SHORT DEBRIS FLOW RECURRENCE PERIODS FOR A SVALBARD DEBRIS FAN: POSSIBLE IMPLICATIONS FOR EARTH AND MARS.
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Introduction: The Arctic is a region of several self-amplifying climate feedbacks and thus considered very sensitive to climate change [1,2]. Rising mean surface air temperatures in the Arctic since the 1960s were suggested as a cause for an increasing frequency of heavy rain events and even warmer temperatures are projected for the upcoming decades [3]. In arctic Mars-analog areas like Svalbard [e.g., 4], such rain events can trigger large mass wasting processes with a profound impact on human activity and geomorphology [5]. However, although debris flows were shown to be primarily caused by rain events and not snow melting [5-7], lichenometry-based estimates for their recurrence periods (also referred to as "return periods") have been very long, ranging around several decades to centuries [5,7]. This also influenced analog-derived conclusions with respect to debris flow activity on Mars [e.g., 8].

Here we present a remote sensing-based study of a debris fan in Hanaskogdalen, Spitsbergen/Svalbard, (Fig. 1, top right) and show that several debris flows occurred during the past decades. We also present lichenometry-based ages for most of these flows, all of which are in agreement with our image analyses.

Location and Methodology: Hanaskogdalen is an approximately 10 km long, ~2.5 km wide, and up to ~800 m deep west-east trending U-shaped valley at the west coast of central Spitsbergen/Svalbard. The valley entrance is opposite to Longyearbyen Airport across the Adventfjorden, therefore providing good accessibility and weather data coverage. The investigated debris fan (Fig. 1, top right) is located at 78.285°N, 15.758°E, about halfway into the valley on its northern side. It is the largest debris fan in Hanaskogdalen (~0.5 km²) and homogeneously vegetated by bog mosses and cotton grasses, thereby providing conditions most suitable for multi-temporal remote sensing analyses of fresh surfaces (i.e., recent debris flows). As its alcove erodes almost exclusively into Carolinefjellet sandstone [9], the debris fan provides a good substrate for lichenometry-suited lichens, e.g., *Pseudophebe miniscula* [e.g., 10].

To detect and date fresh flow features on the debris fan (Fig. 1), we used aerial images, e.g., by an airborne version of the High Resolution Stereo Camera (HRSC-AX), as well as satellite images by Keyhole and GeoEye from the years 1961, 1976, 1990, 2008, 2011, and 2013. As an independent test, we correlated these observations with lichenometry-derived exposure ages which we estimated based on close-up images of rock surfaces within specific debris flows. We used the ImageJ photo analysis software to measure area-derived thallus diameters (ADDs) of *Pseudophebe miniscula* lichens. We then divided the ADDs by updated Svalbard-specific growth rates (~ 0.45 to 0.7 mm/yr; [10]) to obtain lichen colonization ages. Added by the colonization onset period (~12 to 18 years; [10,11]), these result in estimates for rock surface exposure ages, i.e., the approximate age of a debris flow.

Results: Covering five decades (1961-2013), we correlated daily precipitation volumes as well as temperature values measured at Svalbard Lufthavn (~7.5 km southwest of the fan) with changes detected on six high resolution aerial and satellite images of the studied debris fan. We identified nine intense rain events (Fig 1, left), i.e., heavy precipitation (>13 mm/day) or repeated medium precipitation (3 x ~10 mm/day; only in 2013) coinciding with temperatures >0°C. Aside from the general drainage trend moving from the eastern (1961) to the western side of the fan (1976 onwards), we observed appearances of fresh debris flows between every image. Additionally, we derived lichenometry-based exposure ages for rocks within five debris flows, which appear on images from 1976, 1990, and 2008. All these ages are in agreement with the image-based constraints.

Discussion and conclusions: We show that recurrence periods of Svalbard debris flows can be few 10s of years, which is in agreement with predicted accelerated mass wasting in an increasingly warmer Arctic [3]. This is up to an order of magnitude shorter than recurrence periods previously reported based on lichenometry [7,12]. Despite this, we show that lichenometry-derived dating is in agreement with our image analyses and should therefore not be discounted as a viable technique [13]. We tentatively attribute the overestimated lichenometry-derived recurrence periods for Svalbard [7,12] to erroneous, preliminary lichen growth curves, which have since been improved [10,11].

Similarly short recurrence periods (~10s of years) were suggested for a debris fan assemblage in Istok crater on Mars [8]. These periods were interpreted as time frames for the episodic availability of liquid water due to snow melting during past phases of higher obliquity. However, as the performed Svalbard-Mars analogy was still based on much longer debris flow recurrence periods, this was seen as indicator that Istok crater might have been at least as active as Svalbard is today [8]. In light of our results, this might have been an over-estimate, as the correlation between geomorphology and general debris flow activity needs to be re-evaluated for classical Mars analog sites such as Svalbard.

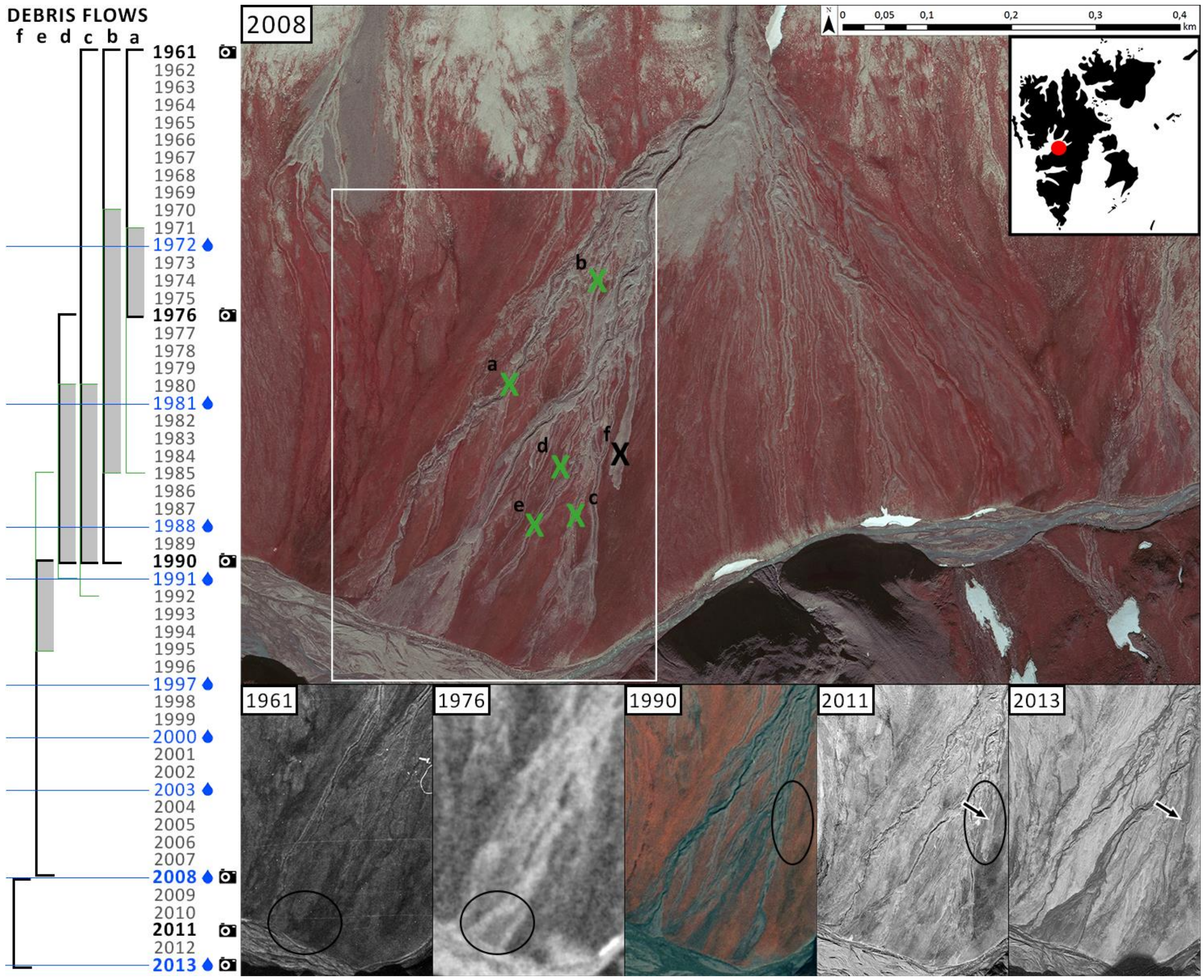

Figure 1: Summary our observations of changes over time on a debris fan (78.285°N, 15.758°E) in Hanaskogdalen, Spitsbergen/Svalbard. **(Left)** Timeline correlating the observed debris flows (a-f) with the years of image acquisition (in bold) and of intense rain events (in blue; events defined in result section). In 2008 and 2013, the images were taken shortly after the respective rain events. Black brackets indicate image constraints (two flows encompass 1976 due to the relatively low resolution of that image); green brackets show the associated lichenometry-based age constraints (total variances due to growth rates of 0.45 to 0.7 mm/yr and colonization periods of 12 to 18 years [10,11]). Grey bars mark the resulting overlaps, and thus most likely windows of formation, which always contain one or two heavy rain events. Debris flow f is too young for lichenometry. **(Right)** HRSC-AX false-color aerial image of the study area (see inlet). Green crosses mark lichenometry locations (flows a-e), where we measured lichen diameters on rock surfaces to derive exposure ages, i.e., likely formation ages of the debris flows they are contained in. The sixth, most recent, image-confirmed flow f is too young for lichenometry and marked with a black cross. The white box indicates the location of the figures below, showing crops of two aerial images (1961 and 1990), as well as three satellite images by Keyhole (1976) and GeoEye (2011 and 2013). Black ellipses and arrows highlight example areas of pronounced change between image pairs.

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References: [1] Walsh, J. E., & Anderson, P. A. (2004). Arctic Climate Impact Assessment (ACIA). Retrieved from http://www.acia.uaf.edu/ [2] Miller, G. H. et al. (2010). *Quaternary Science Reviews*, 29(15–16), 1679–1715. [3] Førland, E. J. et al. (2011). *Advances in Meteorology*, 2011, 1–14. [4] Hauber, E. et al. (2011). *Geological Society of America, Special Paper*, 483, 177–201 [5] André, M.-F. (1995). *Geografiska Annaler*, 77(4), 241. [6] Larsson, S. (1982). *Geografiska Annaler*, 64(3/4), 105. [7] André, M.-F. (1990). *Polish Polar Research*, 11(3–4), 345–363.[8] de Haas, T. et al. (2015). *Nature Communications*, 6(May), 7543. [9] Major, H. et al. (2000), Geological map of Svalbard 1:100,000, sheet C9G Adventdalen, Norsk Polarinstitut Temakart nr. 31. [10] Werner, A. (1990). *Arctic and Alpine Research*, 22(2), 129. [11] Roof, S., & Werner, A. (2011). *Arctic, Antarctic, and Alpine Research*, 43(4), 621–631. [12] van Steijn, H. (1996). *Geomorphology*, 15(3–4), 259–273. [13] Osborn, G. et al. (2015). *Quaternary Research*, 83(1), 1–12.