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An interpretation of the depositional environments, links to volcanic activity and metamorphic conditions of Precambrian rocks on north-eastern Utö, Sweden

Keivan Karamjani

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Department of Geological Sciences
Stockholm University
SE-106 91 Stockholm

Index

Introduction

Background

Utö is an island in the Stockholm archipelago which has been mined since the 12th century due to an abundance of iron ores. It was on Utö that August Arfvedson discovered the element lithium in the mineral petalite found in pegmatites (Smeds and Cerny, 1989, pp.361-362). Mining in Utö continued from the 17th century until 1879 and it is estimated that more than two million tons of iron ore was extracted during that period (Holmquist, 1910, p.865).

Moreover, the oxygen level in the atmosphere increased significantly during the great oxygenation event which occurred around 2,4-2,3 Ga and major glaciations were present at that time (Li, et al., 2019, p.31), although it was probably around 1,8 Ga that the oxygenation of the atmosphere was complete (Marshak, 2018, p.494). As a result, vast quantities of iron precipitated from the oceans to form iron-formations between 2,4 Ga and 1,8 Ga (Marshak, 2018, p.494). The rocks on north-eastern Utö were deposited between 2 Ga to 1,8 Ga which means that they formed during the final stages or after of the great oxygenation event.

Utö is part of the Svecofennian province which encompasses the majority of central, eastern and northern Sweden along with the western part of Finland (Korja and Heikkinen, 2004, p.244). Therefore, the exposed rocks found on Utö are characteristic of the Bergslagen area in central Sweden and central Finland (Gavelin, et al., 1976, pp.5-7). However, the eastern part of Sweden, where Utö is situated is dominated by meta-sediments while the western part of Sweden is dominated by meta-volcanics (Frietsch, 1982, pp.207-208).

East of the Svecofennian province is the older Karelian province while the Southern Scandinavian Domain is in the southwest. The Svecofennian province is overthrust by the Caledonides in the west and to the south lies the East European platform (Korja and Heikkinen, 2004, p.244). According to Korja and Heikkinen (2004) the formation of the Svecofennian accretionary orogeny occurred between 1,96 Ga and 1,75 Ga when several island arc micro-plates started to accrete to the Karelian plate. The former subduction zone and accretionary prism was positioned underneath what today is the Bothnian basin (Korja and Heikkinen, 2004, p.241). These volcanic arcs were separated by sedimentary basins, and it was after the Bothnian Basin and the Sörmland Basin became filled due to accretion of the volcanic arcs to the Karelian plate that the crust thickened. This occurred between 1,82 Ga and 1,815 Ga, and this orogenic thickening produced crustal melts. Some of the melt contained rare-earth-element-rich pegmatites that contain lithium, cesium and tantalum (Romer and Smeds, 1996, pp.85-86). Moreover, a superplume which developed around 2,5 Ga seems to be one of the triggers of the development of the Svecofennian accretionary orogen. The peak of mantle-plume activity around 1,95-1,9 Ga coincides with the start of the Svecofennian accretionary orogen (Mints, et al., 2020, p.1020).

The Svecofennian province was affected by a regional metamorphic event which was caused by the Svecokarelian orogeny between 1,96-1,8 Ga. The metamorphic condition of the rocks belongs to low-pressure greenschist to granulite facies. It is speculated that this was due to crustal growth at the south-west in a volcanic arc system that was situated in accretionary belts (Skelton, et al., 2018, p.1). A study by Skelton, et al. (2018, p.4) obtained P-T estimates (pressure and temperature estimates) of different locations in the Svecofennian province. Three of the measurements are from different sites on Utö which all belong to the amphibolite facies. Two of the measurements were recorded as having low to medium P/T while the third one had a low P/T estimate (Skelton, et al., 2018, p.4). These results indicate that andalusite and sillimanite should be stable in such metamorphic conditions. Both of these Al_2SiO_5 polymorphs were found by Skelton, et al. (2018, p.5) in some of the rocks on Utö. Moreover, the vast majority of the P-T estimates of the Svecofennian province also belong to the amphibolite facies while the rest belong to the granulite facies. The P/T estimates range from low and low to medium too, except for one estimate which was medium to high in north-eastern Voxna (Skelton, et al., 2018, pp.4-5). Furthermore, the average metamorphic field gradient of the Svecofennian province was estimated to be $54 \pm 4\,°C/km$ which is typical for Buchan metamorphism. This type of metamorphism can occur during accretionary orogenesis, and regional heating linked to arc magmatism (Skelton, et al., 2018, p.5).

For this thesis four different models for the geological evolution of north-eastern Utö will be presented and then compared with the interpretations and observations made in this thesis. Some of the texts focus primarily on Utö while some of them focus on the south-central region of Sweden which Utö is a part of. In order to refer to the different localities which are mentioned in the four texts and this thesis, a locality map of north-eastern Utö (figure 1) has been made. This map includes specific localities that were visited by the author of this thesis and larger areas which are referred to by the authors of the previous studies on Utö.

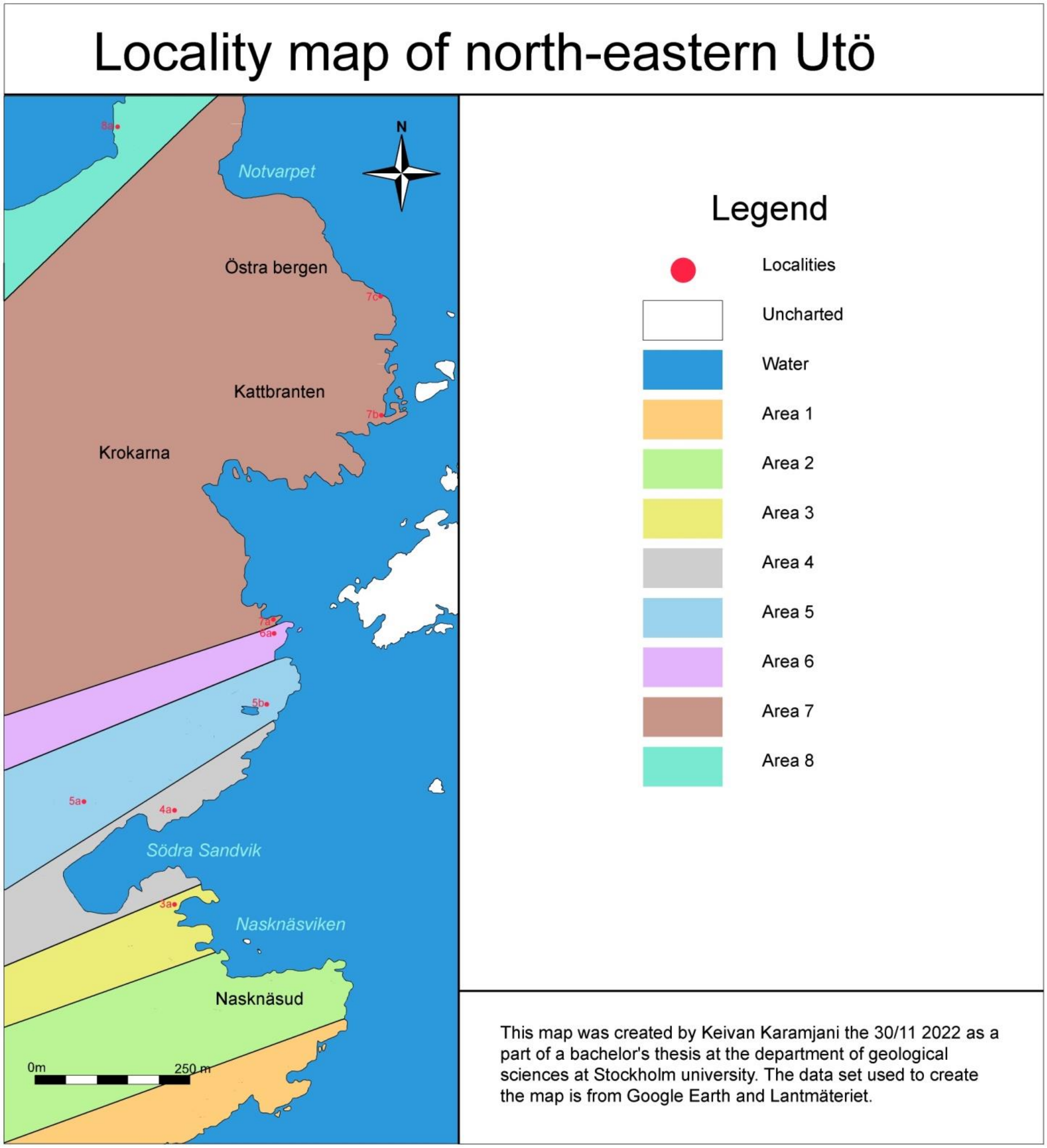

Figure 1. North-eastern Utö has been divided in this picture into different sequences called areas in order to refer to the different parts of Utö more easily. Field observations for this thesis divided the map roughly into these areas with minor alterations. Localities are sub-areas within the larger areas. These localities are specific points of interest within a certain section of an area that were visited and noted for their specific characteristics.

Talbot’s Model

The first model that will be presented is Talbot’s model of north-eastern Utö. Talbot suggests that meta-greywackes on south-eastern Utö stratigraphically south-west of the mapped area in figure 1 contain porphyroblasts of andalusite, cordierite and garnet which have developed as a consequence of the metamorphic conditions (Talbot, 2008, p.61). He suggests that these started to accrete above a subduction zone which formed a shelf-like fore-arc (Talbot, 2008, p.49). The meta-greywackes that dominate south-eastern Utö contain turbidites which indicates that they were deposited on a slope or possibly on an abyssal plain too. According to Talbot a very small section of area 1 consists of un-bedded meta-greywackes (Talbot, 2008, p.52).

Stratigraphically above the meta-greywackes lies a large area of meta-porphyry sheets in Talbot’s map, that encompasses area 5, area 2 and the majority of area 1 (Talbot, 2008, p.52). The appearance of these meta-porphyry sheets varies a lot when it comes to grain-size, texture and color. Talbot’s observation suggests that the colors range from black to pale honey. These rocks primarily contained phenocrysts of quartz and plagioclase that were deformed. He also mentions that some meta-porphyry sheets do not contain these phenocrysts and that the grain-sizes can range from coarse- to medium. The meta-porphyry sheets also seem to usually have angular and rounded inclusions of either meta-porphyry or meta-sandstone. He further suggests that the meta-porphyry sheets originally flowed long distances and probably fragmented earlier porphyry along with entraining and dispersing sediments (Talbot, 2008, p.54). Furthermore, according to Talbot these meta-porphyry sheets are probably intrusive if the observed rock type in locality 6a is a phreatic meta-breccia with veins of meta-porphyry, which is what he interpreted it as (Talbot, 2008, p.54-55). His conclusion is that the phreatic meta-breccia is probably the result of erosion of submarine canyons or earthquakes (Talbot, 2008, p.68).

Between the meta-porphyry sheets lies area 3 and 4 were there are meta-siliciclastic rocks with sedimentary origin in Talbot’s map (Talbot, 2008, p.52). It is suggested by Talbot that siliciclastic sediments were probably deposited on the shelf and in shallow waters. These range generally from muddy sands to silty muds. Furthermore, Talbot also mentions a deposit of deltaic quartzite south of Södra Sandvik which corresponds to area 3 (Talbot, 2008, p.51). While in area 4 Talbot observed meta-mudstone deposits with some graded silt beds. Talbot interprets the meta-mudstone deposits as having been silty muds that passed a sedimentary platform and filled a submarine canyon on the shelf of an accretionary prism (Talbot, 2008, p.53).

Carbonate rocks in this model of north-eastern Utö are composed of both meta-limestones and meta-dolostones. Meta-limestones are described as having grey fresh surfaces and black weathered surfaces. These are interpreted by Talbot as having a high calcite content. Meanwhile the meta-dolostones are described as having a pale honey-covered color on fresh surfaces while the weathered surfaces are dark brown. Talbot describes these as platform carbonates that probably have been deposited on the fore-arc and the shelf. Moreover, he further explains that these carbonates are interlayered with meta-siliceous rocks that probably came from episodical eruptions of pyroclastic material from a magmatic arc. The colors of these fine-grained meta-siliceous pyroclastic rocks range from pink, white and black (Talbot, 2008, pp.51-52). The carbonate rocks cover the vast area of area 7 and 8 along with dispersed layers of pyroclastic meta-cherts and banded meta-iron-formations to a lesser extent, in his model (Talbot, 2008, p.52). Moreover, in Talbots model he suggests that the banded meta-iron-formations have been deposited in calm waters where the magmatic arc supplied chemical sediments. These have been described as beds of red or grey siliceous meta-chert that are interbedded with black hematite-rich or magnetite-rich meta-chert. Furthermore, Talbot mentions that large bodies of sulphides are present in the pyroclastic deposits on Östra Bergen north of locality 7c (Talbot, 2008, p.52).

In conclusion, according to Talbot, meta-greywackes on Utö were probably deposited on an accretionary prism where they were recycled by mass flows. This likely led to the formation of a shelf made up of siliciclastic sediments which carbonates and episodical eruptions of pyroclastic debris started to be deposited on (Talbot, 2008, p.49). Therefore, the depositional environment for the meta-carbonates, meta-cherts, meta-siliceous pyroclastic rocks and banded meta-iron-formations on north-eastern Utö was probably a platform or a forearc basin (Talbot, 2008, p.68).

Allen’s Model

The model presented by Allen, et al. (1996, p.980) refers to a vast portion of south-central Sweden as the Bergslagen area which differs somewhat from what is usually referred as the Bergslagen area. Utö is a part of the Bergslagen area in the model presented by Allen, et al. as the areas included in their model share a similar geological history. The definition of the Bergslagen area presented by Allen, et al. (1996) will be referred to as the Bergslagen area in this thesis from this point.

The meta-pyroclastic rocks in area 1, 2 and 5 have been suggested by Allen, et al. to have been deposited by subaerial pyroclastic flows and pyroclastic flows that became deposited in the sea above the storm wave base (between 50-100 meters) and likely the fair-weather wave base (between 5-20 meters) as well (Allen, et al., 1996, p.991). These rocks have probably been reworked as their model suggests that the meta-volcanogenic rocks in area 1, 2 and 5 have almost no vitric components left in them (Allen, et al., 1996, p.992). Furthermore, meta-ignimbrites seem also to be present in those areas (Allen, et al., 1996, p.995).

There seems to be grey-black meta-mudstones (which is suggested by Allen, et al. to contain biotite, andalusite and cordierite) with thin parallel bedded meta-sandstones and grey-black meta-siltstones higher up in the sequence than then previously mentioned meta-pyroclastic rocks in area 2. Stratigraphically above the meta-mudstones in area 2, is a sequence of meta-quartz-arenite in area 3 and 4 that has cross-beddings and ripples. Therefore, their model suggests that the environment shifted from a very low-energy environment below the storm wave base into below fair-weather wave base that was affected by strong currents which in turn shifted into a fluvial prograding delta lobe (Allen, et al., 1996, p.995).

They have concluded in their study that meta-limestones were chemically precipitated rather than exhalites from hydrothermal vents. Meta-limestones seem to be interbedded with volcanoclastic meta-siltstones, meta-sandstones and meta-breccias according to them (Allen, et al., 1996, pp.995-996). These were observed by Allen, et al. in area 6, 7 and 8 (Allen et al., 1996, p.987). The possible formation of meta-dolostones and magnesium-rich skarns in the Bergslagen area have been suggested as having been formed through hydrothermal solutions reacting with meta-limestones beneath the sea floor (Allen et al., 1996, pp.1004-1005). Skarn iron ores have been described by them to primarily occur among deposits of meta-ash-siltstones, meta-limestones, meta-sandstones and meta-breccias that were deposited below the fair-weather wave base (Allen et al., 1996, p.1006). The mentioned rocks are also suggested to be found in area 6, 7 and 8 in their model (Allen et al., 1996, p.987).

Most ores (in particular iron ores) are primarily found in hydrothermally altered meta-volcanogenic rocks, meta-limestones and skarns from their observations. They interpreted that banded meta-iron-formations are interbedded with rhyolitic meta-ash-siltstone deposits found in area 7 and 8. Furthermore, they also interpret that the banded meta-iron-formations in the Bergslagen area are chemical suspension deposits (Allen, et al., 1996, p.979).

The model by Allen, et al. (1996, p.999) suggests that two main volcano types were present in the Bergslagen area, which were rhyolitic pyroclastic shallow marine-subaerial caldera volcanoes and dacite-rhyolite shallow marine-subaerial complexes. This is primarily due to the abundance of rhyolitic meta-pyroclastic rocks around the entire Bergslagen area. Their conclusion is that the caldera volcanoes formed a broad and low angle shield where a caldera was in a depression in the middle of the volcano. These were mainly situated in shallow seas and their flanks were probably composed of pyroclastic outflow sheets and reworked pyroclastic debris (Allen, et al., 1996, p.1000).

Selective geochemical sampling at Utö by Allen, et al. (1996, p.1000) showed them that the pyroclastic units became more mafic with time and therefore, suggests the presence of a rhyolitic to andesitic magma chamber. The bimodal composition of the pyroclastic rocks in the Bergslagen area suggests that basaltic magma melted the crust which gave rise to magmatism in the area (Allen, et al., 1996, p.1001). Their model further suggests that there must have been caldera collapses on Utö due to the large volume of pyroclastic rocks there. Furthermore, the indications of shallow-marine depositional environments hint that the vents were near sea level (Allen, et al., 1996, pp.1000-1001).

The observed content of the meta-pyroclastic rocks by Allen, et al. suggests that many pumice- and shard-rich pyroclastic volcanic eruptions occurred in most of the Bergslagen area, including Utö (Allen, et al., 1996, p.990). It is suggested in their model that in order to produce pumice- and shard-rich volcanic eruptions, shallow vents likely caused explosive phreatomagmatic eruptions which caused pyroclastic fragmentation of very viscous rhyolitic magma. Furthermore, these were probably deposited in shallow waters as many of these basins were shallow enough to be completely filled with mass flow deposits (Allen, et al., 1996, p.997).

They agree that what can be seen in the Bergslagen area is an extensional setting of continental crust and that the entire region was a continental back-arc region near an active continental margin. Their evidence for extension of the continental crust is the abundance of meta-rhyolites in the area and interpret that when the volcanoes were younger that the volcanic activity was the highest. Due to the high preservation of the meta-volcanogenic rocks, they concluded that much of the meta-volcanogenic rocks were deposited in deep waters (Allen, et al., 1996, p.1002). Furthermore, the volcanoes erupted pyroclastic debris generally from shallow-marine and subaerial areas into primarily shallow- and moderately deep waters (Allen, et al., 1996, p.979).

Sandstones seem to have been deposited when the environment was above the wave base. When the volcanic activity started to decrease, the environment switched into a shallow marine platform where primarily rhyolitic ash-siltstones, limestones, banded iron-formations and some pyroclastic flows were deposited (Allen, et al., 1996, p.1002). These rocks were deposited both below the fair-weather wave base and above the storm wave base which encompasses depths ranging from 10-500 meters (Allen, et al., 1996, p.979). Furthermore, another interpretation made by them is that episodical marine regression and transgression is observed after major volcanic eruptions of pyroclastic debris. After these major eruptions the environment tends to switch into a deeper marine environment (Allen, et al., 1996, p.1003).

The rocks in the Bergslagen area have been subjected to mainly medium- to high metamorphic grade in their model (Allen, et al., 1996, p.980). They conclude that the rocks in the Bergslagen area seem to mostly belong to the lower to upper amphibolite facies according to their model (Allen, et al., 1996, p.983). The interpreted results of their research also indicate according to Allen, et al. (1996, p.981) that the Bergslagen area was probably a mixed terrestrial and marine region situated on a back-arc with felsic calderas that were built on continental crust. Their geochemical analysis of the Bergslagen rocks suggests that the rocks compromise primarily subalkaline, calc-alkaline, andesites and rhyolites (Allen, et al., 1996, p.983). Their model describes the Bergslagen area as having felsic dominant magmatism and more intermediate compositions to the east where Utö is (Allen, et al., 1996, pp.1001-1002).

Gavelin's Model

Some of the rocks mentioned in the model of both Gavelin, et al. (1976), and Holmquist (1910) can seem unknown to many readers. Therefore, this section will introduce a brief summary of the more unknown rocks that are mentioned by Gavelin, et al. (1976), and Holmquist (1910). Leptites are meta-volcanogenic rocks, and their clasts can originate from lavas, tuffs and tuffites (Holmquist, 1910, pp.789-790). The rock called hälleflinta consists of much quartz and feldspar that most likely originated from a volcano, just like leptites and meta-porphyry beds (Holmquist, 1910, p.895). Many of the mentioned rocks such as hälleflinta and banded leptite have a sedimentary origin while schistose porphyries and leptites composed of tuffs and tuffites have a volcanic origin (Holmquist, 1910, p.800).

The map and model presented by Gavelin, et al. (1976) is based on the map produced by Holmquist (1910) along with minor alterations which consists of their interpretations that deviate from Holmquist's interpretations (Gavelin, et al., 1976, p.7). The meta-sedimentary rocks on Nasknäsudd in area 1 consists of primarily meta-sub-greywackes along with meta-conglomerates in their model. These seem to Gavelin, et al. (1976) to be composed of epiclastic sediments and have cross-beddings and occasional graded beddings. Deposition likely occurred in a shallow-marine environment according to them (Gavelin, et al., 1976, p.31).

Another crucial group of rocks that is present on Utö is the meta-quartz-porphyry group which is a type of fine-grained rock with quartz and plagioclase phenocrysts that is present in both Nasknäsudd (area 1 and 2) and northern Södra Sandvik (area 5). It also has abundant xenoliths of fine-grained meta-sediments and possibly hälleflinta too from what they saw (Gavelin, et al., 1976, pp.23-24). Due to this they suspected that the meta-quartz-porphyry has most likely an intrusive origin which is still not entirely certain, such as if these intrusions occurred during volcanic activity as a volcanic intrusion or perhaps later (Gavelin, et al., 1976, p.24). Another reason why they suggest that the meta-quartz-porphyry deposits are intrusions is because they cannot fully determine the stratigraphic position of these deposits. Possible suggestions by Gavelin, et al. (1976) regarding their origin are hypabyssal intrusions, sills and sheets (G Gavelin, et al., 1976, p.31). Moreover, some of the rocks at Nasknäsudd (area 1 and 2) look very similar to meta-quartz-porphyry but Gavelin, et al. (1976) suggest it is most likely that they are a part of the meta-arenites present in the area. It is possible that these either represent coarse epiclastic meta-sediment or a mixture of tuffitic material that marks the earliest volcanic activity on north-eastern Utö according to them (Gavelin, et al., 1976, p.24).

Coarse meta-arenites and conglomeratic meta-arenites observed in area 3 and 4 by Gavelin, et al. (1976), may contain cross-beddings and ripple marks. The meta-conglomerates were present as lenses or as continuous beds (Gavelin, et al., 1976, pp.15-16). The meta-arenites were according to them probably deposited near the wave base in shallow bodies of water and fragments of meta-argillites can be found in the meta-arenites on Södra Sandvik (area 3 and 4) which in turn have experienced a period above the water level. This caused the argillite sediment to dry out and break down into the fragments seen in the meta-arenites according to them. Furthermore, the meta-argillites found in this sequence look like greywackes (Gavelin, et al., 1976, p.16). Meta-argillites may occur to a lesser extent on Södra Sandvik according to Gavelin, et al. (1976), where primarily the 40 m thick upper part (area 4) of the meta-arenite section (which in their model encompasses roughly area 3 and 4) is composed of meta-argillites that have abundant andalusite (Gavelin, et al., 1976, p.15).

In locality 6a, meta-breccia with angular hälleflinta-, meta-arenite- and meta-limestone fragments could be found (Gavelin, et al., 1976, p.9). They are unsure how the meta-breccia formed and suggest that it is possible that it is a volcanic meta-breccia or a meta-agglomerate and that it probably has an epiclastic sedimentary origin. However, due to the meta-breccia having a polymictic composition of its fragments and having many pieces of meta-limestone, makes the meta-breccia's origin difficult to interpret according to them (Gavelin, et al., 1976, p.10). Their conclusion of the origin of the meta-breccia is that it was likely a local erosional break after appreciable quantity of limestone had been deposited, as the meta-breccia contains many meta-limestone fragments (Gavelin, et al., 1976, p.32). Furthermore, the hälleflinta-leptite group (which encompasses the vast areas of area 7 and 8) contains meta-limestones, skarn and iron ores along with hälleflintas and leptites that are in general tuffs with occasional intercalations of epiclastic sediments (Gavelin, et al., 1976, pp.31-32).

Holmquist's Model

Mica-schist was suggested by Holmquist (1910) as the main rock type that encompasses most of the southern part of north-eastern Utö in area 3, 4 and the stratigraphically upper section of area 1. This is a special type of leptite that is a meta-argillaceous rock (Gavelin, et al., 1976, p.5). There are banded leptites on the north-western shores of Sandvik in area 4 while there are quartzitic leptites in area 3 according to Holmquist (Holmquist, 1910, p.882).

Another abundant rock type that Homquist mentions is meta-quartz-porphyry which is according to him quartz-stained leptite (Gavelin, et al., 1976, p.6). Meta-porphyritic rocks present on Utö consist of altered lava-beds and tuffs and three major layers exist on the north-eastern shores of Utö. One of them is south-east of Krokarna in area 5 while the two others are in area 2 and in the stratigraphically lower section of area 1 (Holmquist, 1910, p.869). The meta-porphyry unit near Krokarna in area 5 is a meta-quartz-porphyry that has bluish-grey quartz grains in a grey schist matrix with gneiss or leptite chemical composition (Holmquist, 1910, p.870). The origins of the meta-porphyry rocks have been suggested by Holmquist to be outflows of rhyolitic lava due to the presence of small leptitic fragments in the meta-porphyry rocks. These leptitic fragments were probably created when the lava streams fragmented the older underlying leptites (Holmquist, 1910, pp.871-872).

There is a brecciated hälleflinta deposit south-east of Krokarna in locality 6a, were the meta-limestones carry hälleflinta-layer fragments (Holmquist, 1910, p.883). Meta-limestones can be seen carrying many hälleflinta fragments on the shores of Krokarna in area 7 too, which are stratigraphically below locality 7b. These formed according to Holmquist when hällefinta layers were broken into fragments. These brecciated rocks show a dynamic flow-structure, where the hälleflinta-layers are enclosed in meta-limestones (Holmquist, 1910, p.884).

Northern Utö (area 7 and 8) is primarily composed of meta-limestones with alternating hälleflinta and calcareous hälleflinta according to Holmquist (Holmquist, 1910, p.895). Other rocks found in the northern- and central parts of Holmquist's map (1910) are quartz-banded iron ores and sulphide deposits (Gavelin, et al., 1976, p.5). Many of the hälleflintas and meta-limestones observed by Holmquist are accompanied by banded ferruginous quartzite iron ore (Holmquist, 1910, p.800). Holmquist suggests that the iron ores on Utö probably formed through sedimentary processes in close connection with leptites, hälleflintas and meta-limestones (Holmquist, 1910, p.895). The volcanogenic sediments that the hälleflinta consists of probably mixed with calcareous sediments in order to form the limestone-hälleflinta complexes (Holmquist, 1910, p.895). The different sedimentary rocks that compromise the northern part of Utö (area 7 and 8) were most likely deposited in a marine or lacustrine basin according to Holmquist (Holmquist, 1910, p.896).

Aim

The aim of this study is to make a geological map and stratigraphic column of north-eastern Utö and based on them, make a paleoenvironmental interpretation for the time the rocks on north-eastern Utö were deposited, and an interpretation of the metamorphic conditions experienced after deposition. Moreover, the findings of the paleoenvironmental interpretation will be related to volcanic activity. This thesis will further expand knowledge about the rocks exposed on Utö. The exposed rocks on Utö hold rich paleoenvironmental- and paleoclimate information about the Paleoproterozoic. A pattern can be seen between the rocks on Utö with the rest of the Svecofennian province that is also littered with Precambrian rock deposits. Many of these rocks have very valuable resources, especially iron which has been one of the greatest exports of Sweden throughout history. Therefore, this thesis will update the information that is present about Utö. Many of the older observations can be verified while other observations may be explained by newer discoveries which were not present back then. Furthermore, more interpretations about the rocks on Utö is favorable as readers will then be able to compare the findings of different authors.

Theoretical background

The theory section will go through the basics of some of the rocks, settings and other relevant information that will be analyzed further in conjunction with the results in the discussion section of this thesis.

Volcanic arcs

Volcanic arcs can develop at convergent plate boundaries. Island arcs are developed on oceanic plates while continental arcs form on continental plates (Klein and Philpotts, 2016, p.318). High-alumina basalts, andesites, dacites and rhyolites are the most prominent volcanogenic rocks formed from volcanic arcs. However, if a continental plate is involved at the convergence, then the rocks present will mostly be felsic rock types (Klein and Philpotts, 2016, p.320).

Back-arc basins

Back-arc basins are formed behind convergent plate boundaries when the lithosphere becomes stretched as a result of subduction rollback. This causes extension of the lithosphere, and this spreading of the back-arc basin can cause parts of the lithosphere to rift and form a new ocean floor (Klein and Philpotts, 2016, p.9).

Common volcano types on volcanic arcs

Composite volcanoes erupt silica-rich magma which makes it viscous. Much of the gas in the magma cannot escape and its eruptions are explosive. The composition of the magma is usually andesitic in composite volcanoes, but it can be more felsic if more continental crust is assimilated. Furthermore, they erupt both lava and pyroclastic debris. Therefore, these volcanoes alternate between ejecting tephra and lava, where the tephra can form different types of pyroclastic deposits (Klein and Philpotts, 2016, pp.294-296). Lava domes are volcanoes with very viscous rhyolitic lava in general and its lava needs to be around ten meters in order to flow. The lava cools very rapidly, and the dome usually causes explosive eruptions of primarily volcanogenic ash and other types of pyroclastic deposits rather than lava flows (Klein and Philpotts, 2016, pp.297-298).

Volcanic ash aggregations

Eruptions of ash from volcanoes may create volcanic ash aggregations when ash particles start to stick together through moisture in the environment. These aggregations may occur both near the plume edge (between 0-15 km) and as distal ash clouds. Volcanic ash aggregations formed near the plume edge are formed more rapidly as closer proximity to water, snow and ice sources increases the capacity of ash to stick together to form aggregates. Furthermore, higher concentration of ash erupted also increases the amount of volcanic ash aggregates as there will be more collision between ash particles (Egan, et al., 2020, p.2722).

Breccia

Breccia is a fault rock which contains angular clasts of all sizes. It is usually a mixture of different types of rocks. Due to this Breccia can contain both younger and older rocks. The composition of meta-breccia can therefore vary significantly.

Conglomerates

Conglomerates contain, often rounded, clasts that are larger than two millimeters in diameter (Klein and Philpotts, 2016, pp.396-397). Volcanogenic conglomerates are formed when pyroclastic debris that are at least 2 mm in diameter erupt from a volcano and become lithified. The volcanogenic conglomerates can contain different types of pyroclastic debris. Pyroclastic debris that usually are larger than 2 mm are primarily lapilli, volcanic ash aggregations, bombs and blocks.

Dolostone

Dolostone is a type of sedimentary carbonate rock which is primarily composed of the mineral dolomite. Fresh meta-dolostone is white, although this is very rare to find in the field. The surface of exposed meta-dolostone develops a very distinct sponge texture due to chemical weathering. This is because it is a carbonate rock.

The mineral dolomite can be formed when solid calcite or aragonite reacts with magnesium-bearing groundwater. This reaction can either take place under lagoons during deposition of limestone or when the limestone has been buried in deep depths (Marshak, 2018, pp.221-222). The process which creates dolostone is called dolomitization. It involves solutions with magnesium that causes dissolution of calcium carbonates which then precipitate dolomite were Ca^{2+} is substituted with Mg^{2+} (Klein and Philpotts, 2016, p.380). The majority of all dolostones were originally limestones and therefore, they are found in the same type of environments as limestones. Calcite may be replaced by the mineral dolomite sometimes shortly after deposition in order to form dolostone. However, it is usually after a long time that calcite gets replaced with dolomite, which is in general during deep burial of the limestone (Klein and Philpotts, 2016, p.407). Furthermore, meta-carbonate rocks belonging to the amphibolite facies can generally contain the following minerals, calcite, dolomite, quartz, biotite, amphibole, diopside, k-feldspar and wollastonite (Klein and Philpotts, 2016, p.446).

Iron-formations, ferric sedimentary rocks and the great oxygenation event

Iron-formations were probably deposited in anoxic marine environments below the wave base (Klein and Philpotts, 2016, p.364). Precipitation of iron-formations occurred only during the Precambrian because the anoxic atmosphere and oceans back then allowed transportation and chemical precipitation of Fe^{2+} solutions in depositional areas such as oceans (Klein and Philpotts, 2016, p.412).

When the great oxygenation event occurred, vast amounts of oxygen started to accumulate in the air which made the oceans into oxidizing environments that started to contain oxygen. Oxygen in the ocean prevented iron solutions from accumulating by oxidizing the iron so that it could not be dissolved in water. Precipitation of iron between 2,4 Ga and 1,8 Ga primarily created iron-formations (Marshak, 2018, p.494). However, it is also possible that iron-formations and ferric sedimentary rocks could have formed through volcanogenic hydrothermal activity, which can cause precipitation of different type of minerals in spaces within rocks. Therefore, hydrothermal solutions can pass through rocks with high porosity or open spaces and deposit its minerals there (Klein and Philpotts, 2016, p.397). Hydrothermal systems are common in areas where there are active volcanoes and near plate boundaries (Klein and Philpotts, 2016, p.517).

Limestone

This is another type of sedimentary carbonate rock like dolostone. Limestone is primarily composed of calcite or its polymorph aragonite which is stable at high pressures. Because of this aragonite is rarer in nature as it is less stable at atmospheric conditions (Klein and Philpotts, 2016, pp.338-339). Limestone usually contains scant amounts of detrital siliciclastic grains of different sizes (Klein and Philpotts, 2016, p.399). Exposed meta-limestone is also subjected to chemical weathering as it is also a carbonate rock. Furthermore, fresh meta-limestone is also white like meta-dolostone, and white surfaces are rare to find in the field.

The majority of the limestone formed during the Precambrian were derived from chemical precipitates as this was prior to the Cambrian explosion which saw the massive increase of complex life (Klein and Philpotts, 2016, p.360). The solubility of calcite increases with increasing pressure and reduced temperature. Therefore, calcite will dissolve at a certain depth when these conditions are met which is called the carbonate compensation depth. This depth is usually around 5000 m (less for aragonite) but varies depending on the carbon dioxide content of the atmosphere and the ocean (Klein and Philpotts, 2016, p.363). Carbonate rocks are usually deposited in shallow platforms, passive continental margins and epeiric seas (Klein and Philpotts, 2016, pp.407-408). Moreover, carbonate rocks are usually formed in areas that do not have a large input of detrital sediments (Klein and Philpotts, 2016, p.412).

Quartz arenite

Quartz arenite is a type of sandstone that is very quartz-rich, while also being coarser and more light-colored than siltstone. The grain size in sandstone ranges from 0,0625 mm to 2 mm. Most of the grains are detrital quartz but sandstones may also contain feldspar grains and smaller clasts (Klein and Philpotts, 2016, p.390). Sandstones are more mature if they contain a higher percentage of quartz because as the sediment is transported further then less feldspars and rock fragments are going to remain in the sediment as they are less stable than quartz (Klein and Philpotts, 2016, p.391).

There are four primary types of sandstones, quartz arenite, lithic arenite, arkose and greywackes. Quartz arenite is almost entirely composed of quartz and contains less than 5% feldspar or lithic fragments. Therefore, due to the very high percentage of quartz grains, it is a very mature type of sandstone as almost all the other minerals have been abraded away. This can occur as a consequence of long periods of abrasive settings such as wave action along a beach or the wind in deserts. Beaches around tectonically stable continents (cratons) and deserts usually form quartz arenite deposits (Klein and Philpotts, 2016, pp.391-392).

Siltstone

Siltstone is a sedimentary rock that is primarily composed of a silt- and clay matrix with lesser amounts of quartz. It is darker and finer grained than sandstone. The grain-size in siltstone is less than 0,0625 mm where most of the grains are at least coarser than 0,004 mm (Klein and Philpotts, 2016, p.386). Clay-sized particles are only deposited in waters that have stopped moving because clay-sized particles are suspended even when the water flows very slowly. Therefore, only low energy areas that are below the wave base may deposit siltstones, such as in oceans, lakes and temporarily ponded water on river floodplains (Klein and Philpotts, 2016, pp.386-387). Turbidite currents can deposit siltstone in areas such as forearc basins, foreland basins, continental shelfs, continental slopes and abyssal plains. Other sites of deposition that are not deep waters include shallow epeiric seas, lakes in rift valleys and pull-apart basins (Klein and Philpotts, 2016, p.389). Moreover, during metamorphosis of siltstone, micas such as muscovite and biotite can form in the rock which makes its surface glimmer.

Meta-rhyolites

For this thesis the term meta-rhyolites will be used as a collective term for all metamorphic rocks with a volcanogenic origin that have a rhyolitic mineral composition and where the size of the pyroclastic debris does not exceed 2 mm. They tend to be composed of volcanogenic ash primarily but other types of pyroclastic debris may also occur in meta-rhyolites.

Cordierite and andalusite

Cordierite is a common mineral found in metamorphosed pelitic rocks that contain fine-grained aluminous sediments. It is formed in low pressure and high temperature metamorphic conditions. These conditions are common during contact metamorphism and in low-pressure regional metamorphic assemblages (Klein and Philpotts, 2016, p.429). However, low- to medium-grade metamorphism of aluminous rocks can produce the mineral andalusite. It also develops in low pressure and high temperature metamorphic conditions too (Klein and Philpotts, 2016, p.418). Both minerals are stable in parts of the greenschist- and amphibolite facies. In many cases these conditions form when a lot of magma intrudes shallow depths (Klein and Philpotts, 2016, p.470).

Method

For this thesis a detailed geological map and a stratigraphic column of the exposed bedrock in an area of north-eastern Utö was made. Both the geological map and the stratigraphic column were produced using the software OCAD. The geological map is more extensively mapped on the shorelines due to the excellent exposure of rocks there in comparison to inland. Mapping inland presents more problems such as traversing difficult forest terrains and mapping areas with much vegetation. The stratigraphic column will help determine which rocks are older and present geological features in each rock sequence while the geological map will show what type of rocks are present and where they are. Data from the geological map, stratigraphic column and the literature study will be compiled and analyzed in order to answer the questions posed by this thesis.

In order to map the north-eastern part of Utö, Google Maps was used to see exposed rock outcrops in the area which were then mapped on a paper copy of the map. The north-eastern part of Utö was then surveyed on foot. Exposed rocks were identified as a certain rock type and then mapped. Distinguishing different rock types from each other was made through their color primarily but also if they have been chemically weathered, if they contain fragments of different rock types and if they contain clasts that are 2 millimeters or larger. The entire shoreline was first mapped in the field which was then followed by exposed outcrops in the interior. Ultimately, several other parts of the interior were mapped as they follow the exposed rocks on the shoreline. During the field mapping measurements of dip direction and dip angle were taken using a compass clinometer on recognizable bed surfaces. Furthermore, a hand lens was used to identify minerals found in the rocks.

Results, part 1: Lithological descriptions

This section will introduce the different rock types identified in the field on north-eastern Utö. The exposed rocks in the studied area had to be recognizable so that their main features could be seen. It was only the bedrock which was mapped and identified as loose rocks can originate from anywhere. Many areas with much vegetation were excluded as it was not always possible to identify the rocks in such areas. Most of the exposed rock outcrops that were mapped and identified were from the shorelines as the rocks there usually have fresh surfaces. Furthermore, the prefix meta has been added to all the different rock types listed below as they have all been metamorphosed and are therefore metamorphic rocks. Mentions of igneous-, volcanogenic-, chemical- and sedimentary rocks in the thesis is only used to describe the origin of the different rock types before metamorphism.

Meta-breccia

The meta-breccia (figure 2 and 3) in locality 6a contains fragments of meta-rhyolites, meta-dolostones, meta-siltstones and meta-conglomerates. The fragments in the meta-breccia on Utö are very mixed, angular, chaotic and range greatly in size. This creates a very chaotic texture on the meta-breccia where multiple different rock types can be seen as fragments in the rock.

Figure 2. Four different rock types are found in the meta-breccia in locality 6a. From top-left to bottom-right: meta-dolostone, meta-conglomerate, meta-siltstone and meta-rhyolites. The meta-dolostone to the top-left in the picture is a great example of how unsorted and mixed breccias are. The red lines show large fragments and borders around rocks found in the meta-breccia.

Figure 3. This is a picture from the meta-breccia in locality 6a. It is a good example of a typical meta-breccia where angular fragments of different rock types and sizes mix in one deposit that forms a very chaotic rock type. This meta-breccia sample was also found in locality 6a.

Meta-conglomerate

On Utö the meta-conglomerate generally contained a lot of rounded gravel-sized clasts that were usually about 2-4 mm in a fine-grained matrix. These gravel-sized clasts are lapilli with high quartz content while the matrix is composed of rhyolitic pyroclastic debris of primarily volcanogenic ash. All the observed meta-conglomerates on north-eastern Utö had a volcanogenic origin where the rocks were primarily composed of different types of pyroclastic debris with rhyolitic chemical composition. The largest grain-size rarely exceeded 4 mm in the meta-conglomerates and the rocks were light-colored, poorly sorted and matrix-supported. Colors of the matrix range from orange, beige, brown and grey, while the lapilli are usually pale grey. A good example of a typical meta-conglomerate in the field can be seen in figure 4 which was found in locality 5a.

However, the meta-conglomerates could look somewhat different in appearance from each other which can be seen in figure 5, which is in locality 5b. While it is also composed of pyroclastic ash as well, its gravel-sized clasts are much more irregular and angular than the very common meta-conglomerate seen in figure 4, and it also has black stripes called fiamme. Clear bedding structures and fiamme could only be seen on some of the meta-conglomerates on north-eastern Utö, such as in certain parts of area 1 and area 5. Very recognizable fiamme can be seen in the meta-conglomerate in figure 6, which was in area 1.

Figure 4. This picture shows rounded lapilli that are larger than 2 mm along with smaller pyroclastic debris in between. This typical appearance, sorting and grain sizes occurs in most of the meta-conglomerates found in the mapped area of Utö. Most of the lapilli that are 2 mm or larger have been marked with red circles in the picture. This meta-conglomerate sample is from locality 5a.

Figure 5. The meta-conglomerate in locality 5b can be seen in this picture. It looks a little bit more unusual from the typical meta-conglomerate found in north-eastern Utö. This specific meta-conglomerate does not have as rounded clasts (like lapilli) as most of the meta-conglomerates that was mapped and the shape of many of its clasts look irregular instead. Some of the larger clasts in this meta-conglomerate have been marked with red borders in the picture in order to illustrate their varying shape and angularity. Furthermore, fiamme can be seen in this sample of meta-conglomerate as small black stripes. The larger fiamme have been outlined by orange lines.

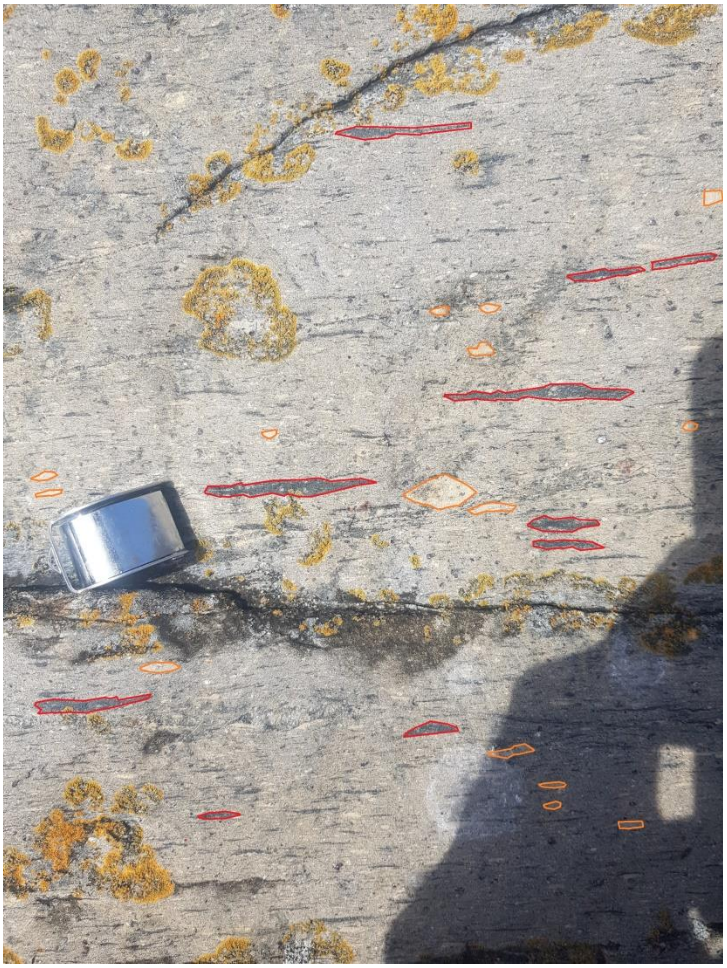

Figure 6. This picture shows a meta-conglomerate deposit with many prominent fiamme in area 1. The black flame-shaped stripes are fiamme which can be created during volcano eruptions. The larger fiamme have been outlined with red lines while the larger euhedral feldspar crystals have been outlined with orange lines.

Meta-dolostone, dolomitic marble

The color of meta-dolostone changes significantly depending on how much it has been weathered and therefore, many different colors could be seen in the field that varied between beige, brown, very dark brown and black depending on the intensity of the weathering. Sponge texture was seen on all the meta-dolostones on north-eastern Utö where the meta-dolostone in figure 7 (which was in locality 7a) shows how they typically looked like in the field. Most meta-dolostones on north-eastern Utö contain clasts, fragments and layers of meta-rhyolites in varying degrees. They were dolomite-rich in the field and there were also green amphibole crystals present in some parts of some of the meta-dolostones. The parts that contain amphibole crystals are skarns.

Figure 7. Chemical weathering of meta-dolostones usually yields a beige color. A distinct feature of chemically weathered meta-dolostones is the sponge texture seen in the picture. This meta-dolostone deposit was found in locality 7a.

Meta-ferric-sedimentary-rocks

In the field meta-ferric-sedimentary-rocks usually have a distinctive dark oily color along with orange rust that is usually present on it and its vicinity. The oily color is very distinctive for the meta-ferric-sedimentary-rocks, because a rainbow of faint colors can be seen on the dark surface, just like in oil. This can be seen on the meta-ferric-sedimentary-rock in figure 8 which is found in locality 7c. Furthermore, layering could be seen in these deposits and the rocks were hard which indicates that the meta-ferric-sedimentary-rocks have a high quartz content. Both the iron ores hematite and magnetite are found in the dark iron-rich oily-colored layers. They were interlayered with meta-rhyolites most of the time and with meta-dolostones to a lesser extent.

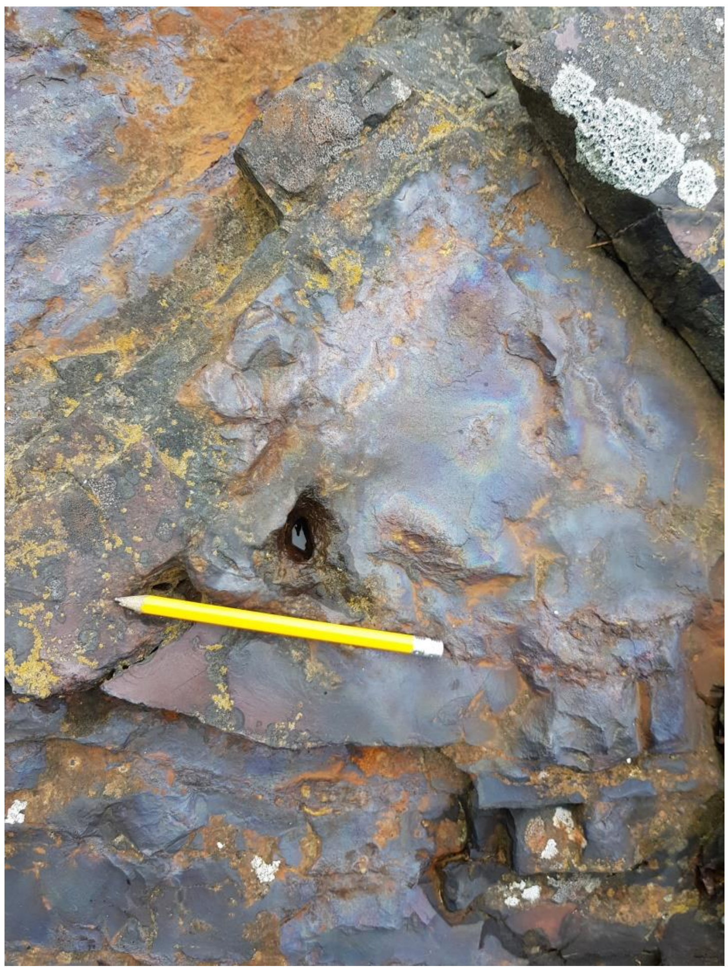

Figure 8. The oily-looking surface of a typical meta-ferric-sedimentary-rock found on Utö can be seen in the picture. They were usually found interlayered with meta-rhyolites in particular but also meta-dolostones. This rock sample is from locality 7c.

Meta-limestone, marble

The chemical weathering of meta-limestones is sponge-like to a lesser extent than the meta-dolostones. Meta-limestones on north-eastern Utö tend to have a rough asphalt texture instead due to chemical weathering, which can be seen in figure 9 from locality 8a. The colors of weathered meta-limestones vary between grey, dark grey and black. Similarly, meta-limestones on north-eastern Utö tend to have clasts, fragments and layers of meta-rhyolites to a varying degree as well. Small meta-rhyolites clast can be found littered to a great extent in many of the meta-limestones on north-eastern Utö. The observed meta-limestones in the field were calcite-rich.

Figure 9. Meta-limestone with interlayered clasts and fragments of meta-rhyolites can be seen in this picture. Almost all of the meta-limestones found on Utö had meta-rhyolites in varying degrees in them. Chemically weathered meta-limestones found on Utö have this distinct dark grey colored surface with an iconic asphalt texture. This meta-limestone sample is from locality 8a.

Meta-quartz-arenite, quartzite

The meta-sandstones present on north-eastern Utö are very well sorted and have a very high quartz content which means that it is a mature meta-quartz-arenite. There were also lesser quantities of muscovite in the meta-quartz-arenite in the field. Meta-quartz-arenite found on north-eastern Utö was usually white or very light grey. Furthermore, the meta-quartz-arenite on Utö also had ripples and cross-beddings. A cross-bedding on a typical meta-quartz-arenite on Utö can be seen in figure 10 which was in locality 3a.

Figure 10. This picture shows a typical meta-quartz-arenite observed in the field. It has a lighter colored surface than most of the rocks found on north-eastern Utö due to the very high content of quartz. The red lines in the picture show cross-bedding on the rock where the two red lines represent two different beds. This meta-quartz-arenite is from locality 3a.

Meta-siltstone

The colors of meta-siltstones on north-eastern Utö ranged from light grey, medium grey and dark grey due to the high content of clay and silt. Meta-siltstones on north-eastern Utö also contained muscovite, biotite and lesser quantities of quartz. Some sequences in the meta-siltstones were very iron-rich and locality 4a along with its nearby surroundings had many rusted cordierite crystals, which can be seen in figure 13 near locality 4a. They were in general medium grey which can be seen in figure 11 which is in locality 4a. There was also an area where the meta-siltstones on north-eastern Utö had black layers of possibly organic remains interlayered in the rocks which was found near locality 4a. Moreover, the meta-siltstones in locality 4a had iron nodules in the rocks which in turn was composed of a biotite- and iron oxide body with cordierite crystals around it. The surrounding area of the iron nodules was light grey (lighter than the average observed meta-siltstones) and had been leeched of its iron content in order to form these iron nodules through diffusion. Iron nodules and their surrounding area can be seen in figure 12 which is in locality 4a.

Figure 11. Meta-siltstone is usually medium grey on north-eastern Utö but the minerogenic- and organic content of the rock affects its coloration. This meta-siltstone is found in locality 4a.

Figure 12. An iron nodule can be seen in the picture which was found in the meta-siltstones in locality 4a. Iron has been leeched through diffusion from the surrounding meta-siltstones which has created the light-colored space around the iron nodule. The leeched iron was used to create cordierite, biotite and iron oxides in order to create the iron nodule, where biotite and iron oxides form the black parts in the middle of the iron nodule while cordierite crystals form the light-colored surfaces around the edges of the iron nodule.

Figure 13. The light-colored rusted crystals found in the upper part of this picture are cordierite crystals. These cordierite crystals are found in a meta-siltstone deposit very near locality 4a. Cordierite minerals form in pelitic rocks subjected to high-temperature and low-pressure conditions which indicate that accretion occurred at the time these cordierite crystals formed.

Meta-rhyolites

All the observed meta-rhyolites on north-eastern Utö were composed of pyroclastic debris of primarily volcanogenic ash. Meta-rhyolites and its pyroclastic debris have a rhyolitic chemical composition which is indicated in general by its felsic light colors. The colors of meta-rhyolites vary between a broad range of colors such as light shades of red, orange, pink, grey, beige and brown. They can also be completely black in some rare cases. Meta-rhyolites in the field generally contained quartz, feldspar and muscovite. Figure 14 illustrates how a typical meta-rhyolites looked like on north-eastern Utö, which can be found in locality 7b. Furthermore, one of the features of meta-rhyolites is that these rocks tend to break angularly. Meta-dolostone- and meta-limestone layers, fragments and clasts are usually found in varying degrees in most of the meta-rhyolites on north-eastern Utö.

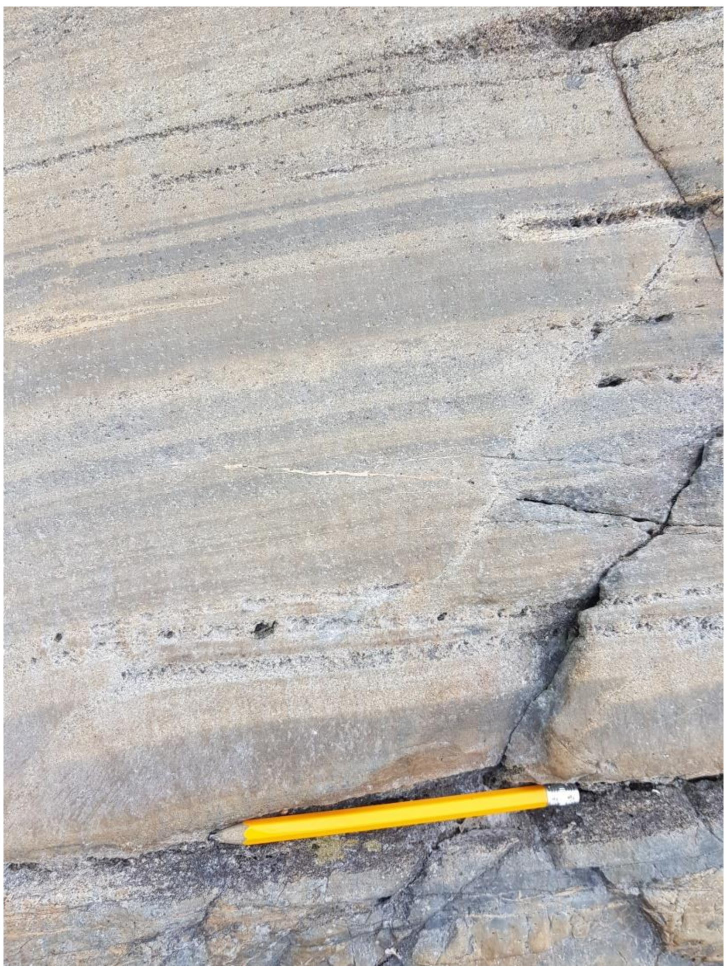

Figure 14. Meta-rhyolites tend to look like this on north-eastern Utö. Many of the meta-rhyolites have alternating light- and dark layers which indicate the mineral composition of the rock. This sample of meta-rhyolites is found in locality 7b.

Results, part 2: Geological map

In this section, the interpretated geological map will be presented in figure 15 below. The map shows the entire area, which was studied for this thesis, which is situated on north-eastern Utö in the Swedish archipelago. All the shaded areas were visited in person and the rocks there were identified on site.

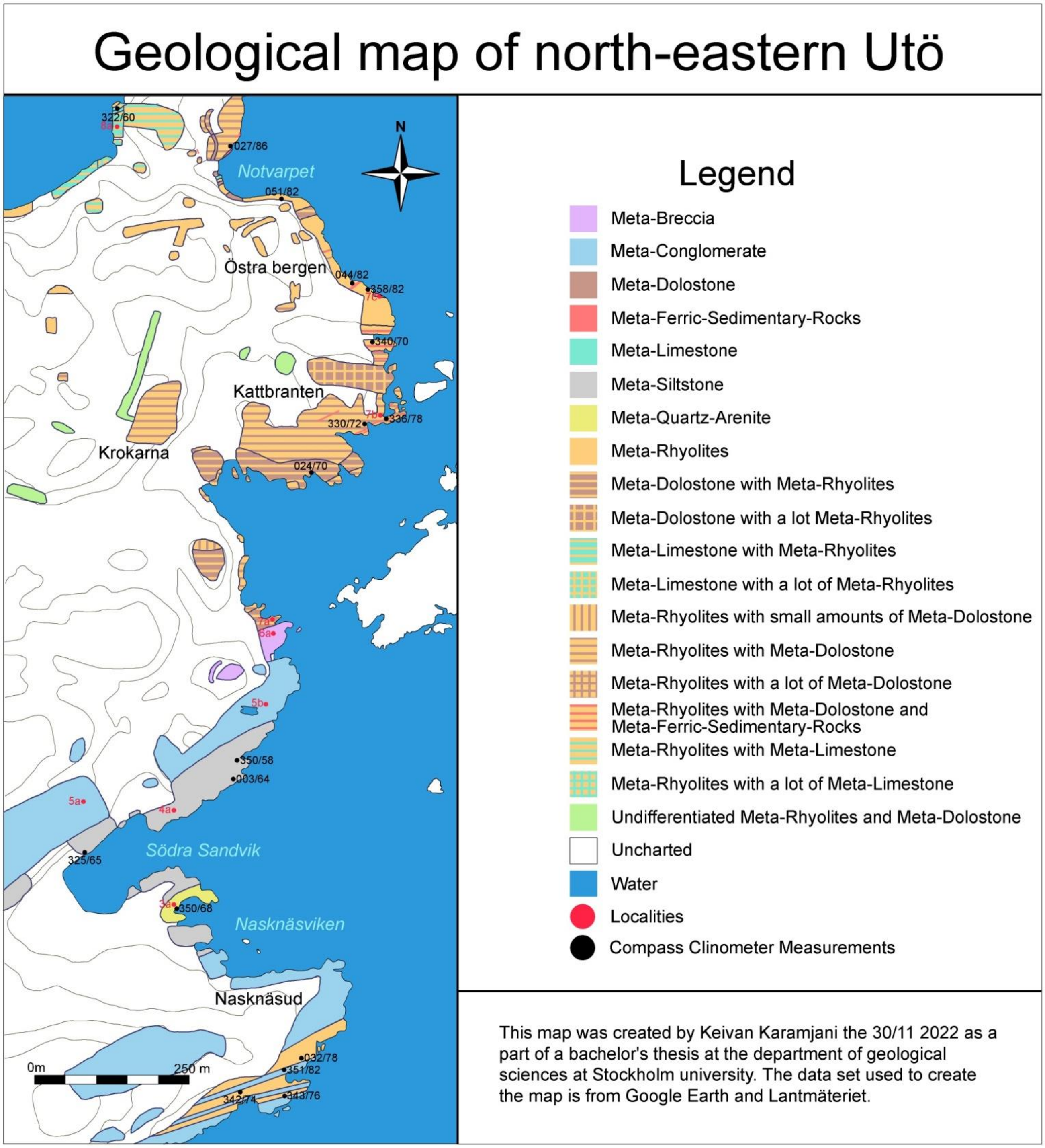

Figure 15. This figure shows a map of the studied area which encompasses the north-eastern part of Utö in Sweden. The areas where the bedrock was exposed and recognizable have been identified as a specific rock type or a mixture of rock types. Areas inland have not been as extensively mapped as there was much vegetation and less exposed bedrock present. The black dots scattered across the map show the dip direction and dip angle in those specific areas. Measurements were taken by a compass clinometer on easily recognizable bed surfaces. Localities in north-eastern Utö have been marked with red dots and comprise different points of interest.

Results, part 3: Stratigraphic column

The rocks identified in the field have been put together into a stratigraphic column below (figure 16). Rocks at the bottom are the oldest outcrops that were identified in the field while those above are the younger outcrops found in the studied area. Younging towards the north-west could be seen in locality 3a on the cross-bedding found on the meta-quartz-arenite in figure 10. Furthermore, the compass clinometer measurements also point towards the north-west generally. The stratigraphic column is accompanied by a description tab which describes the identified rock types and the main features found in each rock layer exposed on north-eastern Utö.

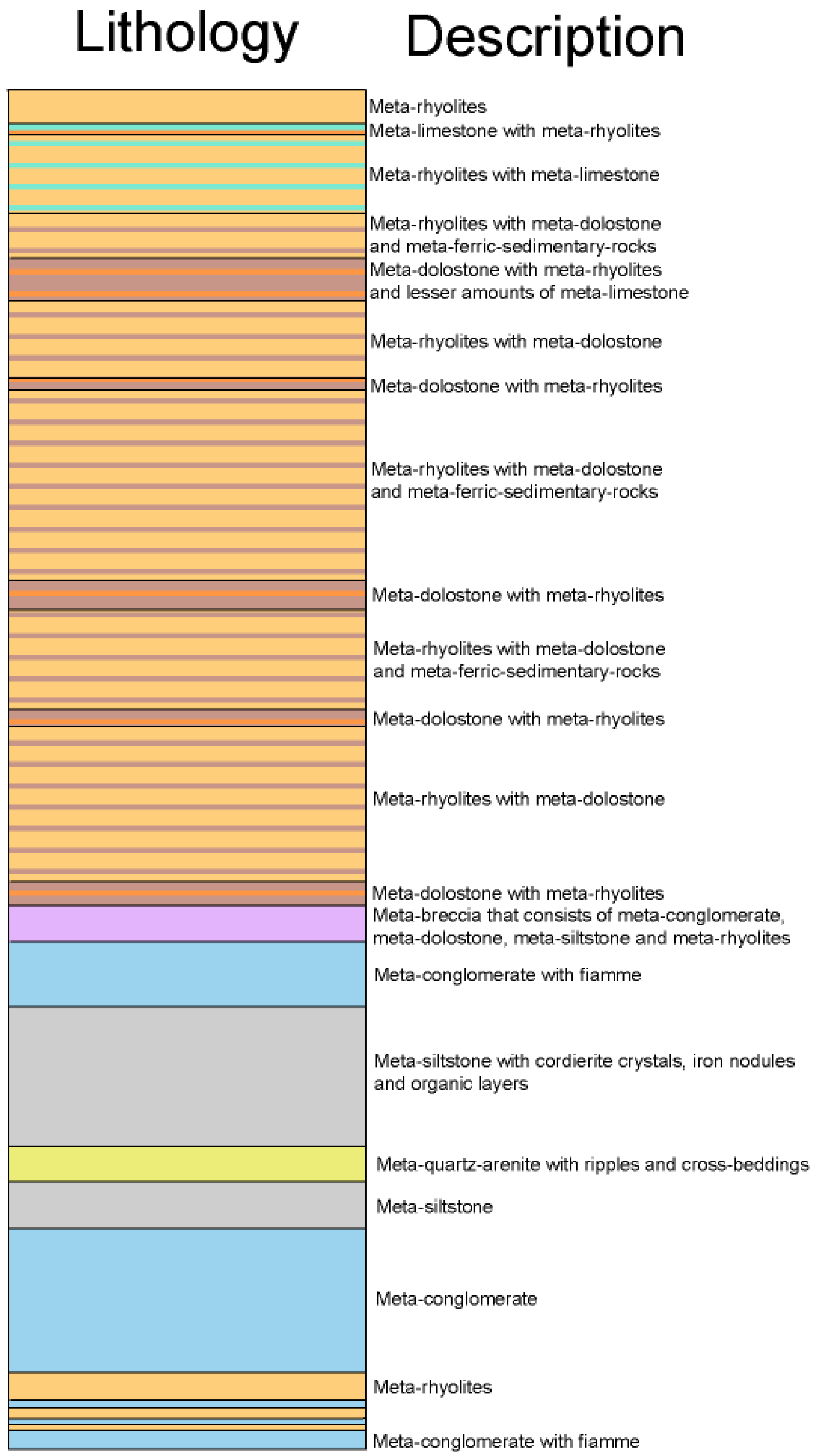

Figure 16. The stratigraphic column shows all the rock deposits present on north-eastern Utö in Sweden. The rocks at the bottom are older and therefore, the transition between the different rock types can be seen in the picture. The description tells what rock types are present along with additional features found in the rocks. Note that many of the different lithologies can contain several rock types.

Discussion, part 1: Paleoenvironmental interpretation

Older meta-conglomerate- and meta-rhyolites deposits

Both of the alternating meta-rhyolites and meta-conglomerates in area 1, along with the meta-conglomerates in area 2, have probably a volcanogenic origin and are therefore, most likely the result of volcanic eruptions. They contain primarily rhyolitic pyroclastic debris which hints that they originated probably from explosive volcanic eruptions with viscous rhyolitic lava. The meta-conglomerate layers probably represent times when there were stronger explosive volcanic eruptions that could deposit both lapilli and volcanic ash while meta-rhyolites were probably deposited when lesser eruptions deposited primarily volcanic ash. It is possible that the large grains seen in figure 4 are lapilli (the diameter of lapilli can range from 2 mm to 64 mm) originating from volcano eruptions (Poret, et al., 2017, p.207). This is a common appearance for the majority of the meta-conglomerates found on north-eastern Utö which further suggests a similar history of the different meta-conglomerates. Although, unlike many of the meta-conglomerates found on north-eastern Utö, fiamme can be found in some of the meta-conglomerates in area 1, which may suggest somewhat more intense volcanic activity during that time (fiamme from area 1 can be seem in figure 6).

Furthermore, the deposits found in area 1 and 2 probably mark the start of volcanic activity on north-eastern Utö and were possibly deposited in low-energy deep waters (probably an ocean that is next to a volcanic arc) below the wave base. This is because there are non-pyroclastic turbidite deposits of sedimentary origin stratigraphically below the mapped area and meta-siltstone deposits stratigraphically above the meta-conglomerates in area 2. Furthermore, both the meta-rhyolites and meta-conglomerates do not show any signs of sorting and they still retain much of their felsic minerals such as feldspar, as seen by their color which further suggests deposition in low-energy deep waters that have prevented weathering and erosion of primarily feldspar. The transition from meta-greywackes with turbidites to meta-siltstones suggests that the environment became less deep and closer to the shores of the volcanic arc. Therefore, the volcanogenic deposits may have also been deposited on the continental shelf below the wave base considering that there are turbidites stratigraphically below these deposits and that there is scant quantities of quartz and abundant quantities of silt that most likely originate from terrigenous sediments from the volcanic arc in the meta-siltstone deposits stratigraphically above these volcanogenic deposits. The quartz- and silt grains were probably not deposited as far away from the volcanic arc as much of the clay particles that were probably deposited in the sea generally.

Older meta-siltstone deposits

The thin layer of meta-siltstones in the stratigraphically lower part of area 3 must have also been deposited in low-energy deep waters as silt and clay requires almost still waters in order for those particles to settle (in particular clay). Therefore, these were also deposited below the wave base. Deposition of the meta-siltstones occurred most likely on the continental shelf as previously mentioned due to the presence of lesser amounts of quartz and vast quantities of silt that are probably derived from the volcanic arc. Therefore, the volcanic arc was probably not too far away from the area of deposition, as quartz- and silt grains are deposited closer to its source than clay particles. The turbidites stratigraphically below the map probably originated from the continental slope and then became deposited on the ocean floor while the layer of meta-quartz-arenite in area 3 stratigraphically above this meta-siltstone was most likely deposited on the coast. Therefore, it would make sense that the meta-siltstone would be deposited on the continental shelf which is in between the coast and the ocean. Moreover, the volcanic activity seems to have been reduced by this time as no lapilli was observed in the meta-siltstones and most of its sediment was most likely primarily silt and clay due to the grey color of the meta-siltstones.

Meta-quartz-arenite deposits

The energy in the environment increased when quartz arenites were deposited stratigraphically above the oldest meta-siltstone deposits in area 3. The meta-quartz-arenites are very quartz-rich, which means that it is very mature and must have been subjected to waves constantly for a long period of time and therefore, was probably deposited above the wave base, most likely on a beach or a delta. These waves ultimately removed most of the other minerals present except for quartz grains as it is the most stable and resistant mineral. Ripple marks and cross-beddings can be seen on this sequence of meta-quartz-arenites which further indicates deposition in high energy shallow waters. This also makes sense stratigraphically as the environment most likely evolved from a continental shelf setting into a coastal setting with time.

Younger meta-siltstone deposits

Stratigraphically above the meta-quartz-arenite deposits lies more meta-siltstone deposits situated in area 4 that unlike the previous meta-siltstone deposits, have possibly interlayered organic layers, abundant cordierite crystals and iron nodules, which means that it has a somewhat different depositional environment. If the black layers are organic remains, then the meta-siltstone must have been deposited in shallow depths as cyanobacteria (a type of common ancient life) needs to receive light to perform photosynthesis and in order for organic remains to be preserved, the depositional area must be anoxic. Furthermore, the meta-siltstones in area 4 were probably deposited in lakes, lagoons or shallow epeiric seas, and if there are organic remains in the rocks then the depositional area also had anoxic conditions at the bottom and the water depth was shallow so that it could host photosynthetic life. Moreover, the depositional area was probably closer to the volcanic arc and shallower than the older meta-siltstones in area 3 considering the gradual shift into shallower environments and, this is especially the case if there are organic remains in the meta-siltstones in area 4. However, the energy of the environment must be low and below the wave base for silt and clay to accumulate at the bottom of these shallow bodies of water, in order to deposit siltstones.

Younger meta-conglomerate deposits

There is another meta-conglomerate deposit in area 5 that looks almost the same as the meta-conglomerates found in area 1 and 2, which means that it probably has a similar history as the previously mentioned meta-conglomerates. There is meta-siltstone stratigraphically below this meta-conglomerate deposit which indicates that these meta-conglomerates were also deposited in low-energy shallow waters. These meta-conglomerate deposits can be seen in figures 4 and 5, where figure 4 shows the typical lapilli-rich meta-conglomerates found in the majority of the meta-conglomerates on north-eastern Utö (especially in area 2 and 5) which indicate rhyolitic explosive volcanic eruptions. This is further confirmed by the color of the lapilli which indicates that the lava was rhyolitic and viscous which in turn means that the volcanic eruptions were probably explosive. Moreover, meta-conglomerates that look like the one in figure 5 are primarily found in area 1 and 5, to a lesser extent which means that most of the volcanic eruptions were lapilli-rich during deposition of the meta-conglomerates. The meta-conglomerates in area 5 and area 1 contain lesser amounts of fiamme that can be seen in figure 5 and 6, which were therefore, structures that rarely formed in the meta-conglomerates on north-eastern Utö. The clasts that are larger than 2 mm in figure 5 could be volcanic ash aggregations because they look like melded ash particles. Furthermore, the shape of the clasts is in general irregular and not as rounded as the typical meta-conglomerate lapilli which means that they were probably formed when wet volcanogenic ash stuck together. Most of these eruptions probably ejected a lot of volcanogenic ash and the ash aggregates are likely the result of phreatomagmatic volcanic eruptions. This further indicates that the meta-conglomerates found in area 5 were most likely deposited in shallow waters, where they were primarily deposited in a shallow epeiric sea.

Meta-breccia

The creation of the meta-breccia found in area 6 must have occurred sometime after deposition of both meta-rhyolites and meta-dolostones as fragments of these two rocks can be found in the meta-breccia. The limestone deposits managed to become dolomitized prior to the formation of the breccia. Considering that dolomitization usually occurs a long time after deposition of limestone, it is likely that the breccia formed a long time after the deposition of limestones. Although, it is also possible that dolomitization of the limestones in area 7 occurred early after deposition of the limestones. Moreover, the minerals cordierite, andalusite and amphibole belong to the amphibolite facies which suggests low-pressure and high-temperature metamorphic conditions, which in turn is characteristic of an extensional setting, accretion and volcanic arcs. This suggests that it is likely that the meta-breccia formed as a result of rifting or extension of the lithosphere due to back-arc spreading as subduction of the oceanic crust beneath the continental crust incites the creation and spreading of back-arc basins.

Furthermore, considering that rhyolites were episodically deposited during deposition of the rocks in area 7 and 8, it is possible that explosive volcano eruptions were occurring frequently. Moreover, the limestones along with the rhyolites were probably deposited in a shallow epeiric sea which raises the possibility that phreatomagmatic volcano eruptions also occurred. Another possibility is that the meta-breccia was created as a result of frequent phreatomagmatic, rhyolitic and explosive volcanic eruptions from the volcanic arc. It is also possible that different types of tectonic activity could have triggered the formation of the meta-breccia such as earthquakes, but less evidence of this was observed in the field. In conclusion, it is most likely that the meta-breccia formed due to an extensional setting involving spreading of back-arc basins as the minerals observed make it evident of the type of setting which comprised ancient north-eastern Utö.

Meta-rhyolites-, meta-dolostone-, meta-limestone- and meta-ferric-sedimentary-rock deposits

The environment starts to receive less terrigenous sediment from the volcanic arc during deposition of the rocks in area 7 and 8, by possibly being in a shallow epeiric sea that probably surrounds the volcanic arc. Reduced sedimentation allows limestone to accumulate in large quantities in those two areas. These limestones became deposited along with rhyolites (that primarily consists of volcanogenic ash) from episodical rhyolitic volcano eruptions originating from the volcanic arcs. This could be the reason for the alternating layers of meta-dolostones/meta-limestones and meta-rhyolites (why the meta-carbonate rocks almost always contain fragments and layers of meta-rhyolites, and vice versa). The older sequences of area 7 (roughly between locality 7a and 7b) are primarily dominated by meta-dolostones while most of the sequences in area 7 stratigraphically above locality 7b are dominated by meta-rhyolites in general. Sequences where meta-rhyolites dominate probably indicate higher frequency of volcanic eruptions and increased volcanic activity while meta-dolostone and meta-limestone dominated sequences most likely represent the opposite.

It could be interpreted as less explosive volcanic eruptions occurred and that the volcanic activity started to slowly decrease after deposition of the meta-conglomerates in area 5, as no lapilli or fiamme can be found stratigraphically above the meta-conglomerates in area 5 and that deposition of limestones occurs a lot more frequently (almost always being interlayered with meta-rhyolites). Volcanogenic deposits of meta-conglomerates and meta-rhyolites stratigraphically below area 7 were not observed being interlayered with other rocks which further hints at the likelihood of very intense and frequent rhyolitic explosive volcano eruptions which made it probably difficult for other types of sediments to accumulate in large quantities. Therefore, the ratio of meta-dolostones/meta-limestones and meta-rhyolites in area 7 and 8 merely indicates the intensity of the processes (volcanic eruptions of rhyolites versus chemical precipitation of limestones) and which of them dominated during a specific period of time.

Considering that meta-dolostones, meta-rhyolites and meta-ferric-sedimentary-rocks are interlayered with each other it can be assumed that they share the same depositional environment. The same is true between meta-limestones and meta-rhyolites as well. Both meta-limestones and meta-dolostones are carbonate rocks that share almost the same depositional environment. Therefore, this interpretation will encompass the probable similar depositional environment that meta-dolostones, meta-limestones, meta-rhyolites and meta-ferric-sedimentary-rocks have. Limestones are usually deposited in warm climates where other types of sedimentations are reduced. However, if the meta-ferric-sedimentary-rocks are related to iron-formations, then it is possible that they were deposited in low-energy and anoxic marine environments. The meta-rhyolites still contain most of their felsic minerals such as feldspar which means that weathering and erosion was minimal. Summarizing these facts, it can be interpreted that the environment had shifted from the low-energy deep water setting that is below the wave base (from area 4 and probably area 5 too) into a low-energy shallow marine environment that is also below the wave base. Therefore, the depositional setting for the meta-dolostones, meta-limestones, meta-rhyolites and meta-ferric-sedimentary-rocks was probably a shallow epeiric sea, lake or lagoon.

The meta-ferric-sedimentary-rocks start to occur in the large meta-rhyolites with meta-dolostone layers sequence near Krokarna and Kattbranten (the same sequence where locality 7b is) and their presence continues to occur occasionally all the way to the top of area 7, which suggests an environmental difference between the deposits in area 7 and area 8. Note that the meta-ferric-sedimentary-rocks are not present in area 8 and therefore, it is possible that the meta-ferric-sedimentary-rocks can have formed through hydrothermal sources (Klein and Philpotts, 2016, p.348). Meta-ferric-sedimentary-rocks seem to be primarily present where deposition of meta-rhyolites dominates, and this may further connect the creation of meta-ferric-sedimentary-rocks on north-eastern Utö with increased activity of volcanogenic hydrothermal sources, which in turn probably increased when the volcanoes were more active. If this is true, then the volcanic activity and the hydrothermal sources were reduced during deposition of the rocks in area 8 as no meta-ferric-sedimentary-rocks are found there, even though episodical volcanism of rhyolites still occurred.

Another possibility is that deposition of meta-ferric-sedimentary-rocks marks the effects of the great oxygenation event and formed as a result of the oxygenated environment. However, deposition of the rocks on north-eastern Utö occurred between 2-1,8 Ga which means that the effects of the great oxygenation event should have been seen earlier as this only encompasses the final stages of or possibly after the great oxygenation event. Therefore, it is more likely that the meta-ferric-sedimentary-rocks formed as a result of the hydrothermal activity of the volcanoes as their connection to iron-formations is still unclear.

No meta-dolostone deposits are present in area 8 and the only carbonate rocks present in area 8 are meta-limestone deposits, which also suggests that the environment in area 8 was different from area 7, despite their similarities. Another interesting note is that no meta-ferric-sedimentary-rocks are present either which means that it is possible that hydrothermal sources are responsible for dolomitization of the limestones on north-eastern Utö by precipitating magnesium-rich solutions into the environment. This also further reinforces that the meta-ferric-sedimentary-rocks were created as a result of hydrothermal sources. Area 8 is primarily dominated by meta-limestone deposits which shows how volcanic activity has probably been reduced along with the hydrothermal sources which are linked to volcanic activity. However, interlayering between meta-rhyolites and meta-limestones still occurs and there are still meta-rhyolites deposits present, which indicates that occasional rhyolitic volcano eruptions still occurred during deposition of the rocks in area 8, but just to a lesser extent.

Paleoclimate of north-eastern Utö

The climate during deposition of these different rocks seems to have been fairly similar. No ancient glacial deposits are found in the area and carbonate rocks such as limestones and dolostones tend to be deposited in warmer climates. Dolostones further indicate that the atmosphere was rich in carbon dioxide which in turn slowly started to decrease with time as no meta-dolostones are found in area 8. The possible organic remains (presumably microbial mats/stromatolites) found in the meta-siltstone deposits in area 4 would most likely prefer a warm climate to photosynthesize in. Therefore, it is most likely that the climate in ancient north-eastern Utö (2-1,8 Ga ago) was in general warm and for the most part had a high atmospheric carbon dioxide content.

Comparison with the four models

Area 1, 2 and 5

According to Holmquist (1910) and Gavelin, et al. (1976), the meta-conglomerates (found in area 1, 2 and 5) are meta-quartz-porphyry, which is very similar to the meta-conglomerates described in this thesis. Therefore, it can be assumed that I interpreted the meta-conglomerates very similarly, especially by remarking that they have a felsic volcanogenic origin. Although Gavelin, et al. (1976) suggest that these are intrusions while Holmquist (1910) suggest that these are outflows of rhyolitic lava, which are neither in line with this thesis' interpretation that these originated from rhyolitic explosive volcanic eruptions of pyroclastic debris. However, when it comes to the meta-rhyolites in area 1, they do not agree with my observations as Holmquist (1910) suggests that these are mica-schists with an argillaceous sedimentary origin while Gavelin, et al. (1976) says that these are meta-arenites of primarily meta-sub-greywackes and meta-conglomerates that consists of epiclastic sediments. Allen, et al. (1996) also suggests that there are pyroclastic rocks in area 1, 2 and 5, that have probably been deposited in a sea environment, like in this thesis. However, they do not mention that there are two different types of rocks in area 1 and 2 unlike the other papers and this thesis. Furthermore, Talbot (2008) seems to have mapped a little bit differently than the others (including this thesis) and he only suggests that the stratigraphically lowermost meta-conglomerate deposit in area 1 is un-bedded meta-greywackes. The rest of area 1, the entire area of area 2 and 5 is suggested by Talbot (2008) to consist of meta-porphyry sheets, which is similar to everyone's interpretations except that he interprets the meta-rhyolites in area 1 as a part of the same rocks that are found in area 2 and 5. He makes some similar observations as the findings of this thesis, such as the presence of quartz-rich phenocrysts and variations among the meta-porphyry sheets (identified as meta-conglomerates in this thesis), while also suggesting an intrusive origin for these deposits unlike this thesis, which regards these rocks as having originated from explosive volcanic eruptions of pyroclastic debris.

Considering all this, the interpretation by Allen, et al. (1996) is the most similar to the interpretation made from the findings of this thesis, even though the model by Allen, et al. (1996) is not the same and makes no clear distinction between the different types of possible volcanogenic rocks that may be present in area 1 (such as if there are two different meta-volcanogenic rocks present). Allen's model (1996) is the most similar due to the other papers mentioning non-pyroclastic rocks of sedimentary origin being present in area 1. It is clear however, that all the papers and this thesis did identify meta-volcanogenic rocks in area 1, 2 and 5, where area 2 and area 5 seem to consist of the same type of volcanogenic rock by everyone. Lastly Allen, et al. (1996) mentions unlike everyone else and this thesis, that there should be some meta-mudstones with thin parallel bedded meta-sandstones in the uppermost part of area 2 which related to the next areas that will be discussed.

Area 3 and 4

Holmquist (1910) mentions that there should be several types of rocks present in area 3 and 4 (primarily leptites) that are considered to be mica-schists and therefore, suggest that the rocks in area 3 are a type of meta-argillaceous rock instead of being a type of meta-arenaceous rock as suggested by this thesis. However, the model proposed by Gavelin, et al. (1976) suggests that area 3 consists of meta-arenites and conglomeratic meta-arenites while area 4 has meta-argillite deposits which is similar to the interpretations of this thesis. These contain fragments of meta-argillite and were deposited in shallow waters near the wave base according to their model, which on the other hand is not entirely in line with the results of this thesis. Allen, et al. (1996) suggests the same interpretation as this thesis regarding area 3 by having also observed meta-quartz-arenite and suggesting a shift in the environment from a low-energy deep marine environment into a high-energy shallow marine environment with strong currents. The only difference being that they also suggest that area 4 also is composed of meta-quartz-arenite with a similar history. According to Talbot (2008) the deposits found in area 3 are deltaic quartzite while the deposits in area 4 are meta-mudstones with silty muds, which is basically what this thesis also interpreted. He suggests that these rocks were deposited in a shallow marine environment, just like what has been proposed by this thesis. Therefore, Talbot’s model (2008) fits best with the interpretation of this thesis regarding area 3 and 4. All of the models describe similar sightings in these two areas and both Gavelin, et al. (1976) and Allen, et al. (1996) have similar interpretations. Holmquist (1910) mentions that there is quartzitic leptites in area 3 which most likely corresponds to the observed meta-quartz-arenites in this thesis, but the difference here is that he regards the quartzitic leptites as a type of meta-argillaceous rock instead of a type of meta-arenaceous rock.

Locality 6a and area 6

The meta-breccia in locality 6a has been explained by Holmquist (1910) as brecciated hälleflinta which is similar to the sightings of this thesis but lacks meta-siltstone-, meta-conglomerate- and meta-dolostone fragments as suggested by the findings of this thesis. He describes that merely the hälleflinta was observed as fragments in the rock, where figure 2 tells otherwise. According to Gavelin, et al. (1976), meta-arenite-, meta-limestone- and meta-hälleflinta fragments are found in locality 6a which is different but similar to the observations for this thesis. They further also suggest that it is possible that this meta-breccia has a volcanogenic origin, but they conclude that it probably was just a local erosional break that formed the meta-breccia which is similar to the interpretation of this thesis. Moreover, the model by Allen, et al. (1996) only mentions briefly that there is meta-breccia in area 6 that contains interlayered meta-limestone which is also a little bit different from this thesis’ model. Lastly, in Talbot’s paper (2008) he mentions that there is a phreatic meta-breccia in locality 6a which was probably created by earthquakes or erosion of submarine canyons, which is partly what this thesis suggests. This thesis supports Talbot’s two suggestions (2008) that the meta-breccia possibly has a phreatic- or earthquake related origin.

However, considering that the meta-breccia was probably created after metamorphism, it is very unlikely that the meta-breccia could have formed from erosion of submarine canyons. He also mentions that there are veins of meta-porphyry in the phreatic meta-breccia, which were not observed in the field during the mapping for this thesis. Therefore, none of the models proposed by the four papers reflect the interpretation of the meta-breccia in this thesis. The model by Gavelin, et al. (1976) of the meta-breccia is the one that is the most similar but considering that they do not mention the presence of meta-siltstone- and meta-conglomerate fragments in the rock and that they do not necessarily imply an extensional setting as the cause of the formation of the meta-breccia makes the model by Gavelin, et al. (1976) different from this thesis interpretation.

Area 7 and 8

Holmquist (1910) suggests that the rocks east of Krokarna in area 7 consist of brecciated hälleflintas unlike everyone else. Area 8 and the rest of area 7 consists of meta-limestones with alternating hälleflintas, calcareous hälleflintas, quartz-banded iron ores and sulphide deposits according to Holmquist (1910), which is different in many ways to the observations of this thesis, although a similar pattern can be seen. Another suggestion that Holmquist (1910) makes is that there are suphide deposits present on north-eastern Utö, which in turn were not observed in field during the mapping for this thesis. He also suggests that all the mentioned meta-sedimentary rocks were deposited in a marine- or lacustrine basin, which is not in line either with the suggestions of this thesis as these environments do not necessarily imply deposition in shallow marine waters. Considering all this, Holmquist's model (1910) is different from the model proposed in this thesis. Gavelin, et al. (1976) mention that there are primarily hälleflintas, leptites, skarn, iron ores and meta-limestones present in area 7 and 8, which therefore, is very similar to the observations of Holmquist (1910), unlike this thesis' interpretations. No mentions of meta-dolostones are made by them either and overall, this model is also different to the interpretations of this thesis. However, according to Allen, et al. (1996), area 7 and 8 consist of volcanoclastic meta-siltstones and meta-sandstones that are interlayered with meta-limestones, and these rocks indicate in turn similar interlayering of different rocks throughout these two areas as suggested by this thesis. This thesis suggests that the volcanoclastic rocks are probably primarily composed of volcanogenic ash, where large portions of the rock are not composed of terrigenous sediments unlike the model proposed by Allen, et al. (1996). They mention that skarn, meta-dolostones and banded meta-iron-formations are also found in the area, which in turn is somewhat more similar to the interpretations of this thesis.

However, Talbot (2008) mentions that both meta-limestones and meta-dolostones are present on north-eastern Utö in area 7 and 8 and that they are interlayered with pyroclastic meta-chert originating from volcanoes and suggest the presence of banded meta-iron-formations, and therefore, these interpretations are fairly similar to the interpretations of this thesis. Talbot (2008) suggests the presence of banded meta-iron-formations while this thesis' model does not support their existence, and this thesis suggests instead that the iron-rich rocks found throughout area 7 are probably meta-ferric-sedimentary-rocks. Another observation made by Talbot (2008) is the presence of sulphide deposits which were not observed in the field during the mapping for this thesis. He suggests that these rocks were deposited in low-energy shallow waters on the shelf where the pyroclastic meta-chert was deposited by episodical volcano eruptions, which is almost the same as the model of this thesis. While none of these models agree perfectly with the interpretations made by this thesis, Talbot's model (2008) of area 7 and 8 is very similar to what was observed in the field during the mapping for this thesis, with only minor differences. None of the four models made the same interpretation as this thesis when it comes to the carbonate rocks. This thesis makes a clear distinction between the different carbonate rocks found in area 7 and 8. Meta-dolostones are found in area 7 while meta-limestones are found in area 8 according to this thesis' model. In conclusion, Talbot's model (2008) of north-eastern Utö was the most similar (not being entirely the same) to this thesis' model except for area 1 which was more similar to the model proposed by Allen, et al. (1996) and locality 6a which was more similar to the model by Gavelin, et al. (1976).

Discussion, part 2: Metamorphic conditions

Interesting minerals and metamorphic structures were mostly found in the possibly organic meta-siltstone deposits in area 4 which contained cordierite, biotite and muscovite along with iron nodules which were formed during metamorphism of the meta-siltstones. Iron nodules are composed of a biotite- and iron oxide body with cordierite crystals surrounding it, where all the surrounding iron around it had been leeched (the meta-siltstones are iron-rich) in order to form iron nodules during metamorphism (an iron nodule can be seen in figure 12). Cordierite crystals which can be seen in figure 13 that are present in the meta-siltstones in area 4 (Gavelin, et al. (1976) suggest that these are andalusite crystals), indicate that the rock must have been subjected to high-temperature and low-pressure metamorphic conditions. There is also andalusite and garnet (and cordierite according to Talbot (2008)) stratigraphically below the mapped area in meta-greywacke deposits with turbidities, where the andalusite also indicates high-temperature and low-pressure metamorphic conditions which is typical of accretion and volcanic arcs. Garnets only indicate that high-temperature metamorphism occurred. The metamorphic low-pressure and high-temperature conditions along with the different minerals present in the rocks of Utö suggests that there must have been volcanic activity, accretion and volcanic arcs on ancient Utö.

Therefore, the metamorphic conditions must have been within the amphibolite facies where both andalusite and cordierite can exist. The green amphibole crystals in the meta-dolostones further indicate this as both amphibole and dolomite tend to be present in meta-carbonate rocks that belong to the amphibolite facies. This is also in line with the measurements by Skelton, et al. (2018, p.4), where their results also suggest that the rocks on Utö belong to the amphibolite facies. Even though no andalusite or garnet was found in the mapped area of north-eastern Utö, the minerals cordierite and amphibole indicate that similar metamorphic conditions persisted throughout north-eastern Utö. Volcanic arcs cause high-temperature and low-pressure metamorphic conditions which in many cases occur when vast amounts of magma intrude shallow depths, and these metamorphic conditions can be seen as a continuation from the meta-greywacke deposits stratigraphically below the map. Further evidence of this is suggested by Allen, et al. (1996) that there is biotite, andalusite and cordierite in area 2, which were not observed during the mapping for this thesis. They also conclude that these rocks should belong to the amphibolite facies, just like this thesis.

Discussion, part 3: Volcanic activity

As mentioned earlier, the minerals andalusite and cordierite indicate that the bedrock must have experienced high-temperature and low-pressure conditions, which are typical for accretion and volcanic arcs, which in turn both occur at convergent plate boundaries. The two volcanogenic rocks observed were meta-conglomerates and meta-rhyolites which were both composed primarily of pyroclastic debris (in particular volcanogenic ash) in the field during the mapping of north-eastern Utö which indicate that many explosive volcanic eruptions of viscous lava occurred. This is further reinforced by the rhyolitic chemical composition of these two types of rocks. This is in line with explosive volcano eruptions as rhyolitic magma is very viscous. Rhyolitic lava does not flow so far either due to its viscosity, slow speed and rapid cooling and considering that no non-pyroclastic meta-rhyolites was observed, it can be interpreted that the volcano that erupted the pyroclastic debris was further away from the area of deposition.

These traits indicate that rhyolitic composite volcanoes and rhyolitic domes were probably the most common type of volcanoes found in the volcanic arc as they tend to primarily erupt pyroclastic debris rather than lava. While composite volcanoes could potentially erupt intermediate volcanogenic rock types, merely rhyolitic volcanogenic rocks were observed in the field which could be attributed to the volcanic arc being developed on continental crust which in turn makes the magma more felsic. Continental crust was therefore involved in forming the rhyolitic chemical composition of the meta-volcanogenic rocks present on north-eastern Utö as only rhyolitic meta-volcanogenic rocks were found throughout Utö. Furthermore, the ash aggregates found in locality 5b (seen in figure 5) hint that phreatomagmatic eruptions did occur, especially when the meta-conglomerates were probably deposited in low-energy deep waters such as in area 1 and 5, which possibly made the volcanoes come in contact with water. No ash aggregations and fiamme were observed in area 2 which may be due to the shift from deep waters to shallow waters. The volcano eruptions that produced the meta-conglomerates were in general also probably more explosive and phreatomagmatic than the volcanic eruptions that deposited the meta-rhyolites, as lapilli, ash aggregations and fiamme can be found in the meta-conglomerates. Furthermore, the meta-conglomerates are also stratigraphically deposited close to rocks that were deposited in deep waters such as meta-siltstones and meta-greywackes which further links them with phreatomagmatic volcano eruptions.

A source that could have supplied magnesium-rich solutions into the environment and helped create the meta-ferric-sedimentary-rocks are volcanogenic hydrothermal sources which may have been more active during the later stages of the volcanic activity as meta-dolostones and meta-ferric-sedimentary-rocks only occur in area 7. Prevalence of interlayered meta-ferric-sedimentary-rocks in volcanogenic meta-rhyolites deposits further links the meta-ferric-sedimentary-rocks to volcanogenic hydrothermal activity. They also both contain a lot of quartz, and it could be possible that the meta-ferric-sedimentary-rocks are altered meta-rhyolites that have been enriched with iron-rich solutions form volcanogenic hydrothermal sources. Another interpretation is that the rocks in area 1, 2 and 5 were further away from the volcanic arc and its hydrothermal sources as the meta-conglomerates were in general probably deposited in deep waters while the meta-dolostones and meta-ferric-sedimentary-rocks were deposited in shallow waters which were closer to the volcanic arc. If this is true then it is also possible that the meta-limestones in area 8 were deposited further away from the volcanic arc than the deposits found in area 7, while still probably being deposited in a shallow epeiric sea. The meta-conglomerates found in area 1, 2 and 5 suggest that more explosive volcanic eruptions occurred during the earlier stages of the volcanoes and that volcanic activity was most likely higher then. This is also implied by the paper of Mints, et al. (2020, p.1020), where their result can be interpreted that the volcanic activity may have been the most active at the same time as the peak of mantle-plume activity around 1,95-1,9 Ga, which likely was when the meta-conglomerates were deposited in area 1 and possibly area 2. This also fits well with the previously mentioned interpretation that the meta-conglomerates were probably deposited further away from the volcanic arc as no meta-ferric-sedimentary-rocks can be found interlayered with them.

Allen, et al. (1996) also suggests similar types of volcanoes to have been present in ancient Utö that in particular are in close proximity to shallow waters, that they were more active when they were younger and caused phreatomagmatic volcanic eruptions. Another similar suggestion they make is that there was an extensional setting. However, they argue that the meta-pyroclastic rocks on north-eastern Utö became more mafic with time, which this thesis found no evidence of. The presence of a continental crust (which they mention was involved) will make the magma felsic, not intermediate as they have suggested for the eastern part of the Bergslagen region. Furthermore, this thesis interpretation is that the environment became shallower with time while they suggest that the environment became deeper after major volcanic eruptions.

Conclusions

- The paleoenvironmental interpretation advocates for a gradual shift from deep water environments into shallow water environments, where episodical deposition of volcanogenic rocks occurred most of the time. Deposition consisted primarily of siliciclastic rocks and volcanogenic rocks in the earlier stages while later stages consisted generally of chemically precipitated rocks interlayered with volcanogenic rocks.

- The climate was probably warm and the carbon dioxide content in the atmosphere was likely high, considering the presence of meta-dolostones and possible organic remains in some of the meta-siltstone deposits in area 4.

- Rhyolitic meta-volcanogenic rocks advocate for the existence of different volcanic activity, such as explosive volcanic eruptions of primarily of pyroclastic debris from composite volcanoes- and domes with viscous rhyolitic lava, along with hydrothermal sources in ancient Utö, which are all related to accretion and originate from volcanic arcs. The volcanic activity decreased with time.

- Andalusite- and cordierite minerals found in the rocks of Utö indicate high-temperature and low-pressure metamorphic conditions which is very characteristic of accretion, extensional settings and suggest that the rocks on Utö should belong to the amphibolite facies, which in turn is further reinforced by the presence of green amphibole crystals in some of the meta-dolostone deposits (skarns).

- Talbot’s model (2008) of north-eastern Utö is the most similar to the model of this thesis, except for area 1 which is more similar to the model by Allen, et al. (1996) and locality 6a which is more similar to the model by Gavelin, et al. (1976). However, this thesis’ model is not the same as the four other papers and therefore, is its own new model of north-eastern Utö.

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