GEO-3900
Master's Thesis in Geology

Moraine chronology and deglaciation of the northern Lyngen Peninsula, Troms, Norway

David Greig

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Abstract

The northern Lyngen Peninsula in Troms, northern Norway, displays a suite of glacial and periglacial landforms that describe both a complex interaction of geomorphological processes and its history of deglaciation during the Late Weichselian and Holocene. These features include: cirque and valley glacier moraines, relict ice-cored moraines, rock avalanches, rock glaciers, a protalus rampart, and other talus-derived landforms.

Morphological relationships of landforms within the three valleys of Strupskardet, Veidalen and Reindalen were studied in detail; using a combination of geographic information systems (GIS), aerial photograph interpretation, and field research. Seven distinctive glacial stages (comprised of up to 13 minor phases) were identified, and presented as a series of maps that describe the chronology of deglaciation within the study area.

Relative-age dating of moraines was performed with a Schmidt hammer, which measured the rebound value (R-value) from boulder surfaces. This technique was found to be an effective tool that offered additional insight into the age of moraines and other landforms. Equilibrium line altitudes (ELA) were also calculated for reconstructed ice limits to elucidate the effects of local topography and regional climatic conditions on glacier formation.

Acknowledgements

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1 Introduction

1.1 Northern Lyngen Peninsula

"Straight below us lay the tranquil blue waters of the Jaegervand. The sea beyond, studded with islands, shimmered in the brilliant light of a perfect summer's day. Beyond the Kjosenfjord, spotless robes of snow covered the mountains. Glaciers with green rifts in their waves of ice swept majestically between the peaks, which stood like cathedral spires to the north. Tiny lakes looked up at us with wide-open sapphire eyes from every little hollow. Clouds drifted lazily here and there, casting deep purple shadows on the hillsides. Not a sound fell on the ear. We seemed detached from the earth." (LeBlond, 1908).

The Lyngen Peninsula is one of northern Norway's most outstanding mountain areas, renowned for its peaks, glaciers and alpine landforms created by a unique history of geological and glacial processes during the Quaternary. The geological, biological, historical and cultural significance of Lyngen has contributed to 96% of its total area being classified as a natural reserve and protected from further influence or development (Jacobsen, 2001).

Lyngen is located in northern Troms approximately 50 kilometres from Tromsø (Figure 1.1.1), and is dominated by the Lyngen Alps (Lyngsalpene); a chain of mountains 20 km wide that runs north-south along its 90 km length. The peninsula (Lyngenhalvøya) is surrounded on its western and eastern coasts by Ullsfjord and Lyngenfjord, and is bisected neatly (but not completely) into northern and southern components by the deep inlet of Kjosen. The total area of northern Lyngen Peninsula is 614 km^2, of which glaciers presently cover 47.26 km^2.

Glacial and periglacial processes have left Lyngsalpene with a dramatic range of mountains decorated with turquoise glacial lakes, talus, steeply eroded cirque headwalls, rock avalanches, rock glaciers, relict ice-cored moraines and other moraines deposited as recently as the Little Ice Age. These natural features have made Lyngen an increasingly attractive destination for tourism, skiing and alpine climbing since the late 19th century, when attention was brought to them by European mountaineers, including Elizabeth Main (Mrs. Le Blond) (Gellatly et al., 1986; Jacobsen, 2001; Ryvarden and Wold, 1991). Prior to this, the steep mountain areas were treated warily by local people, who generally lived by hunting and fishing along the fjords. The commercial export of ice, however, was attempted at Strupen beside Lyngenfjord, where fragments of the glacier tongue where collected from below the icefall and transported by rail to the coast (Ryvarden and Wold, 1991).

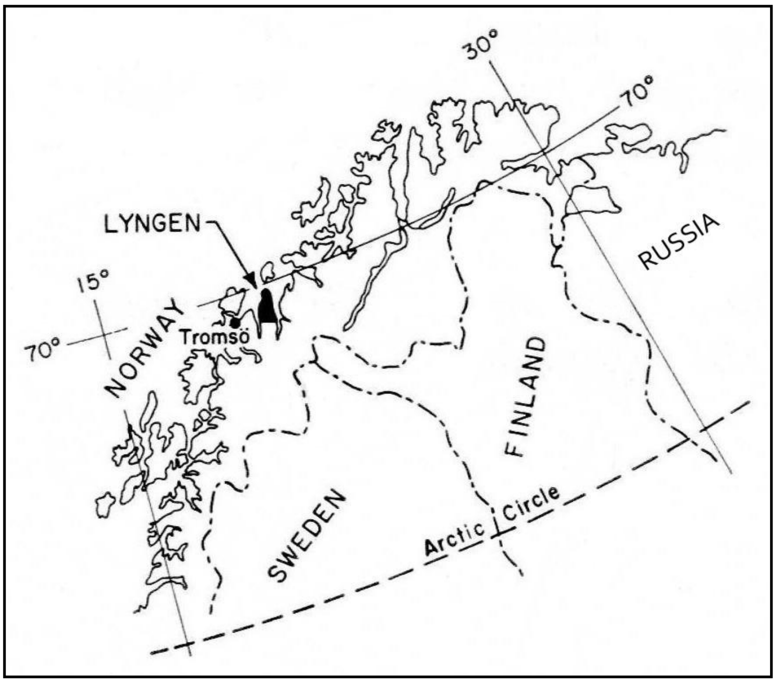


Figure 1.1.1. Location map of the Lyngen Peninsula, Troms (Munday, 1974).

1.2 Aims and objectives

There are five primary aims to this study.

The first aim is to comprehensively map all moraines of the northern Lyngen Peninsula that were deposited during the retreat of Late Weichselian and Holocene glaciers. This includes: analyses of digital maps within a geographic information system (GIS) database, aerial photograph interpretation, and field research.

The second aim is to perform a detailed study of moraines and other landforms within a study area encompassing three adjacent valleys, so as to better understand the geomorphological processes that have shaped the northern Lyngen peninsula on a broader scale. The three valleys: Strupskardet, Veidalen and Reindalen, were selected for their similarities in geology (Lyngen gabbro), alignment (northwest–southeast), aspect of slopes (to prevailing weather conditions), and presence of glaciers.

The third aim is an assessment of the Schmidt hammer as a relative-age dating tool to measure weathering of moraine boulders, which may be correlated other qualities of the moraines, such as clast lithology, sorting, and roundness, as well as a comparison to previous research that has been applied to landforms in Lyngen.

The forth aim is to reconstruct equilibrium line altitudes (ELAs) of former glaciers within the study area to evaluate historical climatic conditions of Lyngen. ELAs indicate a glacier's response to climate change, and allow for reconstruction of paleo-climates and an understanding of glacier behaviour.

The fifth aim is to attempt to interpret the sequence of deglaciation and relative timing of events that led to the shaping of the Lyngen Peninsula, based upon the correlation and morphological relationships between moraines and other landforms. This could provide a a useful foundation upon which to build future research in this area. An important result envisaged was the production of a series of maps that display the sequence of phases of glacial retreat in northern Lyngen.

1.3 Climate

Climatic data is available from several meteorological stations surrounding the Lyngen Peninsula, with the closest located at Nord Lenangen (station number 91190), 15 kilometres north of the study area (Meteorologisk_institutt, 2010). At this station, July is recorded as the warmest month with an average maximum temperature of 11.4° C, while May is the driest with mean rainfall of 50mm. January is recorded as the coldest month with an average minimum of -4°C, while the wettest month is October with mean rainfall of 123mm. The average annual temperature and precipitation at Nord Lenangen is 2.8°C and 950mm (Figure 1.3.1).

Precipitation is generally supplied from offshore and transported by prevailing westerly and southwesterly winds (Bakke et al., 2005; Østrem et al., 1973). This weather pattern is reflected in Lyngen by the orientation of the accumulation area of cirques and snowfences (mountain ridges aligned transverse to wind and precipitation) identified by Østrem et al. (1973).

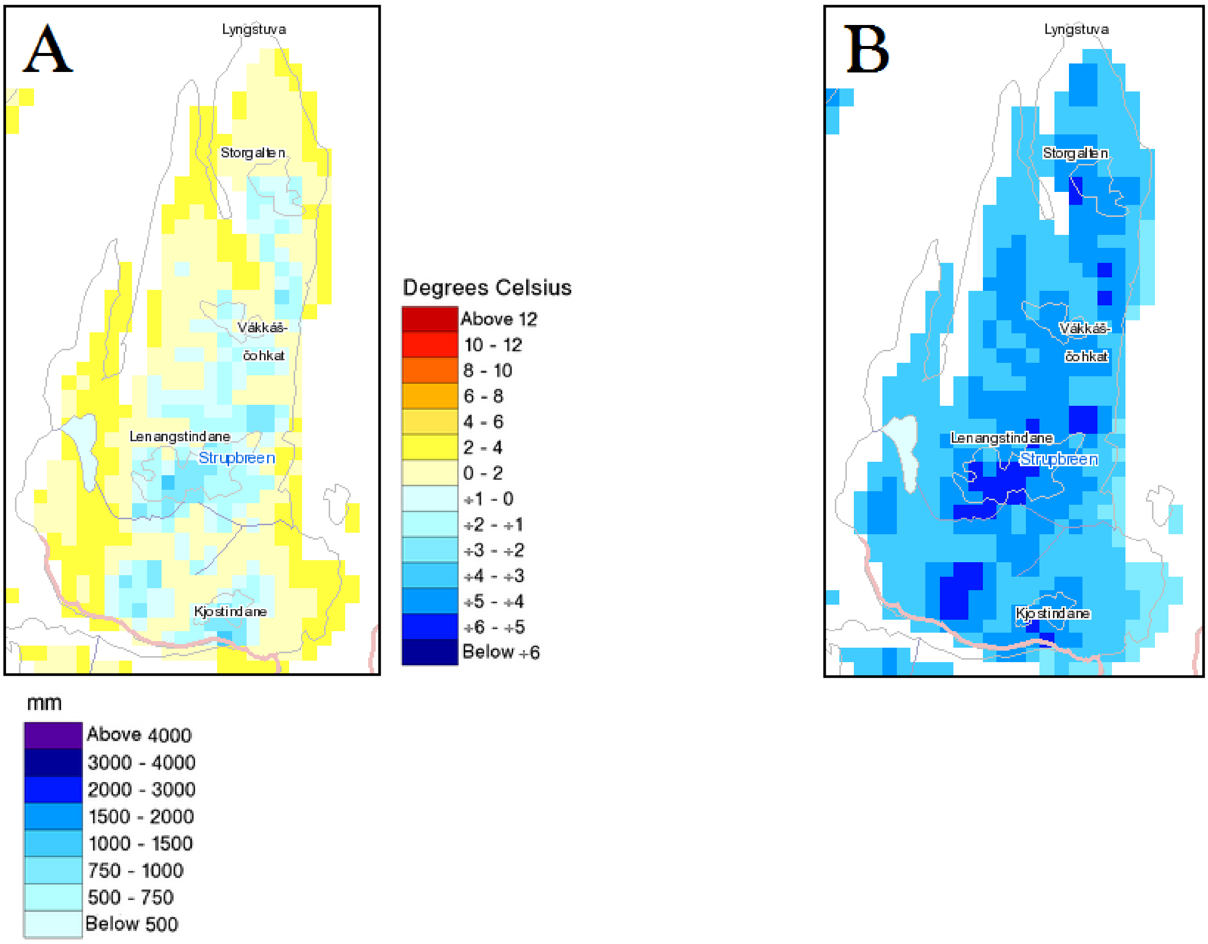


Figure 1.3.1. A: Annual average temperature in Lyngen (seNorge.no, 2010). B: Annual average precipitation in Lyngen (seNorge.no, 2010). Nord Lenangen meteorological station is located directly west of Storgalten.

1.4 **Geology**

The bedrock of the Lyngen peninsula was formed during the Caledonian orogeny when the Baltic continental plate (of Europe/Scandinavia) collided with the Laurentian plate (Greenland/North America) between the early Silurian and the early Devonian 430-380 million years before present (Bøe, 2001). Prior to this event (during the Ordovician or Cambrian 570-480 million BP), these plates were separated by the ancient Iapetus Ocean and an arc of volcanic eruptions beyond the edge of the Baltic plate led to the ejection of magma through the lithosphere, where it quickly cooled as pillow lava on the marine floor (Bøe, 2001; Dahl and Sveian, 2004). As the two continents converged, the Baltic plate was subducted beneath the Laurentian plate and the volcanic material was forced as deep as 100 km beneath the crust where it experienced intense folding and deformation, while the Caledonian mountain range was built several thousand meters above the surface.

Constant erosion has left only remnants on both sides of the Atlantic, but the mountains of Lyngen comprise the largest fragment of early volcanism in Norway, where stretched and flattened pillow lava can still be seen (Dahl and Sveian, 2004). The Lyngen Peninsula is dominated by a gabbro and metagabbro lithology (Bøe, 2001) comprised of light-coloured plagioclase and dark pyroxene and amphibole (Figure 1.4.1). Gabbro is hard and resistant to mechanical weathering, which provides Lyngen with its high and sharp jagged mountains, while the surrounding, softer rock types have been more easily eroded (Dahl and Sveian, 2004).

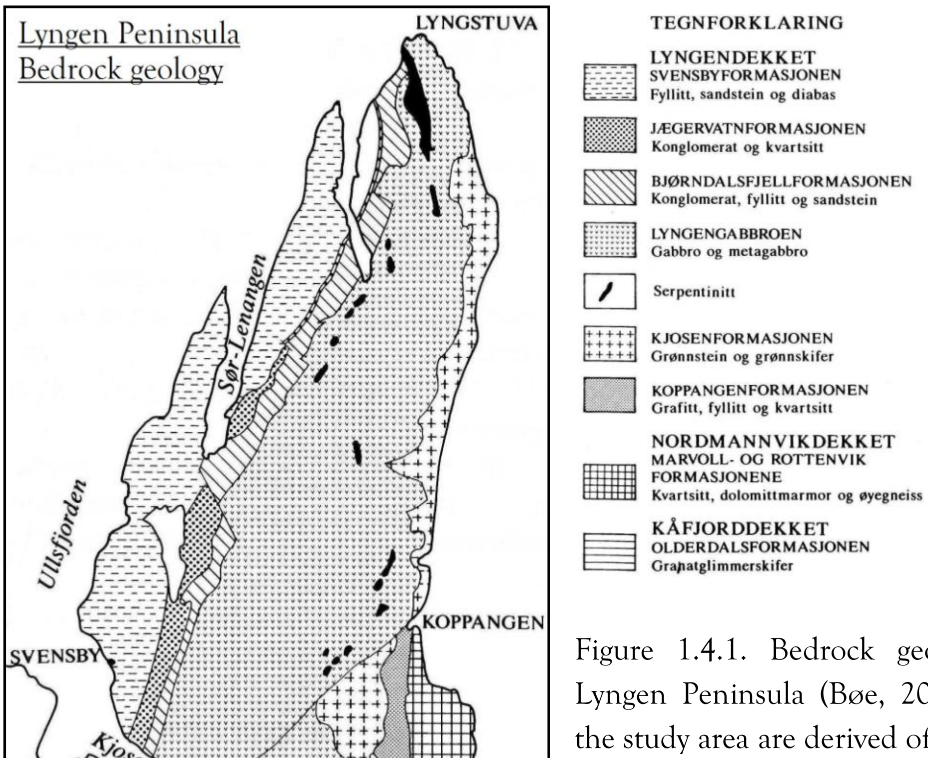


Figure 1.4.1. Bedrock geological map of the Lyngen Peninsula (Bøe, 2001). Moraines within the study area are derived of material eroded from the gabbro bedrock (Lyngengabbroen).

2 Methodology

2.1 Geographic information systems, photogrammetry and field research

Investigations into past glacial events require a combination of indirect and direct methods, such as the analysis of maps, aerial photographs and previous research, and subsequent fieldwork and reconnaissance of areas of interest. Preliminary maps were created using the geographic information system (GIS) program ArcMap (ESRI, 2009a), and used in conjunction with the study of aerial photographs (photogrammetry), so as to direct field research and data collection.

Data and images from previous studies were compiled in an ArcMap GIS project, including:
- Digital topographic map data of Troms: Kartdata 1:50 000 (Statens_kartverk, 2009)
- Digital economic map data of Lyngen: Kartdata 1:5 000 (Statens_kartverk, 2009)
- Digital Quaternary map of surficial deposits in Troms: løsmassekart (NGU, 2009)
- High resolution (1m) orthorectified satellite photos: GeoTIFF images (Norge-i-bilder, 2010)
- Panchromatic 1:30 000 aerial photographs (Fjellanger-Widerøe, 1977)
- A glacial-geomorphological map of Strupskardet, Lyngen (Bakke et al., 2005)
- A glacial map of central Troms (Dahl and Sveian, 2004)
- A glaciological map of Norway (Sollid and Torp, 1984)
- A digital elevation model (DEM) of Troms (Hansen, 2009)

The surficial deposits map (løsmassekart) is an assemblage of many geological deposition features combined into a single layer (Figure 2.1.1) (glossary in appendix 6.1). Using the Select by Attributes dialog in ArcGIS, individual features could be extracted and displayed as separate shapefiles, e.g. Randmorene (lateral and end moraines), Morenematriale (till), Skredmatriale (talus) etc. (details in Appendix 6.2).

Initial research included the compilation of existing geomorphological maps, so as to readily locate moraine positions across northern Lyngen. These were orthorectified and georeferenced within ArcMap to the digital base maps, using a UTM projection of WGS 1984 (Zone 33N); and included: the glacial map of central Troms (Dahl and Sveian, 2004), the glacial-geomorphological map of Strupskardet, Lyngen (Bakke et al., 2005) and the glaciological map of Norway (Sollid and Torp, 1984).

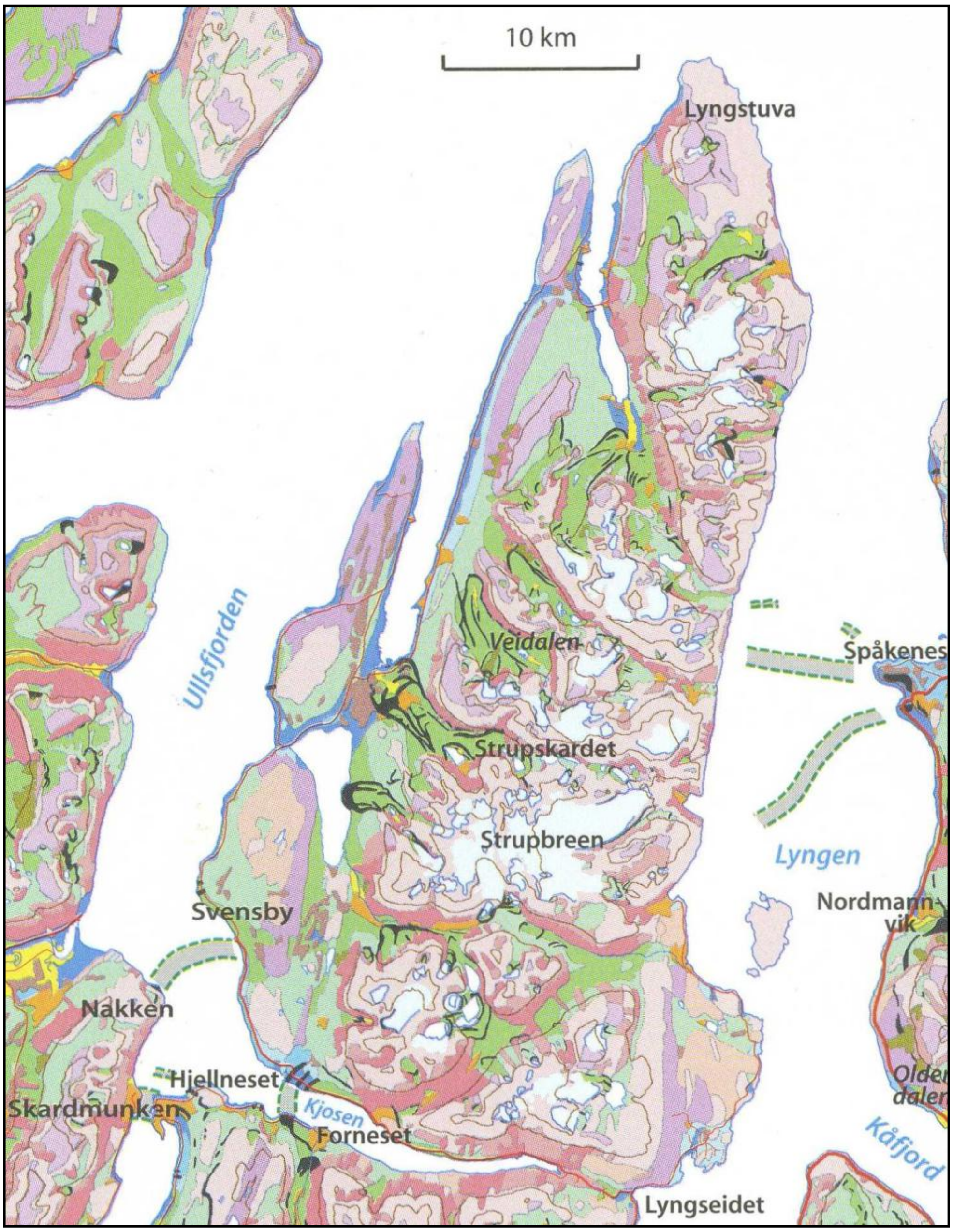


Figure 2.1.1. Losmassekart (Quaternary map of surface deposits) of the northern Lyngen Peninsula (Dahl and Sveian, 2004; NGU, 2009), displaying lateral and end moraines (black), till covered surfaces (green), talus (dark pink) and glaciers (white) etc.. Former positions of the glacier fronts have been mapped in Ullsfjorden and Lyngenfjord for the Skarpnes Event (near Svensby) and the Tromsø-Lyngen Event (Spåkenes and Kjosen) (Dahl and Sveian, 2004).

The panchromatic aerial photographs were also orthorectified and georeferenced, but this time-consuming exercise was eventually abandoned following the acquisition of more accurate, coloured orthophotos (GeoTIFFs) provided by Norge-i-bilder (2010). These images display a high resolution (1m) of satellite photos that have been georeferenced as a single orthophoto mosaic. GeoTIFFs covering northern Lyngen could be selected using parameters within the export module dialogue box of Norge-i-bilder (2010) (details in Appendix 6.3) and imported into ArcMap.

Stereoscopic analysis of the aerial photographs was undertaken to discern changes in tone, texture, and slope of the terrain so as to permit moraines and other landforms to be recognised, including features that might not otherwise be noticed in the field (Chinn, 1979; Graf, 1971). Three-dimensional presentation of the aerial photos through the stereoscope allowed the moraines to be viewed in a morphostratigraphic context, which assisted in understanding the processes that emplaced them. All discernable moraines on the northern Lyngen Peninsula were then digitised (digitally mapped) in ArcMap with a Polyline (shapefile) at a scale of 1:10000. Landforms within the valleys of Strupskadet, Veidalen and Reindalen were digitised at 1:5000.

To accurately locate moraines and other features in the field from the preliminary mapping, a Point shapefile was created and new points were quickly digitised onto the vertices at the extremities of each moraine using the Snap To Feature command. New fields (X,Y) were added to the Attributes Table, and the Calculate Geometry dialogue then allowed the X and Y coordinate of each point to be extracted. These X,Y coordinates could be uploaded to a global positioning system (GPS) or printed out for re-entry in the field. To efficiently conduct fieldwork, the GPS was used to accurately pinpoint (±4m) the limbs of moraines within the three valleys. GPS points were also recorded 'on site', which could later be uploaded to ArcMap and allow for future replication of Schmidt hammer exercises. To present GPS points as a Shapefile in ArcMap, tabular data was converted into a useable format within Microsoft Office Excel and imported into the GIS project (details in Appendix 6.4).

While the terms 'moraine' and 'crest' are used interchangeably in this study to refer to elongated, glacial landforms comprised of till; the expression: 'segments', is applied exclusively to specific lengths of moraines where Schmidt hammer tests and other measurements have been conducted. The moraine segments in Strupskardet, Veidalen and Reindalen were studied and mapped in detail and each has been identified with a combination of initials which indicate, respectively, its:
1) Valley: S=Strupskardet, V=Veidalen, R=Reindalen.
2) Sequence of deposition: based on morphological relationships: 1, 2, 3, 4 etc.
3) Individual section or subdivision: N=north, S=south, and/or a, b, c, d, etc; of which no particular order is implied.

For example, 'S3Nb' represents a segment of a moraine in Strupskardet, from glacial phase 3, section north b. Other landforms have also been included, for example: a rock avalanche in Strupskardet (SRA), and the northern and southern components of a rock glacier in Veidalen (VRGN and VRGS). A bedrock control point from each valley, used in the Schmidt hammer analysis is indicated by the suffix: CTRL. When describing an entire group of segments or an individual phase, the first two letters only may be used in the text. For example: R3 represents all moraine segments belonging to phase 3 in Reindalen.

A total of 39 days fieldwork and reconnaissance were conducted during the summers of 2009/2010, including detailed mapping and field measurements of moraines in Strupskardet, Veidalen and Reindalen. Each moraine segment, as well as rock avalanches and rock glaciers, within the three valleys were studied for their morphological relationships, Schmidt hammer rebound values, and clast lithology, roundness, and sorting.

The roundness or angularity of clasts can be used to differentiate between the processes that emplaced them, and can therefore be used to determine their origin and time since deposition (Birkeland, 1982; Carroll, 1974). A spectrum of clast morphology can be divided into categories (Figure 2.1.2) (after Powers, 1953), and was compared with other results from moraine segments in northern Lyngen. Clast sorting was also determined (after Folk, 1968) for each depostional landform, to evaluate the history and processes of glacially transported material; although these results were not expected to influence or correlate with Schmidt hammer rebound values.

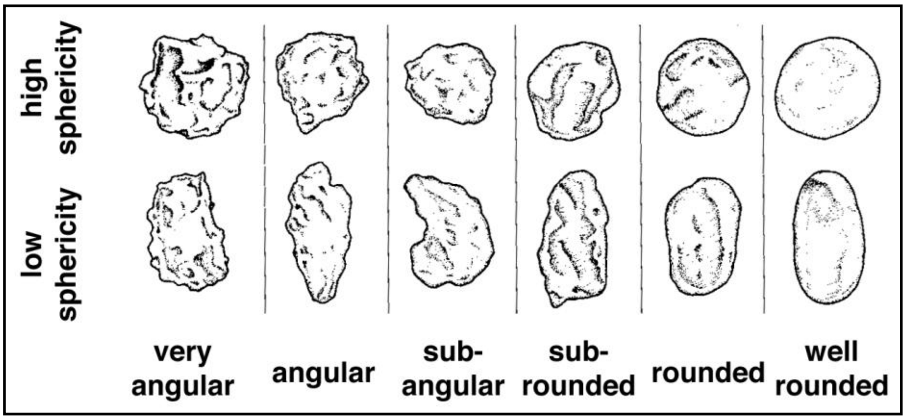


Figure 2.1.2. Powers roundness scale; used to determine modes of transport and time since emplacement (University_of_Saskatchewan, 2005).

Additional field reconnaissance was conducted in the following areas (Figure 2.1.3)
- Russelvdalen, Dalbruna, Russelvfjellvatnet, Lyngstuva, Kalddalen, Gammvikblåisen, Lillegalten, Lassofjellet.
- Nordlenangsbotn, Vassdalen, Raudtindalen, Stefjellblåisen, Bjørndalen.
- Jægervatnet, Kvitberget, Stortindalen, Storvatnet, Tytebærdalen.
- Coastlines of Lenangsåsen and Nordlenangsåsen.

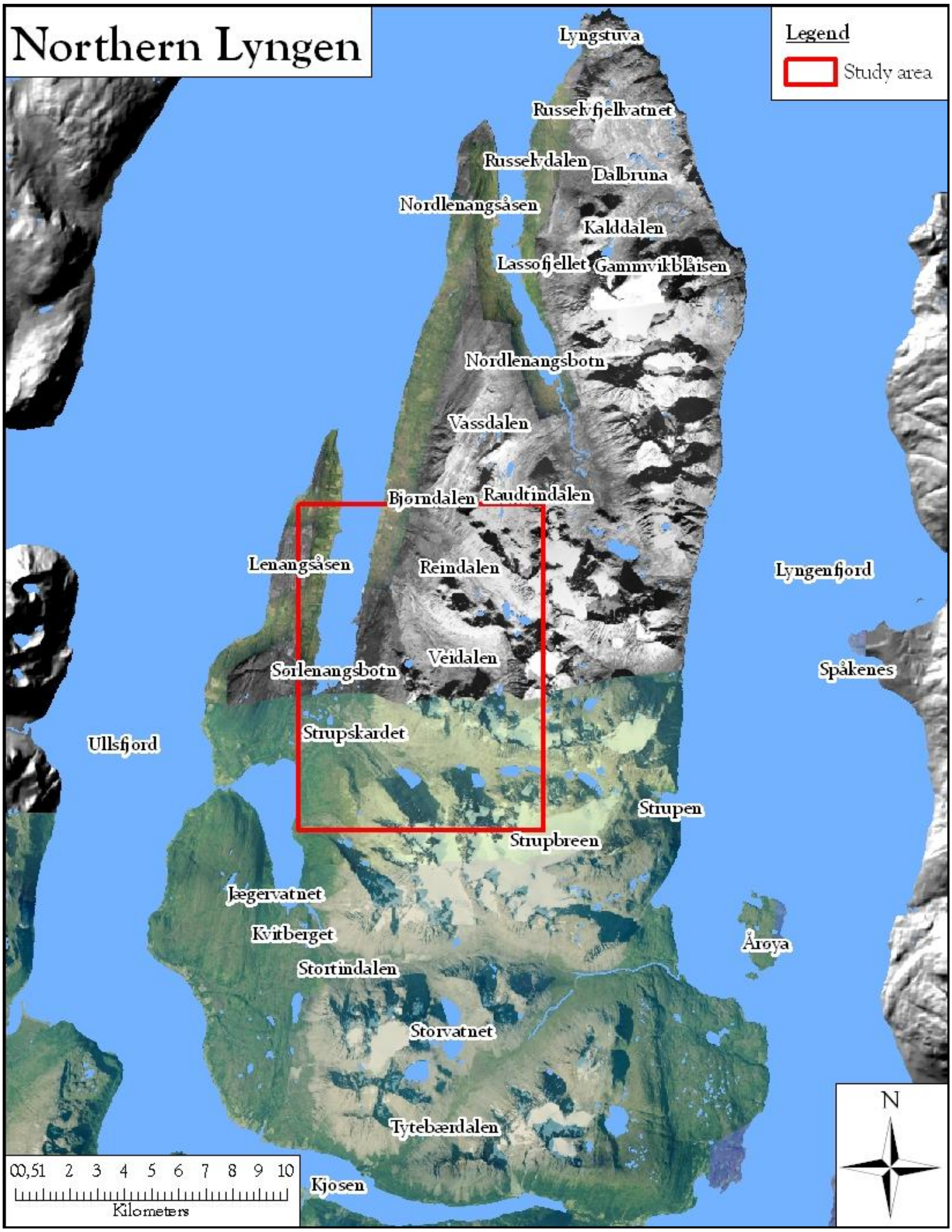


Figure 2.1.3. Study area (ca. 100 km^2), including Strupskardet, Veidalen and Reindalen, on the northern Lyngen Peninsula.

Final maps were created in ArcMap based on initial perceptions and ground-truthing of landforms during field reconnaissance. Recognition of on-ground logistical realities led to a subsequent reduction of the study area from original plans: from the entire northern Lyngen Peninsula (ca. 614 km^2) to a more manageable area covering the three adjacent valleys of Strupskardet, Veidalen and Reindalen (total ca. 100 km^2). The maps included moraines and landforms that had been observed on previous trips but not identified in preliminary mapping, and supplemented with regular aerial photograph interpretation. Each moraine was also tentatively allocated to a series of ice phases and movements of valley glaciers according to its morphological relationships with neighbouring features, which was then cross-checked during further field reconnaissance.

For final reconstruction of the ice limits for each glacial phase within each valley, a boundary was created from several digitised polyline shapefiles, ensuring that each line was 'snapped' (adjoined) to its neighbour. These were converted into a new polygon representing individual areas that had formerly been ice covered, using the Feature To Polygon tool (Arc Toolbox > Data Management Tools > Features > Feature To Polygon) and the following input features:
- cirques (the headwalls of former glaciers)
- segments (of moraines used in Schmidt hammer analyses)
- moraines (other crests and ridges)
- ice limits (assumed topographic positions of reconstructed glaciers).

From this combined polygon shapefile, individual features could be 'selected' and saved as a new shapefile (Selection > Create Layer From Selected Features) that encompassed the area covered by ice during a particular phase. As each new shapefile was comprised of several features, these had to be 'dissolved' into a single polygon. This operation was performed in a GIS extension program: ET GeoWizards (Tchoukanski, 2010), with the Dissolve Polygon Wizard tool that combined all features and attributes into one polygon representing the former ice limit of each phase.

Individual phases were then correlated between valleys, which were then combined into broader 'stages'. These are presented as a series of final maps, representing the sequence of glacier retreat within Strupskardet, Veidalen and Reindalen during the Late Weichselian and Holocene. All dates are presented in calibrated years BP.

2.2 Schmidt hammer rebound values

2.2.1 *Relative dating*

The Schmidt hammer is a light (1.7 kg), portable and robust instrument that records the rebound distance of a spring-loaded mass impacting upon a surface. The distance of rebound (the R-value) ranges from 10 to 100, and indicates the elastic properties of the surface and therefore its compressive strength (McCarroll and Nesje, 1993; Nesje et al., 1994). Originally it was designed for measuring the hardness of concrete, but has subsequently been used in geomorphology to determine the surface hardness of different rock types and the degree of rock-surface weathering (Ericson, 2004; McCarroll, 1989b; Nesje et al., 1994) (Figure 2.2.1.1).

The Schmidt hammer can therefore be used for the relative-age dating of moraines and other landforms, as rebound values are expected to reflect the time since deposition; i.e., fresh, recently exposed rock surfaces provide R-values that are higher than those that are older or more weathered (McCarroll, 1989b; Shakesby et al., 2004). However, the average R-values may be influenced by several factors other than the degree of boulder-surface weathering (McCarroll, 1989b), including:

- Number of impacts collected per landform, i.e., the sample design (McCarroll, 1989a).
- Angle of hammer impact (McCarroll and Nesje, 1993; Nesje et al., 1994; Proceq, 2009; Shakesby et al., 2006; Shakesby et al., 2004)
- Boulder size and stability within the substrate (Shakesby et al., 2006; Shakesby et al., 2004; Williams and Robinson, 1983; Winkler, 2000, 2005)
- Lithology (McCarroll, 1989a; Nesje et al., 1994; Winkler, 2005)
- Surface texture, i.e., boulder roundness and roughness (Ericson, 2004; McCarroll, 1989a)
- Lichen and moss (Aa et al., 2007; McCarroll, 1989a, b; Nesje et al., 1994; Rune and Sjåstad, 2000; Shakesby et al., 2006; Shakesby et al., 2004)
- Surface moisture (Proceq, 2009; Shakesby et al., 2006; Sumner and Nel, 2002; Williams and Robinson, 1983)
- Proximity to edges, cracks, weaknesses and quartz veins (McCarroll, 1989a; Shakesby et al., 2006; Williams and Robinson, 1983; Winkler, 2005)

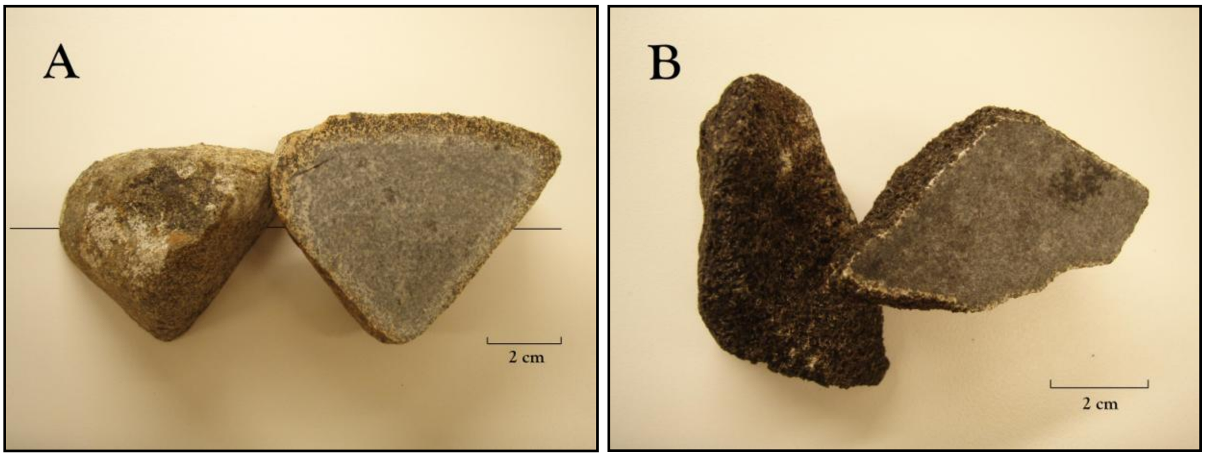


Figure 2.2.1.1. Surface weathering of clasts from the surface of moraines in Strupskardet.

(A) Typical example of Lyngen gabbro (rich in feldspar): collected from moraine segment S3Sb. A weathering rind is visible on the polished facet and indicates its *in situ* position, reflected by lichen growth on the upper surface (black line indicates burial depth). Most weathering has occurred on the top, and decreases towards the buried point.

(B) Sample of Lyngen gabbro (rich in hornblende) located on moraine segment SX. Weathering has led to the exposure of individual hornblende crystals which can be seen to stand out upon the clast surface.

2.2.2 *Schmidt hammer measurements*

The Schmidt hammer used in this study, a Model N Original Schmidt (Figure 2.2.2.1), manufactured by Proceq SA, Switzerland, applies a calibrated energy of 2.207 N·m (Newton metres) to the surface to which it is applied. Regular testing on a calibration anvil is recommended by Proceq (2009), but as this was not available a standard blacksmiths anvil was used. From this, an average R-value of 76.25 was obtained from tests performed before, during and after the field measurements, and which displayed no statistically significant change in variation during the course of research.

A total of 6800 impacts were recorded from 68 landforms within the study area: Strupskardet (31), Veidalen (23), and Reindalen (14). This included measurements from a control point above the highest moraine in each valley: a bedrock/rouche moutonée surface exposed most recently by the retreating glaciers/névés (Figure 2.2.2.2). Studies by previous researchers were used to define parameters for use of the Schmidt hammer during the course of fieldwork. These parameters included:

- A total of 100 Schmidt hammer measurements were collected from each landform: 4 impacts x 25 boulders
- R-values were recorded from the first, most suitable, 25 boulders encountered along the crest of the landform (usually over a distance of 300-1000 metres), and recently deposited material from rockfall or talus was avoided
- Vertical impacts were applied only to the horizontal surfaces of boulders
- Boulders were at least 0.5m in diameter and displayed no sign of instability within the substrate
- A uniform and dominant lithology of boulders were tested on each moraine
- Selected surfaces were clean and devoid of lichen and moss
- Surfaces were dry and had experienced several hours of sunshine or wind prior to testing; lichens that were cold or slimy indicate an insufficient drying time
- The edges of boulders were avoided by at least 5cm, as were cracks, weaknesses and quartz veins.

Figure 2.2.2.1. Proceq Schmidt hammer and ideal gabbro boulder.

Figure 2.2.2.2. Rouche moutonées below Lenangsbreen, Strupskardet; used as bedrock control points for Schmidt hammer measurements.

2.2.3 Statistical analysis of rebound values

Schmidt hammer R-values were statistically analysed to determine the significance of the results and possible age relationships that may exist between moraines within Strupskardet, Veidalen or Reindalen, as well as potential correlations across all three valleys. The results were intended to identify patterns that were not visible by casual observation, and to connect the relative ages of moraines to the sequence of deglaciation in Lyngen.

Determination of the average (mean) R-value and the 95% confidence interval (CI) for each moraine followed the statistical analysis of Schmidt hammer measurements used by previous authors (Aa et al., 2007; Matthews and Owen, 2010; Matthews and Winkler, 2010; McCarroll, 1991; Nesje et al., 1994; Owen et al., 2007; Shakesby et al., 2006; Shakesby et al., 2004; Winkler, 2000, 2005, 2009).

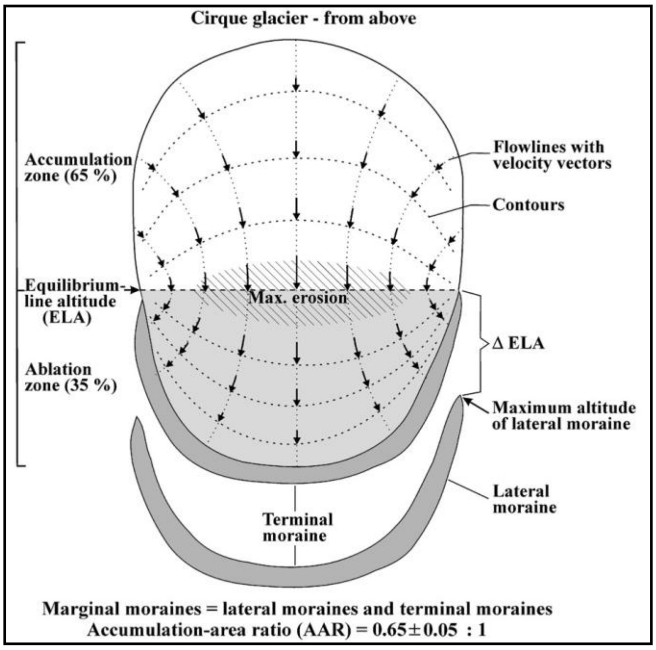
The 100 rebound values from each moraine were in general found to display a normal (Gaussian) distribution, where 95% of the measurements occur within two standard deviations from the mean (Walpole et al., 2002; Winkler, 2000). If the assumptions are correct (that the R-value has Gaussian distribution with the sample mean as mean), then there is a 95% chance that a random future observation mean will fall within the confidence intervals (Møllersen, 2010).

Behrens-Fisher's two-sample t-tests were performed on all possible combinations of moraine pairs within Strupskardet, Veidalen and Reindalen, as well as an inter-valley analysis (representing all 68 landforms). A two-sample t-test is used to determine if the data in the two groups are independent random samples from normal distributions with the same mean (with a significance level of 0.05) and the probability of incorrectly concluding that the samples come from distributions with unequal means when they in fact come from distributions with equal means (Møllersen, 2010).

A graph was produced for each valley to display the mean R-value and 95% CI of the mean for each moraine. If the 95% CI limit of one moraine overlaps the mean R-value of another, then the relationship between the two is considered to be statistically significant. On the graphs, a correlation between one moraine and its sequential neighbours is indicated by a series of numbers aligned beneath the 95% CI bar. For example, where a moraine displays the numbers 1,2,4,5 beneath its 95% CI bar, then a positive relationship has been identified between it and its first, second, fourth and fifth neighbours in succession (left to right). As the number '3' is absent from this sequence, a statistical relationship has not been found between this moraine and the third moraine to its right.

2.3 <u>Equilibrium Line Altitudes</u>

The equilibrium line altitude (ELA) represents the elevation of a glacier where accumulation is balanced by ablation (Nesje and Dahl, 2000) (Figure 2.3.1 and Figure 2.3.2). The ELA responds to winter precipitation, summer temperature and wind transport of dry snow; thus, if accumulation exceeds ablation over a year, or vice versa, the glacier has respectively a positive or negative net mass balance (Siegert, 2001). When the annual net balance is positive the ELA rises, is lowered when negative, or remains in a steady state when accumulation equals ablation (Nesje and Dahl, 2000). ELA fluctuations therefore provide an indicator of glacier response to climate change, and allow for both reconstruction of paleo-climates and future predictions of glacier behaviour (Benn and Evans, 1998). Equilibrium line altitudes were calculated from moraine positions and reconstructed glaciers within the study area so as to elucidate the history of climate change during deglaciation of the Lyngen Peninsula.



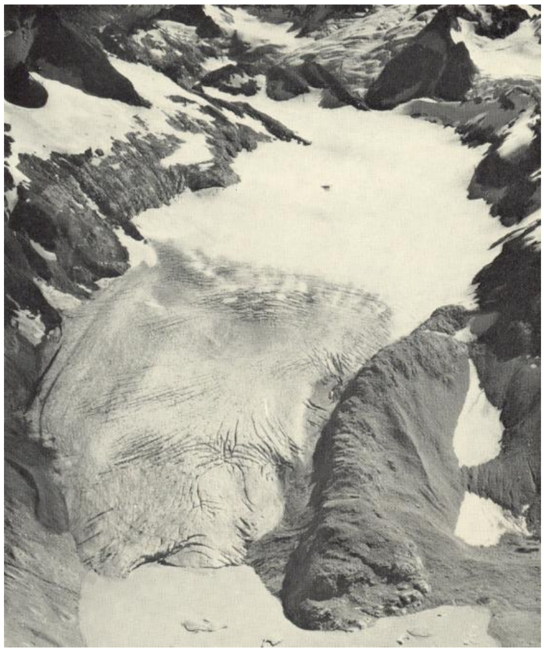


Figure 2.3.1. Equilibrium line altitude of a cirque glacier (Dahl et al., 2003).
Figure 2.3.2. Equilibrium line altitude of a valley glacier, defined by the upper accumulation zone (snow covered) and the lower zone of ablation (exposed ice) (Armstrong et al., 1966).

Reconstruction of former equilibrium line altitudes (paleo-ELAs) was calculated for glacial phases within Strupskardet, Veidalen and Reindalen, using the following methods:
- the maximum elevation of lateral moraines (MELM)
- the median elevation of glaciers (MEG)
- the glacier terminus-to-headwall altitude ratio (THAR)
- the accumulation-area ratio (AAR).

2.3.1 Maximum elevation of lateral moraines

The maximum elevation of lateral moraines (MELM) can be used to determine the ELA of a former glacier, on the assumption that the highest altitude of moraine ridges represents the boundary of the accumulation zone with the ablation zone. When a glacier is in a balanced, steady-state condition, the flow of ice in the accumulation zone will converge and descend towards the ELA (Figure 2.3.1); while in the ablation zone the flowpaths will diverge and ascend toward the margins.

Moraines should, therefore, only be deposited in the ablation zone, the uppermost limit of which reflects the ELA (Figure 2.3.3A) (Benn and Evans, 2010; Dahl and Nesje, 1992; Porter, 2001). However, an underestimation of the ELA may occur where moraines are deposited on steep, unstable slopes, or buried or reworked by subsequent glacial or periglacial processes (Benn and Evans, 2010; Dahl and Nesje, 1992; Nesje and Dahl, 2000; Rea et al., 1999; Torsnes et al., 1993).

2.3.2 Median elevation of glaciers

The median elevation of a glacier (MEG) is a quick method to estimate the ELA; calculated from the headwall of a body of ice to its terminus (e.g. an end moraine). The MEG identifies the midpoint (0.5) of the glacier's total elevation, where the altitudinal range of the accumulation zone is equal to the altitudinal range of the ablation zone (Osipov, 2004; Porter, 2001).

However, the upper limit of a former glacier may be difficult to identify, and an overestimation of the ELA may result (Benn and Evans, 2010; Osipov, 2004). Furthermore, this method does not allow for variations in valley morphology, which affects the area-altitude distribution of the glacier (Nesje and Dahl, 2000; Osipov, 2004; Torsnes et al., 1993).

The MEG ELA of former glaciers in Strupskardet, Veidalen and Reindalen, were measured from the terminus to the uppermost contour line lying within the relevant cirques, and can be calculated with the equation:
MEG = (altitude glacier headwall - altitude glacier terminus)/2 + altitude glacier terminus.
$MEG = (A_h - A_t)/2 + A_t$

2.3.3 *Terminus-headwall altitude ratio*

The terminus-to-headwall altitude ratio (THAR) is the difference in elevation between the terminus and the ELA, divided by the total altitudinal range of the glacier (Porter, 2001). Meierding (1982) considers a THAR of 0.35 to 0.40 to be the most reliable ratio for calculation of the equilibrium line altitude, and values within this range have frequently been used for the determination of paleo-ELAs (Nesje and Dahl, 2000; Osipov, 2004; Porter, 2001; Rea et al., 1999; Torsnes et al., 1993). (Note: a THAR of 0.5 is equal to the MEG).

The THAR technique used the same parameters as for the MEG method, and ratios of 0.35 and 0.40 were calculated for former glaciers within the study area. The equilibrium line altitude is calculated with the equation:

ELA = altitude glacier terminus + THAR x (altitude glacier headwall - altitude glacier terminus)

$ELA = A_t + THAR\ (A_h - A_t)$ (Figure 2.3.3B).

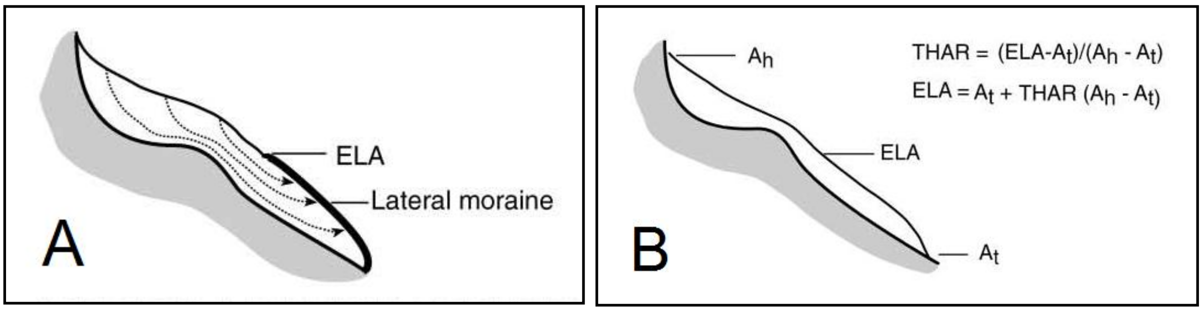


Figure 2.3.3. (A) ELA indicated by the maximum elevation of lateral moraines (MELM) (Porter, 2001). (B) ELA calculated by the glacier terminus-headwall altitude ratio method (THAR) (Porter, 2001).

2.3.4 *Accumulation-area ratio*

The accumulation-area ratio (AAR) method measures the ratio of a glacier's accumulation area to the sum of its accumulation and ablation areas (i.e. the total area). A glacier under balanced conditions will have an AAR of 0.5 - 0.8; a ratio lower than 0.5 implies that the ice is retreating, or higher than 0.8 that it is advancing. An AAR of 0.6 has been used as the most accurate representation of the ELA of steady-state glaciers (Benn and Evans, 2010; Dahl and Nesje, 1992; Nesje and Dahl, 2000; Osipov, 2004; Porter, 2001; Rea et al., 1999; Torsnes et al., 1993). Therefore the accumulation area occupies about two-thirds of the total glacier surface.

Determination of a paleo-ELA requires reconstruction of the former ice limit (based on lateral moraines, end moraines and trimlines) and recreation of the glacier's surface contours. Starting from an estimated ELA (e.g. using THAR), contour lines are drawn that are consistent with glacier flow (Figure 2.3.1), increasing in convexity towards the accumulation area and increasing in concavity in the ablation zone. The area between each successive pair of contours is summed to develop a cumulative curve of the glacier's surface over its altitudinal distribution (Figure 2.3.4.1), and from the AAR can be derived the ELA (Porter, 2001).

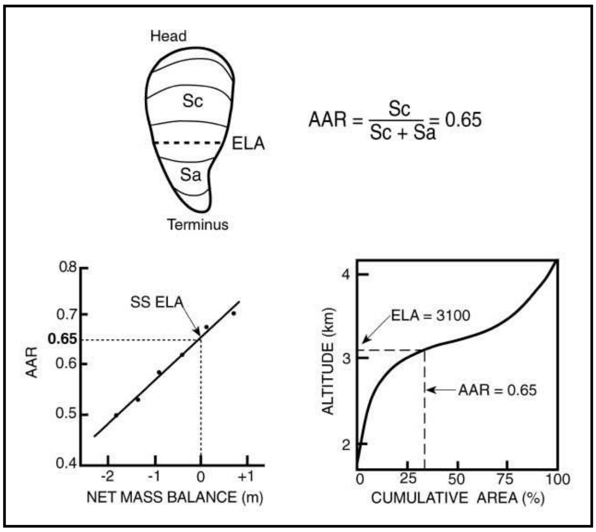


Figure 2.3.4.1. Accumulation-area ratio method for a reconstructed glacier in steady-state conditions (net mass balance = 0). Surface contours are convex above the ELA and concave in the ablation zone. The cumulative area between successive contours is summed over the altitudinal distribution of the glacier and an AAR of 0.65 indicates its ELA (Porter, 2001).

It is suggested that some inaccuracies may be introduced during the application of this method (Dahl and Nesje, 1992; Nesje and Dahl, 2000), especially where the glacier's reconstructed surface contours intersect the valley's topography at acute angles or coincide with them over some distance. However, to determine the ELA of paleo-glaciers in Lyngen (applying an AAR of 0.6 and 0.65), a novel and more accurate technique was developed within GIS, and afterwards found to have been used by previous researchers (Refsnider et al., 2007).

In ArcMap (ESRI, 2009a), a new polyline shapefile was created whose features include a series of lines representing potential ELAs of the reconstructed glacier. These were digitised transverse to the direction of glacier flow, joining equal contours of the valley topography, and 'snapped' to the polygon representing the former ice limit. Within the GIS extension program, ET Geo Wizards (Tchoukanski, 2010), the Split Polygons with Polylines tool enabled the polygon of a former glacier to be fragmented by the ELA polylines into smaller areas.

The total area of a reconstructed glacier is recorded in its Attributes Table (Area field > Statistics), from which the percentages of its accumulation/ablation areas can be calculated. Starting at the lowest elevation, the 'split' polygons were then successively 'selected' until the cumulative value of the ablation zone equalled 0.4 (AAR = 0.6) or 0.35 (AAR = 0.65) of the total glacier area (Attributes Table > Selected Features > Area field > Statistics). The ELA of this cumulative area was then obtained from the surrounding valley contours (Figure 2.3.4.1).

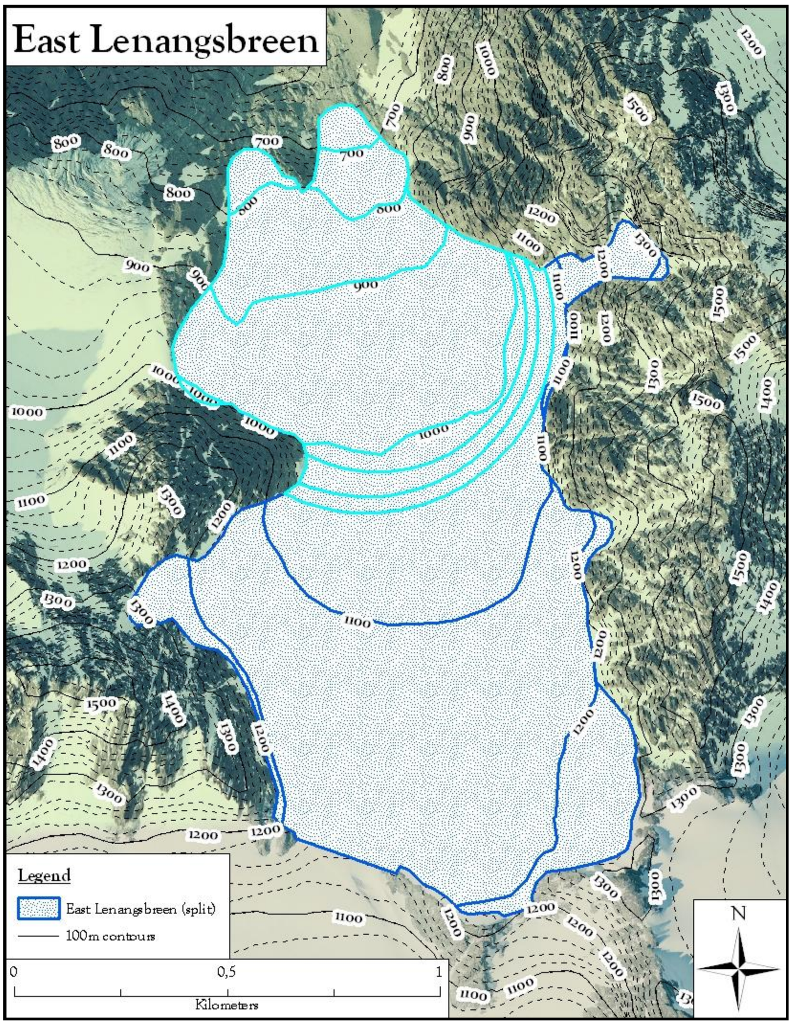


Figure 2.3.4.1. ELA of east Lenangsbreen, Strupskardet; calculated in ArcMap. The present day glacier has been supplemented with additional contour lines (perfect arcs), used to split the surface of the ice into smaller areas. Areas in the ablation zone were selected (edges highlighted in turquoise) until the cumulative total equalled 0.4 (AAR=0.6); the ELA is indicated by the corresponding topographic contours.

3 Results

3.1 Landforms: morphology, distribution and genesis

3.1.1 Strupskardet

Strupskardet is the southernmost valley that was studied in detail on the northern Lyngen Peninsula (Figure 3.1.1.1). It completely transects the Lyngen Alps from Sørlenangsbotn on the western side to the small bay of Strupen beside Lyngenfjord, and the watershed is located slightly east of Lyngen's north-south oriented axis. A small river flows towards Strupen via a few glacial lakes including Strupvatnet, which was dammed as recently as 1971 by the snout of Strupbreen (Whalley, 1971), the largest glacier on the northern Lyngen Peninsula (ca. 13.3 km^2). Strupskardelva flows towards the west via a chain of six blue, glacial lakes including Strupskardvatn, Blåvatnet, and Aspevatnet before entering Sørlenangsbotn.

Many of the moraines studied and mapped in Strupskardet were constructed by ice contributed from the plateau glaciers of east and west Lenangsbreen, although active moraine formation is not present at the moment (Bakke et al., 2005). These glaciers are identified as units 18 and 19 in the Glacier Atlas of Northern Scandinavia (Østrem et al., 1973), with areas of ca. 1.4 km^2 and 0.7 km^2 respectively. The centre of the valley is broad, bouldery, and lightly vegetated, although below 70 m.a.s.l. the vegetation is densely covers the moraines. The valley east of Litle Lenangstinden was not studied or mapped in detail. The major moraines and landforms between Lenangsbreen and Sørlenangen are generally described from distal (outermost) to proximal (innermost).

Talus is ubiquitous throughout Strupskardet (and across the northern Peninsula in general), and occur on both sides of the valley as interrelated depositional landforms. Talus is loose, coarse, material which accumulates along valley rockwalls where clasts have been transported by falling, rolling, sliding or bouncing down the slope (Benn and Evans, 2010). The term talus can describe both the slope form and its constituent material; with such landforms being a prominent feature of mountain areas that experience or formerly experienced a periglacial climate (Ballantyne and Harris, 1994).

Talus sheets cover much of the northern side of the valley, where rockfall debris has accumulated over a relatively uniform slope. Talus cones have evolved where loose material has been concentrated or funnelled down a gully or chute in the rockwall, and subsequently deposited with a fan-like morphology. Coalescing talus cones have developed where individual talus cones laterally intersect (Ballantyne and Harris, 1994); examples of which can be seen beside Blåvatnet in Strupskardet (Figure 3.1.1.2).

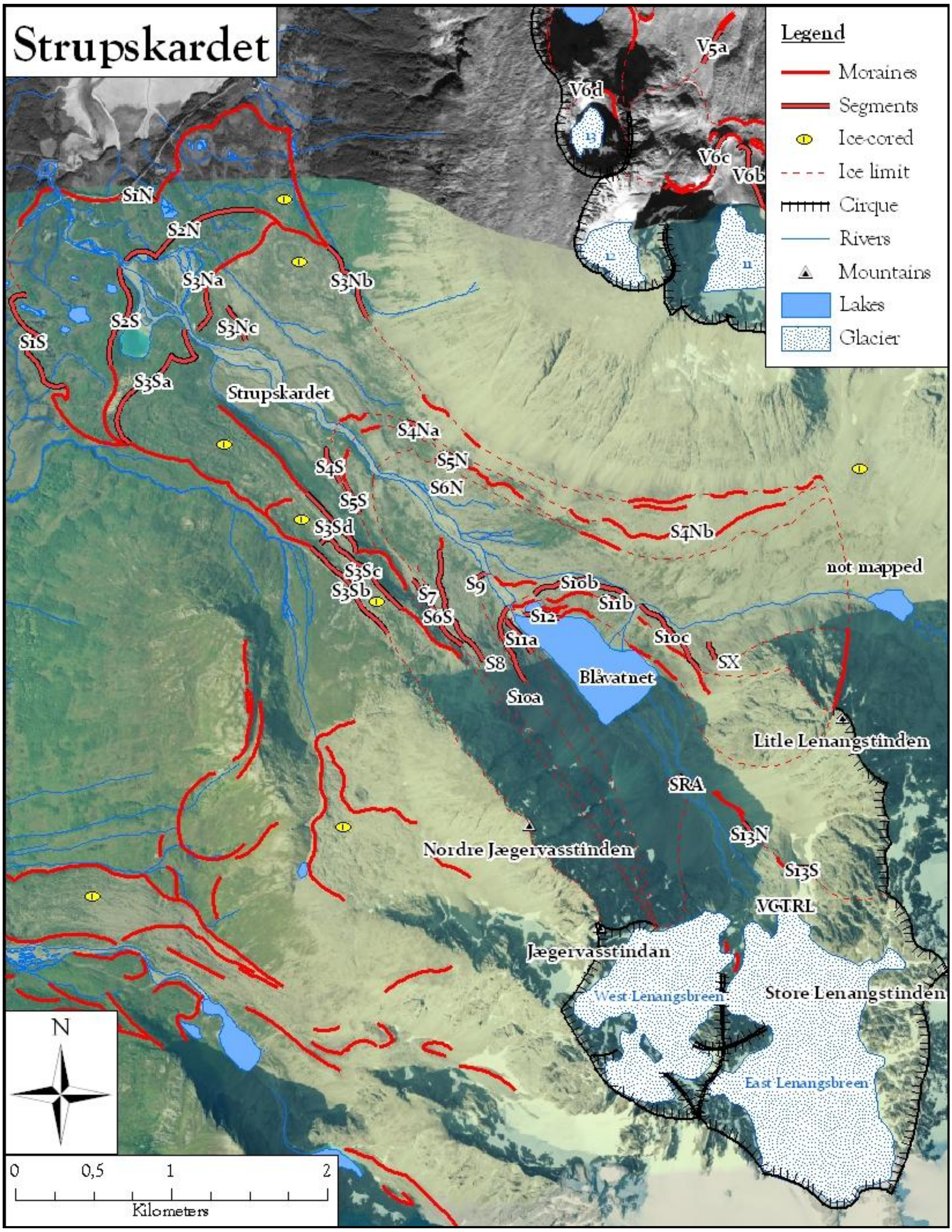


Figure 3.1.1.1. Map of Strupskardet, displaying moraines and their segments that were studied in detail.

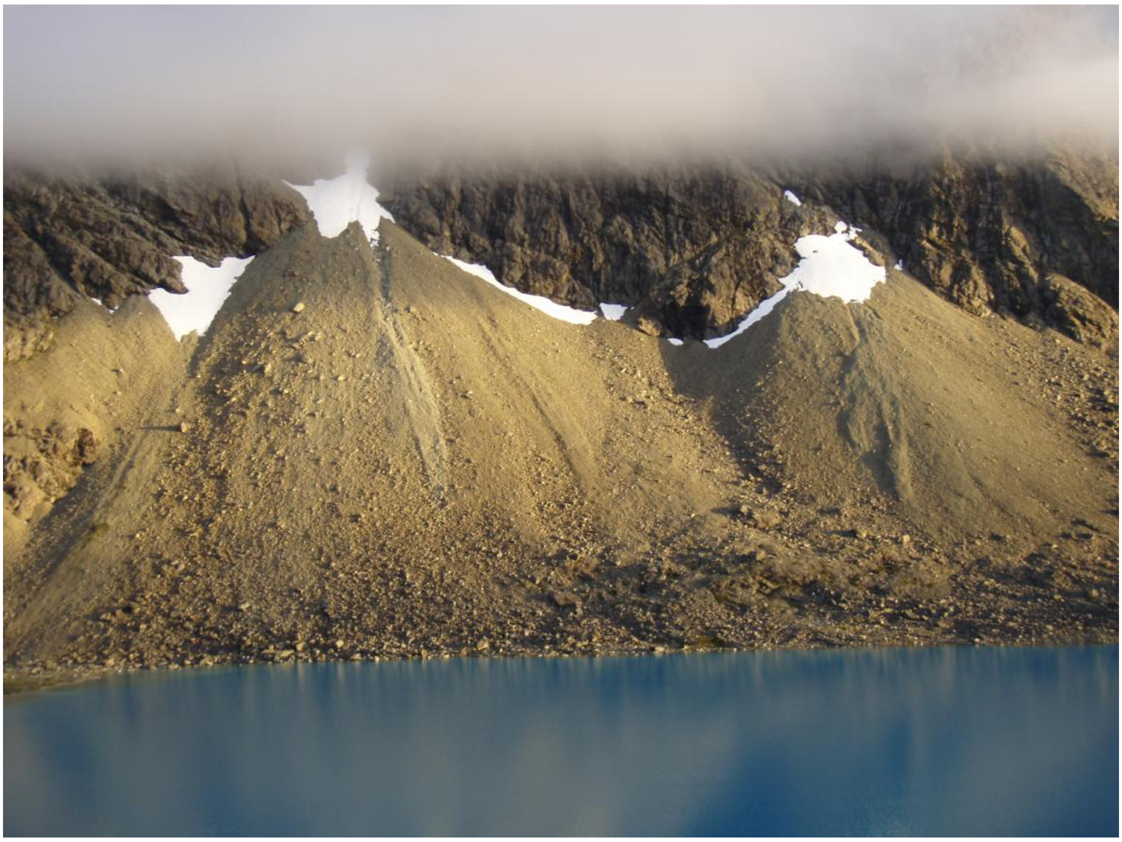


Figure 3.1.1.2. Talus cones coalescing at the foot of nordre Jægervasstindan, beside Blåvatnet, Strupskardet. Debris flows have created secondary, surface modifications on the upper slopes of the talus cones; probably as a result of snow and slush avalanches.

The northern slopes of Strupskardet also display a series of relict rock glaciers, which were also identified by Bakke et al. (2005). A rock glacier is a thick, tongue-like or lobate mass of angular debris which slowly creeps down mountain slopes due to the deformation of internal ice or frozen sediments (Ballantyne and Harris, 1994; Humlum, 2000; Sollid and Sørbel, 1992). Rock glaciers are common in mountainous environments where permafrost conditions provide a rich supply of talus from the rockwalls and initiate a downslope momentum, yet they are not directly responsible for the retreat of adjoining headwalls, but are the result of weathering processes on cold climate rock free faces (Humlum, 2000). Active rock glaciers are typically 20-100 metres thick and can extend for several kilometres with cascading frontal slopes that stand at the angle of repose.

Rock glaciers may not clearly represent a distinctive periglacial landform, but should be considered as part of a larger geomorphic continuum with rockfall talus slopes and valley glaciers at either extreme (Benn and Evans, 2010; Humlum et al., 2007). However, they can be divided into two genetically distinct subgroups: talus-derived rock glaciers and glacier-derived rock glaciers, implying non-glacial (periglacial) and glacial types, respectively (Humlum, 2000).

The outermost moraines identified in Strupskardet are segments S1N and S1S, located in the area of Sørlenangsbotn and Stormyra, approximately 25 m.a.s.l. This moraine lacks a defined crest, but is comprised of intermittent ridges and hummocks, slightly elevated above the surrounding mires and lakes. It can best be discerned from aerial photographs as the ridges are discontinuous and difficult to follow in the field. Their well-drained position and low altitude encourages a thick covering of trees, vegetation and lichen, allowing only the largest boulders to protrude through the substrate.

S2 (S2N and S2S) is a push moraine which is less subdued and more contiguous than S1, and at an altitude of 40 m.a.s.l. surrounds the turquoise lake Aspevatnet to the south side of Strupskardelva, and the braided streams north of the main river channel. This moraine is also heavily wooded and vegetated, which inhibits the identification of sediment qualities.

S3 represents a major glacial advance within Strupskardet, with crests further subdivided into morphologically distinct groups. Moraine segments S3Na and S3Sa define a large end moraine which spans the valley, except where Strupskardelva has eroded a narrow channel completely through the till (Figure 3.1.1.3). On the distal side of S3Sa, a terrace of smoothed and wave-rounded pebbles marks a raised beach at 55 m.a.s.l., indicating the Main shoreline level of the Younger Dryas (Figure 3.1.1.4)


Figure 3.1.1.3. Strupskardelva bisecting the end moraine of phase S3.
Figure 3.1.1.4 A raised beach on the distal side of moraine S3Sa, marks the position of the Younger Dryas Main shoreline.

S3Nb is a lateral moraine and continuation of S3Na, which clings to the northern side of Strupskardet from 90 m.a.s.l. before it disappears upvalley beneath relict rock glaciers and talus accumulations. It also delineates a distinct morphological boundary, a trimline, between the proximal and distal sides of the former glacier. North of S3Nb the terrain is level and forested, while the proximal side is chaotic and features collapse depressions and clast sorting caused by meltout of the ice-cored till (Figure 3.1.1.5). Segment S3Nc is a short, rounded ridge which extends upvalley from the proximal side of S3Na.

Segments S3Sb, S3Sc and S3Sd are individual crests within a larger moraine belt on the southern side of the valley (Figure 3.1.1.6), extending northwestwards from an altitude of 300 m.a.s.l. below Nordre Jægervasstinden, before morphing into the proximal side of S3Sa. S3Sb defines the outermost limit of this hummocky landscape, sloping steeply (ca. 40°) towards Tverrelva on the outside of Strupskardet, while S3Sd marks the proximal edge. Minor crests and furrows can be traced between the proximal and distal ridges; which are believed to be related to the meltout of buried ice. This belt of till appears to have flowed as a debris-rich glacier from the leeside slopes of Nordre Jægervasstinden, and appears to be a relict ice-cored moraine; also suggested by Bakke et al. (2005).


Figure 3.1.1.5. Collapse depressions and clast sorting on the proximal side of moraine segment S3Nb; caused by meltout of ice-cored debris.
Figure 3.1.1.6. Relict ice-cored moraine ridges on the southern side of Strupskardet; including segments S3Sb, S3Sc and S3Sd (top to bottom).

Humlum (1988) defines an ice-cored moraine as being:
- a disproportionately large moraine with minor ridges superimposed upon its surface
- the width of the moraine is often quite broad
- the surface and outline appear rounded

Østrem (1964) has described ice-cored moraines as being 'porridge-like' in appearance (Figure 3.1.1.7 and Figure 3.1.1.8).

Large ice-cored moraine belts are characterised by chaotic hummocks, but sub-parallel linear ridges suggest a degree of organisation to the belts (Benn and Evans, 2010). This is interpreted to be caused by multiple ice fronts, or of ice-rich, debris-covered ridges formed parallel to the glacier margin. These ridges are often arranged in nested suites lying transverse to former glacier flow (Benn and Evans, 2010).

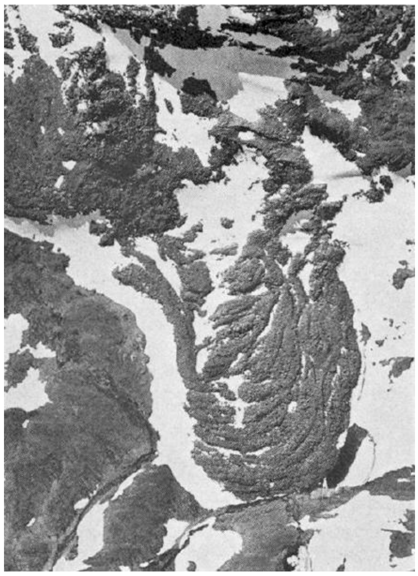



Figure 3.1.1.7. A relict ice-cored moraine deposited from the slopes of Nordre Jægervasstinden in Tverrelvdalen; beside Strupskardet. Another ice-cored moraine is visible in the background, which descended as far as Jægervatnet from a valley to the south.
Figure 3.1.1.8. Aerial photograph of an ice-cored moraine (Østrem, 1971)

S4, S5, S6, S7, S8 and S9 are a series of latero-frontal push moraines along the floor of the valley. On the south side of the river, moraine segments occur below the relict ice-cored ridge of S3Sd and can be followed easily down to the river, both in the field and from aerial photographs. However on the northern side of Strupskardelva, individual segments are discontinuous, appear more rounded and eroded, and are difficult to correlate with those on the southern bank.

The top of segment S5 appears to be buried beneath the uppermost section of the proximal relict ice-cored moraine (segment S3Sd), the upper crest of which seems to have undergone post-depositional creep and descended towards the valley from the shoulder of Nordre Jægervasstinden. The upper crests of S3Sb and S3Sc also display some gravitational deformation; it is suggested that these may have begun to develop into a rock glacier.

Segments S4N, S5N and S6N appear as lateral moraines (Figure 3.1.1.9 and Figure 3.1.1.10), formed by a large valley glacier that once flowed through Strupskardet before converging with ice from the cirques of Lenangsbreen. The continuation of segments S7 and S8 could not be seen or mapped north of the river. Moraine S9 was mapped but not studied in detail.

Figure 3.1.1.9. Moraines on the northern side of Strupskardet. Moraine segments S4Na and S5N have been partially buried by a talus cone. The scalloped ridges (uppermost) are a result of subsequent relict rock glacier development.

Figure 3.1.1.10. Moraines on the southern side of Strupskardet. Segment S5S (foreground) extends towards Strupskardelva; view towards Sørlenangsbotn.

Segment SX is a short, narrow belt of black till found at an elevation of 320 m.a.s.l. below the northwestern slope of Litle Lenangstinden. This crest appears to have been formed as a lateral moraine by East Lenangbreen, and was supplied with debris from a gully in the upper rockwall (Figure 3.1.1.11). The clasts appear blackened and extremely weathered, and were later identified to be comprised of Lyngen gabbro, but of a variety that is particularly rich in hornblende (Figure 2.2.1.1B).

Moraines S10 (segments S10a, S10b, S10c) and S11 (segments S11a, S11b) form well-defined, blocky, latero-frontal push moraines which curve around and create the impoundment of Blåvatnet. They are comprised of large, angular boulders with diameters of 1-5 metres, and represent at least two advances of Lenangsbreen. Their construction has partially diverted the upper section of the river through Strupskardet, and most of the water now cuts through these moraines to form a delta in Blåvatnet (Figure 3.1.1.12). Glaciofluvial outwash is also forming a larger, prograding delta at the head of the lake and provides suspended sediment which refracts light as an intense turquoise colour, giving Blåvatnet (the Blue Lake) its name.

Figure 3.1.1.11. Lenangsbreen and Blåvatnet. The large, bouldery moraine, S10, surrounds Blåvatnet (right), outside of which lies segment SX (centre left). Meltwater from Lenangsbreen can be seen to dissect a rock avalanche in the background, before sediment is deposited on a prograding delta in Blåvatnet.

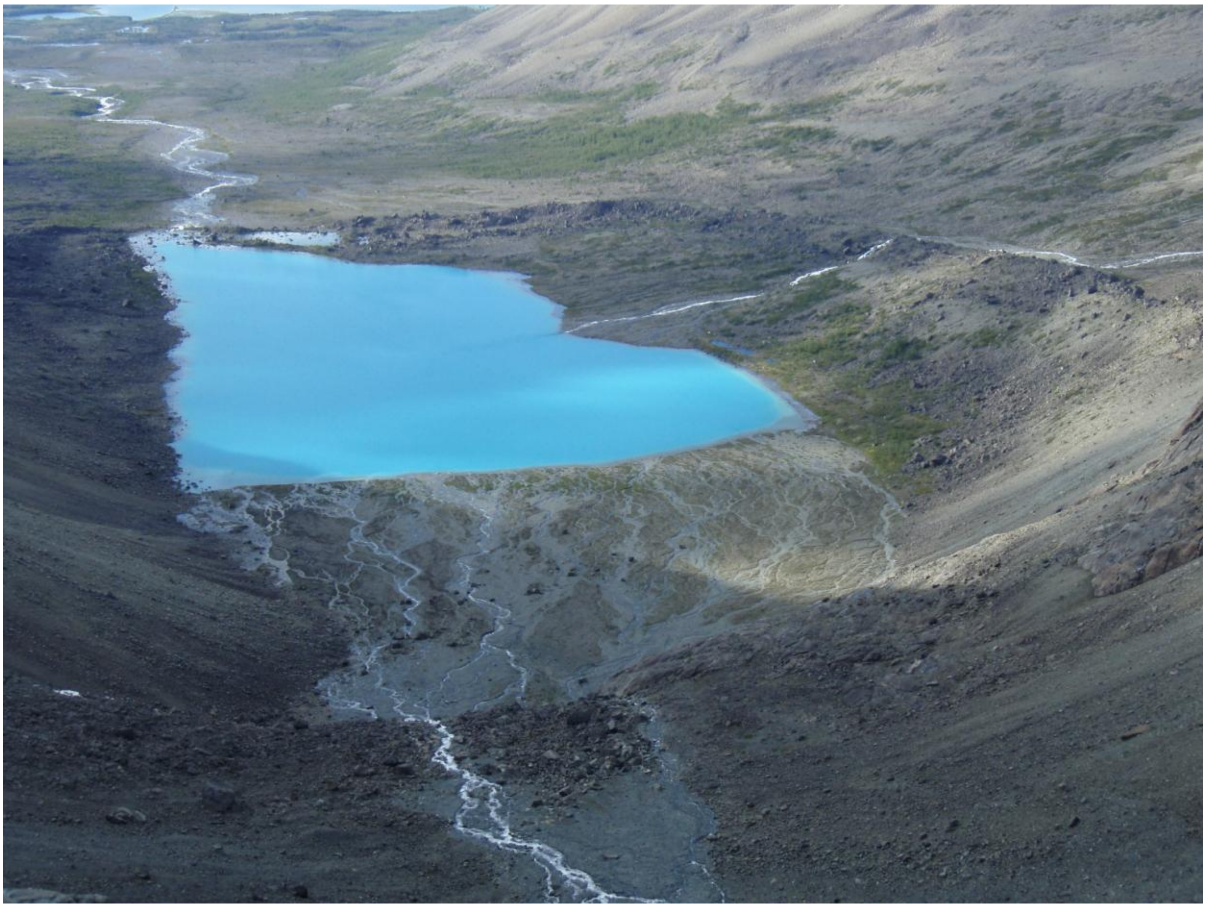


Figure 3.1.1.12. Bouldery moraines surrounding Blåvatnet; moraines S10 and S11 and view of Strupskardet from Lenangsbreen. Meltwater from Lenangsbreen is dissecting a rock avalanche (foreground) and constructing a large glacio-fluvial delta at the head of Blåvatnet. A small delta is also being formed in the lake by Strupskardelva (right).

S12 is a subdued latero-frontal moraine which curves around the northern edge of Blåvatnet. It has relief of only a few metres above the surface of the lake, but can be traced around the northern edge of Blåvatnet, except where it has been buried beneath the delta created by Strupskardelva. A continuation of the moraine cannot be identified along the southern shore where talus rockfalls obscure most of the slope. Fluctuations of the glacier front appear to have created at least three minor moraine crests which has subsequently led to the formation of three small ponds beside the present-day delta (Figure 3.1.1.13)

Figure 3.1.1.13. Strupskardelva delta in Blåvatnet. Moraine S12 is comprised of three subdued, semi-parallel ridges behind which ponds have since formed.

A major rock avalanche, identified as SRA, (Figure 3.1.1.14) has been deposited in the narrow valley between Blåvatnet and Lenangsbreen at 250 m.a.s.l. The debris is blocky and chaotic, contains boulders greater than 5 metres in diameter, and appears to have cascaded from the northeast slope of Jægervasstindan. Smaller avalanches have also descended the adjacent rock faces and talus cones to disperse boulders across the delta above Blåvatnet (Figure 3.1.1.12).

Bakke et al. (2005) describe this landform is a latero-frontal push moraine emplaced by the maximum extent of Lenangsbreen during the Little Ice Age, however, the most recently deposited moraines which continue up the valley almost as far as the present-day icefall have not been mapped by these authors. Aerial photograph analysis suggests that the location of SRA may indeed coincide with the LIA limit, and while this landform appears to contain material of the same calibre of moraines S10 and S11, it is it is broad (ca.200m) rather than crested, and lacks a defined ridge suggestive of glacier advance. The rockfall can be traced down the slope from above, before it stops abruptly in the floor of the valley, where it has since been dissected by glaciofluvial action. Yet it cannot be traced on the opposite slope, which features exposed and striated bedrock and is devoid of till where the glacier front could expect to have been be located (Figure 3.1.1.12).

S13 (segments S13N and S13S) is a lateral moraine crest most recently deposited by Lenangsbreen. S13N features at least 2 subtle ridges which can be traced up a steep slope of talus from an altitude of 280 m.a.s.l. to a bedrock ledge at 460 m.a.s.l. (Figure 3.1.1.14). S13S continues above the ledge as a well-defined lateral moraine, which becomes a sharp, medial moraine at a height of 630 m.a.s.l.: formed between a névé/snowbank on the side of Store Lenangstinden and the former margin of East Lenangsbreen. The crest is sharp, features clasts that are almost completely devoid of lichen, and can be traced to within 200 metres of the current position of East Lenangsbreen.

Figure 3.1.1.14. Rock avalanche below Lenangstindane: identified as SRA. Moraine S13 rises from behind the debris before it continues over the ridge (right) towards Lenangsbreen.

3.1.2 Veidalen

Veidalen lies between Strupskardet and Reindalen, and unlike these two valleys which transect the peninsula, Veidalen extends for less than 10 kilometres before it is enclosed by the arêtes of Veidalstinden (Figure 3.1.2.1). Veidalselva flows from the head of the valley, via two blue lakes, before entering the sea south of Sørlenangen. The northern side of the Veidalen is broad and open, and the steep valley walls feature the remnants of lateral moraines, relict rock glaciers, and cones of avalanched talus. The southern side of Veidalen is surrounded by the headwalls of four cirques which each contain a small glacier (units 10, 11, 12, 13, in Østrem et al. (1973)) while the easternmost part of the valley holds a larger glacier. The total surface area of these glaciers is approximately 1.1 km^2. An elongated landform, identified as a rock avalanche/rock glacier extends from in front of the cirques towards Veidalselva, and the landscape is covered with till and features neatly crested latero-frontal moraines and a hummocky landscape of relict ice-cored moraines. The major moraines and landforms in Veidalen are generally described distally to proximally.

Phase V1 represent the earliest glacial event in Veidalen and the outermost crest, segment V1, is the only moraine that could be identified with this phase. The proximal side of this crest contains hummocky till and subdued ridges, which gives the appearance of a disintegrated ice-cored moraine. This segment can be followed from 140 m.a.s.l. to 260 m.a.s.l., to where it appears to have been overridden by the subsequent moraine complex of phase V2.

V2 includes several moraines which appear to have been formed during the same phase, although of two different glacial processes: via the movement of a central valley glacier which formed lateral moraines, and by the flow of ice-rich debris from the cirque glaciers that deposited a broad belt of ice-cored material.

Segments V2Na and V2Nb form a single lateral moraine that defines the northernmost limit of a major valley glacier during this phase. It can be traced from 190 m.a.s.l. to 480 m.a.s.l. along the northern side of Veidalen, although has been substantially modified along much of its length by rock glaciers that descended from the steep slopes of Veidalsfjellet (Figure 3.1.2.2).

V2Sa and V2Sb form a complementary lateral moraine that is sinuous and undulating, and appears to have been pressed up between the valley glacier that flowed through Veidalen and tongues of debris-laden ice that emerged from the cirques of glaciers 11 and 12. The proximal side of this moraine has been eroded by meltwater flowing along the margins of the former valley glacier (Figure 3.1.2.3).

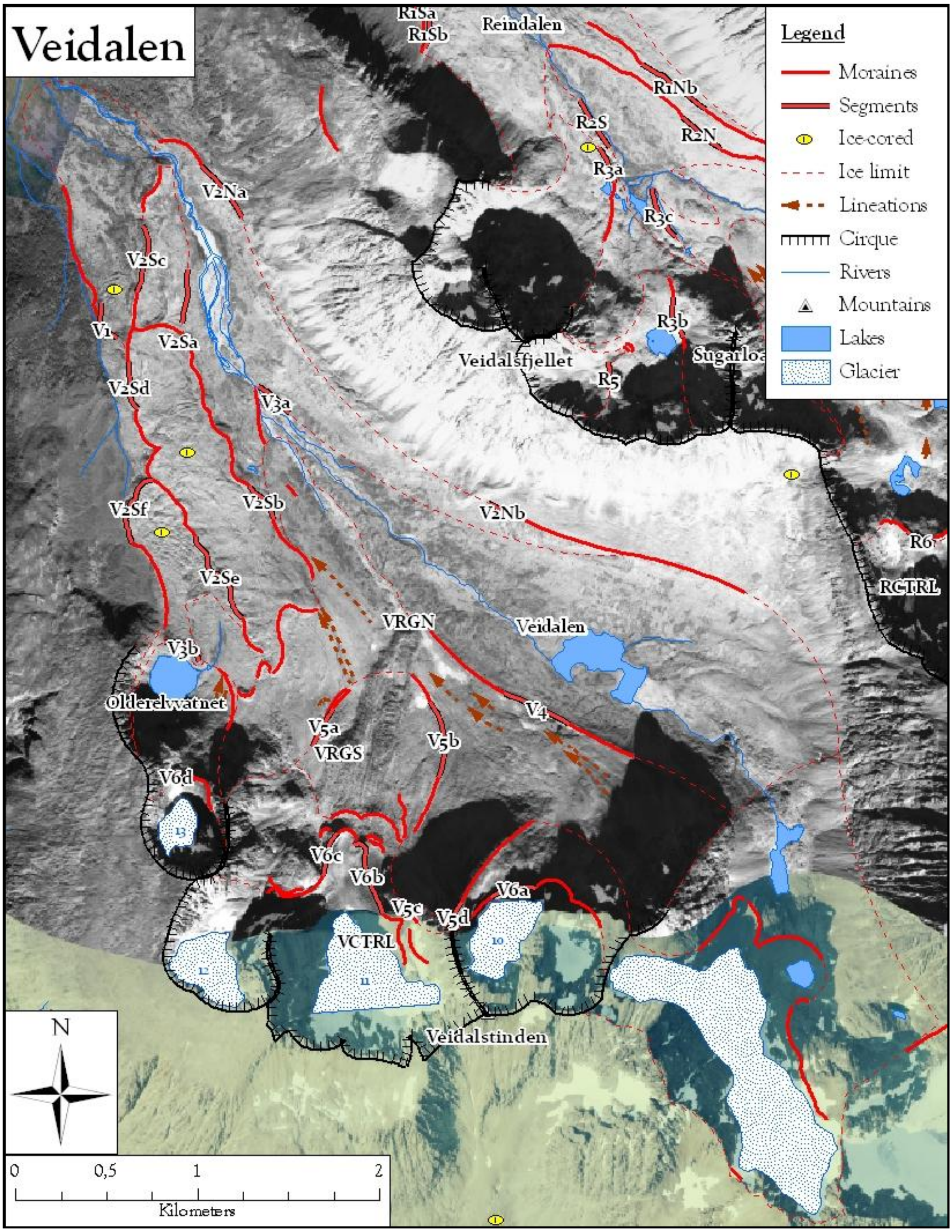


Figure 3.1.2.1 . Map of Veidalen, displaying moraines and their segments that were studied in detail.

Figure 3.1.2.2. Relict talus-derived rock glaciers below Veidalsfjellet, Veidalen. Avalanche boulder tongues have subsequently deposited cones of talus behind the ridges created by the rock glaciers.

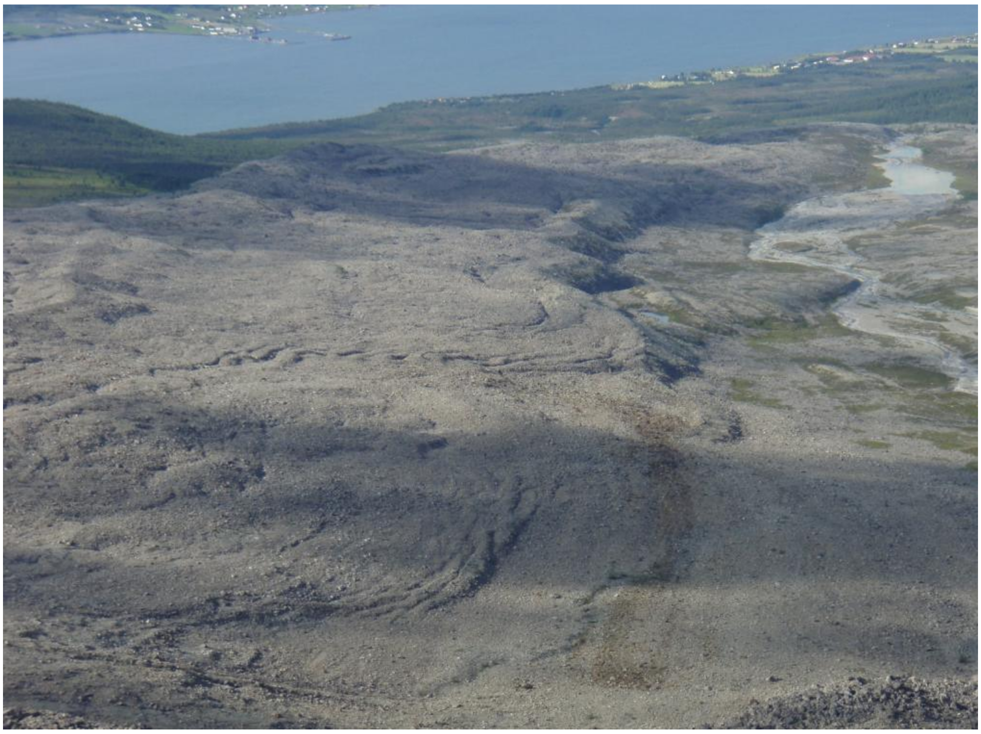


Figure 3.1.2.3. Relict ice-cored moraine belt in Veidalen. Cirque glaciers provided waves of ice-rich debris which was pressed against the margin of a large valley glacier. The contact between these two bodies of ice is visible as a crest (segments V2Sa and V2Sb) between the relict ice-cored belt and Veidalselva.

Segments V2Sc, V2Sd and V2Se form a long, hummocky crest that now buries the outermost section of segment V1. The proximal side of these moraines contain a belt of till that features minor ridges and numerous collapse depressions, suggesting its formation as an ice-cored moraine derived from the cirques of glacier units 11 and 12 (Figure 3.1.2.4). V2Sf is a well-defined crest at 320 m.a.s.l. It separates the unglaciated valley from the rippled landscape of relict ice-cored moraine contained on its proximal side that appears to have flowed from the cirque of glacier 13.

Figure 3.1.2.4. Relict ice-cored moraines overlooking Sørlenangen. Moraine segments V2Sf (left), V2Sd (centre) and V2Sc (back right) contain a hummocky landscape of relict ice-cored debris derived from cirque glaciers on the southern side of Veidalen.

During field research, a talus-derived landform was identified on the southern slopes of Veidalen, which appears to override the moraine beside segment V2Nb (Figure 3.1.2.5). The morphology of this landform has led to a tentative interpretation as a relict protalus rampart. A protalus rampart is comprised of predominantly coarse debris, where clasts have fallen from a steep rockwall and have rolled, bounced or slid to the foot of a perennial snowbank (firn), before accumulating at the base of the slope in the form of an arcuate ridge or bench (Ballantyne, 1990). The volume of material within a protalus rampart is equivalent to that lost from the rockwall above, and the thickness of the deposit is attributed to the volume of the snowbank, such that the crest will migrate outwards away from the talus slope as the rampart accumulates (Ballantyne and Harris, 1994)

The morphology of this ancient rampart displays a significant bulge in the centre of its crest, which may be accounted for by either of two theories. Firstly, that the snowbank was especially thick behind the centre of the rampart, which protected and eventually preserved the underlying moraines behind the crest, while an equal volume of talus continued to be draped over the extremities of the rampart where snow cover was minimal. Secondly, that as the size of the protalus rampart increased, the concentration of snow/ice behind it became sufficient to start pressing the crest outwards, and thus cause it to become distorted and start moving downslope; effectively the embryonic stage of a rock glacier.

Figure 3.1.2.5. Relict protalus rampart on the northern side of Veidalen. Talus in the form of avalanche boulder tongues descend from Veidalsfjellet, partially obscuring moraine segment V2Nb (centre). The protalus rampart (centre right) has been built directly over this moraine. Blocky debris of a rock avalanche/rock glacier is visible in the foreground, extending away from the viewer’s point of view.

V3 moraines include two segments formed by two separate glaciers. Segment V3a is short, rounded moraine located beside Veidalselva at 240 m.a.s.l., with a complementary crest on the adjacent riverbank. This appears to be a push moraine that marks the northern extent of a valley glacier that flowed from the upper reaches of Veidalen. V3b is a short, rounded, moraine built directly in front of the small cirque that now contains the round lake of Olderelvvatnet (Figure 3.1.2.6). This segment has an abandoned meltwater channel at its western end, and has been obviously truncated at its eastern extremity. Its altitude (420 m.a.s.l.), orientation and morphology imply that it was part of a larger moraine; another section of which can be seen as a short, curved hillock to the southeast. These are suggested to have been dissected by a subsequent glacial phase.

Figure 3.1.2.6. Olderelvvatnet and relict ice-cored moraines in Veidalen. Moraine segment V3b in front of Olderelvvatnet appears to have been truncated and dissected from a previously contiguous crest; a remnant of which can be seen in the foreground.

Segment V4 is a long (1300m), neatly-crested moraine that descends from 440 m.a.s.l. and defines a topographical boundary between the centre of Veidalen and the cirque complexes on the southern side of the valley. It was the only moraine examined in detail for this phase. It is identified as a lateral moraine, yet appears to have been built upon a larger ridge: possibly a medial moraine constructed between the valley glacier and cirque glaciers during phase V3 (Figure 3.1.2.7). The landscape between V4 and the cirques appears to have been smoothed out by the movement of ice from glacier units 10, 11 and 12, which simultaneously deposited lineations of rust-coloured boulders (composed of serpentine) that indicate the direction of ice flow (Figure 3.1.2.1 and Figure 3.1.2.3). It is suggested that during phase V4, ice from glacier unit 13 emerged from its cirque and began to override and dissect the moraine in front of Olderelavvatnet (segment V3b) before being diverted and pressed into the belt of ice-cored moraines downvalley.

Figure 3.1.2.7. Lateral/medial moraine overlooked by Veidalstinden. This moraine segment (V4, centre) appears to be a lateral moraine deposited upon a medial moraine, previously formed between a central valley glacier and the ice from cirques beneath Veidalstinden (top right).

Phase V5 is represented by four moraine segments that lie in front of glacier units 10, 11 and 12. Segment V4d is comprised of a pair of crests on the summit of a large talus-decked rampart; Glacier 10 appears to have pressed till over the edge of this landform prior to the formation of V4d. Segment V4c was formed laterally by glacier 11, which had coalesced with glacier 12 and advanced into the valley as a tongue of ice down to 360 m.a.s.l.. V4a and V4b are subtle, arcuate latero-frontal push moraines that each contain at least two minor ridges and mark the front of the combined cirque glaciers.

An elongated tongue of blocky, angular boulders extends approximately 1100 metres towards the centre of Veidalen from in front of the cirques of glaciers 11 and 12 (Figure 3.1.2.8 and Figure 3.1.2.9). The boulders are generally 1-5 metres in diameter, although blocks >10m are not uncommon, and extend from an altitude of 460 to 340 m.a.s.l. This deposit appears to have two components. The western part (VRGS) is thicker, wider and shorter; while the debris comprising the eastern part (VRGN) is not as thick, but extends further to override the arcuate moraine (segments V5a and V5b) on the valley floor. The eastern part also features a moraine-like rim as well as series of transverse ridges that give it a stretched appearance (Figure 3.1.2.5).

Griffey and Whalley (1979) have described the landform in relation to the surrounding moraines and the environmental conditions at the time of genesis, and have subsequently identified it as a rock glacier. They believe that a series of rockfalls from the steep surrounding headwalls were deposited upon the steadily retreating tongue of ice from glacier units 11 and 12. Differential ablation led to separation of the cirque glacier from the debris-covered ice, and while the former continued to recede, the thick debris cover, steep gradient (8°) and periglacial conditions allowed the latter to survive as a very thin tongue of ice that began to flow as a rock glacier.

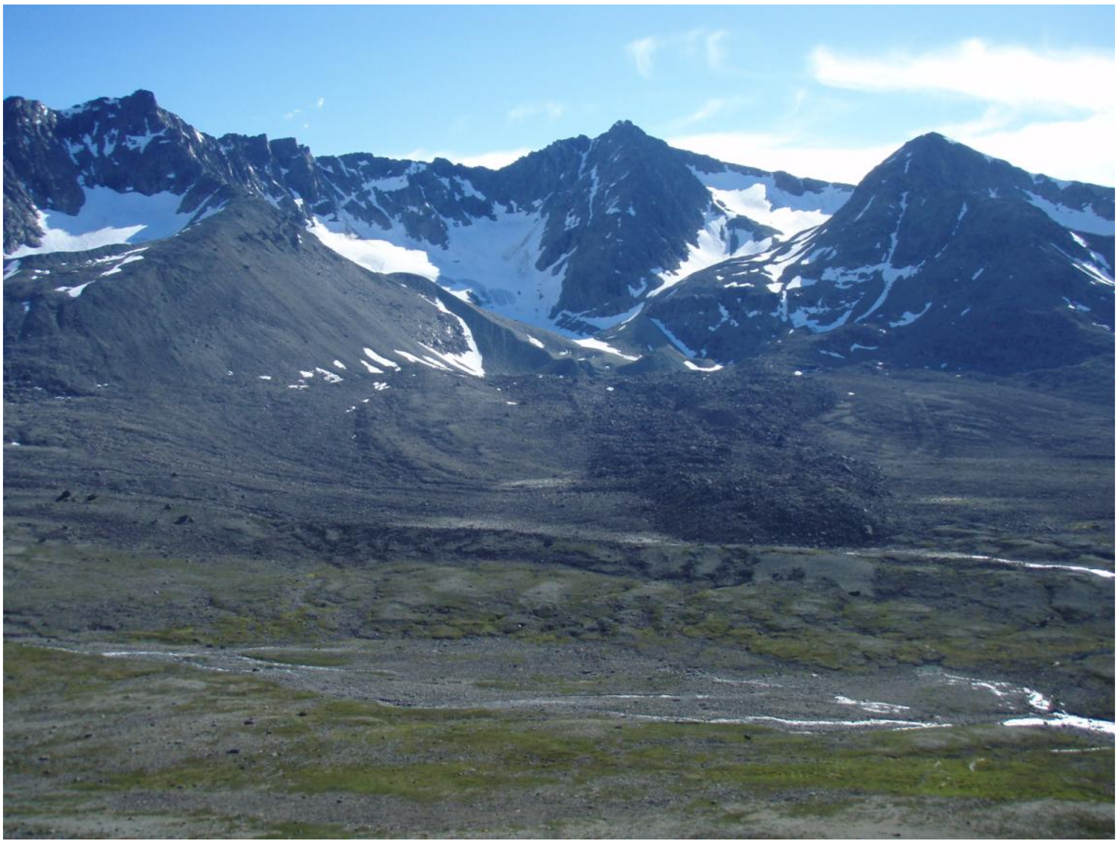


Figure 3.1.2.8. Cirque glaciers in Veidalen: identified as glacier units 10, 11, 12 (left, centre, right, respectively) in Østrem et al. (1973). Moraine segment V5d defines the top of the talus-covered rampart (left). Subtle arcuate crests of segments V5b and V5a surround the large rock glacier in the centre of the valley. Veidalselva and moraine segment V4 are visible in the foreground.

This landform most likely developed from a major rock avalanche (also known as rockslope failure), from a cirque headwall onto the glacier that transported huge blocks of debris at least as far as the western section of the lobe. A rock slope failure is a catastrophic collapse of an over-steepened mountainside, where material rapidly fragments as it descends, and disperses across the valley floor as an extensive field of boulders (Ballantyne, 2003; Benn and Evans, 2010). They are especially common in mountain environments where glacial erosion has steepened rock faces and when recent deglaciation can lead to unloading of the underlying bedrock.

However, the neat, rectilinear extension of the eastern part of the tongue does not conform to rock slope failure appearances or descriptions, and Ballantyne and Harris (1994) point out that often transverse ridges are strongly diagnostic of rock glacier flow. This deposit has therefore been ascribed a catastrophic rock avalanche, of which the eastern element has experienced additional periglacial modification and evolved into a rock glacier.

Figure 3.1.2.9. Rock avalanche and rock glacier in Veidalen; initiated by the catastrophic collapse of a cirque headwall. The thickest part of the deposit: VRGS (left), has retained its morphology as a rock avalanche; while the elongated lobe: VRGN (right) has subsequently evolved into a rock glacier. Rippled waves of till denote the belt of relict ice-cored moraines (background) from phase V2, and a rust-coloured band of serpentine boulders indicate the direction of ice flow during phase V4.

Phase V6 includes the four most recently deposited moraines segments in Veidalen: V6a, V6b, V6c, V6d, deposited in front of the cirques of glacier units 10, 11, 12 and 13, respectively. Each segment appears fresh and sharp, and V6a and V6d contain 2-3 crests indicating minor fluctuations of these cirque glaciers. Segments V6b and V6c have merged together, caused by a convergence of their glaciers into a larger body of ice. Recession of these glaciers back into their respective cirques has formed a micro-relief of retreat ridges as well as flutes over the proximal side of these moraines (Figure 3.1.2.10). The proximal slopes of segment V6c also appears to have been affected by downhill creep, possibly due to subsequent rock glacier development.

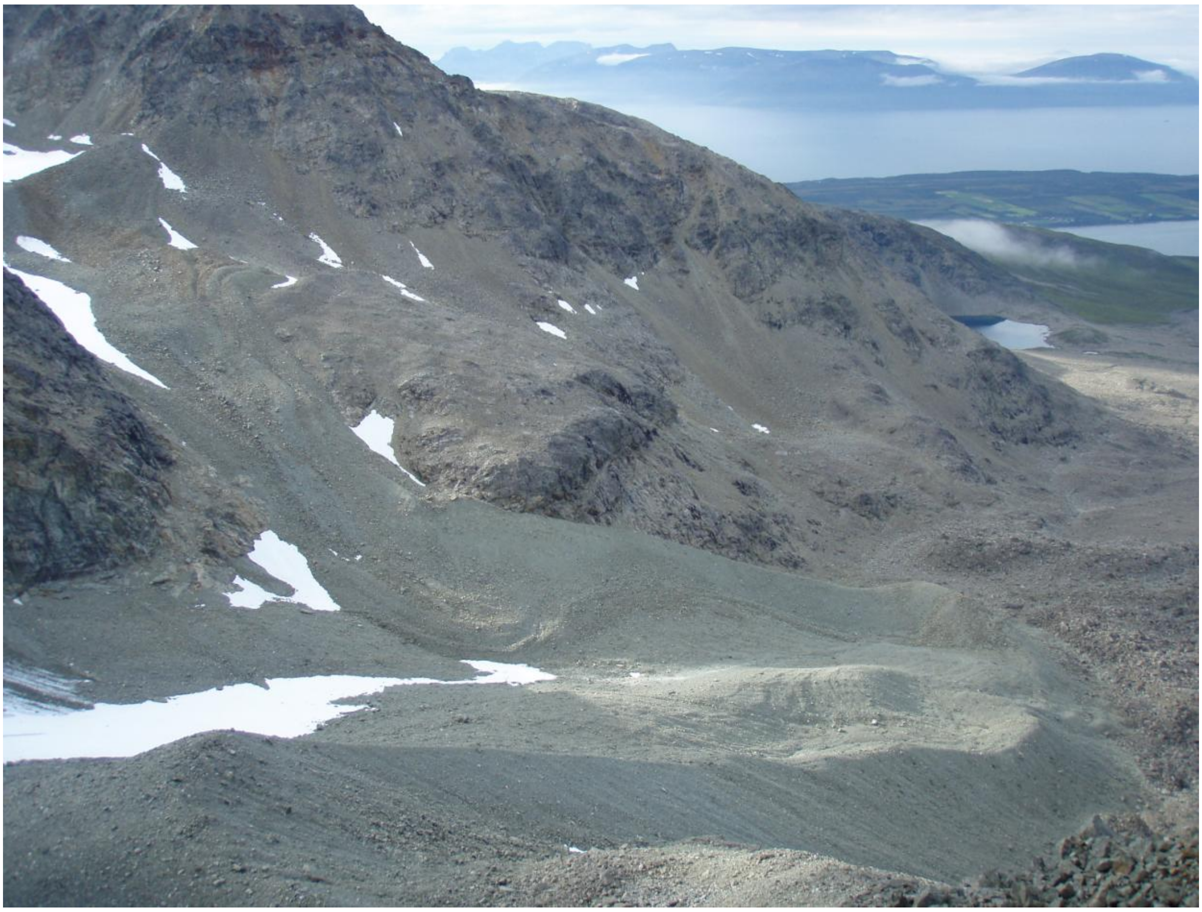


Figure 3.1.2.10. Flutes and retreat ridges over the surface of moraine segments V6b and V6c that merged together at the former confluence of cirque glaciers 11 and 12. The proximal slope of segment V6c (midground) appears to have crept downhill under the influence of subsequent rock glacier development.

3.1.3 Reindalen

Reindalen is the northernmost valley within the study area, and like Strupskardet, it transects the peninsula from west to east. Moraines within Reindalen were studied between Ullsfjord and the watershed, approximately 7 kilometres towards Lyngenfjord. Vestra Reinaelva drains through the till below the cirques at the top of the valley, via three glacial lakes, and reaches the fjord at Sørlenangen. The centre of the valley is relatively broad, open and covered with morainic debris. The northern slopes display lateral moraines and avalanched talus cones while the southern side features deeply incised headwalls that contain the remnants of two small cirque glaciers. Reindalen is dominated by a prominent central peak; informally called the 'Sugarloaf' in this study, for its characteristic conical shape (Figure 3.1.3.1). The major moraines and landforms in Reindalen are described as follows (Figure 3.1.3.2).

Figure 3.1.3.1. Reindalen and the 'Sugarloaf', a prominent peak informally named for its conical shape (left). The surface of the valley is covered with till and northern slopes are decked with avalanched talus cones (right).

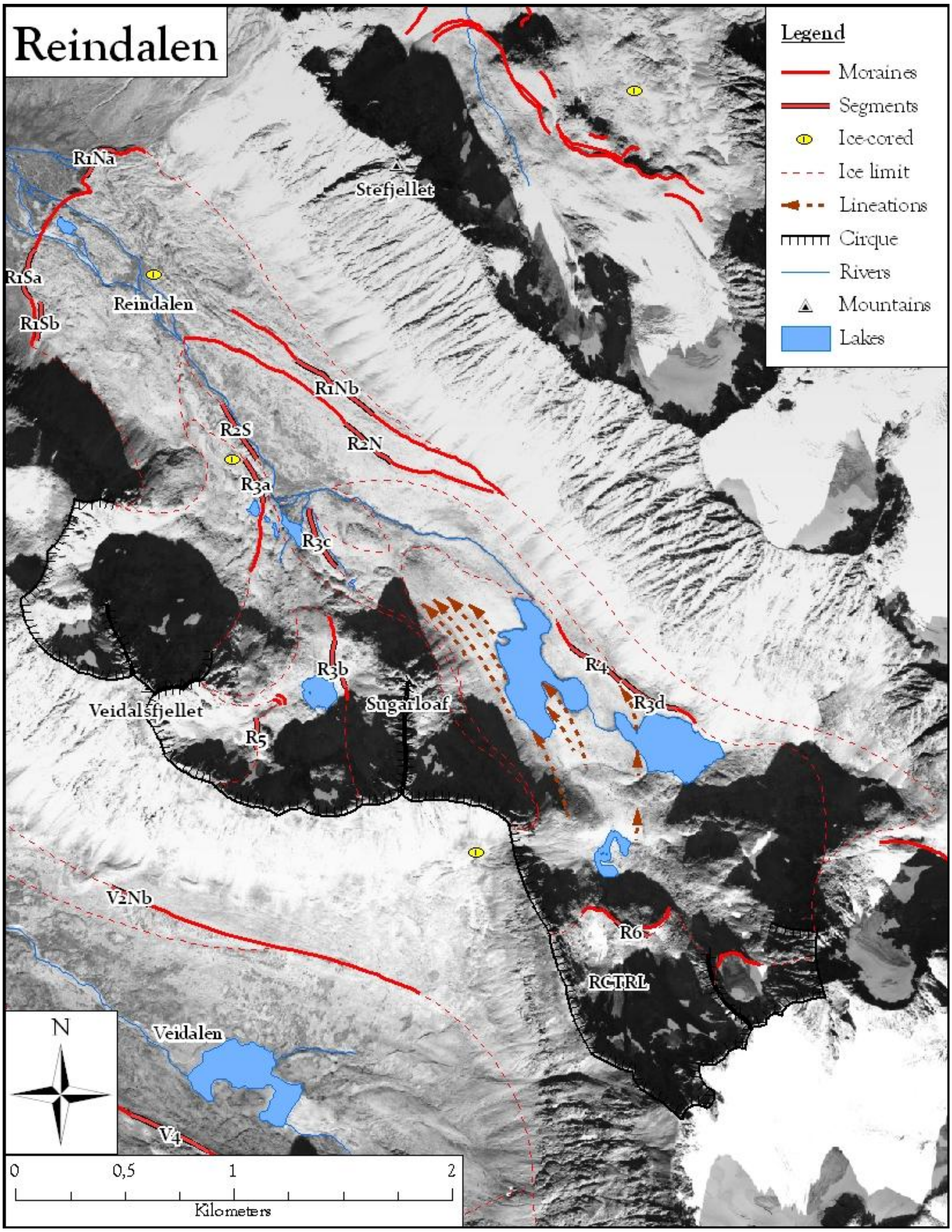


Figure 3.1.3.2. Map of Reindalen, displaying moraines and their segments that were studied in detail. Lineations are comprised of serpentine boulders, and indicate the direction of former glacier flow.

R1 marks the most significant glacial event in Reindalen and is clearly defined by the outermost end moraine that spans the valley at 260 m.a.s.l.; comprised of segments R1Na and R1Sa. Reindalen is lush and vegetated on the distal side of this moraine, while the floor of the valley within is mostly barren and completely covered with till. The proximal side of segments R1Na and R1Sa is covered by a large area of hummocky till with numerous collapse depressions diagnostic of relict ice-cored moraines. The northern side of the valley features two relict rock glaciers on either side this topographical boundary: the outer landform being partially eroded and vegetated, while the inner appears to be fresher and more recently active (Figure 3.1.3.3).

Moraine segment R1Sb lies directly behind R1Sa and appears to be a minor crest formed during the same phase. Segment R1Nb appears as a long, undulating crest that can be traced through a belt of relict ice-cored moraines on the north side of the valley. R1Sb and R1Nb appear to represent slight fluctuations of debris-rich ice that flowed through Reindalen during this phase, which was otherwise dominated by huge volumes of debris being sloughed from both sides of the valley.

Figure 3.1.3.3. Relict rock glaciers and belt of relict-ice-cored moraines mark the outermost glacial limit of phase R1 in Reindalen.

Phase R2 includes two moraine segments, R2N and R2S. R2N is a long, narrow, lateral moraine that descends from 470 m.a.s.l and separates the relict ice-cored moraines on the northern side of the valley side from the ground moraine that blankets the floor of Reindalen. R2S is an undulating and fragmented ridge along the southern riverbank of Reinelva, and appears chaotic and hummocky on its distal side. These two segments appear to mark the northern and southern edges of a former valley glacier that flowed down to 320 m.a.s.l. (within 1 km of the R1 end moraine crest). The poorly-defined distal side of R2S may be attributed to waves of ice-rich debris that flowed from the cirque north of Veidalsfjellet which began to press towards with the valley glacier. Sections of R2S appear to have been washed out, possibly by meltwater flowing along the margin of the glacier, and collapse depressions within the till to have become filled with finer sediments (Figure 3.1.3.4).

Figure 3.1.3.4. Collapse depressions infilled with glaciofluvial outwash in moraine segment R2S at the margin of a former valley glacier. Water flow (from right to left) appears to have eroded sections of the moraine, which washed out larger boulders and filled formerly ice-cored hollows with finer sediments.

Phase R3 is represented by four lateral moraines located in different parts of Reindalen. Segment R3a is a well-defined, curved crest between 350 - 410 m.a.s.l., containing a chaotic, hummocky landscape of numerous small ponds on its proximal side. These appear to be formed within kettle holes as a result of meltout of buried ice (Figure 3.1.3.5). R3a appears to have been constructed by a short tongue of debris-laden ice that flowed from the cirque north of Veidalsfjellet, before it almost converged with segment R2S of the previous phase.

Segment R3b is a short, rounded lateral moraine, that was formed by a small glacier in the adjacent cirque (eastwards), and which has led to the impoundment of a small, round lake beside the 'Sugarloaf' (Figure 3.1.3.6). Segment R3c extends northwards from beneath the Sugarloaf, probably as a lateral valley glacier moraine that diverged around a small knoll, towards a small, blue lake that is currently being filled with a prograding delta (Figure 3.1.3.5).

R3d is a segment of a lateral moraine which skirts the northern shore of a large lake at the top of the main valley, at altitude of 460 m.a.s.l.. It is partially vegetated with grasses, is uniformly comprised of gabbro clasts, and features at least 3 semi-parallel ridges that indicate slight fluctuations of the valley glacier margin during its construction. Phase R3 appears to mark a complex glacial readvance in Reindalen where local conditions simultaneously constructed lateral moraines beside two cirque glaciers and a central valley glacier.

Figure 3.1.3.5. Ponds within kettle holes, formed by the meltout of buried ice behind the hummocky proximal side of moraine segment R3a (left of Reinelva). Segment R3c (right) extends towards the lake and delta below the 'Sugarloaf'. Lateral moraine segment R2N (right background) defines a belt of relict ice-cored moraines on its distal side.

Figure 3.1.3.6. A small lake at the foot of the 'Sugarloaf' is impounded by moraine segment R3b. Lateral moraine segments R1Nb and R2N can be seen below the talus cones in the background.

Lateral moraine segment R4 is found beside the second large lake in the upper reaches of Veidalen, also at an altitude of approximately 460 m.a.s.l. (as per segment R3d). From aerial photographs it appears to merge with the northern end of R3d, however, field observations reveal it to be comparatively fresh, and comprised of only one crest that is devoid of vegetation and characterised by a high volume of serpentine clasts. Across the valley floor north and east of the Sugarloaf, long boulder trains have formed lineations of till comprised of serpentine that can be observed both in the field and in aerial photographs. These can often be traced upvalley to a source of serpentine bedrock, and indicate the motion of the valley glacier during this phase (Figures 3.1.3.7 and Figure 3.1.3.8).

Figure 3.1.3.7. Lineations of serpentine boulders around the 'Sugarloaf' in Reindalen (foreground) can be traced back to a bedrock source (background).
Figure 3.1.3.8. Boulder trains of serpentine till indicate the movement of the former valley glacier through Reindalen.

The cirque east of Veidalsfjellet has produced the only moraines identified with phase R5 in Reindalen. This includes segment R5: a latero-frontal moraine that rests on a bedrock threshold close to the headwall, and which can be traced to a pair of short, cirque glacier push moraines above the small, round lake. The absence of a glacier within this cirque has led to a tentative suggestion that segment R5 preceded phase R6. Moraine segment R6 is located at the head of Reindalen, in front of a cirque glacier which has an area of only 0.14 km^2 (Østrem et al., 1973). The till is bouldery and unstable and also perched on a bedrock threshold.

3.2 **Schmidt hammer rebound values**

3.2.1 Strupskardet

The Schmidt hammer results (R-values) collected from the 31 landforms in Strupskardet range in value from a mean of 35.28 (segment SX) to 62.01 (segment S13N), with the highest overall mean of 67.08 provided by the bedrock control (SCTRL) (Table 3.2.1.1). Schmidt hammer tests were performed on boulders of feldspar-rich Lyngen gabbro, except for moraine segment SX which was composed of hornblende-rich gabbro. The t-tests indicate the actual inter-relatedness of individual segments (Figure 3.2.1.1), and the following results are described relative to the morphological sequence of the moraines.

Moraines segments S1S (37.12±1.39), S2N (39.19±1.40), S1N (39.66±1.35), S2S (41.12±1.11) represent the remnants of the outermost crests in Strupskardet, which (aside from segment SX) also display the lowest recorded R-values. Although they do not directly correlate with their complementary partners, the data supports their morphological position relative to other moraines.

The t-tests suggest that segments S3Sa (41.78±1.10), S3Nc (43.11±1.40), S3Sb (43.11±0.94), S3Na (44.44±1.21) and S3Nb (44.85±1.20) show a positive association with each other and may have been formed during the same event. Although the relict ice-cored moraine ridges of S3Sc (48.51±0.85) and S3Sd (47.75±1.45) show a morphostratographic association to each other and are expected to belong to this group, the value of the former does not conform, while the latter might be explained by rounded clasts giving higher rebound measurements. Roundness has been identified as an important factor which may increase the average R-value results (McCarroll, 1989b). Some of these segments appear to be statistically related to the latero-frontal moraines that lie behind them, although morphologically this is not possible.

The latero-frontal push moraines: segments S4Nb (44.38±1.28), S7 (45.40±1.17), S5S (45.98±1.35), S8 (46.42±1.21), S5N (46.62±1.34), S4S (47.08±1.24), S6S (47.40±1.18) and S4Na (47.89±1.43) display a steady increase of their mean R-values and a similar 95% CI variability, with each segment being related to 4, 5, or 6 of its neighbours (from left to right in Figure 3.2.1.1). Although these moraines display close relationships with each other, the sequence of mean R-values does not imply the sequence in which they were formed. S6N (50.79±1.71) morphologically belongs in the middle of this group, yet this is not supported by its unexpectedly high mean. However, the clasts within this moraine were identified to be rounded, which could therefore yield higher impact results.

Table 3.2.1.1. Descriptions of clasts within landforms and moraine segments of Strupskardet, Veidalen and Reindalen; including: lithology, roundness, sorting, and R-values from Schmidt hammer measurements.

Landform	Roundness	Sorting	Mean R-value ± 95%CI
S1N	obscured by vegetation	obscured by vegetation	39.66 ± 1.35
S1S	obscured by vegetation	obscured by vegetation	37.12 ± 1.39
S2N	obscured by vegetation	obscured by vegetation	39.19 ± 1.40
S2S	obscured by vegetation	obscured by vegetation	41.12 ± 1.11
S3Na	sub-rounded	very poorly sorted	44.44 ± 1.21
S3Nb	sub-rounded	poorly sorted	44.85 ± 1.20
S3Nc	sub-rounded	very poorly sorted	43.11 ± 1.40
S3Sa	sub-rounded	very poorly sorted	41.78 ± 1.10
S3Sb	sub-angular	poorly sorted	43.11 ± 0.94
S3Sc	angular	moderately sorted	48.51 ± 0.85
S3Sd	rounded	moderately sorted	47.75 ± 1.45
S4Na	sub-rounded	poorly sorted	47.89 ± 1.43
S4Nb	sub-rounded	very poorly sorted	44.38 ± 1.28
S4S	rounded	moderately sorted	47.08 ± 1.24
S5N	sub-rounded	very poorly sorted	46.62 ± 1.34
S5S	rounded	poorly sorted	45.98 ± 1.35
S6N	rounded	poorly sorted	50.79 ± 1.71
S6S	sub-rounded	poorly sorted	47.40 ± 1.18
S7	angular	poorly sorted	45.40 ± 1.17
S8	sub-angular	poorly sorted	46.42 ± 1.21
SX	sub-angular	poorly sorted	35.28 ± 1.61
S10a	angular	very poorly sorted	45.16 ± 1.32
S10b	angular	very poorly sorted	49.54 ± 0.96
S10c	angular	very poorly sorted	48.95 ± 1.19
S11a	angular	very poorly sorted	49.09 ± 1.11
S11b	angular	very poorly sorted	49.04 ± 0.89
S12	sub-angular	poorly sorted	47.86 ± 1.23
SRA	angular	very poorly sorted	56.12 ± 1.00
S13N	sub-rounded	moderately sorted	62.01 ± 1.11
S13S	sub-rounded	very poorly sorted	61.01 ± 1.06
SCTRL	polished	bedrock	67.08 ± 0.78

V1	sub-angular	very poorly sorted	44.33 ± 1.06
V2Na	sub-angular	moderately sorted	44.16 ± 1.06
V2Nb	sub-angular	poorly sorted	49.08 ± 1.19
V2Sa	sub-rounded	moderately sorted	45.27 ± 1.12
V2Sb	angular	poorly sorted	47.52 ± 1.05
V2Sc	sub-rounded	very poorly sorted	47.76 ± 1.16
V2Sd	sub-angular	very poorly sorted	46.45 ± 1.08
V2Se	sub-angular	poorly sorted	45.72 ± 1.30
V2Sf	sub-rounded	very poorly sorted	46.02 ± 1.44
V3a	sub-rounded	very poorly sorted	46.04 ± 1.18
V3b	sub-angular	very poorly sorted	45.37 ± 1.41
V4	sub-rounded	very poorly sorted	54.21 ± 1.60
V5a	angular	poorly sorted	49.21 ± 1.34
V5b	angular	very poorly sorted	48.20 ± 0.94
V5c	angular	poorly sorted	50.86 ± 1.06
V5d	sub-angular	poorly sorted	48.07 ± 1.08
VRGN	angular	poorly sorted	50.58 ± 1.10
VRGS	angular	very poorly sorted	48.33 ± 1.27
V6a	sub-angular	very poorly sorted	63.06 ± 1.25
V6b	sub-angular	very poorly sorted	63.07 ± 1.00
V6c	sub-angular	very poorly sorted	62.25 ± 1.15
V6d	angular	moderately sorted	59.32 ± 0.97
VCTRL	polished	bedrock	68.21 ± 0.51
R1Na	sub-angular	moderately sorted	43.92 ± 1.16
R1Nb	sub-rounded	moderately sorted	46.45 ± 1.22
R1Sa	subrounded	very poorly sorted	43.66 ± 1.21
R1Sb	angular	moderately sorted	44.22 ± 1.35
R2N	angular	poorly sorted	45.29 ± 1.36
R2S	sub-rounded	very poorly sorted	44.38 ± 1.35
R3a	sub-rounded	poorly sorted	48.07 ± 1.46
R3b	sub-rounded	very poorly sorted	49.03 ± 1.72
R3c	sub-rounded	very poorly sorted	44.99 ± 1.33
R3d	angular	very poorly sorted	45.92 ± 1.75
R4	angular	moderately sorted	44.66 ± 1.27
R5	angular	moderately sorted	50.47 ± 1.35
R6	angular	very poorly sorted	60.61 ± 1.32
RCTRL	polished	bedrock	66.07 ± 0.98

Segment SX (35.28±1.61) displays the lowest recorded average, with results that do not compare to any other moraines within Strupskardet. Its location relative to other moraines suggests that the Schmidt hammer values are unlikely to be related to age since deposition. This moraine is comprised of a belt of atypical black and weathered clasts, with individual crystals standing out in relief over the rock surface. When a sample was cut in half and polished, it was found to be composed of hornblende-rich gabbro, which deteriorates more rapidly than feldspar-rich gabbro (Figure 2.2.1.1B). The R-values can be considered void for this landform; however, the results reinforce the importance of testing the Schmidt hammer only on moraines with boulders of a uniform and consistent lithology (McCarroll, 1989a; Nesje et al., 1994; Winkler, 2005), as well as the effect that surface smoothness/roughness may have on the rebound (McCarroll, 1989a; Williams and Robinson, 1983; Winkler, 2005).

The two large, blocky moraines that surround Blåvatnet include segments S10c (48.95±1.19), S11b (49.04±0.89), S11a (49.09±1.11) and S10b (49.54±0.96). The average rebound values for these moraines are seen to cluster together in the graph, and the t-tests indicate that they also bear a statistically significant relationship to each other. Segment S10a (45.16±1.32) belongs morphologically to this group, but displays an anomalously low mean value.

Moraine segment S12 (47.86±1.23) on the shore of the lake has a lower average than the S10 and S11 moraines, yet it is considered to be statistically related to them because its 95% CI covers both of their mean rebound values. Although it may also be associated with the same phase, the mean R-value is too low and conflicts with the sequence of moraine deposition.

SRA (56.12±1.00) is the landform interpreted to be a rock avalanche derived from the slopes of Jægervasstindan. This deposit does not display a statistical correlation to any other landforms in Strupskardet, but its mean R-value does conform to its location within the moraine sequence, i.e. between moraines S12 and S13.

Segments S13S (61.01±1.06) and S13N (62.01±1.11) lie closest to East Lenangsbreen and record the highest measurements of all depositional landforms in Strupskardet. These segments correlate only to each other and together they form a unique group that supports their relatively recent construction.

The roches moutonnées directly below the glacier record the highest average measurement and the least variability, which justify SCTRL (67.08±0.78) as a suitable control point.

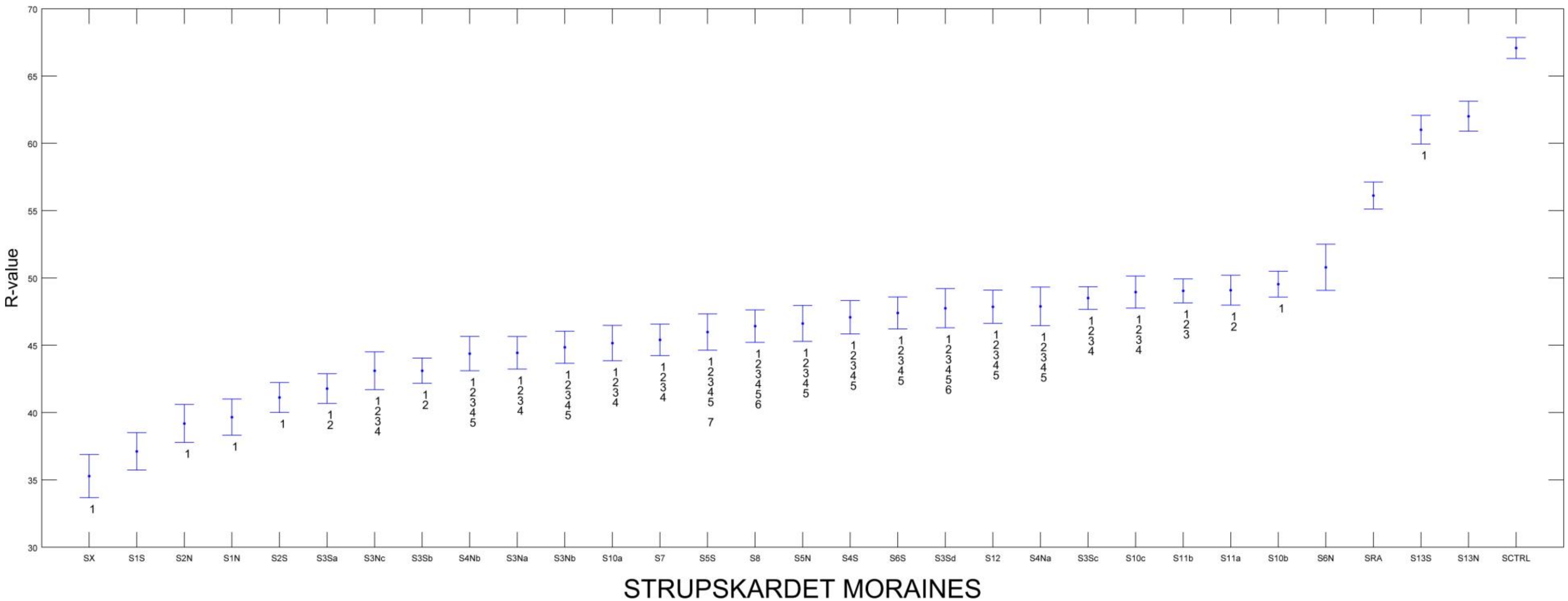


Figure 3.2.1.1. Graph of Schmidt hammer rebound values for all landforms in Strupskardet. Correlations between moraines are considered to be statistically significant (0.05) where the bars of the 95% CI limit of one moraine overlaps the mean R-value of another. A positive relationship between a moraine and its consecutive neighbours (from left to right) is indicated by those numbers beneath the CI bar (detailed description in section 2.2.3).

3.2.2 Veidalen

The measurements from Veidalen were collected from 23 landforms and displayed rebound values within a range of 44.16 (segment V2Na) to 63.07 (segment V5b) with the highest mean measurement of 68.21 collected from the bedrock control point (VCTRL) (Table 3.2.1.1). Schmidt hammer tests were performed on boulders of feldspar-rich Lyngen gabbro. The spectrum of results reflects a general relationship to the sequence of moraines formed during glacier retreat (Figure 3.2.2.1), and are presented in this morphological sequence.

The outermost and relict ice-cored moraines segments are represented by: V2Na (44.16±1.069), V1 (44.33±1.06), V2Sa (45.27±1.12), V2Se (45.72±1.30), V2Sf (46.02 ± 1.44), V2Sd (46.45±1.08), V2Sb (47.52±1.05) and V2Sc (47.76±1.16). Each segment shows a progressive but only slight increase in its average value from one to the next, as well as a very similar 95% CI variation. The t-tests indicate that each segment is statistically related to 2, 3 or 4 of its neighbours (from left to right in Figure 3.2.2.1), and implies that these moraines are indeed the oldest in Veidalen. The mean value of segment V2Nb (49.08±1.19) is within the 95% CI of V2Sb (47.52±1.05) and V2Sc (47.76±1.16), but otherwise appears to display a slightly high value. These two segments also correlate with many of those within phase V5, although this is not reflected morphostratigraphically.

Moraine segments V3b (45.37 ± 1.41) and V3a (46.04±1.18) correlate directly to one another, but also to many of the phase V2 moraines, thereby making them difficult to distinguish statistically as a subsequent glacial phase.

Segment V4 (54.21 ± 1.60) is the long medial/lateral moraine in the centre of Veidalen, and is the only crest attributed to this phase. It stands alone statistically and geographically from all other moraines, and its exceptionally high mean value is considered to be anomalous.

The two arcuate crests: V5a (49.21±1.34) and V5b (48.20±0.94), that enclose the rock glacier/rock avalanche in Veidalen, correlate directly to each other in the t-tests. They also correlate with the multi-crested moraine, segment V5d (48.07±1.08), on top of the large talus-covered rampart. Segment V5c (50.86±1.06) displays a slightly higher mean with a positive relationship only to V5a; however, the overall results suggest that the grouping of these moraines into the same phase has been justified.

Rebound values from the rock glacier, were not collected for a direct correlation, but to place this landform within the context of the surrounding moraines. The R-values for the rock avalanche/rock glacier, VRGS (48.33±1.27) and VRGN (50.58±1.10), lie between the values of the phase V5 segments, suggesting that these landforms are of a similar age. However, the slightly higher mean of the elongated component (VRGN) may imply that these boulders were more recently deposited; thereby supporting Griffey and Whalley's (1979) theory of rock glacier development.

The moraine segments in front of the remaining cirque glaciers: V6d (59.32±0.97), V6c (62.25±1.15), V6a (63.06±1.25) and V6b (63.07±1.00), display the highest measurements from all crests in Veidalen. The t-tests do not suggest a correlation between V6d and its three companions, which show direct inter-relationships, but in comparison to the other landforms throughout the valley, these four moraine segments create a distinct cluster, with R-values that reliably represent the most recent glacial event in Veidalen.

Measurements from VCTRL (68.21±0.51) were collected from bedrock roches moutonnées most recently exposed by the retreating cirque glacier. This provided the highest overall R-values and the lowest variability from all locations in Veidalen, thereby confirming its reliability as a control point.

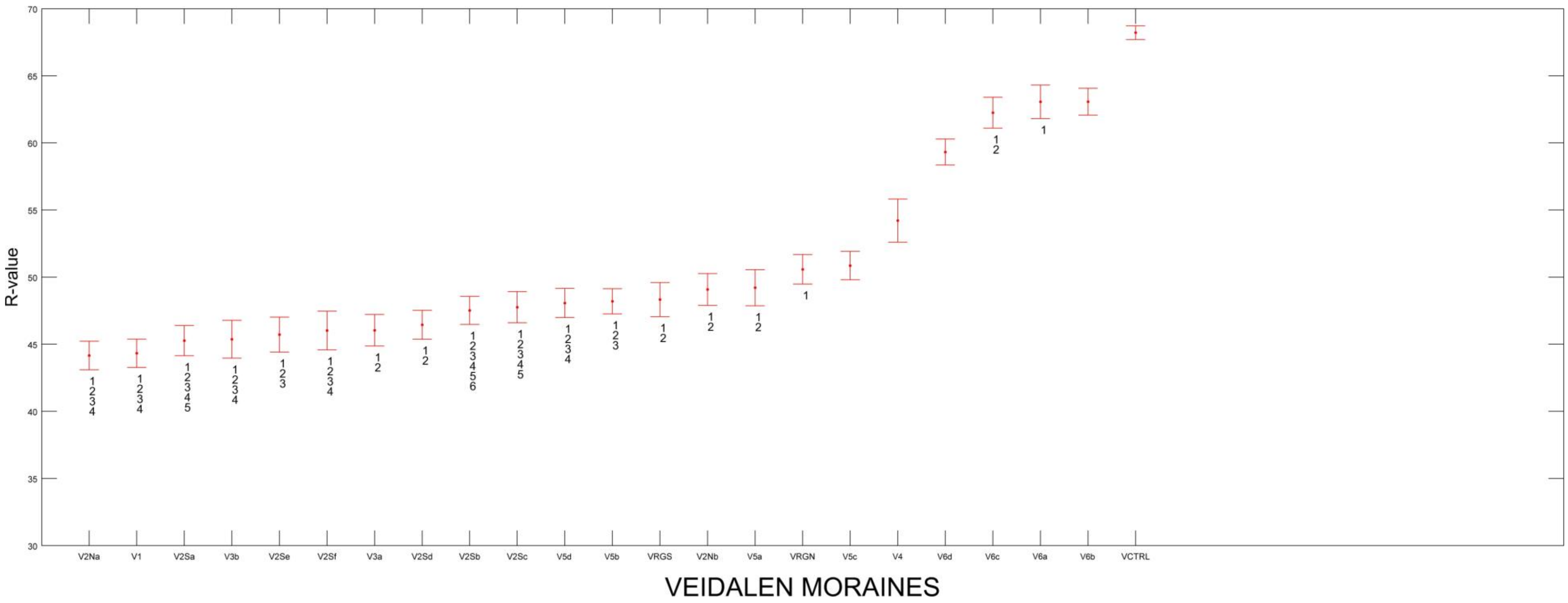


Figure 3.2.2.1. Graph of Schmidt hammer rebound values for all landforms in Veidalen. Correlations between moraines are considered to be statistically significant (0.05) where the bars of the 95% CI limit of one moraine overlaps the mean R-value of another. A positive relationship between a moraine and its consecutive neighbours (from left to right) is indicated by those numbers beneath the CI bar (detailed description in section 2.2.3).

3.2.3 *Reindalen*

The rebound values in Reindalen were collected from 14 landforms, and displayed mean values from 43.66 (segment R1Sa) to 60.61 (segment R6), and the highest overall average of 66.07 from the bedrock control (RCTRL) (Figure 3.2.1.1). Schmidt hammer tests were performed on boulders of feldspar-rich Lyngen gabbro. The rebound values showed a limited degree of variation for most moraines within the valley, with the crests deposited directly in front of the cirques displaying the highest results (Figure 3.2.3.1).

The outmost frontal moraines, segments R1Sa (43.66±1.21) and R1Na (43.92±1.16) (which belong to the same crest) display the lowest averages, and correlate accurately to each other as well as crest R1Sb (44.22±1.35) located just behind them.

Following, from lowest to highest, are segments R2S (44.38±1.35), R3c (44.99±1.33), R2N (45.29±1.36), R3d (45.92±1.75) and R1Nb (46.45±1.22) which display small increases in their mean values and similarly slight variations in their 95% confidence intervals. Each segment exhibits a statistical relationship with up to 7 of its neighbours (from left to right in Figure 3.2.3.1), but provides no correlation with the morphological order of moraines along the valley. The data suggest that the time between the deposition of these moraines is too close to separate their sequence of construction. The R-value from segment R4 (44.66±1.27) also appears in within this group, which does not correspond to the timing of many others.

The lateral moraine segments, R3a (48.07±1.46) and R3b (49.03±1.72), that were produced by two former cirque glaciers either side of Veidalsfjellet, display marginally higher mean values than the previous group and correlate to each other. Lateral moraines R3d (45.92±1.75) and R3c (44.99±1.33) may be expected to belong to this pair, but this is not supported by the data.

The mean of segment R5 (50.47±1.35), in front of the glacier-free cirque, stands apart from the aforementioned landforms and suggests it was deposited more recently. Segment R6 (60.61±1.32) is located in front of the remaining cirque glacier at the top of the valley and its recent deposition is reflected by the highest R-value collected from moraines in Reindalen.

The polished bedrock, RCTRL (66.07±0.98), in front of glacier unit 8, provided the highest overall measurements and a reliable control point data collection for Reindalen.

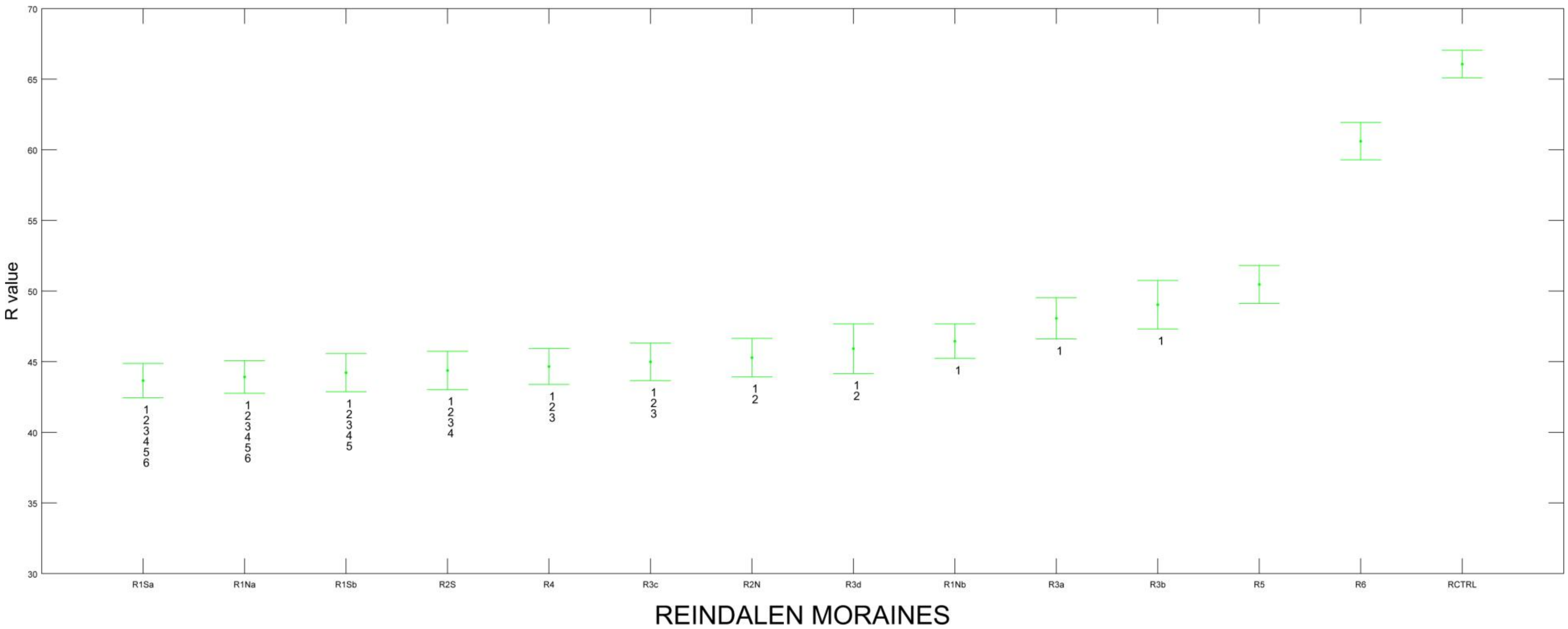


Figure 3.2.3.1. Graph of Schmidt hammer rebound values for all landforms in Reindalen. Correlations between moraines are considered to be statistically significant (0.05) where the bars of the 95% CI limit of one moraine overlaps the mean R-value of another. A positive relationship between a moraine and its consecutive neighbours (from left to right) is indicated by those numbers beneath the CI bar (detailed description in section 2.2.3).

3.2.4 *Intervalley correlations*

The R-values correlated between the three valleys included results from 62 moraine segments, 3 rock avalanche landforms and 3 bedrock control points. The (reliable) mean values for the moraines range from 37.12 (segment S1S, the outermost in Strupskardet), to 63.07 (segment V6b, a cirque glacier moraine in Veidalen), with the highest value overall from the control point, VCTRL in Veidalen.

The graph indicates several clusters of R-values that correlate to the relative positions of moraines across the three valleys (Figure 3.2.4.1), including:

1. the outermost moraines in Strupskardet
2. a spectrum of lower mean values showing a steady retreat of glaciers from all valleys
3. a spectrum of slightly higher mean values representing a readvance of cirque glaciers
4. the most recently deposited crests in front of all cirques
5. a grouping of the 3 control points.

The cluster with the lowest recorded values was collected in Strupskardet, and includes moraine segments S1S (37.12±1.39), S2N (39.19±1.40) S1N (39.66±1.35) and S2S (41.12±1.11). These represent the two outermost stages, S1 and S2, suggesting that these moraines are more weathered or were deposited prior to other moraines from all three valleys.

The following group continues from S3Sa (41.78±1.10) up to S4Na (47.89±1.43), and includes more than half of all moraines measured in Lyngen. The average R-values increase marginally from one crest to the next and generally correlate with 8 to 16 of their sequential neighbours, making it difficult to isolate distinct relationships. However, 3 subgroups may be very loosely observed, relative to their morphological positions, if those moraines with previously mentioned anomalous results are excluded. The first subgroup includes values from S3Sa (41.78±1.10) to V1 (44.33±1.06) and represents moraines from stage S3 in Strupskardet, V1 in Veidalen and R1 in Reindalen. The second subgroup includes values from S4Nb (44.38±1.28) to V2Se (45.72±1.30) and represents moraines from stage V2 in Veidalen, R2 in Reindalen and two crests from stage S3 in Strupskardet. The third subgroup includes values from R3d (45.92±1.75) to S4Na (47.89±1.43) and represents most latero-frontal push moraines in Strupskardet in addition to some crests from Veidalen and Reindalen.

The third assemblage ranges from V5d (48.07 ± 1.08) through to V4 (54.21±1.60) and includes: the well-defined crests of the blocky, push moraines surrounding Blåvatnet, S10 and S11, in Strupskardet; all of the V5 moraines in Veidalen; as well as moraines from stages R3-R5 in Reindalen. The rock glacier landforms in Veidalen, VRGS and VRGN, also appear to have been emplaced during this time.

The most recently constructed moraines, located directly in front of the remaining cirque glaciers, form a neat cluster and represent the highest values of depositional landforms throughout the three valleys. These include all moraines of phase S13 in Strupskardet, phase V6 in Veidalen, and phase R6 in Reindalen. While t-tests indicate that most, but not all, can be directly correlated, the grouping of these results at the higher end of the R-value spectrum suggest they were formed during the same glacial event.

The bedrock control points from each of the three valleys indicate an apparent clustering of the highest measurements of all of the rebound values. The means of SCTRL (67.08±0.78) and RCTRL (66.07±0.98) display a direct comparison to each other, while VCTRL (68.21±0.51) has a slightly higher and also the hardest recorded rebound value.

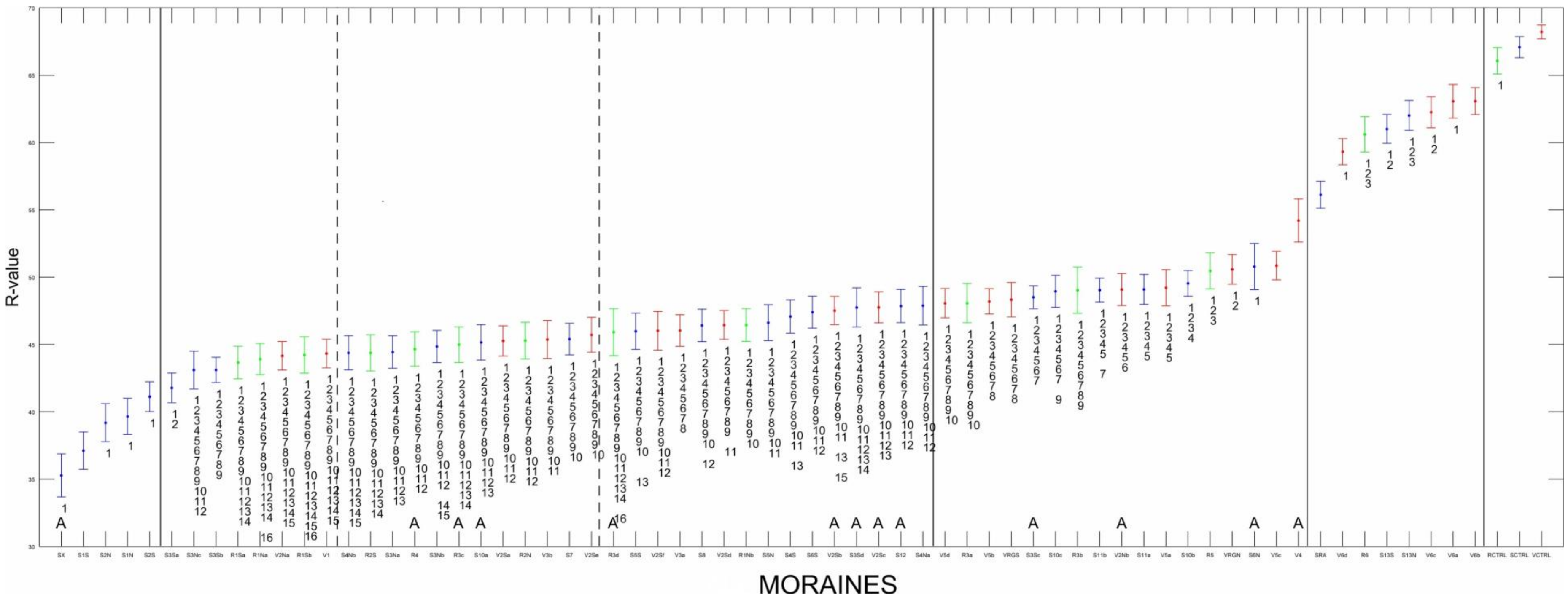


Figure 3.2.4.1. Graph of Schmidt hammer rebound values for all landforms in Strupskardet (blue), Veidalen (red) and Reindalen (green). Correlations between moraines are considered to be statistically significant (0.05) where the bars of the 95% CI limit of one moraine overlaps the mean R-value of another. A positive relationship between a moraine and its consecutive neighbours (from left to right) is indicated by those numbers beneath the CI bar (detailed description in section 2.2.3). (A = anomalous rebound values).

3.3 Equilibrium Line Altitudes

3.3.1 *Maximum elevation of lateral moraines*

The maximum elevation of lateral moraines (MELM) method defines the ELA at the highest altitude of a crest formed by a glacial advance. However, within the three valleys this technique could not be applied to moraines that had been buried by talus from the steep valley walls, or had been buried or reworked by subsequent glacial advances or periglacial processes such as the development of rock glaciers. These restrictions eliminated most crests from the use of this method, which could therefore only be applied to 7 moraines in Strupskardet, 8 in Veidalen, and 6 in Reindalen (Table 3.3.1.1).

The MELM method consistently displays the lowest ELA results of the four equilibrium line altitude techniques. The ELAs derived from lateral moraines within the study area generally (but not always) increase in elevation from the earliest to the most recent events, as should be expected. This is demonstrated in Strupskardet, where the MELM of ice-cored moraines S3Sb (320m) and S3Sc (300m) display a similar or higher altitude than the valley moraines S6S, S7, S8 and S11 (300m, 215m, 275m, and 310m, respectively) which were deposited later when the ELA could only have been higher.

In Veidalen, the results show that a single glacial event may be represented by several different ELAs provided by contemporaneous cirque glacier moraines: V6a, V6b, V6c and V6d (800m, 695m, 695m and 710m). Furthermore, the MELM of moraines V2Nb, V2Sf, V3b and V5d are derived from different sources of ice and influenced by variable topographic effects, thereby introducing inaccuracy into the determination of a single ELA.

In Reindalen, the crests that represent the older to younger events (R1-R6) display a stepwise rise of the ELA, yet each MELM is provided by cirque glacier moraines, valley glacier moraines, and ice-cored moraines dispersed throughout the valley. These ELAs therefore do not represent a sequential retreat of a single body of ice and do not allow for local topographic conditions.

Table 3.3.1.1. Equilibrium line altitude results for glacier elevation methods: the maximum elevation of lateral moraines (MELM), median elevation of glaciers (MEG), and the terminus-to-headwall altitude ratio (THAR) method.

Moraine	Altitude terminus (m)	Altitude headwall (m)	ELA (MELM)	ELA (THAR=0.35)	ELA (THAR=0.40)	ELA (MEG)
S1	10	1400	-	496.5	566	705
S2	25	1400	-	506.25	575	712.5
S3	55	1400	320 (S3Sb)	525.75	593	727.5
S3	-	-	300 (S3Sc)	-	-	-
S4	115	1400	-	564.75	629	757.5
S5	130	1400	-	574.5	638	765
S6	-	-	300 (S6S)	-	-	-
S7	-	-	215	-	-	-
S8	160	1400	275	594	656	780
S9	175	1400	-	603.75	665	787.5
S10	180	1400	-	607	668	790
S11	185	1400	310	610.25	671	792.5
S12	190	1400	-	613.5	674	795
S13	260	1400	640	659	716	830
V2Na	185	1140	480 (V2Nb)	519.25	567	662.5
V2Sc	200	1000	-	480	520	600
V2Sf	320	700	400	453	472	510
V3b	410	700	-	511.5	526	555
V4	235	1140	440	551.75	597	687.5
V5	350	1120	840 (V5d)	619.5	658	735
V6a	660	1140	800	828	852	900
V6b	490	1120	695	710.5	742	805
V6c	480	1000	695	662	688	740
V6d	670	940	710	764.5	778	805
R1N	260	1040	-	533	572	650
R2N	315	1040	-	568.75	605	677.5
R2S	-	-	350	-	-	-
R3a	-	-	410	-	-	-
R3b	470	940	520	634.5	658	705
R3c	370	1040	-	604.5	638	705
R4	-	-	465	-	-	-
R5	540	940	625	680	700	740
R6	610	1040	660	760.5	782	825

3.3.2 *Median elevation of glaciers*

The median elevation of a glacier (MEG) identifies the midpoint of the glacier's altitudinal range. Throughout the three valleys, the frontal parts of push/cirque moraines are generally better preserved than the upper limits of lateral moraines. This allowed the equilibrium line altitude to be calculated for more crests using the MEG than the MELM method (Table 3.3.1.1).

In Strupskardet, the staggered retreat of Lenangsbreen has left a reliable series of moraines that allow for the distance between the terminus to the cirque headwalls to be easily measured. The upper limit of Lenangsbreen currently coincides with the highest contour line within its headwall of the cirque. The results show that from the outermost/oldest moraine, S1 (705m), the ELA steadily rises up to the innermost/most recent, S13 (830m), and provides MEG measurements for almost all phases in Strupskardet. This sequence of ELAs is less haphazard than those from the other two valleys because the same cirque headwall behind the plateau glacier of Lenangsbreen is used for all calculations.

In Veidalen, the MEG for phase V2 is determined from ice-cored moraines, cirque glacier moraines and valley glacier moraines, which provide ELAs differing by as much as 150 metres (V2Sf: 510m; V2Na: 662m); most of which are measured from different headwalls. The ELA for phase V6 is represented by the MEG of four separate cirque glaciers moraines (V6a, V6b, V6c and V6c); each derived from different headwalls and thereby suggesting very different equilibrium line altitudes (900m, 805m, 740m, and 805m respectively).

In Reindalen, the MEG rises from the earliest phase, R1 (650m), up to the most recent, R6 (825m), despite the glaciers flowing from two headwalls. Within Strupskardet, Veidalen and Reindalen, the MEG method requires the use of different cirques with their own topographic variables, which may introduce errors when correlating glacial events between valleys.

3.3.3 *Terminus-headwall altitude ratio*

The terminus-to-headwall altitude ratio (THAR) technique uses the same points of reference as the MEG method, but instead of the ELA being calculated at the midpoint (0.5) of the overall glacier length, the ablation area to the total altitudinal range is calculated as a ratio of 0.35 :1 or 0.4 :1. This technique implies that the ELA with a THAR of 0.35 will always be found at a lower altitude than when a ratio of 0.4 is applied (Table 3.3.1.1).

In Strupskardet, the THAR results show that from the outermost/oldest moraine, S1 (496m, 566m), the ELA rises steadily rises towards the innermost/most recent, S13 (659m, 716m). As per the MEG method, the sequence of ELAs appears to be more regular as the glacier is sourced from the same cirque headwall.

In Veidalen, the problems that occurred with the MEG method arise again when ice-cored moraines, cirque glacier moraines, valley glacier moraines and different headwalls are used to calculate the ELA for phase V2, with the ELAs varying by 70-100 metres (V2Sf: 453m, 472m; V2Na: 519m, 567m). The ELA for phase V6 is represented by four separate cirque glaciers moraines (V6a, V6b, V6c and V6c); each derived from different headwalls and thereby resulting in very different equilibrium line altitudes (828m, 852m; 710m, 742m: 662m, 688m; and 764m, 778m respectively).

In Reindalen, the ELA rises from the earliest phase, R1 (533m, 572m), up to the most recent, R6 (760m, 782m), even although the glaciers flow from two headwalls.

Within Strupskardet, Veidalen and Reindalen, the THAR technique requires the use of different cirques with their own topographic variables, as for the MEG method; this again may introduce a potential for error when correlating glacial events between valleys.

3.3.4 Accumulation-area ratio

The new AAR technique measured the ratio of the ablation area of a reconstructed glacier limit to its total area, much the same as the traditional accumulation-area ratio method. Either technique can only be applied were this area was well defined by moraines or trimlines, such as discrete cirque glaciers or where valleys glaciers were formed by a single body of ice. This procedure was only able to measure those glacial phases that were not comprised multiple separate glaciers and those that were not surrounded by chaotic topographic contours. The equilibrium line altitude was accurately determined for three glacier limits in Strupskardet, two in Veidalen, and three in Reindalen. The results calculated for an AAR=0.65 and an AAR=0.6, respectively, are described as follows (Table 3.3.4.1).

In Strupskardet, the former ice limits of phases S1 to S8 extends further westwards into the valley towards Lyngenfjord and were fed by several cirque and plateau glaciers: an area that has not been mapped and so could not be used in ELA evaluations. The paleo-glaciers of S10 and S12 were supplied with ice from east Lenangsbreen and west Lenangsbreen (glacier units 18 and 19 in Østrem et al., 1973). The ELAs for S10 were located at 1000m and 1050m; and for S12 at 1050m and 1200m. The present day ELA of glacier 18 was found at 1040m and 1070m. The discrepancy between the ELAs of east Lenangsbreen (glacier 18) and paleo-glacier S12 is attributed to the number of glaciers used in this calculation.

In Veidalen, the well-defined valley glacier of V2 recorded ELAs of 570m and 590m. Phase V6 is represented by four cirque glaciers; and the least complex of these (V6a) measured ELAs of 840m and 865m. In Reindalen, the outermost moraine of R1 displayed the lowest ELAs: 540m and 580m. Cirque glacier R5 was found to have ELAs of 750m and 770m. And the cirque glacier of R6 was calculated to have ELAs of 825m and 830m.

Few ice limits permitted the use of the AAR technique in Strupskardet, Veidalen and Reindalen. However, the results indicate a close correlation between the former glaciers of V2 and R1 (ELA ≈ 580m); and V6a and R6 (ELA ≈ 840m).

Table 3.3.4.1. Equilibrium line altitude results for the accumulation-area ratio method (AAR).

Glacier limit	Total area (km^2)	0.35 of total area (km^2)	0.4 of total area (km^2)	ELA (AAR=0.65)	ELA (AAR=0.6)
S10	6.399	2.239	2.559	1000	1050
S12	5.475	1.916	2.190	1050	1200
East Lenangsbreen	1.373	0.480	0.549	1040	1070
V2	13.054	4.569	5.221	570	590
V6a	0.470	0.164	0.188	840	865
R1	6.989	2.446	2.795	540	580
R5	0.170	0.059	0.068	750	770
R6	0.490	0.171	0.196	825	830

4 Discussion

4.1 Equilibrium Line Altitudes

The maximum elevation of lateral moraines (MELM) method could not be applied to most of the moraine crests in the three valleys of northern Lyngen because they were often deposited on steep, unstable slopes, or subsequent burial and reworking by glacial or periglacial processes. This led to the lowest ELA measurements of the four equilibrium line altitude techniques; a result identified as problematic by previous researchers (Benn and Evans, 2010; Dahl and Nesje, 1992; Nesje and Dahl, 2000; Rea et al., 1999; Torsnes et al., 1993). Where individual phases were represented by several separate crests (e.g. from different cirque glaciers), the ELAs did not always rise sequentially upvalley, consistent with uniform glacier retreat, suggesting that local topography has a significant effect on the MELM results. This method is therefore not considered appropriate for determining ELAs within the study area.

The median elevation of glaciers (MEG) technique could be applied to more former glaciers than the MELM method, as the end/cirque moraines were generally better preserved than the upper limits of lateral moraines. However, as altitudes were measured from different (and often separated) cirque headwalls, different ELA results could be obtained for the same glacial event. The MEG method has been found to overestimate equilibrium line altitudes (Benn and Evans, 2010; Osipov, 2004), which was reflected by the highest results of the three techniques that calculate ELAs from elevation data. Furthermore, the MEG fails to allow for variations in valley morphology which affects the area-distribution of a glacier (Nesje and Dahl, 2000; Torsnes et al., 1993). As the MEG is an over-simplified technique, it can only provide a crude interpretation of equilibrium line altitudes in northern Lyngen.

The terminus-to-headwall altitude ratio (THAR) method using ratios of 0.35 and 0.4 in the three valleys provided intermediate ELAs, which are comparable to the results found in Strupskardet by Bakke et al. (2005). In Veidalen and Reindalen, different (and often separated) cirque headwalls meant that different equilibrium line altitudes could be recorded for the same glacial event (as per the MEG method). In Strupskardet, the same headwall altitude was used for all calculations, and a THAR of 0.35 measured ELAs most similar to those of Bakke et al. (2005) for glacier limits of S1 through to S12. Although the THAR method appears to be more reliable to determine the ELA of small, geometrically regular glaciers with normal distributions of area/altitude, it does not take into account glacier hypsometry (surface topography) (Benn and Evans, 2010; Osipov, 2004; Rea et al., 1999; Torsnes et al., 1993). Despite the shortfalls of using the THAR, this was the only technique able to provide ELAs for all paleo-glaciers in northern Lyngen.

The accumulation-area ratio (AAR) is considered the most reliable of the four methods used in this study, where glaciers are assumed to be in equilibrium (i.e. AAR = 0.5 to 0.8) (Dahl and Nesje, 1992; Nesje and Dahl, 2000; Osipov, 2004; Porter, 2001; Rea et al., 1999). However, ELA results may be underestimated on glaciers with relatively large ablation areas or overestimated on those with relatively large accumulation areas (Benn and Evans, 2010; Osipov, 2004), especially where ice is contributed from plateau glaciers above (Rea et al., 1999) as was the case in front of Lenangsbreen, Strupskardet. The present day ELA (AAR=0.65) for east Lenangsbreen (glacier unit 18) was identified at 1040 m.a.s.l., almost identical to the results of Bakke et al. (2005). However, the ELAs that were calculated for reconstructed glaciers in Strupskardet appear to be overestimated, and this may indeed be due to their supply from the plateau glaciers of East and West Lenangsbreen (glacier units 18 and 19).

The new AAR technique using GIS tools appears to identify paleo-ELAs more accurately and more efficiently than the traditional method, while still maintaining the original parameters.
The THAR and AAR both identified similar results (ELA≈570m) for the reconstructed ice limits of phases V2 and R1, suggesting that these events in Veidalen and Reindalen occurred at the same time. These two techniques also found a correlation (ELA≈850m) for the former cirque glaciers of V6a and R6, implying that these events could also have been simultaneous.

4.2 Schmidt hammer rebound values

The results from the Schmidt hammer measurements demonstrate that for each valley, the mean rebound values generally increase from the outermost moraines to those that were most recently deposited, although these do not always correlate precisely with the morphostratigraphic sequence observed in the field. The t-test results infer that individual phases within each valley may be grouped into stages of decreasing glacial intensity, described as follows.

The graph (Figure 3.2.1.1) suggests that landforms in Strupskardet can be divided into the following groups:
- the outermost end moraines (S1 - S2)
- relict ice-cored moraines and valley glacier end moraines (S3 – S8)
- lateo-frontal push moraines with multiple crests surrounding Blåvatnet (S10 - S12)
- rock avalanche (SRA) and most recent moraines in front of Lenangsbreen (S13)
- roches moutonnées/bedrock control point (SCTRL)

The graph (Figure 3.2.2.1) suggests that landforms in Veidalen can be divided into the following groups:
- the outermost moraine, relict ice-cored moraines, and valley glacier end moraine (V1 – V3)
- rock glacier (VRGN, VRGS) and latero-frontal moraines with at least 2 minor crests (V5)
- recent cirque glacier moraines in front of glacier units 10, 11, 12 and 13 (V6)
- roches moutonnées/bedrock control point (VCTRL)

The graph (Figure 3.2.3.1) suggests that landforms in Reindalen can be divided into the following groups:
- the outermost end moraines containing relict ice-cored till (R1)
- lateral moraines formed by cirque and valley glaciers (R2 – R4)
- cirque glacier moraine with 2 minor crests (R5)
- most recent moraine in front of the remaining cirque glacier (R6)
- bedrock control point (RCTRL)

The graph (Figure 3.2.4.1) suggests that landforms throughout Strupskardet, Veidalen and Reindalen can be broadly divided into the following groups:
- the outermost end moraines in Strupskardet (S1 - S2)
- end moraines comprised of belts of relict ice-cored material (S3, V - V2, R1)
- lateral and end moraines generally deposited on the valley floors (S4 – S8, V3, R2 – R4)
- the rock glacier (VRGN, VRGS) and well-defined, multi-crested moraines between cirques and valley floors (S10 – S12, V4 – V5, R5)
- recent cirque glacier moraines (S13, V6, R6)
- and bedrock control points (SCTRL, VCTRL, RCTRL)

Based on chronological moraine sequence that was determined from mapping and field work, a new graph displaying the Schmidt hammer R-values was created to examine the reliability of the Schmidt hammer interpretations (Figure 4.2.1). This graphs displays this sequence of moraines (distal to proximal) for Strupskardet, Veidalen and Reindalen, but has been subdivided into respective glacial phases. This phases have been further combined into broader stages, so that each stage may be correlated to the deglacial history of Lyngen during the Late Weichselian and Holocene.

These results suggest that:
- the bedrock/roches moutonnées do provide reliable control points.
- the most recently deposited moraines in front of the cirques in all valleys define a stage (stage 7) that is distinct from the preceding phases.
- the two phases representing the outermost moraines in Strupskardet (stages 1 and 2) stand apart from subsequent phases.
- the Schmidt hammer measurements representing phases between stage 2 and stage 7 are difficult to distinguish from one another, and interpretation of the R-values may be subjective. This implies that either the correlations based on the relative position of moraines is incorrect, or that the R-values should be interpreted with caution for phases preceding stage 7.

As the chronological sequence of moraines in Strupskardet is well defined in aerial photographs and maps, and is supported by Bakke et al. (2005), this provides a reliable model for ELA measurement, but also reinforces the need for caution when using the Schmidt to correlate moraines prior to stage 7.

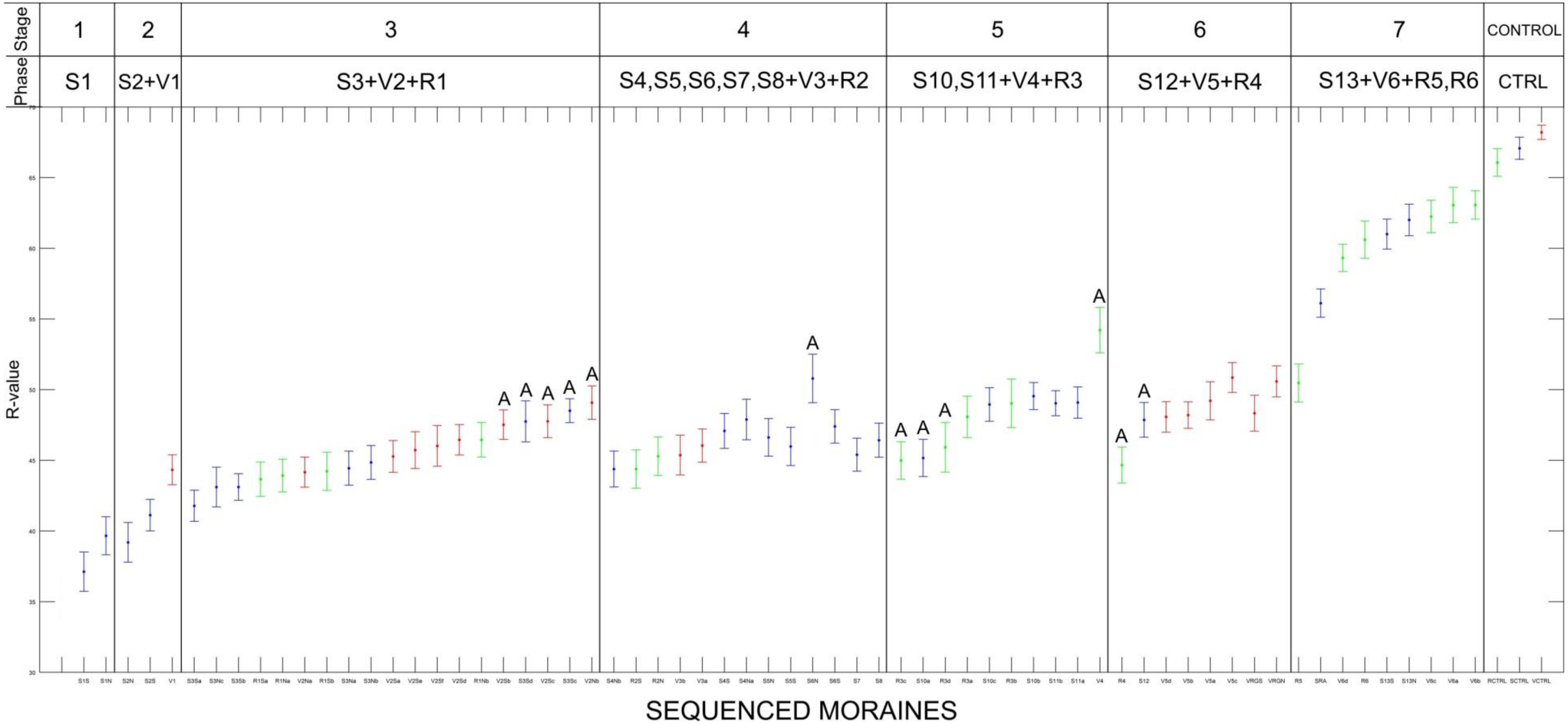


Figure 4.2.1. Graph of Schmidt hammer rebound values arranged from distal (outermost) to proximal (innermost) based on mapping and aerial photograph interpretation. Moraine segments for Strupskardet (blue), Veidalen (red) and Reindalen (green) have been subdivided into chronological sequences of phases and broader stages. (A = anomalous rebound values).

While not being able to date the moraines in absolute terms, the results closely reflect those of previous researchers who have used the Schmidt hammer as a relative dating tool. Winkler (2005) states that Schmidt hammer measurements cannot give a precise absolute dating of the moraines tested, nor differentiate between moraines within single advance periods, but they can allow for distinctions between groups of moraines that may then be correlated with landforms of a known age using other dating techniques. Previous research has found that relative dating using R-values is not able to distinguish between moraines formed during the Little Ice Age (McCarroll, 1991), but this technique enables the separation of sites that were deglaciated during the Little Ice Age from those that were deglaciated during the Lateglacial and early Holocene (Goudie, 2006; Matthews and Shakesby, 1984; McCarroll and Nesje, 1993).

The reliability of Schmidt hammer tests could be improved when combined with other relative dating methods or absolute dating techniques (Goudie, 2006). For example, when R-values are correlated with relative age results from lichenometry (Aa and Sjåstad, 2000; Shakesby et al., 2004; Winkler, 2000) and lacustrine sediment stratigraphy (Aa et al., 2007); or an absolute age-calibration curve may be constructed in association with terrestrial cosmogenic nuclide dating (Matthews and Winkler, 2010; Winkler, 2009). Schmidt hammer results may also be reinforced by ^{14}C dating if organic material is found within the landform being tested (Winkler, 2009). Future research may include the application of relative or absolute dating techniques to the moraines within the study area, so as to construct an age-calibration curve or more precise chronology of deglaciation of the northern Lyngen Peninsula.

The bedrock/roches moutonnées were found to provide reliable control points for each valley, and together these formed a unique statistical cluster with the highest overall R-values; a combined average of 67.12. Although the Schmidt hammer has had limited application to gabbro bedrock in previous research, the results from northern Lyngen may be compared to the Cuillins gabbro/peridotite/granophyrne of Scotland which recorded a mean R-value of 69.9 (Brook et al., 2004).

The variability of weathering rates between different lithologies and mineralogies emphasises the importance of collecting rebound values from only single rock type (Goudie, 2006). This was most clearly demonstrated by the results from moraine segment SX in Strupskardet, which displayed the lowest measurements from all three valleys within the study area. R-values were generally collected from moraines dominated by Lyngen gabbro, however segment SX was found to be comprised of hornblende-rich clasts that weather more rapidly, and surface crystals reduced the rebound of the hammer, thereby recording atypically low results.

The influence of surface texture was noted from moraine segment S6N in Strupskardet that recorded atypically high R-values. This was attributed to the roundness of boulders during course of glacial transport, which is believed to have slightly polished the material tested, not unlike the surfaces of roches moutonnées and bedrock control points. Lichens were also found to limit the availability of boulder surfaces and can cause a dampening effect of the Schmidt hammer rebound. Although lichens were avoided to the best of ability, the obscuration of boulders by vegetation in moraines S1 and S2 meant that surface selection was limited, thereby allowing other variables (such as lithology or structural weaknesses) to introduce potentially erroneous results. The resolution of Schmidt hammer results has been recognised to decrease with increasing age of the rock surface (Černá and Engel, 2010) so as the lowest R-values were collected from the S1/S2 moraines in Strupskardet, they should therefore be interpreted with caution.

The potential for other variables (such as lithology, lichen cover, and boulder surface texture) to influence the rebound values has been recognised, and McCarroll (1989a) recommends that the effect of these should be minimised before the results are uncritically attributed to differences in boulder surface age. As McCarroll (1991) most importantly advises, a critical methodology should be applied when using the Schmidt hammer to measure the degree of surface weathering, and increasing statistical probability should not be confused with establishing the causality of the results.

4.3 Moraine chronology and deglaciation of the northern Lyngen Peninsula

A total of 13 individual glacial phases have been identified in Strupskardet (Bakke et al., 2005), to which the 6 phases in Veidalen and Reindalen may be compared (Figure 4.3.1). These phases were combined into 7 broader stages for comparison to Late Weichselian and Holocene events identified in northern Norway. The chronology of the Late Weichselian and Holocene has been defined by various authors (Andersen, 1980; Berendsen, 2005; Mangerud et al., 1974; Moen, 1999) to which the deglacial history of northern Lyngen has been related.

The most reliable equilibrium line altitude techniques were found to be the AAR and the THAR method, and the ELAs for stages 1 to 7 (combined from all valleys) using these results are presented below (Table 4.3.1).

Table 4.3.1 Equilibrium line altitude results for stages 1 to 7.

Stage	ELA (m.a.s.l)	ELA method	phase/moraine
1	500	THAR=0.35	S1
2	510	AAR=0.65	S2
3	520	THAR=0.35	V2Na
4	570	THAR=0.35	S5
5	620	THAR=0.35	V4
6	760	THAR=0.35	V5d
7	840	AAR=0.65	V6a
Current ELA	1040	AAR=0.65	East Lenangsbreen

Presently, the total area of Strupskardet covered by glaciers within the study area is 2.1 km^2, in contrast to Veidalen (1.1 km^2) and Reindalen (0.14 km^2). While the orientation of the valleys (northwest to southeast) to prevailing snow-bearing winds consistent to each, the area available for snow accumulation is not. Valley glaciers with ice contributed from plateau glaciers (in this case, East and West Lenangsbreen) during marginal periods can react much more rapidly to climate changes favourable for glacier expansion (Rea et al., 1999). The larger catchment in Strupskardet, with ice provided by more sources, implies that glacial advance may be more severe than in Veidalen or Reindalen. This may explain the absence of stage 1 moraines in these two valleys, and stage 2 moraines in Reindalen. Each glacier has its own particular characteristics which will affect the type and speed of its response (Sugden and John, 1976), which may explain differences between glacier fluctuations between the three valleys.

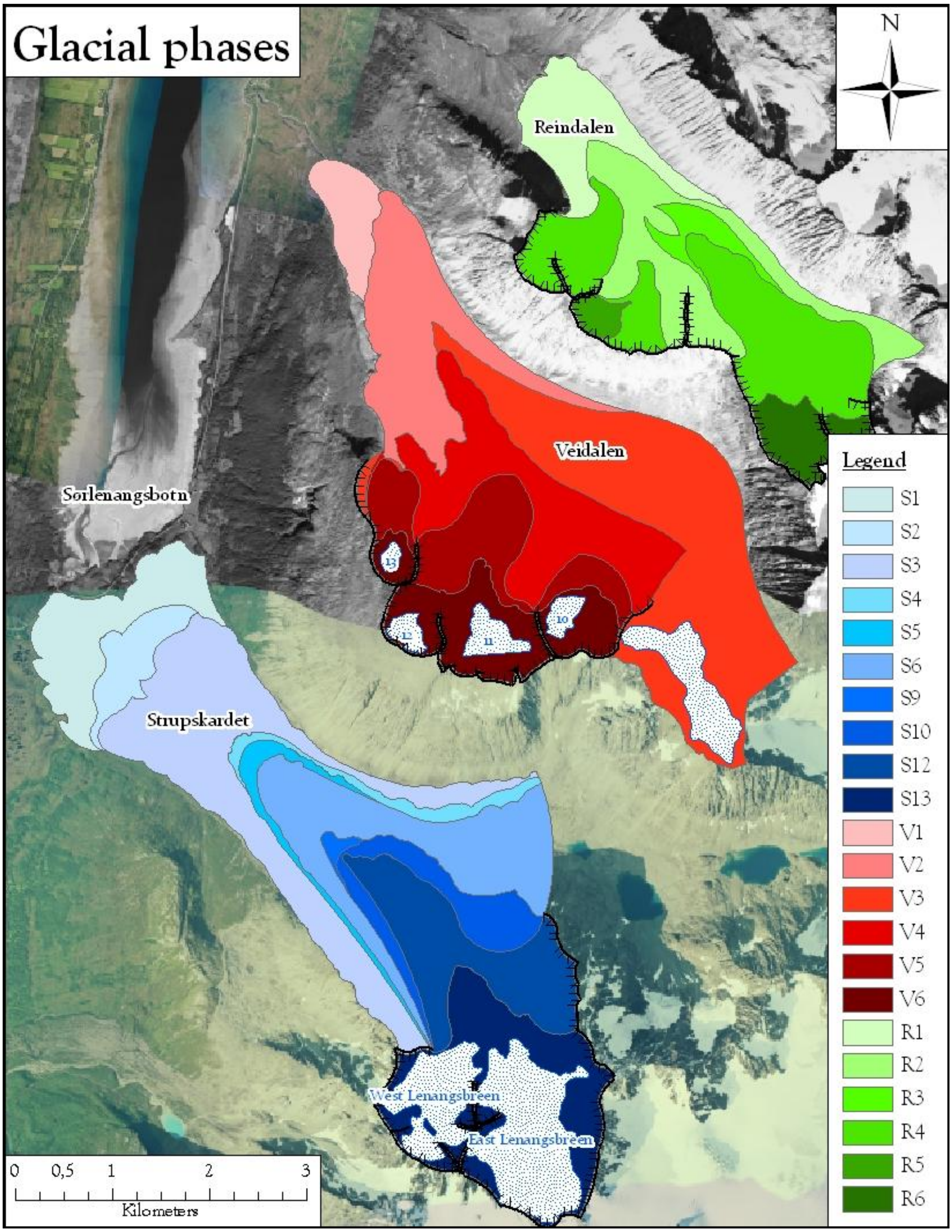


Figure 4.3.1. Ice limits of reconstructed glaciers for all phases in Strupskardet, Veidalen and Reindalen. (The eastern extent of the valley glacier in Strupskardet has not been mapped).

4.3.1 Stage 1

Stage 1 is the oldest glacial event that was recognised in northern Lyngen and appears to be represented only by the outermost moraine segments of phase S1 in Strupskardet. The S1 segments measured two of the three lowest Schmidt hammer values within the study area. The location of the ice fronts of glaciers in Veidalen and Reindalen is not known and the Schmidt hammer results for these valleys do not correlate for those of the S1 moraine.

It is suggested that moraines in Veidalen and Reindalen equivalent to S1 were located further up the valleys and have been reworked or overridden by subsequent phases. An equilibrium line altitude of 500 m.a.s.l. was identified for the reconstructed glacier of S1 in Strupskardet. The coastal area near Sørlenangen was deglaciated ca.12,000-12,500 BP, and the marine limit at this time was 65m higher relative to the elevation of the land (Plassen and Vorren, 2003). This suggests that a glacier emerging from Strupskardet would have begun to calve into the shallow fjord at Sørlenangen, hence the poorly defined moraine crest (S1) at this location.

4.3.2 Stage 2

Stage 2 is represented by the phase S2 push moraines in Strupskardet and V1, the outermost moraine segment in Veidalen (Figure 4.3.2.1). Moraines from Reindalen were not found to correspond with this stage, either morphologically or from the Schmidt hammer tests, and it is suggested that they may have been subsequently erased. Although the rebound values for segment V1 do correlate with some of the V2 segments, the former moraine was allocated to the same event as it was clearly observed in the field to have been overridden by the moraines of phase V2. The R-values suggest that S2 moraines may belong to phase S1, but morphostratigraphically they define distinct and separate phases.

Andersen's (1968) description of the deglaciation of Troms has identified a major readvance of Scandinavian ice sheet, known as the Skarpnes Event. This event has been dated to ca.12,000 BP (Plassen and Vorren, 2003; Vorren and Elvsborg, 1979). Fjord glaciers at this time extended as far as Svensby in Ullsfjord and beyond Spåkenes in Lyngenfjord (Dahl and Sveian, 2004)

During this stage, a major valley glacier filled Strupskardet, with ice supplied from the plateau glaciers of Lenangsbreen and other cirques. This glacier flowed westwards towards Sørlengen from the watershed, and eastwards where it spilled out of the top of the valley at Strupen. The steep topography of the northern Lyngen Peninsula beside Lyngenfjord has generally prevented a record of moraine sequences from being preserved (Figure 4.3.2.2). However, ice from Strupbreen probably contributed to the glacier occupying Lyngenfjord during this stage (Figure 4.3.2.3). Stage 2 is suggested to correlate to the Skarpnes Event of the Older Dryas Stadial (12,000-11,800 BP), when the ELA of glaciers within the study area was located at 510 m.a.s.l.

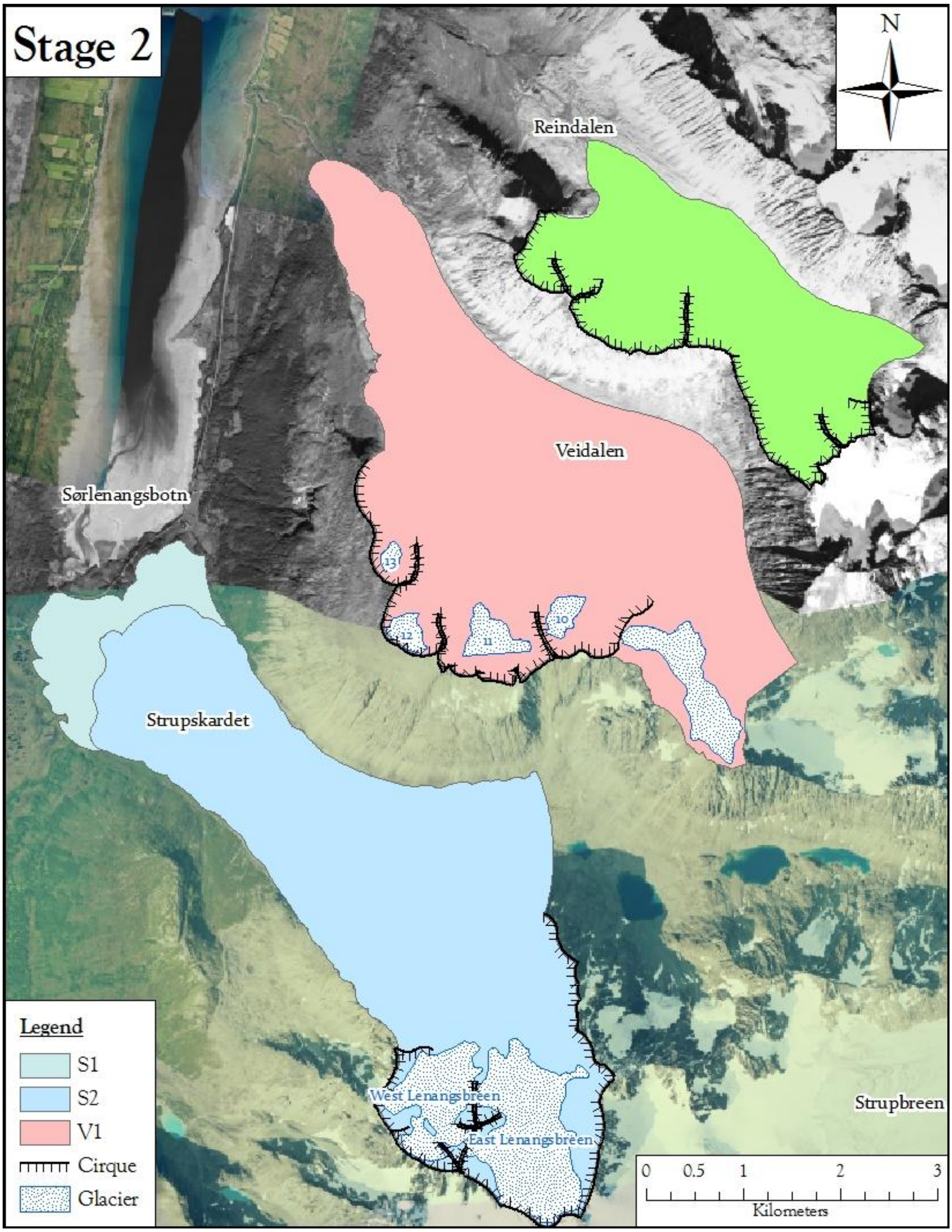


Figure 4.3.2.1. Stage 2 ice limits of reconstructed glaciers within the study area; comprised of phase S2 in Strupskardet, V1 in Veidalen and an assumed ice front (subsequently overridden) in Reindalen. The position of the preceding phase 1 glacier in Strupskardet (S1) is also shown. (The eastern extent of the valley glacier in Strupskardet has not been mapped).

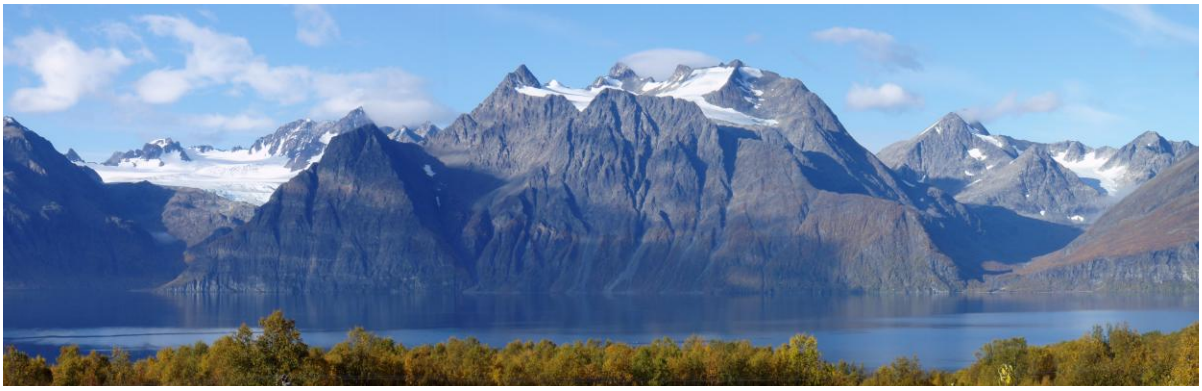


Figure 4.3.2.2. Lyngenfjord and the eastern side of the northern Lyngen Peninsula, showing Strupbreen and Strupen (far left).

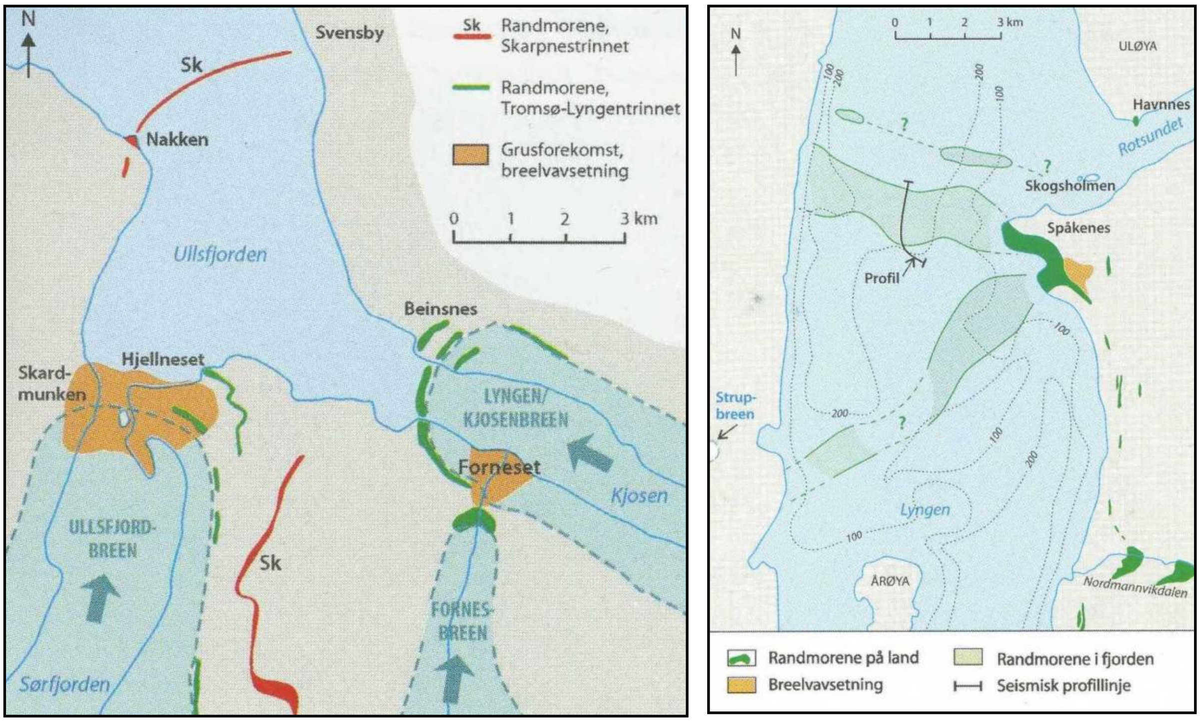


Figure 4.3.2.3. Position of the fjord glaciers in Ullsfjord and Lyngenfjord during the Skarpnes Event and Tromsø-Lyngen Event (Dahl and Sveian, 2004)

4.3.3 Stage 3

Stage 3 was seen to be the most significant glacial event across the whole north Lyngen Peninsula (Figure 4.3.3.1). This stage was characterised by waves of ice-rich till that sloughed from mountainsides and out of cirques while valley glaciers surged through the centres of Strupskardet, Veidalen and Reindalen. Each valley displays belts of hummocky till with numerous collapse depressions, defined along their margins by minor crests that indicate either pulses of ice-cored material or differentiation between the sources of ice from separate cirques.

This stage is represented by the most prominent moraines within all three valleys: S3 in Strupskardet, V2 in Veidalen, and R1 in Reindalen, all of which display concertina ridges and porridge-like landscapes on their proximal sides diagnostic of ice-cored moraines. A total of 40 ice-cored moraine complexes were identified and mapped from aerial photographs, across the northern Lyngen Peninsula in similar topographic settings (Figure 4.3.3.2). This stage indicates a major ice advance and an abrupt and geomorphological climatic contrast to preceding and subsequent stages. For this reason, the similarities of this stage throughout the three valleys provides a reference point to which the other stages may be compared.

Andersen et al. (1995) have recognised that moraines formed during the Younger Dryas (11,000–10,000 BP) are usually the largest and best developed in every fjord district. The particularly cold climate during the Younger Dryas caused inland ice sheets to advance rapidly (B.G. Andersen et al., 1995) which in the process amassed huge end moraines that can be traced almost continuously around Fennoscandinavia (Moen, 1999). The distinction and continuation of these landforms has lead them to be referred to as the 'backbone' of the Norwegian moraine chronology (Andersen, 1979). In northern Norway, the Younger Dryas is identified as the Tromsø-Lyngen event (Andersen, 1979; Ballantyne, 1990; Dahl and Sveian, 2004), when fjord glaciers were separated from alpine and plateau glaciers within the study are of northern Lyngen (Figure 2.1.1). It is suggested that stage 3 corresponds to the Younger Dryas event in Norway, with an ELA of 520 m.a.s.l derived from reconstructed glaciers within the study area.

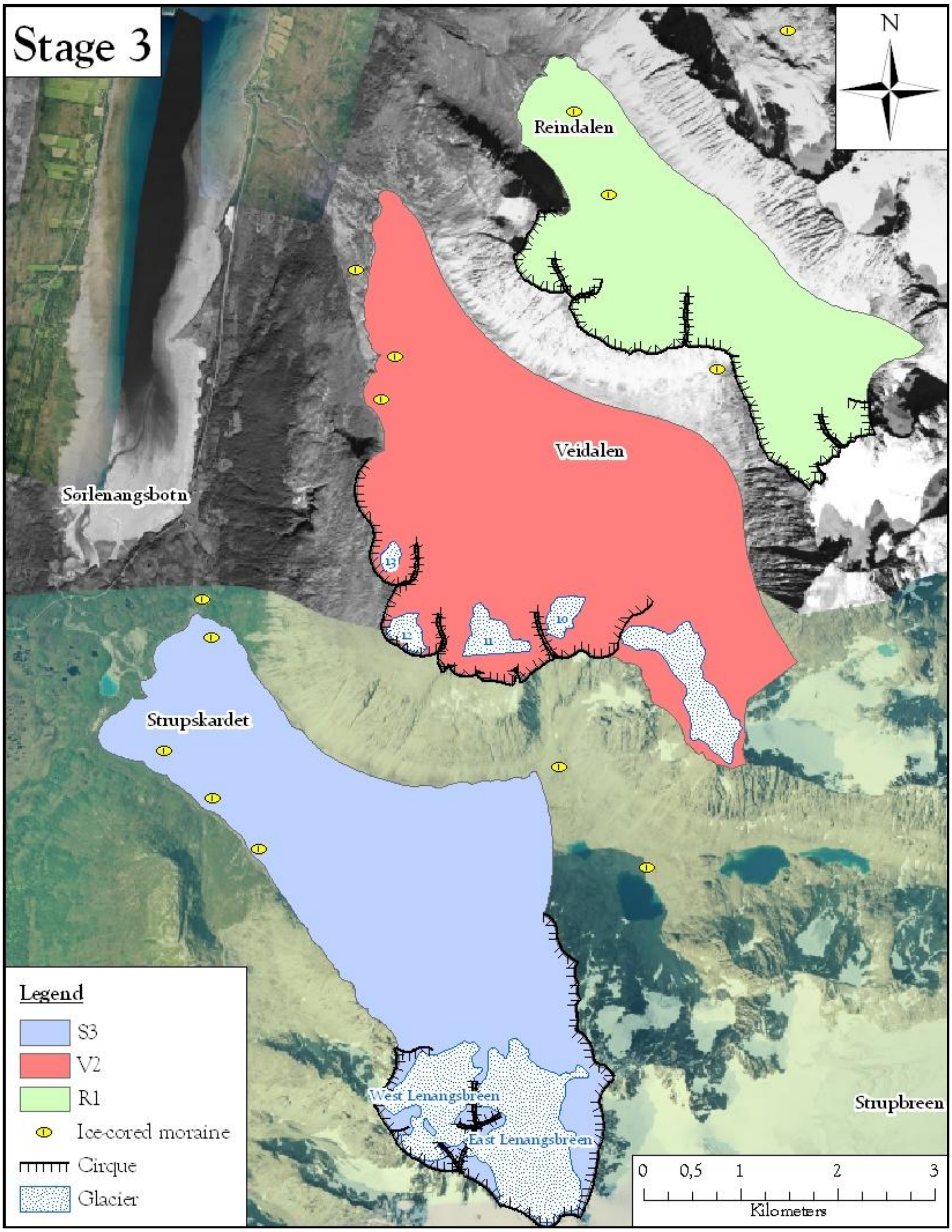


Figure 4.3.3.1. Stage 3 ice limits of reconstructed glaciers within the study area; comprised of phase S3 in Strupskardet, V2 in Veidalen, and R1 in Reindalen. This stage was characterised by the construction of belts of ice-cored moraines in all valleys. (The eastern extent of the valley glacier in Strupskardet has not been mapped).

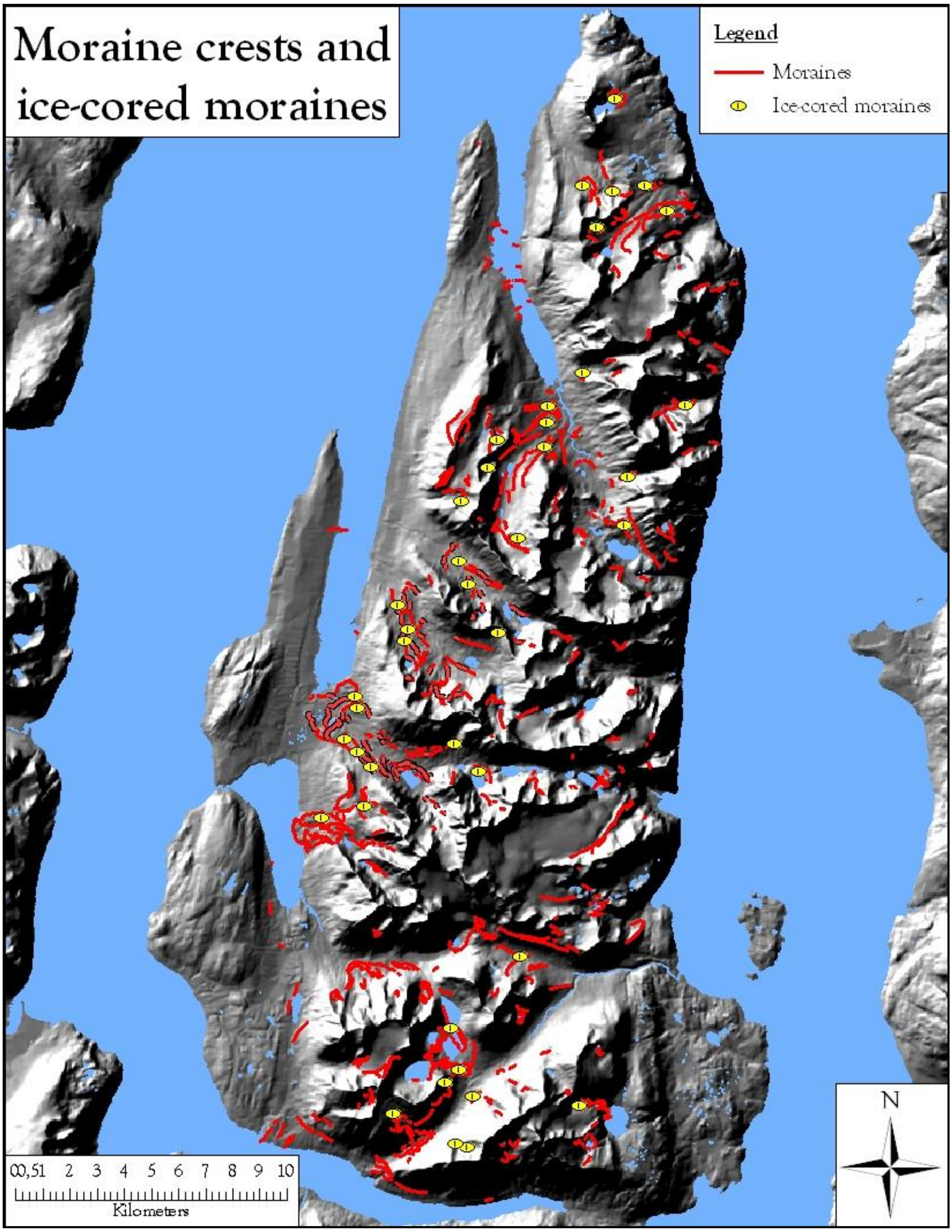


Figure 4.3.3.2. Moraine crests mapped from aerial photographs of the northern Lyngen Peninsula. Forty ice-cored moraine complexes were identified within a total of 800 mapped moraines. (DEM base map modified from Hansen, 2009).

4.3.4 Stage 4

Stage 4 is identified by a steady retreat of the valley glacier in Strupskardet (phases S4 to S8), while glaciers in Veidalen (phase V3) and Reindalen (R2) remained relatively static and filled the valley floors (Figure 4.3.4.1). The ELA at this time was located at 570 m.a.s.l.

Moraine correlations in Troms by Andersen (1968; 1979) have identified a sequence of three glacial readvances, named the Stordal Events (1,2 &3) within the Preboreal (10,000-9,000 BP); which are seen as small moraine ridges formed behind the Tromsø-Lyngen moraines. Stage 4 is proposed to correlate chronologically with the first Stordal Event, which Corner more accurately defines as the Ørnes Event (9900-9800 BP)

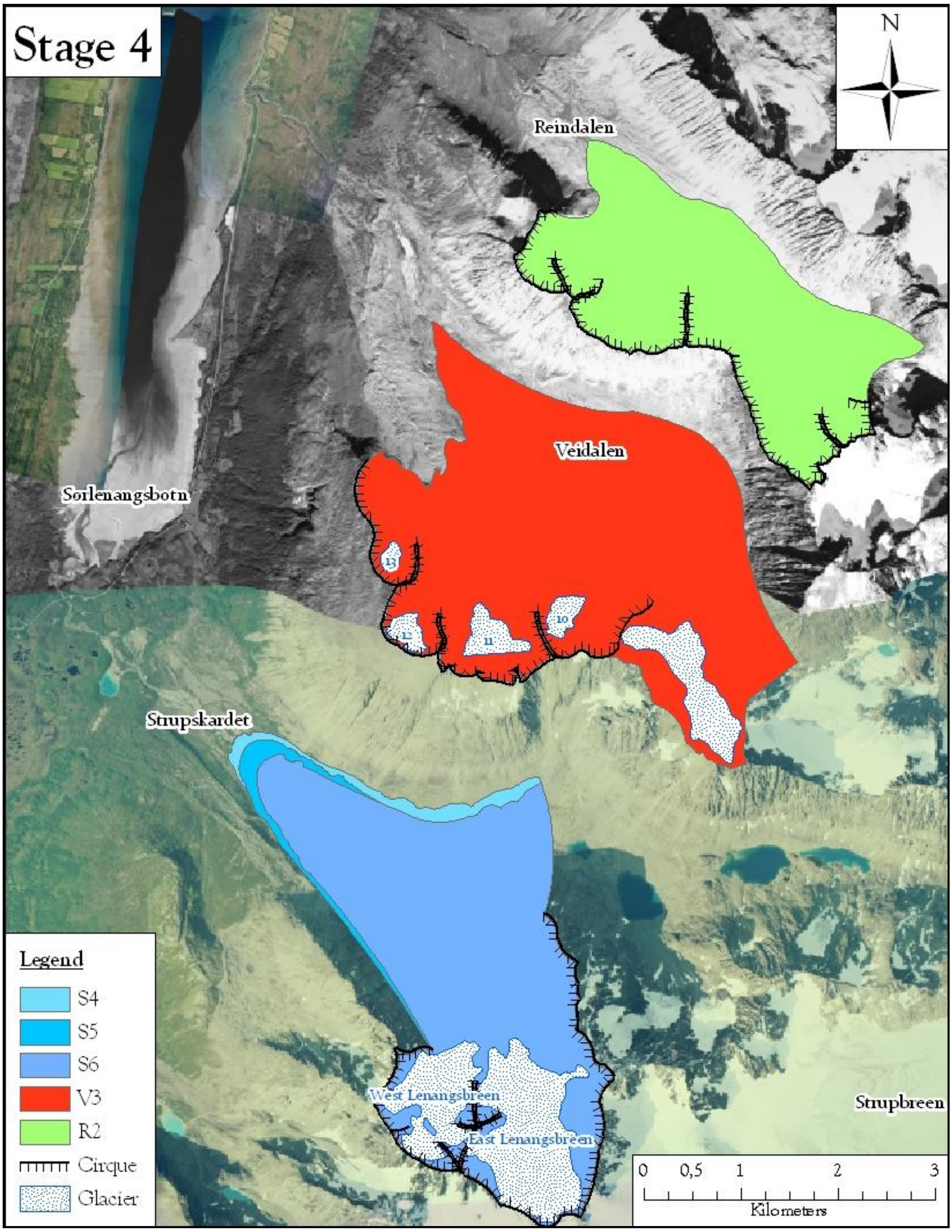


Figure 4.3.4.1. Stage 4 ice limits of reconstructed glaciers within the study area; comprised of phases S4 to S8 in Strupskardet, V3 in Veidalen, and R2 in Reindalen. (The eastern extent of the valley glacier in Strupskardet has not been mapped).

4.3.5 Stage 5

Stage 5 may signify a major cooling event in northern Lyngen when temperatures rapidly decreased and glaciers constructed the largest moraines since the Younger Dryas. This stage is represented by: the large, blocky moraines that surround Blåvatnet (phases S10 and S11) in Strupskardet; glaciers that quickly advanced and began to override the belt of ice-cored material in Veidalen (phase V4); and a re-emergence of cirque glaciers in Reindalen (phase R3) (Figure 4.3.5.1).

An equilibrium line altitude at this time was located at 620 m.a.s.l. within the study area. This stage appears to correlate chronologically with the second of the three Stordal Events identified by Andersen (1968; 1979) within the Preboreal (10,000-9,000 BP). More specifically, it may represent the Skibotn Event identified by Corner (1980) that occurred in Troms 9600-9500 BP.

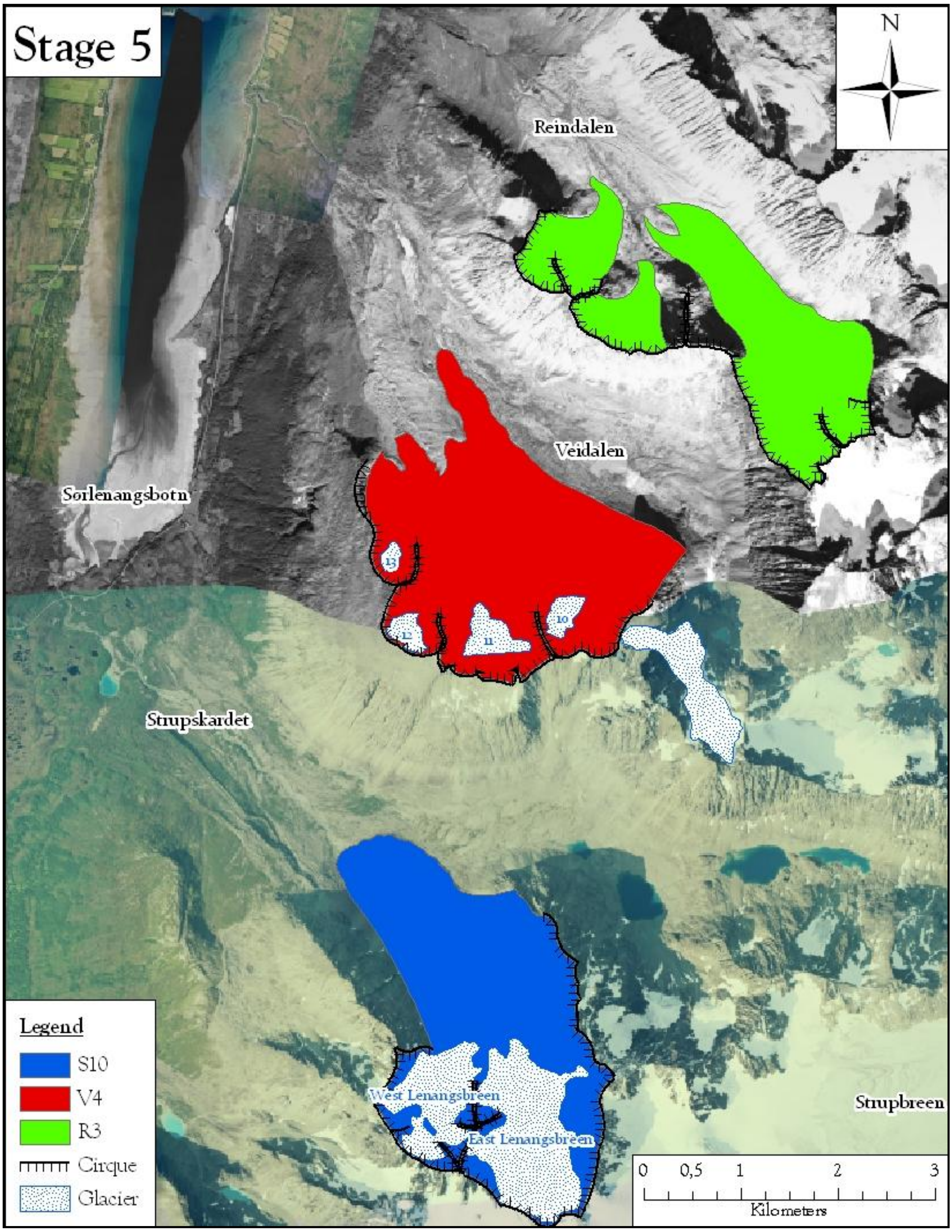


Figure 4.3.5.1. Stage 5 ice limits of reconstructed glaciers within the study area; comprised of phases S10 and S11 in Strupskardet, V4 in Veidalen, and R3 in Reindalen.

4.3.6 Stage 6

Stage 6 is represented by relatively small and subdued moraines in each valley; including S12 in Strupskardet, V5 in Veidalen, and R4 in Reindalen (Figure 4.3.6.1). The Schmidt hammer results suggest that moraine segment R5 in Reindalen may also belong to this stage, although morphostratigraphy it appears to coincide with segment R6 of the subsequent phase in the adjacent cirque. All R-values measured from moraine segments in this stage were found to be relatively high and correlate well to each other and to those of the rock avalanche/rock glacier (VRGS and VRGN) in Veidalen, however they do not clearly define a stage that is separate from earlier phases.

The correlation of phases S12, V5 and R4 to each other is predominately based on morphological similarities of the moraines in each valley. These latero-frontal moraines are not outstanding glacial landforms, but in each valley they are recognised by similar distances between their cirques and the valley floor, and also their morphology which displays at least two small, but distinct, crests. These are interpreted as minor fluctuations of the glacier margin during this stage.

The four different methods used to find the equilibrium line altitude of paleo-glaciers during this stage display significant diversity and were not helpful to identify a reliable ELA. However, an ELA (THAR 0.4) of 670m for moraine segment S12 in Strupskardet is similar to the 650m ELA measured by Bakke et al. (2005)

The deposit of the rock avalanche/rock glacier in Veidalen may be attributed to catastrophic collapse of a cirque headwall onto the glacier during this stage. It is suggested that this may have been caused by seismic activity. During a glaciation, ice volume will function as a support for the slopes, but will also cause compression and increase stress levels in the adjacent and underlying rock masses. Removal of the ice leads to debuttressing and unloading, causing a rebound or paraglacial (glacially-conditioned) stress release and the development of joint systems that reduce rock mass strength. Glacio-isostatic rebound may also trigger seismic activity, such as earthquakes, capable of causing high-magnitude rock slope failures, which can occur during or soon after ice withdrawal, or may be delayed for several thousands of years (Ballantyne, 2003; Wilson, 2009).

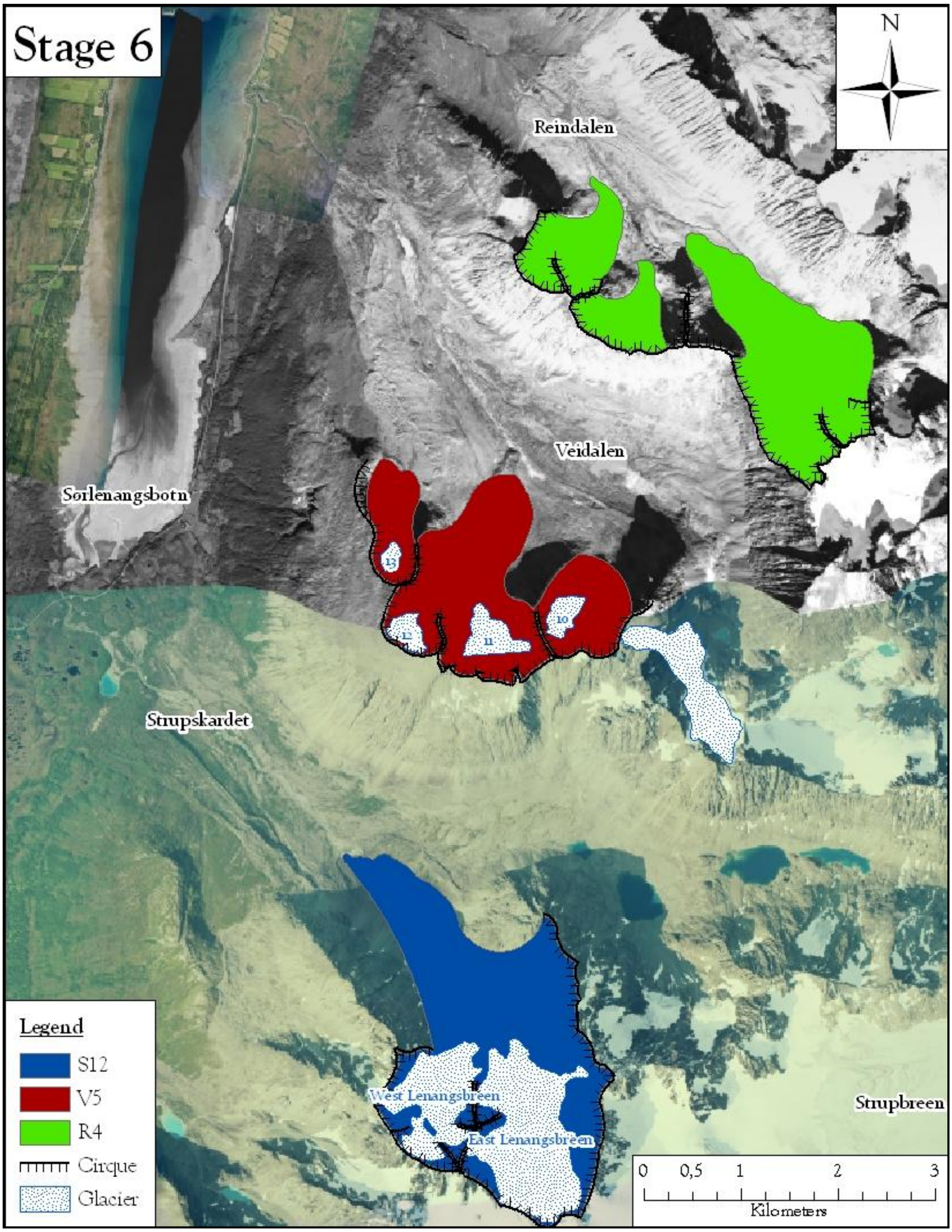


Figure 4.3.6.1. Stage 6 ice limits of reconstructed glaciers within the study area; comprised of phase S12 in Strupskardet, V5 in Veidalen, and R4 in Reindalen.

4.3.7 Stage 7

Stage 7 represents the most recently constructed landforms located directly in front of the cirques within the study area; and includes the moraines of phases S13 in Strupskardet, V6 in Veidalen, and R5 and R6 in Reindalen (Figure 4.3.7.1). While not all rebound values correlate directly for these moraines, the results do suggest a clustering of measurements, including those of the rock avalanche in Strupskardet (SRA), that stand apart from all other landforms.

The moraines of this stage all feature sharp, well-defined crests with loose, unstable till; and in Veidalen, the proximal side of the moraines feature ridges and flutes (Figure 3.1.2.10). These flutes were also observed in front of the remnant cirque glacier of Stefjellblåisen in Raudtinddalen during field reconnaissance (Figure 4.3.7.2). They have also been identified from aerial photographs by Østrem et al. (1973) at five other locations on the northern Lyngen Peninsula, including in front of the largest glacier at the eastern end of Veidalen (which corresponds with this phase).

A rapid but slightly staggered recession of glacier units 11 and 12, back into their respective cirques, has formed a micro-relief of retreat ridges as well as flutes over the proximal side of segments V6b and V6c. Griffey and Whalley (1979) have described this fluting of the till surface as a characteristic of deglaciated till surfaces in Scandinavia following the LIA maximum 18th century. The sub-parallel ridges may be representative of winter readvances of the cirque glacier.

The moraines formed during this stage are therefore believed to represent the Little Ice Age. ELA of these glaciers (derived from the AAR of glacier unit 10 in Veidalen) was located at ca. 840 m.a.s.l.. The Little Ice Age ELA of 849 metres measured in Strupskardet by Bakke et al. (2005) corresponds well with this calculation.

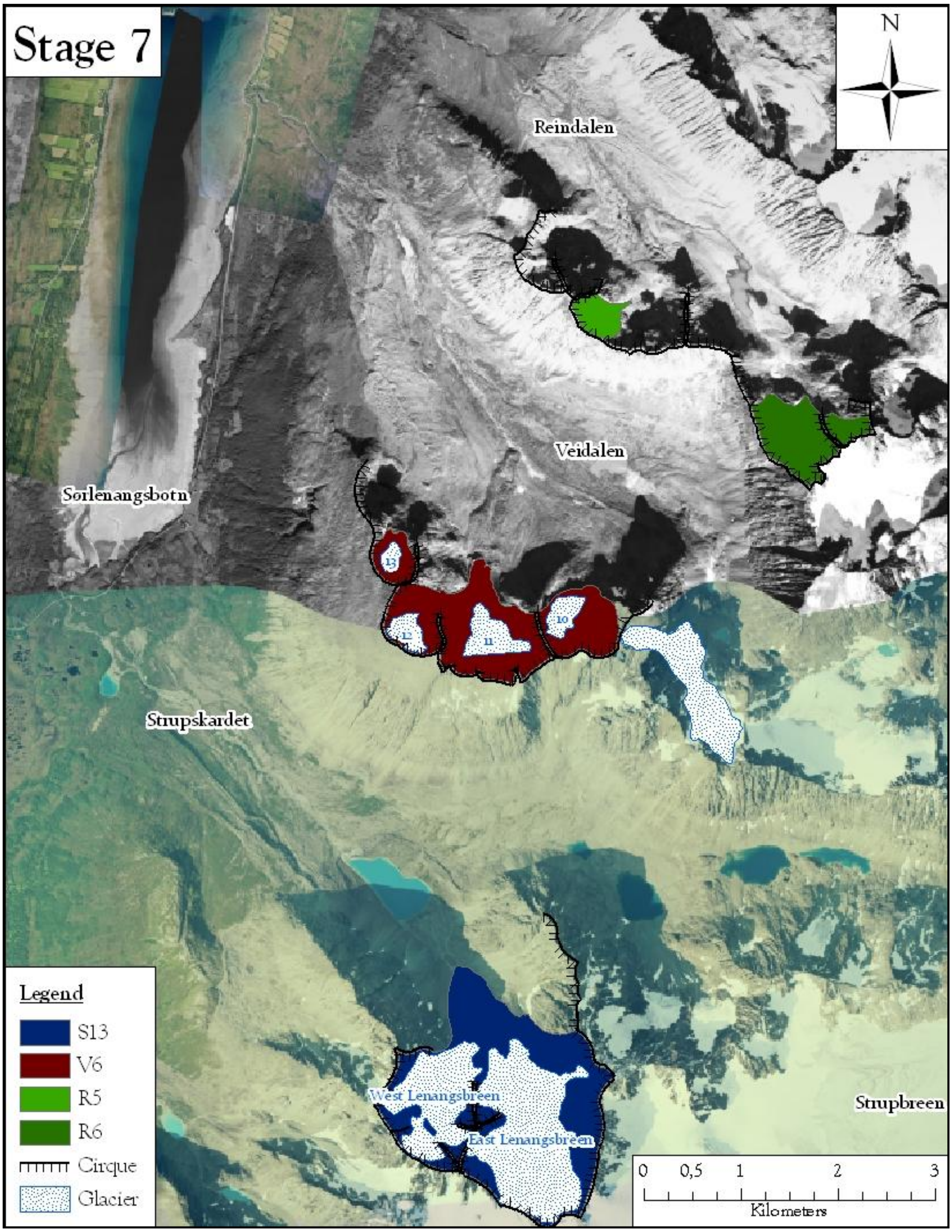


Figure 4.3.7.1. Stage 7 ice limits of reconstructed glaciers within the study area; comprised of phase S13 in Strupskardet, V6 in Veidalen, and phases R5 and R6 in Reindalen.

Figure 4.3.7.2. Flutes on the proximal side of the cirque glacier moraine in front of Stefjellblåisen, Raudtinddalen.

5 Conclusions

Glacial and periglacial processes have sculpted the northern Lyngen Peninsula during the Quaternary, creating a suite of landforms that include: cirque and valley glacier moraines, ice-cored moraines, rock glaciers, rock avalanches, and a spectrum of talus-derived landforms. The morphology and genesis of these features was investigated through field reconnaissance, cartography, and previous research, and describes the complex geomorphological interactions in this region.

Moraines were mapped using a combination of GIS, aerial photograph analysis and field reconnaissance, and presented as a series of maps describing the sequence of glacier retreat within the adjacent valleys of Strupskardet, Veidalen and Reindalen. A total of 800 individual moraines were also identified across the entire northern Peninsula, of which 40 contained complexes of ice-cored material suggesting an intense period of periglacial activity.

The Schmidt hammer was found to be an effective tool for relative-age dating of landforms in Strupskardet, Veidalen and Reindalen, with results that are comparable to those of previous researchers, and which strengthened the tentative correlation of moraines within the study area. However, the potential for other variables (such as lithology, lichen cover, and boulder surface texture) to influence the rebound values was recognised, and emphasises the need for a critical methodology and a cautious interpretation of the results.

Four equilibrium line altitude (ELA) techniques were applied to reconstructed glaciers within the study area; including a new accumulation-area ratio process using GIS, which was seen to be more efficient and accurate than the traditional AAR method. The variability of ELA results was attributed to the influence of parameters unique to each valley (including headwall height, steepness of slopes, and sources of ice). A rigorous approach is therefore recommended when calculating ELAs in areas with complex topographies, such as northern Lyngen.

Seven distinctive glacial stages (comprised of up to 13 minor phases) were identified within the study area covering Strupskardet, Veidalen and Reindalen. These stages represent fluctuations of valley and cirque glaciers during the Late Weichselian and the Holocene, and were correlated to the Older Dryas, Younger Dryas, Preboreal and Little Ice Age glacial readvances. Further research and the use of absolute dating techniques are recommended to support this tentative moraine chronology and to better understand the deglacial history of the northern Lyngen Peninsula.

6 Appendices

6.1 Glossary

AAR - Acronym for accumulation-area ratio. A method for measuring the equilibrium line altitude of a glacier

Attribute - Nonspatial information about a geographic feature in a GIS, usually stored in a table and linked to the feature by a unique identifier. For example, attributes of a river might include its name, length, etc. (ESRI, 2009b)

Attribute table - A database or tabular file containing information about a set of geographic features, usually arranged so that each row represents a feature and each column represents one feature attribute. (ESRI, 2009b)

BP – years before present

CI - Acronym for confidence interval. Confidence intervals for the mean gives a range of values around the mean where the 'true' (population) of the average value is expected to be located. (StatSoft, 2010)

DEM - Acronym for digital elevation model

Dissolve polygons - Dissolves (aggregates) polygons based on user specified attributes. The resulting polygon data set does not contain multi-part polygons. (Tchoukanski, 2010)

ELA - Acronym for the equilibrium line altitude. Represents the altitude of a glacier where accumulation is balanced by ablation (Nesje and Dahl, 2000)

Feature - A representation of a real-world object on a map. (ESRI, 2009b)

Feature class - In ArcGIS, a collection of geographic features with the same geometry type (such as point, line, or polygon), the same attributes, and the same spatial reference. Feature classes allow homogeneous features to be grouped into a single unit for data storage purposes. For example, highways, primary roads, and secondary roads can be grouped into a line feature class named 'roads.' In a geodatabase, feature classes can also store annotation and dimensions. (ESRI, 2009b)

Field - A column in a table that stores the values for a single attribute. (ESRI, 2009b)

Georeferencing - Aligning geographic data to a known coordinate system so it can be viewed, queried, and analysed with other geographic data. Georeferencing may involve shifting, rotating, scaling, skewing, or orthorectifying the data. (ESRI, 2009b)

Geometry - The measures and properties of points, lines, and surfaces. In a GIS, geometry is used to represent the spatial component of geographic features. (ESRI, 2009b)

GIS - Acronym for geographic information system. An integrated collection of computer software and data used to view and manage information about geographic places, analyze spatial relationships, and model spatial processes. A GIS provides a framework for gathering and organising spatial data and related information so that it can be displayed and analysed. (ESRI, 2009b)

GPS - Acronym for Global Positioning System. A system of radio-emitting and -receiving satellites used for determining positions on the earth. The orbiting satellites transmit signals that allow a GPS receiver anywhere on earth to calculate its own location through trilateration. Developed and operated by the U.S. Department of Defense, the system is used in navigation, mapping, surveying, and other applications in which precise positioning is necessary. (ESRI, 2009b)

Layer - The visual representation of a geographic dataset in any digital map environment. Conceptually, a layer is a slice or stratum of the geographic reality in a particular area, and is more or less equivalent to a legend item on a paper map. On a road map, for example, roads, national parks, political boundaries, and rivers might be considered different layers. (ESRI, 2009b)

LIA – Acronym for Little Ice Age

m.a.s.l. – metres above sea level

MEG - Acronym for median elevation of glaciers. A method for measuring the equilibrium line altitude of a glacier

MELM - Acronym for maximum elevation of lateral moraines. A method for measuring the equilibrium line altitude of a glacier

Orthorectification - The process of correcting the geometry of an image so that it appears as though each pixel were acquired from directly overhead. Orthorectification uses elevation data to correct terrain distortion in aerial or satellite imagery. (ESRI, 2009b)

Point - A geometric element defined by a pair of x,y coordinates. (ESRI, 2009b)

Polygon - On a map, a closed shape defined by a connected sequence of x,y coordinate pairs, where the first and last coordinate pair are the same and all other pairs are unique. (ESRI, 2009b)

R-value – The rebound value measured by a Schmidt hammer

Segment – Section of a moraine where Schmidt hammer rebound values and other measurements were performed

Select - To choose from a number or group of features or records; to create a separate set or subset. (ESRI, 2009b)

Selectable layers - Layers from which features can be selected in ArcMap with the interactive selection tools. Selectable layers can be chosen using the Set Selectable Layers command in the Selection menu, or on the optional Selection tab in the table of contents. (ESRI, 2009b)

Snapping - An automatic editing operation in which points or features within a specified distance (tolerance) of other points or features are moved to match or coincide exactly with each others' coordinates. (ESRI, 2009b)

Split – To partition a polygon dataset with the polylines of a polyline dataset. (Tchoukanski, 2010)

THAR - Acronym for terminus-to-headwall altitude ratio. A method for measuring the equilibrium line altitude of a glacier

Tool - A geoprocessing command in ArcGIS that performs specific tasks. (ESRI, 2009b)

YD – Younger Dryas

Polyline - In ArcGIS software, a shape defined by one or more paths, in which a path is a series of connected segments. If a polyline has more than one path (a multipart polyline), the paths may either branch or be discontinuous. (ESRI, 2009b)

Shapefile - A vector data storage format for storing the location, shape, and attributes of geographic features. A shapefile is stored in a set of related files and contains one feature class. (ESRI, 2009b)

6.2 **Extracting shapefiles from an ArcGIS Layer file**

To separate individual types of deposits ('lossemasse') into different shapefiles from the original '4540 flate jordartsgrensef' ArcGIS Layer file, refer to the index of ArcGIS Desktop Help (ESRI, 2009a):
> Select By Attributes dialog. For example:

To identify individual layers (values) from a Layer file such as the losmasse kart:
> right click on the 4540 flate jordardsgrensef layer
> select Properties
> select Symbology tab, to find the Value representing each feature, e.g.:
80 - Skredmateriale, uspesifisert
81 - Skredmateriale, tykt dekke/ur
82 - Skredmateriale, tynt dekke

To create individual layers from a Layer file such as the losmasse kart:
Use the values in the Select By Attributes dialog box to select the required layer/s.
To select one value, dialog should read: "JORDART" = 80
Or multiple values, dialog: "JORDART" = 80 OR "JORDART" = 81 OR "JORDART" = 82
These features will then be selected on the map and in the Attribute Table of 4540 flate jordardsgrensef.
> right click on the 4540 flate jordardsgrensef layer
> go to Selection
> click Create Layer from Selected Features
= the new layer (4540 flate jordartsgrensef selection) has been created in the map. Edit the name accordingly.

6.3 Downloading orthophotos from Norge i bilder

Orthophotos were downloaded from (Norge-i-bilder, 2010) using the following parameters (Figure 6.3.1):

- Velg koordinatsystem for visning: UTM33 (Euref89)
- Select: Eksport av ortofoto
- In the Eksportmodul dialogue box (Figure), choose:

Område:	Skjermebilde	
Nord:	7723000	7777000
Øst:	678000 (=SW corner)	712000 (=NE corner)
Velg:	Flybilder	
Bakkeopplysning:	1 metre	
Filformat:	GeoTIFF	
Koordinatsystem:	UTM 33	
Filoppdeling:	Kartblad	

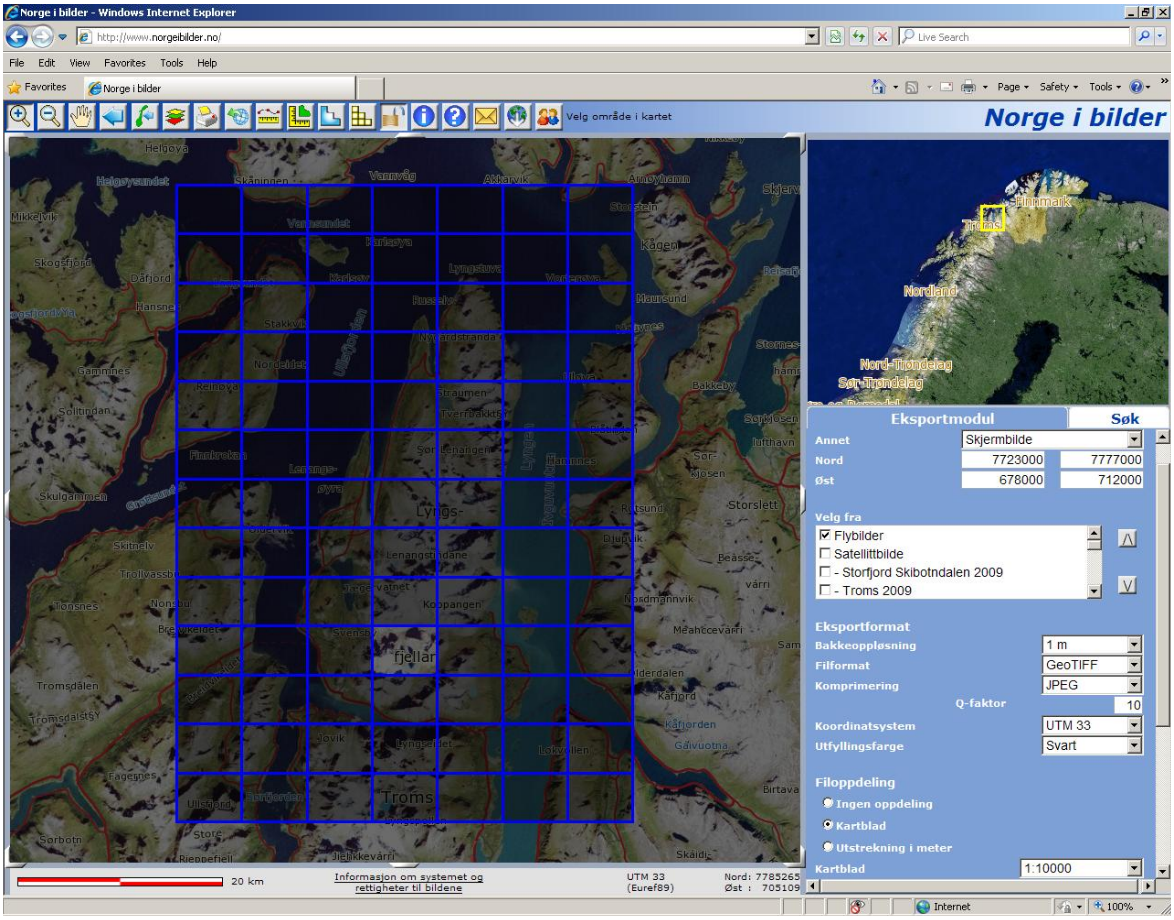


Figure 6.3.1. Norge i bilder - Eksportmodul dialogue.

Select: Vis filoppdeling. This will highlight the area of interest using the chosen parameters.

The entire area of interest could not be downloaded as a single process, but from this could be selected 3 horizontal blocks (using modified coordinates).

The selected files were made available for downloading from Norge i bilder and could then be imported into ArcMap.

6.4 Converting GPS data to a shapefile

- Use Garmin MapSource program to download data from GPS.
Remember to Edit: Preferences > Position > Grid = UTM

- Save data as .txt file

- Copy data in .txt file and paste into 1st Excel page

- In Excel, select and copy required data (x,y coordinates, followed by names), paste into a 2nd Excel page, save this page as a 2nd .txt file (column separated / tabularordelt)

- Within a 3rd Excel page, open the 2nd .txt file,
Text importer steps:
1/3 - select 'data med fast bredde' (Figure 6.4.1).

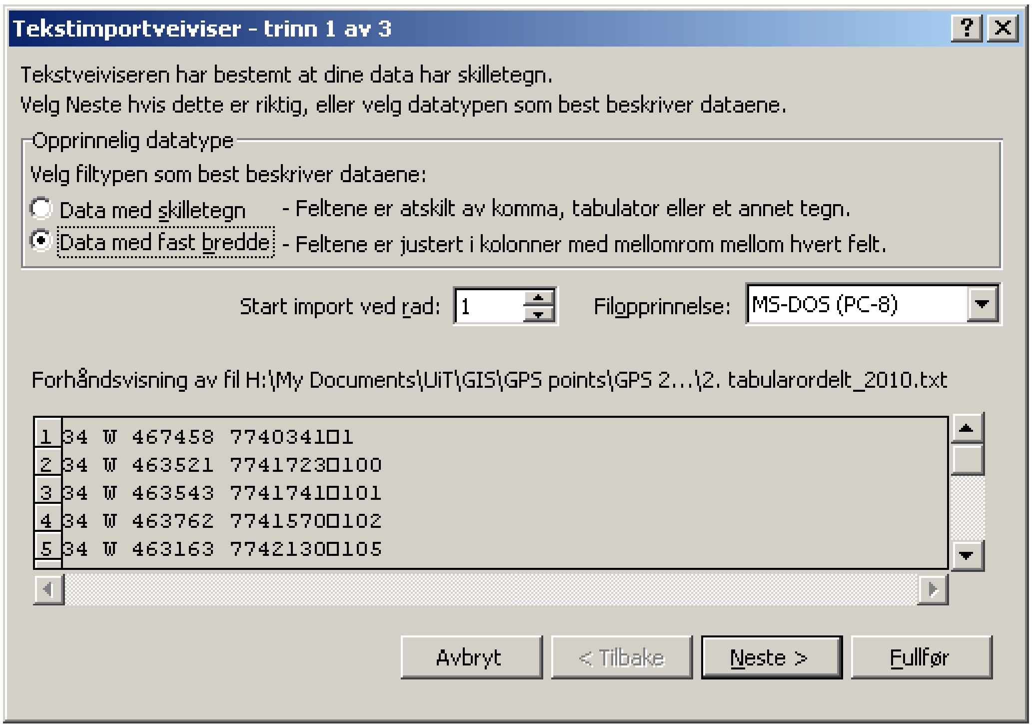


Figure 6.4.1. Text importer steps 1/3.

2/3 – add/remove column dividers to isolate required information (x,y,waypoint) (Figure 6.4.2).

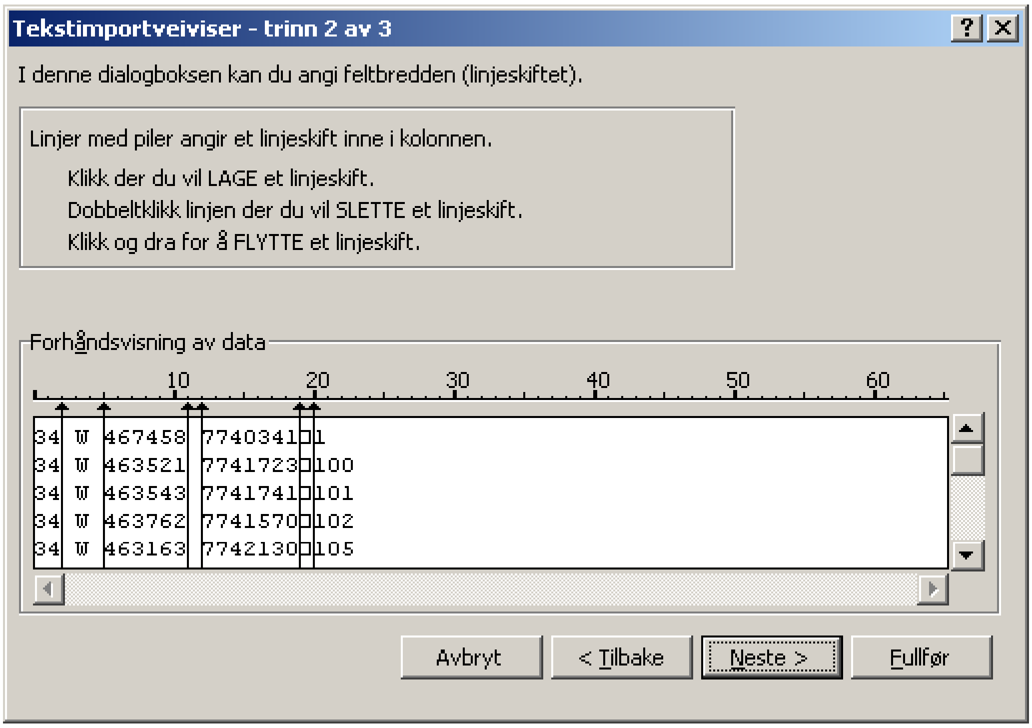


Figure 6.4.2. Text importer steps 2/3.

3/3 – select Kolonnedataformat > ’ikke import kolonne (hoppe over)’ for unwanted columns (34, W, etc) (Figure 6.4.3).

> OK – fullfør. This will save the data as a new Excel document.

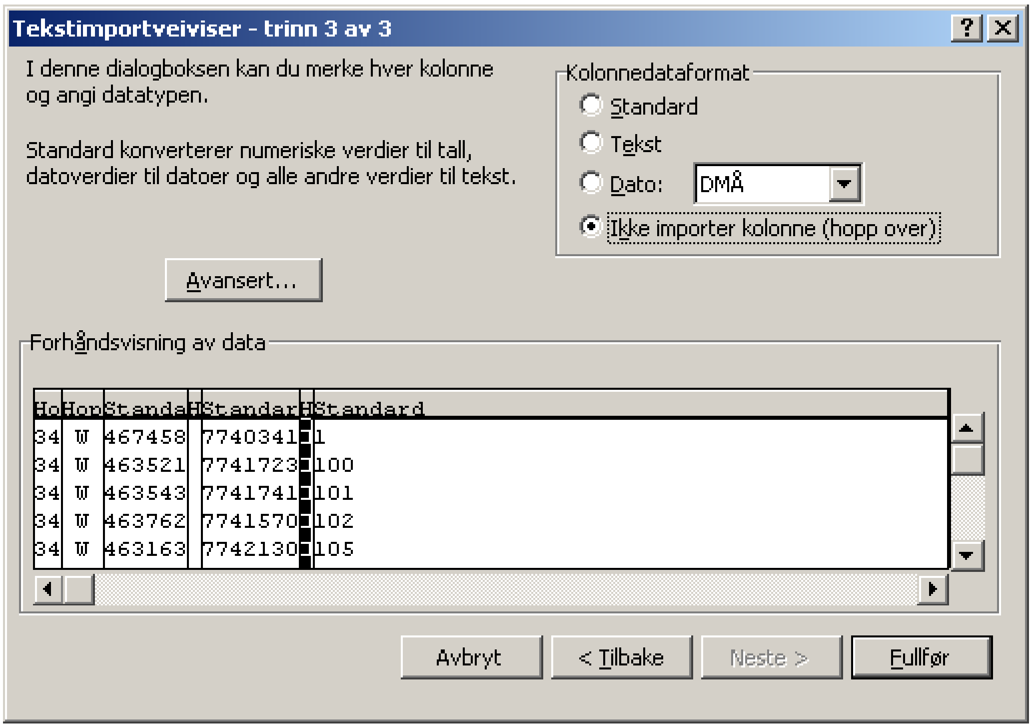


Figure 6.4.3. Text importer steps 3/3.

- Copy this new data and paste into the 3rd Excel page.

- On the 3rd Excel page, add to top of columns the fields: x, y, waypoint, arranged in this order. Save.

- Open ArcMap > Tools > Add XY Data.

- In Add XY Data dialogue box: open Excel page featuring the name, x, y, fields.
X,Y Fields should be opened automatically. Set Coordinate System (UTM-34N). OK.

- These GPS points will appear as 'Events' on the map.

To save these points as a shapefile, see the index of ArcGIS Desktop Help (ESRI, 2009a):
> Exporting, data from ArcMap > Exporting features - Interacting with a map.

7 References

Aa, A.R., Sjåstad, J., Sønstegaard, E., and Blikra, L.H. 2007: Chronology of Holocene rock-avalanche deposits based on Schmidt-hammer relative dating and dust stratigraphy in nearby bog deposits, Vora, inner Nordfjord, Norway. *The Holocene*, v. 17, 955–964.

Aa, A.R., and Sjåstad, J.A. 2000: Schmidt hammer age evaluation of the moraine sequence in front of Bøyabreen, western Norway. *Norsk*

Geologisk Tidsskrift, v. 80, 27-32.

Andersen, B.G. 1968: Glacial Geology of Western Troms, North Norway. *Universitetsforslaget*, Oslo.

Andersen, B.G. 1979: The deglaciation of Norway 15,000-10,000 B.P. . *Boreas*, v. 8, 79-87.

Andersen, B.G. 1980: The deglaciation of Norway after 10,000 B.P. *Boreas*, v. 9, 211-216.

Andersen, B.G., Lundqvistt, J., and Saarnisto, M. 1995: The Younger Dryas margin of the Scandinavian ice sheet - An introduction. *Quaternary International*, v. 28, 145-146.

Andersen, B.G., Mangerud, J., Sørensen, R., Reite, A., Sveian, H., Thorensen, M., and Bergström, B. 1995: Younger Dryas ice-marginal deposits in Norway. *Quaternary International*, v. 28, 147-169.

Armstrong, T., Roberts, B., and Swithinbank, C. 1966: Illustrated glossary of snow and ice. *Scott Polar Research Institute*, Cambridge.

Bakke, J., Dahl, S.O., Paasche, Ø., Løvlie, R., and Nesje, A. 2005: Glacier fluctuations, equilibrium-line altitudes and palaeoclimate in Lyngen, northern Norway, during the Lateglacial and Holocene. *The Holocene*, v. 15, 518-540.

Ballantyne, C. 2003: A Scottish sturzstrom: The Beinn Alligin rock avalanche, Wester Ross. *Scottish Geographical Journal*, v. 119, 159-167.

Ballantyne, C.K. 1990: The Holocene glacial history of Lyngshalvöya, northern Norway: chronology and climatic implications. *Boreas*, v. 19, 93-117.

Ballantyne, C.K., and Harris, C. 1994: The Periglaciation of Great Britain. *Cambridge University Press*, Cambridge.

Benn, D.I., and Evans, D.J.A. 1998: Glaciers and Glaciation. *Arnold Publishers*, London.

Benn, D.I., and Evans, D.J.A. 2010: Glaciers and Glaciation (Second edition). *Hodder Education*, London.

Berendsen, H.J.A. 2005: The Rhine-Meuse delta at a glance, 8th International Conference on Fluvial Sedimentology, Volume Mid-conference excursion guide: *Delft, the Netherlands*.

Birkeland, P.W. 1982: Subdivision of Holocene glacial deposits, Ben Ohau Range, New Zealand, using relative-dating methods. *Geology*, v. 93, 433-499.

Bøe, P. 2001: Berggunnsgeologien på Lyngenhalvøya, *in* Jacobsen, K.-O., ed., Forslag til Lyngsalpen / Lyngsfjellan landskapsvernområde i Troms fylke, Volume 73: *Fylkesmannen i Troms*, Tromsø.

Brook, M.S., Kirkbride, M.P., and Brock, B.W. 2004: Rock strength and development of glacial valley morphology in the Scottish Highlands and northwest Iceland. *Geografiska Annaler*, v. 86, 225-234.

Carroll, T. 1974: Relative age dating techniques and a late Quaternary chronology, Arikaree Cirque, Colorado. *Geology*, v. 2, 321-325.

Černá, B., and Engel, Z. 2010: Surface and sub-surface Schmidt hammer rebound value variation for a granite outcrop. *Earth Surface Processes and Landforms*.

Chinn, T.J.H. 1979: Moraine forms and their recognition on steep mountain slopes, *in* Schluchter, C., ed., Moraines and varves; Proceedings of an INQUA symposium on genesis and lithology of Quaternary deposits, Zurich: *A.A.Balkema*, Rotterdam.

Corner, G.C. 1980: Preboreal deglaciation chronology and marine limits of the Lyngen-Storfjord area, Troms, North Norway. *Boreas*, v. 9, 239-249.

Dahl, R., and Sveian, H. 2004: Ka dokker mein for stein! Geologi, Landskap og ressurser i Troms. *Norges geologiske undersøkelse (NGU)*, Trondheim.

Dahl, S.O., Bakke, J., Lie, Ø., and Nesje, A. 2003: Reconstruction of former glacier equilibrium-line altitudes based on proglacial sites: an evaluation of approaches and selection of sites. *Quaternary Science Reviews*, v. 22, 275-287.

Dahl, S.O., and Nesje, A. 1992: Paleoclimatic implications based on equilibrium-line altitude depressions of reconstructed Younger Dryas and Holocene cirque glaciers in inner Nordfjord, western Norway. *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 94, 87-97.

Ericson, K. 2004: Geomorphological surfaces of different age and origin in granite landscapes: an evaluation of the Schmidt hammer test. *Earth Surface Processes and Landforms*, v. 29, 495-509.

ESRI 2009a: ArcGIS 9.3.1, ESRI: *Redlands, California*.

ESRI 2009b: GIS Dictionary, http://resources.arcgis.com/glossary: *(accessed 1/11/2010), ESRI, Redlands, California*.

Fjellanger-Widerøe 1977: Troms 77, Dekning 5576: *Trondheim, Fjellanger Widerøe AS*.

Folk, R.L. 1968: Petrology of Sedimentary Rocks. *University of Texas*, Austin.

Gellatly, A.F., Whalley, W.B., and Gordon, J.E. 1986: Topographic control over recent glacier changes in soouthern Lyngen Peninsula, North Norway. *Norsk geografisk Tidsskrift*, v. 40, 211-218.

Goudie, A.S. 2006: The Schmidt Hammer in geomorphological research. *Progress in Physical Geography*, v. 30, 703-718.

Graf, W.L. 1971: Quantitative analysis of Pinedale Landforms, Beartooth Mountains, Montana and Wyoming. *Arctic and Alpine Research*, v. 3, 253-261.

Griffey, N.J., and Whalley, W.B. 1979: A rock glacier and moraine-ridge complex, Lyngen Peninsula, north Norway. *Norsk Geografisk Tidsskrift*, v. 33, 117 - 124.

Hansen, J.-A. 2009: Digital elevation model of Troms, *Institutt for geologi, Universitetet i Tromsø*, Tromsø.

Humlum, O. 1988: Rock Glacier Appearance Level and Rock Glacier Initiation Line Altitude: A Methodological Approach to the Study of Rock Glaciers. *Arctic and Alpine Research*, v. 20, 160-178.

Humlum, O. 2000: The geomorphic significance of rock glaciers: estimates of rock glacier debris volumes and headwall recession rates in West Greenland. *Geomorphology*, v. 35, 41-67.

Humlum, O., Christiansen, H.H., and Juliussen, H. 2007: Avalanche-derived Rock Glaciers in Svalbard. *Permafrost and Periglacial Processes*, v. 18, 75-88.

Jacobsen, K.-O. 2001: Forslag til Lyngsalpen / Lyngsfjellan landskapsvernområde i Troms fylke. *Fylkesmannen i Troms*, Tromsø.

LeBlond, E. 1908: Mountaineering in the Land of the Midnight Sun. *T. Fisher Unwin*, London.

Mangerud, J., Andersen, S.T., Berglund, B.E., and Donner, J.J. 1974: Quaternary stratigraphy of Norden, a proposal for terminology and classification. *Boreas*, v. 3, 109-128.

Matthews, J.A., and Owen, G. 2010: Schmidt hammer exposure-age dating: developing linear age-calibration curves using Holocene bedrock surfaces from the Jotunheimen–Jostedalsbreen regions of southern Norway. *Boreas*, v. 39, 105-115.

Matthews, J.A., and Shakesby, R.A. 1984: The status of the 'LIttle Ice Age' in southern Norway: a relative-age dating of Neoglacial moraines with Schmidt hammer and lichenometry. *Boreas*, v. 13, 333-346.

Matthews, J.A., and Winkler, S. 2010: Schmidt-hammer exposure-age dating (SHD): application to early Holocene moraines and a reappraisal of the reliability of terrestrial cosmogenic-nuclide dating (TCND) at Austanbotnbreen, Jotunheimen, Norway. *Boreas*, v. 10, 1-15.

McCarroll, D. 1989a: Potential and Limitations of the Schmidt Hammer for Relative-Age Dating: Field Tests on Neoglacial Moraines, Jotunheimen, Southern Norway. *Arctic and Alpine Research*, v. 21, 268-275.

McCarroll, D. 1989b: Schmidt hammer relative-age evaluation of a possible pre-'Little Ice Age' Neoglacial moraine, Leirbreen, southern Norway. *Norsk Geologisk Tidsskrift*, v. 69, 125-130.

McCarroll, D. 1991: The Schmidt hammer, weathering and rock surface roughness. *Earth Surface Processes and Landforms*, v. 16, 477-480.

McCarroll, D., and Nesje, A. 1993: The vertical extent of ice sheets in Nordfjord, western Norway: measuring degree of rock surface weathering. *Boreas*, v. 22, 255-265.

Meierding, T.C. 1982: Late Pleistocene Glacial Equilibrium-Line Altitudes in the Colorado Front Range: A Comparison of Methods. *Quaternary Research*, v. 18, 289-310.

Meteorologisk_institutt 2010: eKlima: Meteorologisk institutts vær- og klimadatabase, http://sharki.oslo.dnmi.no/portal/page?_pageid=73,39035,73_39049&_dad=portal&_schema=PORTAL: *(accessed 24 November 2010), Meteorologisk institutt, Norge*.

Moen, A. 1999: National Atlas of Norway: Vegetation. *Norwegian Mapping Authority*, Hønefoss.

Møllersen, K. 2010: Personal communication: *Department of Mathematics and Statistics, University of Tromsø, Norway*.

Munday, R.J.C. 1974: The geology of the northern half of the Lyngen peninsula, Troms, Norway. *Norsk Geologisk Tidsskrift*, v. 54, 49-62.

Nesje, A., Blikra, L.H., and Anda, E. 1994: Dating rockfall-avalanche deposits from degree of rock-surface weathering by Schmidt-hammer tests: a study from Norangsdalen, Sunnmøre, Norway. *Norsk Geologisk Tiddskrift*, v. 74, 108-113.

Nesje, A., and Dahl, S.O. 2000: Glaciers and Environmental Change. *Arnold Publishers*, London.

NGU 2009: Kvartærgeologiske kart (løsmassekart), Norges geologiske undersøkelse: *Trondheim, Norway*.

Norge-i-bilder 2010: Norge i bilder, http://www.norgeibilder.no/: *(accessed 12 March 2010), Statens kartverk og Norge Digitalt*.

Osipov, E.Y. 2004: Equilibrium-line altitudes on reconstructed LGM glaciers of the northwest Barguzinsky Ridge, Northern Baikal, Russia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 209, 219- 226.

Østrem, G. 1964: Ice-cored moraines in Scandinavia. *Geografiska Annaler*, v. 3, 282-337.

Østrem, G. 1971: Rock Glaciers and Ice-Cored Moraines, a Reply to D. Barsch. *Geografiska Annaler. Series A, Physical Geography*,, v. 53, 207-213.

Østrem, G., Haakensen, N., and Melander, O. 1973: Atlas over breer i Nord-Skandinavia (Glacier Atlas of Northern Scandinavia). *Norges Vassdrags- og Elektrisetetsvesen og Stockholms Universitet*.

Owen, G., Matthews, J.A., and Albert, P.G. 2007: Rates of Holocene chemical weathering, 'Little Ice Age' glacial erosion and implications for Schmidt-hammer dating at a glacier–foreland boundary, Fåbergstølsbreen, southern Norway. *The Holocene*, v. 17, 829–834.

Plassen, L., and Vorren, T.O. 2003: Sedimentary processes and the environment during deglaciation of a fjord basin in Ullsfjorden, North Norway. *Norwegian Journal of Geology*, v. 83, 23-36.

Porter, S.C. 2001: Snowline depression in the tropics during the Last Glaciation. *Quaternary Science Reviews*, v. 20, 1067-1091.

Powers, M.C. 1953: A new roundness scall for sedimentary particles. *Journal of Sedimentary Petrology*, v. 23, 117-119.

Proceq 2009: Original Schmidt, Concrete Test Hammer: Operating Instructions. *Proceq SA, Switzerland*.

Rea, B.R., Whalley, W.B., Dixon, T.S., and Gordon, J.E. 1999: Plateau icefields as contributing areas to valley glaciers and the potential impact on reconstructed ELAs: a case study from the Lyngen Alps, North Norway. *Annals of Glaciology*, v. 28, 97-102.

Refsnider, K.A., Laabs, B.J.C., and Mickelson, D.M. 2007: Glacial Geology and Equilibrium Line Altitude Reconstructions for the Provo River Drainage, Uinta Mountains, Utah, U.S.A. *Arctic, Antarctic and Alpine Research*, v. 39, 529-536.

Rune, A., and Sjåstad, J.A. 2000: Schmidt hammer age evaluation of the moraine sequence in front of Bøyabreen, western Norway. *Norsk Geologisk Tidsskrift*, v. 80, 27-32.

Ryvarden, L., and Wold, B. 1991: Norges Isbreer. *Universitetsforlaget AS*, Oslo.

seNorge.no 2010: Vær, vann, snø, og klima i Norge, http://senorge.no/mapPage.aspx: *(accessed 23 November 2010), Norges vassdrags- og energidirektorat, Meteorologisk institutt, Statens kartverk*.

Shakesby, R.A., Matthews, J.A., and Owen, G. 2006: The Schmidt hammer as a relative-age dating tool and its potential for calibrated-age dating in Holocene glaciated environments. *Quaternary Science Reviews* v. 25, 2846-2867.

Shakesby, R.A., Matthews, J.A., and Winkler, S. 2004: Glacier variations in Breheimen, southern Norway: relative-age dating of Holocene moraine complexes at six high-altitude glaciers. *The Holocene*, v. 14,6, 899-910.

Siegert, M.J. 2001: Ice Sheets and Late Quaternary Environmental Change. *John Wiley & Sons*, Chichester.

Sollid, J.L., and Sørbel, L. 1992: Rock Glaciers in Svalbard and Norway. *Permafrost and Periglacial Processes*, v. 3, 215-220.

Sollid, J.L., and Torp, B. 1984: Glasialogisk kart over Norge, 1:1 000 000, Nasjonalatlas for Norge, *Geografisk Institutt, Universitetet i Oslo*.

Statens_kartverk 2009: Kartdata, Statens kartverk: *Hønefoss, Norway*.

StatSoft 2010: Statistics Glossary, http://www.statsoft.com/textbook/statistics-glossary/: *(accessed 24 November 2010), StatSoft, Inc.*

Sugden, D.E., and John, B.S. 1976: Glaciers and landscape: A geomorphological approach. *Edward Arnold Ltd.*, London.

Sumner, P., and Nel, W. 2002: The effect of rock moisture on Schmidt hammer rebound: Tests on rock samples from Marion Island, South Africa. *Earth Surface Processes and Landforms*, v. 27, 1137-1142.

Tchoukanski, I. 2010: ET GeoWizards, http://www.ian-ko.com/: *(accessed 1/11/2010), ET SpatialTechniques, Pretoria, South Africa*.

Torsnes, I., Rye, N., and Nesje, A. 1993: Modern and Little Ice Age Equilibrium-Line Altitudes on Outlet Valley Glaciers from Jostedalsbreen, Western Norway: An Evaluation of Different Approaches to Their Calculation. *Arctic and Alpine Research*, v. 25, 106-116.

University_of_Saskatchewan 2005: Sedimentary textures (GEOL 243.3), http://www.usask.ca/geology/downloads/textures.pdf: *(accessed 10/11/2005), Department of Geological Sciences, University of Saskatchewan*.

Vorren, T.O., and Elvsborg, A. 1979: Late Weichselian deglaciation and paleoenvironment of the shelf and coastal areas of Troms, north Norway - a review. *Boreas*, v. 8, 247-253.

Walpole, R.E., Myers, R.H., Myesrs, S.L., and Ye, K. 2002: Probability & Statistics for Engineers & Scientists (seventh edition). *Prentice-Hall, Inc.*, New Jersey.

Whalley, W.B. 1971: Observations of the Drainage of an Ice-Dammed Lake - Strupvatnet, Troms, Norway. *Norsk Geografisk Tidsskrift*, v. 25, 165-174.

Williams, R.B.G., and Robinson, D.A. 1983: The effect of surface texture on the determination of the surface hardness of rock using the Schmidt hammer. *Earth Surface Processes and Landforms*, v. 8, 289-292.

Wilson, P. 2009: Storurdi: a Late Holocene rock-slope failure (sturzstrom) in the Jotunheimen, southern Norway. *Geografiska Annaler*, v. 91, 47-58.

Winkler, S. 2000: The 'Little Ice Age' maximum in the Southern Alps, New Zealand: preliminary results at Mueller Glacier. *The Holocene*, v. 10, 643–647.

Winkler, S. 2005: The Schmidt hammer as a relative-age dating technique: potential and limitations of its application on Holocene moraines in Mt Cook National Park, Southern Alps, New Zealand. *New Zealand Journal of Geology & Geophysics*, v. 48, 105–116.

Winkler, S. 2009: First attempt to combine terrestrial cosmogenic nuclide (10Be) and Schmidt hammer relative-age dating: Strauchon Glacier, Southern Alps, New Zealand. *Central European Journal of Geosciences*, v. 1, 274-290.