Description of units in the geomorphic database of Sweden

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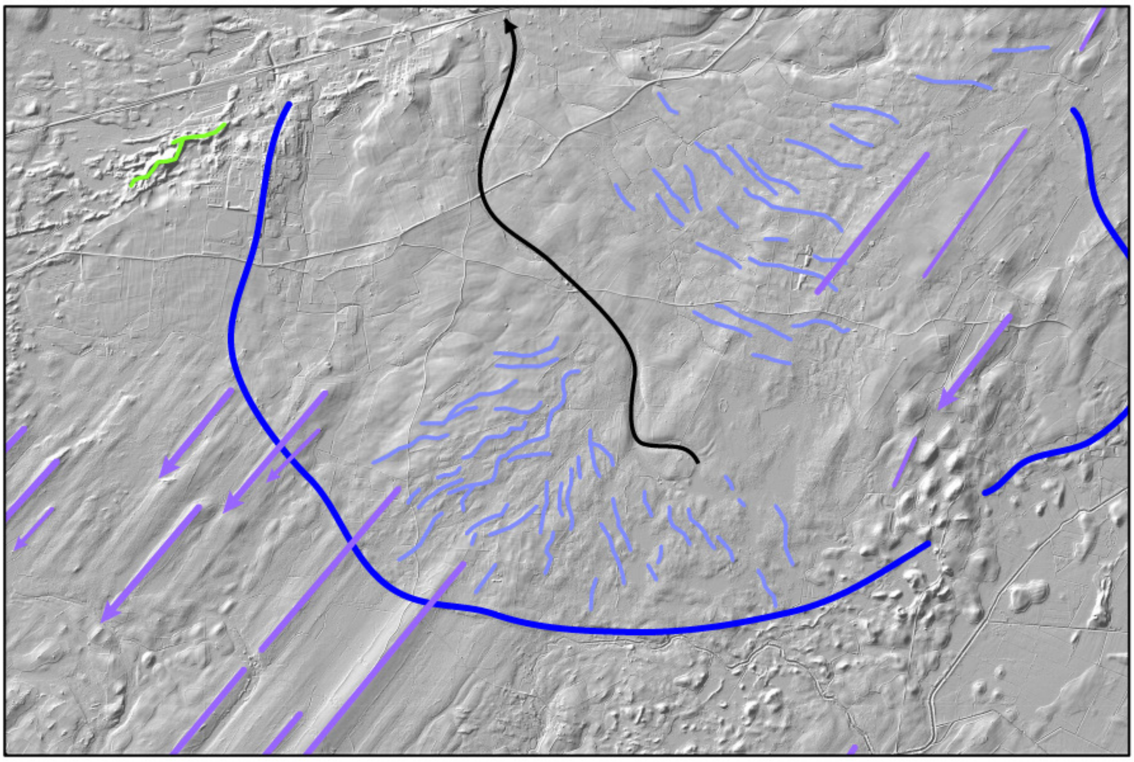

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Hillshade of a detailed digital elevation model (NNH) beneath digitised geomorphic features. The urban area Floby is in the upper left corner of the image. Image width corresponds to approximately 7.5 km.

Maps: © Lantmäteriet, Geodatasamverkan.

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INTRODUCTION

Geomorphic maps are important for both societal development and scientific research. In formerly glaciated regions, like Sweden, geomorphic maps have a variety of applications including hydrogeological investigations (Nilsson et al. 2011), mineral exploration (Klassen 1999), reconstruction of glacial history (Kleman et al. 1997), and ice sheet modelling (Van Tatenhove et al. 1995). Additionally, an inventory of landforms provides a useful tool for land planning and land preservation purposes.

Production of the LiDAR (Light Detection and Ranging) based new national elevation model (NNH) by Lantmäteriet (Swedish mapping agency) has vastly improved our ability to view the geomorphology of Sweden. Following processing to remove anthropogenic structures and vegetation, this digital elevation model (DEM) has a lateral resolution of 2 m and a vertical resolution of 0.25 m (Lantmäteriet 2010). Landforms that are not visible in aerial photographs, due to forest cover or size, stand out clearly in the LiDAR DEM. This makes LiDAR images the ideal medium for mapping geomorphology. Currently, about half of Sweden is covered by these data, and plans exist to obtain coverage of the entire country.

As NNH data becomes available the Geological Survey of Sweden (SGU) plans to map the geomorphology of Sweden, producing a digital nationwide database generated from one uniform dataset and using one conceptual model. A model for the geomorphology is presented here together with a descriptive legend of the landforms to be mapped. Further, the digital format allows us to store non-spatial information about geographic features in an attribute table, a description of the attributes used in the SGU geomorphic mapping are also presented in this report.

Through arrangements with Lantmäteriet, existing NNH data are available to government agencies and universities in Sweden. An outcome of a recent symposium of NNH users, hosted by Lund University, is a desire for a standardised legend of geomorphic units. The rationale behind this is to broadly coordinate the use of colours and symbols for landforms mapped by different workers in Sweden as a means to facilitate communication and understanding between different government agencies and academia. While some uniformity is beneficial, there is also a need to leave room for individuals to add, subtract, or alter units to suit their own application or research. In order to meet this need, we make the SGU geomorphic legend available in this report. However, the mapping of Sweden's geomorphology in this scale is a time consuming project and as work goes on, parts of the legend might change, including addition, subtraction or alteration of units and symbols, to represent better the areas not yet mapped.

CONCEPTUAL MODEL

A conceptual model of how the geomorphic units relate to each other is presented in (Figure 1). Due to its location within the limits of multiple Fennoscandian Ice Sheets, the geomorphology of Sweden and the map legend are dominated by glacial landforms. These are grouped by subglacial, proglacial, and supraglacial origins. Landforms of glaciofluvial genesis are grouped separately and include both erosional and depositional features. Included in this group are also landforms that generally occur in glaciofluvial sediment, such as kettles, and ice-contact slopes. Finally, the post-glacial features that are most useful for land planning and preservation purposes are mapped in a third group. Consequently, the post-glacial group includes only a small subset of the landforms formed after deglaciation. In addition to individual landforms, a means of mapping broader areas, i.e. landscapes, is also included. Landscapes include either hummocky or lineated terrains.

LEGEND

The conceptual model has been transferred into a descriptive legend. This legend is planned to be used in the SGU geomorphic map of Sweden but could be altered in a variety of ways for a variety of different reasons. The legend presented here has been developed to be as efficient as possible and to minimize the time consuming work of digitizing. Consequently, line features are the primary geometry type within this legend and polygon features are used only when necessary. For more detailed studies, it is possible to change geometry types but still keep the overall symbology.

With the use of geographic information systems (GIS), it is possible to present a map with different layers and symbology depending on the scale of the area of interest. For example, when looking at a map at a large scale, every moraine within a moraine complex is visible, but when viewed at a smaller scale the moraine complex is presented as a single object. The digital presentation allows users to select scale-appropriate geomorphological data to their needs. The legend presented in this report is the most detailed symbology of the SGU geomorphic map. For smaller scales the symbology will be altered in an automatic or semi-automatic manner using GIS technology.

Glacial landforms

Proglacial moraines

As an active glacier or ice sheet constantly delivers sediment to the glacier terminus, ridges will be deposited along the margin of the glacier. These ridges are moraines and provide evidence of former ice margins. For example, they could have been produced at the outermost limit of a glacier advance, terminal moraines; by a receding glacier, recessional moraines or end moraines (Benn & Evans 1998). When moraines are assumed to have formed subaquatically, in crevasses below a calving ice sheet, they are called De Geer moraines (Boulton & Hindmarsh 1987). A detailed knowledge of moraine locations is important mainly for ice sheet modelling and reconstruction of ice sheet limits during deglaciation.

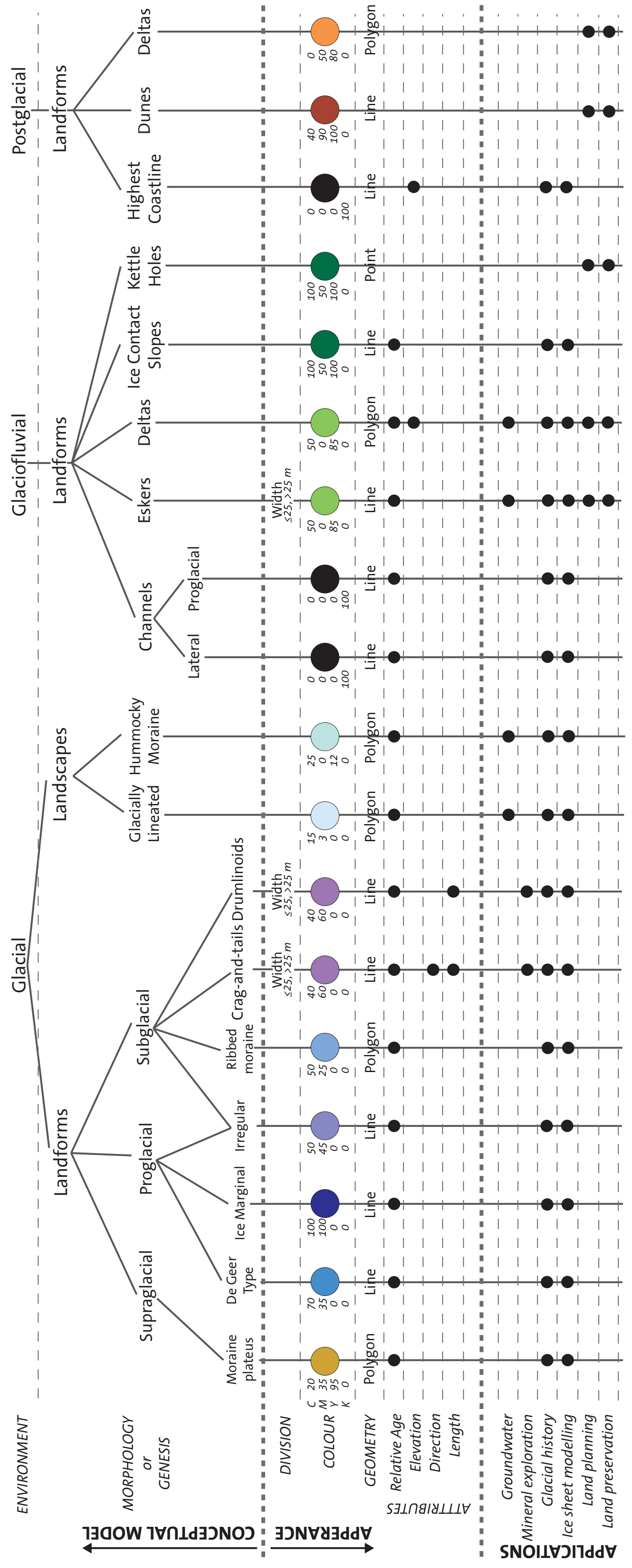

Figure 1. Conceptual model of geomorphic division, landform appearance and attributes in the geomorphic legend. The upper part of the figure presents the scale, environment of formation and morphology or genesis for the landforms and landscapes used in the geomorphic legend. The lower part of the figure presents more detailed division, colour codes, geometry types and attributes for the SGU geomorphic legend and at the very bottom also proposed applications of mapped landforms.

Ice marginal moraines

The category *ice marginal moraines* are used for terminal moraines, end moraines, lateral moraines, or moraine complexes. The unit displays a former glacier standstill or re-advance. The landforms are mapped as line objects (Figure 2).

De Geer type moraines

The *De Geer type moraine* category includes smaller or interrupted moraines developed suaquatically. These features display evidence of a calving glacier. *The De Geer type moraines* are mapped as line objects (Figure 3).

Irregular moraines

Apart from *ice marginal moraines* and *De Geer type moraines*, there are other ridges with more complex appearance that are not yet understood in terms of genesis. The category *Irregular moraines* include theses moraines and those that cannot be assigned to ice-marginal processes. For example, this unit includes moraines created in crevasses below the ice, such as crevasse fill (Sharp 1985), crevasse-squeeze ridges (Kleman 1988), radial moraines or preserved medial moraines. *Irregular moraines* are symbolised by a line object (Figure 4).

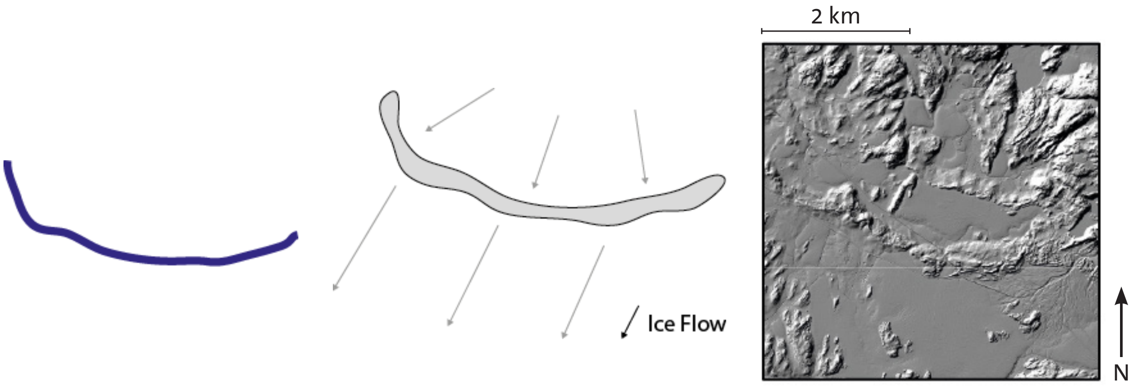

Figure 2. Symbolisation of Ice marginal moraine. **Left:** As presented in the database. **Middle:** Generalised landform. **Right:** LiDAR example of landform.

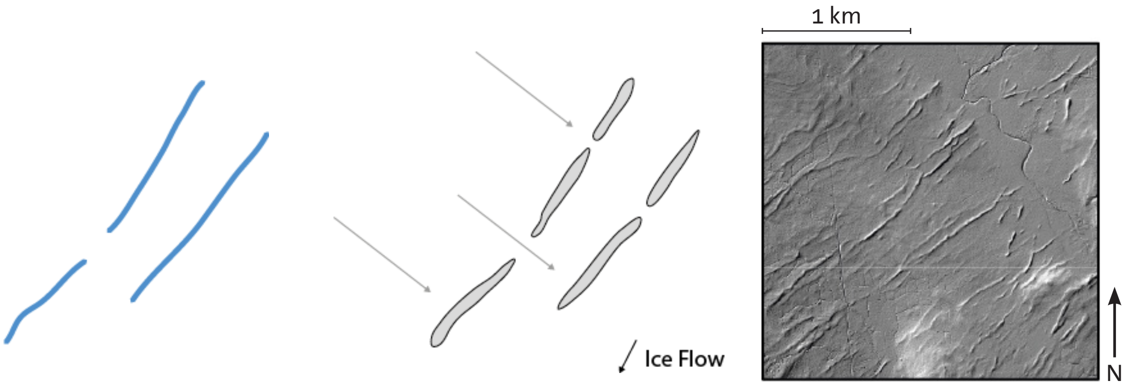

Figure 3. Symbolisation of De Geer type moraine. **Left:** As presented in the database. **Middle:** Generalised landform. **Right:** LiDAR example of landform.

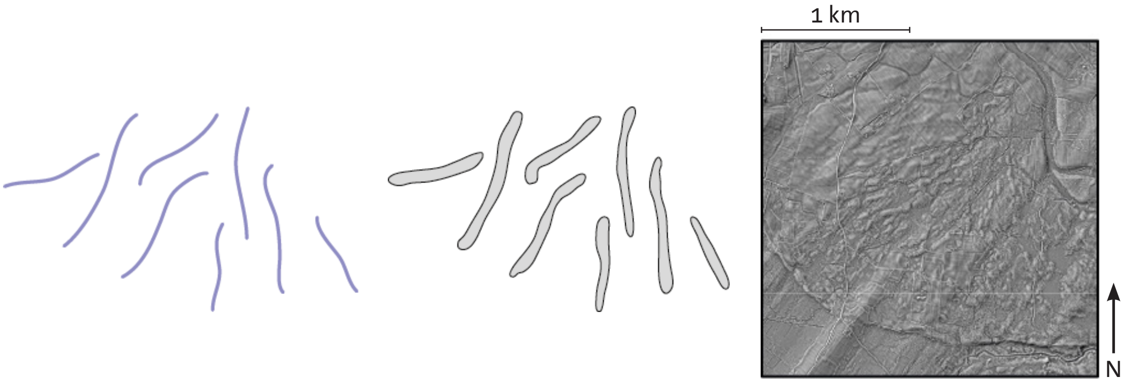

Figure 4. Symbolisation of Irregular moraine. **Left:** As presented in the database. **Middle:** Generalised landform. **Right:** LiDAR example of landform.

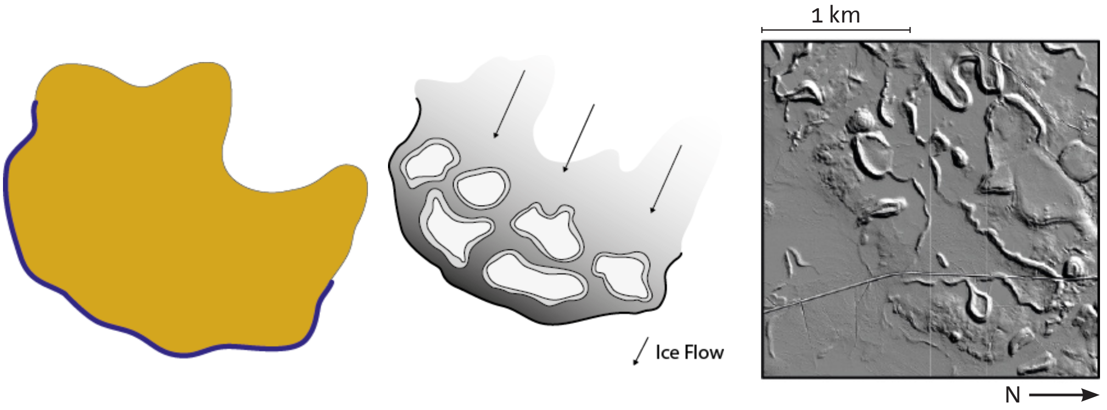

Figure 5. Symbolisation of Moraine plateaus. **Left:** As presented in the database. **Middle:** Generalised landform. **Right:** LiDAR example of landform.

Supraglacial landforms

Moraine plateaus

Moraine plateaus are deposits of supraglacial lakes on a disintegrating ice sheet (Lagerbäck 1988). In northern Sweden referred to as Veiki moraine (Hoppe 1952) and in the North American literature as ice walled lake plains (Clayton et al. 2008). In northern Finland a similar landform is called Pulju moraine (Kujansuu 1967). The landform is often bounded by an outer moraine on its ice-distal side. Moreover, the areas consist of large plateaus with hummocky moraine that in turn hold a series of well-defined bowls with distinct rims. The bowls are often filled with lake sediments or mires. In northern Sweden, they have been shown to originate from a pre-Late Weichselian ice-sheet (Lagerbäck 1988). The *moraine plateaus* are mapped as polygons covering the plateau areas together with line objects symbolizing the distal moraines as ice marginal moraines (Figure 5).

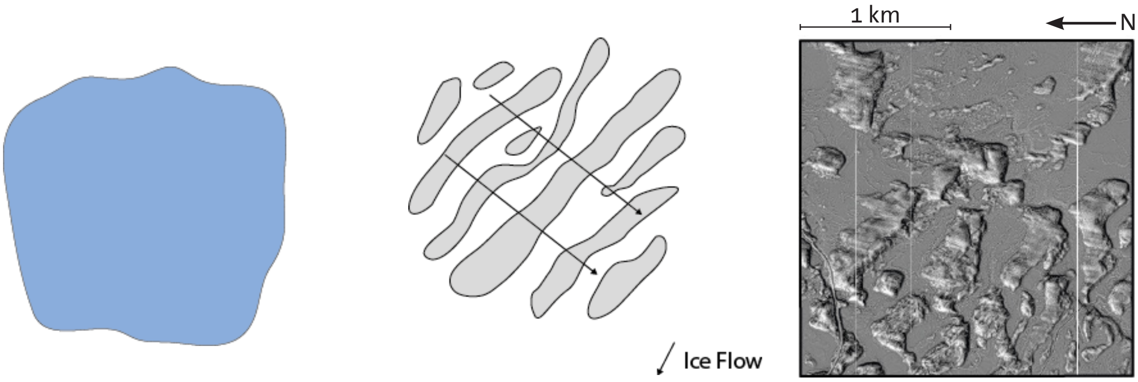

Figure 6. Symbolisation of Ribbed moraine. **Left:** As presented in the database. **Middle:** Generalised landform. **Right:** LiDAR example of landform.

Subglacial landforms

Ribbed moraines

Ribbed moraine is a subglacial landform system composed of ridges transverse to ice flow joining each other in a semi-ordered pattern. There are several hypotheses regarding their formation, both polygenetic and monogenetic; e.g. shearing and stacking of till close to the ice margin (Aylsworth & Shilts 1989, Bouchard 1989, Lindén et al. 2008, Shaw 1983), remoulding of pre-existing ridges (Boulton 1987, Hindmarsh 1999, 1998a, 1998b, Lundqvist 1989, Möller 2006), or the breaking up of a frozen till cover due to a change from cold based to warm based ice (Hättestrand & Kleman 1999, Hättestrand 1997). The landscape is mapped using a broad definition of *ribbed moraine*, i.e. ridges subglacially formed transverse to ice flow (Dunlop & Clark 2006). Ribbed moraine is different from *De Geer type moraines* and ice marginal moraines, because the later two are ice marginal landforms. The mapping is performed regardless of subglacial formation, and the landforms are symbolised by a polygon covering the area of ribbed moraine (Figure 6).

Glacial lineations

Glacial lineations are streamlined subglacial bedforms developed in the direction of ice flow. Flutes are the smallest of the glacial lineations and are generally about 1 m high and often visible in modern glacier forelands (Benn & Evans 1998). However, with new detailed elevation data it is possible to find flutes in areas not glaciated since the last deglaciation. Another type of lineation is the drumlin which are described as ten to a couple of hundred meters wide (Clark et al. 2009). Megaflutes are even larger, not unusual to be wider than 1 km (Clark 1993). If these landforms are developed behind an obstruction, i.e. on the lee side of a crag or boulder, they are referred to as crag-and-tails.

For mapping purposes, the glacial lineations have been divided into two different sizes and two different types; small (S) and large (L) as well as *crag-and-tails* and *drumlinoids*. The two sizes are divided by their width; ≤ 25 meters (S) and > 25 meters (L). In general, the small size division correlates to the descriptions of flutes whereas the large size division correlates to drumlins and megaflutes. The two types of lineations are defined by the presence or absence of an obstruction at the ice-proximal end of the landform. A detailed knowledge of the position and direction of glacial lineations are important mainly for ice sheet modelling, reconstruction of the ice sheets, and mineral exploration.

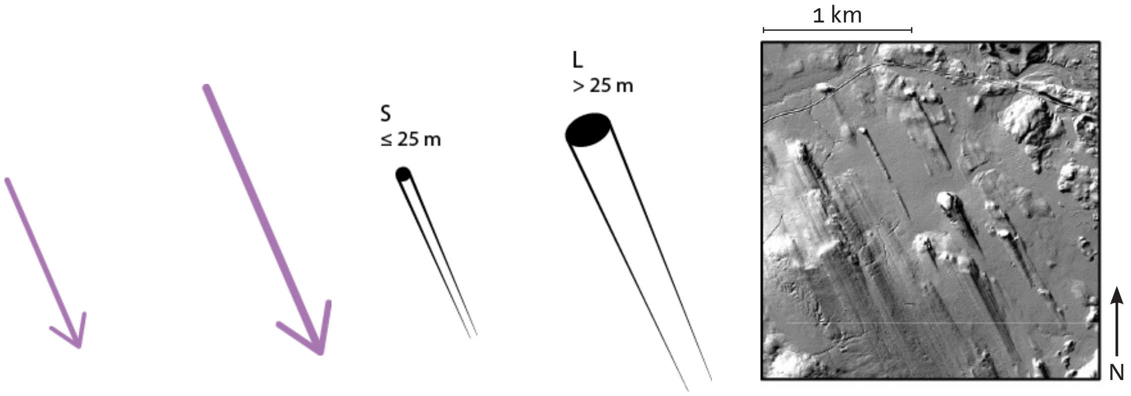

Figure 7. Symbolisation of Crag and tails. **Left:** As presented in the database. **Middle:** Generalised landform. **Right:** LiDAR example of landform.

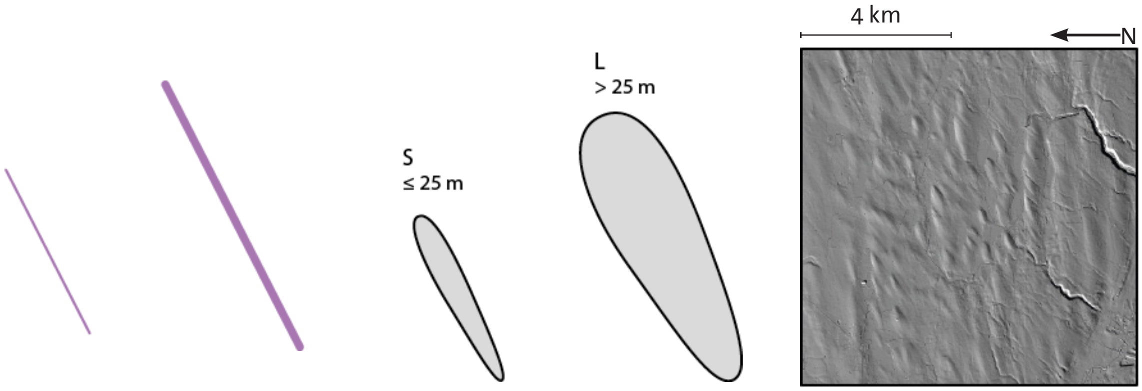

Figure 8. Symbolisation of drumlinoids. **Left:** As presented in the database. **Middle:** Generalised landform. **Right:** LiDAR example of landform.

Crag-and-tails

Crag-and-tails have a tail that points in the ice flow direction. The mapping category *crag-and-tail* is used regardless if a glacial lineation is deposited behind a crag, boulder or clast-cluster. The symbolization of this landform is a line object with an arrow in the direction of ice flow (Figure 7).

Drumlinoids

The category drumlinoids includes all other glacial lineations regardless of genesis. The landform is symbolised by a line object in the direction of ice flow (Figure 8).

Glacial landscapes

Hummocky moraine landscape

A *hummocky moraine landscape* is an area of irregular hills and depressions created during the deglaciation. This landscape is useful in reconstructing the style of deglaciation, and it is denoted by a polygon (Figure 9).

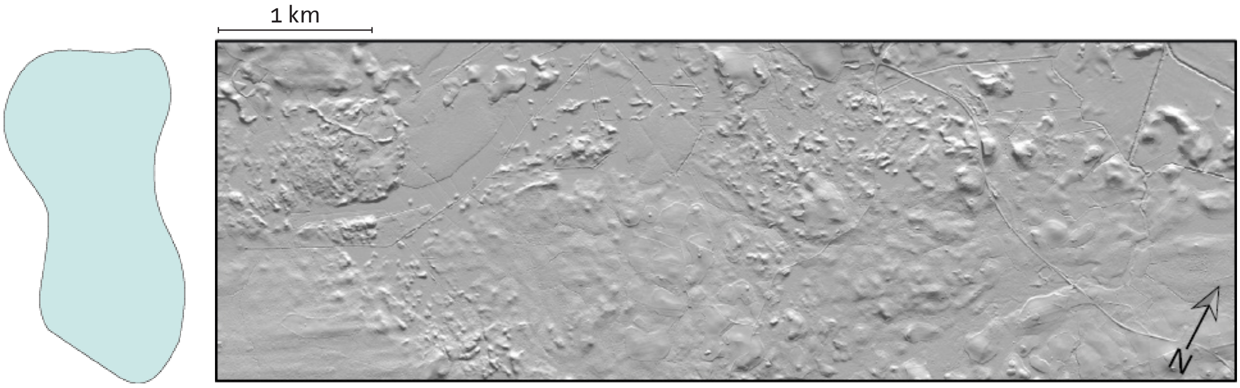

Figure 9. Symbolisation of hummocky moraine landscapes. **Left:** As presented in the database. **Right:** LiDAR example of landform.

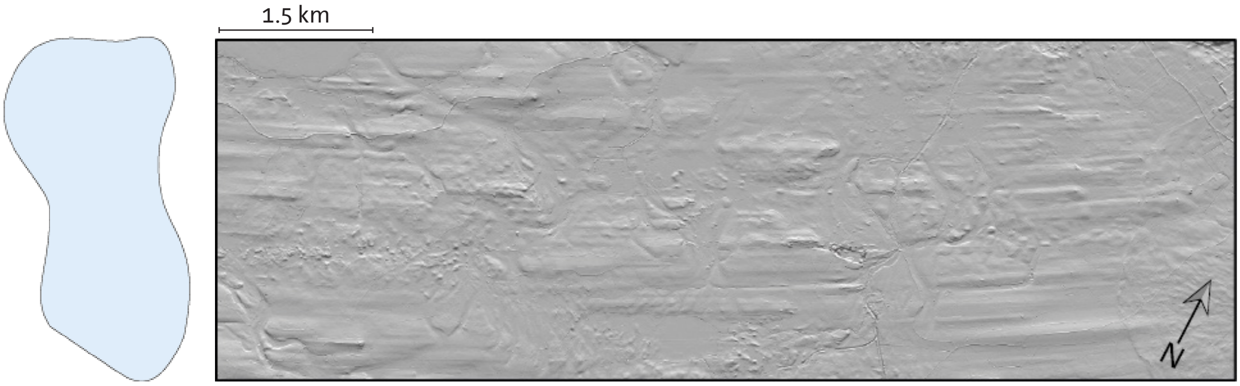

Figure 10. Symbolisation of glacially lineated landscapes. **Left:** As presented in the database. **Right:** LiDAR example of landform.

Glacially lineated landscape

A *glacially lineated landscape* is an area with an abundance of glacial lineations of any size or genesis, including those that are too small to map individually. This till plain represents the former sole of a glacier, and it is useful for reconstructing basal conditions and style of deglaciation. This unit is mapped as a polygon (Figure 10).

Glaciofluvial landforms

Lateral meltwater channels

When glacial meltwater flows along the ice margin it erodes channels into the substrate, *lateral meltwater channels*. The appearance of *lateral meltwater channels* differs from subglacial and subaerial channels, especially in subpolar glacial systems, where meltwater cannot flow beneath the glacier. Consequently, the channels might not flow in the direction of slope.

Rather, they may follow the former ice margin (Benn & Evans 1998). These landforms indicate ice margin positions and are symbolised by a line object with an arrow pointing in the direction of former water flow (Figure 11).

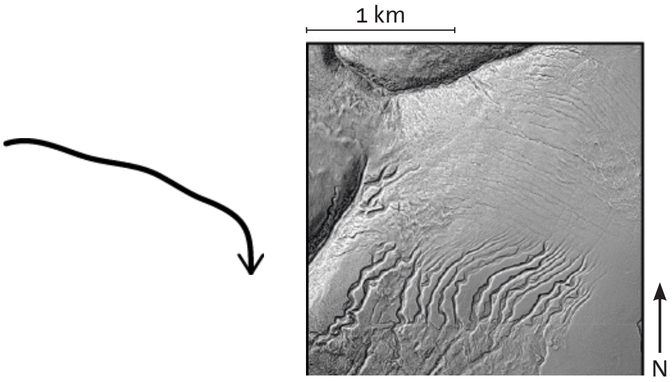

Figure 11. Symbolisation of Lateral meltwater channels. **Left:** As presented in the database. **Right:** LiDAR example of landform.

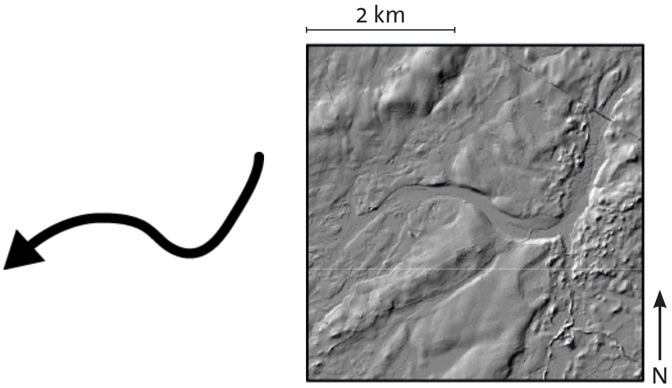

Figure 12. Symbolisation of Large proglacial channels. **Left:** As presented in the database. **Right:** LiDAR example of landform.

Lateral meltwater channels are important as they both show former ice margins as well as hints about the subglacial environment. Therefore they are useful in the reconstruction of ice sheets.

Large proglacial meltwater channels

Proglacial meltwater channels form in front of any glacier with enough discharge to erode into the substrate. Only prominent proglacial meltwater channels are mapped. Therefore these are referred to as *large proglacial meltwater channels*. These channels are often created either by jökhulhlaups or outburst floods from ice-dammed lakes. They are symbolised by a line object with an arrow pointing in the direction of former water flow (Figure 12).

Large proglacial meltwater channels are important indicators for large outbursts of water, such as the draining of glacial lakes. Consequently, these landforms are important for reconstructing the deglacial history of a region.

Eskers

Eskers are formed sub-glacially in ice walled channels and consist mainly of sorted sand and gravel. They often appear as sinuous ridges with lengths up to several hundreds of kilometres and heights of tens of metres. For mapping purposes, eskers have been divided into two different sizes; small (S) and large (L), with width ≤ 25 meters and > 25 meter, respectively. The *eskers* are symbolised by line objects (Figure 13). Moreover, large portions of the *eskers* in

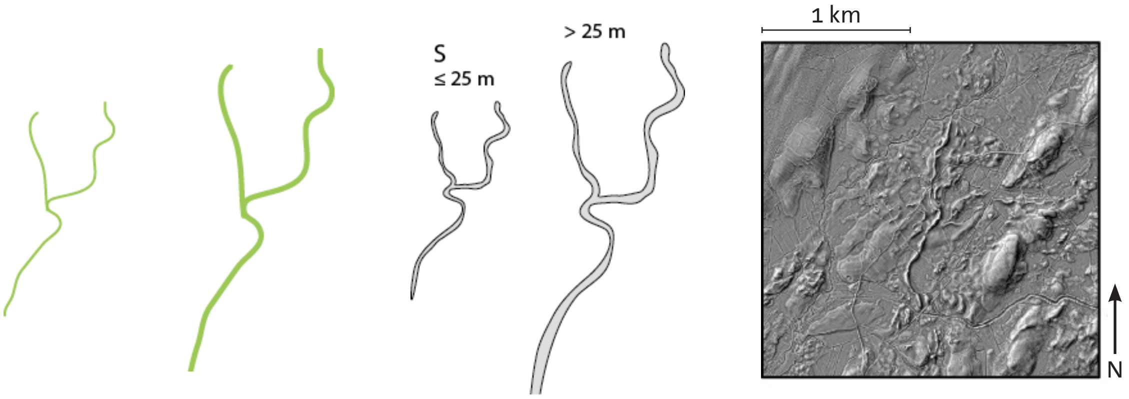

Figure 13. Symbolisation of Eskers. **Left:** As presented in the database. **Middle:** Generalised landform. **Right:** LiDAR example of landform.

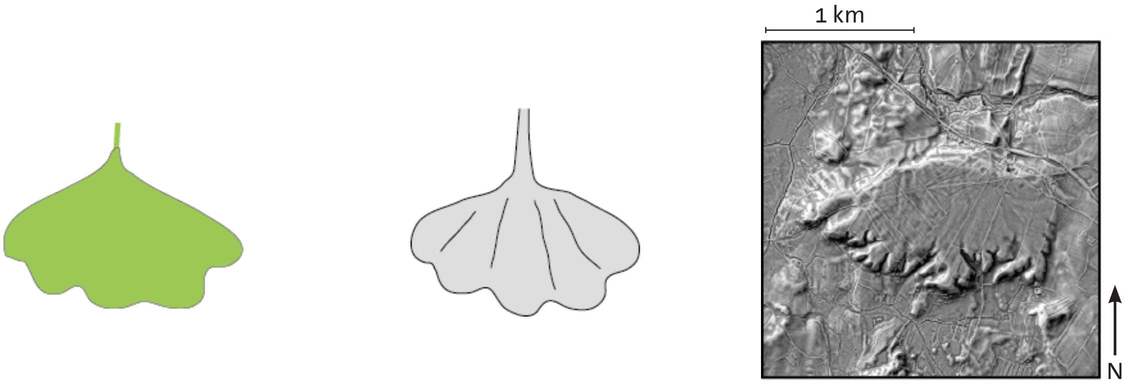

Figure 14. Symbolisation of Glaciofluvial deltas. **Left:** As presented in the database. **Middle:** Generalised landform. **Right:** LiDAR example of landform.

Sweden have been excavated when mining for sand and gravel for societal use. A line feature is used to denote this anthropogenic feature. Even if the *esker* ridge has been excavated the esker core could still be there.

Consequently, mapping of this feature yields important information for groundwater mapping and management. *Excavated eskers* are mapped as dashed line object. The importance of mapping *eskers* lies mainly in groundwater mapping as eskers are important aquifers. Moreover, data of eskers can be used for modelling of the former subglacial environment and for reconstructing the deglacial history of a region.

Glaciofluvial deltas

Glaciofluvial deltas are landforms composed of sand and gravel that has been transported by glacial meltwater and deposited in standing water. Subsequent to deglaciation, the landforms have been separated from the original body of water either by land uplift or lake-level lowering. A polygon symbolizes the glaciofluvial delta (Figure 14). Glaciofluvial deltas are a part of the glaciofluvial system and therefore important for groundwater planning.

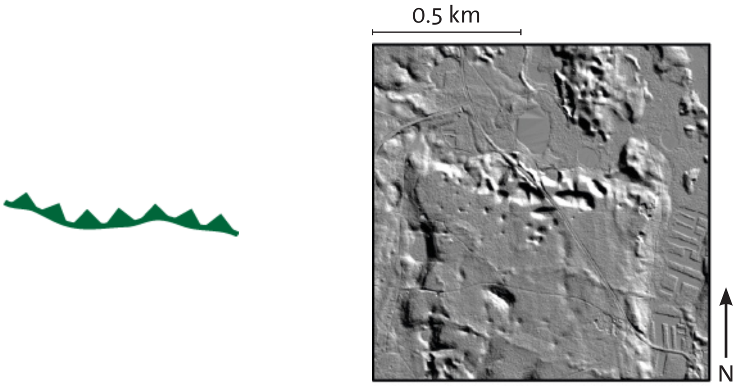

Figure 15. Symbolisation of Ice-contact slope. **Left:** As presented in the database. **Right:** LiDAR example of landform

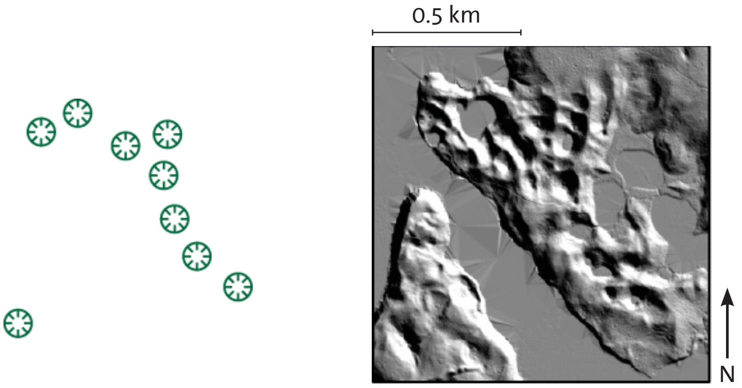

Figure 16. Symbolisation of Kettle holes. **Left:** As presented in the database. **Right:** LiDAR example of landform.

Ice-contact slopes

Often, glaciofluvial deltas are deposited in contact with the ice. When the glacier retreats it leaves an over-steepened slope on the proximal side of the delta, an *ice-contact slope*. The *ice-contact slope* yields information about glacier margin standstills and are mapped as line objects (Figure 15). Knowledge of *Ice-contact slopes* is important mainly for ice sheet modelling and reconstruction of the ice margins during deglaciation.

Kettle holes

As the ice retreats, blocks of ice could be buried by glacial sediments. Later, when the ice melts depressions are formed. These are referred to as kettle holes and are mapped as point features (Figure 16). *Kettle holes* are important to map for natural preservation and conservation purposes.

Postglacial landforms

Highest coastline

After the last glaciation large parts of Sweden were below water, either from the ocean or from glacially dammed lakes in the Baltic basin. The ice sheet had deformed and pushed down the crust and as the load was removed, the land started to rise. The highest position that the water level reached is referred to as the *highest coastline.* Wave action creates beach ridges, the highest of these in any geographic region is mapped as a line object (Figure 17).

Aeolian dunes

Winds can erode, transport, and deposit fine sand as *aeolian dunes*. During deglaciation, winds where strong close to the ice margin. The area was not vegetated which allowed for transport of sediment and accumulation of *aeolian dunes*. These are symbolised by a line object along the crest of the dune (Figure 18). The significance of mapping dunes lies mainly in the field of natural heritage.

Modern deltas

Deltas are fluvial landforms composed of postglacial sand and gravel deposited in standing water. Only geomorphologically distinct deltas are mapped using a polygon to symbolize the landform (Figure 19). *Modern deltas* are important to map for natural preservation and conservation purposes.

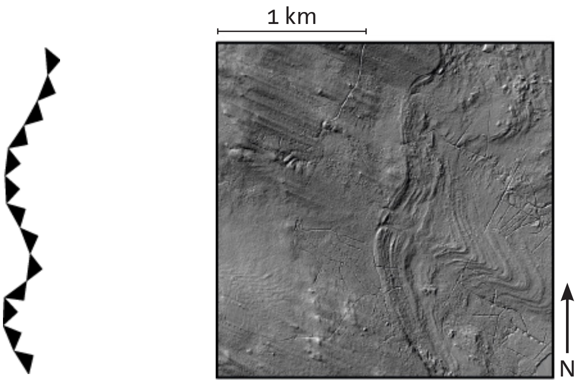

Figure 17. Symbolisation of the Highest coastline. **Left:** As presented in the database. **Right:** LiDAR example of landform.

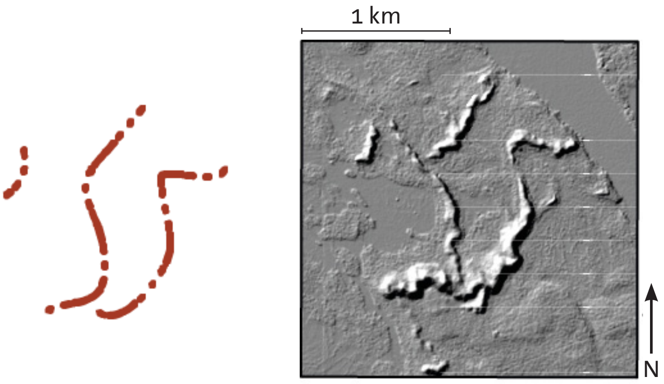

Figure 18. Symbolisation of the Dunes. **Left:** As presented in the database. **Right:** LiDAR example of landform.

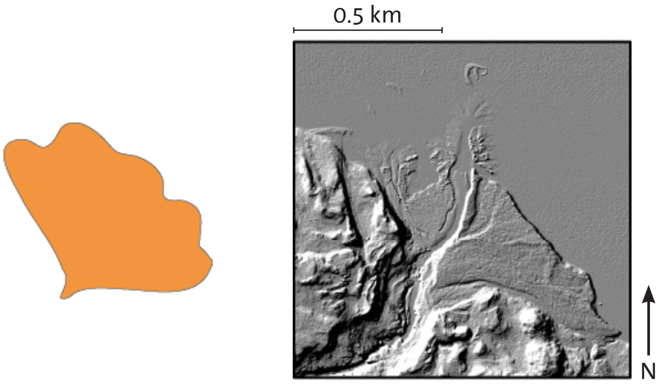

Figure 19. Symbolisation of Modern deltas. **Left:** As presented in the database. **Right:** LiDAR example of landform.

APPEARANCE AND ATTRIBUTES

The colours used are based on the SGU legend for maps of Quaternary deposits and are included in Figure 1. We suggest that when workers add units of their own, features of similar genesis and morphology be given similar colours.

To add non-spatial data to the geomorphic units, attribute tables are used. With the use of attributes it is possible to store data about the landforms that otherwise could be hard to present as part of a traditional map product. For any landform where the storage of non-spatial data is of interest, any of the following attributes may be used; elevation, direction, length, or relative age. For glaciofluvial deltas and the highest coastline, elevation data are stored in meters. For crag-and-tails, the directions, in degrees are recorded together with the length in meters of all glacial lineations. Moreover, the relative age is stored for any group of landforms where applicable. The relative age is stored when landforms cross cut each other. To store information about these relationships, we use two attribute fields. The first is for the group of landforms that are related to each other, and the second is the actual relative age per landform.

CONCLUDING REMARKS

SGU plans to apply this legend to make a geomorphic map of Sweden. While this product will provide a valuable data set with multiple applications for both society and science, it will not address specific, small scale, scientific problems. These problems will be addressed by other workers. We welcome them to use this legend as a starting point for their own mapping in hopes that a level of standardization will lead to increased and better communication between working groups in Sweden.

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