Faculty of Science

GLACIAL LINEATIONS IN VÄSTERBOTTEN COUNTY, SWEDEN

Karol Schultz

Degree of Bachelor of Science
with a major in Earth Sciences
15 hec

Department of Earth Sciences
University of Gothenburg
2023 B-1217

UNIVERSITY OF GOTHENBURG

UNIVERSITY OF GOTHENBURG
Department of Earth Sciences
Geovetarcentrum/Earth Science Centre

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Karol Schultz

ISSN 1400-3821

B1217
Bachelor of Science thesis
Göteborg 2023

Mailing address
Geovetarcentrum
S 405 30 Göteborg

Address
Geovetarcentrum
Guldhedsgatan 5A

Telephone
031-786 19 56

Geovetarcentrum
Göteborg University
S-405 30 Göteborg
SWEDEN

INTRODUCTION

During the Quaternary, Scandinavia has been subject to multiple periods of major glaciation. During these last 2.588 million years, Quaternary glacial-interglacial cycles are estimated to have occurred approximately thirty times (Marshall, 2009). Each cycle of the last seven to eight glaciations lasted approximately 100 000 years (Gornitz, 2021). During each cycle, the ice slowly expanded over a period of 80 000 - 90 000 years with glaciation usually ending within a 10 000 year period. The most recent last glacial maxima (LGM) occurred approximately 20 000 years ago (Hughes et. al. 2014).

During the last 1.0 Myr, previous research indicates that the ice divide could primarily be found east of the Scandinavian Mountain range (also called the Scandies). During deglaciation, the ice flowed away from the ice divide while the ice margin retreated towards the center of the dome-like ice mass where the ice was the thickest. This ice flow leads to the formation of glacial lineations which can be found throughout the landscape. When considering the ice margin on a time-based basis, estimates based on till thickness hint that the ice margin has resided the most amount of time east of the Scandies during the Quaternary (Kleman et. al. 2008).

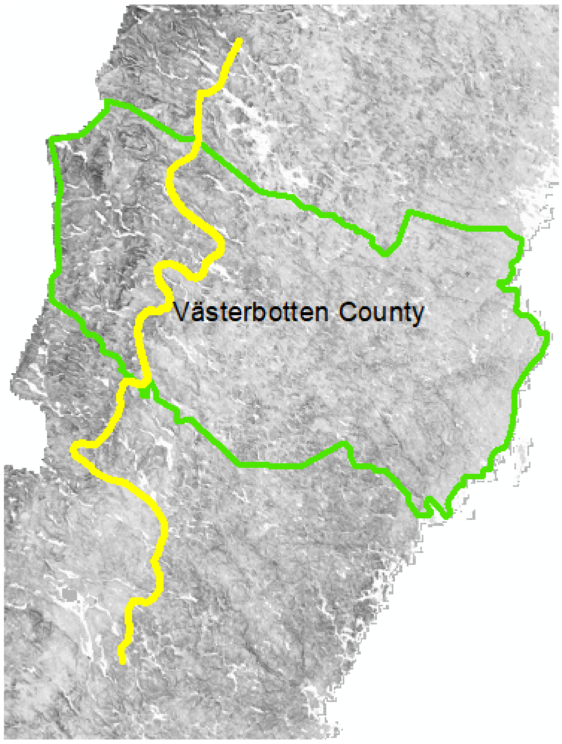


Fig. 1: Ice divide (yellow) over the boundary of Västerbotten county (green) (Lundqvist et. al. 1942).

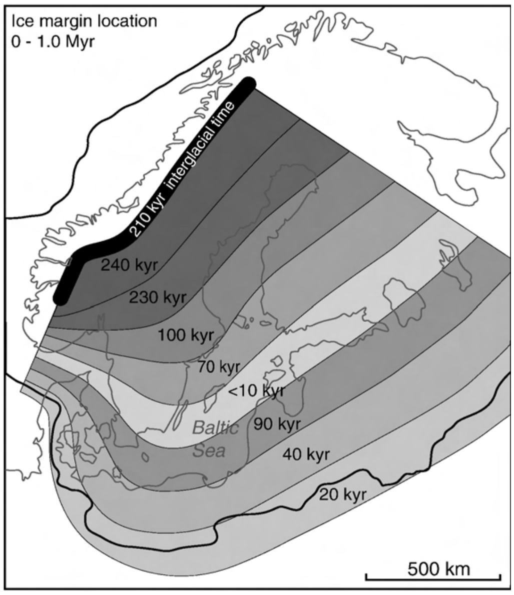


Fig. 2: The amount of time that the ice sheet margin has resided in each segment (Kleman et. al. 2008).

The Scandies exhibit distinct patterns of glacial scouring as well as linear erosion (Kleman et. al. 2008). Among the evidence left behind from the latest period of glaciation is glacial till. This soil covers great parts of Sweden and constitutes the bulk of glacial landforms such as drumlins, moraine ridges and ribbed moraines.

What Are Glacial Lineations?

Even though glacial lineations are commonly referred to in geological literature, the term is not uniformly defined. In spite of this, geological researchers recognize glacial lineations to be a category of subglacial landforms that are erosional, constructional and elongated-to-oval in nature. Landforms which constitute glacial lineations are orientated in the direction of the ice flow (Peterson et. al. 2017). The landforms that make up glacial lineations are drumlins, crag-and-tail ridges, mega-scale-glacial-lineations (MSGL), and flutings. Through mapping glacial lineations, it is possible to visualize the direction of glacial movement over large areas of land. Such mapping endeavors have shown to have the potential to serve as the basis for geological reconstructions related to the geological events of our past. For example, Fu et. al. (2012) has mapped glacial lineations from an area of 104 000 km^2 belonging to the Shaluli Shan mountain range in the southeastern Tibetan Plateau. Their work was based on satellite derived digital elevation models with a 90 meter spatial resolution.

Previous Charting Attempts

During the years 1975 – 1983, a team of researchers at the Department of Physical Geology at Stockholm University have attempted to chart the vegetation of Sweden's northern territories in a project called “Geomorfologisk kartering i fjällen”. During the project, photos were taken using infrared (IR) color photo film as opposed to black-and-white film. The adaptation of this technology proved to be superior over the standard black and white film (Blomdin et. al. 2021). From the infrared photos taken during aerial reconnaissance, maps have been created of the select regions in northern Sweden (Borgström, 1979). Maps such as the ones created by Borgstöm attempted to outline the locations of glacial lineations.

Since most glacial lineations remain hidden underneath the canopies of the Earth's vegetation, many lineations could in the past be observed primarily through direct first person encounters or partially through aerial photography-based remote sensing methods. On account of this, an overwhelming portion of Sweden's glacial lineations remain unmapped to this day. With recent advances in technology and the adaptation of Light Detection and Ranging-based (LiDAR) surface mapping, the removal of the overlying canopy has been made possible through digital means in a software environment. This uncovers great amounts of land from the cover of vegetation and allows it to be charted remotely.

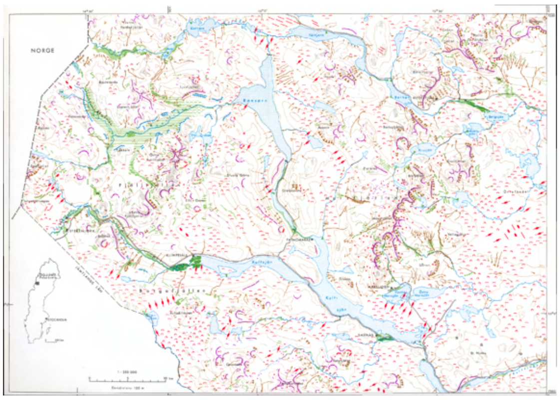


Fig. 3: An example of a map created from infrared aerial photography (Borgström, 1978).

To date, glacial lineations in select Swedish regions have been charted by SGU cartographers from LiDAR-based basemaps. Regions located in Halland, Kronoberg, Kalmar and Småland counties have been charted by Peterson et. al. (2007). The Örebro region has been charted by Öhrling et. al. (2020). Västra Götaland, Östergötland, Uppsala and Jämtland counties by Blomdin et. al. (2021). In addition to this, Siljan in a part of Dalarna has been charted by Smith et. al. (2014). In 2009, Lantmäteriet finished scanning the entire surface of Sweden using LiDAR (Motaz, 2015). Lantmäteriet's effort has resulted in nationwide LiDAR-based elevation data coverage. This has exposed glacial lineations that were otherwise hidden underneath the surface of vegetation and has allowed them to be charted remotely from the LiDAR basemaps with great accuracy and efficiency.

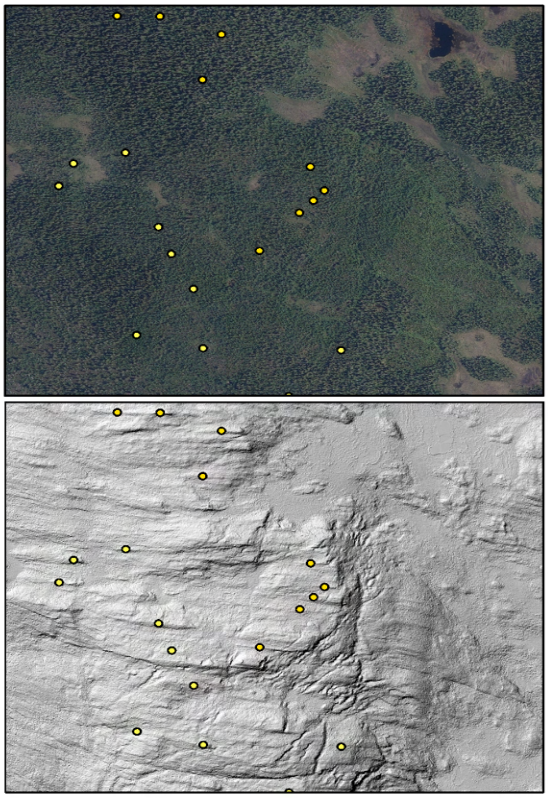


Fig. 4: Glacial lineations (yellow) as seen through aerial photography (above) compared to LiDAR based imagery (below).

The Study Area

Västerbotten county is a 55 000 km² piece of land located approximately 200 km south of the arctic circle. The county displays an alpine landscape to the west that transitions into a low relief landscape towards the east. Vegetation covers approximately 55% of the surface of the county (LRF, 2016).

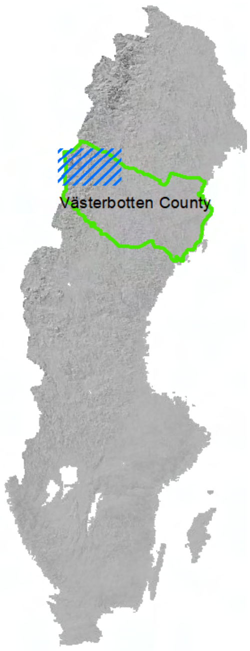


Fig. 5: Extent of Västerbotten county (green) and the 150x100 km² study area (blue).

The Aim Of The Study

To develop an understanding of the glacial lineations of Västerbotten county, this study seeks to investigate the relationship between the topographic relief and the charted lineations.

Primary objectives of the study include the investigation of frequency, morphology and the locations of the glacial lineations. Consecutively, the relief of the study area will be investigated. Finally, the study aims to investigate how the orientation of the ice margin relates to the bearing of the charted lineations. For this purpose, a reconstruction of the ice margin will be used.

To achieve these goals, this study will be split into two sections: a primary section and a secondary section. The primary section is dedicated to the amassment of data through mapping. During this section, glacial lineations contained within the boundaries of the segments will be charted. Following the completion of charting, the initiation of the secondary section will be commenced. The secondary section will be characterized by the analysis of the amassed lineations which will later be compared to the reconstruction of the ice margin for the region.

METHOD

The study has been carried out with the intention of charting glacial lineations in land that has not previously been charted using LiDAR. To locate an uncharted territory, the study has utilized SGU's web-based map service *Quaternary Geomorphology*. In consideration for the time constraints of the study, the area has been delimited to an area with the dimensions of 150 km x 100 km located in the north-western aspect of Västerbotten county (Fig. 5).

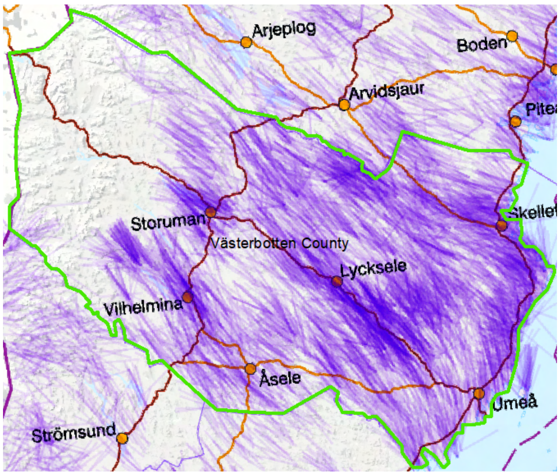


Fig. 6: General direction of known ice grooves (purple) over Västerbotten County (green) (SGU's Kartvisare).

Data Use Table

The following data and tools have been used during the course of the study.

Type	Origin
LiDAR Elevation images. Spatial resolution 2m.	Lantmäteriet http://maps.lantmateriet.se/capabilities/hojdmodell/wms/v1.1?version=1.1.1&
Elevation Raster. Spatial resolution 50m.	Lantmäteriet https://zeus.slu.se/get/?drop=
Reconstructed Ice Margin.	Stroeven et al. (2016)

Table 1: Data type and origin used during the course of conducting the study.

Research Software Used

The Analysis and mapping of glacial lineations has been carried out exclusively in a software environment using ESRI ArcMaps version 10.8.1. The study utilizes LiDAR based elevation data provided by Lantmäteriet. This elevation data comes in the form of a Web Mapping Service (WMS) with nationwide coverage. This LiDAR data has a 2-meter spatial resolution. The LiDAR data is accessible in the form of a hillshade or a slope. Due to the visual clarity that the hillshade mode offers, charting has been done primarily using the hillshade basemap.

Preparation and Segmentation

Prior to charting the study area, consideration has been given to the establishment of a systematic charting methodology. To thoroughly chart the area, charting has been done using a grid which overlays the basemap. The square shaped blocks of the grid measure 25 km along all their extents. The top row of segments is called the C-row. Segments that are related to this row are segments C1, C3 and C5. The second row of segments is the D-row to which segments D2, D4 and D6 are related. The third row is the E-row, to which segments E1, E3 and E5 are related. The final row is the F-row, which includes segments F2, F4 and lastly, F6.

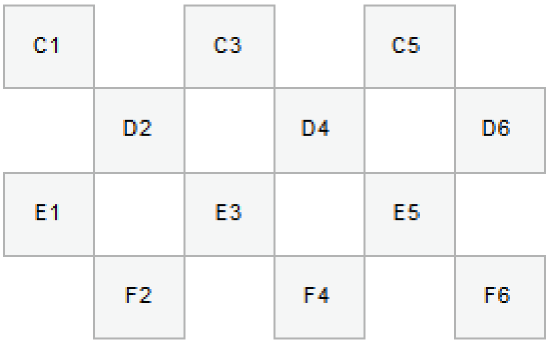


Fig. 7: Diagram of the 12-segment grid.

To cover as large of an area as possible, charting was done to every second block, hence why block names C2, C4, C6 etc. have been hidden from sight in Figure. 7. To ensure the optimal visual scale during mapping, the terrain has been scaled using a 1:5000 magnification ratio at a FHD monitor resolution. Using this magnification ratio, the 12 individual segments have been scanned progressively from the left to the right. In total, the segments account for a total charted territory of approximately 6268 km^2.

Description of Charted Landforms

Drumlins are elongated teardrop shaped landforms that are made out of sediment deposited by glaciers (Thomas & Goudie, 2000). The highest elevation point of a drumlin, also called the summit point, is located immediately after the incline of its blunt side that is located at its stoss side. The elevation of a drumlin gradually decreases towards its lee side point that is located towards its trailing end. Drumlins are made out of glacial till. Common elongation ratios of drumlins are 2:1 to 7:1 (Spagnolo et. al. 2012). The relative age of drumlins can be determined through observations of cross lineations (Boulton, 2001).

Crag-and-tails are drumlin-like features that are composed of a hard rock stoss side. The ridge, or trailing edge is composed of tapering amounts of glacial till (Evans, 1996). The length of a crag-and-tail can range from several meters in length up to over a few kilometers. Crag-and-tails are believed to form where the ice overburden pressure is low (Sugden, 1992). This means that the landform likely formed as a result of the conditions present during deglaciation.

Glacial scouring is a prominence with universal signs of glacial erosion in a direction parallel to ice flow and the absence of glacial till (Sugden, 1976). Mountains covered in large scale glacial scouring have been charted in this study.

Mapped Feature Catalog

During charting, the underlying topography was scanned for glacial lineations using the LiDAR data. To find glacial lineations, consideration was given to the surrounding topography from which straight linear patterns in the topography could be observed. When interest was drawn to a particular, oftentimes clear and distinct prominence, an assessment was made whether the object of interest could be identified as a glacial lineation. When the glacial origin of the landform could be determined, the landform was charted with the help of a two-point polyline. Through this, the landform was subsequently added to the mapped feature catalog.

For the purpose of the study, charted elements contained in the feature catalog are primarily composed of drumlins and crag-and-tails. In mountainous locations, ridge-groove-type corrugations have also been charted together with elements of large-scale glacial scouring. Heavily eroded cliff sides that exhibit distinct signs of linear glacier erosion have also been charted. It is worth noting that these lineations may not always be formed solely by the movement of the glacier; the variation in bedrock resistance can also play a role in their formation. Bedrock with higher resistance to erosion is more likely to form ridges and other topographic features as it is less easily worn away by the glacier, while bedrock with lower resistance to erosion is more likely to be worn down and smoothed out by the glacier, resulting in a more featureless landscape. Throughout the study, ridges and grooves have also been charted as glacial lineations.

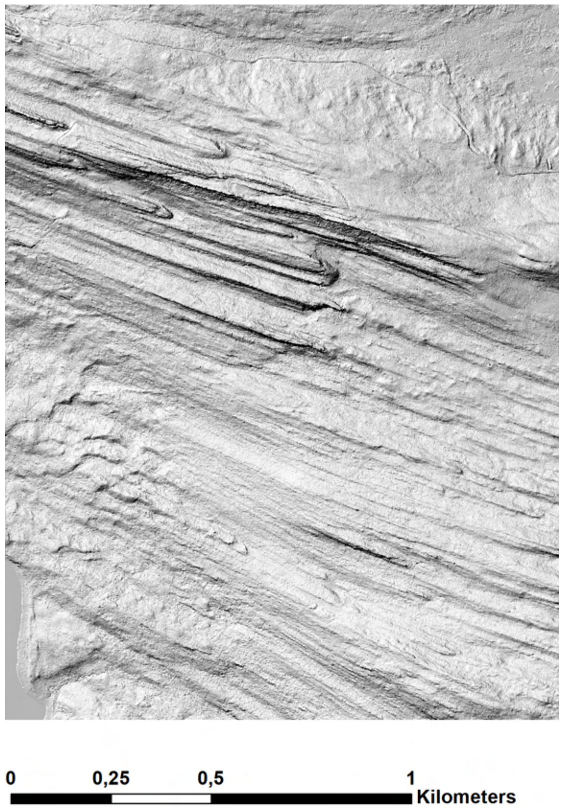


Fig. 8: Glacial lineations located at segment D4.

When charting cliffs that show signs of glacial erosion, consideration has been given to differentiate between cliffside glacial erosion and erosion caused by weathering. The intention was to include as many accurate landforms as possible while eliminating data that could have been influenced by the orientation of beds. The differentiation was done by examining the smoothness and roughness of grouped striations, as well as by looking at the surrounding geology for evidence that could connect the heavy erosion of a particular cliff to nearby glacial lineations. Rough, crooked, and often small striations that could not be linked to the geological context were excluded, while straight, parallel, and smooth striations were charted as glacial lineations and were therefore included.

During charting, all landforms have been charted using the same common marker that did not differentiate between the different types of landforms. Using a common marker with one attribute type was an efficient way to conserve time and accelerated charting. All charted lineations have been charted in a west to east direction with the lineation starting point in the west and end point in the east. This west to east direction is the assumed direction of ice margin retreat for the location of the study area during the period of the last glacial maxima (Kleman et. al 2008). During other glacial periods not related to the last glacial maxima, the center of the ice dome could have been located west of the study area. This suggests that the ice has retreated towards the west, with ice flow occurring from a west to east direction (Kleman et. al. 1997). As a result, some of the west-to-east lineations that were charted could have an inverted orientation when compared to the one assigned to them during charting.

Quality Check

After charting, the extents of all 12 charted segments have been re-checked to verify the quality and to correct for improper data entries. The quality check process included the correction of offset lineations, the removal of inaccurate features and the addition of features that have previously been overlooked. Similarly, all segments have been scanned progressively from the left to the right. Lineations that have been corrected for offset have been adjusted manually by moving the lineation over the centerline of the feature. The quality check process has been carried out with the same maximum level of magnification as the initial charting process, namely 1:5000.

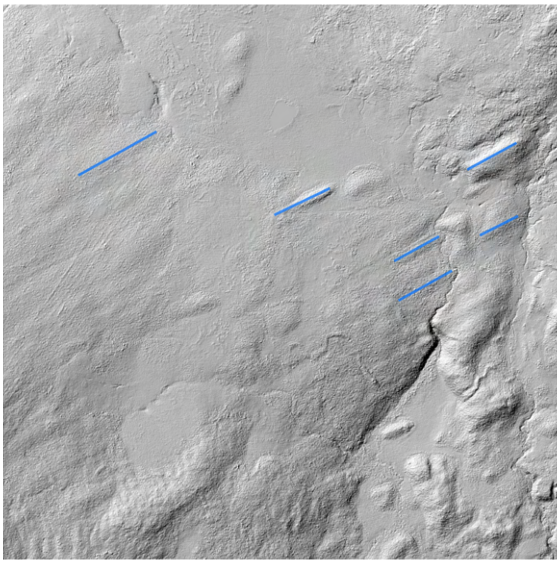


Fig. 9: Example of charted drumlins.

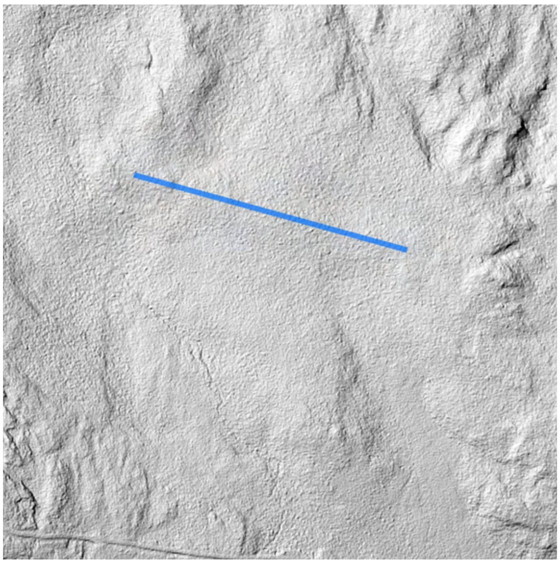


Fig. 10: A stand-alone drumlin in a field.

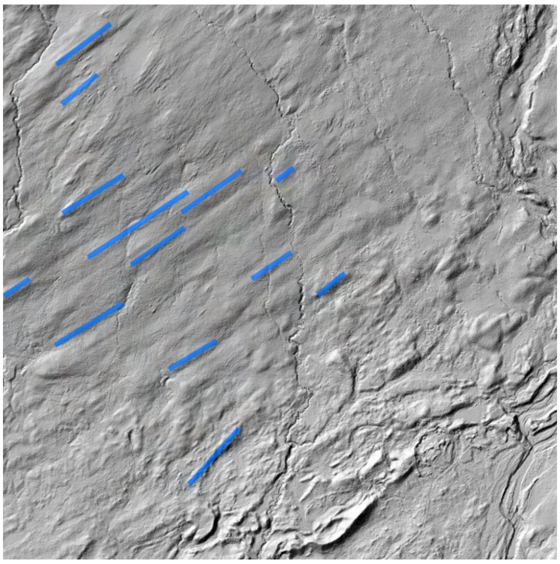


Fig. 11: Drumlins and one crag-and-tail.

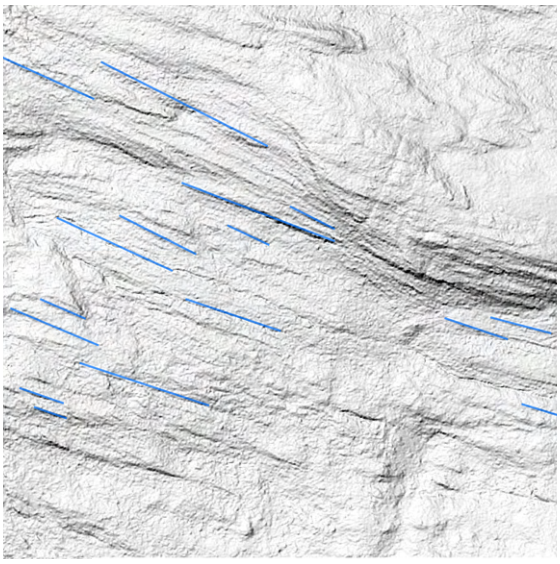


Fig. 12: Glacial scouring on a mountain face. It is unclear whether these structures are not the result of bedrock structure.

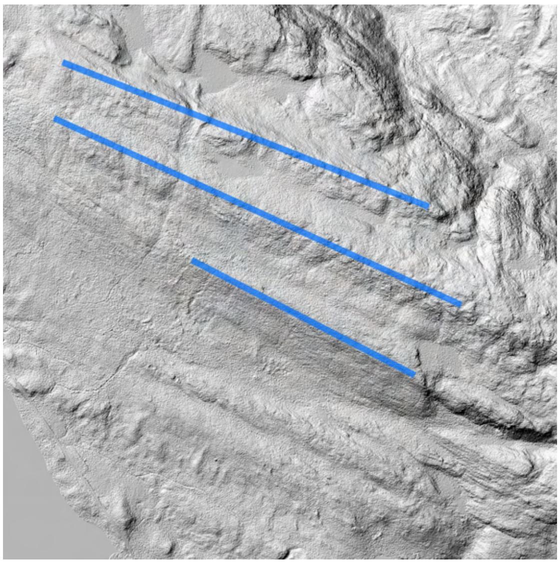


Fig. 13: Larger glacial grooves at a mountain face.

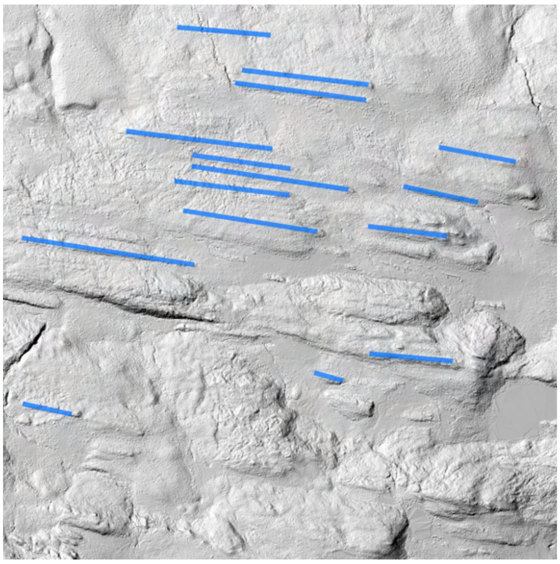


Fig. 14: Mixed glacial lineations on a slope.

Data Preparation

To prepare the feature catalog for analysis, all charted lineations have been attributed with values corresponding to their length in meters and bearing in degrees. These calculations were based on the A and B points of the polylines. The lineations were consecutively grouped by affiliation to the confinements of the 12 segments. Since Lantmäteriet's WMS LiDAR data service does not contain elevation data, a separate elevation raster has been acquired for the purpose of attributing the charted lineations with elevation data. This elevation raster has been acquired from Lantmäteriet's website (Table 1). The elevation raster is LiDAR based and has a spatial resolution of 50 meters.

Prior to use, the elevation raster data was scanned for entry points containing the value 0 which were consecutively converted into "NODATA"-entries. To extract a mean elevation measurement for each lineation, every polyline was first converted into a series of six points that were distributed along each polyline. From the elevation raster, the elevation of each of the six points was acquired. The elevation of each charted lineation was determined from the mean elevation of its six elevation points.

Relief Analysis

The relief analysis was done with the help of a buffer. Through the application of a buffer around a lineation, near lying minimum and maximum elevation values could be extracted. The radius of the buffer has been determined to a value of 2500 meters. This value has been set by considering the topographic extent that the buffer would cover. The radius value of 2500 meters was determined to be optimal as the perimeter was of sufficient size to cover the extent of the near lying valleys and mountains. Through analyzing the elevation data points contained within each buffer, the minimum and maximum elevation measurements could be extracted. This process extracted the data for the purpose of conducting the relief analysis.

Creating Elevation Models

In relation to standard rasterized elevation maps, 3D models have a greater capacity to declutter large mountainous areas and were therefore chosen for the purpose of this study. The 3D model that is used in the study has been rendered from the same elevation raster that was used during the relief analysis. To convey depth, a vertical extent exaggeration of 1.0 x (z-factor = 1) has been assigned to the model together with a hillshade.

Analysis of Lineations in Relation to Ice Margin Reconstruction

To analyze all charted lineations in relation to the reconstructed ice margin, the study has used a file created by Stroeven et al. (2016). This reconstruction of the ice margin is based on the pattern of eskers and ice-marginal positions. According to the authors of the reconstruction, few eskers could be found in mountain regions due to cold-based conditions. For these locations, the authors compensated by basing their reconstruction on lateral channels and ice-dammed lakes. In terms of output, the reconstruction is a raster that displays the bearing value for the assumed direction of ice margin deglaciation. The reconstruction could be compared to the lineations by counting the difference in bearing. Through conducting the comparison between the lineations and the reconstruction, the accuracy of the reconstruction could be investigated thanks to the higher resolution picture brought about by the volume of the charted lineations. When conducting the investigation, it is essential to clarify that the charted lineations are not all related to the period of the last glacial maxima, as their origin could be from outside of the LGM. Additionally, this paper assumes that the lineations form close to the ice margin.

RESULTS SECTION

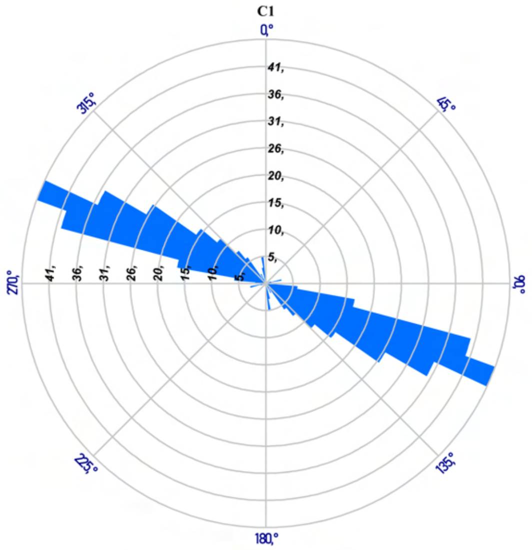


Fig. 15: Bi-directional rose diagram of the interpreted lineation bearings.

C1 segment. N = 232

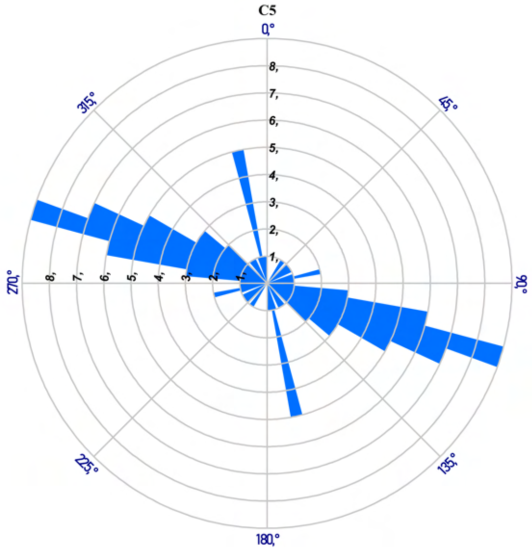
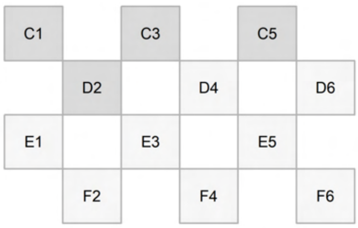


Fig. 17: Bi-directional rose diagram of the interpreted lineation bearings.

C5 segment. ***N = 61.***



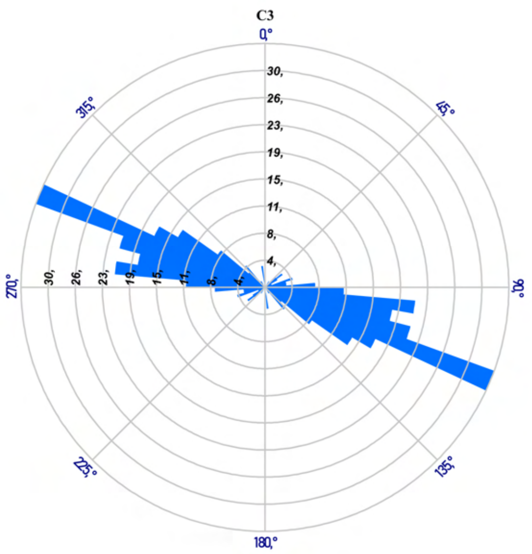


Fig. 16: Bi-directional rose diagram of the interpreted lineation bearings.

C3 segment. N = 183

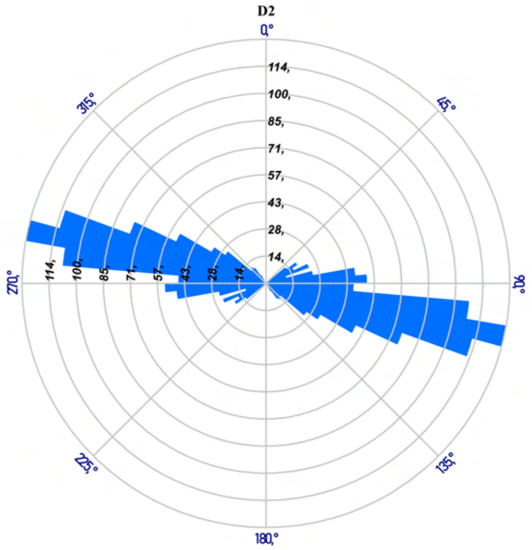


Fig. 18: Bi-directional rose diagram of the interpreted lineation bearings.

D2 segment. N = 821

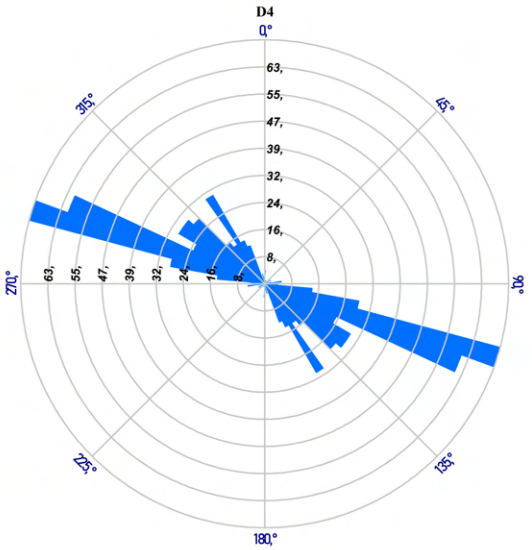


Fig. 19: Bi-directional rose diagram of the interpreted lineation bearings.
D4 segment. N = 403

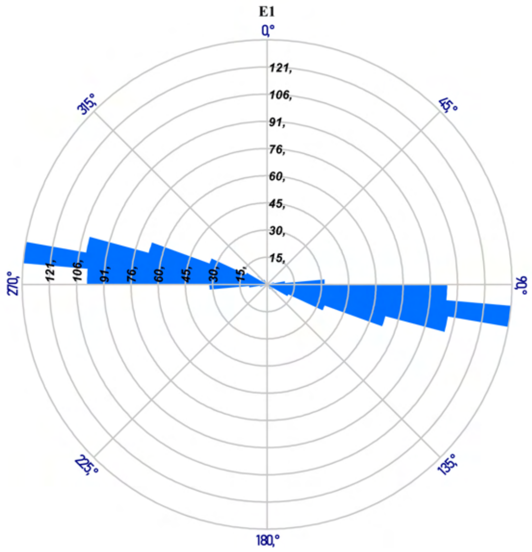
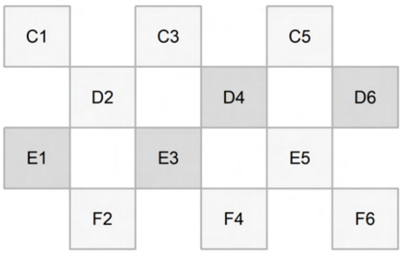


Fig. 21: Bi-directional rose diagram of the interpreted lineation bearings.
E1 segment. N = 529



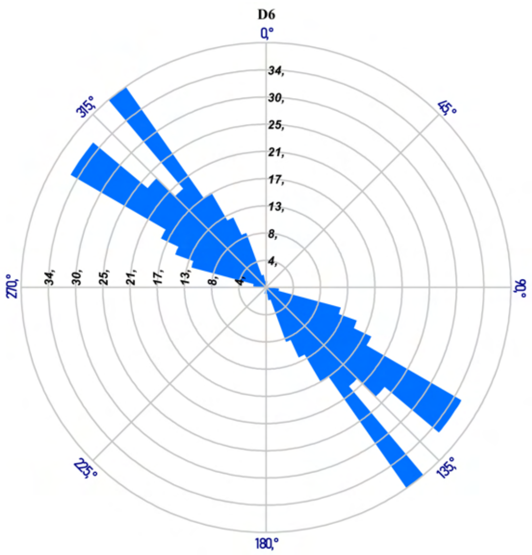


Fig. 20: Bi-directional rose diagram of the interpreted lineation bearings.
D6 segment. N = 247

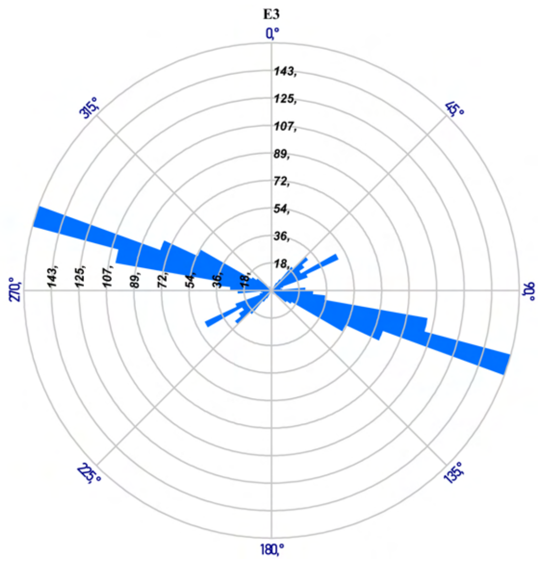


Fig. 22: Bi-directional rose diagram of the interpreted lineation bearings.
E3 segment. N = 731

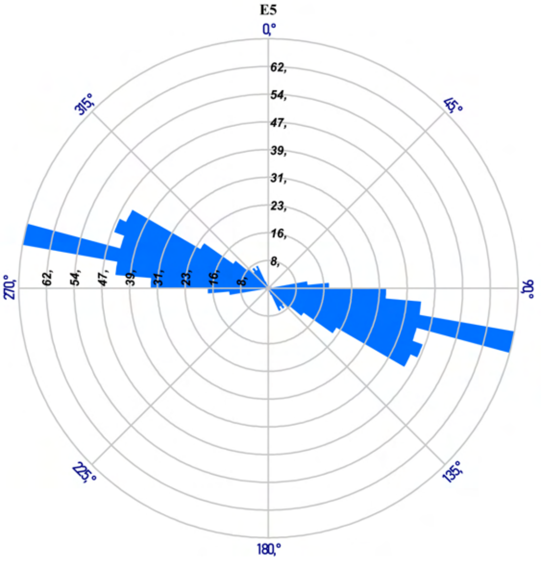


Fig. 23: Bi-directional rose diagram of the interpreted lineation bearings.
E5 segment. N = 381

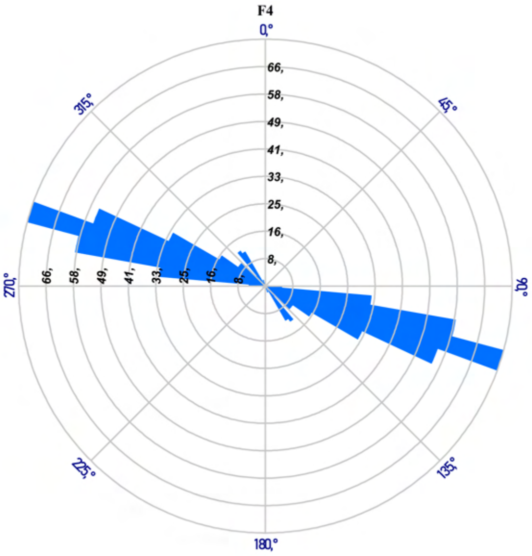
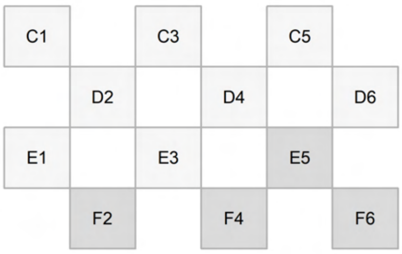


Fig. 25: Bi-directional rose diagram of the interpreted lineation bearings.
F4 segment. N = 328



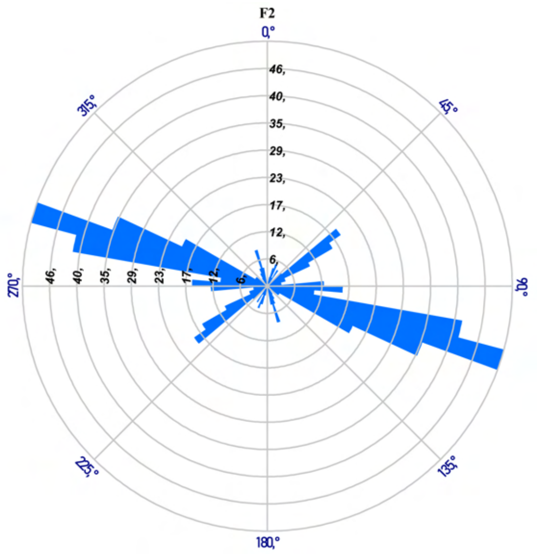


Fig. 24: Bi-directional rose diagram of the interpreted lineation bearings.
F2 segment. N = 300

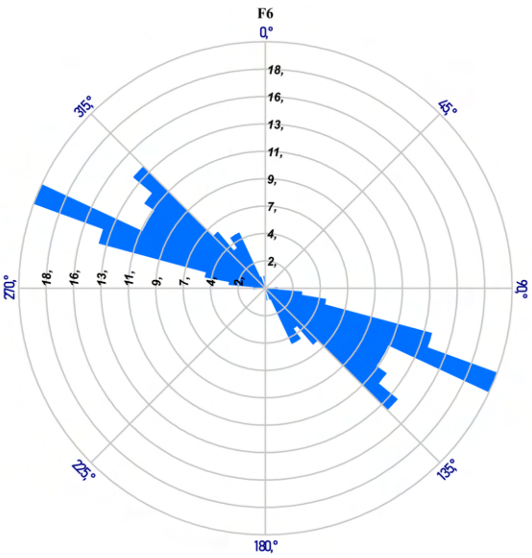


Fig. 26: Bi-directional rose diagram of the interpreted lineation bearings.
F6 segment. N = 114

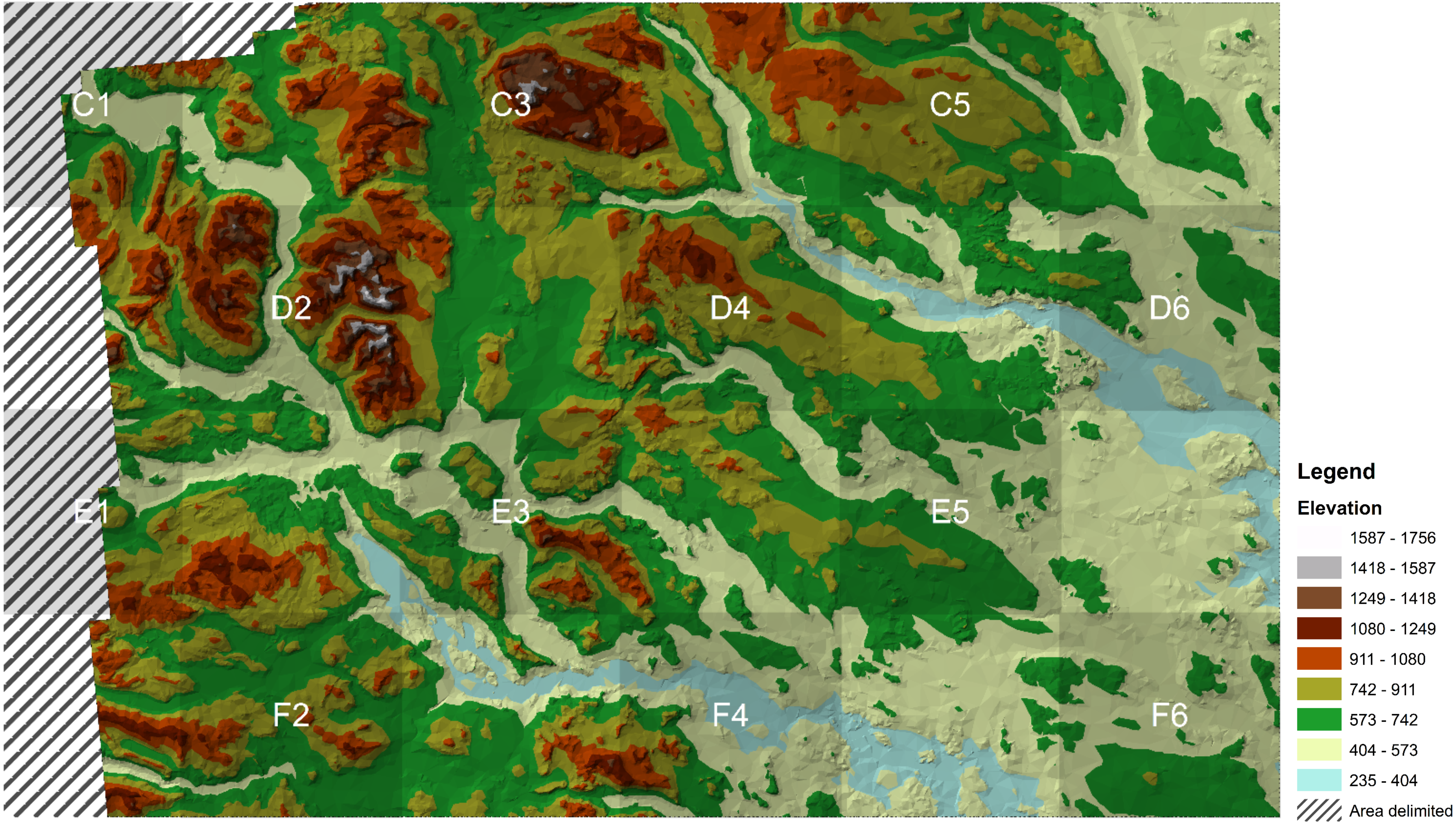


Fig. 27: LIDAR-based 3DTIN elevation map of the study area. Frame dimensions 150 km x 100 km.

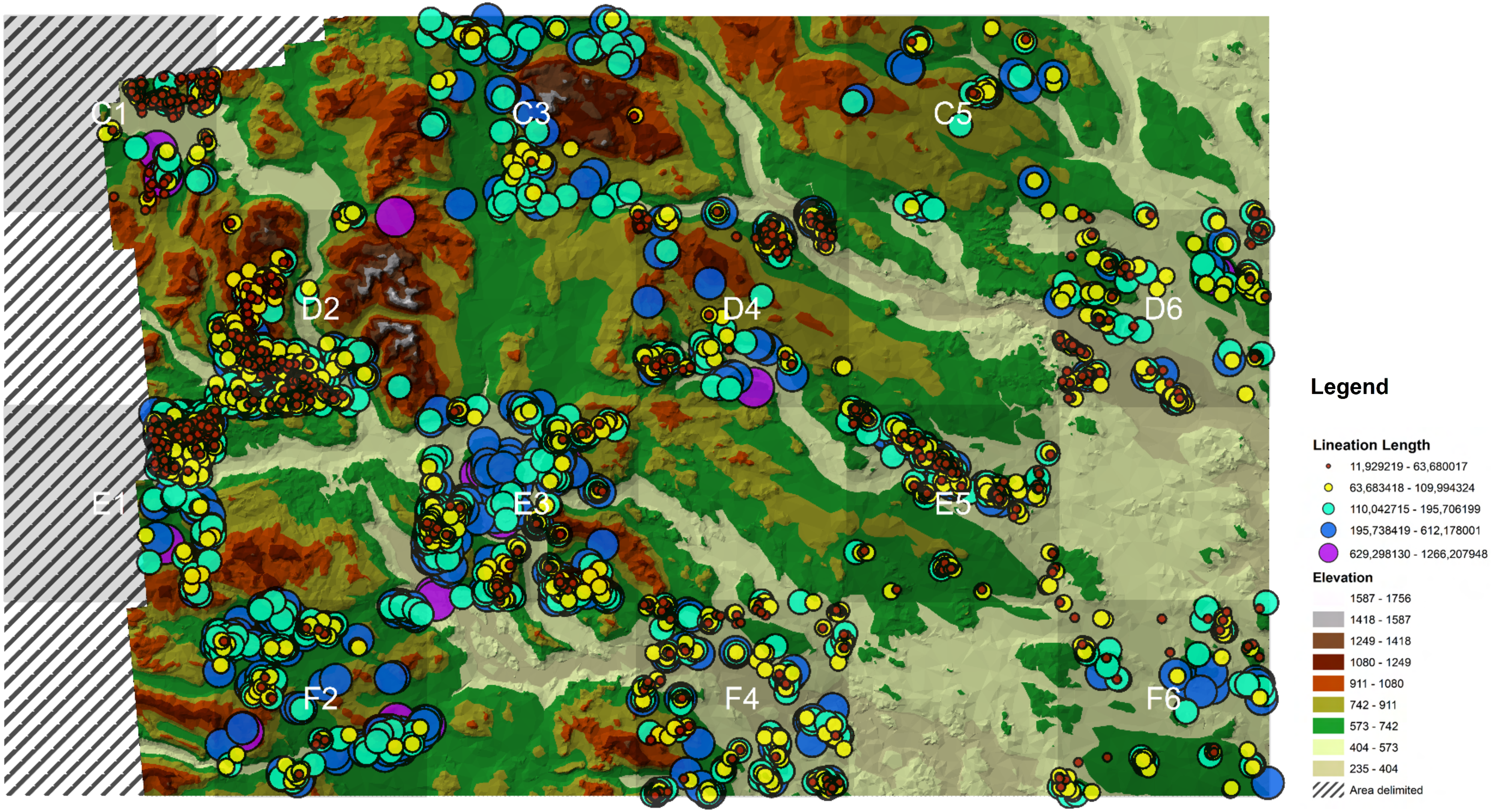


Fig. 28: Distribution of charted lineations throughout the extent of the study area.

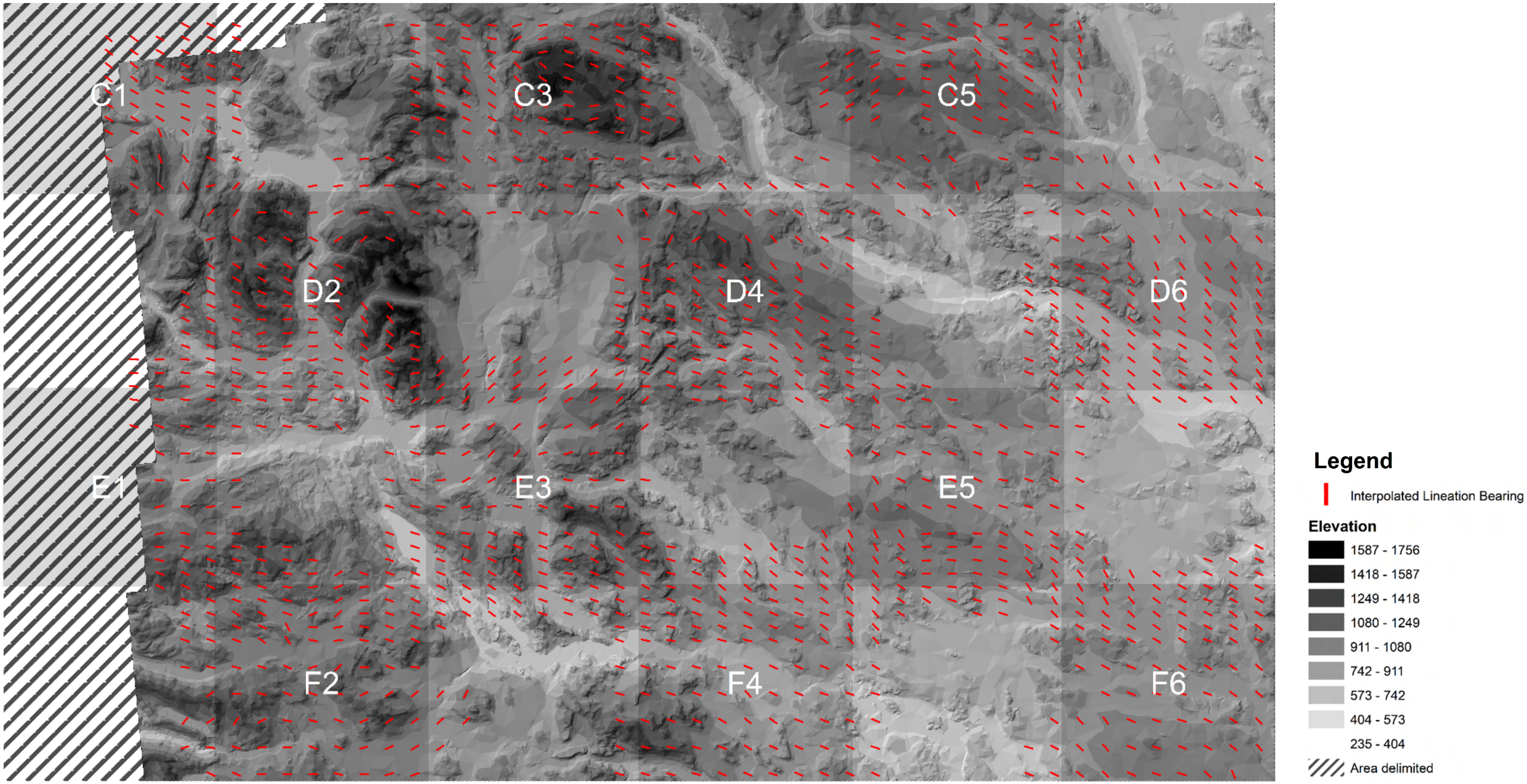


Fig. 29: Interpolation of lineation bearing (kriging).

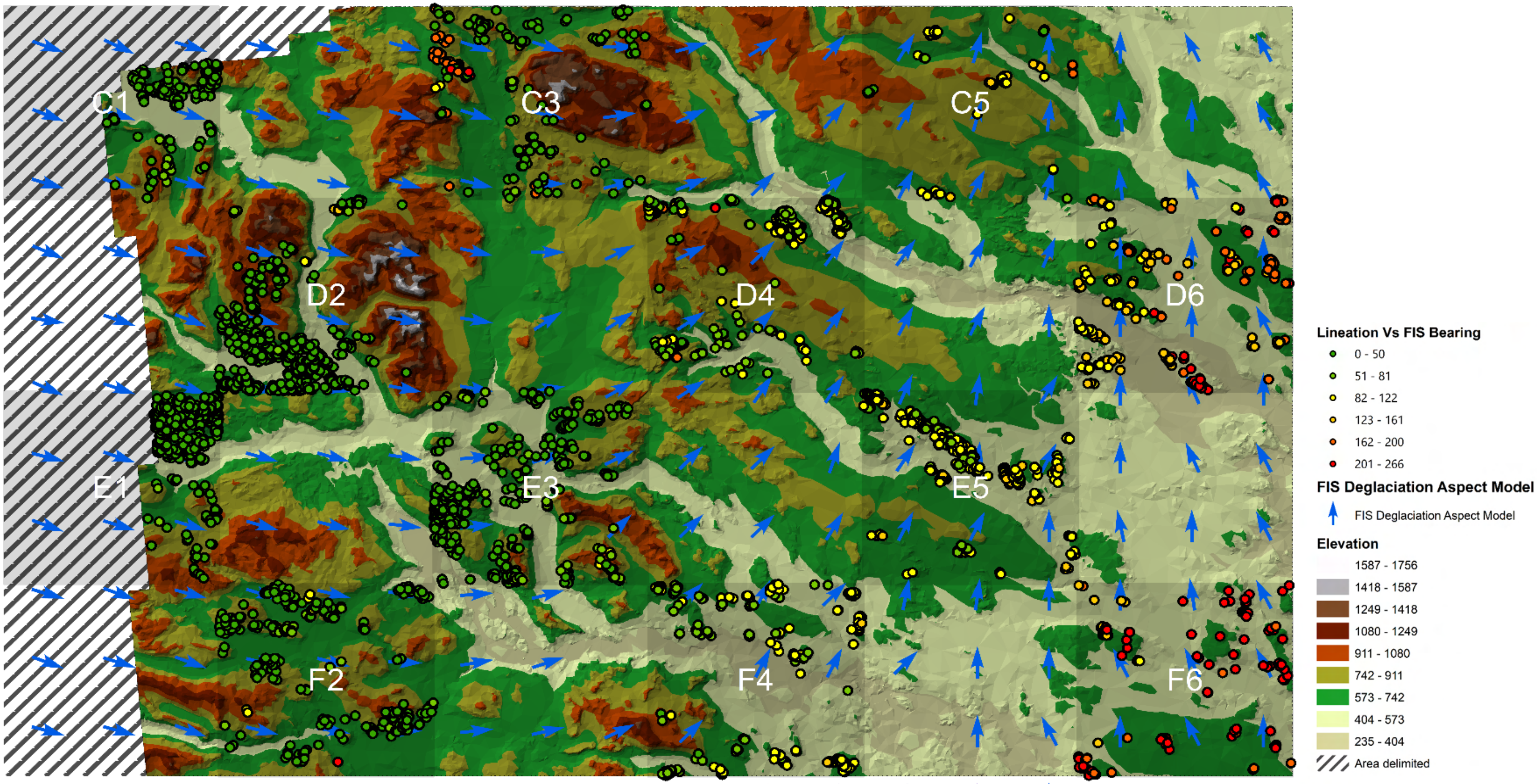


Fig. 30: Ice-margin retreat (blue arrows) compared to the lineations (multi-colored points). The direction of ice-margin retreat is opposite to the direction of ice-flow. Points which lean into yellow are lineations which were charted perpendicular to the modeled direction of ice flow.

The bearings of the charted lineations are presented in Figures 15 – 26. The results in these figures are presented in the form of rose grams. From the results, the 12 segments have an apparent mean bearing of approximately 110 degrees. Segments C5, E3 and F2 of Figures 17, 22 and 24 respectively have lineations with bearings that cross cut the mean distribution of the bearings for the segments.

The rendered elevation map is presented as a 3D-TIN render and is shown in Figure 27. The highest elevations are presented in white and denote an elevation of approximately 1600 – 1700 meters. Segments containing this elevation range are segments C3 and segments D2. These maximum elevation segments are located on the western aspect of the study area. As the study area progresses from the west towards the east, while passing the midline of the central segments D4 and F5, the topography transitions into a low relief landscape in which the maximum elevation leaves the 1100 – 900-meter range and declines into the sub-900 meter elevations.

The elevation basemap of Figure 27 has been reused for Figures 28 and 29. Figure 28 presentes the location of all charted lineations together with their respective lineation length. The lineation lengths are portrayed using different colors with a set sphere size that represents a certain range of lineation length. This range has been divided into 5 equal segments spread out over 12 – 1250 meters. Segments C1, E1 and D2 contain most of the smaller lineations which fall between the 12 – 64-meter range. In terms of quantity, most of the longer lineations can be found within the confinements of segments F2 and E3. These lineations are found in the 195 – 612-meter range. Select super long lineations can be found scattered throughout the study area.

The orientations of the charted lineations are shown in Figure 29. The figure is based on an interpolated raster that has been rendered from the bearings of the 4375 charted lineations. In the figure, an approximation of an overall direction of the lineations can be observed. The lineations are orientated which follows the topography of the study area.

The angular variability between the lineation bearing and the reconstructed ice margin model is shown in Figure 30. The charted lineations that are found on western aspect of the study area (segments C1, D2, C3, E1, F2 and E3) align with the direction of the reconstructed ice margin model within a range of approximately 0 – 50 degrees. Shortly prior to crossing the midline of the study area, the west-to-east orientation of the reconstructed ice margin changes direction by turning upwards; towards the ENE direction. After the reconstructed ice margin crosses the midline of the study area, a change in direction can be observed for the western lineations that are located in both the D4 segment as well as its southern counterpart, the F4-segment. Together, the western lineations of these segments deviate from the bearings of the reconstructed ice margin by an initial number of 51 – 81 degrees. For eastern lineations within these segments, the range grows further to an approximate difference of 82 – 122 degrees. From here on, further migration towards the east equates to an exceedingly flattening topography. The E5 segment has a cluster of centrally located lineations which deviate from the orientation of the reconstruction of the ice margin by a range of 51 – 81 degrees. Subsequent lineations for this E5 segment fall within a range of 82 – 161 degrees. The C5 segment contains few charted lineations and is therefore intentionally excluded from this section. Easternmost segments, namely segment F6 and E6 see a very clear difference in the charted orientation and the deglaciation model. The initial westernmost 162 – 200-degree range transitions into a bold range of 201 – 266 degrees. Lineations that are at, *or near*, the value of 180 degrees conform to the direction of the reconstruction of the ice margin but have presumably been charted inversely due to the systemic west-to-east charting direction.

Segment Name	Segment Area (km2)	Mean Elevation (m)	Min Elevation (m)	Max Elevation (m)	Elevation Difference (m)
C1	206	702	235	1189	954
C3	581	860	541	1601	1060
C5	581	762	481	1125	644
D2	581	901	455	1756	1301
D4	581	760	382	1247	865
D6	581	509	342	856	514
E1	193	748	485	1146	661
E3	581	679	395	1400	1005
E5	581	596	410	856	446
F2	581	739	395	1245	850
F4	581	548	350	1210	860
F6	581	540	396	788	392
Average	517	695	406	1202	796

Table. 2: Table of the segments and their accompanying environmental parameters.

The topographic parameters of each segment are listed in Table 2. From the table, the mean elevation throughout the study area is 695 meters. The overall highest mean elevation of 901 meters can be found at the location of segment D2. On the other hand, the lowest mean elevation can be found at the location of segment F6. There, the mean elevation is 540 meters. Throughout the study area, the lowest minimum elevation can be found at the location of the C1 segment, 235 meters. This is 58% lower than the average lowest elevation across all the segments. Looking up, the highest maximum elevation can be found at the location of the D2 segment where the elevation of 1756 meters exceeds the mean by 146%. For all segments, the elevation range is on average 796 meters. The range is largest at the location of the D2 segment where an elevation of 1301 meters separates the lowest point from the segment's highest. The smallest range is 392 meters and can be found at the location of F6. Apart from the C1 and E1 segments whose total charted area is 206 km^2 and 193 km^2 respectively, the total charted area of each segment is otherwise approximately 581 km^2.

Segment Name	Lineation count (n)	Mean Lineation Elevation (m)	Mean Lineation Length (m)	Mean Lineation Bearing (deg)
C1	233	705	61	118
C3	183	854	162	151
C5	61	781	147	121
D2	835	708	96	102
D4	403	734	94	124
D6	247	551	88	133
E1	529	759	92	101
E3	731	754	165	93
E5	381	610	98	109
F2	300	753	223	97
F4	328	665	101	113
F6	114	564	113	123
Average	362	703	120	115

Table. 3: Segments and lineation statistics.

The statistics of lineations within an individual segment can be found in Table 3. During the study, the average number of charted lineations for each segment was 362 lineations. Segment D2 has the most charted lineations, namely 835. The least amount of lineations have been charted in segment C5 with only 61 entries. Regarding the average length of the lineations, the longest lineations were found in the segment F2 (223 m), followed by E3 (165 m), C3 (162 m) and C5 (147 m). Segments where the lineations were the shortest were segment C1 (61 m), followed by segments E1 (92 m), D4 (94 m), D2 (96 m) and finally E6 (98 m). The average orientation of each lineation was approximately 115 degrees.

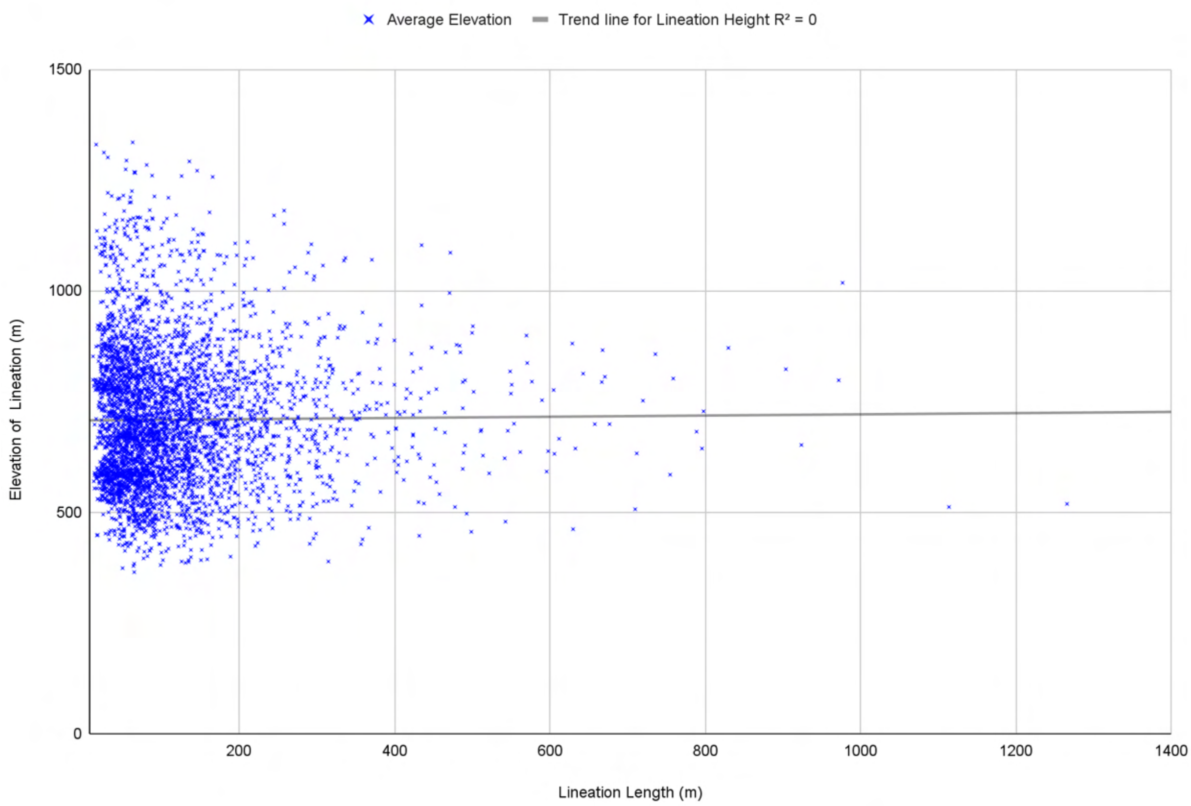


Fig. 31: Length of lineations plotted against lineation height.

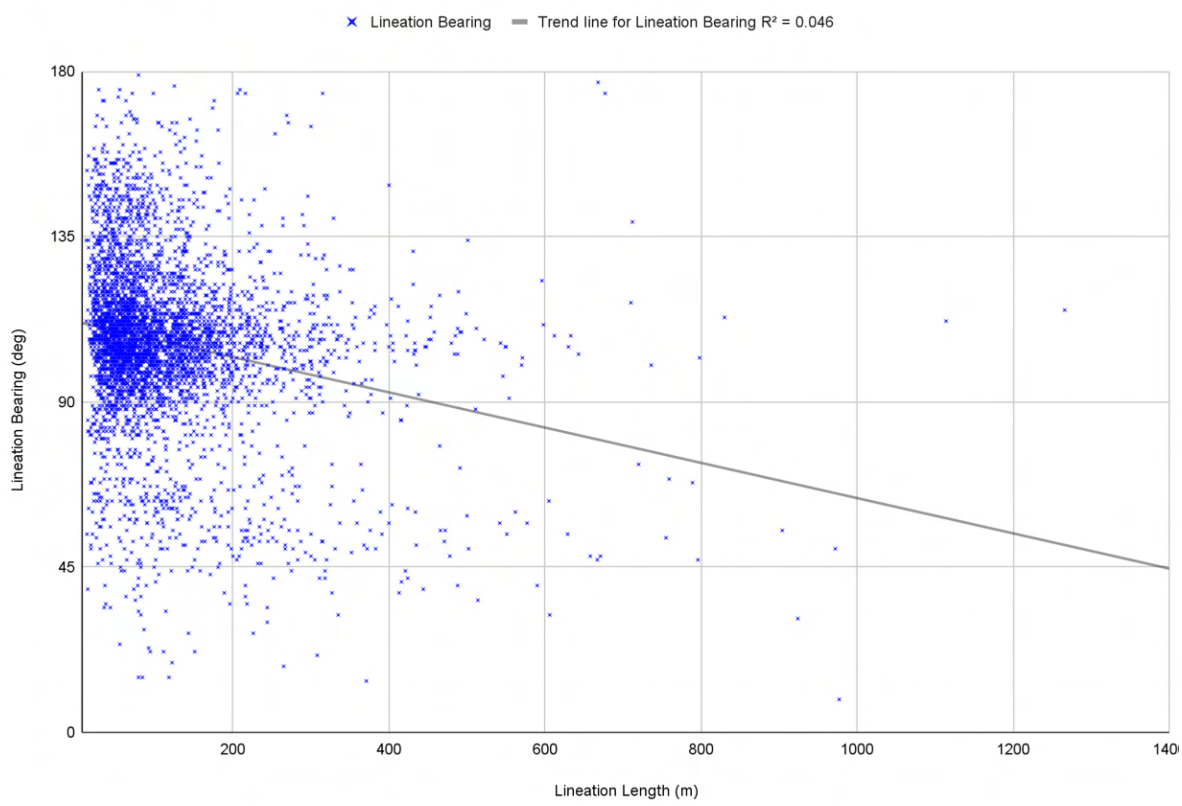


Fig. 32: Length of lineations plotted against lineation bearing.

Fig. 33: Elevation of lineations plotted against lineation bearing.

The relationship between lineation parameters, such as lineation length, lineation bearing and lineation elevation are presented in the form of scatter plots. They are shown in Figures 31 to 33.

Figure 31 shows that there exists no correlation between lineation length and the elevation of the lineations - The R^2 value is 0.

Figure 32 shows that there exists no correlation between the length of the lineations and their bearing - The R^2 value is -0.046.

Figure 33 shows that there exists no correlation between the elevation of the lineations and their bearing - The R^2 value is 0.004.

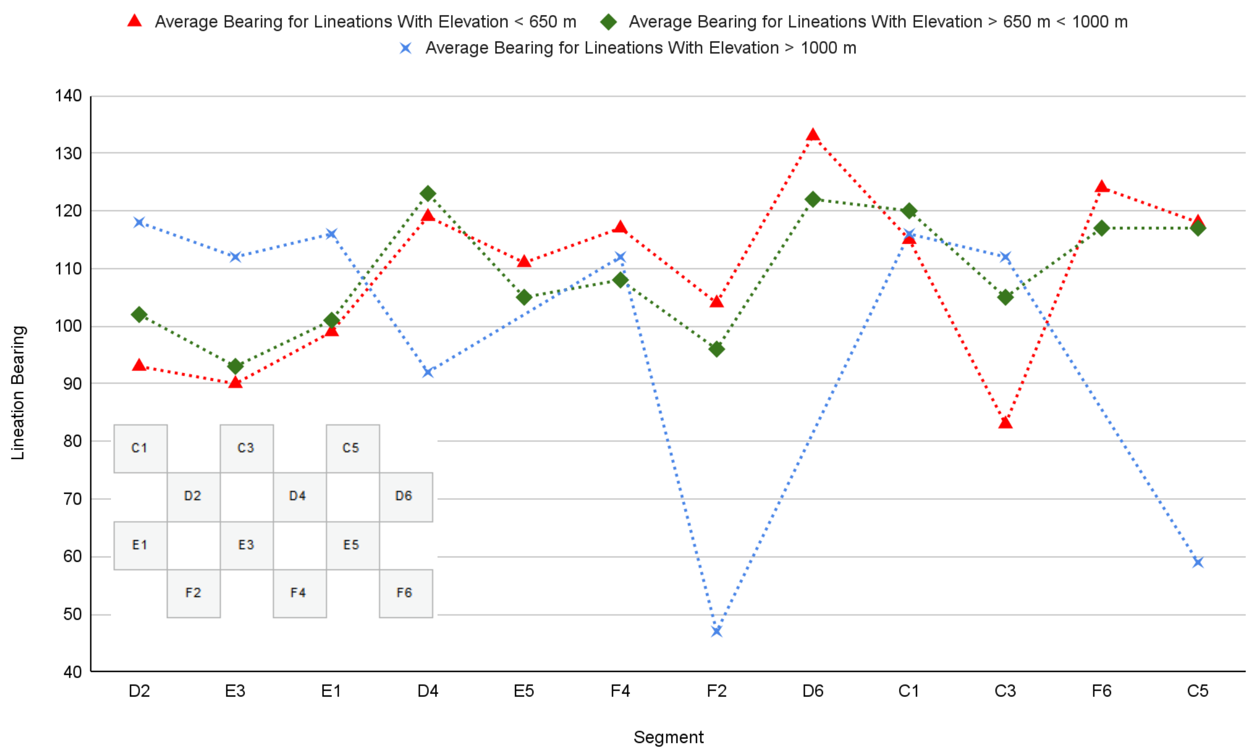


Fig. 34: The average bearing for lineations sorted into groups by elevation.

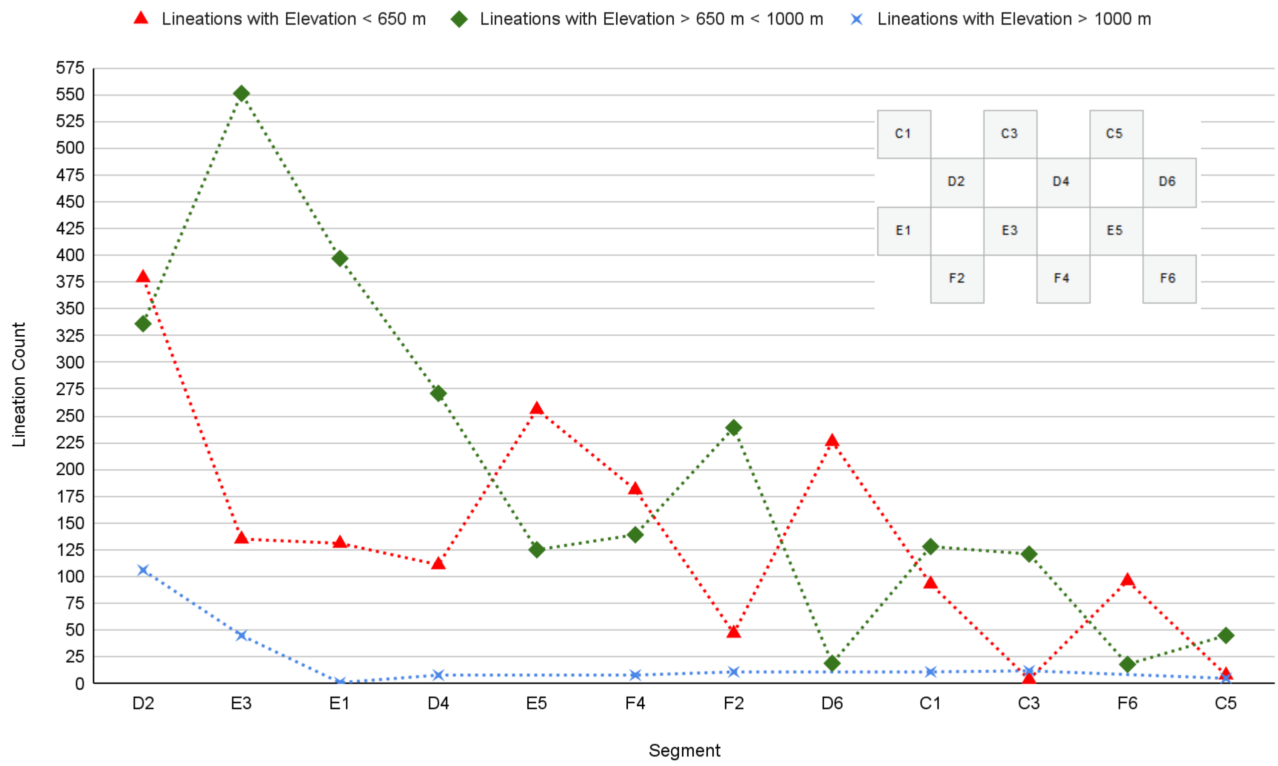


Fig. 35: Lineation count for lineations sorted into groups by elevation. n = 1667 (< 650 m), n = 2389 (> 650 m < 1000 m), n = 207 (> 1000 m)

Figure 34 shows the bearings of short, medium and long lineations per segmented area. Short lineations with a length of under 650 meters have an average bearing of approximately 108.8 degrees. Medium lineations, between 650 and 1000 meters have an average bearing of approximately 109.3 degrees. Long lineations with a length exceeding 1000 meters have an average bearing of 98.2 degrees.

Figure 35 shows the lineation count within each segment and elevation group. The majority of lineations can be found in the 650 – 1000-meter elevation range. This is followed by 39% of lineations in the range that is lower than 650 meters. Finally, 5% of lineations can be found in the excess of 1000 meters.

DISCUSSION

This study seeks to investigate the relationship between glacial lineations and topographic relief. To conduct the study, 4735 lienations have been charted from an area of 6261 km^2.

After comprehensively mapping the lineations in the segmented areas, the lineations have been analyzed. The results found that 65% of all lineations are shorter than 120 meters. The mean lineation is oriented in the bearing of 115 degrees and has a mean length of 118 m (Table 3). In terms of distribution, most lineations have been charted in the segments E1, D2, E3 and D4. These segments have the highest elevation and are located in the western aspect of the study area. In relation to non-mountainous segments, the mountainous segments have excessive surface area due to their higher topographies and higher maximum elevation values.

When comparing the average lineation count of 362 to the lineation count of the individual segments, the mountainous segments are of particular interest. The mountainous segments E1, D2, E3, and D4, count 529, 835, 731 and 403 lineations respectively. On average, these numbers account for an approximate 72.5 % increase in the charted lineations compared to the average count of 362 lineations per segment.

Lineation Clusters

The D2 segment could be considered to be one of the study's most thought-provoking segments. Topographically, the D2 segment could be described as having a rocky western aspect that progressively declines towards the midline of the segment. At the midline of the segment, an intermittent valley can be found which measures approximately 2000 meters wide. This valley separates the flatter, declining west and the mountainous east. D2's mountains are the highest in the entire study area and are additionally the steepest.

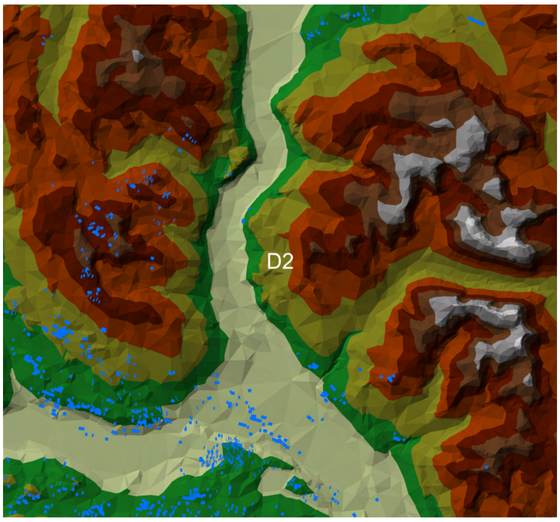


Fig. 40: Magnification of the D2 segment with charted glacial lineations (blue).

Immediately east of the valley, the mountains have an inclination of approximately 60 degrees. Although the D2 segment has the most charted lineations, the 835 lineations are not uniformly distributed. The majority of the lineations in the D2 segment are found within the segment's third quadrant on a declining slope towards the ESE direction. At the same time, the eastern mountainous aspect of the D2 segment has a lineation count of approximately zero (Fig. 40).

As shown by the topography of the D2 segment and the location of the charted lineations in Figure 40, the increase in lineation count does not necessarily relate to the increased surface area of the segment solemnly brought about by the prevalence of a high topographic relief. Instead, the prevalence of an increased lineation count could be due to favorable conditions brought about by the variations to the local topography or conditions otherwise related to the bedrock structure.

Mountains

When inspecting the mountainous areas of other segments, such as the E3, C3, and partially the D4 segment, it can be noted that few lineations have been charted in the areas that are immediately related to the mountainous aspects of those segments.

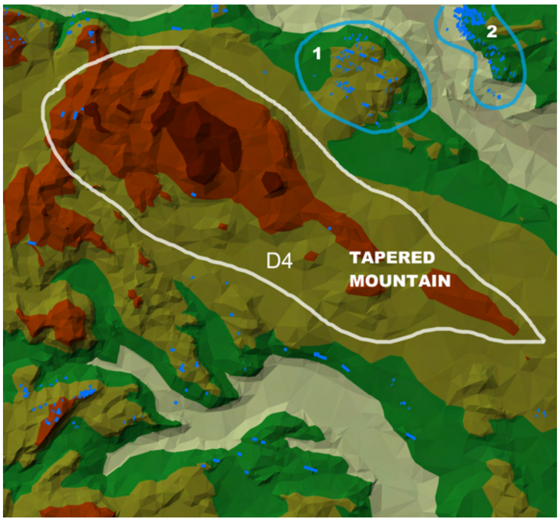


Fig. 41: D4 segment with charted glacial lineations (blue). The boundary of a tapered mountain (white) as well as the 1st and 2nd clusters (1) & (2).

Topographically, the D4 segment exhibits similarities to the topography of the previously mentioned D2 segment. For example, the D4 segment exhibits areas where lineations are more prevalent as well as a mountainous area that is void of lineations. The first quadrant of the D4 segment is similar to the third quadrant of the D2 segment - At this location, the majority of the D4 segment's lineations can be found. These lineations are located north-east of a teardrop shaped mountain which can be found spanning the area horizontally across the middle of the segment towards the ESE direction (approximately 110 degrees). The lineations of the first quadrant can be divided into two clusters which are separated from each other by a shallow valley spanning around 3000 meters. The first cluster is located closest to the mountain at approximately 2000 meters. The second cluster of lineations is located across a valley on the face of an inclining slope.

When consideration is given to the shape of the tapered mountain (Fig. 41), it is possible to estimate that previous periods of glaciation have through time exerted a net erosive force originating from the WNW- to ESE direction. Interestingly, the tapered mountain does not contain profound evidence that could support such an assumption, such as evidence in the form of glacial lineations simply since the mountain does not exhibit many lineations on its mountain face. Therefore, to acquire insight concerning the history of this location consideration can be given to the orientation of lineations in the first cluster of lineations (*marked as 1 in Figure 41*). The lineations of the first cluster are oriented perpendicular to the slope of the tapered mountain in the bearing of approximately 106 - 128 degrees. Due to the amount of lineations contained within this cluster (116), it is possible to assume that the D4 segment has once seen glacial movement related to the valley in between the 1st and 2nd cluster of lineations in the D4 segment's first quadrant.

Glacial Sculpting

The tapered mountain of the D4 segment exhibits near zero charted lineations. This observation is prominent as it allows us to explore a possible function of mountains in relation to glaciers during previous periods of glaciation - that under the correct circumstances such as being in the open, mountains might have the capability to serve a modulatory role related to the inhibition of the processes related to glacial erosion and the formation of glacial lineations during times of glaciation.

Previous research such as the one conducted by Robl et. al. (2020) has through the analysis of 16 000 mountains discovered that glacial erosion in cold climates reduces the topographic load of mountain ranges and enables the growth of high mountain peaks. According to their study, the steepest mountains have been found in locations of higher altitudes, where glacial sculpting predominates.

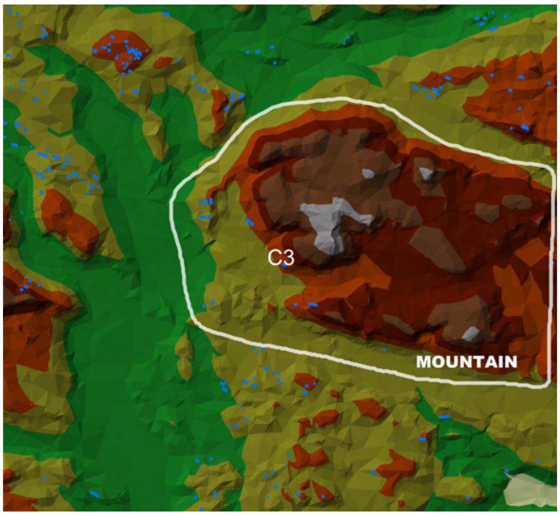


Fig. 42: C3 glacial lineations (blue). Boundary of a mountain (white).

From Figure 30, which contains the reconstruction of the ice margin, the known direction of ice margin deglaciation for the location of segments D2 and C3 is approximately ESE while the direction for D4 is approximately NE. Depending on the accuracy of the reconstruction, the average lineations throughout the study area should at least in part be assumed to align with the direction given by the reconstruction. Generally, this is correct throughout the extents of the segments with the exceptions of lineations found at locations where the topography could be believed to have altered the trajectory of a glacier.

The mountain of the C3 segment has approximately 12 charted glacial lineations. This number is insignificant compared to the segment's 183 total charted lineations but might be considered prominent when the lineations of the mountain's western face are inspected individually. The bearing given by the reconstruction of the ice margin is approximately 115 degrees whereas the bearing of the average lineation for the entire C3 segment is 151 degrees. It is true that some of the lineations of the mountain are oriented in the direction of the reconstruction as they are oriented in the bearing of approximately 120 degrees.

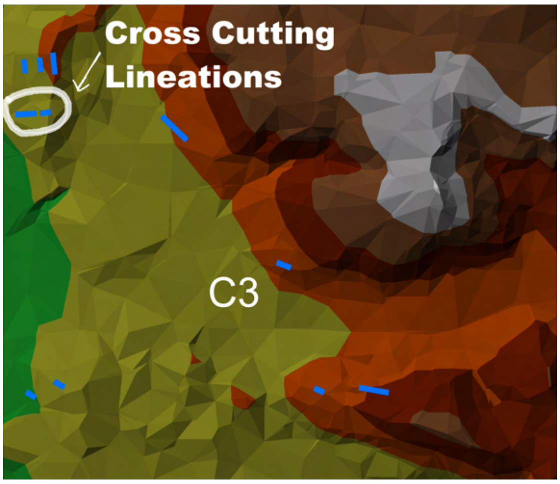


Fig. 43: C3 mountain with lineations (blue). Cross cutting lineations (white).

The orientation of the lineations at the mountain suggest that they could have been formed by a force that has over time been directed around the mountain as opposed to one that overcomes it. This is because it can be observed that the lineations that are closest to the mountain are also ones that are oriented perpendicular to the slope of the mountain. Despite this, outliers tell us that this does not always have to be the case. For example, two lineations in the upper portion of Fig. 43 can be seen to crosscut the other lineations by approximately 90 degrees. These two cross-cutting lineations are outliers as they lie immediately proximal to the lineations which are aligned perpendicular to the slope. A plausible explanation for this occurrence could be that the two crosscutting lineations could have formed during a previous period of glaciation in which glaciation occurred in the direction of the two cross cutting lineations.

"Anchoring" A Glacier To Mountain (Cold-based glacier)

The previously mentioned study conducted by Robl et. al. (2020) draws attention to glacial sculpting in the vicinity of steep mountains. Through considering the geometry of mountains and the surrounding valleys which exhibit a prevalence of a greater number of lineations, the movement of glaciers is influenced by the topography. Throughout the study area many landmarks of glacial erosion can be found, such as U-shaped valleys. Depending on the orientation of all valleys in relation to the overall slope of the study area, over time, glacial erosion can be observed to be incapable of eroding the landscape evenly. The mountains of the study area are evidence of this uneven erosion. Even though glacial sculpting affects the landscape immediately related to steep mountains, such as the mountains of the D2 segment (show below). There should exist a mechanism where the steep mountains are further protected from the destructive forces of glaciers as evident in part by the lack of charted lineations and intact mountainous topography. Such a mechanism would in part be related to cold based glaciers but would rather be described by the overall shape of the underlying topography.

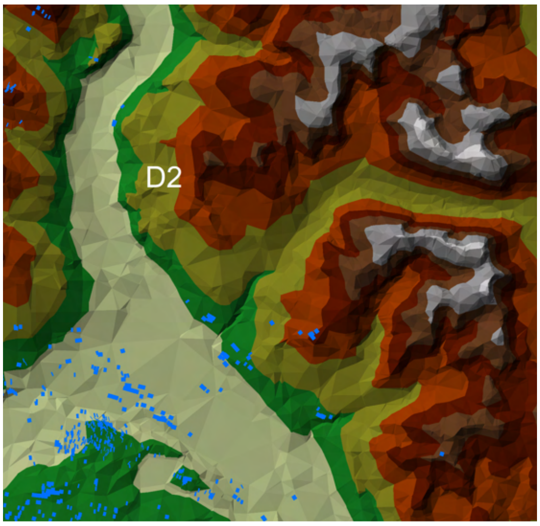


Fig. 44: Zoomed in view of the mountains found at the location of D2.

Depending on the thickness of the ice, mountainous areas, such as the one present in the D2 segment provide the ice with additional points of contact due to the increased surface area exhibited by the troughs and crests of the mountains. This causes a degree of interlocking between the topography and the overlying ice and decreases the probability of movement by anchoring the ice to the contours of the mountains. Cold-based conditions could therefore be thought to exist at select locations throughout the study area and would be a plausible explanation for the lack of lineations at these locations. In addition to this, these conditions would also be a plausible reason for the preservation of the mountainous landscape.

Lineations at sloping passages between mountains

Similar to the mountainous D2 segment and the "tapered-mountain" D4 segment, segments C1, E1 and F2 have lineations that can be found to be prevalent at locations related to sloping passages. At these locations, ice flow traffic has presumably been substantial or the lineations could have formed due to a favorable orientation of the underlying bedrock.

Lineations In Relation to The Reconstruction of The Ice Margin

The slope gradient trends towards the SE for the western segments whereas the slope gradient for the eastern segments trends increasingly towards the E. When the slope is compared to the bearing of the lineations (Fig. 29), it can be observed that the lineations are predominantly oriented in line with the slope of the study area. When we now consider the reconstruction of the ice margin, a similar trend can be observed for the western parts of the study area where the reconstruction follows the slope up to the C3 and E3 segments. As the study area transitions into the boundary of segments D4 and F4, the reconstruction indicates that the ice margin turns from the overall southeastern bearing to retreat towards the north (Fig. 29). From the lineations present at the first quadrant of the D4 segment above the tapered mountain, we know that the lineations clusters are almost perfectly perpendicular to the reconstruction of the ice margin deglaciation. For the particular location of the D4 segment, the lineations have been charted in the bearing of approximately 95 – 130 degrees. From the reconstruction, the corresponding bearing is 30 degrees. Glacial lineations are formed in the direction of ice flow, opposite to the direction of ice margin retreat. Throughout the study area, the topographic slope is often opposite to the direction of ice flow. Although it might be perceived as counterintuitive at first, that the direction of ice flow would be against the slope, it is important to remember that the location of the study area lies to the west of the ice divide (Fig. 1). In terms of the ice divide, the ice sheet would melt towards the center of the ice divide while the ice flows in the opposite direction. In terms of the study area, the direction of ice flow during a time of deglaciation could therefore plausibly be orientated against the slope gradient of the study area. Whether the slope gradient has a direct effect on the ice flow for an ice sheath is unclear but might be of importance related to deglaciation and the shape of the post glacial landscape.

When we consider the reconstruction of the location of the ice margin, we can see that the reconstruction is at least partially based on a local topographic factor that is related to the aspect. For example, at the location of the D4 segment, a variability of around 30 degrees has been observed at a marker interval of approximately 1000 meters. Considering that the reconstruction spans the entire extent of Scandinavia including the Baltic Sea, the small differences that are observed at the scale of the segments might be insignificant. However, as we do not truly know the accuracy of the reconstruction, small local scale factors that have been omitted from the model might prove to be problematic in sensitive areas such as the one present between the study area's mountainous west and the flatter east.

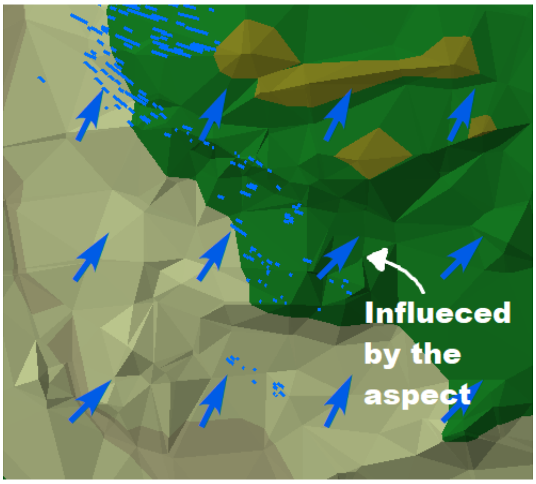


Fig. 45: At the location of D4, a topographic variability has been observed related to the ice margin reconstruction.

Referring back, to contrast the 90 degrees of non-alignment between the lineations and the reconstruction found at the location of D4, a closer look can be given to the F6 segment that can be found at the eastern end of the study area. The reconstruction of the ice margin at the location of the F6 segment is orientated in the bearing range of 280 to 359 degrees. Throughout this location, the 114 lineations have been charted inversely in a mean bearing of 123 degrees. Due to the fact that all lineations have been charted from the west to the east, lineations found in the F6 segment have most probably been charted incorrectly in a direction that is inverted in relation to the supposed real-life direction of the lineations. Through 'flipping' the direction of the lineations at F6, a corrected mean bearing of 246 degrees could be achieved. For 16 out of the segments 114 total lineations, a comparison against the reconstruction of the ice margin allows these lineations to align with the direction given by the reconstruction. Strikingly, when the reconstruction is read for the E5 segment located immediately NW of the F6 segment, the direction of reconstruction is found to have now shifted by approximately 90 degrees to the bearing of 00 – 40 degrees. Lineations found throughout the location of the E5 segment are similar to the lineations of the D4 segment in that they are perpendicular to the direction given by the reconstruction. As deglaciation is affected by temperature, naturally, the reconstruction could be expected to point towards the middle of the ice mass that was once located northeast of the study area (Kleman et. al. 2008). In fact, the reconstruction does this, however, the higher elevations of the study area's western segments should have a lower temperature than the flatter segments of the east and should because of this contain the ice for a longer period of time thereby shifting the direction of deglaciation somewhat towards the northwest. As the reconstruction is partially based on assumptions, this might perhaps be what we are observing at the F6 segment where the bearing of deglaciation is 280 – 359 degrees.

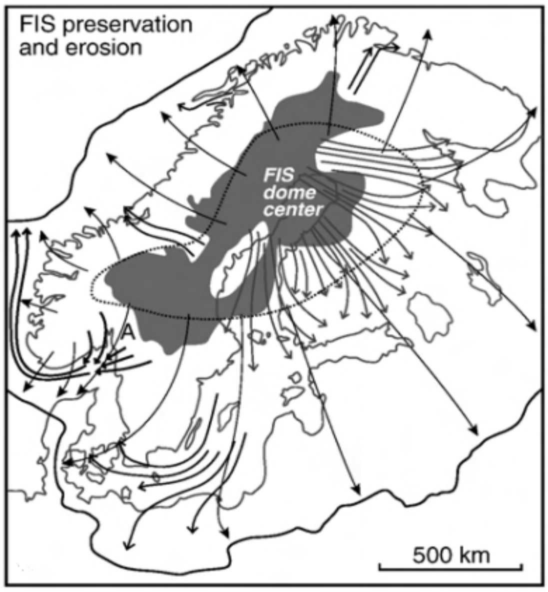


Fig. 46: Center of the FIS (FIS dome center) as shown in Kleman et. al (2008).

Cross Cutting Lineations

Since the mean lineation orientation of the study area is approximately 110 degrees, the prevalence of cross cutting lineations could hint that lineations have been formed by glaciation events different than the one related to the last period of glaciation. Segments which have cross cutting lineations are segments C5, E3 and F2. These segments have 61, 731 and 300 lineations respectively. The C5 segment has 61 lineations. The low lineation count of the segment is the reason for the apparent high variability in the bearing range of Figure 17 as a group of 5 lineations is located in a bearing of approximately 170 degrees. As the bulk of the lineations for the C5 segment are located in the bearing of approximately 100 – 120 degrees, the outliers could be lineations from a different period of glaciation. The E3 segment has a flat, low lying topography in the west which transitions into a choppy mountain range in the first quadrant and fully intact mountains in the second quadrant.

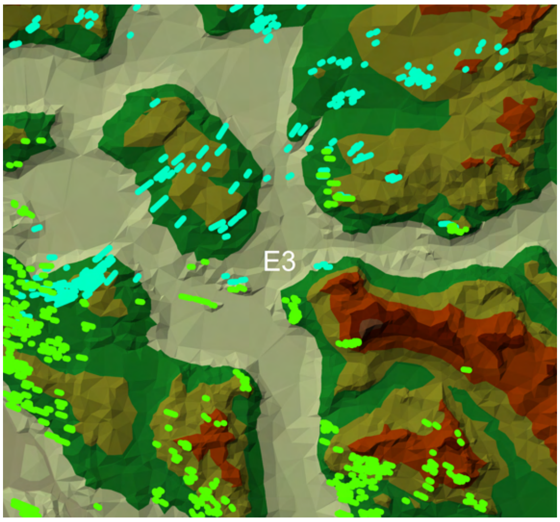


Fig. 47: Green lineations are in the bearing of 30 – 90 deg while blue lineations are in the bearing of 90 – 140 deg.

In this lineation rich segment, lineations are primarily located on areas of land which are located at an elevation range of approximately 500 – 750 meters. The E3 segment has lineations in a primary orientation of approximately 110 degrees and a secondary orientation group in which the lineations have a mean bearing of 60 degrees. The bulk of the primary lineations have probably formed as a result of ice flow towards the western neighboring segments, namely D2, E1 and F2 (together with the surrounded western uncharted segment). The secondary lineation range was either formed during previous periods of glaciation or from glacial drift originating from its northern unmapped segment. This northern unmapped segment slopes towards the SW – SSW and could describe why there are groups of lineations in the cross cutting secondary bearing of 60 degrees (or 240 degrees if they were inverted) as the lineations from both the primary group and the secondary group clearly overlap. Whether the primary and the secondary lineations have formed during a common period of time cannot be answered surely but should be kept in consideration. By continuing to the third segment, the F2 segment has a geology reminiscent of the C5 segment in that the geology of this segment has a flat sloping topography. The F2 segment is located at an altitude of approximately 570 – 750 meters. The lineations of the bottommost F2 segment are located along a primary orientation of approximately 110 degrees and secondary lineations orientated in a bearing of 45 degrees. The flat topography of the F2 segment gradually slopes towards the NE and SE directions.

To determine if any relationships exist between the lengths of the lineations, bearing, count and the segments, all lineations have been grouped into three elevation groups. These groups consisted of lineations that are shorter than 650 meters, between 650 to 1000 meters and finally, lineations that were longer than 1000 meters. The segments were then compared to the lineation bearing in Figure 34. From the figure, it was discovered that there is a 7.25-degree difference between the lineations that were located at elevations shorter than 650 m and the lineations that fell into the elevation range of 650 – 1000 m. The lineations that were located higher than 1000 m differed by 50.83 degrees compared to the lineations that were found at elevations smaller than 650 m and 45.58 degrees with the intermittent group. With the exception of segments D2 and E3, lineations that were located at elevations in excess of 1000 m did not exceed the count of 25 lineations per segment. For the D2 and E3 segments, the count of lineations located at elevations in excess of 1000 m is 102 and 45 lineations respectively. The D2 segment is mountainous - This implies that the bulk of the elevations have a higher probability of being located in the higher elevations. The E3 segment has less surface area at the elevation of 1000 m and has consequently fewer lineations in that elevation range. The difference in bearing between the lineations in the different elevation classes suggest that the ice flow follows the topography for the lower lying lineations. Because the higher lying lineations are located higher up when compared to the lineations in valleys, lineations found at higher elevations might give us a truer picture of the original direction of ice flow prior to the change of direction brought about by topography. This might allow lineations that are located higher in the topography to serve as markers for the overall direction of ice flow. Since a comprehensive analysis has not been done for the data in which the lineations were sorted into groups based on elevation, it has not been determined if the results in Figure 34 and Figure 35 are correlated. Results from Figure 31, which show the length of lineations potted against the elevation of the lineations showed that there was no correlation (r^2=0) between the length of a lineation and its elevation above sea level. Similarly, results from Figure 33 indicate that there is no overall correlation between the lineation bearing and lineation height above sea level (r^2=0.004). However, for

Figures 31 and 33 the lineations have not been grouped into groups by elevation like they have been done for Figures 34 and 35.

Charting the area by segments

The decision to chart individual segments as opposed to charting the entirety of the 150 x 100 area of Västerbotten county was done with the intention of maximizing the chartable area in the least amount of time. After charting the first segments, it has been observed that it is possible to observe an overall trend. Charting the entire area would therefore not necessarily benefit the purpose of the study as it would come with an exaggerated expense of time.

CONCLUSION

The location of the study area is geologically unique due to the fact that it lies close to Scandinavia's glaciation center. Glaciers have historically had their origins in the highest part of the Scandies where they exponentially grew and expanded into the western laying study area as well as parts of Europe (Kleman et. al. 2008).

The 4375 charted lineations have been used to create maps showing the distribution of lineations throughout the study area in relation to the topography. The lineations have also been used in the comparison with a reconstruction showing the direction of deglaciation for the ice margin.

Key takeaways related to the catalog of charted lineations is that the lineations are on average 118 meters long and are oriented in an average bearing of 110 degrees. Throughout the landscape, the majority of lineations (56%) can be found in the elevation range between 650 to 1000 meters.

Lineations are more common in the western mountainous part of the study area compared to the eastern region where the topography is flatter. Although a positive correlation has been discovered for lineations and the topographic relief related to minimum and maximum buffer elevations r-values 0.466 and 0.647 respectively, individual mountainous segments have been found to have severely overinflated lineation counts. Upon analyzing the individual topography of these mountainous regions, it could be determined that the lineations are not immediately related to the high relief and high elevation regions of the mountains but are instead related to the proximal extents of those regions. These proximal extents are oftentimes sloping and are suspected to have favorable bedrock conditions that could favor the formation of glacial lineations.

When the charted lineations were compared to the reconstructed deglaciation of the ice margin, it was noted that lineations of the western part of the study area aligned with reconstruction in an overall eastern orientation and an approximate 50 degree margin of error. When the topography shifts towards the east, the reconstruction changes direction towards the north. Lineations that were found at the eastern side of the study area expressed a greater degree of disagreement between their bearing and the bearing of the reconstruction.

Individual charted lineations have been found perpendicular to the slopes of mountains, along valleys and in between sloping passages. Through this, it is possible to assume that topography might play a greater role in the formation of glacial lineations than the direction of deglaciation. At the locations where the lineations deviate from the orientation of the topography, the disparity in orientation suggests that the lineations have their origin in a period of glaciation not related to the last glacial period.

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