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Debris Flow or Deformation? Ground-Penetrating Radar Patterns of Alpine Moraines

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GPR has been repeatedly used to understand the structure and evolution of moraine deposits in arctic areas and mid-latitude lowlands. However, GPR has not been extensively applied to glacial sediments in Alpine environments to date and, consequently, the versatility of this method has not been explored systematically. We present data from moraines in various alpine study areas, obtained with a RAMAC GPR device equipped with 50, 100 and 200 MHz antennas. In study areas in Austria and Switzerland, late-glacial moraines (mostly Younger Dryas) were investigated while at the Gornergletscher in Switzerland, we measured profiles across moraine ridges dating from the 1920 and 1980 advance, annual moraines and at the immediate glacier snout. At this site, the GPR measurements were combined with detailed field sedimentology. Exposures through moraines were created using trenching tools and spades.

In the limestone study areas in Austria, a penetration depth of up to 20 m with high-resolution 100 and 200 MHz antennas was reached. Thus, GPR proved to be a powerful tool for investigating structures and related formation mechanisms at these sites. In areas built up of metamorphic rock (e.g. gneiss and mica-schist), penetration depth was much lower and the structures were less clearly discernable. The reason lies probably in a higher clay content and thus, higher attenuation of the radar waves. Applying several working frequencies proved to be rewarding to characterise the main structures of interest. 200 MHz was the best frequency for depicting small-scale internal structures down to a depth of several meters while the 100 and 50 MHz radargrams provided valuable additional information from greater depth, which made it easier to

estimate the position of the bedrock surface.

At study sites in Austria, different sedimentary facies could be distinguished from the radargrams. While some moraines, or parts of them, are characterized by deformation structures (folds, faults), others seem to consist mainly of subparallel debris flow deposits. At Gornergletscher, sedimentological investigations show that the sediments are the result of stacking of supraglacially-derived debris flows that appear not to have been affected subsequently by significant fluvial reworking or dead-ice meltout. These findings are confirmed by the GPR results. Even if mostly incoherent reflections were found in the shallow subsurface and only few continuous reflectors could be traced, the predominantly surface-parallel structure of the strata is evident. The radargrams show steeper-than-usual distal slopes, but an absence of clear deformation structures such as thrusts or overturned folds observed elsewhere.

Dead ice was identified in the immediate proglacial surroundings of the snout which is consistent with field observations and test diggings. However, the thickness and extent of such dead ice is very limited and does not appear to have a significant impact on the final shaping of annual moraines. GPR data from the glacier snout indicate a presence of englacial tunnels and absence of shear planes. Together with visual clast shape data, this suggests that Gornergletscher deposits dominantly glaciofluvial sediments from the base of the glacier which (a) have been elevated near the snout to slide down the glacier surface where they form debris flow-dominated ice-contact fans or (b) have been deposited as outwash in the foreland to then be bulldozed by smaller seasonal advances and pushed up into moraines.

The radar and sedimentological facies correspond to each other well and can be used to extend the observations from exposures to greater depths along larger profile lines, thereby providing a meaningful insight into the continuation of these structures and the larger-scale relationships between individual moraines. Comparing results from late-glacial moraines with findings from modern deposits may help to gain insights into glacier behaviour in the past, demonstrating how modern moraines can effectively serve as analogues for past depositional systems.