Stockholm University

Bachelor Thesis

Degree Project in
Geology 15 hp

A sedimentological study of the Middle Formations of the Svecofennian Group on NE Utö

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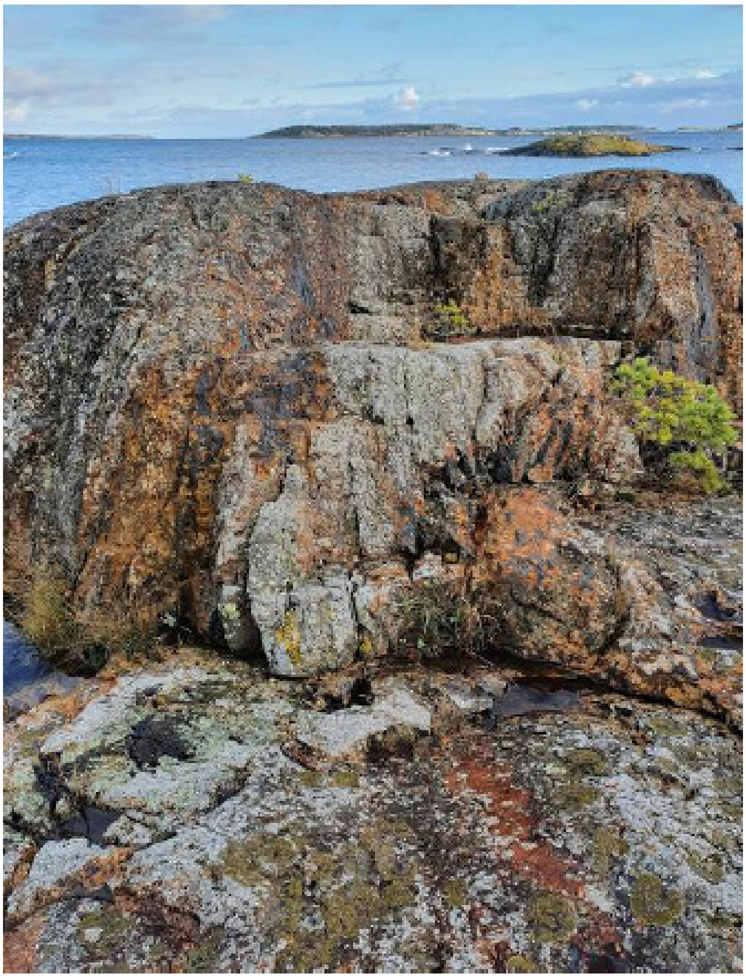

Stockholm 2021

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Abstract

Utö is an island located in the southern archipelago of Stockholm and is part of the Svecofennian bedrock. The bedrock on Utö was formed during an accretionary collision around 2 billion years ago, and consist of siliclastic, volcanoclastic, chemical and biochemical rocks, which were thereafter metamorphosed. Utö is the residual from a forearc that was created from the subduction.

The aim of this project is to construct a sedimentological log over the middle formation on NE Utö and determine the depositional environment. The main purpose of constructing a sedimentary log is to obtain a graphical overview of what was visually interpreted in the field. Geology can tell a story about past climate, where each rock type helps with analysing the depositional environment, thereby we can visualize how our planet looked million or even billion years ago. The methods used for logging the sequence were visual interpretations, determination of protolithic grainsize, minerals in fresh samples and usage of 10% hydrochloric acid (HCl) to diagnose carbonate in the bedrock. A 433m long sequence was logged and divided into 12 sections which can be divided in to 3 larger groups. These 3 groups are siliclastic rocks, carbonate rocks and banded iron formations.

The base of the log sequence reflects a shallow sea deposition of silicic sediments, more specifically, silty mudstone and sandstone. Further up the log sequence, masses of carbonate layers are interspersed with cherts, reflecting carbonate precipitation in a tropical shallow sea environment induced by cyanobacteria in the sea, which produced oxygen as a biproduct. Oxygen increased rapidly and produced the Great Oxygenation Event (GOE). Iron rich oceans precipitated ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) and Banded Iron Formations (BIF) were formed. BIFs are seen at the finale of the sedimentary log done at NE Utö.

From the results of the log we can conclude that the Middle Formations on Utö are interpreted to have deposited in a shallow sea and at tropical conditions, most probably associated with tidal zones.

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Introduction

Sedimentary rocks are excellent indicators of past climate change through the history of the Earth. Rocks hold a record of the climate conditions during the time they were deposited and lithified. Therefore, each rock type is indicative for a specific depositional environment. By studying the bedrock, it is possible to understand and analyse past climate changes through geological time. Sedimentary rocks are formed from weathering and erosion of igneous, metamorphic, and older sedimentary rocks. The eroded particles are often transported by fluvial, marine, glacial or aeolian processes until they are deposited (Marshak, 2005). Thereby, particle grain sizes are sorted as a function of the energy of the depositional environment. Higher energy means larger rock fragments being transported. Depending on the energy, three main types of rocks are created: conglomerate, sandstone, and mudstone, in the order from highest to lowest energy level. Pyroclastic particles can be included if there is active volcanism in the source region (Klein and Philpotts, 2017).

Utö is an island located in the archipelago of south eastern Stockholm (figure 1). The rocks which crop out on Utö belong to the Svecofennian Group. At the time the Svecofennian Group was being deposited, 2-1.8 billion years ago (2-1.8 Ga), the rocks and mountains that formed today’s Sweden were situated at a lower latitude than today, closer to the equator. The environment was tropical with a shallow sea (Larsson and Tullborg, 2015). Types of rocks formed under these conditions are clastic, volcanoclastic, biochemical, and chemical sedimentary rocks. The rocks on Utö are mostly metasedimentary, meaning they were originally sediments or sedimentary rock, but were put under a lot of pressure and heat and were metamorphosed. The cause of this pressure and temperature change is continental accretion associated with subduction, where the sea sediments were uplifted and metamorphosed (Möller and Andersson, 2018).

The aim of this project is to construct a sedimentological log over a ~400m long sequence on NE Utö and determine the depositional environment. The log covers the middle formation of the Svecofennian group on the island.

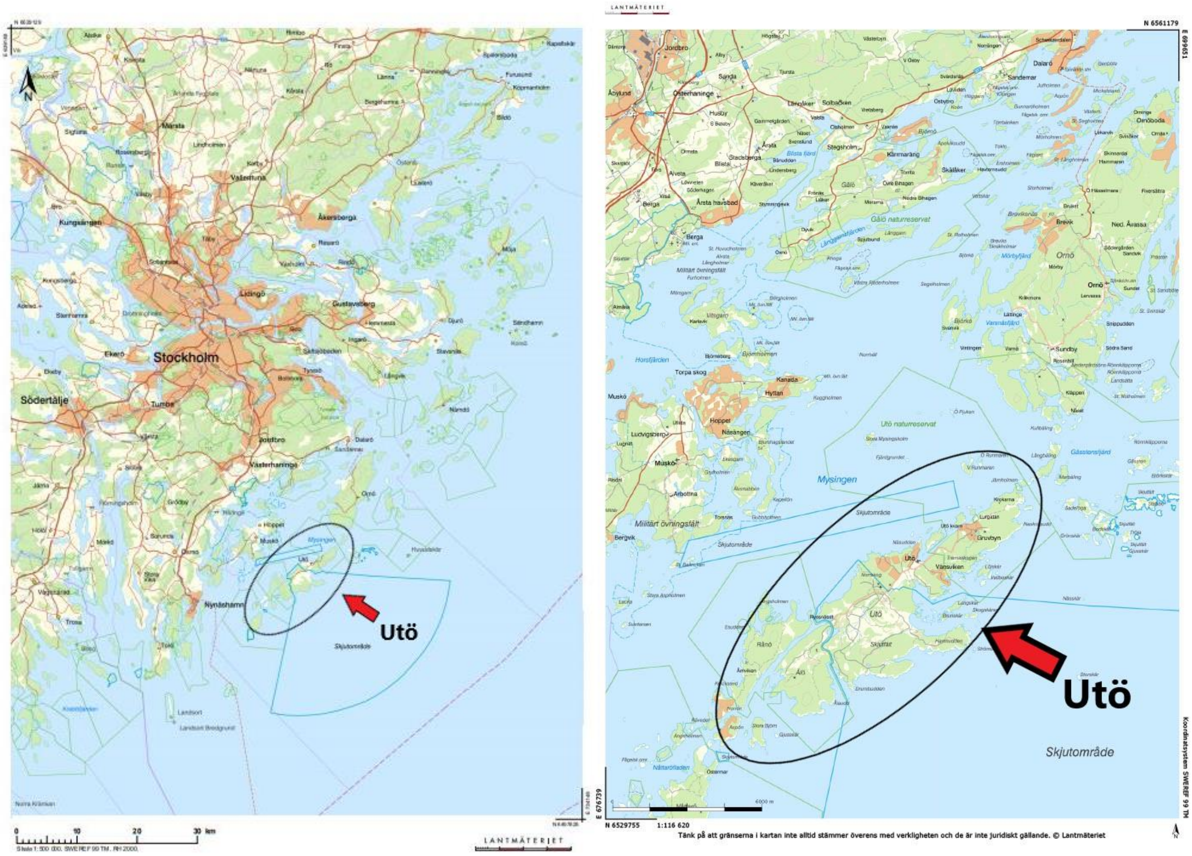

Figure 1. Utö is an island situated in the South-East of Stockholm archipelago (in the circle).

Geological background

Summary of the geology of Sweden

The oldest rocks of Sweden are situated in the northernmost part of the country and were formed during the Archean Eon (3-2.5 Ga) (Fredén and Wastensom, 2009). The largest part of the Swedish bedrock was formed by accretion of small volcanic islands during the Svecokarelian Orogeny (Larsson and Tullborg, 2015). From the orogeny, small islands were converged and formed the Svecofennian group. The rocks we see in the Svecofennian today are mostly metagranites and metasedimentary rocks.

The Svecofennian basement

The sedimentation of the Svecofennian basement started at 2.0 Ga and continued over a time period of ~140 Myrs (Welin, 1987). At this time, south central Sweden was located at a subduction zone and sediments were accumulated in an accretionary prism (Talbot, 2008). The formally horizontal beds were folded into an almost entirely vertical position. Closer to the subduction zone, at the accretionary prism, turbidites and greywackes were deposited. Zircon dating of the Svecofennian greywackes and mica-schists suggests that these sediments originated from the Archean basement and older Svecofennian volcanic rocks (Welin, 1987). The subduction caused shallow submarine arc-volcanism, creating extrusive volcanic rock, mostly silicic and intermediate metavolcanics found in south-central Sweden. However, the northern Svecofennian Province is more dominated by subaerial metavolcanics. These volcanic activities mark the later stages of the Svecofennian marine sedimentation, at 1.880 Ga. According to Welin (1987) it is not determined whether the Svecofennian supracrustal rocks lay on an older basement or if they themselves are the basement. However, the limited quantity of mafic and ultramafic rocks and the lack of ophiolites in the Svecofennian implies that the marine basin had a continental basement rather than oceanic (Welin, 1987). The volcanic processes and sedimentations were terminated in this part of the marine basin by 1.860 Ga.

Geological setting

The rocks on Utö were formed almost 2 billion years ago. The age is uncertain, as some metavolcanic rocks found on Utö are said to be 1.9 Gyrs old (Wahlgren et al., 2018) whereas other rocks, mainly extrusive rocks are given the age of 1.87-1.9 Gyrs. Close to volcanic activity carbonate rocks have sometimes been deposited. Magnesium rich dolomites are common. A less common rock type in the Svecofennian is quartzite, but it occurs in the southern and middle parts of the bedrock (Fredén and Wastenson, 2009).

According to Talbot (2008) Utö is the residual from a forearc that was created from the subduction. The metasediments are interspersed with silicic pyroclastic rocks of rhyolitic and andesitic composition. The NE part of Utö starts with a section with very clear bedding. Graded greywackes and turbidites can be spotted as well. Turbidites are formed in the trench at the accretionary prism by gravity flows, forming repeated fining up-ward sequences. This indicates deep sea conditions. Further up the sequence, the beds are less obvious, and quartz is more abundant in the rock. This indicates a shallower sea at the place where these sediments were deposited. At the middle formation, chemical precipitation is present (Talbot, 2008). In the NW part of Utö, pegmatites are present (Gavelin et al, 1976). The pegmatites have probably been created from late stage hydrous melts. When the cooling is slow or fluids are present, bigger crystals can form (Gavelin et al, 1976).

Clastic sedimentary rocks found on Utö consist of mudstones, silty mudstones, and sandstones. The minerals which comprise these clastic sediments are quartz, felspar and other silicate minerals. Sandstone, which has the biggest grain size in this category, contains mostly quartz, but can also contain feldspar and clay. Depending on the quartz quantity, the rock will be more, or less sustainable to erosion. A mudstone is made from clay minerals, meaning fine-grained aluminium silicates. These minerals are more easily eroded than quartz and can erode into very small grain sizes. A silty mudstone is a mixture of sand and mud (Marshak, 2005).

Volcanoclastic rocks are sedimentary rocks derived from a volcanic source. Silicic magma is very viscous and creates explosive eruptions. As the particles settle and solidify, they create a volcanoclastic sedimentary rock. (Marshak, 2005). The type of volcanoclastic rocks seen on Utö are of rhyolitic composition. These are metamorphosed to form metarhyolite. (Gavelin et al, 1976). Metamorphosed rhyolite can produce a chert-like rock with the local name "hälleflinta".

Biochemical sedimentary rocks are rocks derived from biological activity. Microorganisms can change the form and composition of a sediment or rock and absorb parts of a sediment as nutrients. As this happens, the sediments get depleted in different components and can change colour or shape (Marshak, 2005). Stromatolites are trace fossils from cyanobacteria. The tightly laminated structures, typically formed as a dome, are created in a shallow sea, where the cyanobacteria can access sunlight and photosynthesize. The cyanobacteria create a sticky substance to which the sand sticks. When new cyanobacteria settle on this sand layer, the same process takes place, and thus the sediments get the laminated structure. (Lee, 2021). First evidence of stromatolites and other biomarkers show to be atleast 3.5 Ga and stromatolites can be found in some rocks of this age (Marshak, 2005). Concretions, also called nodules are common in some sedimentary rocks. These are spherical structures, often having a halo around the edges. The concretions grow from the nucleus and outward. They form while the sediments are still soft and are most common in silty carbonates or in shales (Gregory et al. 2019). The formation of concretions can be associated with biological activity.

Chemical rocks are rocks precipitating from an aqueous solution, due to oversaturation of a mineral. The interesting thing with calcium carbonate is that it becomes less soluble in warmer water than in colder water. This phenomenon is called retrograde solubility (Turner and Smith, 1998). The most common chemical rock is limestone, which is abiotically precipitated calcium carbonate. Limestones can also be biochemical rock from biogenic components, such as skeletons shells from organisms living in the ocean. But such species had not yet evolved at the time of sedimentation on Utö. If the sediments contain a large amount of iron, it can precipitate when it becomes oxidized and create banded iron. This type of sediment occurred during the great oxygenation event (Marshak, 2005).

The Great Oxidation Event (GOE) occurred around 2.45 Ga (Sessions et al., n.d.), reoccurring at 1.8-2.0 Ga. These events can be seen in the lithological record by the appearance of banded iron formations (BIF). These iron formations were widespread during the Archean but had a brief comeback at ~1.8Ga and at ~0.73 Ga, before disappearing completely. These BIFs are a thin-bedded chemical sediment with more than 15% of iron of sedimentary origin (Condie, 2016). BIFs are formed by the precipitation of ferric iron (Fe^{3+}). Ferric iron is oxidized ferrous iron (Fe^{2+}), which is stable in an aqueous solution under anoxic conditions. The ferrous iron was widespread in the ocean prior to the GOE. The ocean was oxidized through oxygen (O_2) being a biproduct of the carbon fixation done by cyanobacteria (Condie, 2016). In the 20th century mining for the iron was done on Utö, but the mines are not active today.

Metamorphism on Utö

The metamorphism and deformation found on Utö is caused by the convergence of two plates during the Archean, causing accretion. The forearc at which the sediments on Utö were deposited got metamorphosed, which gave features such as metapelites with garnets, andalusite, cordierite and biotite (Talbot, 2008), all of which are metamorphic minerals (Palin and Dyck, 2021). These minerals are typical for low pressure and high temperature metamorphism (Klein and Philpotts, 2017). Other types of metamorphic minerals found on Utö are skarn minerals (calc-silicates), which are formed when silicic and carbonate rocks interact metasomatically.

The middle and upper formation on Utö are separated by a shear zone, and the sediments in the upper formations experienced a higher grade of metamorphism, producing minerals such as sillimanite (Barrientos, 2012). The upper formations also display migmatites due to partial melting, and pegmatites, which are rocks with very large crystals (cm-dm) that formed from water-rich melts. Both migmatites and pegmatites can be seen on Persholmen, NW Utö, but sillimanite is only visible in the microscope (Barrientos, 2012).

Except for metamorphism, the accretion caused deformation with many small parasitic folds and some other features such as breccia and crenulations (Gavelin et al. 1976), both of which can be seen in the middle formation.

Method

The main purpose of constructing a sedimentary log is to obtain a graphical overview of what was visually interpreted in the field. When the log is done, it is easier to notice patterns and changes throughout the logged sequence. These changes can be used to get an idea of past environment and climate.

In order to construct the sedimentary log, close observations of the middle formations on Utö were made, to get a good perspective of the whole sequence. After establishing the way up of the bedding and the stratigraphic succession, a starting point could be chosen. This would be the base of the sedimentary log. To find a clean rock surface without lichen is not always simple, and therefore a hammer was necessary, to break up pieces of the rock and get rock samples with fresh surfaces.

On the rock sample, a fresh surface was visually analysed by looking at grain size and composition. If the grain size was very small, a hand lens was used to get a better view of the different minerals. For deciding the protolith, the most abundant grain size and most abundant minerals in the sample were examined. Since grain size is not very helpful for metamorphosed rock, mineral composition was the main indicator for the protolith, but grain size, or the texture, were also helpful indicators. If there was abundant biotite and other aluminosilicate minerals present in the sample, it was interpreted as a mudstone before metamorphism. If the sample contained bigger grains of quartz, it was interpreted as a sandstone or arenite. The interpreted grain sizes were divided into mud, fine sand, medium sand, and coarse-grained sand.

When carbonates were suspected, 10% hydrochloric acid (HCl) was used. By pouring a drop of the acid on the fresh sample with a pipette, it was possible to see if the rock reacts to the acid and starts to fizz. If it reacted, it was interpreted as a carbonate rock, and if it didn´t react, it was interpreted as a rock of silicic composition.

Because the exposed sequence was not exactly perpendicular to the strike of the beds, the profile used to construct the log was staggered. When choosing a new section, it was important to follow the bed that marked the top of the previous section and use the overlying bed as the beginning of the new section. This is done to prevent gaps in the log. In the presence of parasitic folds, this was not done, and instead the fold would be excluded from the log, and a new location was chosen on the other side of the fold, where the starting point was determined by visual comparison with beds from the previous section. The length of each segment varied and was based on whether the bedrock was exposed or covered in lichen. It was also based on accessibility, folding, and other hinderances such as trees and water. For each section, a log was drawn and divided into sub-sections, where each sub-section showed a slight difference to the previous sub-section. The logs were drawn in a chronological order, starting with section 1 (southernmost part of the log) and ending at section 12 (northernmost part of the log).

Results

A 433 m long sequence from 12 different sections (figure 2) was logged on a scale of 1:100. Within these logs there are three gaps. The first gap is 6 m, the second is 18 m and the last one is 20 m long. These gaps are located at section 8, where the coast lacked in exposed rock surface and a bay interrupted the sequence. A summary log (scale 1:1000) is presented below (figure 3), and afterwards, the 12 individual sections are described. These 12 sections can be collected in to 3 larger groups, where the first group is mainly siliclastic rocks. The second group include the carbonate rocks and the third group contains banded iron formations.

Figure 2. Section 1-12 from the logging of the Middle formations.

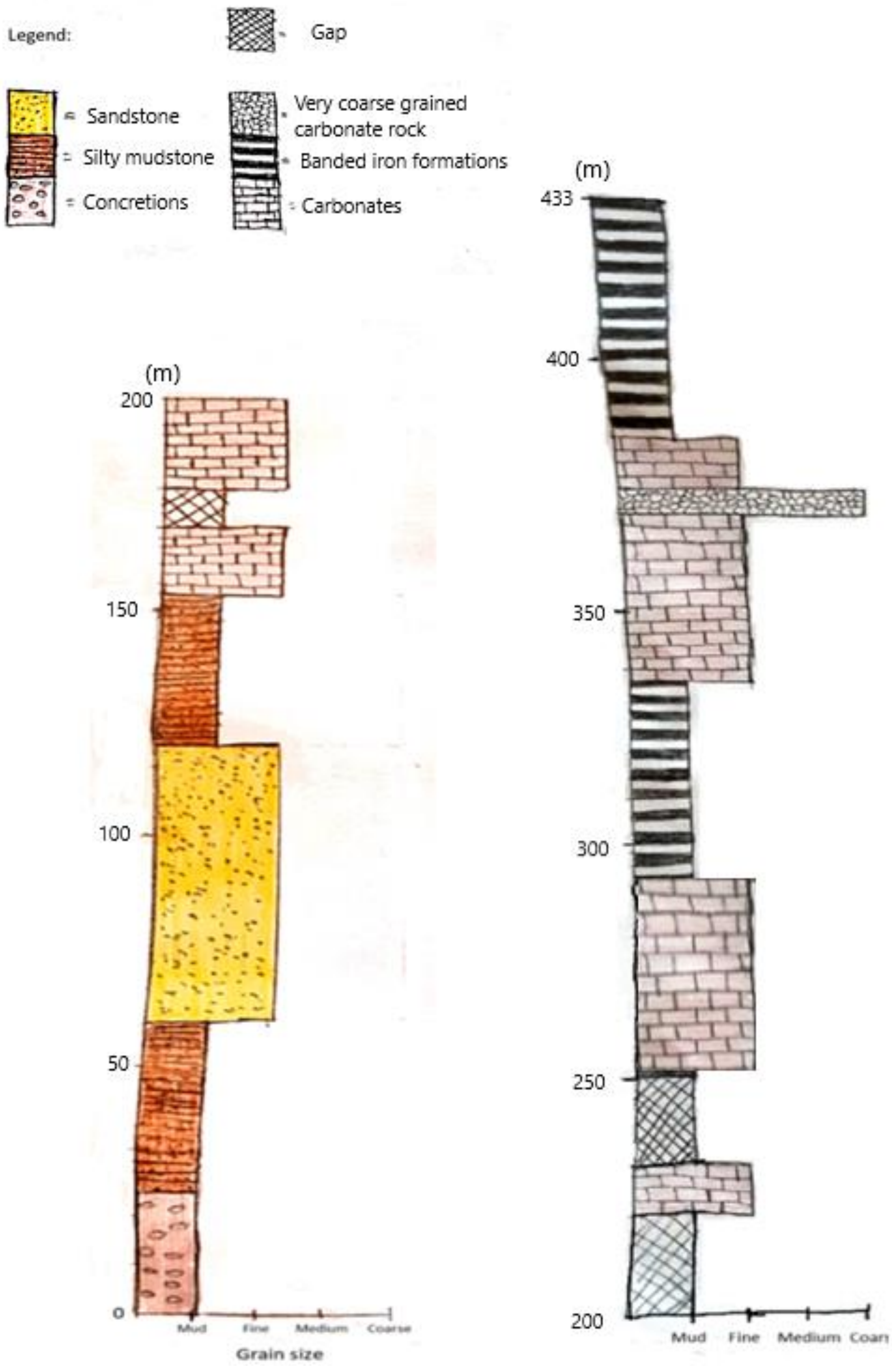

Figure 3. Sedimentary log showcasing the sedimentary units of the Middle Formation at NE Utö.

Section 1

Coordinates: **N**58º58’17’’ **E**18º21’35’’

Log section: 0-18m

Field area description:

The section consists of rounded, pale grey bedrock covered in lichen. Some layers have clearer bedding than others. There is some visible bedding close to the shoreline with clear striations from the last glacial ice. When looking at the bedrock closer, a braided pattern with darker and paler layers is seen interacting in a wavy/knitted pattern. The matrix is surrounding larger black to brownish, pea sized minerals. The majority of these minerals seem to have eroded away and have left a rusty void.

The section contains oval shaped concretions, which are elongated with the bedding direction with approximately 0.2-0.5m between each concretion (figure 4). The concretions contain a dark-grey, fine-grained matrix, and are rimmed by rusty pea-sized minerals, similar to the surrounding rock and are interpreted as cordierite. Around the concretions is a halo which is paler in colour. The matrix of this bed is mostly made of aluminosilicates such as biotite. Before metamorphism, much of the rock would have been made of clay minerals. Because of the presence of a proportion of quartz, the protolith was probably a silty mud. Sixteen concretions were measured, ranging from 6-16 cm, with the mean length of 11.6 cm. The strike of the concretions is 40-80º NE, but mostly 40-60º which means that they follow the bedding direction.

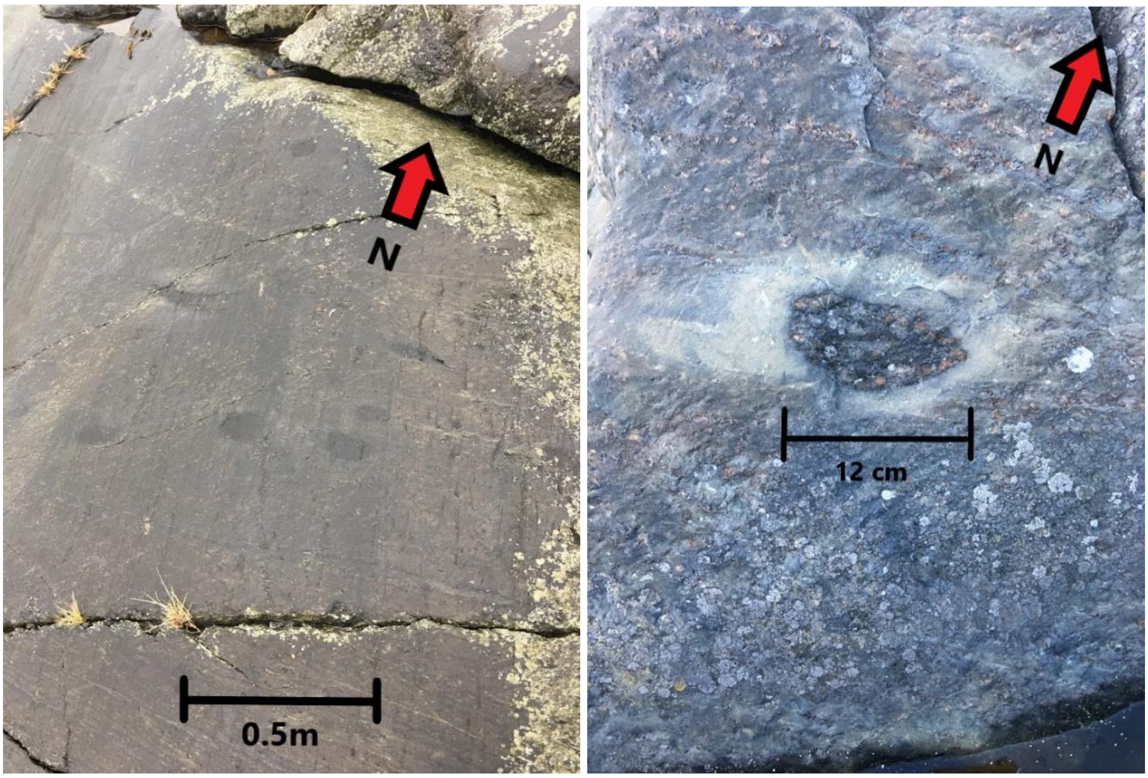

Figure 4. Bedrock from Section 1. The picture on the left side displays several concretions whereas the right picture zooms in on one concretion to see details. The left picture is taken from the top, on the flat surface, and the right picture is taken from the side, on the bedding wall.

<u>Section 2</u>

Coordinates: **N**58º58’58’’ **E**18º21’38’’

Log section: 18-27m

Field area description:

This section is situated just before a folded part with a big boulder/rock ~30m to the NE of this section. Otherwise, this section is very similar to the first section. A braided pattern is seen and a muddy-silty protolith is interpreted here as well. The matrix consists of primarily biotite and quartz. Additionally, the bedrock displays thick silty layers submerging into underlying clay layers, in a bendy form. This structure is interpreted to be “balls and pillows” (figure 5) and can be seen frequently throughout the layers at section 1, 2 and 3. This structure is created when heavier sediments fall into layers underneath and create dips or u-shaped structures.

Figure 5. The bedrock is displaying a soft sediment deformation called “balls and pillows”.

<u>Section 3</u>

Coordinates: **N**58º58'17'' **E**18º21'38''

Measurements and logging were not made at this location due to a fold, making these layers older than the ones in the previous section. The beds are tilted downwards, towards the coast, in an angle measured to 70º. When measuring the strike of the fold, it shows 60º on the west limb of the fold, 70º in the middle part, and 100º on the east limb of the fold. Even though this part was not logged it has some noticeable features that were observed. The bedrock displays lenticular bedding with alternating millimetre thin layers to decimetre thick layers of clay and silt (Figure 6). The thicker layers are interpreted as having been siltier and gave wavy bedding.

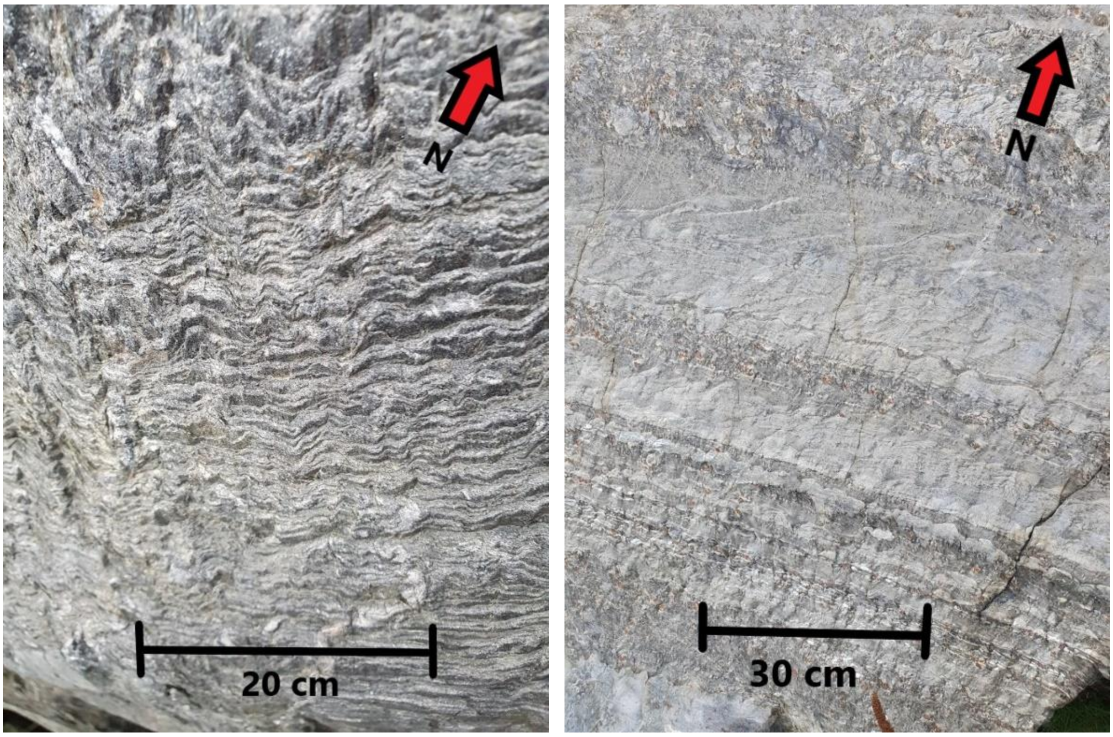

Figure 6. Lenticular bedding on the left and wavy bedding on the right image. Clear mica beds are visible in the left figure, displaying millimetre thin layering, whereas the right figure displays decimetre thick layering with a braided pattern and rusty voids from former minerals.

<u>Section 4</u>

Coordinates: **N**58º58'21'' **E**18º21'45''

Log section: 27-37m

Field area description:

The bedrock at section 4 has similar features as the former sections. The bedding is striking in a 070 direction. The bedrock has a pale grey colour with some rusty patches. This section contains more quartz than the former sections, but the matrix is still mostly biotite and muscovite.

Section 5

Coordinates: **N**58º58’22’’ **E**18º21’46’’

Log section: 37-54m

Field area description:

The strike of the beds starts at 070 and at the end of the log section the strike is at 050. The fold is less distinct here. The bedrock has coarse quartz grains, but the majority of the minerals are still biotite and muscovite, and the protolith is thus interpreted as silty mudstone. The bedrock is slowly becoming more quartz rich.

Section 6

Coordinates: **N**58º58’22’’ **E**18º21’47’’

Log section: 54-113.5m

Field area description:

The beds strike in a 050 direction. Biotite and muscovite take up ~20-30% of the bedrock. The bedrock has distinct beds and contains mostly quartz. This log section marks the shift between the concretion-containing silty bedrock to a quartzite. Even though aluminosilicate minerals are present in the bedrock on this section, the rock is mainly made of quartz, which leads to the interpretation of sandstone being its protolith.

Section 7

Coordinates: **N**58º58’25’’ **E**18º21’46’’

Log section: 113.5-154.5m

Field area description:

The bedrock at this location is pale and covered in white and green lichen. There is a small beach with big pebbles and boulders nearby. The start of this section displays an exposed surface with different colours. The bedrock is brown where the rock is rusty and pale with a blue tint at other places. After approximately 7 m from the start of this section, an exposed surface appears with poorly sorted clasts in an amorphous, silicic matrix. The biggest clasts are ~30cm. Some of the clasts are angular and some are more rounded (figure 7). The clasts are a mix of carbonate rocks and silicic rocks. Further on, the bedrock starts to show more consistent layers without clasts. The layers alternate between silicic and pitted weathered carbonate bedrock (figure 7).

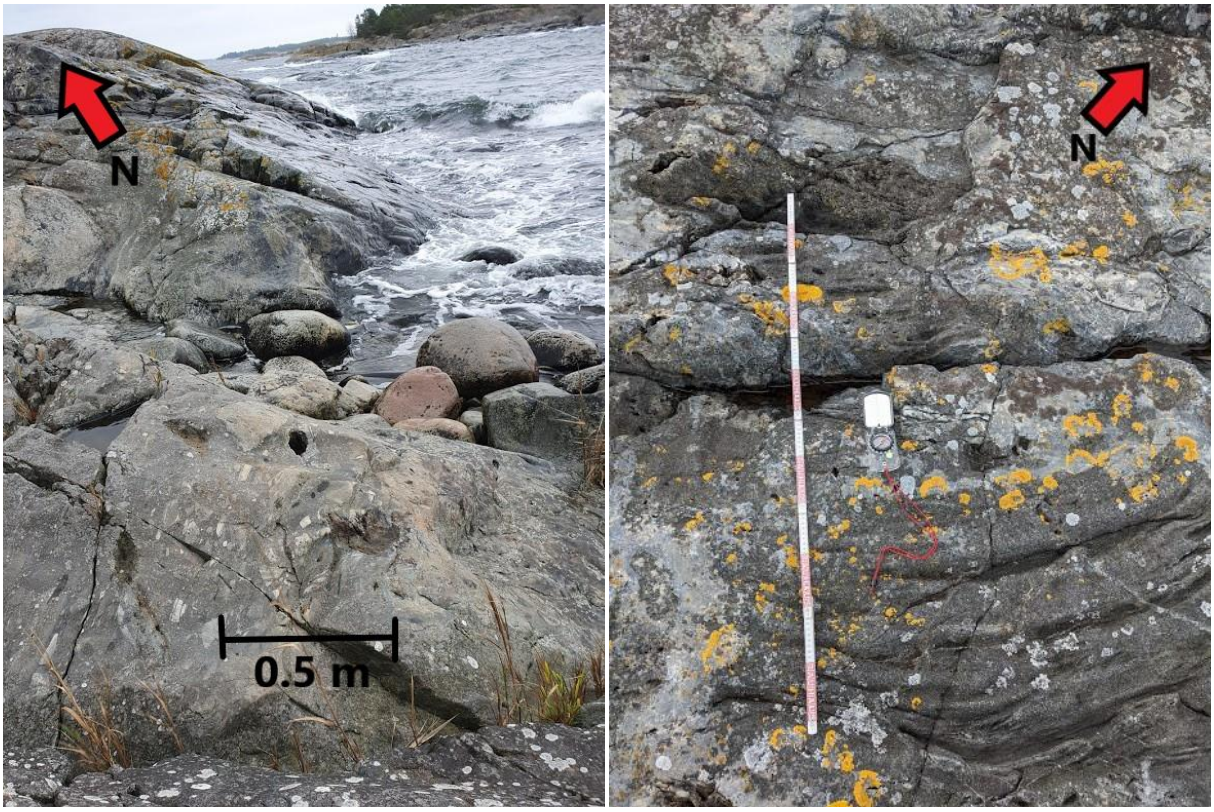

Figure 7. Pictures from section 7. The left picture shows clasts of various size and composition. Some clasts are of silicic composition and some of carbonate composition. The left picture shows the silicic bedrock with elements of carbonate rock, which is later dominating in section 8.

<u>Section 8</u>

Coordinates: **N**58º58’26’’ **E**18º21’46’’

Log section: 154.5-249m (Gaps at 171-177m, 200-220m and 231-249m)

Field area description:

This section displays a 2-3-metre-thick carbonate rock surface with pitted weathering and a pinkish colour (figure 8). The beds strike at 060. The carbonate layer is interbedded with a pale grey layer that is less eroded and stands proud from the pink layers. These grey layers are of amorphous silicic composition and display conchoidal fracture. Further on, the silicic layers are approximately 0.5-1m thick and appear once every meter or so, in between the carbonate layers.

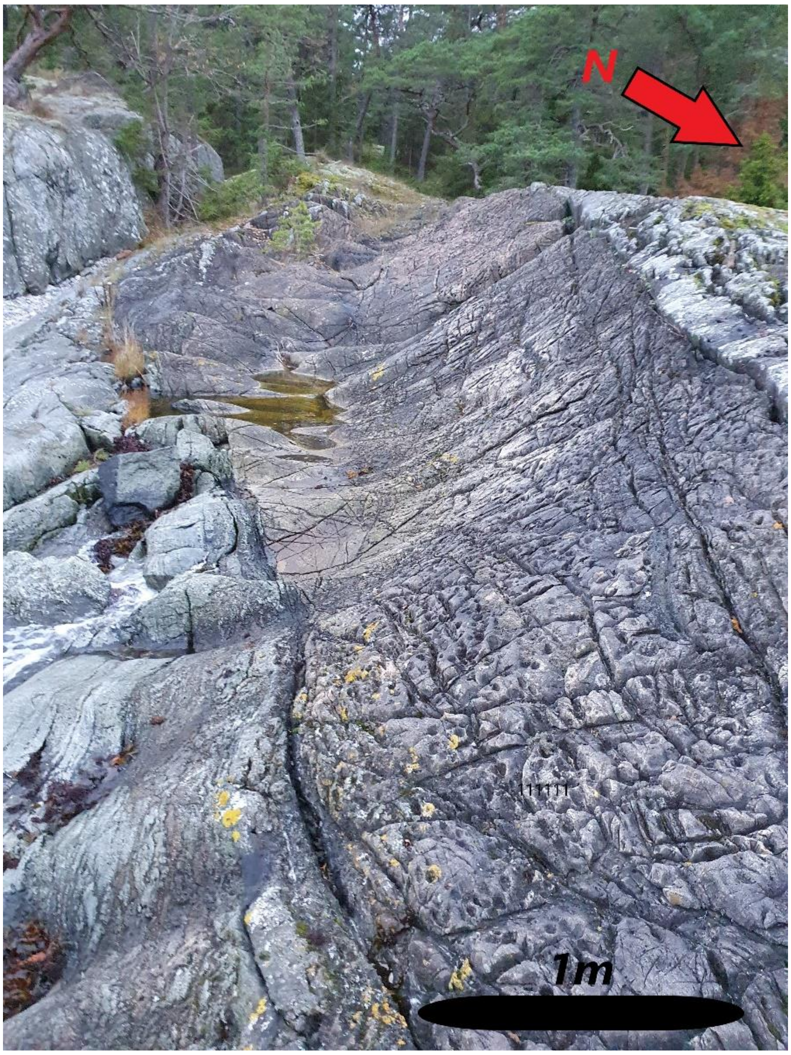

Figure 8. The section is displaying a thick carbonate layer in between two silicic layers.

<u>Section 9</u>

Coordinates: **N**58º58’36’’ **E**18º21’55’’

Log section: 249-305.5m

Field area description:

This section starts after the last gap in the log and is located close to "Krokarna" (figure 2). The carbonate bedrock is mixed with pale grey, quartz rich clasts (figure 9). These units are elongated parallel to an almost E-W direction (70-80º and in some cases 100-120º). The bedrock displays a mishmash of silicic units and carbonate layers, with many small folds. The softer carbonates flow around the more rigid silicate clasts. Between the silicic units and carbonate layers are skarn minerals. In some of the skarn samples there are a few grains of what is interpreted as pyrite, with its cubic shape and yellowish gold colour and metallic lustre. The silicic units display a red rusty colour both on the outside and on the fresh surface.

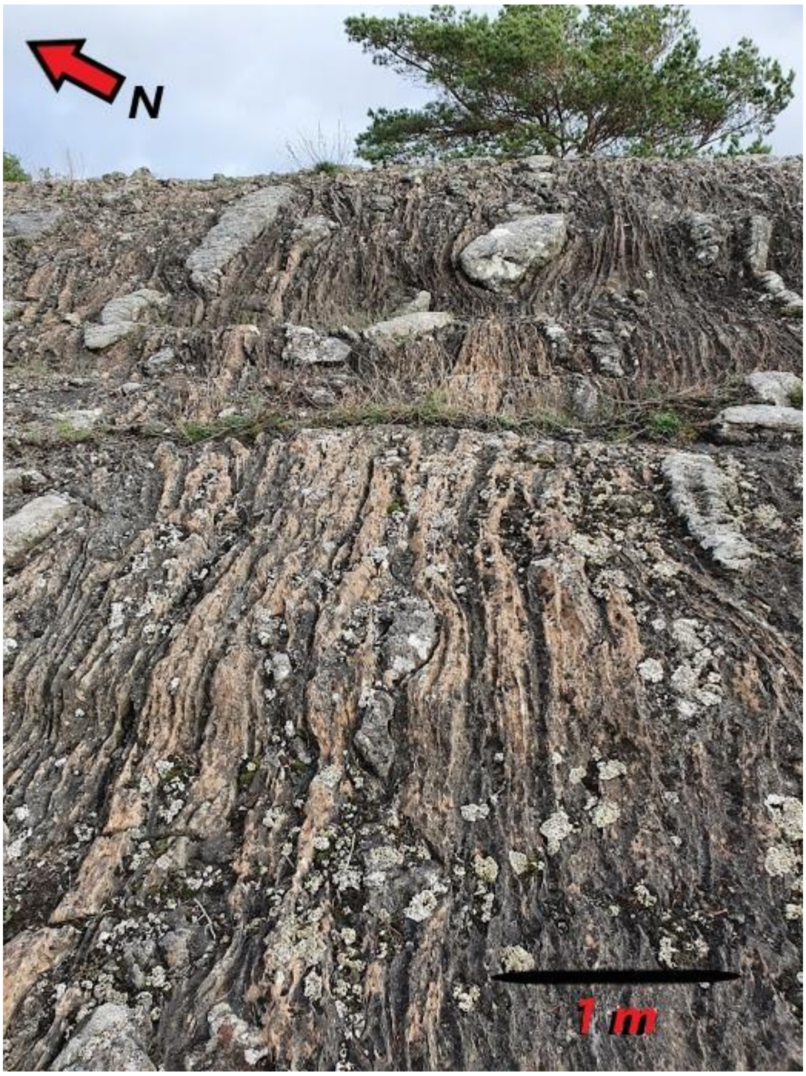

Figure 9. Extruded silicic clasts surrounded by a softer, more elastic carbonate bedrock.

Section 10

Coordinates: **N**58º58'36'' **E**18º21'56''

Log section: 305.5-323m

Field area description:

The beds go in a 070 direction and are folded. The features of this location resemble the previous one, meaning they exhibit silicic units interspersed with carbonates and skarn minerals between the layers. More and more iron is visible on the surface of the bedrock and in the hand samples, going upwards in the sequence, which leads to labelling it banded iron formations. The iron rich layers appear very dark and almost shiny (figure 10).

Figure 10. Iron rich layer (dark) and carbonate layer (pale grey). The beds are folded.

Section 11

Coordinates: **N**58º58’37’’ **E**18º21’59’’

Log section: 323-394m

Field area description:

The bedrock at section 11 consists of amorphous silicic layers that appear very rusty (figure 11A), interlayered with thin carbonate layers with eroded parts covered by soil. The bedrock in figure 11B appears to be very dark, while underneath the soil, beige carbonate rock appears and is interlayered with silicic clasts. Approximately 375m into the log there is a sequence with very coarse-grained carbonate bedrock.

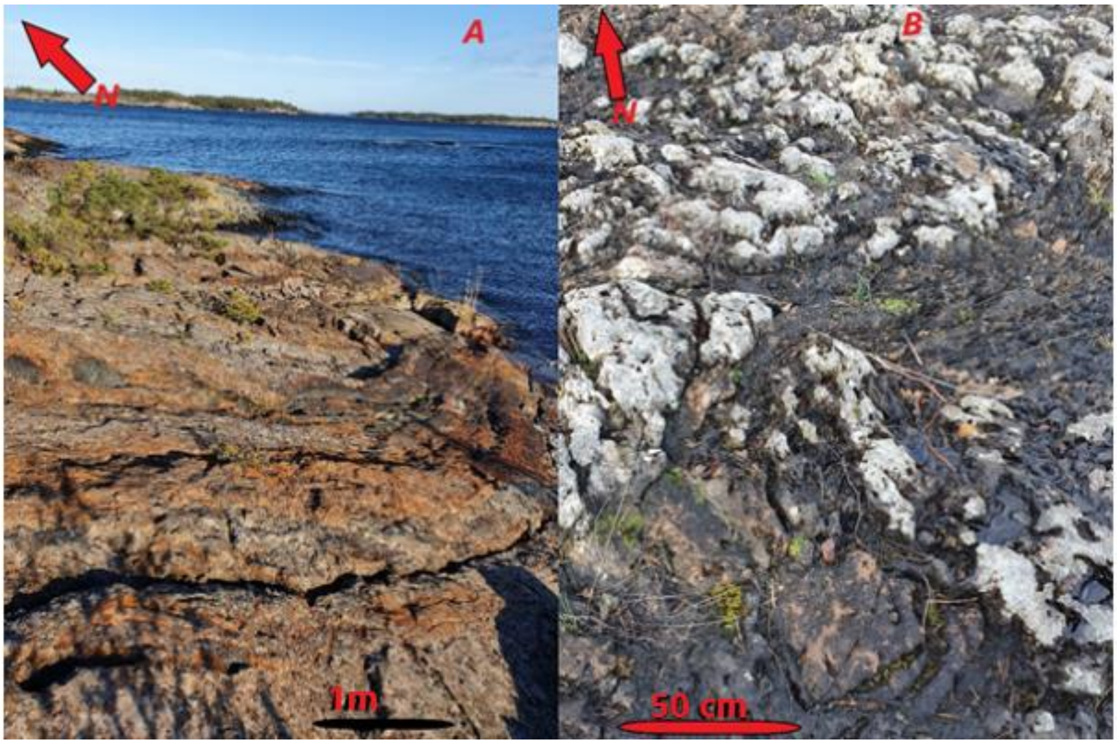

Figure 11. Iron rich layers. Figure 11A displays rusty silicic bedrock with a small fold. Figure 11B is showcasing the dark carbonate layers with a beige colour underneath and the extruding paler silicic clasts.

Section 12

Coordinates: **N**58º58’40’’ **E**18º21’60’’

Log section: 394-433m

Field area description:

This section shows some folding, and the beds go in a ~100º NE direction at first but then return to 060-070. The bedrock is red and rusty and broken into pieces, probably from the fold. Parts of this location is characterized by a mixture of iron rich silicic layers and carbonate layers alternating every 1-2 meters. The rest of the log looks similar to each other in the samples even though the eroded surface varies a bit. Some parts have a smooth surface and look like chert, whereas other parts look very rusty. In some places, the silicic beds are cm-thin, with some mm-thin limestone layers in between (figure 12). These are the folded parts of this location. This last part of the log is analysed as banded iron formations with its rusty appearance. The log ends beside a small bay.

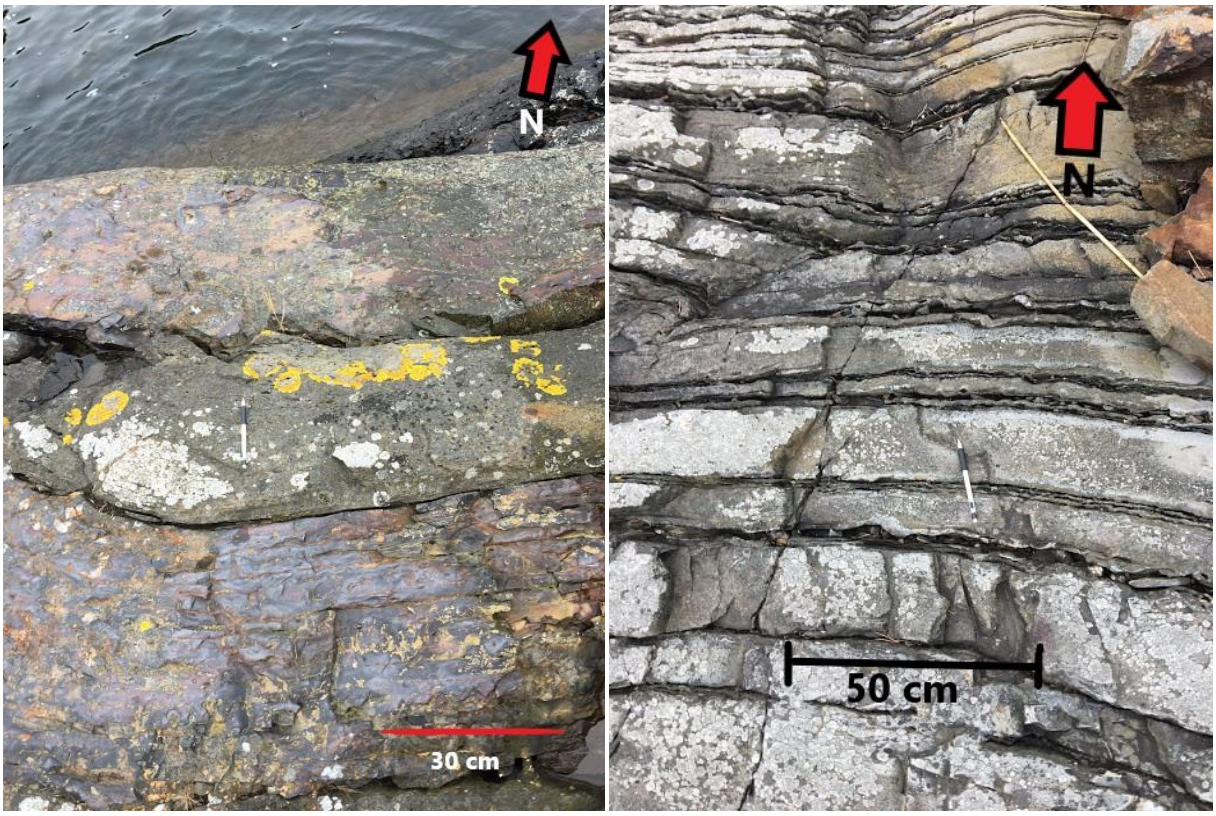

Figure 12. Decimetre thick iron rich layers with a carbonate layer in between is displayed on the left image and centimetre thick silicic layers with millimetre thin carbonate layers in between is displayed on the right image.

Discussion

As seen from the results, the log sequence representing the middle formations on Utö shows a gradual transition from siliclastic metasediments to carbonate bedrock and finally iron rich layers. An analyse of the different sections of the log will be presented below.

Interpretation of the different units

In this section all the different parts of the log (figure 3) will be discussed, starting with the muddy/silty layers, and finishing with the banded iron formations. In each section where the lithology changes in shape or mineralogy, a new unit, with a different legend starts on the log. In analysing the rock types, we can get an idea of what depositional environment was responsible for their creation.

The first 27 meters, which are called "concretions" in the log, contain mostly quartz, biotite and muscovite, where the two latter are formed from metamorphosed clay minerals. This would make the protolith a mudstone. Since quartz is abundant in the samples, the conclusion is that this was formally a silty mud. The depositional environment for silty mud can for example be a calm, shallow part of the shelf, where silt particles can settle. Concretions can grow during the early stages of diagenesis (Gregory et al. 2019) and this seems to be the case on Utö, since the concretions are following the bedding. The bedrock exhibits a wavy pattern, which is interpreted either as crenulation or as "balls and pillow" structures. In the case of Utö, it could probably be an effect of both. Crenulations are caused by stress coming from different directions causing microfolds in the sedimentary rock (Cosgrove, 1976). This can occur in conjunction with metamorphism. "Balls and pillows" are formed if deformation occurs during diagenesis of soft sediments (Owen, 1978). The silt layers are denser than the clay layers and thereby sink into the clay layers, forming rounded, ball-like structures, commonly with zig zag shapes (figure 5). The beds are a mixture of millimetre thin to decimetre thick beds of alternating mud and silt and this type of structure is interpreted as lenticular bedding and wavy bedding, where the former is dominant in clay deposits whereas the latter is 50/50 mud and sand deposit. The ripples are caused by fluctuations in the tidal flow (Fruergaard, 2015) and depending on the energy of the flow, more or less mud or sand can settle. In the case of the middle formations on Utö, the tidal flow must have been fluctuating since the layers are very thin and there is a similar quantity of mud and sand, and wavy bedding is the most frequently observed sedimentary structure (figure 6).

The next section of the log (27-60 m) also displays quartz, biotite, and muscovite and therefore its protolith is interpreted as a silty mudstone deposited in a shallow marine environment. If the depositional environment had been in a deeper sea, quartz would not be present. In the case of a deltaic environment, water level is not as big of a factor, and instead the different grain sizes might have been deposited contemporaneously. Tidal flats are also a possible option, seen as very thin layers of clay and silt alternating is typical in this type of environment (Fruergaard, 2015) and this is the kind of structure we see in the first part of the log on Utö.

The third section of the log (60-120m) shows a bigger abundance of quartz grains, which is thus interpreted as a quartzite with a sandstone as its protolith. Sand deposits in coastal regions, where the energy level is high, meaning waves are present (Marshak, 2005). The lack of cross stratification in the quartzite from the log indicates that its deposition was below the wave base. Since biotite and muscovite are present in the quartzite, this agrees that the deposition was below the wave base, meaning the water depth was deep enough and calm enough for clay particles to settle. Since the log shows a silty mudstone later (at 120-155m), this would indicate that there was a transgression of the sea or a varying input from rivers, where a heavier river flux would carry sandy sediments further out in the ocean.

Log section 120-155m contains mostly silty mudstone, but some pitted weathering, indicative for carbonate minerals starts to appear. Where the bedrock contains clasts in an amorphous matrix, it is interpreted as a fault breccia, formed during later brittle deformation of the sedimentary units on Utö (Gavelin et al, 1976). This is consistent with the presence of silicic and carbonate clasts in the amorphous matrix, i.e. clasts from stratigraphically above and below the breccia, implying that it could not be sedimentary in origin.

Log section 155-250m reveals another type of rock. Fine grained dolostones are featured in this part of the log. These carbonates represent a shallow sea with tropical temperatures since chemical precipitation of calcium carbonate ($CaCO_3$) is induced in tropical waters (Bundeleva et al., 2012). Additionally, calcium carbonate may also precipitate chemically during bacterial degradation, for instance, sulphate reducing activities (Kellerman and Smith, 1914; Bundeleva et al., 2012). Therefore, an increase in photosynthesizing bacteria may be linked to an overall increase in carbonate deposition. An example of that are Precambrian stromatolite communities, growing in shallow epicontinental seas by repeated growth sequences of accreted inorganic material (Dupraz et al., 2006). These sediments are glued together by the mucus from cyanobacteria. The cyanobacteria induce $CaCO_3$ precipitation by forming a basic microenvironment around itself during photosynthesis (Dupraz et al., 2009). Considering there were no shell bearing organisms in the Precambrian, all the carbonate rocks must be chemical precipitates.

Log section 250-335m contains banded iron formations. The banded iron formations formed when the ocean experienced an increase in oxygen content which oxidised ferrous iron (Fe^{2+}) and precipitated it as ferric iron (Fe^{3+}) on the sea floor. The banding of the iron formations is not fully understood. One alternative could be that it originated from climatic or circulation fluctuations in the ocean causing periodic influxes of oxygen. The more resistant parts (more resistant to weathering) of the sequence contain more quartz whereas the more easily eroded parts are carbonates. The iron is enriched in the silicic layers. Based on the results, the iron formations are interpreted as iron rich cherts interlayered with carbonate rocks.

Log section 335-385m is similar to the previous section but has thicker carbonate layers than iron layers and thus the section is interpreted as a carbonate bedrock. The coarser grained carbonate found in this section is ~5m thick and is not interpreted as a sedimentary, but rather a metamorphic feature, since increasing crystal size is typically associated with metamorphism. Heat or pressure change give possibilities for the crystals to grow bigger.

The last section (385-433m) exhibits more iron on the surface than the previous section and is therefore labelled as an iron formation in the log. Small, parasitic folds with centimetre thin chert layers make up most of the first few meters of this section. The thin layering could either be pre deformation, or they could be an effect of the stress caused by the folding.

Interpreting the succession of the sedimentary log

From analysing the bedrock of the middle formation on Utö, three main categories can be determined. These three categories are the siliclastic layers, the carbonate layers, and the banded iron formations. A more thorough analyse of the depositional environment of these three layers will be discussed below.

The siliclastic layers

The first 155 meters of the log are the siliclastic layers on Utö. The protoliths carried in composition from clay-rich to quartz-rich, ranging between meta-argillite and meta-arenites (Gavelin et al, 1976). This could imply fluctuating water depths or sediment input fluxes. The energy level decreases with water depth, and thus clay particles can settle here. This means clay indicates a lower energy environment. In shallow or coastal environments, where the energy of the environment is higher, clay particles are suspended in the water and only bigger silicic particles, meaning sand, get deposited.

The meta-argillites are interpreted as a former tidal flat or mud flat where oval shaped Fe-rich concretions grew under anoxic conditions. As stated before, the concretions follow the bedding and were thus formed before metamorphism. Towards the top of this section the bedrock transitions into a meta-arenite, implying shallower waters.

The carbonate layers

Moving upwards in the log, metamorphosed dolostones and limestones dominate the sequence. These carbonate rocks form in warm coastal environments, where the water gets saturated in bicarbonate from weathered rocks and turns into carbonates sometimes aided by cyanobacteria (Marshak, 2005). The carbonates precipitate from the water and settle on the sea floor. If comparing this to the log, this would suggest that the local environment got warmer and biological activity was higher. Warm climate means faster weathering. The CO_2 reacts with water to become carbonic acid, leading to corrosion of the rocks and the cations in the rock are released. By chemical weathering of rocks, for example, Ca-ions are released into the water and react with bicarbonate to form carbonates.

$$H_2CO_3 + CaAl_2Si_2O_8 + H_2O + H^+ \rightleftharpoons Al_2Si_2O_5(OH)_4 + Ca^{2+} + HCO_3^- \quad (1)$$

$$Ca^{2+} + HCO_3^- \rightleftharpoons H^+ + CaCO_3 \quad (2)$$

The dolostone either replaced pre-existing limestone directly after deposition or later during burial or is a primary precipitate. A suitable depositional environment for dolomites is in evaporite basins where gypsum precipitation increases the magnesium content while using calcium (Chilingar et al., 2011). This means dolomite formation generally indicate a saline sea environment, but a mixture of saline and fresh water can also create dolomites (Klein and Philpotts, 2017). However, no salt or gypsum can be seen in the log section. If they were present in the sedimentary rock, they must have turned into new minerals during metamorphism. Evaporites containing NaCl can turn into sodic and magnesian aluminosilicates, magnesites or calc-silicates and marbles (Warren, 2016), where the last two can be seen in this section of Utö.

Chert can either have a biogenic protolith, meaning dissolved silicate shells from plankton settled on the ocean floor and precipitated (Marshak, 2005) or originate from a volcanic ash. The cherts derived from episodic explosive volcanism, producing ash, settled on the sea floor, and ware later metamorphosed into metaryolite, hälleflinta. Hälleflinta is made from leptities, which are fine grained silicic sediments of volcanic origin. The silicic ash is what gave the amorphous texture to the chert. Another hypothesis is that chert can be chemically precipitated from silica rich oceans close to hydrothermal vents (Boorn et. al., 2007). Additionally, according to Cloud (1973), the Proterozoic hydrosphere's absence of silicate shell-bearing organism results in saturation of silicic acid (H_4SiO_4). At near neutral pH silica precipitation was favoured, thereby the cherts on Utö may have formed through this mechanism.

The banded iron formations

The banded iron formations on Utö contain layers of oxidized iron, however, a complication with the interpretation arises since the rusty appearance of these extruded layers varies throughout the sequence. These less rusty quartz-rich layers could be chemically precipitated cherts (Cloud, 1973) or rocks of volcanic origin. The former alternative is consistent with the ferric iron enrichment in the cherts, since this means that they may precipitate contemporaneously. In that case, the more rusty layers reflect a period of higher iron to silica precipitation.

According to Talbot (2008), the banded iron formations contain chert of volcanic origin interbedded with limestone. The chert, more specifically Hälleflinta, derived from volcanic ash, whereas the limestone must have accumulated during calmer periods without volcanic eruptions. This hypothesis does not explain in the iron enrichment in the Hälleflinta but explains the interbedding of silicic and carbonate rock better. The cherts in the banded iron formations might be chemical precipitates, while the cherts interbedded with the carbonates might be metarhyolites.

For the accumulation of iron ions in the sea, anoxic conditions must have been necessary before the Great Oxygenation Event (Cloud, 1973). Anoxic conditions can either be found in the deep sea, or where there is lack in circulation. Anoxia can also be found in isolated water basins where there are no waves or any inflow from a potential river. The latter hypothesis would be more suitable since the banded iron formations are interbedded with carbonate layers which are interpreted to deposit in a shallow sea environment. The main source of iron in the water column is from the mantle. (Trendall, A.F., 2002) and is later brought up to the surface water by overturning, which is an effect of changing climate states. According to Cloud (1973) the banding is suggested to be cyclical changes in procaryotic populations or the variation of Fe^{2+} supply, or both. He also suggests a variation in water depth. Furthermore, Klein and Philpotts (2017) argue that the oldest iron formations could be derived from deeper oceans, since the layers are consistent and spread over large distances whereas that younger iron formations, with less distinct beddings, were probably formed in a shallow sea. The latter alternative is what we witness on Utö.

Since BIFs are often forming in siliclastic sediments, they are usually associated as chemical precipitates in shallow sea environment along continental shelfs or continental arcs. According to this theory, Fe^{2+} was saturated thanks to hydrothermal sources in the deep ocean and got upwelled to the surface water and the iron precipitated on the continental margins (Kato et al., 2006). BIF can also be associated with Snowball Earth, where the ice covering the globe could cause anoxia in the ocean (Hoffman et al., 1998). The Snowball Earth hypothesis is however not applicable for Utö, since the BIFs on Utö are older and were formed more than a billion years before the Snowball Earth is thought to have happened.

Summary of the depositional environment

According to the observations, the results display silicic sediments in a shallow sea to coastal setting. The beginning of the log features concretions, which are thought to be caused by biogenic activity. Further up in the log, carbonate rock occurs, which can also be indicative of biogenic activity, although no evolved life forms were yet developed at this time. Carbonate rocks are also typical indications for a warmer regional climate. More and more cyanobacteria thrive, which causes outburst of oxygen and thus iron can precipitate, and we see iron formations in the top section of the log. In between the iron formations is a section with more limestone, which indicates a warmer period. At the end of the log, banded iron formations appear again. Arguments for oxidation events occurring on several occasions have been discussed. The latter oxidation events are thought to have been more local, depending on where there were gatherings of cyanobacteria.

Conclusion

The middle formation on Utö was most probably deposited in a shallow sea and at tropical conditions. Most calcareous rocks are formed in tropical latitudes, where cyanobacteria thrive. Photosynthesis by the cyanobacteria may have triggered oxygenation of the atmosphere, which made it possible for the banded iron formations to form. Since most of the rocks on Utö are metamorphosed, the rocks must have experienced pressure and temperature changes, in this case associated with accretion.

Sources of errors

All the results from the log constructed on Utö were based on a visual examination, which may influence the interpretations and conclusions of the depositional environment. The rocks on Utö are metamorphosed, which makes it harder to interpret the sedimentary structures.

Structural deformations in the sequences caused disturbance in logging. This could give 1–2-meter gaps in the log. Since the final bed from the former section featured the same rock type as the first bed in the new section, these possible gaps were excluded from the log.

Acknowledgements

I wish to acknowledge the help provided by Professor Alasdair Skelton, my supervisor, who has guided me in the right directions throughout my thesis. I would also like to thank my co-supervisor Mirren Green, who guided me with the practical parts of the thesis.

I want to express my appreciation to my fieldwork partner Elise Lindell, who always had a good spirit and inspired me in the field.

Last but certainly not least I want to thank Sylvia Morawiecki, Vidar Jakobsson and Mikaela Lindström for emotional support and endless discussions and inspiration.

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