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Detailed sedimentology and geomorphology elucidate mechanisms of formation of modern and historical sequences of minor moraines in the European Alps

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Suites of closely-spaced minor moraines may help further understanding of glacier retreat and predict its geomorphological effects through the observations of moraine formation on short timescales. This research is common in lowland, maritime settings (Sharp, 1984; Boulton, 1986; Krüger, 1995; Reinardy et al., 2013), but remains sparse in high-mountain settings (Hewitt, 1967; Ono, 1985; Beedle et al., 2009; Lukas, 2012).

This research presents detailed sedimentological and geomorphological research on minor moraines at two high-mountain settings in the Alps: Silvrettagletscher, Switzerland, as a modern setting and Schwarzensteinkees, Austria, as a historical setting. Geomorphological investigations included mapping and measurements through field observations and assessing aerial imagery. Additionally, terrestrial laser scanning and ground-penetrating radar data were collected in the Schwarzensteinkees foreland. Detailed sedimentological investigations followed excavation of seven moraines at Silvrettagletscher and five moraines at Schwarzensteinkees and include multiple scales of observation and measurements to support interpretations of sediment transport and deposition (e.g. Evans and Benn, 2004).

The modern moraines at Silvrettagletscher, in the immediately proglacial foreland, have been forming since before 2003. Four mechanisms of formation show distinct sedimentological signatures: formerly ice-cored moraines (e.g. Kjær & Krüger, 2001; Lukas, 2012; Reinardy et al., 2013) , push moraine formation on a reverse bedrock slope (e.g. Lukas, 2012), push moraine formation incorporating sediments deposited in a former proglacial basin, and basal freeze-on (e.g. Andersen & Sollid, 1971; Krüger, 1995; Reinardy et al., 2013). Schwarzensteinkees still exists but is currently restricted to steeply-dipping bedrock slabs above the main valley. This study therefore investigates the moraines in the foreland that formed between approximately 1850 and 1930. The minor moraines here formed as push moraines in two groups separated by a former proglacial basin and are composed dominantly of pre-existing proglacial outwash gravel through efficient bulldozing of the glacier front (Lukas, 2012).

These findings show a range of mechanisms responsible for moraine formation. Furthermore, basal freeze-on processes incorporating subglacial sediment (till) have not been recorded in high-mountain moraine formation, suggesting a commonality of seasonal climatic controls between the glacier dynamics of high-mountain glaciers and those in more lowland, maritime settings.

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