We present a 1:100,000 scale Quaternary geomorphic map covering 2500 km$^2$ in Central Sweden and including the Siljan Impact Structure. Because of the crater, the area is currently under consideration to become a geopark, and this project was undertaken to document Quaternary geology that may be of interest to park organizers and future visitors.

A high-resolution digital elevation model with a vertical resolution of 0.25 m and a lateral resolution of 2.0 m was used as the base to map sub-, pro-, and post-glacial landforms. Consideration of the suite of landforms indicates ice flow from the northwest, multiple paleo-lake levels, and unstable landscapes into the Holocene. Additionally, the impact structure has played a role in routing both glacial and post-glacial drainage.

**Keywords:** glacial geomorphology; Siljan; map; Sweden; glacial geology; glacial landforms; quaternary

1. Introduction

The Siljan impact structure is located in Dalarna, central Sweden (Figure 1). It includes a raised central dome (32 km diameter) composed of Precambrian granite, and a surrounding circular depression (44 km diameter) which has retained the Ordovician and Silurian age sedimentary rocks (Kresten, Aaro, & Karis, 1991a, 1991b, 1991c, 1991d; Svensson, 1971). A meteorite impact origin of the structure was hypothesized by Fredriksson and Wickman (1963) and supported by measurements of deformation lamellae in quartz by Svensson (1971). Laser argon dating of melt breccias associated with the impact provides an age of 377 ± 2 Ma for the event (Reimold, Kelley, Sherlock, Henkel, & Koeberl, 2005).

The Siljan meteorite impact had a profound effect on local, and perhaps global, geology. It has been proposed that heat from the impact was responsible for hydrothermal production of local metal ores (Wickman, 1994). Additionally, the impact corresponds temporally to the Frasnian/Famennian boundary and may be responsible for the associated extinction event (Reimold et al., 2005).

Due to its unusual geologic history and the appeal of this geology to the general public, the Siljan area is being considered as a location for a geopark. While the focus of the park will be the meteorite impact, all visible geology is of interest to geopark organizers and, perhaps, future
visitors. An example of visible geology in the region is the Quaternary geology, specifically the geomorphology.

Glacial landforms dominate the Quaternary geomorphology of the Siljan area (Ulfstedt & Yrgård, 1983). Although both geomorphic (Kleman & Borgström, 1990) and stratigraphic (Möller, Anjar, & Murray, 2013) evidence of preserved landscapes have been found in other parts of Dalarna, our geomorphic mapping showed no definitive evidence of preserved landforms, such as cross-cutting lineations. There are, however, areas of ribbed moraine which have been interpreted as largely preserved landforms (Möller, 2006) or, at the least, evidence of cold-based ice (Hättestrand, 1997). With these caveats in place, we make the claim that the late-Weichselian Fennoscandian Ice Sheet created the majority of glacial features in the Siljan region. According to varve chronologies, the ice sheet retreated across the area about 9500 BP (Fromm, 1964). Although field evidence suggests that deglaciation included both retreat of active ice and downwasting of stagnant ice (Nordell, 1984), much of the Quaternary geologic research in the area has focused on varve records and the various paleo-lake levels, including the Ancylus stage of the Baltic ice lake (Calles, 1985). The Siljan area, however, contains a rich collection of sub-, pro-, and post-glacial landforms (Ulfstedt & Yrgård, 1983) that, in addition to educating the public, can be used to interpret the Quaternary history of the region. These landforms are the basis of the accompanying map (Main map).

2. Methods
Geomorphic landforms were mapped manually on derivatives of a light detection and ranging (LiDAR) derived digital elevation model (DEM) using Esri ArcGIS 10.1. After processing to

Figure 1. A map of Sweden and Norway with the study area outlined in red.
remove vegetation and anthropogenic structures, the LiDAR DEM provides a ‘bare earth’ view of the landscape with a vertical resolution of 0.25 m and a lateral resolution of 2 m (Lantmäteriet, 2010). Landform mapping was conducted twice at two different scales (1:10,000 and 1:20,000) in order to facilitate recognition of landforms of different sizes. At both scales, multiple illumination angles and a slope raster were used to aid in detection of linear landforms with different orientations. The digital data from surficial geologic maps of the area were also consulted to check interpretations, especially regarding deltas and the highest Baltic coastline (Ek, 2010; Ising & Svedlund, 2008; Mikko & Backström, 2010; Norrlin, 2011; Svedlund, 2008; Svedlund & Dahlberg, 2009). The current map covers an area similar to that mapped by Ulfstedt and Yrgård (1983) who used a combination of aerial photographic interpretation and field investigation to present detailed geomorphic maps at a scale of 1:50,000. Unfortunately, these maps are out of print and difficult to obtain. The map presented here uses different units and a higher resolution base, and it is presented in an easily accessible digital format.

This map is part of a larger project being carried out by the Geological Survey of Sweden to produce a digital geomorphic map of Sweden (Peterson & Smith, 2013) based on the new national height model being produced by the Swedish National Mapping Agency (Lantmäteriet, 2010).

3. Landform definitions and map units

The description of map units is carried out from the bottom of the legend toward the top in approximate stratigraphic order. This is done, however, with the understanding that different units may have formed simultaneously in different locations. Examples of these landforms and explanations of their geneses can be found in Peterson and Smith (2013).

3.1. Area of ribbed moraines

Ribbed moraine is a subglacial landform composed of till ridges trending transverse to ice flow that appear to fit together in a semi-ordered pattern. The arrows indicate the direction of former ice flow.

3.2. Drumlinoid

A drumlinoid is a subglacial landform that is streamlined in the direction of ice flow. They are differentiated from crag-and-tails by the fact that there is no visible obstruction at the up-ice end of the feature. Small drumlinoids are less than 25 m wide, and large drumlinoids are greater than 25 m wide.

3.3. Crag-and-tail

A crag-and-tail is a subglacial landform created in the lee of a boulder or a bedrock outcrop and streamlined in the direction of ice flow. Small crag-and-tails are less than 25 m wide, and large crag-and-tails are greater than 25 m wide. The arrows point in the direction of former ice flow.

3.4. Esker

An esker is a subglacial landform consisting of a sinuous ridge of glaciofluvial sediment, often sand and gravel. Eskers are the deposits of subglacial streams. Small eskers are less than 25 m wide, and large eskers are greater than 25 m wide. Excavated eskers are used to indicate areas where sand and gravel mining has significantly altered the esker landform.
3.5. *Ice-marginal moraine*
Ice-marginal moraines are linear ridges of till deposited by ice at the margin the ice sheet. They delimit former standstills or re-advances of the ice margin.

3.6. *Glaciofluvial delta surface*
Glaciofluvial deltas are landforms composed of sand and gravel that have been transported by glacial meltwater and deposited where the stream or esker enters a standing body of water. The flat to gently sloping surfaces of glaciofluvial deltas that are mapped approximate the height of the former body of water.

3.7. *Lateral meltwater channel*
Lateral meltwater channels are formed by fluvial erosion as glacial meltwater flows along the margin of the former ice sheet. Because the ice sheet prohibited the water from following the surface gradient, these channels do not follow modern topography. Often, they trend sub-horizontally along slopes. The arrow indicates the direction of former water flow.

3.8. *Proglacial channel*
Proglacial channels are formed by fluvial erosion as glacial meltwater follows the surface gradient. Generally, these channels trend away from the retreating ice margin. However, when ice-dammed lakes drain, due to the thinning and retreating of the ice margin, the channels may trend in other directions. The arrow indicates the direction former water flow.

3.9. *Highest coastline*
The highest coastline is the highest position that either marine or ice dammed water in the Baltic basin reached following deglaciation. Under favorable conditions, a beach ridge formed at this elevation. The highest coastline is mapped only where it is geomorphically expressed.

3.10. *Aeolian dunes*
Aeolian dunes are linear ridges of wind-transported fine sand.

3.11. *Lakes*
Lakes are the modern limits of standing bodies of fresh water.

3.12. *Modern delta*
Modern deltas are flat-topped landforms composed of post-glacial fluvial sediment deposited where a stream enters a body of standing water.

4. **Conclusions and points of interest**
Quaternary geomorphology can be used to reconstruct the glacial and post-glacial history of the Siljan region, and the locations described here may be used as interpretative sites for future
visitors. First, glacial lineations, specifically crag-and-tail features, indicate ice flow from the northwest (Figure 2). Second, glaciofluvial deltas and drainage channels provide evidence of multiple ice dammed lakes following deglaciation (Figure 3). Third, eskers, glaciofluvial channels, and modern rivers have been directed by the annular depression surrounding the impact crater.

Figure 2. Glacial crag-and-tail and drumlinoid features indicate the direction of former ice flow from the northwest toward the southeast. The largest crag and tail features in the center of the map are up to 1500 m long and 200 m wide with a maximum relief of 4 m. A complete legend is found on the accompanying map.

Figure 3. Lake Salutjärnen was dammed by the glacier margin as it retreated toward the northwest. The dashed yellow line approximates the shoreline of the former ice-dammed lake that emptied into Lake Brossen to the southeast. As the ice margin retreated, the ice dam failed, and water drained toward the northwest. This catastrophic lake-level lowering scoured the channel that is the current outlet from the lake.
Figure 4. Locally, eskers follow the annular depression surrounding the Siljan Impact Structure and trend nearly perpendicular to the direction of ice flow. These were likely deposited near the margin of the thinning ice sheet where bed topography becomes increasingly important in directing meltwater flow.

Figure 5. Dunes developed on deltaic sediments exposed by lake-level lowering. The abrupt termination of the dunes to the east occurs along another paleo-lake shoreline. The lack of dunes east of this shoreline suggests that the landscape had stabilized, perhaps with vegetation, when lake level was lowered.
Finally, the presence of dunes suggests an unstable landscape as lake levels dropped during the Holocene (Figure 5).

Software

Mapping was carried out using Esri ArcGIS 10.1, and Adobe Illustrator CS6.

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