

Presence of acid sulfate soils in Väröbacka, southwestern Sweden

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Abstract

Acid sulfate soils are a global problem that can have negative environmental effects such as surface-water acidification and leaching of toxic metals. To prevent this, it is important to map and investigate where and how these soils are formed. This thesis reveals three sample sites with acid sulfate soils in Väröbacka, southwest Sweden. These sites are located in low elevations, in soil mapped as postglacial fine-grained sediments. Inductively Coupled Plasma Sector Field Mass Spectrometry (ICP-SFMS) analyses confirmed high levels of sulfur in the soil samples. A reconstruction of postglacial landscape suggests that the acid sulfate soils were developed in sediment during the Tapes Transgression. Further mapping of the presence, distribution, and formation of acid sulfate soils in southwest Sweden is necessary.

Sammanfattning

Sura sulfatjordar är ett globalt problem som kan ha negativa effekter på miljön, så som försurning i ytvatten och urlakning av tungmetaller. För att förhindra detta så är det viktigt att kartera och undersöka vart och hur dessa jordar bildades. Den här uppsatsen påvisar sur sulfatjord hos tre lokaler i Väröbacka, sydvästra Sverige. Dessa lokaler är belägna på låga höjder i jordarter karterade som postglaciala finsediment. Inductively Coupled Plasma Sector Field Mass Spectrometry (ICP-SFMS) analyser bekräftade höga halter av svavel i jordproverna. En rekonstruktion av det postglaciala landskapet föreslår att sura sulfatjordar bildades i sediment under Tapes Transgressionen. Ytterligare kartläggning av förekomst, utbredning och formation av sura sulfatjordar i sydvästra Sverige behövs.

Table of contents

1 Introduction	1
1.1 Aim and research questions	1
2 Background	2
2.1 Acid sulfate soils.....	2
2.2 Quaternary history	4
2.2.1 Deglaciation processes in Sweden	4
2.2.2 Tapes Transgression	4
2.3 Previous studies in southwest Sweden on AS soils	6
2.3.1 Falkenberg	6
2.3.2 Western Västra Götaland.....	6
3 Methods	7
3.1 Selection of sample area	7
3.2 Sample sites	7
3.3 Collection of field samples and pH measurements.....	8
3.4 H ₂ O ₂ -oxidation.....	9
3.5 ICP-SFMS analysis.....	10
3.6 GIS reconstruction and modelling	10
4 Results	11
4.1 Findings of AS soils.....	11
4.1.1 Sample site H22004 - a potential AS soil.....	11
4.1.2 Sample site H22007 - an active AS soil.....	12
4.1.3 Sample site H22009 - a potential AS soil.....	12
4.2 Pseudo and non-AS soils	13
4.3 ICP-SFMS analysis.....	14
4.4 Reconstruction of postglacial landscape.....	14
5 Discussion	17
5.1 Limitations.....	19
6 Conclusion	20
7 Acknowledgements	21
8 References	22
Appendix 1	25

1 Introduction

In 2019, during the construction of a cultural center in Falkenberg, a problem occurred with the water pumps as they were lowering the groundwater level. The pumps became corroded and the reason for this was unknown at first. After sending soil samples to a laboratory, it was confirmed by Gustav Sohlenius at the Geological Survey of Sweden, that the concentration of sulfur (S) was high in both soil and water, which indicated presence of acid sulfate (AS) soils (Gustafsson, 2019).

AS soils are a natural occurring soil that are assumed to have been deposited following the melting of the last ice sheet, when large parts of Sweden were depressed below the sea level. In present time, when lowering of the groundwater level is required for construction, agriculture, forestry etc., oxidation of the sulfide deposits in the AS soils results in acidification. This in turn results with negative effects on the surroundings (Becher, Sohlenius, & Öhring, 2019). Since AS soils can have a severe effect on the environment, it is important to investigate where these soils may be located geographically (Sohlenius et al., 2004).

1.1 Aim and research questions

This project, with field work and laboratory analyses, aims to investigate the area of Väröbacka, in the county of Halland, where active and/or potential AS soils may exist. If they exist, the soils will be further examined to find out if any leaching of toxic metals occurs. This project also aims to reconstruct maps of the postglacial landscape in Väröbacka, to see if any pattern of the occurrence of AS soils is observable relative to former sea-level positions associated with the latest glaciation. This thesis will be carried out alongside with a thesis (Nevo, 2022) that focuses on the soil analysis and depositional setting.

Research questions:

- *Do AS soils exist in Väröbacka?*
- *How have AS soils been formed on the west coast?*
- *What is the relationship between the distribution of AS soils and Holocene relative-sea-level changes?*

2 Background

2.1 Acid sulfate soils

In many places around the world, AS soils are a problem. In Europe the largest region with AS soils can be found in Finland, which in 2006 were implicated in a severe large-scale fish kill (Wu et al., 2013). AS soils can be formed when organic material is decomposed by bacteria at the bottom of a sea or a lake. The bacteria will use oxygen as its primarily source for decomposition, but when the oxygen is depleted, it will instead use sulfate (SO_4^{2+}) and trivalent iron (Fe^{3+}). These can in turn be reduced, react with each other, and form ferrous sulfides such as pyrite (FeS_2) (Becher et al., 2019). A so-called potential AS soil is formed by this process and can in turn develop to an active AS soil by being exposed to oxygen. The oxidation causes the formation of sulfuric acid, which is indicated by a low pH, and hence the definition of an active AS soil (Becher et al., 2019).

In Sweden, most soil materials that form an AS soil are said to be deposited due to the activity related to the last ice sheet in postglacial, marine sediments (Boman et al. 2018). As a result of the land uplift, these soil materials have emerged to the surface and now often occur in coastal areas. The sulfide-rich sediments are considered stable, in other words not forming sulfuric acid, if they are in environments that are low in oxygen, for example, below the groundwater table. However, during construction work or ditching, the groundwater level can be lowered in the soil, which in turn can expose the potential AS soil to oxygen and hence, become an active AS soil instead (Becher et al., 2019). The pH in the soil can then be reduced to <4 and cause acidification in catchment areas, as well as leaching of toxic metals (Sohlenius et al., 2004). In the worst case, this could lead to negative effects such seen in the example from Finland. Active AS soils are often located above potential AS soils, which makes it important to avoid the deeper soil to be exposed for oxygen as well (Sohlenius, 2020).

In Sweden, the deposition of sulfide containing soils is believed to be found in areas below the highest coastline, which is the highest sea level that has been reached after the latest glaciation (Sohlenius et al., 2004). The level of the highest coastline varies in different places in Sweden. On the west coast, where the study area Väröbacka is situated, the highest coastline is also called the marine limit (Figure 1). On the eastern coast of Sweden, it was formed due to the different lake and sea stages that were formed in the Baltic Sea during the deglaciation of the ice sheet (Adriellsson, 2006). In Sweden, AS soils have been mostly observed on the coast of

Norrland, mainly in areas where postglacial clay and silt occur (Sohlenius, 2011). This is because the land uplift was, and still is, greater along the coast of Norrland and more sulfide-containing soils has been drained (Becher, 2019). Therefore, AS soils have been examined and mapped more frequently in this part of Sweden, and they are estimated to cover an area of at least 600 km². On the west coast, there is less knowledge about AS soils, and its presence has only been confirmed recently (Sohlenius, 2020; Lindgren et al., 2022). It is also confirmed that AS soils in southern Sweden most often occurs in areas of postglacial, marine clay gyttja (Sohlenius et al., 2004).

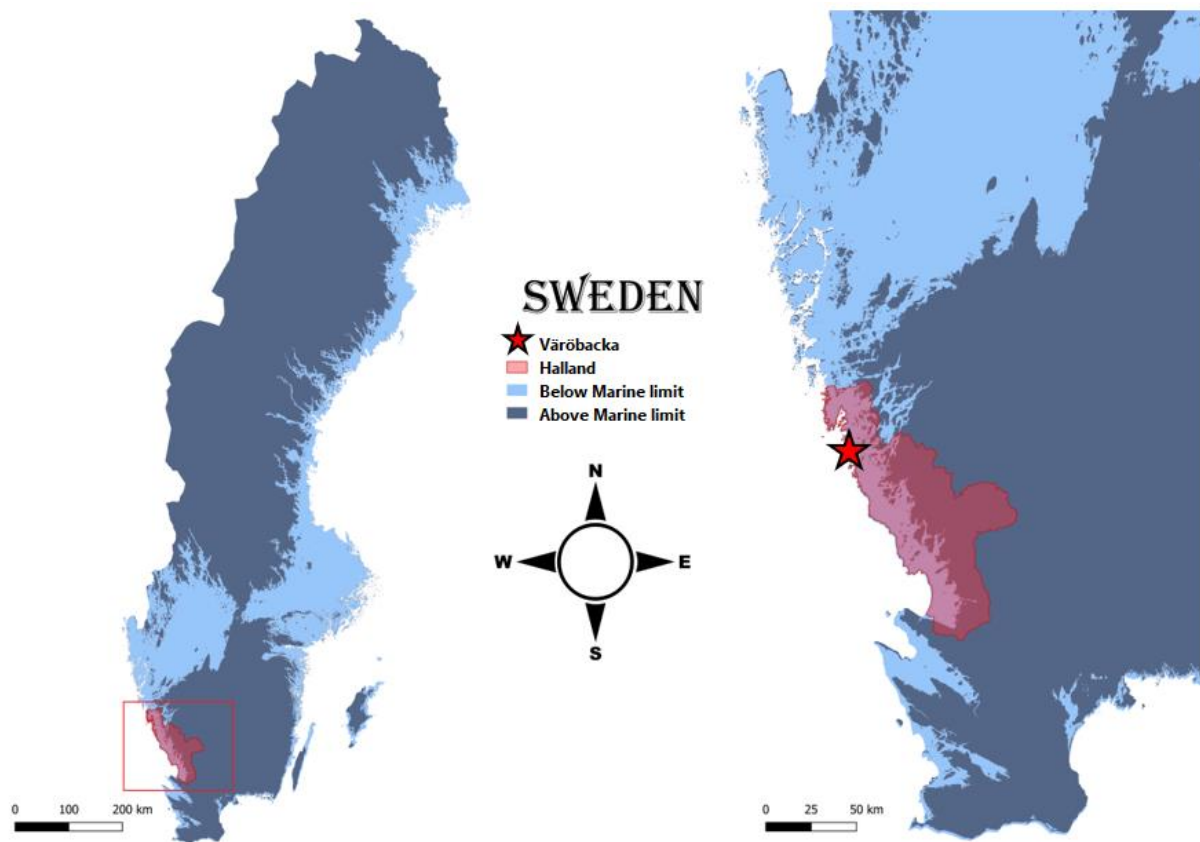


Figure 1. Map of Sweden. Light-blue area represents the marine limit, the red area represents Halland and the red star represents the study area Väröbacka. Data source: Sweden and Halland outlines retrieved from DIVA-GIS ©; Marine limit retrieved from SGU© provided by Christian Öhrling.

2.2 Quaternary history

2.2.1 Deglaciation processes in Sweden

The Quaternary history in Sweden is important for AS soils since the soil materials that form them were said to be deposited in relation to deglaciation (Boman et al. 2018). In the Baltic area in Sweden, four major stages have occurred since the latest deglaciation. The latest of them is the Littorina stage, which is characterized by an increase in organic content, seen in sediment records (Sohlenius & Westman, 1998). The name Littorina is retrieved from the gastropod *Littorina littorea*, which was a common organism during a period when the salinity was high in this stage. The Littorina stage was also characterized by the decrease of the Scandinavian ice sheet and the sea level of Littorina being at the same level as the global sea (Björck, 2006).

During the first 1000 years of the Littorina stage the sea level on the Swedish coast was rising while the land uplift was decreasing, which led to a regression. In the southern part of the Baltic Sea on the other hand, the land uplift had ceased, and a transgression occurred instead. About 8500 y.B.P, the land uplift in southern Sweden changed and was dominated by sea level rising that caused a transgression consisting of up to five pulses in southwest Sweden and Denmark during approximately 3000 years (Björck, 2006).

In the Baltic Sea, these transgressions are called *Littorina transgressions* while in the western they are referred to as the *Tapes Transgression* (Björck, 2006). In the area of the Baltic Sea, AS soils are assumed to have been deposited during the Littorina transgressions. This could be explained by the higher salinity and favorable climate for organisms, which caused the seafloor to be low in oxygen and sediment rich in sulfides (Bayard & Karlsson Mood, 2014). AS soils have been well mapped along the northern coast since they occur more frequently in this area (Sohlenius, 2011).

2.2.2 Tapes Transgression

The Holocene Epoch at 11 600 y.B.P and its postglacial period is characterized by deglaciation and a rapid climate change, where the temperature in Europe increased by 7-10 C° (Barnekow, 2006). It was during the mid-Holocene that the Littorina and Tapes transgressions manifested in the Baltic Sea by sea level rise (Yu, 2003). These transgressions created the Tapes and Littorina limits, which are the highest sea levels reached by the transgression on the west coast and in the Baltic Sea area respectively (Håkansson, 2000). It should be noticed that the height

of these limits is different in different places throughout Sweden and were established at different times as well (Christensen et al., 2008). An illustration of the highest shoreline of the Littorina sea in Kattegat indicates a shore-level of 23 m in Gothenburg, approximately 60 km north of Väröbacka, and a shore-level of 15 m in Varberg, approximately 20 km south of Väröbacka (Figure 2). The reason for the Tapes Transgression to reach different levels in different places, and at different times, is due to the varying velocity of the land uplift.

For the study area Väröbacka, the most current shore-level displacement curve is by Påsse (1990). The curve represents the shore-level displacements in Varberg, in the county of Halland (Figure 3). As shown in the figures, the Tapes Transgression reached its maximum of 15-16 m.a.s.l. around 6000 y.B.P in this specific area (Påsse, 1990).

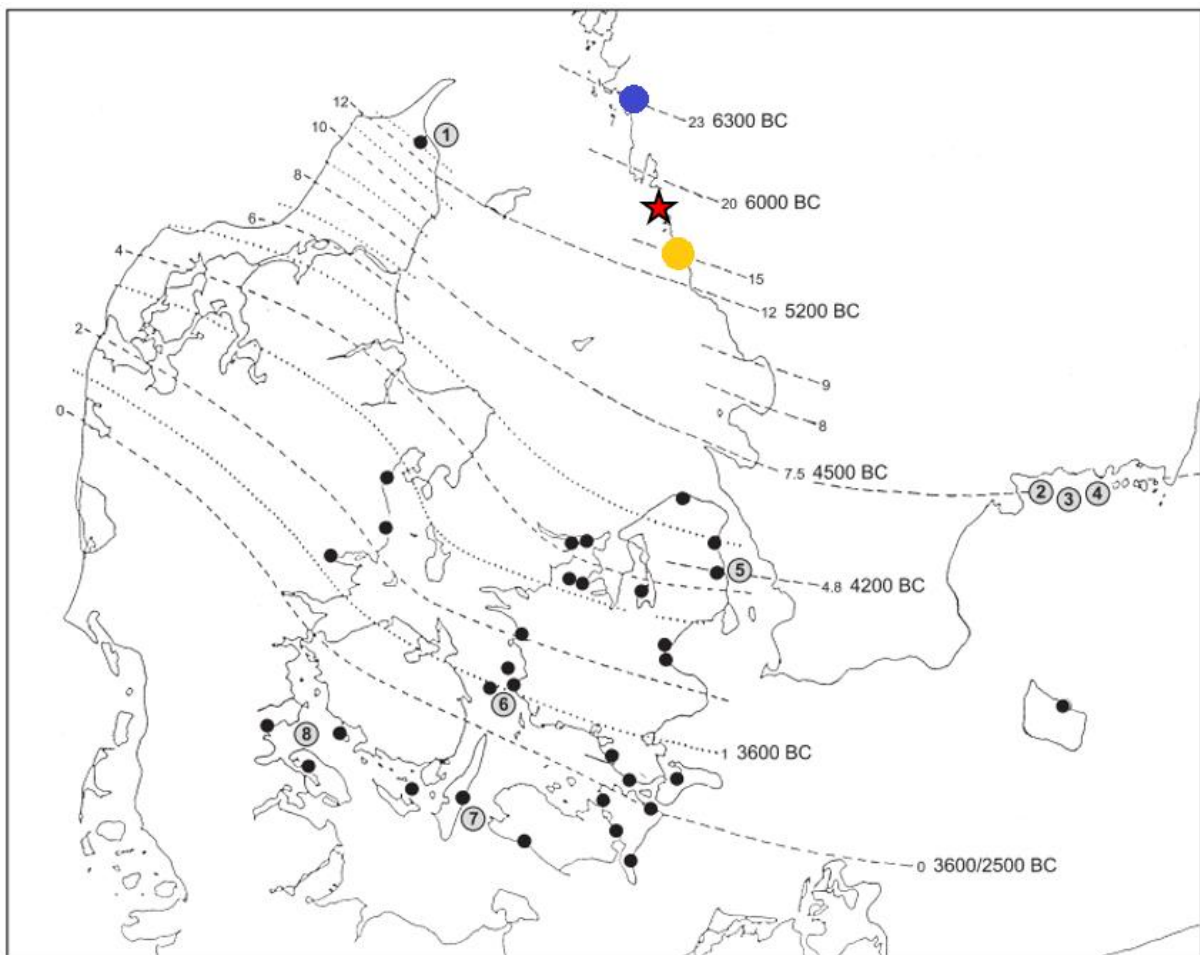


Figure 2. Illustration of the highest shorelines of the Littorina Sea in Denmark and Sweden and their ages, retrieved from Christensen et al. (2008) with modifications. Red star represents Väröbacka, blue dot represents Gothenburg and orange dot represents Varberg.

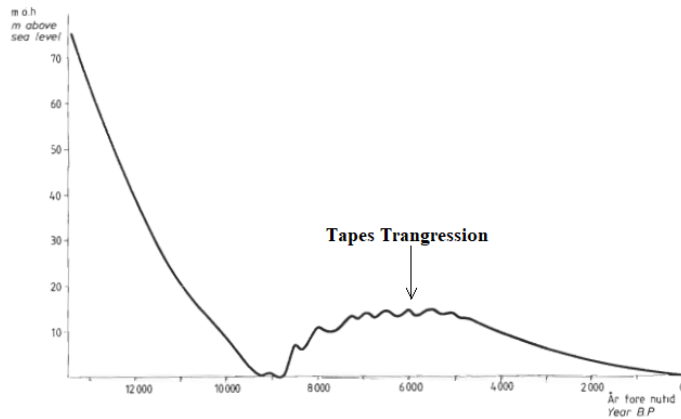


Figure 3. The shore-level displacement curve over Varberg, county of Halland, retrieved from Påsse (1990) with modifications. Arrow indicating the Tapes Transgression 6000 y.B.P.

2.3 Previous studies in southwest Sweden on AS soils

2.3.1 Falkenberg

In 2020, Kling (2020) confirmed with her master's thesis that AS soils exist in Falkenberg. Out of 15 sample sites, four were confirmed with active and potential AS soil, and one with just potential AS soil. All the samples were located in an area of a drained lake and the soil type was interpreted as postglacial silt and peat, according to the soil map (SGU, Jordarter 1:25000-1:1000000). Kling concluded that the observed sediments were created from transgression sequences that, at some point, had been interrupted by a regression sequence with peat. The AS soils were believed to have been formed in former protected, shallow lagoons and bays during the Tapes Transgression. Kling (2020) also concluded that all the sites were located below the limit for Tapes transgression, which in Falkenberg is below 13 m.a.s.l.

2.3.2 Western Västra Götaland

In 2021 Johansson (2021) confirmed the existence of AS soils in different parts of western Västra Götaland in his bachelor thesis. Out of 14 sample sites, stretching from near Kungsbacka in the south to near Mellerud in the north, three were potential AS soils and one was an active AS soil. They occurred in organic-rich sediments in soils mapped as gyttja clay (SGU, Jordarter 1:25000-1:1000000). Compared to Kling's (2020) study, these AS soils were not formed during the Tapes Transgression. According to Johansson (2021), some of the sample sites were too far north, elevated, and inland to have been reached by the Tapes Transgression. However, the sample sites that had at some point been flooded by the sea since the ice retreated, were located well below the highest coastline, and in topographic conditions that allowed for the accumulation of organic clays.

3 Methods

3.1 Selection of sample area

Locating suitable sites for soil sampling was made through QGIS (Version 3.16.15) by using layers downloaded from SLU's download service "geodata extraction tool"; *Jordarter* resolution 1:25 000-1:100 000 (SGU), *Höjddata 2m* (Lantmäteriet) and *Fastighetskartan Hydrografi* (Lantmäteriet). To increase the chances of obtaining samples with potential or active AS soil, different aspects were considered. Areas of primary interest were soil mapped as clay gytjtja, gytjtja, clay, silt, and other fine-grained sediment. Since AS soils can affect the water quality, the area also had to be close to a small stream and to a catchment area, if possible. The sample sites needed to be below the marine limit. Where samples were collected near or in a slope, it is helpful to take several samples along the slope, to see how sediment changes with elevation (C. Öhrling, personal communication, March 15, 2022).

3.2 Sample sites

A total of 17 sampling points were identified in Väröbacka, located in Varberg municipality in the county of Halland (Figure 4). All the sampling sites were below the marine limit and on soil mapped as fine-grained sediments. Of the 17 proposed sample sites, a total of 13 sites were sampled (Figure 5). All the sample sites are located on cultivated fields. Due to lack of time, sown fields or fields with numerous larger clasts (gravel) in the soil, not all 17 sample sites could be sampled.

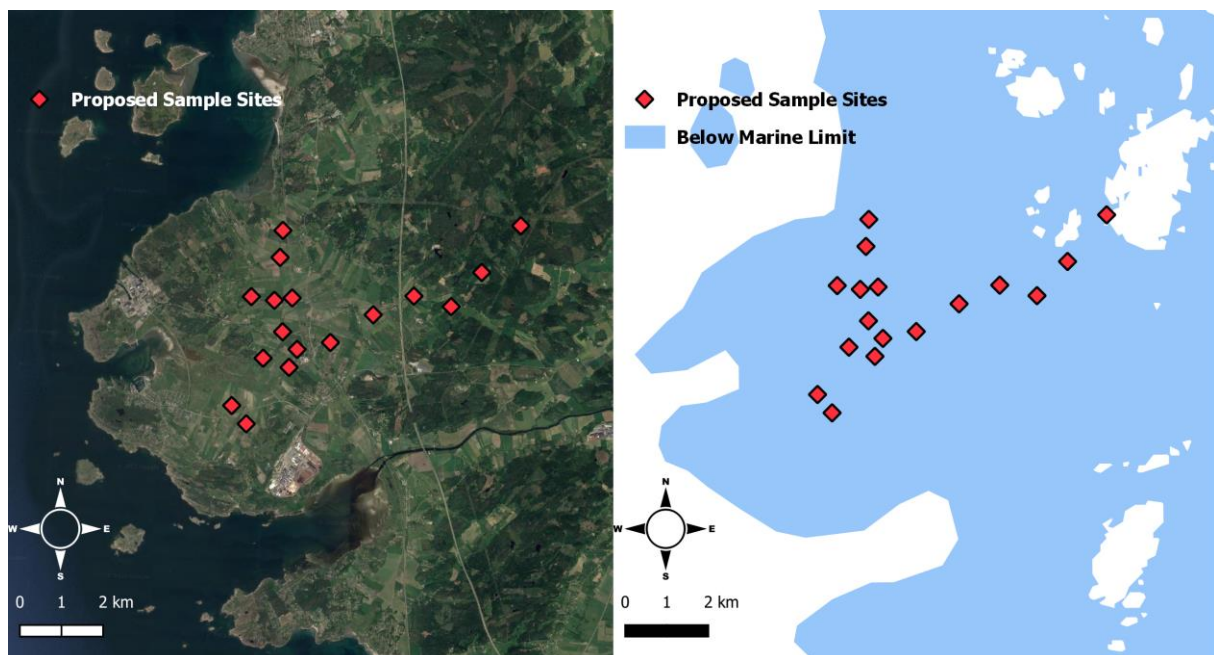


Figure 4. The 17 proposed sampling sites in Väröbacka. The left image shows the sample sites in relation to surrounding area. The right image shows that all the sample sites are located below the marine limit, which is represented by the blue color. Marine Limit data was retrieved from SGU© provided by Christian Öhrling.

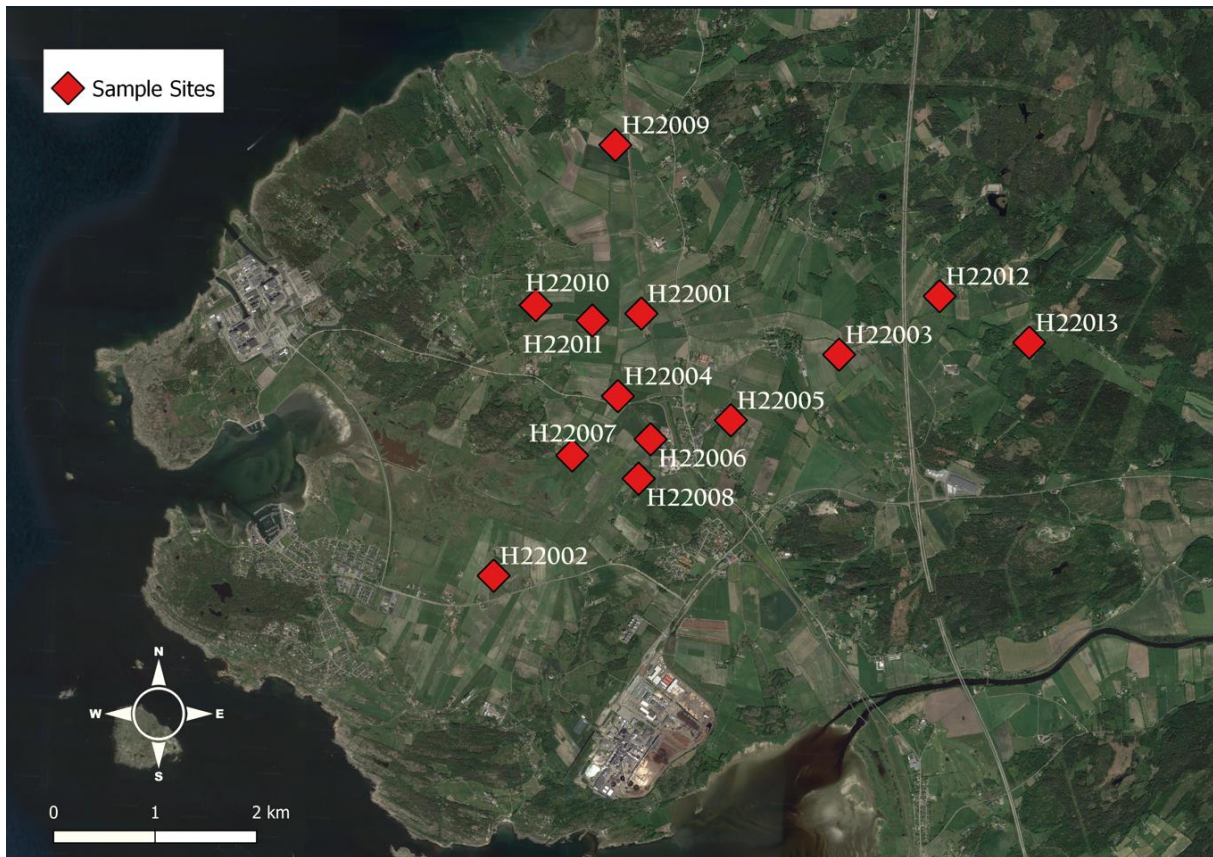


Figure 5. The 13 sites where samples were extracted in Väröbacka, Halland.

3.3 Collection of field samples and pH measurements

Soil samples were collected between the 11th and the 14th of April. The samples were collected at least 10-20 m away from any ditch, water course or the edge of the field, as well as any artificial objects to avoid influence on the groundwater. The sample sites are referred to as H22001-H22013. The soil was sampled every 10 cm with an Edelman auger and arranged along a folding rule (Figure 6). To reach below the groundwater table where the condition is reduced, samples were extracted down to approximately 2 m if possible. For every soil level sampled, the pH was measured with an WTW pH 3110 and registered. Further descriptions of the soil such as water level, color and content of organic material or seashells was noted as well. To get the precise location for the sample sites, the application “SW Maps – GIS & Data collector” was used.



Figure 6. Image from site H22001 presenting how samples were arranged. Photo: Erika Fondin.

3.4 H₂O₂-oxidation

From the 13 sites, 23 soil samples were brought back to the lab for further investigation and were analyzed 5-7 days after to see if any potential AS soils would occur (Figure 7). The method description designed by Sullivan, Ward, Topples & Lancaster (2018) was used. From each soil sample, 2 g were placed into a test tube. Hydrogen peroxide [H₂O₂] (30%) was added to a beaker along with diluted sodium hydroxide [NaOH] (aq) until a pH of 4.9 was reached. The H₂O₂ solution was then added to each test tube, 1 mL at a time. Strong reactions were subdued by adding additional deionized water to the test tubes. The procedure was repeated until a total of 5 mL H₂O₂ had been added. After approximately 60 minutes, the sample was stirred, and pH was measured with an WTW pH 3110. The sample was marked as a potential AS soil if the pH was below <3 (Boman et al. 2018).



Figure 7. 21 out of the 23 samples that were brought back to the laboratory for further analysis with H₂O₂-oxidation.

3.5 ICP-SFMS analysis

A subset of nine soil samples from five sites was selected to be sent to the accredited laboratory *ALS Scandinavia AB* in Luleå for analysis of metal leaching. The isotope analysis ICP-SFMS was carried out for each sample to analyze the presence and quantity for following elements: Arsenic (As), Barium (Ba), Beryllium (Be), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Lead (Pb), Mercury (Hg), Mangan (Mn), Nickel (Ni), Phosphorus (P), Sulphur (S), Strontium (Sr), Vanadium (V) and Zink (Zn).

3.6 GIS reconstruction and modelling

A reconstruction of the postglacial landscape was carried out to further investigate a relationship between occurrence of AS soils and postglacial sea-level changes. The reconstructions were created in QGIS (Version 3.16.15) with the following layers:

- *Höjddata 2m* downloaded from SLU's download service "geodata extraction tool".
- *Highest coastline* by SGU retrieved by Christian Öhrling.
- *Strandförskjutningsmodell* by Påsse and Daniels (2015) retrieved by Christian Öhrling.

The level of the *highest coastline* is a varying elevation throughout Sweden and is measured out by SGU at some locations, one of them was used to construct one of the reconstructions. For the lowest sea level during the regression, a reconstruction was carried out by extracting a sea level from the SGU *Strandförskjutningsmodell* by Påsse and Daniels (2015). For the last reconstruction, the shore-level displacement curve over Varberg (Påsse, 1990) was used to find shoreline landforms that were interpreted to correspond to the highest maximum sea-level reached during the Tapes Transgression.

Three maps were constructed displaying different postglacial landscapes over Väröbacka. This was done by using the extracted sea levels to create contour lines that followed the specific elevation. A fourth map was constructed including all reconstructions merged, to display all the sea levels in relation to the sample sites.

4 Results

Of the 13 sample sites that were sampled, one site revealed an active and a potential AS soil, whereas two of them were only potential AS soil (Figure 8). The results from H₂O₂-oxidation, field notes and selected ICP-SFMS results from all soil samples retrieved from field work are shown in Appendix 1.

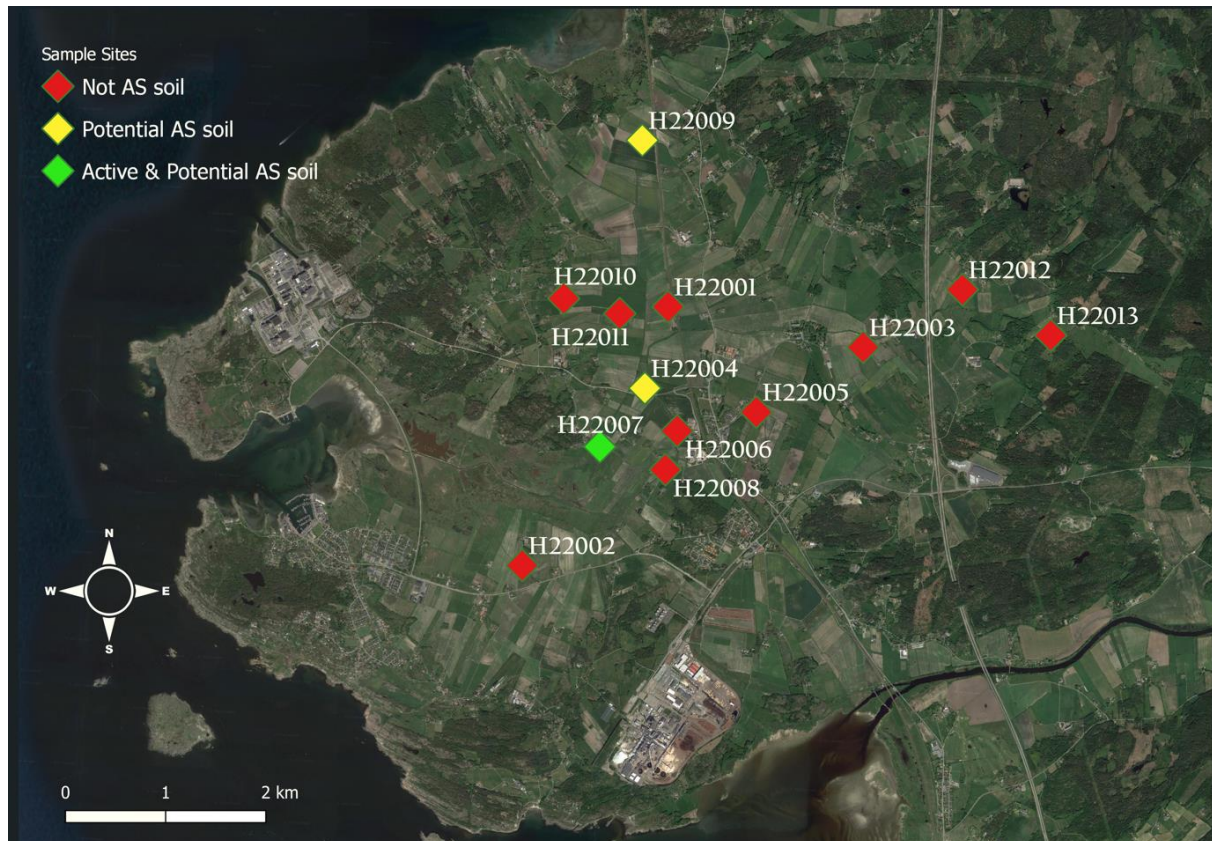


Figure 8. Distribution of Not AS soil, Potential AS soil and Active and Potential AS soil in the 13 sample sites, displayed with different colors.

4.1 Findings of AS soils

4.1.1 Sample site H22004 - a potential AS soil

Sample site H22004 was located at 2.5 m.a.s.l. and in a cultivated field. The soil in this area is mapped as clay gytija (SGU, Jordarter 1:25000-1:1000000), and the extracted soil samples were collected down to 1.8 m and contained organic matter. The pH-value measured in the field varied from 5.2 to 7.0 (Figure 9). Samples were taken at 0.4 m, 1.1 m, and 1.4 m. After H₂O₂-oxidation, the two samples from a depth of 1.1 m and 1.4 m presented a pH of 3 and 1.5 respectively, indicating presence of potential AS soil.

4.1.2 Sample site H22007 - an active AS soil

Sample site H22007 was located at 1.9 m.a.s.l. and in a cultivated field. The soil in this area is mapped as fluvial sediment with clay and silt (SGU, Jordarter 1:25000-1:1000000), although when observing in field it resembled something that was more likely to be clay gyttja. The extracted soil samples went down to 2 m and the groundwater level was reached at 1.1 m. The pH-value measured in the field varied from 4.1 to 6.8 (Figure 9). Samples were extracted at 0.7 m and 1.7 m. After H₂O₂-oxidation, the samples presented a pH of 2 and 1.4 respectively, which indicates presence of potential AS soil. Since the pH-value of the upper soil was <4.5 and followed by samples that indicate presence of potential AS soils this proves that this was also an active AS soil.

4.1.3 Sample site H22009 - a potential AS soil

Sample site H22009 was located at 6.1 m.a.s.l. and in a cultivated field. The soil in this area is mapped as postglacial fine clay. The soil samples were extracted down to 2 m and contained seashells. The water level was reached at 1.3 m. The pH-value measured in field varied from 5.1 to 7.7 (Figure 9). Samples were taken at 0.7 m and 1.4 m. After H₂O₂-oxidation, the samples presented a pH of 3.4 and 2.9 respectively, which indicates presence of potential AS soil in the latter sample.

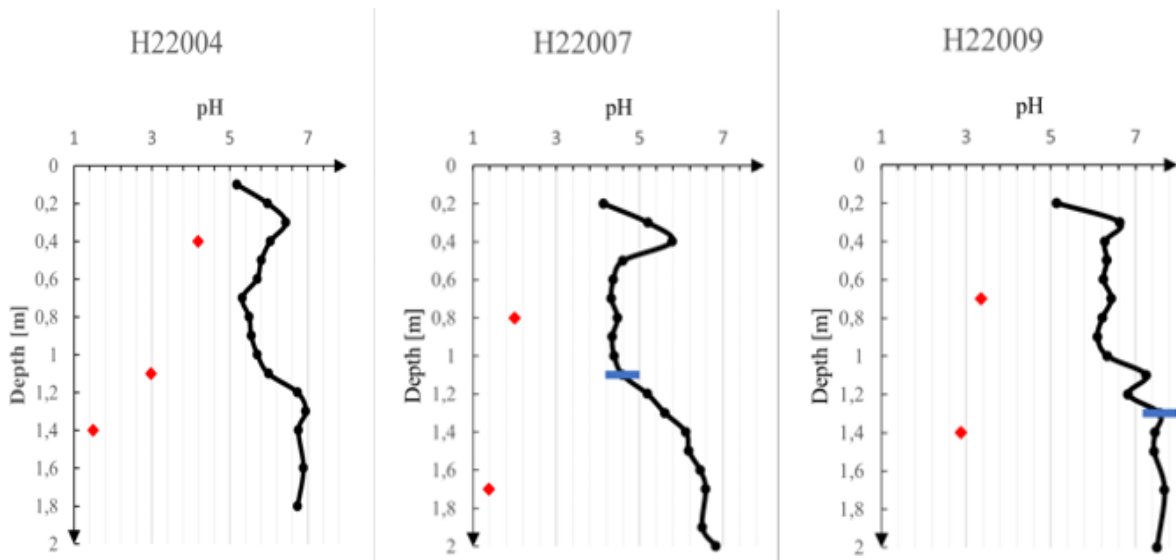


Figure 9. pH-values from sample sites confirming the presence of AS soils. Red dots marks pH-value after H₂O₂-oxidation, the blue line marks the water level (note that data for water level was not retrieved from sample site H22004). Graphs by Nevo (2022).

4.2 Pseudo and non-AS soils

Eight sample sites were classified as not being an active or potential AS soil either directly in field or after H_2O_2 -oxidation (Figure 10). However, the samples sites H22001 and H22006 were classified as pseudo AS soils because they were on the limit for being AS soils and did not meet the full requirements (Boman et al. 2018). The soil at sample site H22001 was mapped as clay gytija and contained organic matter. Sample site H22006 were mapped as postglacial fine clay. Considering the other non-AS soils, sample sites H22002 and H22010 were mapped as postglacial fine clay and contained seashells. Sample site H22011 were mapped as postglacial fine clay as well but contained organic matter and no sea shells. Sample sites H22003, H22005, H22012, and H22013 were mapped as glacial clay and did not contain either organic matter or seashells. Lastly, sample site H22008 was mapped as fluvial sediment with clay and silt and contained both seashells and organic matter. Soil mapping was carried out with SGU Surficial deposit map (Jordarter 1:25000-1:1000000). All samples were located in cultivated fields.

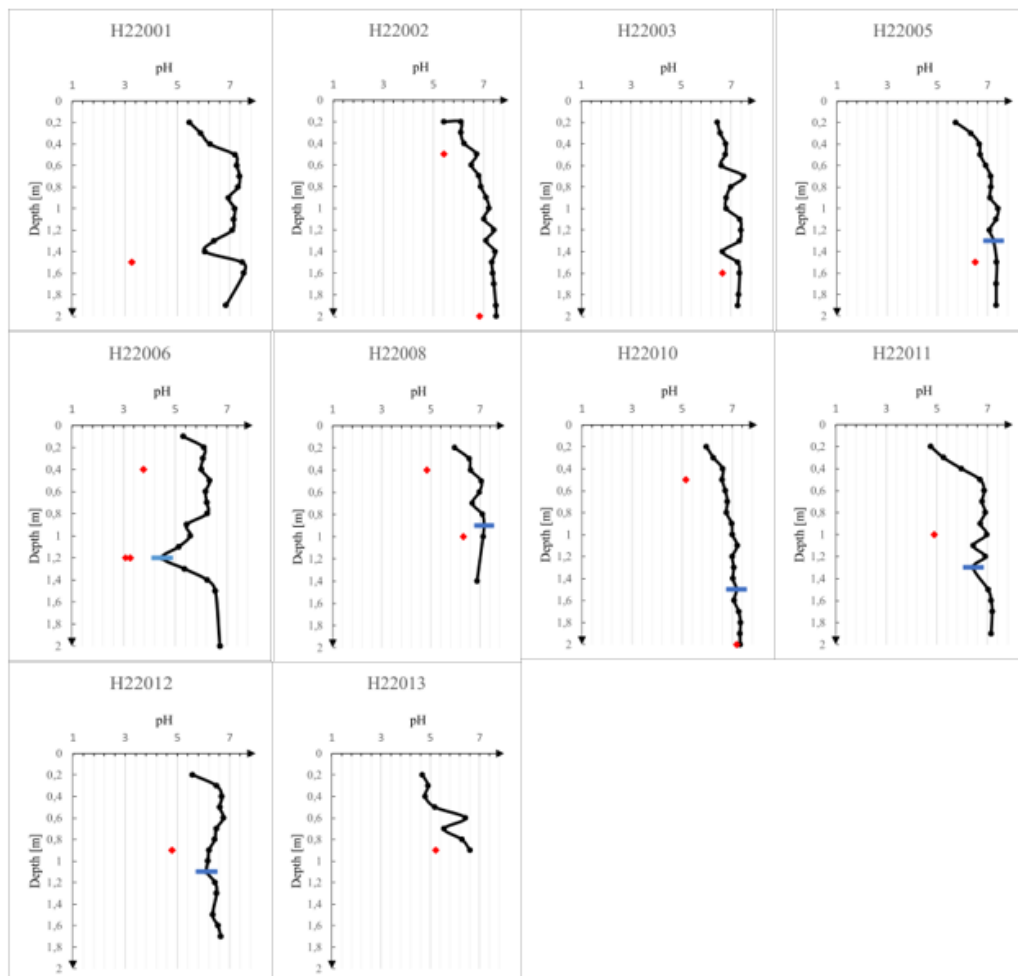


Figure 10. pH-values for the 10 sample sites not showing any presence of active or potential AS soils. Red dots indicate pH-values after H_2O_2 -oxidation and blue lines where the water level was reached (note that data for water level was not retrieved from sample site H22001, H22002, H22003 and H22013). Graphs by Nevo (2022).

4.3 ICP-SFMS analysis

The following results present the concentrations of toxic metals in the samples that, through H₂O₂-oxidation, showed result of potential AS soils (Table 1). The remaining samples, that were non-AS soils, were not sent to the laboratory since they did not confirm any presence of potential or active AS soil. An exception was made for sample H22001:1 which was motivated by its low pH-value, which was on the threshold for being a potential AS soil through H₂O₂-oxidation.

All samples, except sample H22010:1 and H22010:2, had a concentration of S >600 mg/kg TS indicating that there is an acidic effect, but not to which extent. Samples H2200:1, H22004:1, H22007:2 and H22009:1 all showed a Fe/S ratio <3, which would indicate a high acidic effect (Pousette, 2010). For the AS soils, the concentrations of Cd, Mn and Sr is lower in all the soil samples retrieved from the oxidized layers at a shallow depth, compared to the samples retrieved from deeper depth (Table 1).

Table 1. ICP-SFMS for 9 selected samples. The grey box represents the sample sites with AS soil and the dark gray rows represent the most noteworthy elements. Table by Nevo (2022)

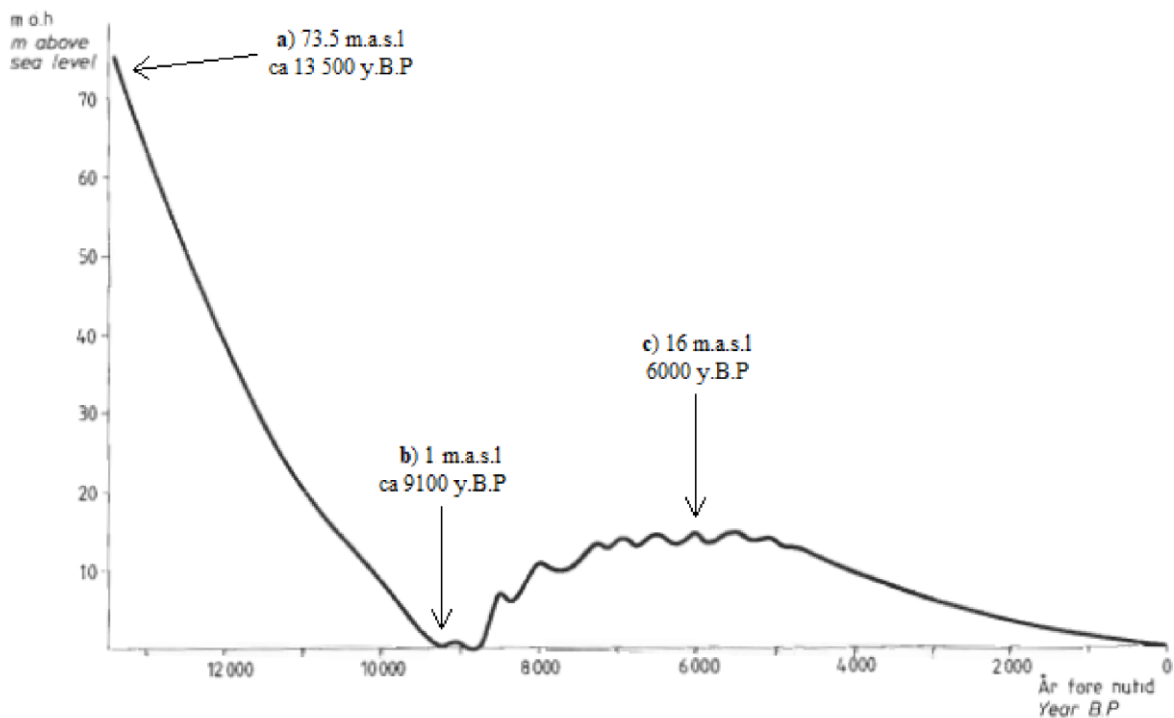
	Sample	H22001:1	H22004:1	H22004:2	H22007:1	H22007:2	H22009:1	H22009:2	H220010:1	H220010:2
	Sample depth [m]	1.5	1.4	1.1	0.7	1.7	1.4	0.7	0.5	2
Elements										
As	mg/kg TS	8.41	6.8	7.79	13.4	8.25	5.69	13.8	13.1	4.56
Ba	mg/kg TS	54.4	53.5	53.7	53.4	47.4	43.1	53.4	87.4	86.2
Be	mg/kg TS	1.33	1.22	1.35	0.839	1.03	1.09	1.26	1.52	1.61
Cd	mg/kg TS	0.439	0.34	0.112	<0.1	0.478	0.458	0.48	<0.1	<0.1
Co	mg/kg TS	13.5	11	9.93	5.64	8.64	11.7	13.3	7.86	12.8
Cr	mg/kg TS	49.1	44.3	43.7	44	37.1	41.2	48	42.9	36.2
Cu	mg/kg TS	21.7	18.9	17.2	26.4	26.3	19.4	26.9	19.3	18.1
Fe	mg/kg TS	34800	33800	39200	38400	31400	32200	28100	48700	35500
Hg	mg/kg TS	<1	<1	<1	<1	<1	<1	<1	<1	<1
Mn	mg/kg TS	371	347	250	158	292	359	206	201	437
Ni	mg/kg TS	35.4	29.8	25.8	14.2	27.1	31.1	38.1	19	24.6
P	mg/kg TS	648	627	682	925	706	558	475	338	826
Pb	mg/kg TS	15.6	14.9	17.2	12.4	11.7	13.2	15.7	17.3	16.5
S	mg/kg TS	12800	13400	1540	2450	17000	17300	1670	442	358
Sr	mg/kg TS	59.3	45.7	29.5	19.7	43.5	58.4	38.8	50.6	70
V	mg/kg TS	67.3	58.5	58.6	95.5	60.8	59.6	87.2	70	58.5
Zn	mg/kg TS	86.2	76.8	79.5	49.7	68	69	70.9	52.8	76.5
Fe/S ratio		2.7	2.5	25.5	15.7	1.8	1.9	16.8	110.2	99.2

4.4 Reconstruction of postglacial landscape

A sea level of 73.5 m.a.s.l, representing the highest coastline, approximately 13 500 y.B.P was retrieved from data points carried out by SGU. By using the SGU *strandförskjutningsmodell* in QGIS created by Påsse and Daniels (2015), a sea level of 1 m.a.s.l. was extracted, representing the lowest regression level approximately 9100 y.B.P. For the maximum Tapes transgression,

a sea level of 16 m.a.s.l. was extracted from the shore-displacement curve (Påsse, 1990) which occurred approximately 6000 y.B.P (Figure 11). The values were tuned by identifying landforms in detailed elevation data with 2 m resolution LiDAR (Lantmäteriet). Since the highest coastline varies throughout Sweden due to the land uplift, the actual level could be slightly higher in the upper part of the area and lower in the lower. Since this thesis is referring to a very small area it is not motivated to add a tilt gradient for the postglacial reconstructions.

Reconstruction of the extracted sea levels, representing the postglacial landscape at these different times with their respective sea levels in Väröbacka is displayed in Figure 12. The merged reconstructions of the postglacial landscapes together illustrates that most of the sample sites are below both the highest coastline/marine limit and below the Tapes transgression. All the sample sites are above the sea level of the lowest regression, implying that these sites were drained before it was again flooded by sea water (Figure 13).



- a) Highest coastline
- b) Lowest regression level
- c) Maximum Tapes Transgression

Figure 11. Shore-level displacement curve of Varberg from Påsse (1990) with modifications. Arrows indicate extracted sea levels and their age used for reconstructions of postglacial landscape of Väröbacka. Each sea level is represented by a specific event, which is described by a), b) and c) below the graph.

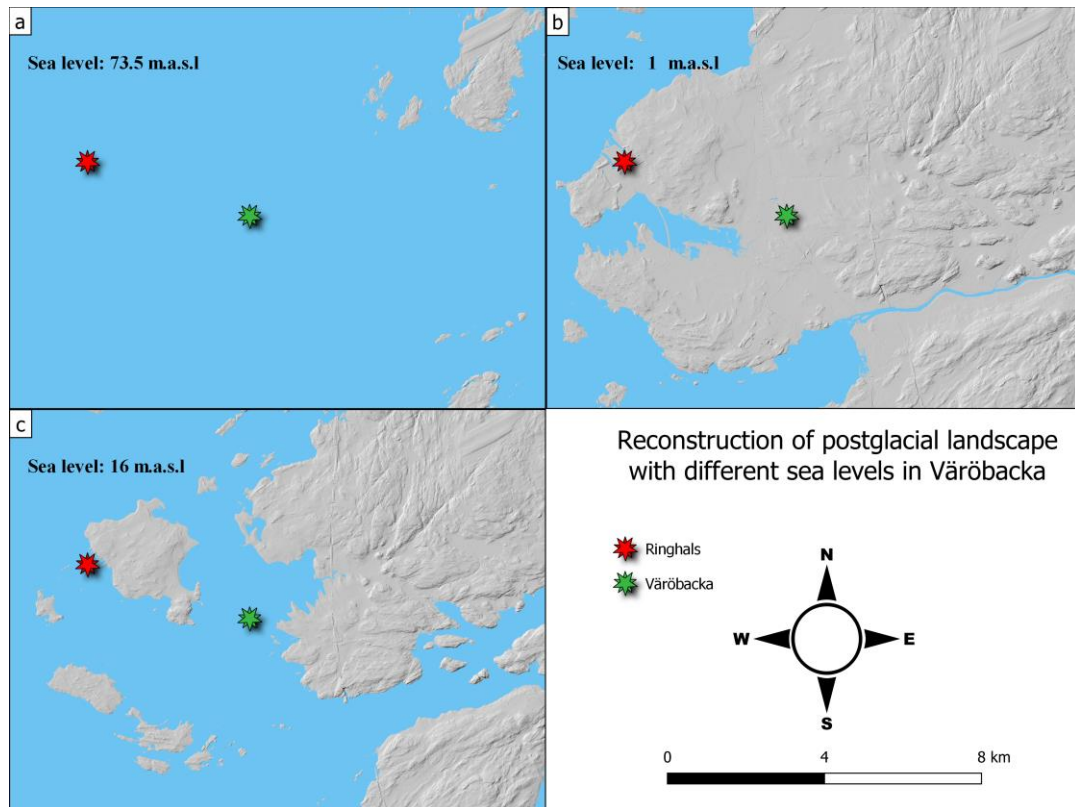


Figure 12. Reconstruction of postglacial landscapes in Väröbacka where a) represents the highest coastline b) represents the lowest regression sea level c) the sea level during the maximum Tapes Transgression. Red dot represents the nuclear power station Ringhals and the green dot represents the center of Väröbacka, both the dots function as references points.

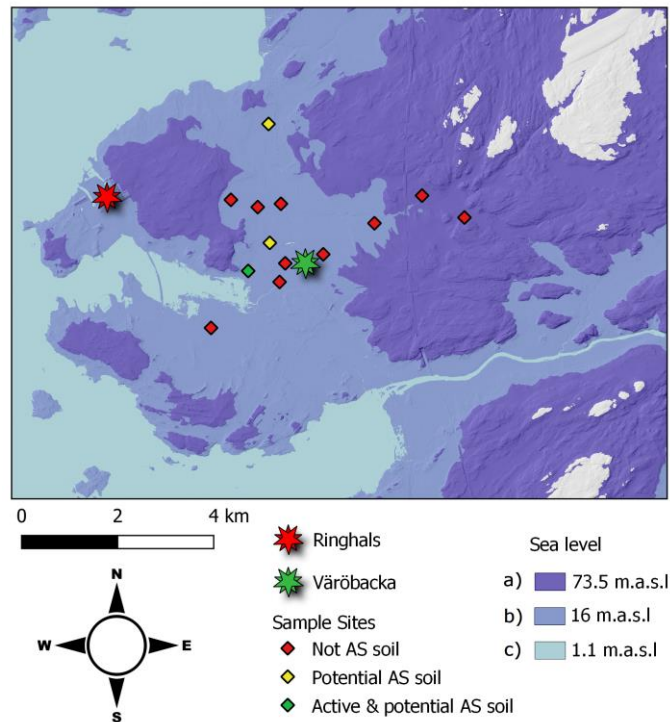


Figure 13. Sample sites relative to the merged sea levels from reconstructed postglacial landscapes. Red dot represents the nuclear power station Ringhals and the green dot represents the center of Väröbacka, both the dots function as references points.

5 Discussion

This thesis confirms that both active and potential AS soils do exist in Väröbacka in the county Halland. The sample sites where AS soils exist were mapped as fine-grained sediments such as postglacial clay and clay gyttja. They were found in cultivated fields, which is a cause for a lowering of the groundwater level and could also be the cause for presence of active AS soil, which was the case for sample site H22007. If further lowering of the groundwater level will occur at sample sites H22004 and H22009, where potential AS soils occur, the risk of them becoming active will increase as well. Additionally, sites H22001 and H22006, which are pseudo AS soils, are also vulnerable to acidification. This could lead to additional leaching of toxic metals (Sohlenius et al., 2004).

The sample sites that indicate presence of AS soils showed both similarities and differences. They were all located on low elevations, where sample H22009 were on a slightly higher elevation compared to the sample sites H22004 and H22007. They were all located in cultivated fields but with different mapped soils. Clay gyttja and postglacial clay are sediments deposited in the ocean during a warmer period in Holocene and are found on levels lower than 15 m.a.s.l. (Påsse, 1990). This is consistent with sample sites H22004 and H22009 which were mapped as these soils and found on elevations of 2.5 m.a.s.l. and 6.1 m.a.s.l. This is also coherent with the fact that ferrous sulfides are found in postglacial sediments (SGU, 2020). Sample site H22007 were located on soil mapped as fluvial sediment (SGU, Jordarter 1:25000-1:1000000) and thus have been flooded by water after the sea level was lowered and streams were flooded by high tides (SGU, 2020). According to Becher (2019), there are many sites where AS soils can be covered by younger non-AS soils such as fluvial sediment. Although, at this site, no obvious fluvial sediment was observed in the field. The soil samples H22007:1 and H22007:2 consisted of mostly clay and did not contained any seashells or organic material.

The sample sites H22001 and H22006 that were classified as pseudo AS soils and are capable for moderate acidification and can have an increased risk for negative effects on the environment (Boman et al. 2018). These sample sites should therefore be kept in mind if lowering of the groundwater level is necessary in these areas. According to the ICP-SFMS result, sample site H22001 contained a high amount of S and a low calculated Fe/S ratio, which both indicates a high acidic effect (Pousette, 2010). Even so, the H₂O₂-oxidation did not give the result for this sample to be a potential AS soil. This could for example be due to buffering

of small seashells or adding too much deionized water to the test tube during H₂O₂-oxidation. Both of these could have increased the pH of the sample. In conclusion, sample site H22001 could maybe be defined as a potential AS soil after all. The sediments at sample sites H22003, H22005, H22012 and H22013 were mapped as glacial clay and did not present any presence of AS soils. This could have been known in advance since the occurrence of AS soils is presumed to be found in postglacial sediments and not glacial sediments (SGU, 2020).

In earlier studies, peat has been found below clay gyttja in samples that presented presence of AS soils. This led to the conclusion that a terrestrial event had occurred and were followed by a transgression (Lindgren et al. 2022). This conclusion is also shown by Kling (2020) where peat was found in soil samples from Falkenberg and supports the fact that the sediments were made from transgression sequences that at some point had been disrupted by a regression. This was then followed by an additional transgression, which covered the peat with postglacial clay gyttja. Similar type of regression and transgression sequences can be seen in the area of Väröbacka as well, although peat was not found in the retrieved samples. When observing the postglacial landscapes in Väröbacka, it confirms that all sample sites are located below the highest coastline and above the lowest regression sea level (Figure 13). This means that each of the sites with AS soils was exposed for several hundred years during the pre-Tapes transgression, which may have allowed organic material to accumulate. However, the 2-m sample holes dug may have been too shallow to have encountered any pre-Tapes organic material. The majority of the sample sites, including all of the confirmed AS soils, are below the sea level of the maximum of Tapes transgression. This result is consistent with the sample sites described in Falkenberg, also located on the west coast (Kling, 2020). The confirmed sample sites with AS soils in this thesis have been flooded by water when the highest coastline was reached and then drained during to lowest regression. After that, they have been flooded once again by the Tapes transgression (Figure 12).

Since clay gyttja is assumed to be associated with AS soils in southern Sweden (Sohlenius et al., 2004) it became a preference when selecting sample sites for this thesis. Clay gyttja is described to be deposited in shallow basins and found on levels lower than 15 m.a.s.l (Påsse, 1990). The sites where active and potential AS soils were found are in such places where the sea could have been calm due to the surrounding land above sea level. This could contribute with evidence that AS soils could have been developed during the Tapes Transgression, which is coherent with the findings of AS soils in Falkenberg (Kling, 2020).

Of all the metals measured in the soil samples sent to ALS laboratory for ICP-SFMS analyses, only S and Fe were found and described to be indicating acidification of the soils. The lower concentrations of Cd, Mn and Sr in the different samples at different depths, could indicate a leaching in the oxidized layer. Further discussion is found in Nevo (2022). A comparison with “*Naturvårdsverket – Riktvärden för förorenad mark*” is also suggested to be used for further investigation of leaching of toxic metals from the AS soils in Väröbacka.

5.1 Limitations

The measuring of pH-values was done by hand, both in the field and in the lab. This could cause man-made errors when interpreting the values from the measurements. Also, it should be considered that seashells can buffer the soil and cause a higher pH-value than what the soil actually have (Pousette, 2010). Another error effecting the true pH-value could be adding too much of the deionized water to the sample which in turn could cause a higher pH-value. These limitations could result in fewer samples indicating presence of potential AS soils. For the reconstruction of the postglacial landscape, an elevation was roughly followed and could be more accurate with further observations and precision. More sample sites would have contributed with more data and thus could have provided more evidence for the presence and formation of AS soils in southwest Sweden.

6 Conclusion

Both active and potential AS soils exist in Väröbacka in the county of Halland. The verified samples can have an acidic effect in the soil if exposed to oxygen. If this occurs, it can result in leaching of toxic metals. The AS soils in Väröbacka have, by observing the reconstructions of the postglacial landscapes, gone through several events of transgressions and regressions. They were all above lowest regression, and below Tapes transgression and highest coastline. This indicates that they have been flooded by water, then drained and then flooded again. Further investigation is required to study if any possible pattern exist, as well as to conclude further presence, distribution, and formation of AS soils in southwest Sweden.

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Appendix 1

Table 2. Table presenting results of depth, pH in field, elevation (m.a.s.l) H₂O₂-oxidation, and soil type (SGU, Jordarter 1:25000-1:1000000) from all 23 soil samples retrieved from field work. ICP-SFMS results for Fe and S in [mg/kg TS] and Fe/S of 9 samples. Table by Nevo (2022).

Sample	Depth [m]	pH in field	pH H ₂ O ₂	a.m.s.l	Soil type from SGU	Fe		S		AS Soil
						[mg/kg TS]	[mg/kg TS]	[mg/kg TS]	[mg/kg TS]	
H22001:1	1.5	7.5	3.3	13	Clay gyttja	34800	12800	2.72		
H22002:1	2	6.7	6.8	2.7	Postglacial fineclay					
H22002:2	0.5	7.5	5.4	2.7						
H22003:1	1.6	7.3	6.7	3.6	Clay gyttja					
H22004:1	1.4	6	1.5	2.6	Clay gyttja	33800	13400	2.52	Potential	
H22004:2	1.1	6	3.0	2.6		39200	1540	25.45	Potential	
H22004:3	0.4	6.8	4.2	2.6						
H22005:1	1.5	7.4	6.5	8.7	Glacial Clay					
H22005:2	0.8	7.1	8.3	8.7						
H22006:1	1.2	5.0	3.1	2.3	Postglacial fineclay					
H22006:2	0.8	6.2	3.3	2.3						
H22006:3	0.4	6.0	3.8	2.3						
H22007:1	0.7	4.3	2.0	1.9	Fluvial siltyclay	38400	2450	15.67	Active	
H22007:2	1.7	6.6	1.4	1.9		31400	17000	1.85	Active	
H22008:1	0.4	6.6	4.8	2	Fluvial siltyclay					
H22008:2	1	7.1	6.3	2						
H22009:1	1.4	7.5	2.9	6.4	Postglacial fineclay	32200	17300	1.86	Potential	
H22009:2	0.7	6.4	3.4	6.4		28100	1670	16.83	Potential	
H22010:1	0.5	6.6	5.2	11.5	Postglacial fineclay	48700	442	110.18		
H22010:2	2	7.3	7.2	11.5		35500	358	99.16		
H22011:1	1	7.0	4.9	5.1	Postglacial fineclay					
H22012:1	0.9	6.2	4.8	19.3	Glacial Clay					
H22013:1	0.9	6.6	5.2	21.3	Glacial Clay					