., 2016. Glacier change and glacial lake outburst flood risk in the Bolivian Andes. *Cryosph.* 10, 2399-2413.
- Cook, S.J., Porter, P.R., Bendall, C.A., 2013. Geomorphological consequences of a glacier advance across a paraglacial rock avalanche deposit. *Geomorphology* 189, 109-120. <https://doi.org/10.1016/j.geomorph.2013.01.022>
- Coquin, J., Mercier, D., Bourgeois, O., Cossart, E., Decaulne, A., 2015. Gravitational spreading of mountain ridges coeval with Late Weichselian deglaciation: Impact on glacial landscapes in Tröllaskagi, northern Iceland. *Quat. Sci. Rev.* 107, 197-213. <https://doi.org/10.1016/j.quascirev.2014.10.023>
- Coquin, J., Mercier, D., Bourgeois, O. and Decaulne, A., 2019. A paraglacial rock-slope failure origin for cirques: a case study from Northern Iceland. *Géomorphologie: relief, processus, environnement*. Vol. 25 -No2. P. 117-136. <https://doi.org/10.4000/geomorphologie.13057>
- Cossart, E., Mercier, D., Decaulne, A., Feuillet, T., Jónsson, H.P., Sæmundsson, T., 2014. Impacts of post-glacial rebound on landslide spatial distribution at a regional scale in northern Iceland (Skagafjörur). *Earth Surf. Process. Landforms* 39, 336-350. <https://doi.org/10.1002/esp.3450>
- Costa, J.E., 1984. Physical geomorphology of debris flows. *Dev. Appl. Geomorphol.* https://doi.org/10.1007/978-3-642-69759-3_9
- Costa, J.E., Schuster, R.L., 1988. The formation and failure of natural dams. *Geol. Soc. Am. Bull.* 100, 1054-1068.
- Couture, R., Riopel, S., 2008. Regional landslide susceptibility mapping and inventorying in the Mackenzie Valley, Northwest Territories, in: *Proceedings of the 4th Canadian Conference on Geohazards: From Causes to Management*, Presse de l'Université Laval, Québec. pp. 375-382.
- Crandell, D.R. & Fahnestock, R.F. 1965: Rockfalls and avalanches from Little Tahoma Peak on Mount Rainier, Washington. *Geological Survey Bulletin* 1221A. 30 pp.
- Crosta, G. B., Chen, H., & Lee, C. F. (2004). Replay of the 1987 Val Pola landslide, Italian alps. *Geomorphology*, 60(1-2), 127-146.
- Crozier, M. 1989 *Landslides: Causes, Consequences And Environment*, Helm, London, p. 252, <https://doi.org/10.1111/j.1745-7939.1989.tb01143.x>.
- Crozier, M., 2002. Landslides, in: *Applied Geography*. Routledge, pp. 111-122.
- Crozier, M.J., 2010. Deciphering the effect of climate change on landslide activity: A review. *Geomorphology* 124, 260-267. <https://doi.org/10.1016/j.geomorph.2010.04.009>
- Crozier, M.J., Glade, T., 2005. Landslide hazard and risk: issues, concepts and approach. *Landslide hazard risk* 1-40.
- Cruden, D.M., Varnes, D., 1996. Landslide types and processes, in: *Transportation research board, U.N.R.C. (Ed.), Landslides Investigation and Mitigation*. Washington, DC, pp. 36-75.
- Czekirda, J., Westermann, S., Etzelmüller, B., Jóhannesson, T., 2019. Transient modelling of permafrost distribution in Iceland. *Front. Earth Sci.* 7, 1-23. <https://doi.org/10.3389/feart.2019.00130>
- D'Agata, C., Zanutta, A., 2007. Reconstruction of the recent changes of a debris-covered glacier (Brenva Glacier, Mont Blanc Massif, Italy) using indirect sources: Methods, results and validation. *Glob. Planet. Change* 56, 57-68. <https://doi.org/10.1016/j.gloplacha.2006.07.021>

- Dahl-Jensen, T., Larsen, L.M., Pedersen, S.A.S., Pedersen, J., Jepsen, H.F., Pedersen, G.K., Nielsen, T., Pedersen, A.K., Von Platen-Hallermund, F., Weng, W., 2004. Landslide and tsunami 21 November 2000 in Paatuut, West Greenland. *Nat. Hazards* 31, 277-287. <https://doi.org/10.1023/B:NHAZ.0000020264.70048.95>
- Dai, C., Higman, B., Lynett, P.J., Jacquemart, M., Howat, I.M., Liljedahl, A.K., Dufresne, A., Freymueller, J.T., Geertsema, M., Ward Jones, M., 2020. Detection and assessment of a large and potentially-tsunamigenic periglacial landslide in Barry Arm, Alaska. *Geophys. Res. Lett.* e2020GL089800.
- Darrow, M.M., Daanen, R.P., Gong, W., 2017. Predicting movement using internal deformation dynamics of a landslide in permafrost. *Cold Reg. Sci. Technol.* 143, 93-104.
- Davies, M.C., Hamza, O., Harris, C., 2001. The effect of rise in mean annual temperature on the stability of rock slopes containing ice-filled discontinuities. *Permafr. Periglac. Process.* 12, 137-144. <https://doi.org/10.1002/ppp>
- Davies, T.R.H., McSaveney, M.J., 2012. Mobility of long-runout rock avalanches, in: *Landslides: Types, Mechanisms and Modeling*. Cambridge University Press, pp. 50-58.
- Decaulne, A., Saemundsson, P., 2006a. Meteorological conditions during slush-flow release and their geomorphological impact in northwestern Iceland: A case study from the Bildudalur valley. *Geogr Ann Ser -Phys Geogr* 88A, 187-197.
- Decaulne, A., Saemundsson, T., 2006b. Geomorphic evidence for present-day snow-avalanche and debris-flow impact in the Icelandic Westfjords. *Geomorphology* 80, 80-93. <https://doi.org/10.1016/j.geomorph.2005.09.007>
- Decaulne, A., Sæmundsson, Þ., 2010. Distribution and frequency of snow-avalanche debris transfer in the distal part of colluvial cones in central north iceland. *Geogr. Ann. Ser. Phys. Geogr.* 92, 177-187. <https://doi.org/10.1111/j.1468-0459.2010.00388.x>
- Delaney, K.B., Evans, S.G., 2014. The 1997 Mount Munday landslide (British Columbia) and the behaviour of rock avalanches on glacier surfaces. *Landslides* 11, 1019-1036.
- Deline, P., 2009. Interactions between rock avalanches and glaciers in the Mont Blanc massif during the late Holocene. *Quat. Sci. Rev.* 28, 1070-1083.
- Deline, P., Gruber, S., Delaloye, R., Fischer, L., Geertsema, M., Giardino, M., Hasler, A., Kirkbride, M., Krautblatter, M., Magnin, F., 2015a. Ice loss and slope stability in high-mountain regions, in: *Snow and Ice-Related Hazards, Risks and Disasters*. Elsevier, pp. 521-561.
- Deline, P., Hewitt, K., Reznichenko, N. & Shugar, D. 2015b: Rock avalanches onto Glaciers. In: *Hazards and Disaster Series. Landslide Hazards, Risk and Disasters*. Tim Davies (ed), 263-320.
- Dobinski, W., 2011. Permafrost. *Earth-Science Rev.* 108, 158-169.
- Draebing, D., 2020. Identification of rock and fracture kinematics in high Alpine rockwalls under the influence of altitude. *Earth Surf. Dyn. Discuss.* 1-31.
- Draebing, D., Krautblatter, M., 2019. The efficacy of frost weathering processes in alpine rockwalls. *Geophys. Res. Lett.* 46, 6516-6524.
- Draebing, D., Krautblatter, M., Hoffmann, T., 2017. Thermo-cryogenic controls of fracture kinematics in permafrost rockwalls. *Geophys. Res. Lett.* 44, 3535-3544.
- Dramis, F., Govi, M., Guglielmin, M., Mortara, G., 1995. Mountain permafrost and slope instability in the Italian Alps: the Val Pola landslide. *Permafr. Periglac. Process.* 6, 73-81.
- Dramis, F., Sorriso-Valvo, M., 1995. Deep-seated gravitational slope deformations, related landslides and tectonics. *Int. J. Rock Mech. Min. Sci. Geomech.* 5, 203A.
- Dufresne, A., Davies, T.R., 2009. Longitudinal ridges in mass movement deposits. *Geomorphology* 105, 171-181. <https://doi.org/10.1016/j.geomorph.2008.09.009>
- Dufresne, A., Geertsema, M., Shugar, D.H., Koppes, M., Higman, B., Haeussler, P.J., Stark, C., Venditti, J.G., Bonno, D., Larsen, C., Gulick, S.P.S., McCall, N., Walton, M., Loso, M.G., Willis, M.J., 2018a. Sedimentology and geomorphology of a large tsunamigenic landslide, Taan Fiord, Alaska. *Sediment. Geol.* 364, 302-318. <https://doi.org/10.1016/j.sedgeo.2017.10.004>
- Dufresne, A., Ostermann, M., and Preusser, F. 2018b: River-damming, late-Quaternary rockslides in the Ötztal Valley region (Tyrol, Austria). *Geomorphology*, 310, 153-167, 2018.
- Dufresne, A., Wolken, G.J., Hibert, C., Bessette-Kirton, E.K., Coe, J.A., Geertsema, M., Ekström, G., 2019. The 2016 Lamplugh rock avalanche, Alaska: deposit structures and emplacement dynamics. *Landslides* 16, 2301-2319. <https://doi.org/10.1007/s10346-019-01225-4>
- Dunning, S.A., Rosser, N.J., McColl, S.T., Reznichenko, N.V., 2015. Rapid sequestration of rock avalanche deposits within glaciers. *Nat. Commun.* 6, 7964.
- Dussallant, A., Benito, G., Buytaert, W., Carling, P., Meier, C., Espinoza, F., 2010. Repeated glacial-lake outburst floods in Patagonia: an increasing hazard? *Nat. hazards* 54, 469-481.
- Duvillard, P.-A., Ravel, L., Marcer, M., Schoeneich, P., 2019. Recent evolution of damage to infrastructure on permafrost in the French Alps. *Reg. Environ. Chang.* 19, 1281-1293.
- Eckerstorfer, M., Christiansen, H.H., 2012. Meteorology, Topography and Snowpack Conditions

- causing Two Extreme Mid-Winter Slush and Wet Slab Avalanche Periods in High Arctic Maritime Svalbard: Two Mid-winter Slush and Wet Slab Avalanche Periods in Svalbard. *Permafr. Periglac. Process.* 23, 15-25. <https://doi.org/10.1002/ppp.734>
- Ekstrom, G., Stark, C.P., 2013. Simple Scaling of Catastrophic Landslide Dynamics. *Science* 339, 1416-1419. <https://doi.org/10.1126/science.1232887>
- Elder, K., Kattelmann, R., 1993. A low-angle slushflow in the Kirgiz Range, Kirgizstan. *Permafr. Periglac. Process.* 4, 301-310. <https://doi.org/10.1002/ppp.3430040403>
- Evans, S.G., Clague, J.J., 1994. Recent climatic change and catastrophic geomorphic processes in mountain environments, in: *Geomorphology and Natural Hazards*. Elsevier, pp. 107-128.
- Evans, S.G., Clague, J.J., 1988. Catastrophic rock avalanches in glacial environments, in: Bonnard, C. (Ed.), *Landslides - Proceedings of the Fifth International Symposium on Landslides*, Lausanne, Switzerland. Lausanne, Switzerland, pp. 1153-1158.
- Evans, S.G., Bishop, N.F., Fidel Smoll, L., Valderrama Murillo, P., Delaney, K.B., Oliver-Smith, A., 2009a. A re-examination of the mechanism and human impact of catastrophic mass flows originating on Nevado Huascarán, Cordillera Blanca, Peru in 1962 and 1970. *Eng. Geol.* 108, 96-118. <https://doi.org/10.1016/j.enggeo.2009.06.020>
- Evans, S.G., Tutubalina, O.V., Drobyshev, V.N., Chernomorets, S.S., McDougall, S., Petrakov, D.A., Hungr, O., 2009b. Catastrophic detachment and high-velocity long-runout flow of Kolka Glacier, Caucasus Mountains, Russia in 2002. *Geomorphology* 105, 314-321. <https://doi.org/10.1016/j.geomorph.2008.10.008>
- Evans, S.G., Tutubalina, O. V, Drobyshev, V.N., Chernomorets, S.S., McDougall, S., Petrakov, D.A., Hungr, O., 2009c. Catastrophic detachment and high-velocity long-runout flow of Kolka Glacier, Caucasus Mountains, Russia in 2002. *Geomorphology* 105, 314-321.
- Falaschi, D., Kääb, A., Paul, F., Tadono, T., Rivera, J.A., Lenzano, L.E., 2019. Brief communication: Collapse of 4 Mm³ of ice from a cirque glacier in the Central Andes of Argentina. *The Cryosphere* 13, 997-1004. <https://doi.org/10.5194/tc-13-997-2019>
- Fan, X., Dufresne, A., Subramanian, S.S., Strom, A., Hermanns, R., Stefanelli, C.T., Hewitt, K., Yunus, A.P., Dunning, S., Capra, L., 2020. The formation and impact of landslide dams-State of the art. *Earth-Science Rev.* 203, 103116.
- Fischer, L., Huggel, C., Kääb, A., & Haeberli, W. (2013). Slope failures and erosion rates on a glacierized high-mountain face under climatic changes. *Earth surface processes and landforms*, 38(8), 836-846.
- Fischer, L., Eisenbeiss, H., Kääb, A., Huggel, C., Haeberli, W., 2011. Monitoring topographic changes in a periglacial high-mountain face using high-resolution DTMs, Monte Rosa East Face, Italian Alps. *Permafr. Periglac. Process.* 22, 140-152. <https://doi.org/10.1002/ppp.717>
- Fischer, L., Huggel, C., 2008. Methodical design for stability assessments of permafrost-affected high-mountain rock walls.
- Fischer, L., Kääb, A., Huggel, C., Noetzi, J., 2006. Geology, glacier retreat and permafrost degradation as controlling factors of slope instabilities in a high-mountain rock wall: the Monte Rosa east face. *Nat. Hazards Earth Syst. Sci.* 6, 761-772. <https://doi.org/10.5194/nhess-6-761-2006>
- Forcella, F., 1984. The Sackung between Mount Padrio and Mount Varadega, Central Alps, Italy: a remarkable example of slope gravitational tectonics. *MeAditerraneAe* 51 (1±2), 81±92.
- Forcella, F., Orombelli, G., 1984. Holocene slope deformations in Valfurva, Central Alps, Italy. *Geogr. Fis. Dinam. Quat.* 7, 41±48.
- Frauenfelder, R., Isaksen, K., Lato, M.J., Noetzi, J., 2018. Ground thermal and geomechanical conditions in a permafrost-affected high-latitude rock avalanche site (Polvartinden, northern Norway). *Cryosph.* 12, 1531-1550.
- French, H.M., 2007. The periglacial environment, Third Edit. ed, *The Periglacial Environment*. [https://doi.org/10.1016/0031-0182\(71\)90005-8](https://doi.org/10.1016/0031-0182(71)90005-8)
- Frost, G. V, Epstein, H.E., Walker, D.A., Matyshak, G., Ermokhina, K., 2018. Seasonal and long-term changes to active-layer temperatures after tall shrubland expansion and succession in Arctic tundra. *Ecosystems* 21, 507-520.
- Gariano, S.L., Guzzetti, F., 2016. Landslides in a changing climate. *Earth-Science Rev.* 162, 227-252. <https://doi.org/10.1016/j.earscirev.2016.08.011>
- Geertsema, M., Clague, J.J., Schwab, J.W., Evans, S.G., 2006a. An overview of recent large catastrophic landslides in northern British Columbia, Canada. *Eng. Geol.* 83, 120-143.
- Geertsema, M., Hungr, O., Schwab, J.W., Evans, S.G., 2006b. A large rockslide - Debris avalanche in cohesive soil at Pink Mountain, northeastern British Columbia, Canada. *Eng. Geol.* 83, 64-75. <https://doi.org/10.1016/j.enggeo.2005.06.025>
- Geertsema, M., Highland, L., Vagueouis, L., 2009. Environmental impact of landslides, in: *Landslides-Disaster Risk Reduction*. Springer, pp. 589-607.

- Gilbert, A., Leinss, S., Kargel, J., Kääb, A., Gascoin, S., Leonard, G., Berthier, E., Karki, A., Yao, T., 2018. Mechanisms leading to the 2016 giant twin glacier collapses, Aru Range, Tibet. *The Cryosphere* 12, 2883-2900. <https://doi.org/10.5194/tc-12-2883-2018>
- Gisnås, K., Etzelmüller, B., Lussana, C., Hjort, J., Sannel, A.B.K., Isaksen, K., Westermann, S., Kuhry, P., Christiansen, H.H., Frampton, A., 2017. Permafrost map for Norway, Sweden and Finland. *Permafr. Periglac. Process.* 28, 359-378.
- Gooseff, M.N., Balser, A., Bowden, W.B., Jones, J.B., 2009. Effects of hillslope thermokarst in northern Alaska. *Eos, Trans. Am. Geophys. Union* 90, 29-30.
- Grämiger, L.M., Moore, J.R., Gischig, V.S., Ivy-Ochs, S., Loew, S., 2017. Beyond debuttressing: Mechanics of paraglacial rock slope damage during repeat glacial cycles. *J. Geophys. Res. Earth Surf.* 122, 1004-1036.
- Grosse, G., Romanovsky, V., Jorgenson, T., Anthony, K.W., Brown, J., Overduin, P.P., 2011. Vulnerability and Feedbacks of Permafrost to Climate Change. *Eos, Trans. Am. Geophys. Union* 92, 73-74. <https://doi.org/10.1029/2011EO090001>
- Gruber, S., 2012. Derivation and analysis of a high-resolution estimate of global permafrost zonation. *Cryosph.* 6, 221-233.
- Gruber, S., Fleiner, R., Guegan, E., Panday, P., Schmid, M.-O., Stumm, D., Wester, P., Zhang, Y., Zhao, L., 2017. Inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region.
- Gruber, S., Haeberli, W., 2007. Permafrost in steep bedrock slopes and its temperatures-related destabilization following climate change. *J. Geophys. Res. Earth Surf.* 112, 1-10. <https://doi.org/10.1029/2006JF000547>
- Gude, M., Scherer, D., 1995. Snowmelt and slush torrents - preliminary report from a field campaign in Karkevagge, Swedish Lapland. *Geogr. Ann. Ser. A* 77 A, 199-206.
- Guðmundsson, S., Björnsson, H., Pálsson, F., Magnússon, E., Sæmundsson, Þ. & Jóhannesson, T., 2019: Terminus lagoons on the south side of Vatnajökull ice cap, SE-Iceland. *Jökull*, 69. 1-34.
- Guglielmin, M., 2012. Advances in permafrost and periglacial research in Antarctica: a review. *Geomorphology* 155, 1-6.
- Haeberli, W., 2013. Mountain permafrost - research frontiers and a special long-term challenge. *Cold Reg. Sci. Technol.* 96, 71-76. <https://doi.org/10.1016/j.coldregions.2013.02.004>
- Haeberli, W., 1997. Slope stability problems related to glacier shrinkage and permafrost degradation in the Alps. *Eclogae Geol. Helv.* 90, 407-414.
- Haeberli, W., Buetler, M., Huggel, C., Friedli, T.L., Schaub, Y., Schleiss, A.J., 2016. New lakes in deglaciating high-mountain regions-opportunities and risks. *Clim. Change* 139, 201-214.
- Haeberli, W., Huggel, C., Kääb, A., Zraggen-Oswald, S., Polkvoj, A., Galushkin, I., Zotikov, I., Osokin, N., 2004. The Kolka-Karmadon rock/ice slide of 20 September 2002: an extraordinary event of historical dimensions in North Ossetia, Russian Caucasus. *J. Glaciol.* 50, 533-546.
- Haeberli, W., Noetzi, J., Arenson, L., Delaloye, R., Gärtner-Roer, I., Gruber, S., Isaksen, K., Kneisel, C., Krautblatter, M., Phillips, M., 2011. Mountain permafrost: Development and challenges of a young research field. *J. Glaciol.* 56, 1043-1058. <https://doi.org/10.3189/002214311796406121>
- Haeberli, W., Rickenmann, D., Zimmermann, M., 1990. Investigation of 1987 debris flows in the Swiss Alps: general concept and geophysical soundings. *Hydrol. Mt. Reg. II - Artif. Reserv. Water Slopes. IAHS Publ. np.* 194 303-310.
- Haeberli, W., Schaub, Y., Huggel, C., 2017a. Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology* 293, 405-417. <https://doi.org/10.1016/j.geomorph.2016.02.009>
- Haeberli, W., Schaub, Y., Huggel, C., 2017b. Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology* 293, 405-417. <https://doi.org/10.1016/j.geomorph.2016.02.009>
- Haque, U., Blum, P., Da Silva, P.F., Andersen, P., Pilz, J., Chalov, S.R., Malet, J.-P., Auflič, M.J., Andres, N., Poyiadji, E., 2016. Fatal landslides in Europe. *Landslides* 13, 1545-1554.
- Haque, U., Da Silva, P.F., Devoli, G., Pilz, J., Zhao, B., Khaloua, A., Wilopo, W., Andersen, P., Lu, P., Lee, J., 2019. The human cost of global warming: Deadly landslides and their triggers (1995-2014). *Sci. Total Environ.* 682, 673-684.
- Harris, C., 2005. Climate change, mountain permafrost degradation and geotechnical hazard, in: *Global Change and Mountain Regions. An Overview of Current Knowledge.* pp. 215-224.
- Harris, C., Arenson, L.U., Christiansen, H.H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, C., Hoelzle, M., Humlum, O., 2009. Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses. *Earth-Science Rev.* 92, 117-171.
- Harris, C., Haeberli, W., Vonder Mühll, D., King, L., 2001. Permafrost monitoring in the high mountains

- of Europe: the PACE project in its global context. *Permafr. Periglac. Process.* 12, 3-11.
- Harris, S.A., Pedersen, D.E., 1998. Thermal regimes beneath coarse blocky materials. *Permafr. Periglac. Process.* 9, 107-120.
- Harrison, S., Kargel, J.S., Huggel, C., Reynolds, J., Shugar, D.H., Betts, R.A., Emmer, A., Glasser, N., Haritashya, U.K., Klimeš, J., 2018. Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *Cryosph.* 12, 1195-1209.
- Hasler, A., Geertsema, M., Foord, V., Gruber, S., Noetzli, J., 2015. The influence of surface characteristics, topography and continentality on mountain permafrost in British Columbia. *Cryosphere* 9, 1025-1038. <https://doi.org/10.5194/tc-9-1025-2015>
- Hétu, B., Fortin, G., Dubé, J., Boucher, D., Buffin-Bélanger, T., Gagnon, J.-P., 2017. Les conditions nivologiques et hydro-météorologiques propices au déclenchement des coulées de slush: l'exemple du Québec (Canada). *Climatologie*.
- Hewitt, K. 1988. Catastrophic landslide deposits in the Karakoram Himalaya, *Science* 242. 64-67.
- Hewitt, K., Clague, J.J. and Orwin F.J. 2008: Legacies of catastrophic rock slope failures in mountain landscapes *Earth Sci. Rev.*, 87 (2008), pp. 1-38.
- Hewitt, K., 2009a. Rock avalanches that travel onto glaciers and related developments, Karakoram Himalaya, Inner Asia. *Geomorphology* 103, 66-79. <https://doi.org/10.1016/j.geomorph.2007.10.017>
- Hewitt, K. 2009b: Catastrophic rock slope failures and late Quaternary developments in the Nanga Parbat-Haramosh Massif, Upper Indus basin, northern Pakistan *Quat. Sci. Rev.*, 28 (2009), pp. 1055-1069
- Hewitt, K. 2009c: Glacially conditioned rock-slope failures and disturbance-regime landscapes, Upper Indus Basin, northern Pakistan. J. Knight, S. Harrison (Eds.), *Periglacial and Paraglacial Processes and Environments*, Geological Society, London (2009), pp. 235-255
- Hewitt, K., Gosse, J. and Clague, J.J. 2011. Rock avalanches and the pace of late Quaternary development of river valleys in the Karakoram Himalaya. *GSA Bulletin* (2011) 123 (9-10): 1836-1850. <https://doi.org/10.1130/B30341.1>
- Hilger, P., Hermanns, R. L., Czekirka, J., Myhra, K. S., Gosse, J. C., & Etzelmüller, B. (2021). Permafrost as a first order control on long-term rock-slope deformation in (Sub-) Arctic Norway. *Quaternary Science Reviews*, 251, 106718.
- Hilley, G.E., Bürgmann, R., Ferretti, A., Novali, F. and Rocca, F. 2004. Dynamics of slow-moving landslides from permanent scatterer analysis. *Science* 304(5679): 1952-1955. <https://doi.org/10.1126/science.1098821>.
- Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., Steltzer, H., 2019. High Mountain Areas. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Ipcc.
- Hubbard, B., Heald, A., Reynolds, J.M., Quincey, D., Richardson, S.D., Luyo, M.Z., Portilla, N.S., Hambrey, M.J., 2005. Impact of a rock avalanche on a moraine-dammed proglacial lake: Laguna Safuna Alta, Cordillera Blanca, Peru. *Earth Surf. Process. Landforms J. Br. Geomorphol. Res. Gr.* 30, 1251-1264.
- Huggel, C., Clague, J.J., Korup, O., 2012. Is climate change responsible for changing landslide activity in high mountains? *Earth Surf. Process. Landforms* 37, 77-91. <https://doi.org/10.1002/esp.2223>
- Huggel, C., Gruber, S., Caplan-Auerbach, S., Wessels, R.L., Molnia, B.F., 2008. The 2005 Mt. Steller, Alaska, rock-ice avalanche: A large slope failure in cold permafrost.
- Huggel, C., 2009. Recent extreme slope failures in glacial environments: effects of thermal perturbation. *Quat. Sci. Rev.* 28, 1119-1130.
- Huggel, C., Salzmann, N., Allen, S., Caplan-Auerbach, J., Fischer, L., Haeberli, W., Larsen, C., Schneider, D., Wessels, R., 2010. Recent and future warm extreme events and high-mountain slope stability. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 368, 2435-2459.
- Huggel, C., Zraggen-Oswald, S., Haeberli, W., Kääb, A., Polkvoj, A., Galushkin, I., Evans, S.G., 2005. The 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: assessment of extraordinary avalanche formation and mobility, and application of QuickBird satellite imagery. *Nat. Hazards Earth Syst. Sci.* 5, 173-187. <https://doi.org/10.5194/nhess-5-173-2005>
- Hungr, O., 2007. Dynamics of rapid landslides, in: *Progress in Landslide Science*. Springer, pp. 47-57.
- Hungr, O., Evans, S.G., 2004. Entrainment of debris in rock avalanches: An analysis of a long run-out mechanism. *Bull. Geol. Soc. Am.* 116, 1240-1252. <https://doi.org/10.1130/B25362.1>
- Hungr, O., Leroueil, S. & Picarelli, L. 2014: The Varnes classification of landslide types, an update. *Landslides* 11, 167-194. <https://doi.org/10.1007/s10346-013-0436-y>.
- Huscroft, C. a, Lipovsky, P.S., Bond, J.D., 2004. Permafrost and landslide activity: Case studies from southwestern Yukon Territory. *Yukon Explor. Geol.* 2003 107-119.
- Huscroft, C.A., Lipovsky, P., Bond, J.D., Emond, D.S., Lewis, L.L., 2003. Permafrost and landslide

- activity: Case studies from southwestern Yukon Territory. *Yukon Explor. Geol.* 107-119.
- Hutchinson, J.N., 1968. Field meeting on the coastal landslides of Kent: 1-3 July 1966. *Proc. Geol. Assoc.* 79, 227-237.
- IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (eds Field, C. B. et al.) (Cambridge Univ. Press, 2012).
- Iribarren Anacona, P., Mackintosh, A., Norton, K.P., 2015. Hazardous processes and events from glacier and permafrost areas: lessons from the Chilean and Argentinean Andes: GLACIER AND PERMAFROST HAZARDS IN THE EXTRATROPICAL ANDES. *Earth Surf. Process. Landf.* 40, 2-21. <https://doi.org/10.1002/esp.3524>
- Isaksen, K., Ødegård, R.S., Eiken, T., Sollid, J.L., 2000. Composition, flow and development of two tongue-shaped rock glaciers in the permafrost of Svalbard. *Permafr. Periglac. Process.* 11, 241-257.
- Iverson, R.M., 1997. The Physics of Debris Flows. *Rev. Geophys.* 3, 245-296.
- Jia, H., Xiang, W., Krautblatter, M., 2015. Quantifying rock fatigue and decreasing compressive and tensile strength after repeated freeze-thaw cycles. *Permafr. Periglac. Process.* 26, 368-377.
- Jomelli, V., Francou, B., 2000. Comparing the characteristics of rockfall talus and snow avalanche landforms in an Alpine environment using a new methodological approach: Massif des Ecrins, French Alps. *Geomorphology* 35, 181-192. [https://doi.org/10.1016/S0169-555X\(00\)00035-0](https://doi.org/10.1016/S0169-555X(00)00035-0)
- Jones, M.K.W., Pollard, W.H., Jones, B.M., 2019. Rapid initialization of retrogressive thaw slumps in the Canadian high Arctic and their response to climate and terrain factors. *Environ. Res. Lett.* 14, 55006.
- Jorgenson, M.T., Osterkamp, T.E., 2005. Response of boreal ecosystems to varying modes of permafrost degradation. *Can. J. For. Res.* 35, 2100-2111.
- Kääb, A., Huggel, C., Fischer, L., Guex, S., Paul, F., Roer, I., Salzmann, N., Schläefli, S., Schmutz, K., Schneider, D., 2005. Remote sensing of glacier-and permafrost-related hazards in high mountains: an overview.
- Kääb, A., Leinss, S., Gilbert, A., Bühler, Y., Gascoin, S., Evans, S.G., Bartelt, P., Berthier, E., Brun, F., Chao, W.-A., Farinotti, D., Gimbert, F., Guo, W., Huggel, C., Kargel, J.S., Leonard, G.J., Tian, L., Treichler, D., Yao, T., 2018. Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability. *Nat. Geosci.* 11, 114-120. <https://doi.org/10.1038/s41561-017-0039-7>
- Kenner, R., Phillips, M., Hauck, C., Hilbich, C., Mulsow, C., Bühler, Y., Stoffel, A., Buchroithner, M., 2017. New insights on permafrost genesis and conservation in talus slopes based on observations at Flüelapass, Eastern Switzerland. *Geomorphology* 290, 101-113.
- Khanal, N.R., Hu, J.-M., Mool, P., 2015. Glacial lake outburst flood risk in the Poiqu/Bhote Koshi/Sun Koshi river basin in the Central Himalayas. *Mt. Res. Dev.* 35, 351-364.
- Khomutov, A., Leibman, M., 2014. Assessment of landslide hazards in a typical tundra of Central Yamal, Russia, in: *Landslides in Cold Regions in the Context of Climate Change*. Springer, pp. 271-290.
- Kjartansson, G. 1967. The Steinsholtshlaup, Central-South-Iceland, on January 15th 1967. *Jökull* 17, 249-262.
- Kjekstad, O., Highland, L., 2009. Economic and Social Impacts of Landslides. *Landslides - Disaster Risk Reduct.* 573-587. <https://doi.org/10.1007/978-3-540-69970-5>
- Kokelj, S.V., Jorgenson, M.T., 2013. Advances in thermokarst research. *Permafr. Periglac. Process.* 24, 108-119.
- Kokelj, S. V., Lacelle, D., Lantz, T.C., Tunnicliffe, J., Malone, L., Clark, I.D., Chin, K.S., 2013. Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales. *J. Geophys. Res. Earth Surf.* 118, 681-692. <https://doi.org/10.1002/jgrf.20063>
- Kokelj, S. V., Tunnicliffe, J., Lacelle, D., Lantz, T.C., Chin, K.S., Fraser, R., 2015. Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. *Glob. Planet. Change* 129, 56-68.
- Korup, O. (2006). Effects of large deep-seated landslides on hillslope morphology, western Southern Alps, New Zealand. *Journal of Geophysical Research*, 111, F01018.
- Korup, O., Tweed, F., 2007. Ice, moraine, and landslide dams in mountainous terrain. *Quat. Sci. Rev.* 26, 3406-3422.
- Kos, A., Amann, F., Strozzi, T., Delaloye, R., von Ruetten, J., Springman, S., 2016. Contemporary glacier retreat triggers a rapid landslide response, Great Aletsch Glacier, Switzerland. *Geophys. Res. Lett.* 43, 12-466.
- Krautblatter, M., Funk, D., Günzel, F.K., 2013a. Why permafrost rocks become unstable: a rock-ice-mechanical model in time and space. *Earth Surf. Process. Landforms* 38, 876-887.
- Krautblatter, M., Funk, D., Günzel, F.K., 2013b. Why permafrost rocks become unstable: A rock-ice-mechanical model in time and space. *Earth Surf. Process. Landforms* 38, 876-887.

- <https://doi.org/10.1002/esp.3374>
- Kuhn, D., Redfield, T.F., Hermanns, R.L., Fuchs, M., Torizin, J. & Balzer, D. 2019: Anatomy of a mega-rock slide at Forkastningsfjellet, Spitsbergen and its implications for landslide hazard and risk considerations. *Norwegian Journal of Geology* 99, 1-21. <https://dx.doi.org/10.17850/njg99-1-03>.
- Kuhn, D., Redfield, T.F., Hermanns, R.L., Fuchs, M., Torizin, J. & Balzer, D. 2021: Forkastningsfjellet Rock Slide, Spitsbergen: State of Activity in a Changing Climate. In: V. Vilímek et al. (eds.), *Understanding and Reducing Landslide Disaster Risk, ICL Contribution to Landslide Disaster Risk Reduction*, https://doi.org/10.1007/978-3-030-60319-9_21
- Kummert, M., Delaloye, R., & Braillard, L. (2018). Erosion and sediment transfer processes at the front of rapidly moving rock glaciers: Systematic observations with automatic cameras in the western Swiss Alps. *Permafrost and Periglacial Processes*, 29(1), 21-33.
- Lacelle, D., Bjornson, J., Lauriol, B., 2010. Climatic and geomorphic factors affecting contemporary (1950-2004) activity of retrogressive thaw slumps on the Aklavik plateau, Richardson mountains, NWT, Canada. *Permafr. Periglac. Process.* 21, 1-15. <https://doi.org/10.1002/ppp.666>
- Lafrenière, M.J., Lamoureux, S.F., 2019. Effects of changing permafrost conditions on hydrological processes and fluvial fluxes. *Earth-science Rev.* 191, 212-223.
- Lamoureux, S.F., Lafrenière, M.J., 2009. Fluvial impact of extensive active layer detachments, Cape Bounty, Melville Island, Canada. *Arctic, Antarct. Alp. Res.* 41, 59-68.
- Lane, S.N., Bakker, M., Gabbud, C., Micheletti, N., Saugy, J.-N., 2017. Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. *Geomorphology* 277, 210-227.
- Lantuit, H., Overduin, P.P., Couture, N., Wetterich, S., Aré, F., Atkinson, D., Brown, J., Cherkashov, G., Drozdov, D., Forbes, D.L., 2012. The Arctic coastal dynamics database: a new classification scheme and statistics on Arctic permafrost coastlines. *Estuaries and Coasts* 35, 383-400.
- Lantuit, H., Pollard, W.H., 2008. Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada. *Geomorphology* 95, 84-102. <https://doi.org/10.1016/j.geomorph.2006.07.040>
- Lantuit, H., Pollard, W.H., Couture, N., Fritz, M., Schirrmeister, L., Meyer, H., Hubberten, H.W., 2012. Modern and Late Holocene Retrogressive Thaw Slump Activity on the Yukon Coastal Plain and Herschel Island, Yukon Territory, Canada. *Permafr. Periglac. Process.* 23, 39-51. <https://doi.org/10.1002/ppp.1731>
- Larocque, S.J., Hétu, B., Filion, L., 2001. Geomorphic and dendroecological impacts of slushflows in central gaspé peninsula (québec, canada). *Geogr. Ann. Ser. Phys. Geogr.* 83, 191-201. <https://doi.org/10.1111/j.0435-3676.2001.00154.x>
- Leibman, M.O., 1995. Cryogenic landslides on the Yamal Peninsula, Russia: preliminary observations. *Permafr. Periglac. Process.* 6, 259-264.
- Lewin, J., Warburton, J., 1994. Debris Flows in an Alpine Environment. *Geography* 79, 98-107.
- Lewkowicz, A.G., 2007. Dynamics of active-layer detachment failures, Fosheim peninsula, Ellesmere Island, Nunavut, Canada. *Permafr. Periglac. Process.* 18, 89-103.
- Lewkowicz, A.G., 1990. Morphology, frequency and magnitude of active-layer detachment slides, Fosheim Peninsula, Ellesmere Island, N.W.T., in: *Permafrost-Canada, Proceedings of the Fifth Canadian Permafrost Conference, National Research Council of Canada*. pp. 111-118.
- Lewkowicz, A.G., Dixon, J.C., Abrahams, A.D., 1992. Factors influencing the distribution and initiation of active-layer detachment slides on Ellesmere Island, Arctic Canada.
- Lewkowicz, A.G., Harris, C., 2005a. Morphology and geotechnique of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada. *Geomorphology* 69, 275-297. <https://doi.org/10.1016/j.geomorph.2005.01.011>
- Lewkowicz, A.G., Harris, C., 2005b. Frequency and magnitude of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada. *Permafr. Periglac. Process.* 16, 115-130.
- Lewkowicz, A.G., Kokelj, S. V, 2002. Slope sediment yield in arid lowland continuous permafrost environments, Canadian Arctic Archipelago. *Catena* 46, 261-283.
- Lewkowicz, A.G., Way, R.G., 2019. Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. *Nat. Commun.* 10, 1-11. <https://doi.org/10.1038/s41467-019-09314-7>
- Luckman, B.H., 1992. Debris flows and snow avalanches landforms in the Lairig Ghru, Cairngorm Mountains, Scotland. *Geogr. Ann. Ser. -Phys. Geogr.* 74, 109-121.
- Lugon, R., & Stoffel, M. (2010). Rock-glacier dynamics and magnitude-frequency relations of debris flows in a high-elevation watershed: Ritigraben, Swiss Alps. *Global and Planetary Change*, 73(3-4), 202-210.
- Lukas, S., Nicholson, L.I., Ross, F.H., Humlum, O., 2005. Formation, meltout processes and landscape

- alteration of high-Arctic ice-cored moraines—Examples from Nordenskiöld Land, central Spitsbergen. *Polar Geogr.* 29, 157-187.
- Luo, J., Niu, F., Lin, Z., Liu, M., Yin, G., 2019. Recent acceleration of thaw slumping in permafrost terrain of Qinghai-Tibet Plateau: An example from the Beiluhe Region. *Geomorphology* 341, 79-85.
- Lutz, A., Immerzeel, W.W., Bajracharya, S.R., Litt, M., Shrestha, A.B., 2016. Impacts of climate change on the cryosphere, hydrological regimes and glacial lakes of the Hindu Kush Himalayas: a review of current knowledge. *ICIMOD*.
- Magnin, F., Etzelmüller, B., Westermann, S., Isaksen, K., Hilger, P., Hermanns, R.L., 2019. Permafrost distribution in steep slopes in Norway: measurements, statistical modelling and geomorphological implication. *Earth Surf. Dyn. Discuss.* 1-35. <https://doi.org/10.5194/esurf-2018-90>
- Magnin, F., Haeberli, W., Linsbauer, A., Deline, P., Ravel, L., 2020. Estimating glacier-bed overdeepenings as possible sites of future lakes in the de-glaciating Mont Blanc massif (Western European Alps). *Geomorphology* 350, 106913. <https://doi.org/10.1016/j.geomorph.2019.106913>
- Marcet, M., Ringsø, Nielsen, S., Ribeyre, C., Kummert, M., Duvillard, P. A., Schoeneich, P., ... & Genuite, K. (2020). Investigating the slope failures at the Lou rock glacier front, French Alps. *Permafrost and Periglacial Processes*, 31(1), 15-30.
- Masson-Delmotte, V., Kageyama, M., Braconnot, P., Charbit, S., Krinner, G., Ritz, C., Guiliardi, E., Jouzel, J., Abe-Ouchi, A., Crucifix, M., 2006. Past and future polar amplification of climate change: climate model intercomparisons and ice-core constraints. *Clim. Dyn.* 26, 513-529.
- Masyagina, O. V., Evgrafova, S.Y., Bugaenko, T.N., Kholodilova, V. V., Krivobokov, L. V., Korets, M.A., Wagner, D., 2019. Permafrost landslides promote soil CO2 emission and hinder C accumulation. *Sci. Total Environ.* 657, 351-364.
- Matsuoka, N., Murton, J., 2008. Frost weathering: recent advances and future directions. *Permafr. Periglac. Process.* 19, 195-210.
- Mège, D. and Bourgeois, O. 2011: Equatorial glaciations on Mars revealed by gravitational collapse of Valles Marineris wallslopes *Earth Planet. Sci. Lett.*, 310 (2011), pp. 182-191.
- McColl, S.T., 2012. Paraglacial rock-slope stability. *Geomorphology* 153, 1-16.
- McColl, S.T., Davies, T.R.H., 2013. Large ice-contact slope movements: glacial buttressing, deformation and erosion. *Earth Surf. Process. Landforms* 38, 1102-1115.
- McColl, S.T., Draebing, D., 2019. Rock slope instability in the proglacial zone: State of the Art, in: *Geomorphology of Proglacial Systems*. Springer, pp. 119-141.
- McSaveney, M., 2002: Recent rock falls and rock avalanches on Mount Cook National Park, New Zealand. In: Evans, S.G., DeGraff, J.V. (Eds), *Catastrophic Landslides: Effects, Occurrence, and Mechanisms*, Reviews in Engineering Geology, vol. 15, pp. 35-70.
- Mercier, D., Coquin, J., Feuillet, T., Decaulne, A., Cossart, E., Jónsson, H.P., Sæmundsson, Þ., 2017. Are Icelandic rock-slope failures paraglacial? Age evaluation of seventeen rock-slope failures in the Skagafjörður area, based on geomorphological stacking, radiocarbon dating and tephrochronology. *Geomorphology* 296, 45-58. <https://doi.org/10.1016/j.geomorph.2017.08.011>
- Monnier, S., Kinnard, C., 2015. Internal structure and composition of a rock glacier in the dry Andes, inferred from ground-penetrating radar data and its artefacts. *Permafr. Periglac. Process.* 26, 335-346.
- Mool, P.K., Maskey, P.R., Koirala, A., Joshi, S.P., Lizong, W., Shrestha, A.B., Eriksson, M., Gurung, B., Pokharel, B., Khanal, N.R., 2011. Glacial lakes and glacial lake outburst floods in Nepal. *The World Bank*.
- Moreiras, S., Lisboa, M.S., Mastrantonio, L., 2012. The role of snow melting upon landslides in the central Argentinean Andes: LANDSLIDE ACTIVITY IN THE ACONCAGUA PARK, ARGENTINA. *Earth Surf. Process. Landf.* 37, 1106-1119. <https://doi.org/10.1002/esp.3239>
- Morino, C., Conway, S.J., Sæmundsson, Þ., Helgason, J.K., Hillier, J., Butcher, F.E.G., Balme, M.R., Jordan, C., Argles, T., 2019. Molards as an indicator of permafrost degradation and landslide processes. *Earth Planet. Sci. Lett.* 516. <https://doi.org/10.1016/j.epsl.2019.03.040>
- Mourey, J., Marcuzzi, M., Ravel, L., Pallandre, F., 2019. Effects of climate change on high Alpine mountain environments: Evolution of mountaineering routes in the Mont Blanc massif (Western Alps) over half a century. *Arctic, Antarct. Alp. Res.* 51, 176-189.
- Muller, S.W., 1945. ... Permafrost, Or Permanently Frozen Ground: And Related Engineering Problems. Army map service, US Army.
- Murton, J.B., 2001. Thermokarst sediments and sedimentary structures, Tuktoyaktuk Coastlands, western Arctic Canada. *Glob. Planet. Change* 28, 175-192. [https://doi.org/10.1016/S0921-8181\(00\)00072-2](https://doi.org/10.1016/S0921-8181(00)00072-2)
- Murton, J.B., Edwards, M.E., Lozhkin, A. V., Anderson, P.M., Savvinov, G.N., Bakulina, N., Bondarenko, O. V., Cherepanova, M. V., Danilov, P.P., Boeskorov, V., Goslar, T., Grigoriev, S., Gubin, S. V., Korzun, J.A., Lupachev, A. V., Tikhonov, A., Tsygankova, V.I., Vasilieva, G. V., Zanina, O.G.,

2017. Preliminary paleoenvironmental analysis of permafrost deposits at Batagaika megaslump, Yana Uplands, northeast Siberia. *Quat. Res. (United States)* 87, 314-330. <https://doi.org/10.1017/qua.2016.15>
- Murton, J.B., Peterson, R., Ozouf, J.-C., 2006. Bedrock fracture by ice segregation in cold regions. *Science* (80-). 314, 1127-1129.
- Nyberg, R., 1989. Observations of Slushflows and Their Geomorphological Effects in the Swedish Mountain Area. *Geogr. Ann. Ser. Phys. Geogr.* 71, 185-198.
- Oliva, M., Ruiz-Fernández, J., 2015. Coupling patterns between para-glacial and permafrost degradation responses in Antarctica. *Earth Surf. Process. Landforms* 40, 1227-1238.
- Oppikofer, T., Saintot, A., Hermanns, R., Böhme, M., Scheiber, T., Gosse, J., and Dreiås, G., 2017, From incipient slope instability through slope deformation to catastrophic failure—Different stages of failure development on the Ivasnasen and Vollan rock slopes (western Norway): *Geomorphology*, v. 289, p. 96-116.
- Oppikofer, T., Hermanns, R.L., Jakobsen, V.U., Böhme, M., Nicolet, P., Penna, I., 2020. Forecasting dam height and stability of dams formed by rock slope failures in Norway. *Nat. Hazards Earth Syst. Sci. Discuss.* 1-24.
- Osterkamp, T.E., Jorgenson, M.T., Schuur, E.A.G., Shur, Y.L., Kanevskiy, M.Z., Vogel, J.G., Tumskey, V.E., 2009. Physical and ecological changes associated with warming permafrost and thermokarst in interior Alaska. *Permafr. Periglac. Process.* 20, 235-256.
- Pacione, M. 1999: *Applied Geography: Principles and Practice*. Routledge, London, 664 pp.
- Panda, S.K., Marchenko, S.S., Romanovsky, V.E., 2014. High-resolution permafrost modeling in Denali National Park and Preserve. *Nat. Resour. Techn. Rep* 1-44.
- Pánek, T., Smolková, V., Hradecký, J., Baroň, I. and Šilhán, K. 2013: Holocene reactivations of catastrophic complex flow-like landslides in the Flysch Carpathians (Czech Republic/Slovakia) *Quat. Res.*, 80 (2013), pp. 33-46.
- Pánek, T. and Klimeš, J. 2016: Temporal behavior of deep-seated gravitational slope deformations: A review. *Earth-Science Reviews*. Volume 156, May 2016, P. 14-38.
- Pastick, N.J., Jorgenson, M.T., Wylie, B.K., Nield, S.J., Johnson, K.D., Finley, A.O., 2015. Distribution of near-surface permafrost in Alaska: Estimates of present and future conditions. *Remote Sens. Environ.* 168, 301-315.
- Patton, A.I., Rathburn, S.L., Capps, D.M., 2019a. Landslide response to climate change in permafrost regions. *Geomorphology* 340, 116-128. <https://doi.org/10.1016/j.geomorph.2019.04.029>
- Patton, A.I., Rathburn, S.L., Capps, D.M., 2019b. Landslide response to climate change in permafrost regions. *Geomorphology* 340, 116-128. <https://doi.org/10.1016/j.geomorph.2019.04.029>
- Pautler, B.G., Austin, J., Otto, A., Stewart, K., Lamoureux, S.F., Simpson, M.J., 2010. Biomarker assessment of organic matter sources and degradation in Canadian High Arctic littoral sediments. *Biogeochemistry* 100, 75-87.
- Pedrazzini, A., Jaboyedoff, M., Loye, A. and Derron, M.H. 2013: From deep seated slope deformation to rock avalanche: destabilization and transportation models of the Sierre landslide (Switzerland) *Tectonophysics*, 605 (2013), pp. 149-168
- Pérez-Guillén, C., Tsunematsu, K., Nishimura, K., Issler, D., 2019. Seismic location and tracking of snow avalanches and slush flows on Mt. Fuji, Japan. *Earth Surf. Dyn.* 7, 989-1007. <https://doi.org/10.5194/esurf-7-989-2019>
- Petley, D., 2012. Global patterns of loss of life from landslides. *Geology* 40, 927-930. <https://doi.org/10.1130/G33217.1>
- Petrakov, D.A., Chernomorets, S.S., Evans, S.G., Tutubalina, O.V., 2008. Catastrophic glacial multi-phase mass movements: a special type of glacial hazard. *Adv. Geosci.* 14, 211-218. <https://doi.org/10.5194/adgeo-14-211-2008>
- Péwé, R., Brown, T., 1973. Distribution of permafrost in North America and its relationship to the environment: a review, 1963-1973, in: *Permafrost: North American Contribution [to The] Second International Conference*. National Academies, p. 71.
- Péwé, T.L., 1983. Alpine permafrost in the contiguous United States: a review. *Arct. Alp. Res.* 15, 145-156.
- Pirulli, M., 2009. The Thurwieser rock avalanche (Italian Alps): Description and dynamic analysis. *Eng. Geol.* 109, 80-92. <https://doi.org/10.1016/j.enggeo.2008.10.007>
- Post, A.S. 1965: Alaskan Glaciers: recent observations in respect to the earthquake-advance theory. *Science* 148. 366-368.
- Price, M.F., Byers, A.C., Friend, D.A., Kohler, T., Price, L.W. (Eds.), 2019. 4. Snow, Ice, Avalanches, and Glaciers, in: *Mountain Geography*. University of California Press, pp. 85-126. <https://doi.org/10.1525/9780520956971-008>
- Prick, A., 2003. Frost weathering and rock fall in an arctic environment, Longyearbyen, Svalbard, in:

- Proceedings of the Eighth International Conference on Permafrost. Balkema Lisse, pp. 907-912.
- Pröbstl-Haider, U., Dabrowska, K., Haider, W., 2016. Risk perception and preferences of mountain tourists in light of glacial retreat and permafrost degradation in the Austrian Alps. *J. Outdoor Recreat. Tour.* 13, 66-78.
- Pudasaini, S.P., Krautblatter, M., 2014. A two-phase mechanical model for rock-ice avalanches. *J. Geophys. Res. Earth Surf.* 119, 2272-2290. <https://doi.org/10.1002/2014JF003183>
- Racine, C., Jandt, R., Meyers, C., Dennis, J., 2004. Tundra fire and vegetation change along a hillslope on the Seward Peninsula, Alaska, USA. *Arctic, Antarct. Alp. Res.* 36, 1-10.
- Ravel, L., Deline, P., 2008. La face ouest des Drus (massif du Mont-Blanc): évolution de l'instabilité d'une paroi rocheuse dans la haute montagne alpine depuis la fin du petit âge glaciaire. *Géomorphologie Reli. Process. Environ.* 14, 261-272.
- Ravel, L., Magnin, F., Deline, P., 2017. Impacts of the 2003 and 2015 summer heatwaves on permafrost-affected rock-walls in the Mont Blanc massif. *Sci. Total Environ.* 609, 132-143. <https://doi.org/10.1016/j.scitotenv.2017.07.055>
- Rebetez, M., Lugon, R., Baeriswyl, P.-A., 1997. Climatic change and debris flows in high mountain regions: the case study of the Ritigraben torrent (Swiss Alps), in: *Climatic Change at High Elevation Sites*. Springer, pp. 139-157.
- Reznichenko, N.V., Davies, T.R.H., Alexander, D.J., 2011. Effects of rock avalanches on glacier behaviour and moraine formation. *Geomorphology* 132, 327-338. <https://doi.org/10.1016/j.geomorph.2011.05.019>
- Richardson, S.D., Reynolds, J.M., 2000. Degradation of ice-cored moraine dams: implications for hazard development. *IAHS Publ.* 187-198.
- Robinson, T.R., Davies, T.R.H., Reznichenko, N.V., De Pascale, G.P., 2014. The extremely long-runout Komansu rock avalanche in the Trans Alai range, Pamir Mountains, southern Kyrgyzstan. *Landslides* 1-13. <https://doi.org/10.1007/s10346-014-0492-y>
- Romanovsky, V.E., Smith, S.L., Christiansen, H.H., 2010. Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007-2009: a synthesis. *Permafr. Periglac. Process.* 21, 106-116.
- Sæmundsson, P., Morino, C., Helgason, J.K., Conway, S.J., Pétursson, H.G., 2018. The triggering factors of the Móafellshyrna debris slide in northern Iceland: Intense precipitation, earthquake activity and thawing of mountain permafrost. *Sci. Total Environ.* 621, 1163-1175. <https://doi.org/10.1016/j.scitotenv.2017.10.111>
- Saroli, M., Stramondo, S., Moro, M. and Doumaz, F. (2005). Movements detection of deep seated gravitational slope deformations by means of InSAR data and photogeological interpretation: Northern Sicily case study. *Terra Nova*, 17, 35-43.
- Sattler, K., Keiler, M., Zischg, A., Schrott, L., 2011. On the connection between debris flow activity and permafrost degradation: a case study from the Schnalstal, South Tyrolean Alps, Italy. *Permafr. Periglac. Process.* 22, 254-265.
- Schild, A., 2008. ICIMOD's position on climate change and mountain systems. *Mt. Res. Dev.* 28, 328-331.
- Schleier, M., Hermanns, R.L., Rohn, J., Gosse, J.C., 2015. Diagnostic characteristics and paleodynamics of supraglacial rock avalanches, Innerdalen, Western Norway. *Geomorphology* 245, 23-39. <https://doi.org/10.1016/j.geomorph.2015.04.033>
- Schleier, M., Hermanns, R. L., Krieger, I., Oppikofer, T., Eiken, T., Rønning, J. S. and Rohn, J., 2016, Gravitational reactivation of a pre-existing post-Caledonian fault system: the deep-seated gravitational slope deformation at Middagstinden, western Norway: *Norwegian Journal of Geology*, v. 96, p. 1-24.
- Schlögel, R., Torgoev, I., De Marneffe, C., Havenith, H., 2011. Evidence of a changing size-frequency distribution of landslides in the Kyrgyz Tien Shan, Central Asia. *Earth Surf. Process. Landforms* 36, 1658-1669.
- Schneider, D., Huggel, C., Haeblerli, W., Kaitna, R., 2011. Unraveling driving factors for large rock-ice avalanche mobility: UNRAVELING DRIVING FACTORS FOR LARGE ROCK-ICE AVALANCHE MOBILITY. *Earth Surf. Process. Landf.* 36, 1948-1966. <https://doi.org/10.1002/esp.2218>
- Schoeneich, P., Dall'Amico, M., Deline, P., Zischg, A., 2011. Hazards related to permafrost and to permafrost degradation. *PermaNET Proj. state-of-the-art Rep.* 6.
- Schuur, E.A.G., Bockheim, J., Canadell, J.G., Euskirchen, E., Field, C.B., Goryachkin, S. V, Hagemann, S., Kuhry, P., Lafleur, P.M., Lee, H., 2008. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *Bioscience* 58, 701-714.
- Schuur, E.A.G., Vogel, J.G., Crummer, K.G., Lee, H., Sickman, J.O., Osterkamp, T.E., 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature* 459, 556-559.

- Schwanghart, W., Worni, R., Huggel, C., Stoffel, M., Korup, O., 2016. Uncertainty in the Himalayan energy-water nexus: Estimating regional exposure to glacial lake outburst floods. *Environ. Res. Lett.* 11, 74005.
- Screen, J.A., Deser, C., Simmonds, I., 2012. Local and remote controls on observed Arctic warming. *Geophys. Res. Lett.* 39.
- Segal, R.A., Lantz, T.C., Kokelj, S. V., 2016. Acceleration of thaw slump activity in glaciated landscapes of the Western Canadian Arctic. *Environ. Res. Lett.* 11. <https://doi.org/10.1088/1748-9326/11/3/034025>
- Shrestha, A.B., Eriksson, M., Mool, P., Ghimire, P., Mishra, B., Khanal, N.R., 2010. Glacial lake outburst flood risk assessment of Sun Koshi basin, Nepal. *Geomatics, Nat. Hazards Risk* 1, 157-169.
- Shreve, R.L., 1966. Sherman Landslide, Alaska. *Science* 154, 1639-1643. <https://doi.org/10.1126/science.154.3757.1639>
- Shugar, D.H., Clague, J.J., 2011. The sedimentology and geomorphology of rock avalanche deposits on glaciers: Rock avalanches on glaciers. *Sedimentology* 58, 1762-1783. <https://doi.org/10.1111/j.1365-3091.2011.01238.x>
- Shulmeister, J., Davies, T.R., Evans, D.J.A., Hyatt, O.M., Tovar, D.S., 2009. Catastrophic landslides, glacier behaviour and moraine formation - A view from an active plate margin. *Quat. Sci. Rev.* 28, 1085-1096. <https://doi.org/10.1016/j.quascirev.2008.11.015>
- Sidle, R.C., Ochiai, H., 2006. Natural factors influencing landslides. *Landslides Process. Predict. L. Use* 18, 41-119.
- Slater, A.G., Lawrence, D.M., 2013. Diagnosing present and future permafrost from climate models. *J. Clim.* 26, 5608-5623.
- Smith, W.D., Dunning, S.A., Brough, S., Ross, N., Telling, J., 2020. GERALDINE (Google Earth Engine supRaglAciAl Debris INput dEtector): a new tool for identifying and monitoring supraglacial landslide inputs. *Earth Surf. Dyn.* 8, 1053-1065. <https://doi.org/10.5194/esurf-8-1053-2020>
- Sosio, R., Crosta, G.B., Hungr, O., 2008. Complete dynamic modeling calibration for the Thurwieser rock avalanche (Italian Central Alps). *Eng. Geol.* 100, 11-26. <https://doi.org/10.1016/j.enggeo.2008.02.012>
- Sosio, R., Crosta, G.B., Chen, J.H., Hungr, O., 2012. Modelling rock avalanche propagation onto glaciers. *Quat. Sci. Rev.* 47, 23-40. <https://doi.org/10.1016/j.quascirev.2012.05.010>
- Stearns, S.R., 1966. Permafrost (perennially frozen ground).
- Stoffel, M., Huggel, C., 2012. Effects of climate change on mass movements in mountain environments. *Prog. Phys. Geogr.* 36, 421-439.
- Strom, A., Korup, O., 2006. Extremely large rockslides and rock avalanches in the Tien Shan Mountains, Kyrgyzstan. *Landslides* 3, 125-136. <https://doi.org/10.1007/s10346-005-0027-7>
- Subcommittee, P., 1988. Glossary of permafrost and related ground-ice terms. *Assoc. Comm. Geotech. Res. Natl. Res. Counc. Canada, Ottawa* 156.
- Svennevig, K., Solgaard, A.M., Salehi, S., Dahl-Jensen, T., Merryman Boncori, J.P., Larsen, T.B., Voss, P.H., 2019. A multidisciplinary approach to landslide monitoring in the Arctic: Case study of the March 2018 ML 1.9 seismic event near the Karrat 2017 landslide. *Geol. Surv. Denmark Greenl. Bull.* 43. <https://doi.org/10.34194/GEUSB-201943-02-08>
- Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G., Zimov, S., 2009. Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochem. Cycles* 23.
- Teshebaeva, K., Ehtler, H., Bookhagen, B. and Strecker, M. 2019 Deep-seated gravitational slope deformation (DSGSD) and slow-moving landslides in the southern Tien Shan Mountains: new insights from InSAR, tectonic and geomorphic analysis. *Earth Surf. Process. Landforms* 44, 2333-2348.
- Thomas, H.R., Cleall, P., Li, Y.-C., Harris, C., Kern-Luetschg, M., 2009. Modelling of cryogenic processes in permafrost and seasonally frozen soils. *Géotechnique* 59, 173-184. <https://doi.org/10.1680/geot.2009.59.3.173>
- Tian, L., Yao, T., Gao, Y., Thompson, L., Mosley-Thompson, E., Muhammad, S., Zong, J., Wang, C., Jin, S., Li, Z., 2017. Two glaciers collapse in western Tibet. *J. Glaciol.* 63, 194-197. <https://doi.org/10.1017/jog.2016.122>
- Tricart, J., 1956. Etude expérimentale du problème de la gélivation. *Biul. Peryglac.* 4, 285-318.
- Turetsky, M.R., Abbott, B.W., Jones, M.C., Anthony, K.W., Olefeldt, D., Schuur, E.A.G., Koven, C., McGuire, A.D., Grosse, G., Kuhry, P., 2019. Permafrost collapse is accelerating carbon release.
- Uhlmann, M., Korup, O., Huggel, C., Fischer, L., Kargel, J.S., 2013. Supra-glacial deposition and flux of catastrophic rock-slope failure debris, south-central Alaska. *Earth Surf. Process. Landforms* 38, 675-682.
- UNDHA, 1992. Internationally agreed glossary of basic terms related to disaster management. UNDHA (United Nations Dep. Humanit. Aff. Geneva).

- Vadakkedath, V., Zawadzki, J., Przeździecki, K., 2020. Multisensory satellite observations of the expansion of the Batagaika crater and succession of vegetation in its interior from 1991 to 2018. *Environ. Earth Sci.* 79, 150. <https://doi.org/10.1007/s12665-020-8895-7>
- Van Vliet-Lanoë, B., Fox, C.A., 2018. Frost action, in: *Interpretation of Micromorphological Features of Soils and Regoliths*. Elsevier, pp. 575-603.
- Varnes, D. J., Radbruch-Hall, D., Varnes, K. L., Smith, W. K. and Savage, W. Z. (1990). Measurement of Ridge-spreading Movements (Sackungen) at Bald Eagle Mountain, Lake County, Colorado, 1975-1989. US Geological Survey, Open File Report 90-543.
- Varnes, D.J., 1984. Landslide hazard zonation: a review of principles and practice. *Nat. Hazard Ser.* <https://doi.org/10.1007/BF02594720>
- Varnes, D.J., 1978. Slope Movement Types and Processes. *Transp. Res. Board Spec. Rep.* 11-33. <https://doi.org/10.1007/BF02594720>
- Veh, G., Korup, O., von Specht, S., Roessner, S., Walz, A., 2019. Unchanged frequency of moraine-dammed glacial lake outburst floods in the Himalaya. *Nat. Clim. Chang.* 9, 379-383.
- Verdonen, M., Berner, L.T., Forbes, B.C., Kumpula, T., 2020. Periglacial vegetation dynamics in Arctic Russia: decadal analysis of tundra regeneration on landslides with time series satellite imagery. *Environ. Res. Lett.* 15, 105020.
- Vieira, G., López-Martínez, J., Serrano, E., Ramos, M., Gruber, S., Hauck, C., Blanco, J.J., 2008. Geomorphological observations of permafrost and ground-ice degradation on Deception and Livingston Islands, Maritime Antarctica.
- Walls, M., Hvidberg, M., Kleist, M., Knudsen, P., Mørch, P., Egede, P., ... & Watanabe, T. (2020). Hydrological instability and archaeological impact in Northwest Greenland: Sudden mass movement events signal new concerns for circumpolar archaeology. *Quaternary Science Reviews*, 248, 106600.
- Washburn, A.L., 1980. Permafrost features as evidence of climatic change. *Earth-Science Rev.* 15, 327-402.
- Wegmann, M., Gudmundsson, G.H., Haeberli, W., 1998. Permafrost changes in rock walls and the retreat of alpine glaciers: a thermal modelling approach. *Permafr. Periglac. Process.* 9, 23-33. [https://doi.org/10.1002/\(SICI\)1099-1530\(199801/03\)9:1<23::AID-PPP274>3.0.CO;2-Y](https://doi.org/10.1002/(SICI)1099-1530(199801/03)9:1<23::AID-PPP274>3.0.CO;2-Y)
- Westermann, S., Peter, M., Langer, M., Schwamborn, G., Schirrmeister, L., Etzelmüller, B., Boike, J., 2017. Transient modeling of the ground thermal conditions using satellite data in the Lena River delta, Siberia. *Cryosph.* 11, 1441-1463.
- Westoby, M.J., Glasser, N.F., Hambrey, M.J., Brasington, J., Reynolds, J.M., Hassan, M.A.A.M., 2014. Reconstructing historic Glacial Lake Outburst Floods through numerical modelling and geomorphological assessment: Extreme events in the Himalaya. *Earth Surf. Process. Landforms* 39, 1675-1692.
- Wood, J.L., Harrison, S., Reinhardt, L., Taylor, F.E., 2020. Landslide databases for climate change detection and attribution. *Geomorphology* 355, 107061.
- Woods, G.C., Simpson, M.J., Pautler, B.G., Lamoureux, S.F., Lafrenière, M.J., Simpson, A.J., 2011. Evidence for the enhanced lability of dissolved organic matter following permafrost slope disturbance in the Canadian High Arctic. *Geochim. Cosmochim. Acta* 75, 7226-7241.
- Yamasaki, S., Nagata, H., Kawaguchi, T., 2014. Long-traveling landslides in deep snow conditions induced by the 2011 Nagano Prefecture earthquake, Japan. *Landslides* 11, 605-613. <https://doi.org/10.1007/s10346-013-0419-z>
- Yu, G.-A., Yao, W., Huang, H.Q., Liu, Z., 2020. Debris flows originating in the mountain cryosphere under a changing climate: A review. *Prog. Phys. Geogr. Earth Environ.* 0309133320961705.
- Zischinsky, U. (1966). On the deformation of high slopes. In *Proceedings of the First Conference of the International Society for Rock Mechanics*, Vol. 2, pp. 179-185.
- Zimmermann, M., 1990. Debris flows 1987 in Switzerland: geomorphological and meteorological aspects. *Hydrol. Mt. Reg. II - Artif. Reserv. Water Slopes* 1, 387-394.
- Zimmermann, M., Haeberli, W., 1992. Climatic change and debris flow activity in high-mountain areas. A case study in the Swiss Alps. *Catena. Suppl.* 59-72.
- Zongxing, L., Qi, F., Wang, Q.J., Song, Y., Aifang, C., Jianguo, L., 2016. Contribution from frozen soil meltwater to runoff in an in-land river basin under water scarcity by isotopic tracing in northwestern China. *Glob. Planet. Change* 136, 41-51.
- Zou, D., Zhao, L., Yu, S., Chen, J., Hu, G., Wu, T., Wu, J., Xie, C., Wu, X., Pang, Q., 2017. A new map of permafrost distribution on the Tibetan Plateau. *Cryosph.* 11, 2527.