Héðinsdalsjökull, northern Iceland: geomorphology recording the recent complex evolution of a glacier

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Abstract

The objective of this work is to conduct a detailed mapping of the Héðinsdalsjökull foreland, northern Iceland (65°39′N, 18°55′W). This cirque currently shows a variety of glacial and periglacial landforms derived from a complex deglaciation. Mapping was performed combining traditional hand-drawn and digital mapping. A hand-drawn sketch was georeferenced in ArcMap 10.7.1, supported on an aerial photograph (year 2000). Its vectorization, symbolization and final design were done in the computer-aided design (CAD) software MicroStation Connect. Complementary high-resolution Digital Surface Models were obtained from historical aerial photographs and ground-view field photographs through the application of Structure from Motion (SfM) photogrammetry. To improve the topographic expression of the geomorphological map, a photorealistic 3D view has been generated. The final map highlights the complexity of the foreland and the coexistence existence of a range of different units and landforms. The map will ease future studies on the transformation of receding glaciers.

1. Introduction

The diversity of landforms that characterize glacial cirques and their clear paleoclimatic significance has been reported in numerous studies, especially in mountain areas that have been glaciated during the Late Pleistocene and deglaciated in the last thousands of years (Barr & Spagnolo, 2015, 2017; Barth et al., 2016; Benedict, 1973; Dahl & Nesje, 1992; Ipsen et al., 2018). Most of the cirque landforms derive from the effects of successive glacial phases (Evans & Cox, 1974, 1995), this does not necessarily imply that these landforms do not continue to evolve after partial or total deglaciation of the cirque. On the contrary, in many cases, the geomorphological evolution of the cirques continues in the following interglacial within the so-called paraglacial phase (Ballantyne, 2002, 2013; Beniston et al., 2018; Knight & Harrison, 2014).

Many of the landforms derived from paraglacial processes transforming cirques are related to the existence of internal frozen masses, e.g. glaciers or ice derived from the existence of permafrost, under vertical walls (Beniston et al., 2018; Jones et al., 2019; Knight & Harrison, 2014; Knight et al., 2019). In fact, paraglacial processes have been considered responsible for an increase of the debris supply onto debris-free glaciers and their transformation into debris-covered glaciers or into rock glaciers (Anderson et al., 2018; Berthling, 2011; Hambrey et al., 2008; Janke et al., 2013, 2015; Jones et al., 2019; Knight et al., 2019; Monnier & Kinnard, 2015, 2016). However, the speed and time required for this transformative process still remains unknown and depends on multiple factors (Anderson et al., 2018; Jones et al., 2019; Knight et al., 2019). An appropriate method to study this transformation is mapping glacier derived landforms and their changes over time (Dusik et al., 2015; Emmer et al., 2015; Monnier & Kinnard, 2015, 2016; Monnier et al., 2014).

The Tröllaskagi peninsula, northern Iceland, is an area with many alpine-type glacial cirques, which host a few debris-free glaciers, and numerous debris-covered glaciers and rock glaciers. For example, Lilleoðren et al. (2013) have identified 118 rock glaciers in Tröllaskagi. Debris-free glaciers have been identified as highly sensitive to climate change and with short reaction and response times, with rapid advances or retreats of their fronts that form numerous moraine ridges in their forelands (Caseldine, 1985a, 1985b; Fernández-Fernández et al., 2017, 2019; Háberle, 1991; Kugelmann, 1991). Some debris-covered glaciers and rock glaciers have been studied according to their...
morphology and dynamics, and a number of authors have highlighted their low (or even null) dynamism, especially at rock glaciers, whose main dynamics is by surface subsidence (Andrés et al., 2016; Campos et al., 2019; Martin et al., 1991; Tanarro et al., 2019). Mapping of the Iceland proglacial cirque areas is a first approach to the complex geomorphological evolution that accompanies deglaciation (Evans et al., 2017; Tanarro et al., 2018).

This work addresses with the geomorphological study of the deglaciation of a peculiarly complex alpine cirque, located at the head of a valley in the Tröllaskagi peninsula (Northern Iceland), namely Héðinsdalur. In this cirque and its associated foreland, the coexistence of a current debris-free and debris-covered sectors of the glacier, a debris-covered marginal zone and also a rock glacier have been observed. Thus, the objective of this work is to perform a detailed geomorphological mapping in order to differentiate the phases through which this transformation occurred.

2. Regional setting

This study focuses on the glacier of Héðins (Héðinsdalsjökull in Icelandic), located at the head of the Héðinsdalur (65°39′N, 18°55′W) in western Tröllaskagi. The Tröllaskagi peninsula is located in northern Iceland between the Skagafjörður and Eyjafjörður to the west and east, respectively. The head of the valley connects with the culminating plateau of this peninsula, at altitudes between 1200 and 1330 m a.s.l. The geology of the peninsula is composed of Miocene basaltic lavas (Tertiary Basalt Formation) in a sub-horizontal arrangement, alternating with sedimentary strata (Sæmundsson et al., 1980). Numerous valleys are carved out in this plateau, with steep and unstable slopes, where rock falls, landslides and debris-flows frequently occur (Cossart et al., 2014; Decaulne et al., 2016; Jónsson & Sigvaldason, 1976; Mercier et al., 2013; Sæmundsson et al., 2018; Whalley et al., 1983). Most of the glacier catchments in Tröllaskagi are occupied by debris-covered glaciers and rock glaciers, whose fronts are at altitudes between 900 and 950 m a.s.l., where the mean annual air temperature (MAAT) ranges between −1.8 and −2.6°C (Etzelmüller et al., 2007).

The MAAT on the Tröllaskagi peninsula (1901–1990 series) ranges between 2°C and 4°C at sea level, and between −2°C and −4°C at the summits (Etzelmüller et al., 2007). The lower limit of mountain permafrost in Tröllaskagi is located at ∼900 m a.s.l. (Czekirda et al., 2019; Etzelmüller et al., 2020, 2013; Sæmundsson et al., 2018). The mean annual rainfall in the period 1971–2000 ranges from 400 mm in the coastal areas to 2500 mm at the summits (Crochet et al., 2007).

The Héðinsdalsjökull currently shows a number of different morphological zones, namely the present debris-free and the debris-covered sectors of the glacier and a rock glacier. In front of the current glacier

| Table 1. Landforms represented on the geomorphologic map of Héðinsdalsjökull. |
|-----------------------------------------------------------------------------|
| **Legend of the main map** | **Clarifications on the origin of the landforms** | **Typology of landforms** |
| **Geomorphological features** | **Steep slope discontinuity** | **Slope** |
| **Scarp** | **Upper glacial trough trim** | **Erosion** |
| **Debris flow** | **Cirque cliff** | **Glacial** |
| **Minor collapsed depression with underlying ice** | **Hummocky moraine** | **Moraine ridges** |
| **Major collapsed depression with underlying ice** | **Frontal-lateral push moraine** | **Erratics** |
| **Collapsing depressions without underlying ice** | **Big boulder** | **Rock glacier** |
| **Water-filled depression** | **Ridges and furrows** | **Incipient rock glacier derived from a push moraine** |
| **Hummocky moraine** | **Ridges and furrows** | **Glacial-to-periglacial transition** |
| **Debris-free sector of the glacier in 2000** | **Glacial and periglacial units** | **Landform derived from the Neoglacial maximum extent** |
| **Margin of the debris-free sector of the glacier in 2019** | **At present as independent glacier** | **Present glacier** |
| **Debris-covered sector of the glacier** | **Debris-covered marginal zone** | **At present an ice stagnant debris-covered glacier** |
| **At present an ice stagnant debris-covered glacier** | **A former debris-covered glacier, collapsed after the ice melted away** | **Glacial landforms** |
| **Rock glacier** | **Periglacial** | **Glacial-to-periglacial transition** |
| **Incipient rock glacier** | **Periglacial** | **Glacial-to-periglacial transition** |
| **Frontal glacial depression** | **Frontal glacial depression** | **Depression previously occupied for the front of a glacier** |
| **Other units** | **Other units** | **Culminating lava flow surfaces** |
| **Plateau** | **Plateau** | **Structural** |
| **Cirque wall** | **Cirque wall** | **Glacial** |
| **Talus cone** | **Talus cone** | **Slope** |
| **Braided river flood plain** | **Braided river flood plain** | **Fluvioglacial** |
| **Fluvioglacial terrace** | **Fluvioglacial terrace** | **Fluvioglacial** |
terminus, i.e. the marginal zone, there are sediments of a collapsed debris-covered marginal zone, whose outermost moraine has been dated to 3–2 ka, using $^{36}$Cl cosmic-ray exposure dating (Fernández-Fernández et al., 2020).

3. Methodology

3.1. Analogue geomorphological mapping from aerial photographs and fieldwork

Geomorphological mapping was performed through the interpretation of hard-copy aerial photographs from 1994 (National Land Survey of Iceland) and in situ field mapping (Chandler et al., 2018) (See Main map). Mapped landforms were transformed onto a transparent acetate sheet at 1:4,200 scale, with orthophotos from 2000 and 2019 (National Land Survey of Iceland) used as a base map. The hand-drawn map was then scanned at high resolution (600 dpi) for digital processing. We georeferenced the hand-drawn map in ESRI ArcMap 10.8.1 using the UTM grid of the base map as control points. Georeferencing was performed using a 3rd order polynomial transformation, which provided the lowest root mean square error (RMS: 0.33 m) and the best visual fit. The hand-drawn map was then vectorized in the Computer-Aided Design (CAD) software MicroStation Connect, which provided an efficient and intuitive approach to vectorization as well as the capacity to visualize the mapping in 3D. After vectorization, topological errors were corrected using the topology clean-up tools in Bentley Map software.

The main landforms were classified and grouped into geomorphological units (see Table 1). The current limit of the glacier was also drawn based on an aerial photo obtained in 2019 from the online geoviewer Kortasjá/MAP IS (2020), which was also georeferenced with a 3rd order polynomial transformation.

The symbolization and final design of the geomorphological map were performed and carried out in the CAD MicroStation Connect platform. The devised representation system synthesized the graphic style of the geomorphological base map and includes adaptations of widely accepted proposals in geomorphological mapping (Lambiel et al., 2012; Peña Monné et al., 1997; Tricart, 1976). The main elements were custom lines and polygon features to which simple fills and repeating symbol patterns were applied.

In addition, a degree of transparency was applied to the polygon entities in order to highlight the relief shading and to emphasize their topographic expression. The shading was generated from a Digital Elevation Model (DEM) derived from the interpolation of the elevation points and contour lines (20-m interval) for the year 2000 (Icelandic Land Survey, 2020). The final map layout was built in CAD MicroStation Connect.

3.2. 3D model generation from historical aerial photographs

The application of Structure from Motion (SfM) photogrammetric techniques from historical aerial photographs (Chandler et al., 2016; Ewertowski et al., 2019; Gomez, 2012; Gomez et al., 2015; Mertes et al., 2017; Midgley & Tonkin, 2017) was used to obtain a complementary high-resolution digital surface models (DSM) and DEMs. The geomorphological map was draped on the DEM shading in order to apply rendering and lighting techniques and generate 3D views, which considerably improved the understanding and interpretation of the map. In the Bentley ContextCapture photogrammetry software, four aerial photographs of Heönsdalur, corresponding to the year 1994 (focal length of 152.82 mm; Icelandic Land Survey, 2020) were used to obtain the DEM and the orthophoto. First, in the ArcMap work environment, 13 well-distributed control points were added in the area of interest, easily identifiable with common elements in the 1994 stereo-pairs and the 2000 orthophoto. As a requirement for correct processing of the images, each of the control points was located in at least three of the photographs used. The XYZ coordinates of the control points were obtained in ArcMap, using the orthophoto of the year 2000 (XY coordinates) and the abovementioned DEM (Z coordinate). Then, in Bentley ContextCapture, the control points and their coordinates were entered in at least three different photograms. Next, the aerial triangulation and alignment of the photographs were carried out, from which the 3D model was obtained. In this process, the global 3D RMS error was 5.7 m. Finally, the DEM (in Ascii grid format) and the orthophoto (in GeoTiff format) were produced, at a default spatial resolution of 0.45 m.

To improve geovisualization of the geomorphology in the study area, a photorealistic 3D view of the geomorphological map was generated using the 3D tools of the CAD MicroStation Connect through the application of rendering techniques and solar lighting (Tanarro et al., 2018). This required the elaboration of a polygonal mesh from a point cloud, which was previously derived from 3D photo-reconstruction. Finally, the geomorphological map was draped on the polygon mesh in a three-dimensional view.

One of the advantages of CAD software is the realism of its views thanks to the rendering tools, which allow for configuration of the illumination settings and drape the map on the 3D mesh as a texture. In this case, the solar position was established based on the coordinates of the study site, on 17 July 2020 at 03:30 GMT.

3.3. 3D model generation from ground-view field photographs

The SfM technique was used complementarily as being capable of obtaining high-resolution 3D
cartographic products in a simple way and at very low cost (Micheletti et al., 2014). The Bentley Context Capture photogrammetry software was also used to process 43 terrestrial photographs of a section of the southern slope of Héðinsdalur, taken on 30 August 2018 from the opposite slope, and at a distance between 500 and 1300 m from the photographed landforms. This section coincides with the sector occupied by the glacier during the Neoglacial maximum advance (Fernández-Fernández et al., 2020). From this technique, we produced a DSM and an ortho-photo of the lower sector of the debris mantle located in the marginal zone, with a resolution higher (0.27 m) compared to that of the aerial photographs. In fact, the derived stereo-orthophoto greatly helped to recognize and map the chaotic collapsed landforms of this sector. The photographs were taken with the integrated camera of a GPS Garmin Monterra, with a focal length of 4.6 mm and 8 megapixels (3266 x 2450 pixels) of resolution. In this case, the identification of control points was not necessary since the photographs were already geolocated by default (Micheletti et al., 2015).

4. Results

4.1. Glacial and periglacial landforms

The geomorphological map obtained in this work distinguishes different units, defined as present debris-free and debris-covered sectors of the glacier, a debris-covered marginal zone and a rock glacier, all of them within the same cirque. Considering that the outermost moraines date to about 3–2 ka (Fernández-Fernández et al., 2020), the recent evolution of Héðinsdalsjökull has been rapid. The obtained cartography offers a more realistic and expressive appearance in a three-dimensional view (Figures 1–3, Table 1).

4.1.1. Debris-free sector of the glacier

The current debris-free glacier sector is located at the head of the valley (Figures 1–4). With data from the year 2000, this glacier had an area of 4.9 km² (2.3 km long and 2.6 km wide), while in 2019, its surface had been slightly reduced (to 4.7 km²). The glacier ends in a wide front, of 3.1 km long and located between 1040 and 900 m a.s.l. The westernmost part of this debris free glacier terminus is covered by a thin layer of debris <0.5 m thick. Towards the center and east, the debris cover disappears and the front of the glacier is completely debris-free, which coincides with the areas where there was a greater retreat between 2000 and 2019, as happened in the nearby debris-free glacier Western Tunghahryggssjökull (Fernández-Fernández et al., 2019).

4.1.2. Active debris-covered sector of the glacier

The terminus of the debris-free sector of the glacier overlaps an underlying debris-covered stagnant sector of the glacier, with a dense layer of supraglacial debris (Figures 1–5). This unit has been characterized and classified as a debris-covered glacier on the basis on: the supraglacial debris mantle covers ≥50% of the ablation area, with a thickness of >0.5 m, a predominance of ridges longitudinal to the glacier flow and the presence of lateral moraines (Azócar & Brenning, 2010; Brenning, 2005; Hamrey et al., 2008; Kirkbride, 2000, 2011; Monnier & Kinnard, 2015). This debris-covered glacier has an area of 1.2 km² with an altitudinal range between 1080 and 700 m a.s.l.

Apart from the longitudinal ridges and moraines, collapse depressions are also abundant. Differentiation has been made between major collapse depressions, with almost vertical walls, and minor collapsed depressions, with gentle slopes. Some of these depressions are water-filled, which explains their small-lake-type appearance. Between these depressions there are many mounds and small moraine hills, of chaotic morphology.

The general morphology of the active debris-covered sector of the glacier is dominated by thermo-karst-like features. Moreover, sections of frontal or fronto-lateral moraine arches of different morphology and sizes are preserved and allow for differentiation at four stages of advance or stabilization of the glacier front.

The central axis of the debris-covered sector of the glacier is reworked by meltwater stream and tends to erode all the glacial and collapse-derived landforms described above.

Other active debris-covered glaciers have been studied in nearby Tröllaskagi cirques, such as Hóladalsjökull (Tanarro et al., 2018, 2019) and Hofsjökull (Campos et al., 2019). From a morphological point of view, Héðinsdalsjökull differs from them by the much higher density of collapse depressions and the limited preservation of moraine landforms.

4.1.3. Incipient rock glacier (proto-rock glacier)

Inside the active debris-covered glacier there is a sector characterized by having an abrupt front and the predominance of ridges and furrows parallel to each other and perpendicular to the flow. Although this sector is within the active debris-covered glacier, it has been interpreted as a developing of a rock glacier or ‘proto-rock glacier’, based on the abovementioned features (Figures 1–3 and 6). Incipient rock glaciers have also been detected in some nearby Tröllaskagi cirques, as in the Fremri-Gríjótaraldalur cirque (Tanarro et al., 2018, 2019) (Figure 7).
4.1.4. Debris-covered marginal zone
Ahead of the active debris-covered sector of the glacier are the deposits of a former debris-covered glacier, currently collapsed due to the complete melting of the subglacial ice (Figures 1–3 and 8). This unit descends from 820 m a.s.l. in its upper part up to 600 m a.s.l. in the former frontal area.

Within the debris-covered marginal zone, collapse depressions and melt depressions predominate. Their flat-bottomed appearance denotes the absence of ice at their base. Moraines are also common in this sector, showing different morphologies, with a predominance of ridges longitudinal to the flow. The moraine ridges on the front have been dated through

Figure 1. Main geomorphological units of Héðinsdalsjökull: debris-covered marginal zone (without glacial ice); debris-covered sector (with underlying stagnant glacial ice), rock glacier and debris-free sector. The limit of the last Neoglacial advance is indicated according to Fernández-Fernández et al. (2020).

Figure 2. Three-dimensional view of the Héðinsdalsjökull (orthophoto from year 2000) and main geomorphological units.
the $^{36}$Cl cosmonuclide to 3–2 ka, and interpreted as the date of their final stabilization (Fernández-Fernández et al., 2020). This advance coincides with clear Neoglacial advances of other debris-free glaciers, such as Tungnahryggsjökull (Fernández-Fernández et al., 2019). In addition to these moraine ridges, small moraine mounds or hills are very abundant, contributing to a hummocky moraine landscape (Grindvik-Knudsen et al., 2006).

The landforms of the debris-covered marginal zone are affected by a braided stream that drains the melt waters of the glacier and has reshaped the entire central axis of this geomorphological unit as it has already been observed in other cases (Janke et al., 2013; Monnier & Kinnard, 2016).

4.1.5. Rock glacier

Facing the NE of Héðinsdalsjökull and resting on a platform at 1000 m a.s.l., a rock glacier extends, with its characteristic morphology of steep front and surface boulders arranged in parallel ridges and furrows, perpendicular to the flow (Figures 1–3 and 9). Although the collapse depressions are rare, in some of them the great thickness of the debris cover and the proportion of interstitial ice can be observed.

The rock glacier covers an area of 0.2 km$^2$, with a maximum length and width of 1.2 km and 245 m, respectively. This formation has its root at 1020 m a.s.l., and descends to the minimum elevation of 920 m a.s.l., with an average slope of 10.9%. Its front reaches a depression occupied by a small lake (0.01 km$^2$).

In similar rock glaciers, located in nearby cirques and at similar altitudes, ice has been detected below a dense layer of debris 2–3 m thick (Andrés et al., 2016; Campos et al., 2019; Farbrot et al., 2007; Kellnerer-Pirklbauer et al., 2007; Tanarro et al., 2019; Wangensteen et al., 2006).

4.1.6. Frontal-glacial depression

In front of the rock glacier there is a frontal-glacial depression dotted with erratic boulders. In the outermost sector of the depression, the erratic boulders are aligned and delimit the maximum glacial advance that closed this depression (Figure 9).

4.1.7. Glacier cirque and scarps

The head of Héðinsdalur presents the characteristic morphology of a glacial cirque (Figures 1–4), which is semi ellipsoidal and with steep slopes. The walls of the cirque delimit the glacier at its upper end and occupy an area of 2.5 km$^2$, with altitudes between 1360 and 960 m. These bedrock walls are characterized by an almost vertical inclination in some sections, especially at the head of the glacier and in the southern part.

4.2. Other landforms

The cirque is carved out on a plateau summit, at altitudes between 1180 and 1400 m a.s.l. These surfaces are covered by patterned ground, which evidences the presence of active permafrost. At the NE of Héðinsdalsjökull, there is an intermediate plain, at
Figure 4. Workflow including the different steps for the production and visualization of the geomorphological map of Héðinsdalsjökull.
altitudes of 1080–1160 m a.s.l. Below this, there is a lower one, with lower altitudes, between 1040 and 760 m a.s.l. The NE sector of the rock glacier rests on the latter surface.

Rockfall talus is deposited on the cirque walls in the south and in the northern lower plain. This unit occupies an area of 1.1 km², with an average slope of 62.6%. On the rock fall talus numerous debris flows are formed. These debris flows usually begin at the limit that separates the talus and the walls of the cirque. Their lengths range from 400 to 200 m, although some can be >800 m along slopes of 60%. A fluvioglacial plain, rises in front of the collapsed debris-covered glacier from 600 m a.s.l.

5. Conclusions

The combination of field surveys, detailed traditional cartographical techniques, the application of tools based on the latest photogrammetry techniques, and different software allowed obtaining cartographical products, that show great graphic expressiveness and transmit a large amount of information. In this sense, the use of CAD software stands out as an efficient tool both for map vectorization and visualization. In addition, the use of

Figure 5. Headwall of Héðinsdalsjökull cirque (August, 2018). (A) Héðinsdalsjökull viewed from the north. The rock glacier can be seen ahead of the debris-free glacier on the lower platform. (B) Héðinsdalsjökull viewed from the west.

Figure 6. Debris-covered sector of Héðinsdalsjökull. (A) The debris-covered sector extends between the debris-free sector and the marginal debris-covered zone. (B) The thickness of the debris mantle and the underlying stagnant glacial ice can be seen in numerous collapse depressions.

Figure 7. Proto-rock glacier on the debris-covered sector. (A) View from the front. (B) View from the upper part.
realistic 3D isometric view obtained through SfM photogrammetry techniques based on aerial photography and field photographs allows the most complex areas to be analyzed and displayed remotely with greater clarity.

This work provides a map of the Héðinsdalur cirque and foreland at 1:4000 scale. The detailed geomorphological map allows differentiating several units within the Héðinsdalsjökull complex, and highlights the existence of different types of large units related to icy formations within an evolution continuum of debris-free glacier, active debris-covered glacier, collapsed debris-covered glacier and rock glacier. The landforms inside the large units are used to classify them as moraines, hummocky moraines, ridges, furrows and the different collapse landforms. In addition, the gravitational slope landforms are also highlighted, such as talus and debris flows, which reworked the interior of the glacier complex by destroying or covering glacial landforms, and consequently, have influenced its evolution. In fact, these slope processes still influence the evolution of the debris-free glacier, supplying debris to its front and slowing down its retreat during recent decades.

Figure 8. Debris-covered marginal zone, outermost ridges and the hummocky moraine landscape. (A) High resolution orthophoto obtained from SfM. (B) Oblique view from the east. (C) 3D oblique view of the reconstructed orthophoto from the north. (D) Front viewed from the north.
The information provided by the map will improve subsequent studies on the evolution of glaciers in paraglacial environments. The continuous contribution of debris from the cirque walls can transform a debris-free glacier into a debris-covered glacier, to end up transforming into a rock glacier. These different phases have usually been identified in different cirques and the process of evolution has been deduced and modeled, but this transformation has rarely been observed. The contribution of the Héðinsdalsjökull map is that all these phases have occurred in the same glacier and in a very short time, for 2–3 ka. The different genetic units outlined in the map reveal a number of evolutionary phases. First there was a debris-covered glacier, which melted and completely collapsed, although above 700 m a.s.l., an active debris-covered glacier still survives. Then, above 900 m a.s.l. a rock glacier was formed, and finally the front of the debris-free sector overlapped, and still does, the debris-covered sector of glacier, that remains stagnant. The map provides this valuable information for further investigation on the chronology and processes involved in these phases.

The glacier complex of Héðinsdalsjökull continues to evolve, under intense slope processes and the effects of present climate change. The final map constitutes an important source of information to establish the magnitude of future changes within this complex.

**Software**

We used the ArcGIS 10.8.1 (ESRI) to georeference the base map and the CAD Bentley MicroStation Connect Edition to vectorize the geomorphological features and units and to create the 3D geovisualization of the map. We used the photogrammetry software Bentley Context Capture to create SFM products. Bentley map was used to fix the topology. Also, we produced the final composition and graphic design of the geomorphological map using MicroStation Connect.

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**Data availability statement**

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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