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Multi-temporal DEMs used to quantify the geomorphological impact of a late 20th century glacier re-advance at Schwarzberggletscher, Switzerland

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ABSTRACT

Sedimentological investigations have advanced understanding of moraine formation at Alpine glaciers; however, few studies use multitemporal elevation datasets to observe landform generation during a period of glacier re-advance. Archive aerial image sets from 1974 to 2010 were processed using a photogrammetric workflow to visualise and quantify geomorphological change at the margin of Schwarzberggletscher, Switzerland. A combined co-alignment and iterative closest point-based approach was adopted to improve the comparative accuracy of the topographic datasets derived from the historical aerial imagery. This enabled the geomorphological impact of a glacier re-advance that occurred between 1974 and the early 1990s to be monitored. In the geospatial data, we recognise: (i) landform development associated with the advancing glacier terminus between 1974 and 1990; (ii) moraine erosion at the advancing, but fluctuating glacier margin; and (iii) the ablation of buried ice in the proglacial area between 1999 and 2010. The implications of this re-advance on the geomorphological record of glacier change are discussed, with this study providing a median and maximum error thresholded rate of surface lowering for ice-cored moraines of ~0.2 ma^{-1} and ~0.4 ma^{-1}, respectively. Finally, this study highlights the potential of now-readily accessible datasets, and refined image processing workflows involving image co-alignment and fine registration, for aiding future geomorphological research in the Swiss Alps.

1. Introduction

Moraines are important archives of environmental change within glaciated terrains and help us understand glacier dynamics and the response of glaciers to climatic forcing (e.g., Braumann et al., 2022; Rowan et al., 2022; Boston et al., 2023). More broadly, understanding how glacial landscapes respond to climate change is important as reducing glacier extent impacts water resources (e.g., Pellicciotti et al., 2014; Schaefli et al., 2019) and geohazard management (e.g., Haeberli et al., 1989; Evans and Clague, 1994; Huggel et al., 2012; Kos et al., 2016). Where process-form relationships are well established, assemblages of glacial landforms and sediments can be used to infer how glaciers have responded to past climate change (e.g., Chandler et al., 2016); however, real-time observations of moraine formation – that are used to inform conceptual models of glacier behaviour and landform development – are hampered by the global trend of glacier recession recorded in many high-mountain areas (Hock et al., 2019). In the European Alps, a regional trend of rapid glacier recession has been observed (Fischer et al., 2015; Sommer et al., 2020; The GlaMBIE Team, 2025), and this means that there are few opportunities to directly observe landform development at the margins of advancing glaciers.

Periods of glacier advance, particularly in Iceland and Norway, have offered the opportunity to observe moraine formation and proglacial landform development directly (e.g., Krüger, 1985; Winkler and Nesje, 1999; Winkler and Matthews, 2010). There have been fewer such studies that have directly assessed moraine formation in the European Alps (e.g., Small et al., 1984). During the 1970s and 1980s, many glaciers in the European Alps advanced in response to cooling in the preceding decades (Zemp et al., 2008; Huss et al., 2015). The geomorphological impact of advancing glaciers during these decades has only been subject to limited study. In particular, Cook et al. (2013) investigated the modification of a paraglacial rock avalanche deposit by the 1980s advance of Feegletscher Nord, Switzerland. Small et al. (1984) quantified the volume of sediment transfer onto moraine slopes at the lateral margin of Glacier De Tsidjiore

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Nouve, between 1977 and 1982. Push moraine development at the margin of Turtmannglacier was observed by Eybergen (1986), who reported rates of moraine deformation associated with the 1986 advance of this glacier. Other studies have considered the geomorphological consequences of shorter, often seasonal glacier advances, associated with the development of 'minor moraines' (Rettig et al., 2023) including those formed at the margins of readvancing Alpine glaciers during the 1980s (e.g., Lukas, 2012; Wyshnytzky et al., 2020). These studies – which provide a valuable record of landform development at the margins of Alpine glaciers – are often underpinned by a combination of geomorphological mapping and the shallow excavation of moraine sections to investigate moraine sedimentology and infer the mode of formation. With some exceptions (e.g., Small et al., 1984; Eybergen, 1986), studies on moraine formation are inferential because they are typically undertaken long after the studied glacier has advanced, without direct observation of moraine formation.

One less explored source of data that can be used to track landform development at advancing glaciers is archive aerial imagery (e.g., Korsgaard et al., 2015). When used in combination with modern photogrammetric approaches, multi-temporal topographic datasets can be generated. In the Swiss Alps, regular aerial surveys and digital photogrammetry provide opportunities for the quantitative assessment of surface change over annual and decadal time scales (Gabbud et al., 2016). For example, Micheletti et al. (2015) investigated decadal landscape response to cooling in Hérens Valley, Switzerland, by using archival image sources to produce multitemporal Digital Elevation Models (DEMs). However, a review by Śledź et al. (2021) highlighted that where archive imagery is used to derive historical DEMs, datasets can have large uncertainties. There has been discussion of these issues in the context of Structure-from-Motion (SfM) photogrammetry (James et al., 2019). Errors in DEMs derived from archive imagery using SfM can be large, therefore permitting only considerable displacements in the land surface to be detected. In such scenarios it is useful for researchers to validate surface change using field and geophysical evidence (e.g., Tonkin et al., 2016; Midgley et al., 2018). As a result of both random and systematic errors, our ability to reliably detect more subtle surface changes in glacial and other landscapes can be detrimentally impacted. While concern has been expressed, developments in image processing workflows involving the co-alignment of multi-temporal images (e.g., Feurer and Vinatier, 2018) alongside the co-registration of point clouds (Parente et al., 2021) show great potential for improving the comparative accuracy of any derived datasets, improving the detection of surface change over time.

In summary, we argue that there are relatively few studies documenting landform generation at the margins of advancing glaciers in the European Alps using historical DEMs. Valuable archives of aerial imagery have the potential to facilitate the assessment of sediment remobilisation and transfer by the advance of glaciers during this period and can provide additional lines of evidence on landform generation in lieu of direct observation or sedimentary analysis, which are not always possible. The aim of this study is to explore the processes of moraine formation and degradation at a formerly advancing glacier margin, in order to support the accurate interpretation of ancient (relict) landforms found widely in deglaciated mountain environments. Therefore, this work: (i) describes landforms developed as a result of the 1980s readvance of an Alpine glacier; (ii) quantitatively constrains sediment transfer to the proglacial zone during a period of glacier re-advance; and (iii) discusses the role of archive aerial imagery in supporting future glacial geomorphological studies in the Alps.

This work is important because it: (i) provides a demonstration of how error can be reduced through archive image co-alignment and this can be applied globally to processing aerial imagery from a wide range of geomorphological contexts; (ii) provides surface lowering rates for ice-cored moraines where a paucity of data exist in the Alpine setting; and (iii) illustrates the geomorphological impact of Alpine glacier advance, which in a world characterised by glacier recession, provides a rare opportunity to better understand the relationship between ice margin advance and proglacial response.

2. Study site and previous research

Schwarzberggletscher (46° 01′ N; 7°56′ E) is a temperate valley glacier located in the Valais canton of the Swiss Alps, adjacent to the Italian border and covers an area of ~4.9 km^2 (GLAMOS, 2022; Fig. 1). The mass balance of this glacier has been monitored since 1955, with monitoring coinciding with the development of the Mattmark dam (Huss et al., 2015). According to Gharehchahi et al. (2021), the glacier occupies an elevation range of 2680 to 3566 m above sea level. Whilst Schwarzberggletscher is one of the glaciers that experienced strong mass balance gains in the 1970s, with an average of +0.53 m w.e.a^{-1}, it now routinely experiences a negative mass balance (Huss et al., 2015). This is reflected in recent reductions in glacier length, which are likely exacerbated by its 'bottom heavy' hypsometry and a currently unfavourable accumulation area ratio (see Gharehchahi et al., 2021). Fig. 2 depicts the GLAMOS (2022) glacier length record for this site, with advance recorded between ~1974 and ~ 1990, and recession recorded since the early 1990s. According to the MeteoSwiss (2025) spatial climate normals (1 km grid), the site experienced a mean annual air temperature (MAAT) of −3.4 °C for the 1961–1990 period. This increased to −1.9 °C for the 1991 to 2020 observation period. The section of the proglacial zone investigated by this study is not found to be an area of 'potential ice-rich permafrost' according to indicative mapping by Kenner et al. (2019) and is only at the lowermost limit of possible 'warm / shallow' permafrost according to the global permafrost distribution model of Grüber (2012). The site has previously been subject to geomorphological study. For example, Bircher (1982) dated palaeosols found within the Little Ice Age large lateral moraines. A more recent geomorphological study used the proglacial area to investigate structural controls on glacial quarrying (Hooyer et al., 2012).

By 2010, the terminus of Schwarzberggletscher was receding and thinning across a gently sloping bedrock shelf that sits at ~2700 m with a steep slope down to the valley below at ~2500 m. The glacier had two main meltwater drainage channels toward the north and the south of the ice margin. The northern margin was characterised by a prominent ice-cored supraglacial lateral moraine. The more effective lateral moraine development along the north margin compared to the south reflects the asymmetry in valley cross-profile, with a much steeper and higher relief north valley wall than the south side, which could shed debris onto the ice surface (c.f. Evans, 1999). The glacier surface exhibited several englacial structures, including flow-parallel foliation, as well as a prominent debris-charged arcuate foliation that swept across much of the northern half of the terminus region. These englacial structures indicate substantial englacial debris transfer to the ice margin.

3. Methods

3.1. Datasets and image processing

Multitemporal DEMs were derived using historical archive imagery provided by the Swiss Federal Office for Topography Luftbild-Informations system (LUBIS). The selected image sets used in this study spanned the re-advance of Schwarzberggletscher (Fig. 2), and covered the following years: 1974, 1979, 1983, 1990, 1999 and 2010. Images were acquired from approximate flight heights of 3400–4100 m, from single flight lines running either broadly parallel or transverse to the direction of ice-flow (Table 1). The image processing used here adopts a Structure-from-Motion (SfM) workflow: a now commonplace approach for deriving elevation data from historical aerial imagery of glaciers (e.g., Mertes et al., 2017; Midgley and Tonkin, 2017; Mölg and Bolch, 2017). Missing camera calibration information for selected image sets led to low comparative accuracy in the DEM products initially produced by this study. Poorly calibrated camera models are known to

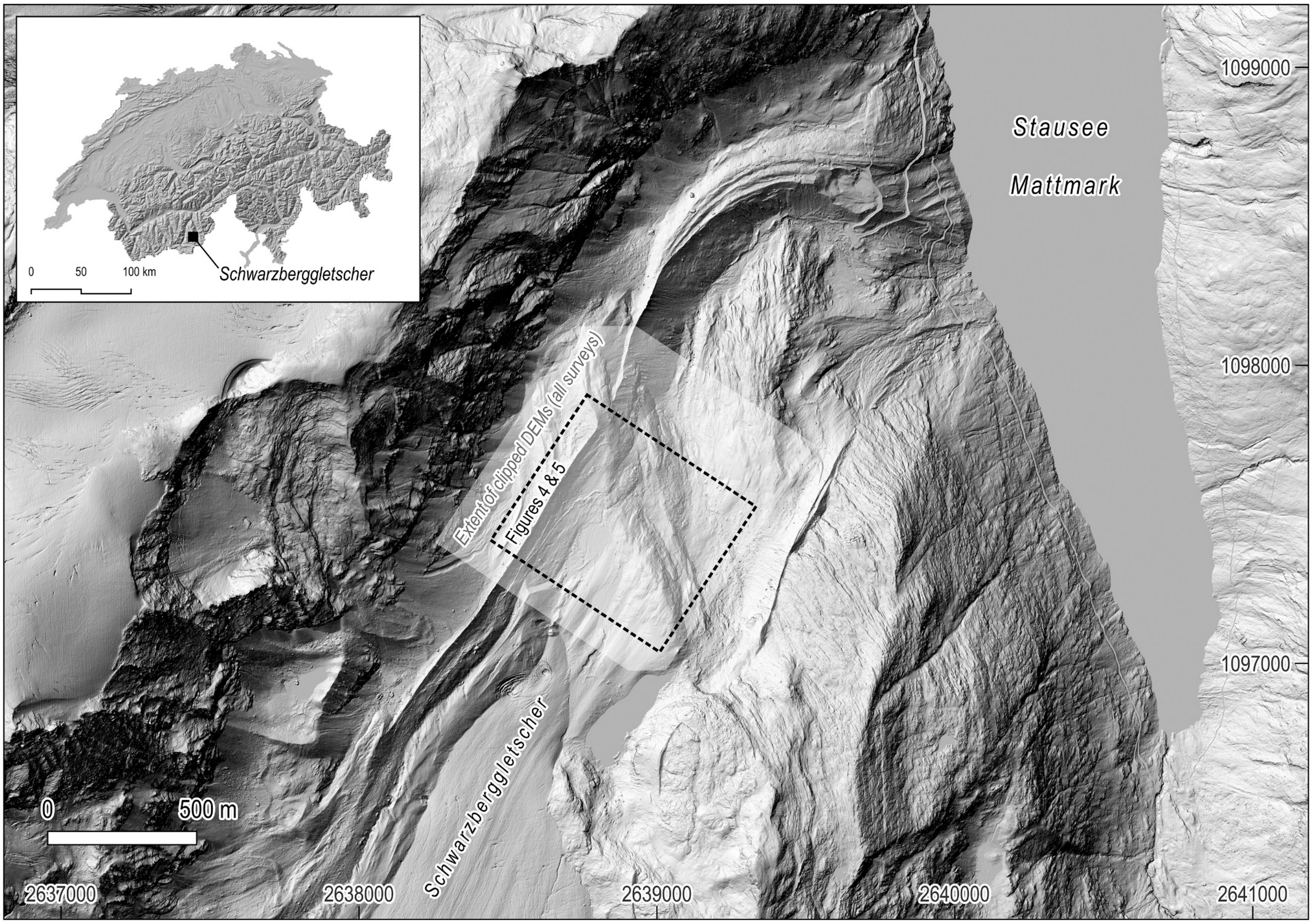

Fig. 1. Location of Schwarzberggletscher as depicted in the SwissAlti^{3D} hillshaded digital elevation model (Federal Office of Topography, © swisstopo). The extent of the clipped multitemporal DEMs analysed in this study is shown. Coordinates relate to the CH1903+ / LV95 system.

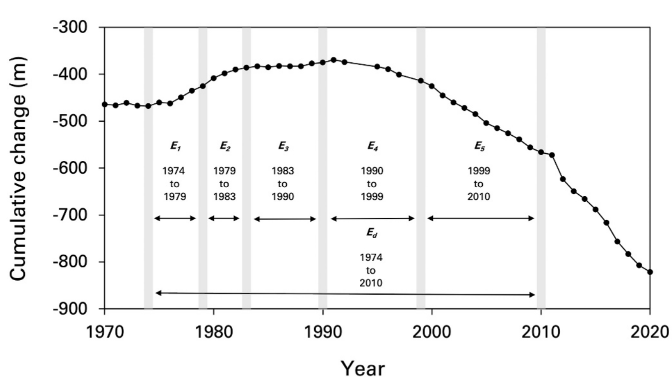

Fig. 2. Cumulative length change at Schwarzberggletscher (adapted from the GLAMOS (2022) dataset). The grey lines show the DEMs produced by this study. Additional annotation highlights the epochs where DEMs are compared.

influence the quality of derived elevation data when using a SfM workflow (Stark et al., 2022), and data quality issues are known to impact the ability to reliably detect geomorphological change (Bakker and Lane, 2017). To circumvent these issues, a refined workflow involving a co-alignment approach was adopted following Cook and Dietze (2019). Co-alignment is a now well-documented image processing technique that has been used to improve the comparative accuracy of data derived from SfM image processing (de Haas et al., 2021; Nota et al., 2022; Dille et al., 2022). It involves the alignment of multi-epoch image sets as a single block (Feurer and Vinatier, 2018). A co-alignment approach has also been applied in studies using unpiloted aerial vehicles for data acquisition for a range of purposes, including the assessment of coastal cliff erosion (Dietze et al., 2020), talus slope development (Hendrickx et al., 2020), channel change in response to glacial lake outburst flooding (Tomczyk and Ewertowski, 2021), and ice-cored hummocky moraine degradation (Śledź et al., 2023). Watson et al. (2020) used a co-alignment approach when processing historical imagery for the purpose of assessing calving glacier margins in the Himalaya. This permitted the matching of stable ground between image sets obtained over multiple historical surveys.

In the current study, this co-alignment approach involved aligning all images ($n = 24$; Table 1) acquired over six aerial surveys in a single chunk using an adaptive camera model in Agisoft Metashape ver. 2.1.2 ('medium' alignment accuracy quality, generic preselection). To add scale to the respective dense clouds, the centres of prominent boulders ($n = 33$) located on stable terrain (i.e., boulders that have not moved over the observation period) were used to provide ground control. The positions and elevations of these ground control points were obtained from swissSURFACE3D LiDAR point cloud tiles derived from a 2021 aerial survey. The reported altimetric and planimetric accuracy of the swissSURFACE3D LiDAR dataset is ±0.1 m and ± 0.2 m (1 sigma) respectively (SwissTopo, 2024). Following initial image alignment and camera optimisation, the chunk was duplicated six times, and in each case images and tie points (see Table 1) only from each time step were used to produce each dense point cloud ('medium' quality, 'mild' filtering). Six spatially concurrent DEMs were generated from these

Table 1

Camera and processing information for the data used in this study. DEM validation involves the assessment of spot heights ($n = 723$) against a LiDAR derived DEM acquired in 2021 for the clipped area of interest shown in Fig. 1. The values are derived from the datasets subject to fine registration as detailed in the 'DEM quality and refinement' section. The flight altitudes are taken from the image metadata as provided by the Swiss Federal Office for Topography.

Date of acquisition	Camera & film type	Flight altitude (m)	Flight line	No. of images used	Tie points	Dense count mean point density (pts/m^2)	Spot height vertical differences (m) [SfM DEM – LiDAR DEM][1]		
							Mean difference	Standard deviation of differences	Mean absolute error
13-09-1974	RC10 B&W	~3400	Transverse to ice-flow	4	25,147	13.8	−0.03	0.48	0.31
05-09-1979	RC10 B&W	~3400	Transverse to ice-flow	4	30,756	15.9	0.04	0.36	0.25
15-09-1983	RC10 B&W	~4100	Transverse to ice-flow	4	35,222	4.8	0.01	0.38	0.27
23-08-1990	RC20 B&W	~4000	Parallel to ice-flow	4	37,714	5.0	−0.07	0.33	0.23
02-09-1999	RC30 B&W	~4000	Parallel to ice-flow	4	50,031	5.6	−0.06	0.36	0.26
20-09-2010	RC30 B&W	~4173	Parallel to ice-flow	4	38,197	5.1	0.03	0.28	0.21

[1] Values relate to spot heights on stable terrain within the clipped extent of the survey data, as shown in Fig. 1.

dense point clouds in CloudCompare ver. 2.13.2 and exported at a 50-cm spatial resolution using a projected coordinate system (EPSG:2056 CH1903+ / LV95).

3.2. DEM quality assessment and refinement

Assessment of DEM quality was underpinned by using a regularly distributed sample of spot heights from the respective DEMs. These cells were located on terrain deemed stable (i.e. not in ice-cored areas, not overridden by ice, not on unstable slopes, not in snow-covered areas) throughout the duration of the study within the clipped extent of all the surveys (Fig. 1). For this study, stable ground includes snow-free cells on the ice-distal slope of large lateral moraines and bedrock in the proglacial area. In each case the sample cells (spot heights) were compared with the LiDAR derived DEM to provide an assessment of quality. Initial visual inspection revealed slight offsets between the six co-aligned DEMs and the validation LiDAR dataset. To improve the registration between the photogrammetrically derived dense point clouds and LiDAR point cloud, we used an iterative closest point algorithm. A similar approach has previously been used to improve co-registration and remove systematic errors in photogrammetrically derived point clouds (e.g., Parente et al., 2021; Stark et al., 2022). In the current study, we use the fine registration tool in CloudCompare ver. 2.13.2, with farthest point removal and scale adjustment both enabled. From these corrected point clouds, we generated a refined set of spatially concurrent DEMs. The standard deviation of the vertical differences calculated from the regularly distributed snow-free stable spot heights ($n = 723$) in the SfM derived DEMs and the SwissTopo LiDAR DEM ranged between 0.28 and 0.48 m (Fig. 3). For all datasets, between 98 and 99 % of the vertical differences for the sampled cells were within ±1 m, with root-mean-square (RMS) error values ranging between 0.29 and 0.48 m (Table 1; Fig. 3). The distribution of vertical errors appear to be largely random; however, we note errors are associated with: (i) shadowed areas in proximity to large boulders; (ii) steep slopes; and (iii) shaded bedrock slopes. The significance of this is that erroneous surface change – exceeding the minimum level of detection – appears on differenced raster data in these areas. Visual inspection of hillshaded DEMs reveal excellent alignment among the six elevation datasets, although in the 1999 DEM there was a minor systematic horizontal offset.

3.3. Geomorphologic change detection

To visualise change, raster differencing was used to generate a series of Digital Elevation Models of Difference (DoDs). In line with other studies investigating landform evolution in glacial environments (e.g., Chandler et al., 2020; Śledź et al., 2023; Tonkin, 2023), we propagate the standard deviation (σ) of the vertical errors from each DEM to derive a minimum level of detection (LOD_{95}) at the 95 % confidence interval (equation below; $t = 1.96$).

$$LoD = t\left({\sigma_{z1}}^2 + {\sigma_{z2}}^2\right)^{\frac{1}{2}}$$

The level of detection derived from the vertical errors ranged between 1.17 m for the oldest DoDs (1974 to 1979) and 0.89 m for the most recent epoch (1999 to 2010). The error thresholded DoDs were generated using GCD standalone (Geomorphic Change Detection) (ver. 7) (Wheaton et al., 2010), for a masked area of interest (Fig. 1 – clipped extent of the DEMs).

4. Results

4.1. DEMs of difference

Between 1974 and 1979 (E_1) GLAMOS (2022) record a cumulative glacier length change from −460 m to −425 m (Fig. 2): an advance of 35 m (Fig. 4a). This glacier change is visible on the DoD and surface raising was detected in the proglacial area in proximity to the true left of the advancing glacier terminus (Fig. 4a - i). In this location the vertical displacement of material in the proglacial area occasionally exceeds ~9 m. Whilst the advancing terminus is clearly visible on the DoD in areas characterised by debris-free ice, the supraglacial lateral moraine area experienced negative surface vertical displacement over this observation period with change exceeding ~5 m in selected areas (Fig. 4a - ii). Positive surface displacement at the central portion of the ice-margin is detected, associated with ice-marginal landform development (Fig. 4a - iii). Detectable positive surface change on the associated DoD shows positive surface changes of ~2 to ~5 m in this location. Other vertical displacements are associated with late-lying snow present across talus slopes and on the ice-distal moraine slope (Fig. 4a - iv).

Over the 1979 to 1983 (E_2) period, GLAMOS (2022) records indicate that Schwarzberggletscher advanced by 39 m (Fig. 2). In the DoD, continued positive vertical displacement is seen across the glacier surface. The development of landforms along the ice-margin are noted in the DoD and the associated hillshaded DEM (Fig. 4b - v). Other vertical change is associated with the changing distribution of late lying snow between 1979 and 1983 (Fig. 4b - vi). Surface raising across the proglacial area continued between 1983 and 1990 (E_3), reflecting the continuing advance of the glacier terminus (Fig. 4c - vii).

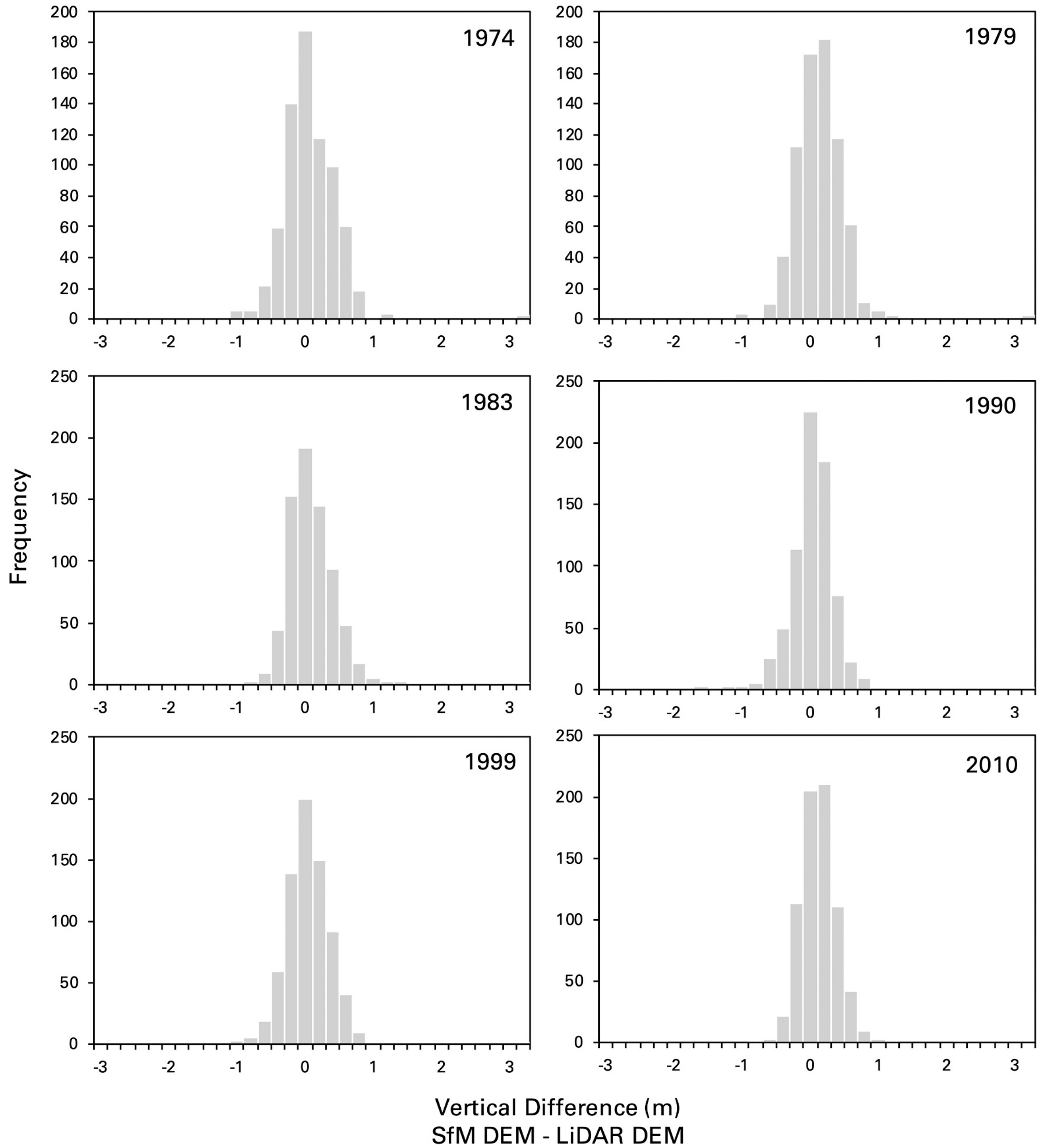

Fig. 3. Vertical Differences for each DEM and a LiDAR reference dataset for a sample of 723 regularly distributed spot heights on stable terrain within the clipped area of interest shown in Fig. 1.

The final epochs spanning from 1990 to 1999 (E_4) and 1999 to 2010 (E_5) are characterised by glacier recession and thinning, with the GLAMOS (2022) cumulative record of glacier length change showing recession of approximately 39 m and 151 m, respectively. This glacier response is reflected in the associated DoDs with surface lowering detected across the glacier terminus (Fig. 4, d & e). Change is also detected in the proglacial zone, with surface lowering detected on a newly developed moraine ridge demarcating the extent of the re-advance (Fig. 4d - viii). This surface vertical displacement over the 1990 to 1999 period exceeds 8 m lowering at one location. Between 1999 and 2010, surface lowering on the landform is also recorded at two locations over the observation period (Fig. 4d - ix). The median (thresholded) amount of surface lowering was found to be ~2.0 m across this landform, with a maximum surface lowering of ~4.5 m detected between the 1999 and 2010 surveys.

Further differencing of the earliest DEM (1974) and latest DEM (2010) produced in this study revealed variability in the erosion and deposition of sediment in the proglacial area and pronounced thickening of the supraglacial lateral moraine (Fig. 5). A proglacial zone overridden by the glacier between 1974 and 1990 experienced both surface lowering and surface raising, with approximately 54.5 % of the volume change in the error thresholded change surface associated with positive elevation change. Detectable erosion in this overridden zone (i.e., change exceeding the minimum level of detection of ±1.09 m) accounts for the removal of more than 5900 m^3 of material. This detected surface lowering appears to relate to areas previously occupied by ice-marginal moraines in proximity to the 1974 glacier margin, which were subsequently removed by the later glacier advance (Fig. 6). Areas downslope of the topographic step were characterised by surface raising (Fig. 6c), accounting for >99 % of the detected surface change by volume.

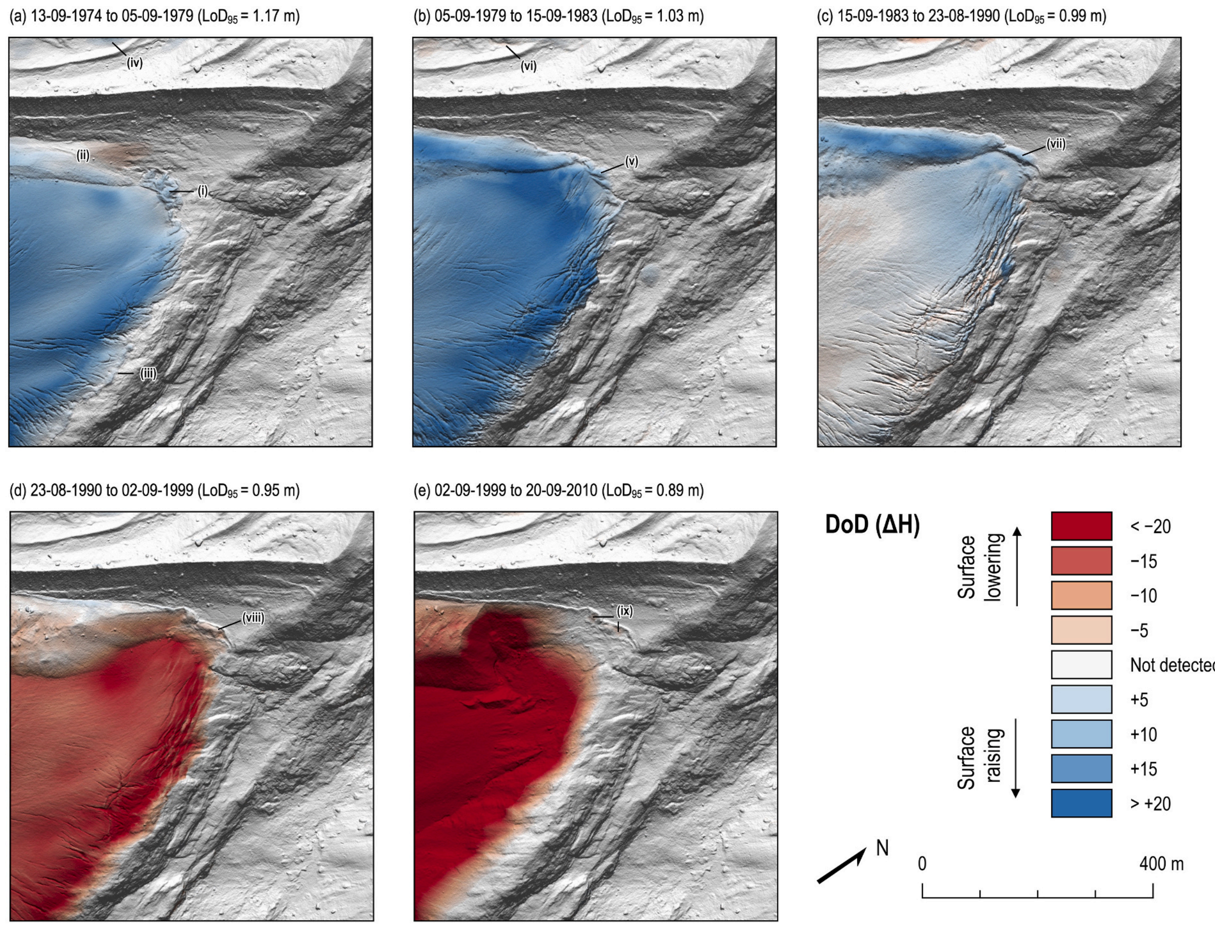

Fig. 4. DEMs of Difference for the respective epochs reported on in this study. In each epoch the latter DEM was used as a basemap. For example, in the first panel (a) a mono-directionally hillshaded version of the 1979 DEM is shown alongside the change between 1974 and 1979 (E_1).

5. Interpretation and discussion

5.1. Landform development at an advancing Alpine glacier

The value of the approach adopted in this study is the ability to quantitively constrain the vertical surface deformation associated with moraine development (Fig. 5a; Profile 1–1′). Significant surface elevation increases were detected in the proglacial area on the two DoDs between 1974, 1979, and 1983 (Fig. 4 a & b; Fig. 6a; Fig. 7a & b). Schwarzberggletscher advanced across existing moraine, till and outwash sediments (Fig. 8a), and excavation of the landform at one location revealed a composition of sand and gravel with occasional striated clasts. Archive photos from 1977 also indicate that the central portion of the glacier was advancing into and over what appears to be subglacial till, with the moraine sediment exhibiting what appear to be edge-worn clasts and boulders sat within a finer matrix (Fig. 8b).

Our interpretation of the detected surface change is that proglacial sediment was deformed in front of the advancing glacier terminus as a push moraine (Sharp, 1984; Winkler and Nesje, 1999; Bennett, 2001; Evans and Twigg, 2002; Winkler and Matthews, 2010; Boston et al., 2023; Evans, 2025). Archive photographs (Fig. 8 a - c) are also consistent with a pushing (or bulldozing) origin, or at least a composite push moraine origin involving other processes such as squeezing of water-saturated subglacial sediments during summer, melt-out and dumping of sediment, or the freeze-on of slabs of subglacial sediment during winter with melt-out during summer (e.g., Bennett, 2001; Evans and Hiemstra, 2005; Chandler et al., 2020). Some moraines have an asymmetric cross-profile (Fig. 8b), which is consistent with previous descriptions of push moraines (e.g., Bennett, 2001; Eybergen, 1986; Sharp, 1984). According to the archive imagery, which was captured as the glacier was advancing (Fig. 8c), Schwarzberggletscher appears in places to have overridden the moraine material, meaning that there may have been moraine-building contributions from both pushing and the deposition of sediment from sub-, en- and supra-glacial sources. In other places, the apex of the ice-marginal moraines sits well above the level of the advancing glacier indicating that pushing processes were more dominant (Fig. 8).

We further speculate that bed topography may have had a role in moraine development at Schwarzberggletscher, as has been demonstrated elsewhere (Barr and Lovell, 2014; Boston et al., 2023). It is evident from the DEMs and archive photographs (Figs. 6 and 8) that the central portion of the glacier was advancing up along a reverse bed slope. The presence of the reverse slope may have promoted the accumulation of sediments at this location, which could then be used to build the moraine. Sediment accumulation could have been promoted (a) during previous phases of glacier extension where the efficacy of subglacial meltwater sediment export would have been limited as a consequence of water and sediment having to ascend the adverse slope (e.g., Cook and Swift, 2012; Swift et al., 2021); and/or (b) during earlier phases of glacier recession where the area between the glacier and the apex of the reverse slope would have served as accommodation space for sediment accumulation. This sediment escaped erosion by meltwater streams, which were focused in the northern and southern parts of the glacier terminus. Furthermore, compression generated by glacier advance against the reverse slope may have concentrated sub- and englacial sediment loads through glaciotectonic thickening of basal ice and subglacial sediment, which may have enhanced sediment contributions to moraine formation (e.g., Eybergen, 1986; Bennett, 2001;

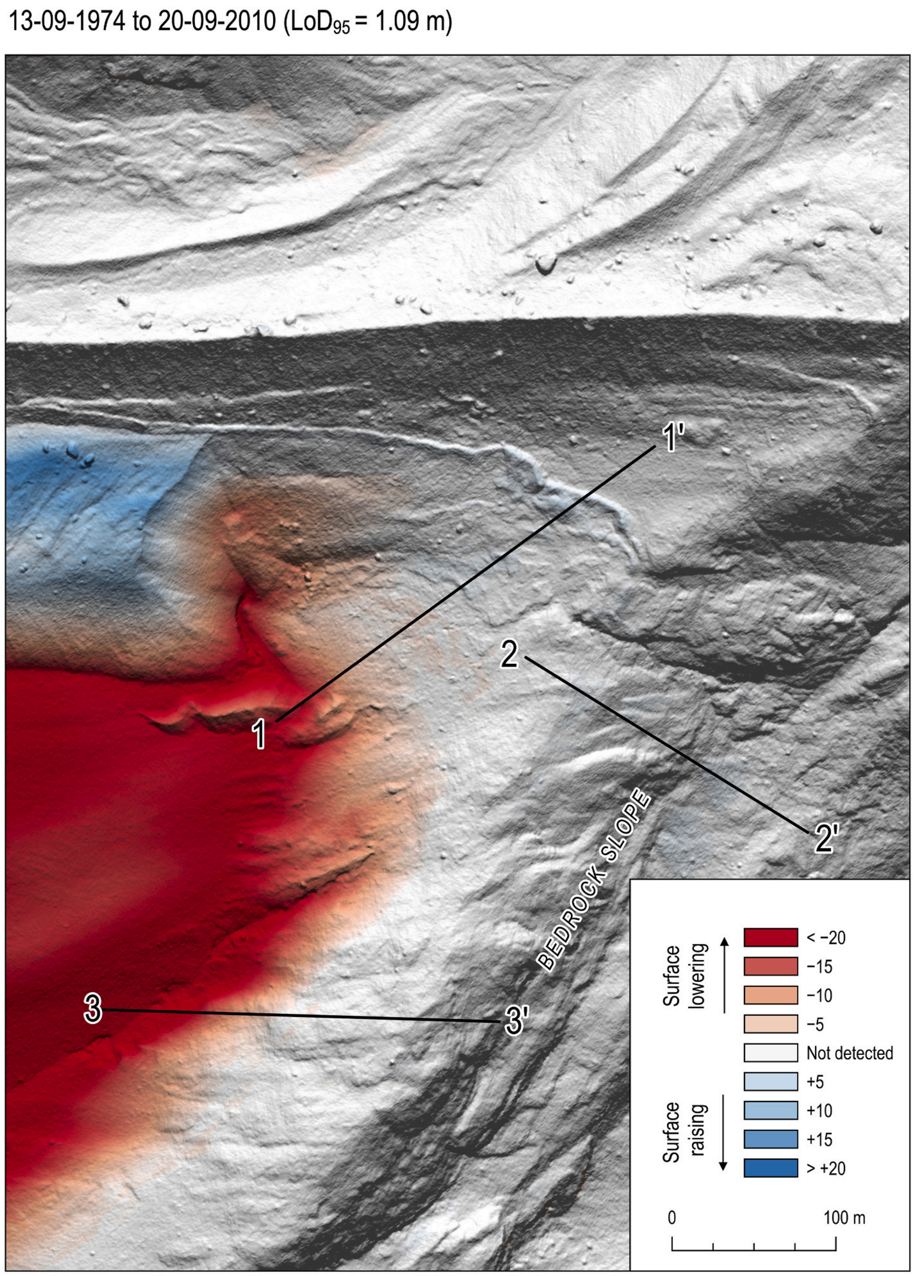

Fig. 5. DEM of Difference used for volumetric assessment over the entire duration of the study (1974–2010; E_d). Topographic profiles for transects 1–1′, 2–2′, and 3–3′ are shown in Fig. 6.

Cook et al., 2011). By 1983 these moraines at the central portion of the terminus appear to have been overridden by ice. From this point onwards, until the return to deglaciation, material was released from the central portion of the glacier terminus over a steep bedrock step (Fig. 6c). This contrasts with other sectors of the glacier front, which advanced on to more level terrain, producing landforms reflecting the position of the former ice margin (Fig. 7).

Existing genetic models of moraine formation developed from observations at the nearby Gornergletscher highlight that pushing of sediment is a common mechanism of minor moraine formation in the European Alps (Rettig et al., 2023). Push moraine formation has also been directly observed at Turtmanngletscher associated with a re-advance in the 1980s against a reverse bedslope (Eybergen, 1986; Bennett, 2001). It is argued that this, alongside visual interpretation of the DoDs (Fig. 7), visual interpretation of archive photography (Fig. 8), supports a hypothesis of pushing and remobilization of glacial-fluvial and subglacial sediments over the initial stages of the re-advance, principally documented in the 1979 and 1983 datasets (Fig. 6a).

Landform development at the latero-frontal moraine involved the gradual down wastage of the glacier terminus relative to the moraine surface (Fig. 6b; Fig. 7). This is interpreted as differential ablation, where sufficiently thick supraglacial debris at the ice-margin protected underlying ice from higher-rates of ablation (Østrem, 1959), leading to the decoupling of active ice up-valley following the conclusion of the glacier advance (Fig. 6b). In the current study, the persistence of ice within the structure of the landform is evidenced by locations of surface lowering identified between 1990, 1999, and 2010 (Fig. 7). While we are cautious not to use our validation LiDAR data for change detection, comparison of the 2010 morphology of this landform with these data indicate there has subsequently been limited change between 2010 and 2021. The potential reasons for the rapid ablation of buried ice at this site are discussed further in section 5.2.

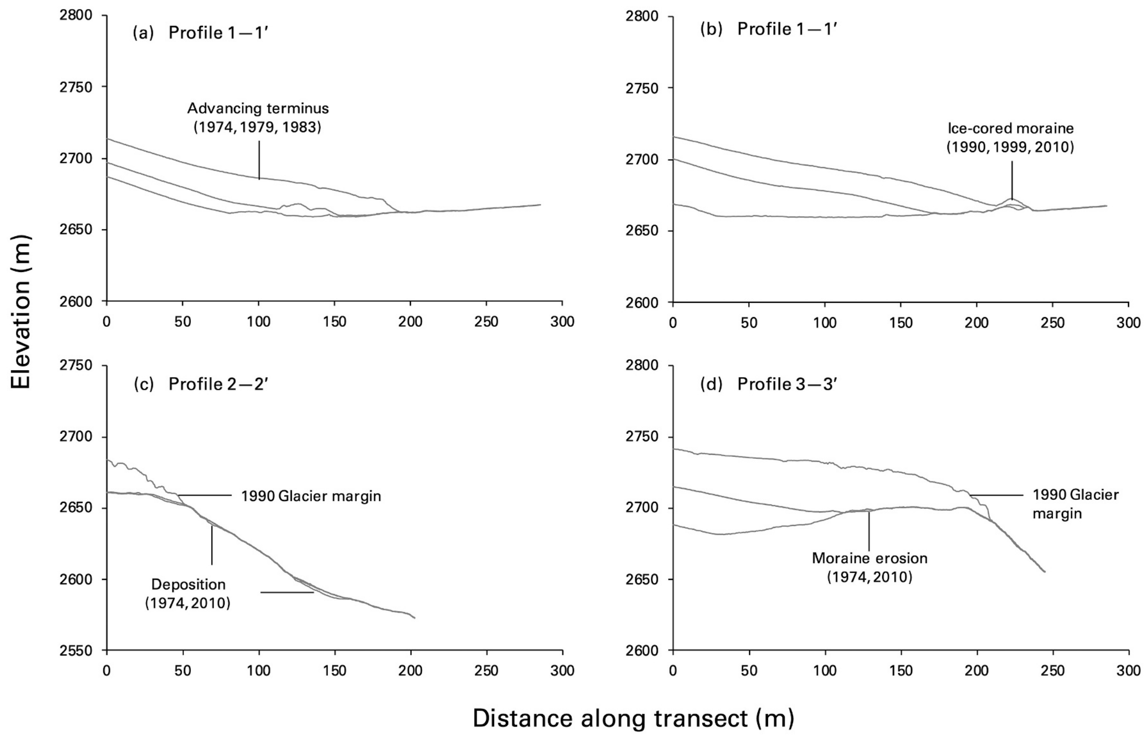

Fig. 6. Topographic profiles across the proglacial area. (a) The advance of Schwarzberggletscher as recorded in the 1974, 1979 and 1983 DEMs. (b) The extent of the re-advance as of 1990, and subsequent degradation of moraine topography during deglaciation (1999 & 2010). (c) Topographic change in the proglacial area associated with the release of material from the glacier front. In this profile the 1974, 1990 and 2010 datasets are depicted. (d) The removal (erosion) of a moraine ridge that is present in the glacier forefield in 1974, overridden (by 1990), and absent in the 2010 DEM.

In summary, a two-stage sequence of moraine development is proposed, involving the initial deformation of existing proglacial sediments, possibly with input of sediment from the debris-charged terminus, followed by the incorporation of buried ice into the structure of the moraine and the subsequent down-wasting of that ice-cored moraine over time. This broadly conforms to existing genetic models of moraine formation developed for Alpine glaciers (Lukas et al., 2012; Rettig et al., 2023). As a final note, this study provides an example of erosional censoring ('obliterative overlap') (Gibbons et al., 1984; Kirkbride and Winkler, 2012) associated with the advance of the glacier over older moraines. Landforms indicating the former ice-margin prior to 1974 at the central portion of the terminus were removed by the subsequent re-advance of the glacier in the late 1970s through to the early 1990s (profile 3–3′ in Fig. 5 and Fig. 6d). In this example a pattern of glacier re-advance superimposed on an overall pattern of retreat has obscured the landform record of glacier change at this site. This has relevance to researchers seeking to reconstruct glacier behaviour from moraine sequences at sites that do not have extensive archival imagery, highlighting the incompleteness of the moraine record of glacier change.

5.2. *The evolution of ice-cored moraine in Alpine glacial landsystems*

In this study, upon a return to deglaciation (i.e. the early 1990s onwards), moraine morphology continued to evolve following the recession of the glacier margin. The detected elevation change is interpreted as evidence of buried ice within the 'minor moraine' ridge. The degradation of ice-cored moraine is now well documented in high-Arctic locations (e.g., Midgley et al., 2013; Ewertowski and Tomczyk, 2015; Tonkin et al., 2016; Midgley et al., 2018) and as discussed in section 5.1, the degradation of buried ice has been identified as an important process of moraine development at other Alpine sites (e.g., Rettig et al., 2023). Recent studies in other glacial environments – particularly the Norwegian high-Arctic – have resulted in an improved understanding of landform response to deglaciation, such as the notion of 'paraglacial transience' in buried-ice landsystems (Ewertowski et al., 2019) and improved our understanding of the switch between stable and unstable landform conditions (Ewertowski and Tomczyk, 2020). However, rates of ice-cored moraine degradation vary, depending on factors including whether back- or down-wastage occurs (Schomacker, 2008). In the current study the values derived here indicate median rates of change (error thresholded DoD) of ~0.2 m a^{-1}, and a maximum rate of surface lowering of ~0.4 m a^{-1} over the 1999 to 2010 observation period. Visual interpretation of the DEMs did not reveal any evidence of back-wastage, so it is assumed down-wastage was the predominant mechanism of degradation.

This work provides numerical constraints on the rate of ice-cored moraine degradation in the European Alps. Unfortunately, there is a paucity of studies investigating ice-cored moraine degradation in the region to compare this rate of change to. Whilst the processes are well represented in existing conceptual models, the potential rate of landform transformation has, to date, been less well studied. Supraglacial debris cones formed following the 1979/1980 advance of the nearby Findelengletscher where buried ice in selected sections of these landforms may have melted out by 2005 (Lukas et al., 2012). Ravanel et al. (2018) used multi-temporal terrestrial laser scanning surveys to monitor the evolution of the ice-proximal slope of a lateral moraine complex, finding that the greatest rates of change were concentrated at the base of the lateral moraine slope. However, the topographic context of this site differs from the current study in that Ravanel et al. (2018) surveyed a large lateral moraine complex adjoining the glacier margin.

High rates of ice-cored moraine degradation are often linked to thermokarst features such as ponding water and back-wasting (Schomacker, 2008). These typical thermokarst features are notably absent in the respective DEMs (Fig. 7e). Previous work has identified that rates of down wastage are related to other factors such as debris cover, thermal conductivity, thickness, and water content, and this makes it challenging to link rates of change directly to climatic controls (e.g., annual and summer precipitation, annual and summer air

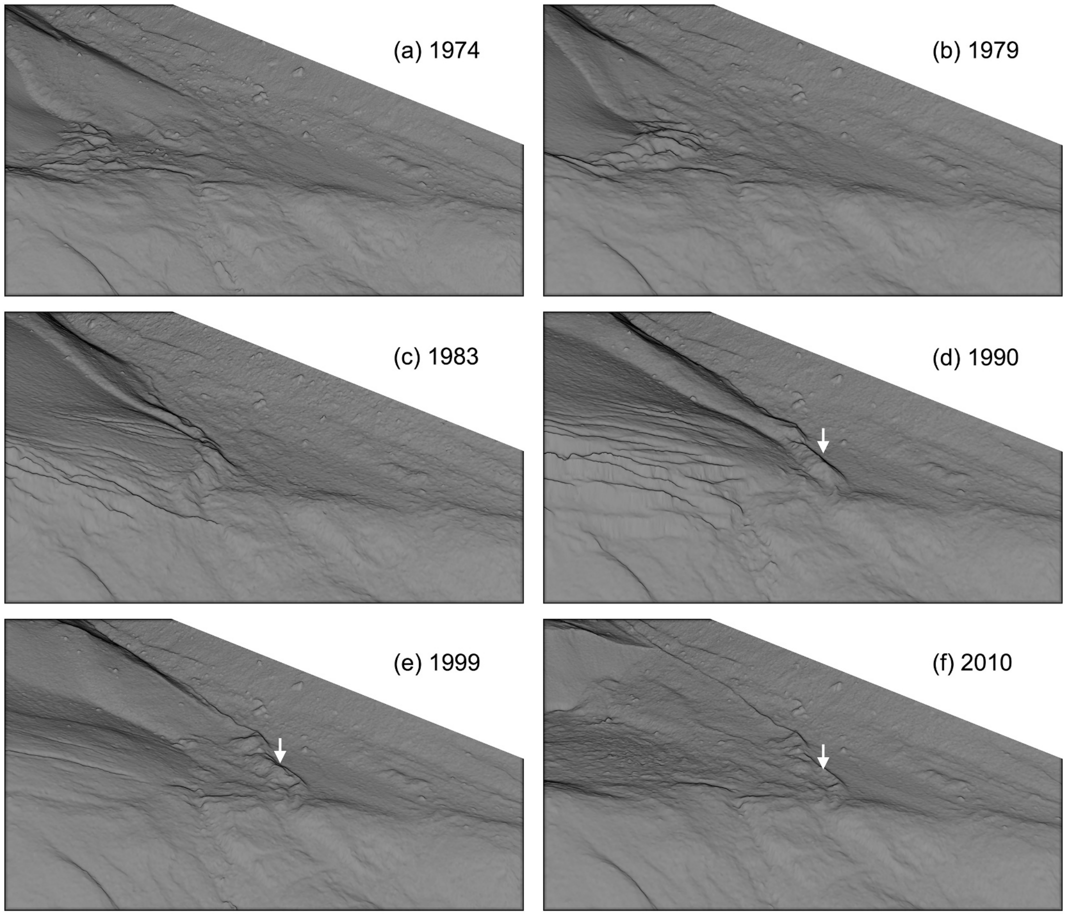

Fig. 7. Oblique render of the DEMs illustrating the sequence of landform development at the true left glacier margin as revealed by the production of the six co-aligned DEMs. The white arrow in panels d – f indicate the location of moraine degradation.

temperature, positive degree days) (Schomacker, 2008). However, the proglacial area, which includes the landform studied, falls outside the limits of the ice-rich permafrost zone in the indicative permafrost and ground ice map of Kenner et al. (2019), likely explaining the short-term persistence of any buried (dead) ice associated with this advance. The nature of the current study, involving the reconstruction of the glacier advance from archive imagery, means that it is difficult to determine the previous likely thickness of the overlying debris. A field survey in August 2013, which involved shallow excavation of the moraine at one location to ~1 m depth, found sediments within the landform to contain a predominantly sand and gravel component with a lack of outsized clasts. When subject to rainfall, highly permeable debris covers, such as sand, are known to impact the rate of ablation for buried ice (Reznichenko et al., 2010). Percolating rainfall is known to advect heat from overlying sediment to the underlying buried ice, and therefore promotes ice ablation (Reznichenko et al., 2010). This offers a further possible explanation for the rate of landform transformation found at this site.

In summary, de-icing is recorded on a moraine ridge isolated from the glacier and we highlight that the degradation of these types of glacial landforms is less well documented in Alpine locations. Importantly, limited change is recorded between the 2010 dataset and the reference 2021 LiDAR dataset, and this indicates that these types of landforms may stabilise rapidly over a decadal timescale in Alpine locations. In the current study, the landform stabilised between 1999 and 2010. The rate of landform transformation is perhaps unsurprising, given the dimensions of the landform, but it is in stark contrast to other glaciers where ice within larger moraine systems may persist for millennia (e.g., Crump et al., 2017).

5.3. *Outlook for future landform studies in the Swiss Alps*

This study has explored the use of now-commonplace image processing, in combination with two more recent methodological developments for refining the comparative accuracy of derived historical DEMs. These DEMs were subsequently used for the novel purpose of assessing landform development at an advancing glacier. In adopting a co-alignment approach (here six time-specific image sets were processed as a single block) in combination with fine registration, it is possible to rapidly minimise elevation errors allowing for the recognition of metre magnitude surface change. Previous studies have applied a similar co-alignment approach to datasets derived from unpiloted aircraft systems (e.g., Dietze et al., 2020; Tomczyk and Ewertowski, 2021). This study provides an example of multi-epoch co-alignment using archive image sets, processed with incomplete camera calibration data, spanning several decades. In addition to using a co-alignment approach, an improved assessment of change over time was made possible due to several factors, detailed below, which unlock the potential for future geomorphological research in this region.

Firstly, the Swiss Federal Office for Topography now release archive and contemporary datasets in adherence with its "Open Government Data" policy (e.g., SwissTopo, 2024). This means for locations across Switzerland, image sets for Alpine glaciers are now available for download by researchers. Furthermore, glaciers across Switzerland have now been surveyed using LiDAR. In combination with the now readily accessible archive image sets, these accessible LiDAR point clouds now provide opportunities for improved geo-referencing of any data derived from a SfM approach. For example, the workflow described in this study would not have been possible without the existence of this high-

Fig. 8. Archive photography depicting (a) the glacier foreland in August 1971 prior to the re-advance_(Excerpt from image Hs_1458-GK-B900-1970-0004); (b) a view looking broadly northwards across the glacier terminus in September 1977 (Excerpt from image Hs_1458-GK-B003-0000-0034-F); and (c) a view across the glacier terminus in October 1979 (Excerpt from image Hs_1458-GK-B900-1979-0093-F). All images are derived from the ETH Library's Image Archive and are reproduced under a Creative Commons BY-SA 4.0 license.

resolution topographic data. LiDAR-derived point clouds provide an opportunity to extract accurate ground control for archive image sets (e.g., James et al., 2006; Barrand et al., 2009). Without LiDAR-derived point clouds, ground control points would need to be recovered from stable terrain in the field – a time-consuming task, where it is often made difficult to achieve a robust distribution of ground control points due to the inaccessible nature of the terrain being investigated. Alternatively, reference ground control can be derived from existing elevation data products (e.g., Mölg and Bolch, 2017; Tonkin, 2023); however, selected DEMs produced by other methods may involve metre level accuracies. Importantly, high-quality reference LiDAR point clouds are essential for improving the registration of photogrammetrically derived point cloud datasets, when using the Iterative Closest Point approach (e.g., Stark et al., 2022).

In summary, the parallel developments in data availability for the region, alongside the co-alignment (and fine registration) approach present great opportunities for future geomorphological studies in the area. For example, in the current study, moraine formation at a single site has been successfully quantified remotely; however, there is scope to better understand glacier fluctuation and landscape response more broadly, by applying the approach in other areas of Switzerland that are covered by extensive archive image sets and high-resolution LiDAR surveys. In the current study, image-sets for six years were used, but a near-complete yearly record exists. Interannual assessment of landscape response to glacier change, spanning multiple decades is possible across a range of sites, and this opens new avenues for geomorphological research where the quantification of surface change is required. Examples could include, but are not limited to, investigations of paraglacial rockfalls, detecting permafrost degradation, and establishing rock-glacier dynamics. As noted previously, studies investigating minor moraine formation at Alpine glaciers have not previously applied this approach. Elsewhere the use of high temporal and spatial resolution topographic surveys have yielded new insights into changing ice-marginal process regimes at rapidly receding glaciers (e.g., Chandler et al., 2020). Therefore, there is the potential for future workers to make use of these archive high-spatial and temporal resolution datasets, which are an untapped source of valuable glacial geomorphological information.

6. Summary

This study set out to explore landform development at an advancing Alpine glacier using historical archive imagery. The outcomes of this study are three-fold:

1. A co-alignment SfM workflow using historical aerial imagery was adopted to produce multi-temporal elevation models. These models were used for the purpose of assessing moraine formation at an advancing Alpine glacier. High comparative accuracy between the multi-temporal DEMs permitted the assessment of landform development at an advancing glacier margin.
2. The geomorphological impact of the re-advance of Schwarzberggletscher has been quantified, illustrating the controls on moraine formation associated with the advance of the glacier between ~1974 and ~1990. This study also quantifies the degradation of moraine ridge, associated with ablating buried ice, deriving a maximum rate of surface lowering of ~0.4 m a^{-1} over the 1999 to 2010 observation period.
3. The general workflow used for point cloud generation provides a robust approach for improving the comparative accuracy of multi-temporal DEMs derived from archive image sets. This, alongside recent developments in open access geospatial data availability in Switzerland present scope for the future high-temporal resolution assessment of landform development extending back into the late 20th Century. We argue that leveraging the benefits of these parallel developments in methodologies and data availability could unlock other avenues for future glacial geomorphological research.

CRediT authorship contribution statement

Toby N. Tonkin: Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicholas G. Midgley:** Writing – review & editing. **Simon J. Cook:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The historical aerial imagery and LiDAR datasets used in this study are available from the Swiss Federal Office for Topography (SwissTopo). Additional data generated by this study will be made available via the University of Northampton's Research Explorer.

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