

THE FIRST ACTIVE ACID SULFATE SOIL FOUND OUTSIDE THE BALTIC BASIN, IN VISKA VALLEY WEST COAST OF SWEDEN

Johanna Bergström

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**Department of Earth Sciences
University of Gothenburg
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Faculty of Science



UNIVERSITY OF GOTHENBURG

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Mailing address
Geovetarcentrum
S 405 30 Göteborg

Address
Geovetarcentrum
Guldhedsgatan 5A

Telephone
031-786 19 56

Geovetarcentrum
Göteborg University
S-405 30 Göteborg
SWEDEN

Abstract

Acid sulfate (AS) soils are naturally formed but are responsible for environmental problem due to its low pH. Drainage of active AS soils can lead to mobilization of harmful metals and a severe pH drop in nearby aquatic environments, which in turn may harm the ecological conditions. Most AS soil in Sweden has been found mainly along the northeast coast, and this area has received much research attention. A few discoveries have also been made in Mälardalen and Skåne. Recently, during a geological survey by the Geological Survey of Sweden (SGU) in the Viska Valley in Halland, old drilling profiles were found that showed sulfide-rich layers that hinted about the possible existence of AS soil. Focusing on the Viska Valley, this project aims to investigate the existence of AS soil in southwestern Sweden and find clues about its formational environment. Electrical Resistivity Tomography's (ERT) suitability was evaluated as a method for locating AS soil on the west coast, and the ERT data was compared to the old drilling profiles. This study together with another master thesis study in Falkenberg was carried out during September 2019 to June 2020 in collaboration with SGU. Sampling sites were determined based on the old drilling data and SGU's soil map. Samples were collected by using an Edelmann drill and brought to the laboratory for oxidation and further analyses, including grain-size distribution, metal-, sulfur- and organic content. Two ERT-measurements were made along one of the drilling profiles. This study is the first that proves the existence of AS soil outside the Baltic basin. In two areas of the valley, AS soil was found, one which was active and one potential, both in post-glacial gyttja clay covered by floodplain sediments. The gyttja clay is believed to have formed during the Tapes transgression when the valley consisted of a fjord-like bay, protected from wind and currents with saltwater input from Kattegat. The data from the ERT measurements displayed anomalies where the AS soil was found, but the information is not sufficient to determine with certainty whether the layer of AS soil is present. However, the study made simultaneously in Falkenberg showed more optimistic results with the ERT, which suggests that it may be an appropriate method with different electrode spacing and a larger number of measurements. This study only covers a small area of the Viska Valley, and most likely it is possible to find more AS-soil in the area as well on the entire west coast in areas that were below the highest coastline.

Keywords: Acid sulfate soil, AS soil, ERT measurements, resistivity, Baltic basin, Swedish west coast, acidification, Tapes transgression

Sammanfattning

Sur sulfatjord (SSJ) bildas genom en naturlig process och är ett globalt miljöproblem främst på grund av dess försurande egenskaper. Dränering av aktiv SSJ kan leda till mobilisering av skadliga metaller och ge en kraftig pH-sänkning i närliggande vattenmiljöer, vilket i sin tur kan påverka de ekologiska förhållandena negativt. I Sverige har SSJ huvudsakligen hittats längs kusten i nordost där mesta av forskningen gjorts, men upptäckter har också gjorts i Mälardalen och Skåne. Under en geologisk undersökning av SGU i Viskadalen i Halland, hittades gamla borrhöjningar som visade sulfidrika lager som skvallrade om en eventuell existens av SSJ. Med fokus på Viskadalen syftade det här projektet till att undersöka förekomsten av SSJ i västra Sverige och samtidigt få en bild av bildningsmiljön. ERT mätningar gjordes även och utvärderades som metod för att identifiera SSJ på västkusten. Mätningarna jämfördes sedan med de gamla borrhöjningarna. Denna studie genomfördes under september 2019 till juni 2020 i samarbete med SGU. Provtagningsplatser bestämdes baserat på den gamla borrhöjningen samt SGU:s jordkarta. Prover samlades in med en Edelmann-borr för oxidation i laboratoriet och ytterligare analyser som inkluderar kornstorleksfördelning, metall-, svavel- och organiskt innehåll. Två ERT-mätningar gjordes längs en av borrhöjningarna. Denna studie är den första som bevisar förekomsten av SSJ utanför Östersjöbassängen. I två områden i dalen hittades SSJ. En aktiv och en potentiell, båda postglaciala gyttjeleror täckta av svämsediment. Bildningen av SSJ i området har mest troligt inträffat under Tapestransgressionen när dalen bestod av en fjordliknande vik, skyddad från vind och strömmar med saltvattentillförsel från Kattegatt. ERT-mätningarna visade anomalier där SSJ finns, men informationen är inte tillräcklig för att med säkerhet bestämma om lagret av SSJ kan urskiljas eller om det är något annat. En masterstudie som gjordes simultant i Falkenberg visade dock mer optimistiska resultat, vilket tyder på att det kan vara en lämplig metod med annat elektroavstånd och fler mätningar. Denna studie täcker endast en liten del av Viskadalen och troligtvis finns större areor av SSJ i dalen men också längs hela västkusten i områden som ligger under högsta kustlinjen.

Nyckelord: Sur sulfatjord, SSJ, resistivitet, svenska västkusten, högsta kustlinjen, Tapestransgressionen

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Abbreviation used for soil descriptions

sa – sand

cl – clay

si – silt

ts – top soil

gr – gravel

gy - gyttja

The last soil abbreviation and with a capital letter in a description always stands for the dominating soil type. For example, *sasiCl* stands for a clay with some accessory sand and silt in it.

1. Introduction

Acid sulfate soil (AS soil) is a term describing a soil rich in iron sulfides, which is acidic or has the potential to become acidic due to sulfide oxidation.

These sulfide-rich soils start as organic-rich sediment deposited on the sea floor where aerobic bacteria consume the organic material creating anoxic conditions and eventually the formation of sulfide minerals. In the Baltic Basin, the soils are mainly found in areas that have been below the Littorina Sea (7000-4000 BP), which is the brackish-water stage of the Baltic sea after the latest deglaciation (Björck, 1995). It is this area that has received much research attention. (Fig. 1). In Sweden and Finland, the areas with AS soil are located along the coast, and isostatic uplift has brought many of them above present sea level. In waterlogged and reduced conditions, these soils are commonly named *potential* acid sulfate soils or hereafter: *potential AS soil*, as they possess a potential to become acidic if they are exposed to oxygen. When the water table is lowered and the reduced conditions ceases, the sulfides in the soils oxidize. This can lead to a severe drop in pH and, if the oxidation exceeds the buffering capacity of the soil, the formation of very acidic soil horizons (Becher, Sohlenius, & Öhrling, 2019; Boman, 2008; Sohlenius & Öborn, 2004). Oxidized AS soil is referred to as *active AS soil* and was referred to by Dent and Pons (1995) as “the nastiest soil in the world”. The sulfuric acid that is formed will lower the pH (<4.0) and mobilize metals that can later leach out, causing severe damage when leaked into drainage-ways, streams, and floodwaters (Dent & Pons, 1995).

AS soil is brought up to the oxidation zone either by natural processes (i.e. uplift in glaciated regions) or artificially (e.g. drained for agricultural purposes) where the latter is the most common cause (Boman, 2008). That AS soil can have a considerable negative effect on the environment has been seen in Finland where many streams with low pH and high concentrations of metals cause fish death and deterioration of fish spawning grounds (Åström & Björklund, 1995). It has also been shown that certain metals released from active AS soil exceed the emissions from all Finland’s industries together (Sundström, Åström, & Österholm, 2002). In Sweden, AS soil also contribute to deteriorating ecological conditions in a number of aquatic environments in the coastal areas of Norrbotten and Västerbotten (Becher et al., 2018).

Besides the environmental hazards, potential AS soil possesses weak ground stability. The sulfide soil generally has a low shear strength and high compressibility, which gives rise to geotechnical problems in both stability and settlements when building on this soil. (Andersson, 2012; Larsson, Westerberg, Albing, Knutsson, & Carlsson, 2007; Pousette, 2007).

AS soil is not only found in Scandinavia but also in several other places in the world. It is most common on coastal plains in tropical and subtropical areas, for example, in Australia and Southeast Asia, West Africa and South America (Pousette, 2010). In these areas the AS soil is normally found in mangrove swamps or in marshlands (Beek et al., 1980). The global extent of AS soil has been estimated as high as 240 000 km² (Andriessse & Van Mensvoort, 2006). However, areal estimations over time have increased, which is a strong indicator that the total area of AS soil is still underestimated due to the fact that the mapping of AS soil is still an ongoing process.

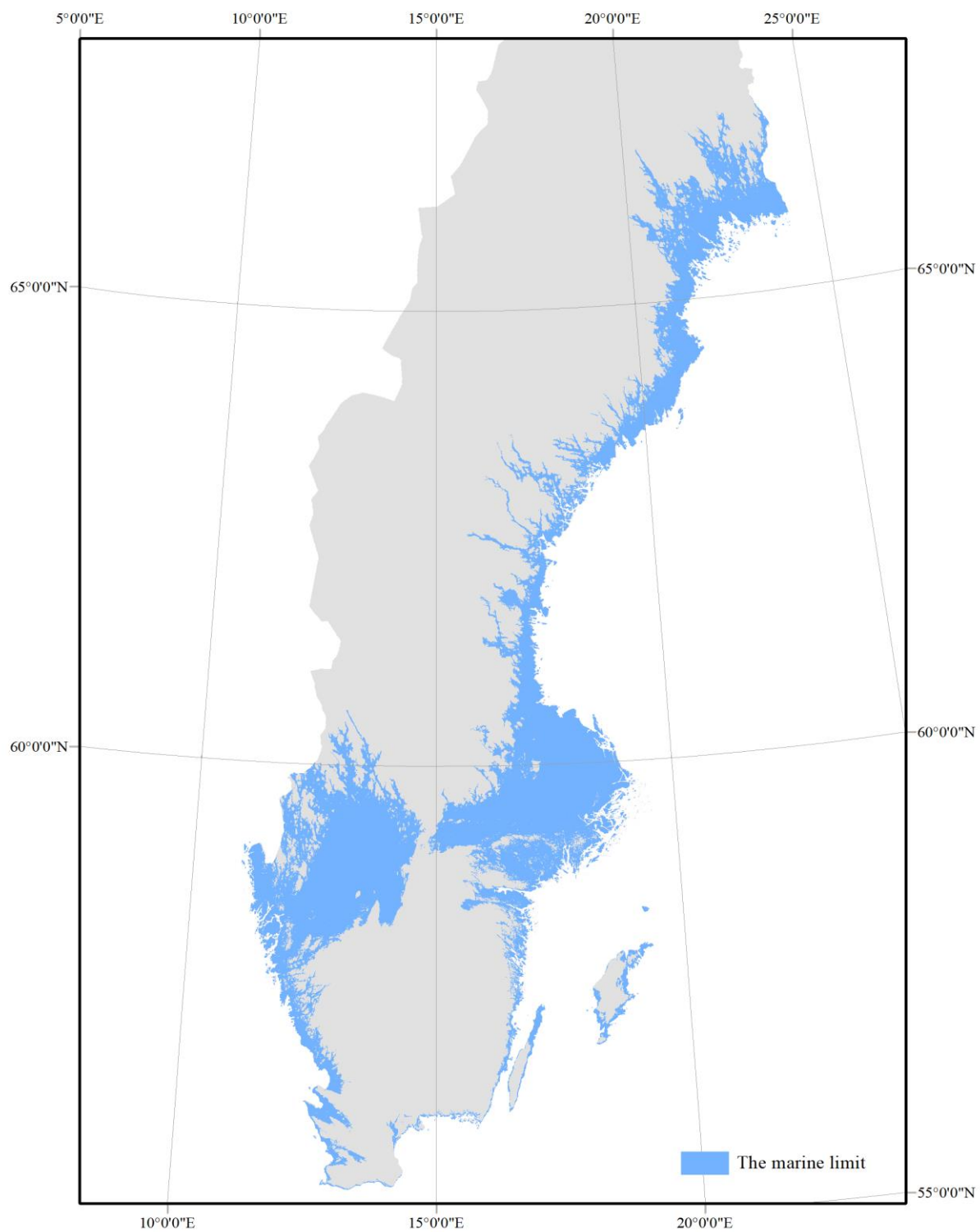


Figure 1. Map over the marine limit (area covered with marine water). On the east coast this boundary is the extent of the Littorina Sea. GSD-Sverigekartor © Lantmäteriet, The marine limit © Sveriges geologiska undersökning.

The AS soil in Scandinavia is mainly found in areas along the coasts of Bothnian bay and Bothnian Sea since this is where the uplift has been greatest. However, there are a few studies that show that AS soil also occurs in the more southern parts of Sweden as well (Becher et al., 2019). In the region around Mälaren, there are several known areas with AS soil (Bayard & Karlsson Mood, 2014; Sohlenius, Persson, Lax, Andersson, & Daniels, 2004), and a more recent discovery of AS soil was made in an area with lake sediments in Skåne near Kristianstad (Åbjörnsson, Stenberg, & Sohlenius, 2018). An area that has been unexplored in terms of AS soil, is western Sweden. So far, the western part of Sweden has not been investigated at all, but it is likely that AS soil is more or less common along all coasts, since the entire Swedish coast is affected by the uplift of marine sediments (Becher et al., 2019). Recently, a survey was carried out in Viska valley with the purpose to describe the geological conditions. The survey was carried out by the Geological Survey of Sweden (SGU) at the request of the Swedish Geotechnical Institute (SGI). During this survey SGU, found old drilling profiles made by Von Post (1956) where several sections displayed sulfide-rich layers, which could indicate AS soil material (Fig. 2).

Maps of the marine limit are often used to localize potential areas with AS soil. It has also been shown in several studies that it is possible to identify the soils in the field since AS soil have many characteristic features. Along the northern coast of Sweden, iron monosulfide (FeS) is the dominating sulfide mineral in AS soil and gives the soils a characteristic black colour, which makes them easy to recognize. In the more southern parts of Sweden, pyrite (FeS₂) is the most common mineral and does not affect the color of the soil. However, these soils often contain more gyttja (sedimented, fine organic material) which gives it a greenish-grey colour (Becher et al., 2019; Sohlenius et al., 2004). Other field characteristic features in AS soil are vertical fracture systems with deep purple-red coloured coating caused by the oxidized iron sulphides (Sohlenius et al., 2004).

It is well known that active AS soil can mobilize metals. It has been shown that some metals like Ni and Co can accumulate in high concentrations in stream plants that grows in areas with active AS soil, which is why biochemical maps can be another useful tool to identify potential locations (Sohlenius et al., 2004). Another method to localize AS soil is airborne geophysical measurements. The data from the measurements can give a quick overview where to possibly find AS soil (Sohlenius et al., 2004; Suppala, Lintinen, & Vanhala, 2005) because sulfide-rich sediments have a very low resistivity/high electric conductivity (100–500 mS/m²–10Ωm) in comparison with the surrounding fine-grained sediments (Suppala et al., 2005). However, one shortcoming with these maps is that they only give an overview of the area and should be combined with ground measurements as well (Puranen et al., 1999). Additionally, other properties that affect resistivity, including porosity, is grain size, water content, salinity of the water and clay minerals (Sohlenius, Persson, & Bastani, 2007). For example, Puranen et al. (1999) showed that soluble chlorides in sulfide bearing sediments were an important component causing high electronic conductivity. What is known so far is that the resistivity of the sulfide-rich sediments seems to differ between northern and southern Sweden. Sohlenius et al. (2007) show that the sediments along the northern coast have a higher resistivity than the corresponding sediments

in the Mälaren Valley in the southern part of Sweden. However, quick clay also has a lower resistivity than normal clay, and it is common on the Swedish west coast (Dahlin, Löfroth, Schälin, & Suer, 2013). To distinguish quick clay from AS soil might therefore be a challenge. What is important to point out is that resistivity measurements can only localize soils rich in sulfides, which means, it is not possible to identify active AS soil (since the sulfides have been oxidized) but only potential AS soil with this method.

1.1. Objectives and scope

To maintain a healthy natural environment, the Swedish parliament has established 16 national environmental goals, and these form the basis for the Halland County Administrative Board's work on AS soil. The board's work strives for sustainable social development that includes both social and economic as well as ecological aspects. Some of the national goals have been specified with reference to environmental quality standards following EU-directives. For water, this means that ecological and chemical status should not be worsened, and the status in poor quality waters should be increased. Today, AS soil is a risk factor for both chemical status in surface waters and ground water due to its acidification capacity and metal leaching, this contributes to difficulties in achieving 8 of the 16 environmental goals (Åberg, 2017).

Due to the environmental risk AS soil poses and the importance to achieve the Swedish environmental goals, the interest of investigating these types of soils more thoroughly has increased. There is a knowledge gap regarding the AS soil extent and distribution in western Sweden, which is why it is of importance to start mapping this area as well.

This report is one of two made in collaboration with SGU with the purpose to increase the knowledge of the extent and distribution of AS soil in Halland County. This report focuses in the area of the Viska valley (Fig. 2) and the other in the area of Falkenberg performed by (Kling Jonasson, 2020). Data collected for both sites was collected simultaneously. The reason why the Viska valley is of particular interest is the drilling data from Von Post (1956)'s work, where he made an extensive exploration of the Viska valley when investigating the sea levels of the ancient lake Veselången, including 118 levelled profiles. Many of the profiles contain sulfide-rich layers that can be possible AS soil. Additionally, no geophysical measurements with the purpose of finding AS soil have ever been carried out in western Sweden. Since the soil types differ from the soils in the north and the other parts in Sweden, the resistivity might also be different. Thus, the intention was to investigate if it was possible to use ERT (resistivity i.e. Electrical Resistivity Tomography) in western Sweden as well as a method to localize the extent of an area with AS soil. The ERT data from the Viska valley is interpreted together with the data from Kling Jonasson (2020) in Falkenberg.

The aims of this study therefore are: (1) to investigate if there is any potential or active AS soil located on the west coast of Sweden and specifically in the Viska valley; (2) to determine in what environment they were formed; (3) to use geophysical measurements (resistivity) to see if it can be used as a method in western Sweden to identify the extent of a known AS soil layer; and finally (4) to interpret how well the geophysical data correspond to the drilling data made by Von Post (1968).

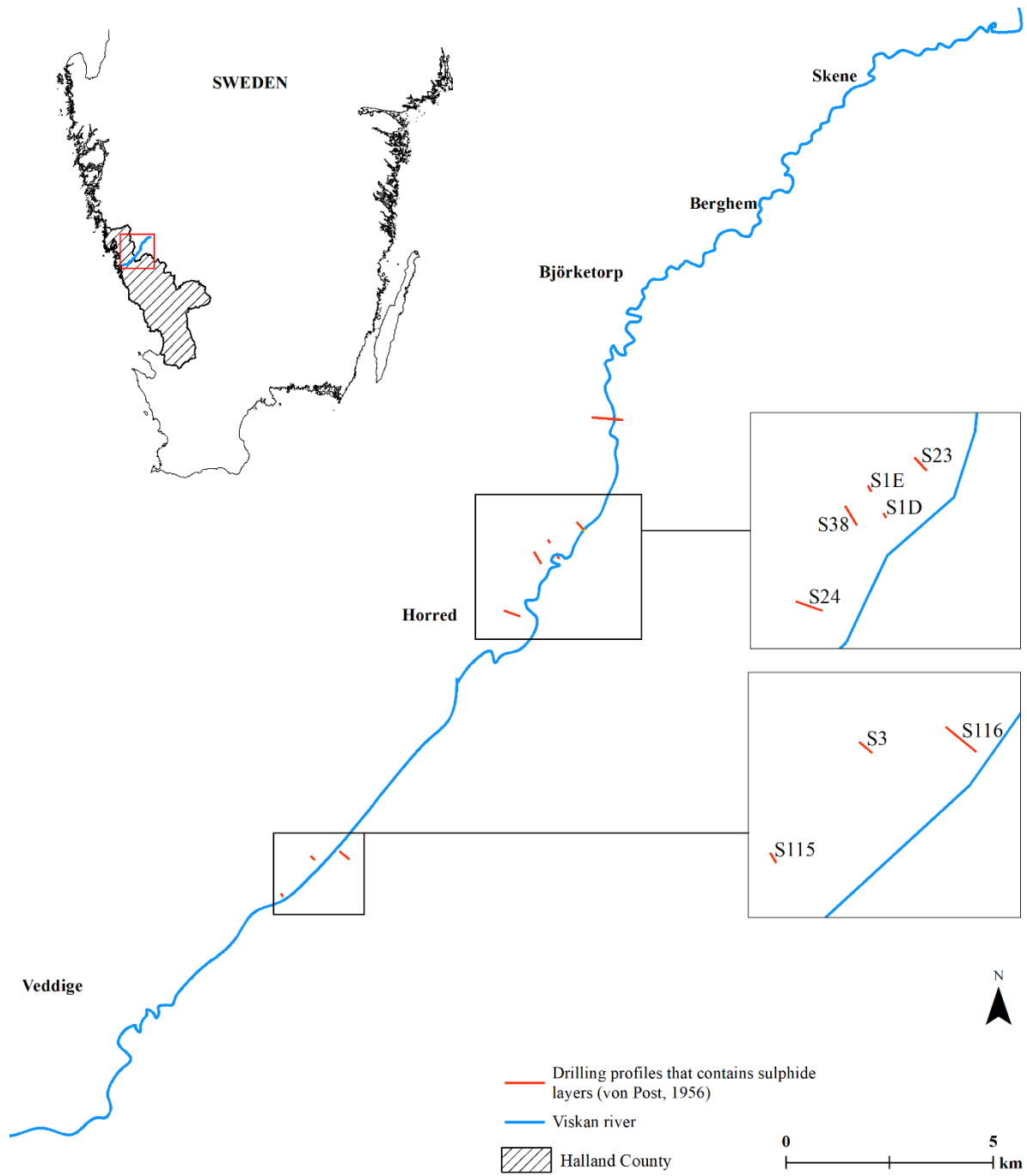


Figure 2. Study area. Overview of the Viska valley. The red lines are showing the drilling profiles by von Post (1956). The profiles are of interest since many of them contains sulfide rich layers. The drilling profiles can be seen in appendix 3. GSD-Sverigekartor/Ortnamn 2018 © Lantmäteriet. Drilling profiles by von Post (1968) digitalized by Elin Norström, SGU.

2. Acid sulfate soil

AS soils are developed from natural predominantly fine-grained sediments that contain iron sulfides (Becher et al., 2019). The properties of sulfide sediments can vary widely depending on parent material and depositional environment, but in order to call it sulfide sediment it needs to contain a minimum concentration of 0.01% sulfur in sulfide form (dry weight). High sulfur content is an indicator of how high of an acidification potential the soil has, which is highly relevant when investigating AS soil (Boman et al., 2018).

The general definition of an AS soil is a soil that contains enough sulfide materials to make the pH drop below 4 as a result of oxidation and additional formation of sulfuric acid (Boman et al., 2018). In this report the term 'sulfide sediments' will be used when talking about parent material for possible AS soil.

2.1. Formation

2.1.1. Sulfide sediment

Sulfides in sediment accumulate in waterlogged sediments where there is a high accumulation of organic matter, minimal water mixing and no oxygen input (Dent, 1986). When bacteria are decomposing the organic matter, they primarily consume oxygen, however, when the oxygen is running out, the bacteria will start to reduce sulfate (SO_4^{2-}) to sulfide ions (S^{2-}) and trivalent iron (Fe^{3+}) to bivalent iron (Fe^{2+}) instead (Becher et al., 2019) (eq.1). The two ions will react with each other and form metastable iron monosulfides (FeS) (Berner, 1970). Under certain conditions (i.e. the availability of sulfur) some of the FeS will be sequestered as pyrite (FeS_2), but it can take a very long time (Berner, 1970, 1984).



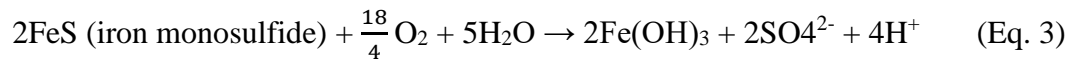
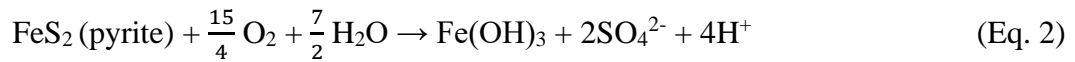
Normally, sulfide-forming conditions can occur in places on the open ocean floor, but they also exist in anoxic wetlands and in marine bays (Pousette, 2010). It has been suggested that sulfide soils were formed only in saline or brackish water (Dent, 1986). But, sulfide minerals can also form in lake sediments, which is why AS soil may exist anywhere where ancient lakes occurred and not only where the sea has been (Becher et al., 2019; Åbjörnsson et al., 2018). Even though the sulfide-rich soils we find today mainly were formed during and after the latest deglaciation, the sulfide-forming process is ongoing in the present, wherever the conditions are favourable (Pousette, 2010).

2.1.2. Potential and active AS soils

If the sulfide sediments contain enough sulfide, the soil will become acidic when oxidized as a result of drainage and sulfide oxidation, this is called an active AS soil. Under waterlogged conditions, sulfides are in a reduced environment and no oxidation occurs. In waterlogged and reduced conditions, these soils are called potential AS soils, as they possess a potential to

become acidic if exposed to oxygen. Oxidation of sulfides occurs with both chemical oxidation as well as biological microbial catalysis and is a complex process (Pousette, 2010).

The two most common AS soil sulfide minerals in Sweden are pyrite and iron monosulfides, and the oxidation reactions can be summarized as (Pousette, 2010):



There are several possible intermediate reactions that can occur before the ultimate formation of sulfuric acid. Initially Fe^{3+} will be reduced to Fe^{2+} , the soluble Fe^{2+} can further be oxidized to Fe^{3+} . These reactions depend on the environmental conditions such as temperature, pH, grain-size distribution, Fe^{3+} , oxygen and the presence of bacteria (Ward, 2004). The majority of the Fe^{3+} will crystallize as the oxihydroxide goethite as a coating in fractures, mottles, and nodules within the soil. Some of the Fe^{2+} can be transported to drainage waters where it precipitates under more oxidizing conditions, this leads to increased formation of acid and the pH in the stream will drop.

Under neutral pH the chemical oxidation of pyrite is slow. But if the pH drops to <4.0 it is possible for Fe^{3+} to remain in free form, and iron-oxidizing bacteria can accelerate the oxidation without the presence of oxygen. This reaction will lead to formation of a considerable amount of acid. The reaction will go on as long as there is available Fe^{3+} (Pousette, 2010).

The chemical oxidation process of iron monosulfides differs from pyrite since it can be rapid over a wide range of pH, and the iron monosulfides are considerably more reactive than pyrite. Under very acid conditions (pH 2-4), precipitation of the sulfate mineral Jarosite ($\text{KFe}^{3+}_3(\text{OH})_6(\text{SO}_4)_2$) may occur. It has a characteristic pale-yellow colour and can be found as coatings or pore fillings in the soil. Other intermediate products from the oxidation reaction of pyrite are iron monosulfides and elementary sulfur (S). However, the S amount is usually very small, since most of it has been oxidized to sulfate (Ward, 2004).

2.2. Fe/S ratio

Iron sulfides define the characteristics of sulfide sediments. The iron content normally varies between 2 and 5% dry matter and the S content between 0.1 and 2% dry matter.

The Fe/S ratio has been suggested as a parameter for classifying the soil acidification effect (Mácsik, 2000). In the report by Pousette (2010), the Fe/S ratio is one of the parameters for assessing acidification effects in a soil. The acidification effect of a soil is not unambiguously dependent on the Fe/S ratio, but it can be used to identify the extremes. The assessment is that with a low Fe/S ratio (≤ 3), the soil has very high acidification effect and with a high Fe/S (>60), the soil is not classified as a sulfide soil. (Pousette, 2007).

2.3. Field Characteristics of potential and active AS soil

It is possible to identify AS soil already in the field partly based on its location in the terrain and partly of the appearance of the soil. Based on earlier studies and their results, some field characteristics for sulfide-rich sediments and AS soil can be ascertained.

In Sweden AS soil is often found in places that are mapped as fine-grained sediments (clay-silt) on SGU's surficial-sediment maps. It is most common in the areas of low elevation, in the outermost part of the sea and lake bays or along the coast. AS soil often contains organic material and the term 'gyttja clay' is commonly used (Sohlenius et al., 2004). However, Mattbäck, Boman, and Österholm (2017) observed that AS soil can form in sandy soils and till as well. And in some cases, peat also has the ability to form AS soil after oxidation. But, when looking at the environmental problems associated with larger areas of active AS soil, it is the drained, clay and silty soils that are the primary soil type involved (Becher et al., 2019).

In Västerbotten and Norrbotten (Northern Sweden) the AS soil often forms in a soil type referred to as "svartmocka" which has a black colour and looks like black shoe polish. It is the sulfide mineral FeS that gives it its characteristic dark colour. When the soil gets oxidized the colour changes from black to grey in just a few hours. Svartmocka is most common in areas with post-glacial silt that contains around 1-2% organic material.

In the southern part of Sweden, the AS soil found is often formed in gyttja clay and contain more organic material than the AS soil in the north. These soils are located around lake Mälaren and other nearsea-level lakes around Mälardalen. These soils contain FeS₂ rather than FeS and do not possess the black colour as in the northern parts. Instead they often have a blue-grey or greenish colour (Sohlenius et al., 2004). FeS is more reactive than FeS₂ and it is easier for oxygen to penetrate silty soils; this is why the pH drop in northern Sweden often is more severe (Eriksson, Nilsson, & Simonsson, 2005).

Common for clay soils rich in organic material is when it dries the soil volume shrinks, this causes formation of vertical fracture systems in the upper soil layer, that often reaches down to the groundwater table. The fractures often revealing a purple-red coating caused by oxidized iron sulfides. Oxidation can also cause formation of the pale-yellow sulfate mineral jarosite that appears as mottles or coatings in the soil, usually in soil with pH<3. These are typical field characteristics features for active AS soil (Pousette, 2010).

2.4. Environmental and engineering problems related to AS soil

As mentioned, AS soil is a problematic soil in many aspects and can adversely affect the environment in many ways. The problems arise when the groundwater level is lowered, which often is a consequence of ditching agricultural land for cultivation purposes. In order to grow crops on sulfide soils, liming is often used to raise the pH in the soil down to the ploughing depths. Liming increases the oxidation processes that releases sulfate which accelerates the leaching of sulfur. Active AS soil can also form in the process of construction work; the sulfide-rich sediments get excavated and exposed for oxygen. In some places where excavation waste has been dumped, the consequent acidification has caused poor or no plant growth (Pousette, 2007). When sulfuric acid is formed, it will also accelerate chemical

weathering. The hydrogen ions are the reasons for metal leaching through ion exchange; 2H^+ can change place with Mg^{2+} and so on (Brandt & Gröndahl, 2000), and elevated concentrations of metals such as Al, Co, Cu, Ni, Mn and Zn have been registered in many studies (Roos & Åström, 2005; Åström & Spiro, 2000). Because nutrients like Mg and K are leached out and unwanted cations like H^+ , Fe and Al get enriched in the soil, active AS soils are often considered nutrient poor (Händel, 1995).

The low pH and leached metals can negatively affect many aquatic organisms. Trout and roach for example are very sensitive to acidic waters (Pousette, 2010), and there are cases in both Finland and Sweden where entire fish populations have been eliminated in the presence of active AS soil (Byrsten & Sandberg, 2005; Erixon, 2009).

AS soil not only affects living organisms but can restrain construction work as well. The low pH for example, can cause severe corrosion on concrete and steel constructions. Other problems are related to buoyancy. AS soil (or sulphide-rich sediments in general) are rich in organic material and clay which often means high water content. They are very sensitive to subsidence and have a poor shear strength ($\tau_{\text{fu}} = 5\text{-}20$ kPa) (Andersson, 2012). This means if the soil is to be subjected to stress (buildings for example) several actions such as soil reinforcement are often needed for the construction to work well. If the soil needs to be excavated and replaced by other soil, it must be handled appropriately so that it does not cause environmental problems as a result of acidification (Pousette, 2007).

3. The latest deglaciation

In Sweden, most of the surface sediments were formed during the Quaternary period, which began around 2,5 Ma and is still going on today. The latest ice age, the Weichselian glaciation (115,000 and 11,600 BP), has had the most influence on what soil types Sweden has today. In Scandinavia, the deglaciation of the Weichselian ice sheet started around 16-17 000 BP in the south and was more or less completed by 9,700 BP (Stroeve et al., 2016).

The archipelago landscape in the Viska area gradually transformed into a fjord as the melting proceeded. The speed of ice-margin retreat has been calculated to be approximately 100 m/year and Viska valley became ice free around 14,500 BP. The marine limit was reached just after the ice was melted away and varies between 65 m.a.s.l. in the south of the valley to 85 m.a.s.l. in the north (Fig. 3A). The period after the marine limit until 9200 BP was characterized by a relatively rapid land rise and shoreline regression. The area covered with water was similar to the conditions today, with a sea-level about 2 meters above today's sea level, measured at the mouth of the Viska valley (Fig. 3B). At around 10 000 BP, a new period with warmer climate was introduced, and land ice all around the globe started to melt more quickly. The melting ice caused a rising sea level, and a transgression was induced. The transgression proceeded throughout the entire warm period, with the west coast isostatic rebound still ongoing. The speed of the sea-level rise was likely fluctuating, which led to a shoreline that oscillated up and down over a period of time (Påsse, 1986). This event is called the post-glacial transgression (PG) and also known as the Tapes transgression on the west coast (Fig. 3C(M. Lindström, Lundqvist, & Lundqvist, 1991). In the Viska valley the post-glacial transgression maximum of 18.5 m.a.s.l. (at lake Veselången) was reached 7000 BP

(Påsse, 1986). This transgression allowed the Baltic Sea's to be connected to the sea through the Danish/German straits (Great Belt and Fehmarn Belt) and in Öresund, and marine water re-entered the Baltic Sea. The hydrographic conditions in the Baltic basin changed from freshwater environment to a brackish circulation system, called the Littorina Sea. The name originates from the findings of the gastropod *Littorina littorea*.(G. Lindström, 1886)

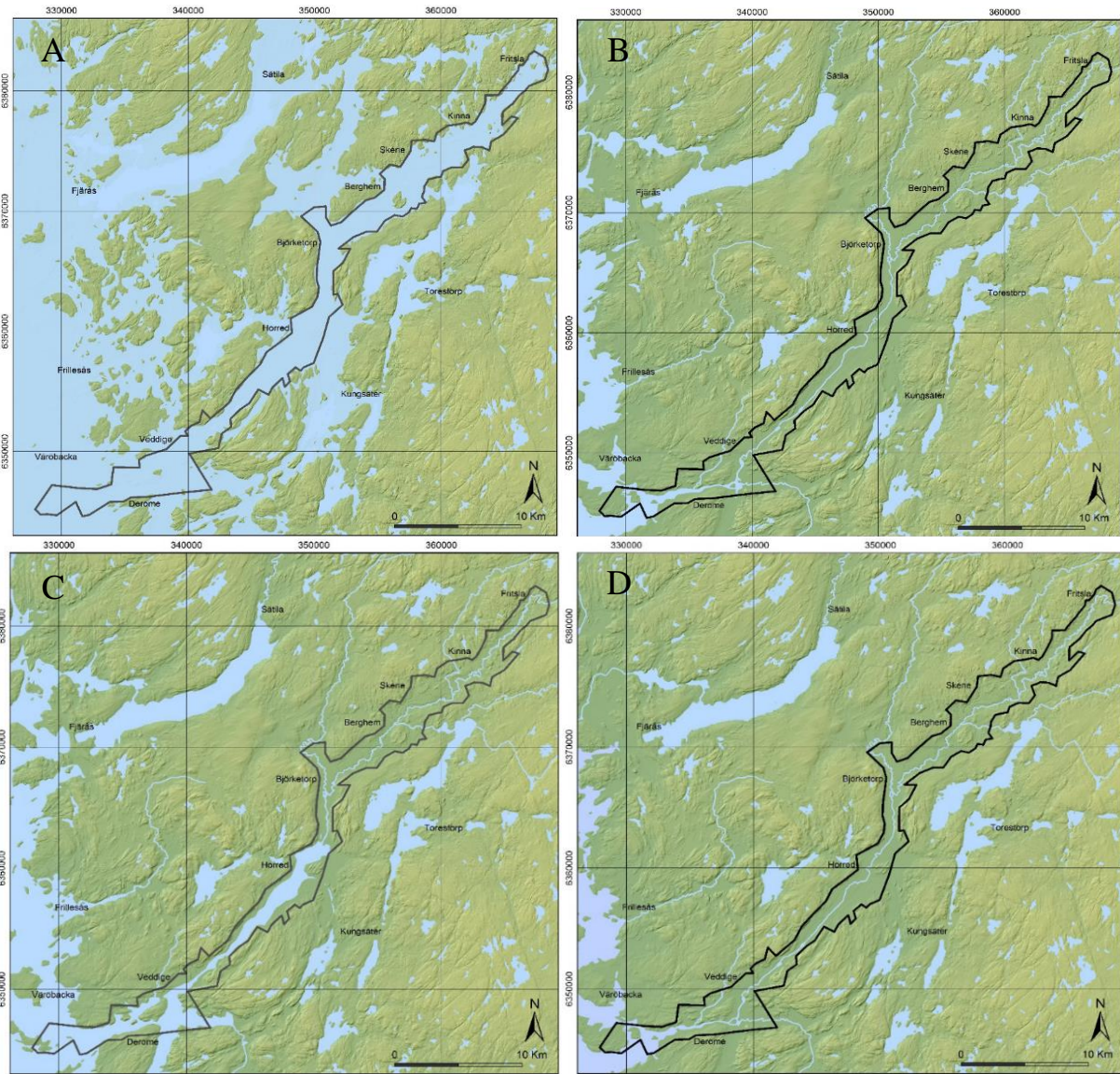


Figure 3. Maps over the Viska valley during the stages of the Weichselian deglaciation. A) 13 600 BP. Just after the deglaciation, the map is showing the marine limit ca. 80 m.a.s.l. The valley is covered by water. B) 10 000 BP. This period is characterized by a rapid land rise. Viska valley is now mostly covered by land. C) 7000 BP. The postglacial-transgressions maximum (17 m.a.s.l.). At this time the sea-level rise exceeded the land rise. D) 2 000 BP. The shoreline is back to 2 m.a.s.l. Figures retrieved from Engdahl & Pile (2019).

4. Material and methods

4.1. Study area

The study area is located on the west coast of Sweden in Halland county in the 142 km long valley where the northeast–southwest oriented Viska River flows. The bedrock topography is mainly determined by the weathering during the Mesozoic (245-65 Ma) and is characterized by a joint-aligned valley landscape. In the southwest-oriented valley there are joints oriented in a more north-south direction as well (Lidmar-Bergström, 1995).

Much of the early Quaternary geologic work done in the Viska Valley was made by von Post (1968) and Mörner (1969). Based on their work, the valley's stratigraphy is interpreted as a consequence of a series of lakes that existed during different periods of time. This interpretation is questioned though by Pässe (1983), who believes that the "lake model" should be updated, and that many layers represented as lake sediment should in fact be interpreted as floodplain sediment. Pässe (1983) is in general critical to von Post and Mörner's soil interpretations and has made his own suggestions, which will be used in this report together with SGU's soil map.

Fine-grained sediments are the most dominant soil type in the valley and consist mostly of glacial clay and post-glacial clay, sometimes overlain by coarser floodplain sediments. The thickness of the clay varies up to 70 m and generally decreases towards the edges of the valley. Due to the post-glacial transgression some of the areas with peatland or floodplain sediments are overlain by post-glacial clay. Post-glacial clay is found at ground level from the mouth of Viska River up to Veddige and around Veselången. Veselången is the name given to a former lake covering a large part of the area between Veddige and Horred. The lake is now drained since the middle of the 1800th century but the area still gets flooded during high tide in the valley. Between Horred and Björketorp, the post-glacial clay deposited in conjunction with the transgression also occurs under post-glacial sand at ground level 20–25 m.a.s.l. the thickness of the post-glacial clay is usually not thicker than 2 meters.

Glaciofluvial deposits can be found in three different areas (near Veddige, Berghem and Haby) in the form of end moraines, lateral terraces and deltas. (Pässe, 1986; von Post, 1968). Till can be found on the higher elevations and on the slopes of the valley. Larger accumulations of till can be seen at Horred, east of Björketorp and on both sides of the valley at Berghem.

The clay and silt found in the valley is deposited in three different depositional environments; proximal glaciomarine (glacial clay), distal glaciomarine (glacial clay) and shallow marine (mostly post-glacial clay). The glacial clay is predominantly in the valley and was formed during the deglaciation and afterwards in an arctic sea during a period of 4000 years. Proximal glaciomarine clay often contains layers of sand and silt in the profile's lower part with a lower shear strength. Distal glaciomarine and the younger shallow marine clay can also contain silt and sand, but the only method to distinguish the clays is to do analyses from fossils since different species prefer different environments, e.g. salinity and water depth (Stevens, 1990).

In many places, the clay is overlain by younger sediments, such as floodplain sediments (clay-sand) and wave-washed sediments, often sand with a thickness that varies between 1–5 meters. The silt and the fine-grained sand are deposited by currents in shallow sea coves.

Closest to the river, the composition of the floodplain sediments are finer with high organic content, further away from the river the floodplain sediments have a coarser composition. Gyttya clay and post-glacial clay can be found under the floodplain sediments (Påsse, 1986; von Post, 1968).

Most of the flat area in the valley is used for agriculture purposes, and almost all sites are located on croplands, the exceptions are; H19015 which is located in a deciduous forest, H19025 which is located on grassland inside an old trotting track and H19013 which is located on pasture for cows (Fig. 4 and 5). Much of the cropland closest to the Viska River gets flooded during rainy periods causing difficulties to access the area. All sampling sites in this study are situated below the marine limit.

4.2. GIS- Analysis

Selection of sites was largely done through map studies conducted in ArcGIS as well as on the basis of the location of von Post's profiles. The sections of interest chosen (von Post, 1968) were based on the depth of the sulfide layers that should not be deeper than 3 m since this is the maximum depth reachable with the Edelman drill. ©SGU's soil map was used to localize areas with fine grained sediments, and ©Lantmäteriets elevation map was used to find locations as flat as possible. Finally, the locations needed to be close to and easily accessible from the road.

4.3. Field work

4.3.1. Soil sampling and pH measurements

Soil sampling and pH measurements were collected and measured on 17 sites along the Viska valley during September to November 2019. An additional three samples were collected in the end of January 2020. All soil samples except from the three were collected with an Edelman drill (available in this study), extendable up to 3 meters. The other three samples were collected with a tracked drilling rig in conjunction with a road project Sweco is currently working on.

The drilling with the Edelman drill was made as deep as possible (maximum 3,10 m) or as long as soil material stayed on the drill up to the surface. Very wet soil was harder to get samples from, which is why the drilling depth varies among the sites. The soil cores were placed next to a folding rule and pH was measured for every 10 cm. Soil type was determined, and characteristics was noted (for example colour, smell, minerals, and iron precipitation). For further oxidation in the laboratory, 57 samples were collected, homogenized and placed in a chip tray. The samples were selected based on pH and characteristics; where the pH was the lowest and highest or/and where the soil displayed characteristics of particular interest (for example, signs of jarosite, iron precipitation and sulfide spots). Samples with low pH in field or after oxidation together with typical

characteristics like sulfide spots were collected and sent to an accredited laboratory for sulfur and metal analysis, in total 17 samples from 6 sites (Tab. 1). All the soil samples for laboratory were stored at +5°C prior to analysis.

Table 1. Method and analysis overview.

ID	Oxidation in laboratory	LOI	Sulfur and metal analysis	Grain-size analysis	Sampling method
H19005	x	-	-	-	Edelman drill
H19006	x	-	-	-	Edelman drill
H19007	x	-	-	-	Edelman drill
H19008	x	-	x	-	Edelman drill
H19009	x	-	-	-	Edelman drill
H19010	x	x	-	x	Edelman drill
H19011	x	-	-	-	Edelman drill
H19012	x	-	-	-	Edelman drill
H19013	x	x	-	x	Edelman drill
H19014	x	-	-	-	Edelman drill
H19015	x	x	-	x	Edelman drill
H19024	x	-	x	-	Edelman drill
H19025	x	-	-	-	Edelman drill
H19026	x	x	x	x	Edelman drill
H19027	x	x	-	x	Edelman drill
H19028	x	x	-	x	Edelman drill
H19029	x	x	x	x	Edelman drill
H19033	x	-	x	-	Tracked drilling rig
H19033B	x	-	-	-	Tracked drilling rig
H19034	x	-	x	-	Tracked drilling rig

4.3.2. Resistivity measurements

The location of the resistivity profile was determined after the oxidation process. The profile was placed where a proven ASS layer was found. On the 21st of November 2019, resistivity measurements were performed in the area close to Horred next to the sample sites H19029 and H19006. An 80-meter-long profile was placed in line with the most southern part of Von Posts profile *S23*. For these investigations an ABEM Terrameter LS was used according to CVES approach gradient measurement and roll-along layouts. Electrode spacing was chosen to 1.0 meters. A car battery was used as a power supply to the instrument.

To create a resistivity model the resistivity data was processed in the inversion software RES2DINV version 3.57. An elevation correction made from ©Lantmateriets DEM-raster was computed in ArcMap 10.6 and added to the DAT-file in the inversion software.

4.4. Lab work

4.4.1. Oxidation and pH

In order to classify the sediment samples as ASS, the pH is also measured in the lab after the sediment has had time to be oxidized. For the first 4 samples, pH measurements were made after 6 weeks with the same instrument and again after 9 weeks. The rest of the samples was measured after 9 weeks. If the samples did not fulfil the conditions to be classified as AS soil, new measurement was made again every week until the pH showed a value below 4 or was stabilized or had increased.

4.4.2. Loss on ignition (LOI)

Based on the field observations, LOI was made for sample sites that were classified as an active AS soil in field or showed interesting field characteristics. The analyses were done with a standard operating procedure. The air-dried samples were dried overnight in an oven at 100°C to remove all water and after placed in a furnace at 550°C for 4 hours to burn off the organic matter. The organic content was given by the weight difference before and after the burning with the equation:

$$\text{Loss on ignition} = \frac{\text{weightloss after } 550^{\circ}}{\text{weight after } 100^{\circ}} * 100$$

4.4.3. Grain-size analysis in SediGraph

The grain size distribution in the soil samples was determined by dry sieving and sedimentation analysis in a SediGraph. The grain size when sieving corresponds to the smallest free mesh width that the grain can pass through.

The SediGraph method is based on the assumption that the dispersed particles from a sample will settle according to Stoke's law (the diameter of a sphere with the same density as the grain and which falling at the same velocity as the grain). By monitoring at which rate the particles are settling and removed from the volume (this by measuring the gravity-induced settling of the different sized particles in a known liquid) it is possible to receive an accurate measure of the cumulative size distribution of the sediment in suspension.

Before the SediGraph analysis the samples dispersed in 0.05% So-Met solution.

4.5. AS soil classification system

Based on pH measured in the field and pH measured after oxidation in the laboratory the soil layers were classified according to the Swedish-Finnish classification-system as far as possible (Tab. 2) (Boman et al., 2018).

Table 2. Soil-layer classification and description based on pH criteria following the Swedish-Finnish classification-system for AS soil.

Classification	Description
Not AS soil	Oxidized horizon where pH measured in field is > 4 .
Not potential AS soil	Reduced horizon where pH after incubation in laboratory is not < 4 .
Active AS soil	Oxidized horizon where pH measured in field is < 4 , or below 4,5 if the horizon is overlaying a potential AS soil.
Potential AS soil	Reduced horizon where pH after incubation in laboratory is < 4 and pH in field is > 6 .

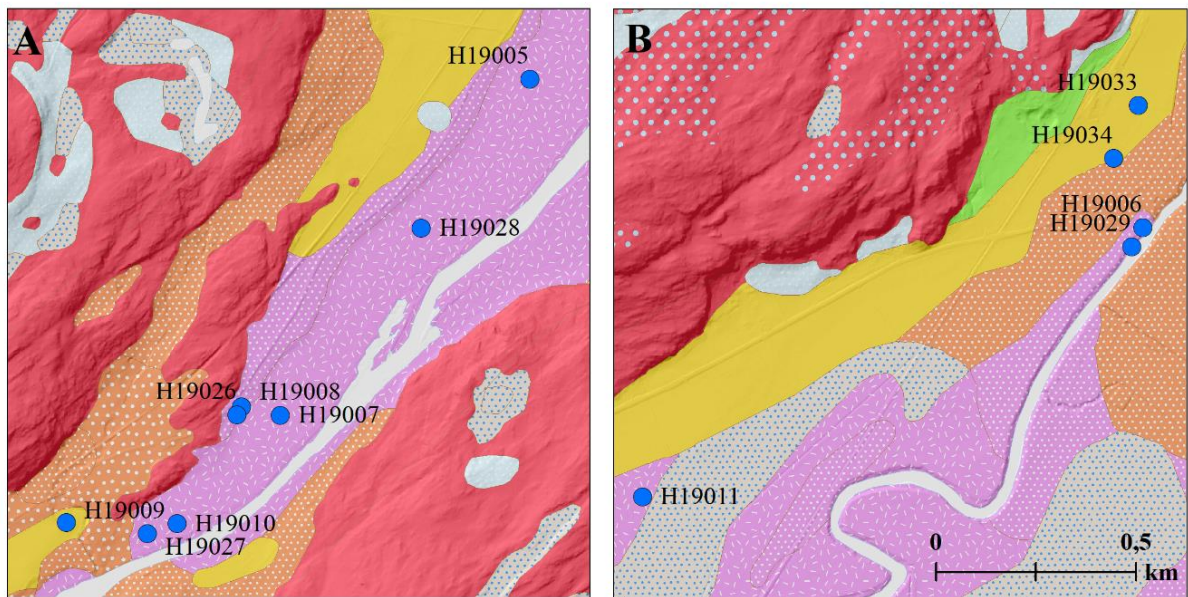
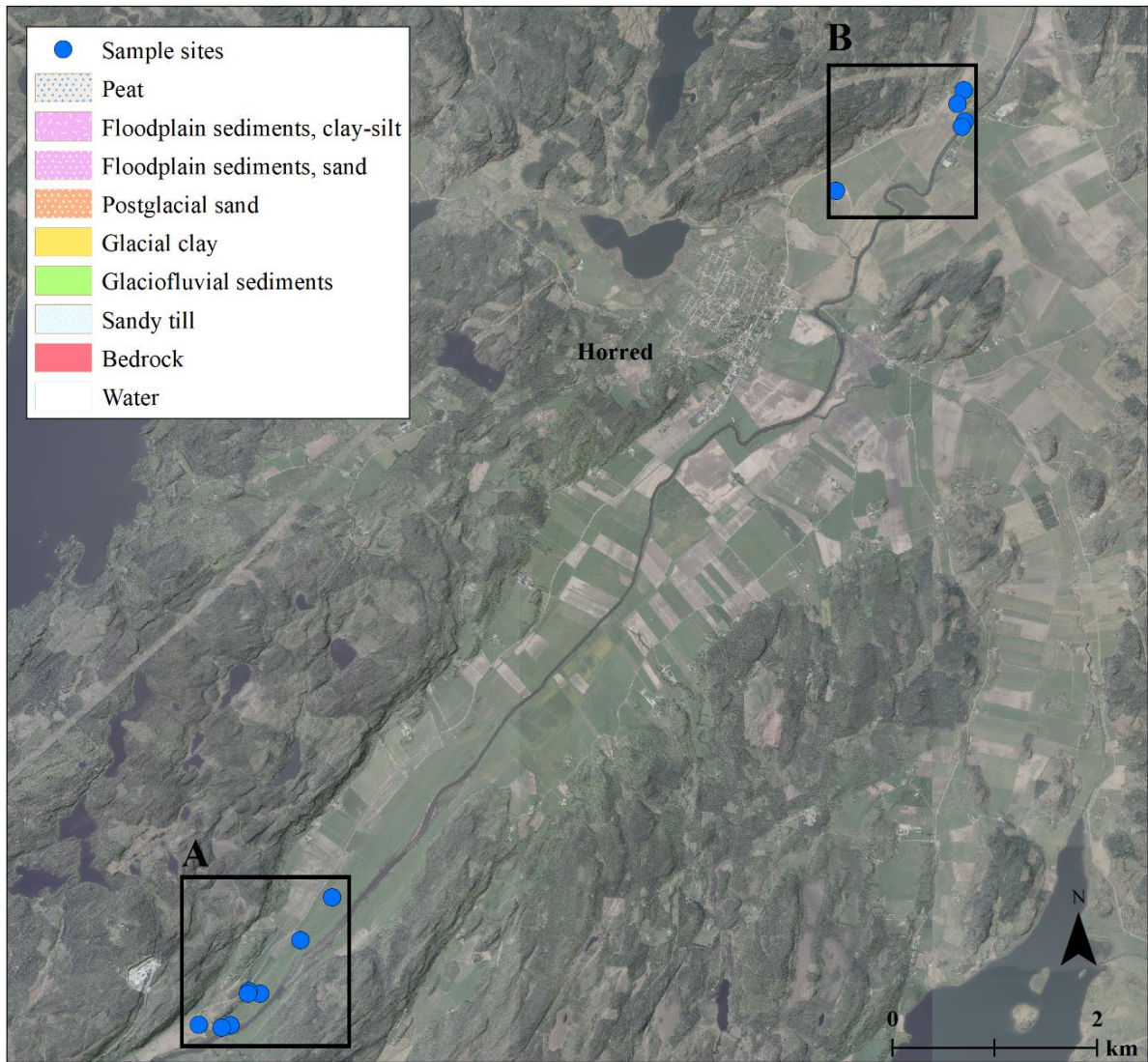


Figure 4. Sample sites in the southern part of the valley. Most of the sample sites are in floodplain sediment and some in glacial clay. Ortophoto/elevation raster grid 2+ 2019 © Lantmäteriet, Jordarter 1: 25 000 - 1:100 000 © Sveriges Geologiska Undersökning.

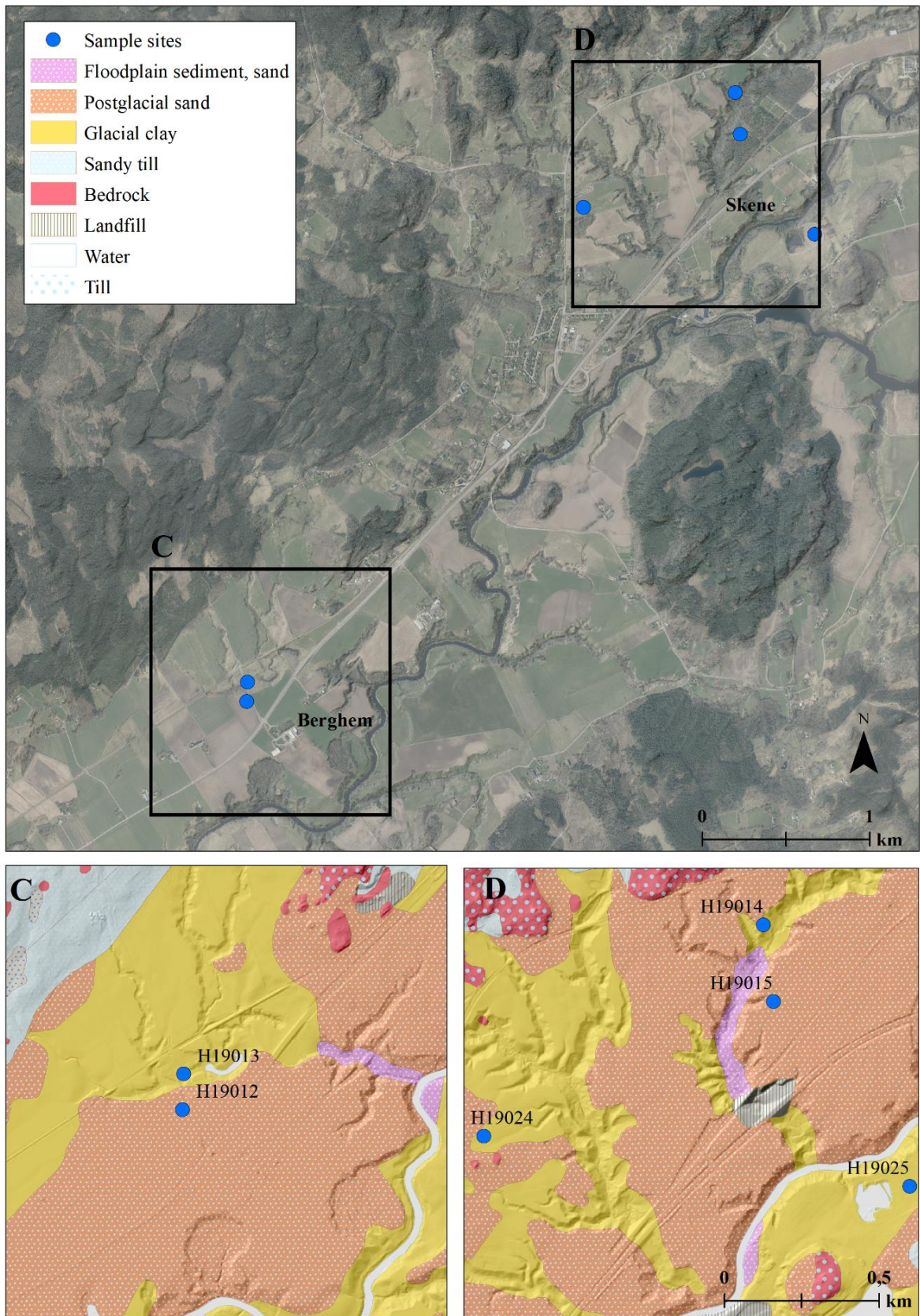


Figure 5. Sample sites in the southern part of the valley. Most of the sample sites are in glacial clay and postglacial sand. Orthophoto/elevation raster grid 2+ 2019 © Lantmäteriet, Jordarter 1: 25 000 - 1:100 000 © Sveriges Geologiska Undersökning.

5. Results

5.1. Classification

The pH measurements in the field varies between 4.42 at the lowest (H19026) and 8.33 (H19033). One site could be classified as active AS soil, two sites were classified as potential AS soils and 18 as not AS soils (Fig. 6). Regardless of the classification the general trend was a lower pH higher up in the sediment profile in the oxidized zone and a higher pH with depth in the reduced zone. Based on the field soil classification, the majority of the sites consist of clay, gyttja clay, silty gyttja-clay and sometimes sand. The sites that displayed a more stable pH with less variation in depth (<1.5 units) were sandier. With a field pH of 4.42, H19026 is the only one of the 21 sites that fulfils the conditions to be classified as an active AS soil overlying a potential AS soil. Two sites, H19008 and H19006, showed a significant drop after oxidation in lab and thus classified as PASS. For sample sites that fulfils the conditions to be classified as an AASS or a PASS or close to the classification limits, field pH from collected samples and lowest pH measured in laboratory are presented in the table below (Tab. 2). For a complete table of pH see Appendix 1.

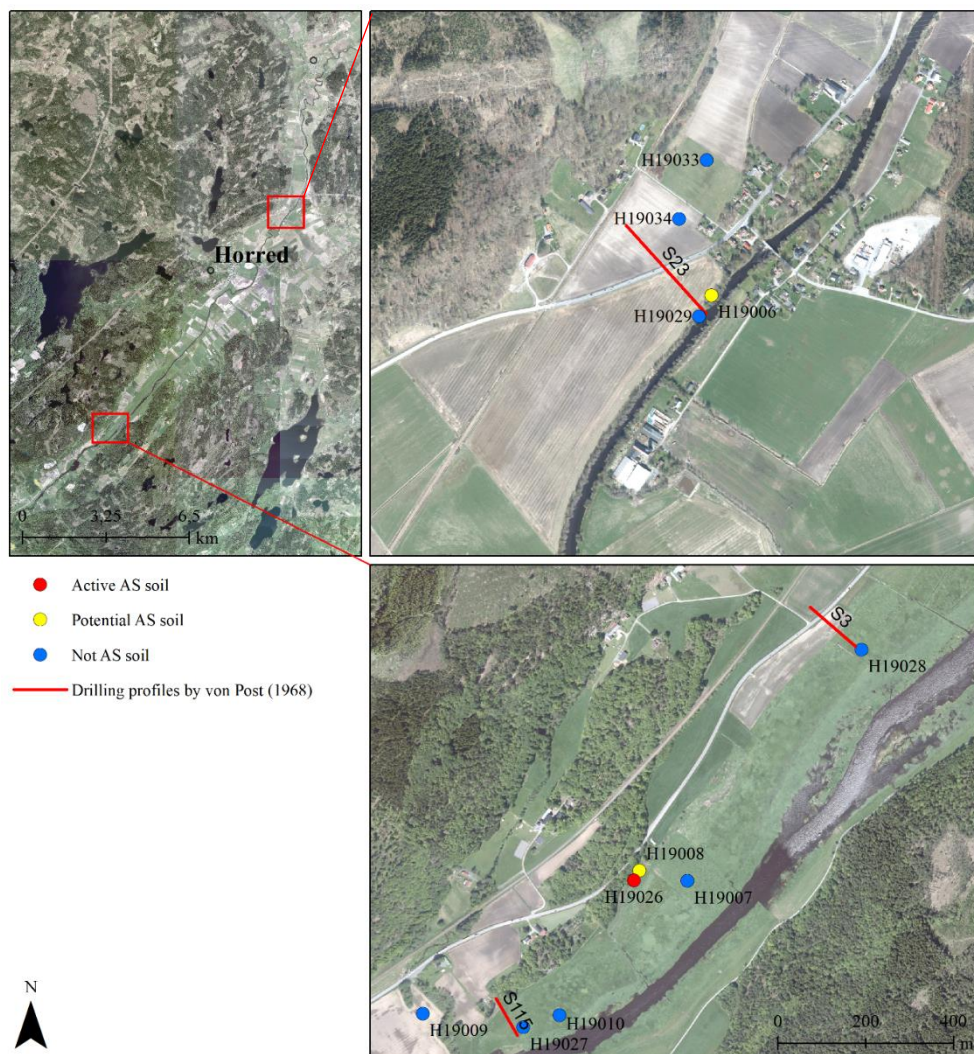


Figure 6. Map with the sample sites classified as active AS soil (red) and potential AS soil (yellow). Orthophoto © Lantmäteriet

5.2. Description of the active AS soil

The site classified as active AS soil is, According to SGU's soil map, sandy floodplain sediment. The field soil-classification showed gyttja-clay with sand.

5.2.1. H19026

This is one of the southernmost sites, found between Horred and Veddige. The area consists of grassland, and the sample site is located around 200 meters from the river. The upper 0.2 m consist of topsoil. The rest is a sandy gyttja-clay with an exception at the depth of 1.0 meters were a 0.5-meter gyttja-clay layer with no sand is found. The total drilled depth was 2.5 meters. The pH showed a variation of 4.42 – 7.26 and generally increased in more reduced conditions (Fig. 7). Large dark red- and orange-coloured mottles was found at depths of 0.6 to 1.0 meters which changed to a more orange colour when entering the in the ASS layer (Fig. 8). Small (< 2 mm) rust-coloured grains that crumble was found at depths of 0.5 meters and down. The soils contain organic material in forms roots and organic fragments.

5.3. Description of the potential AS soil

Two sites were classified as potential AS soil. According to SGU:s soil map, the potential AS soil found in the Viska valley is situated in sandy floodplain sediment. The field soil classification showed distribution of gyttja and sandy clay at the sample sites.

5.3.1. H19008

The first potential AS soil is located on the grassland in the same area as H19026, but 25 meters further northeast with a 0.3 meters higher elevation. The upper 0.3 meters consist of sand that gradually turns into sandy gyttja-clay and continues down to 0.9 meters were the soil changes to a silty gyttja. At 2.2 meters a 30 cm sand-rich layer with some clay is encountered. The rest consists of silty clay down to the end of the drill depth of 3.2 meters (Fig. 8).

Despite the short distance between the two sites, the soil composition differs from H19026. It is slightly less sandy, and the large red and orange rust mottles and coatings are absent. The smaller rust grains (< 2 mm) however, are found at depth from 1.1- to 1.6 meters. Some shell fragments can be seen at 2.1 meters. Larger pieces of organic material are found at 1.3-1.4 meter. The total drilled depth was 3.2 meter. The lowest field pH was measured in the topsoil (4.75) and highest in the deepest part of the profile (7.28). The pH follows the general trend with lower pH in the upper more oxidized parts and increasing with depth in more reducing conditions. 2 of the 3 samples shows a significant drop in pH after oxidation in laboratory (Fig.7).

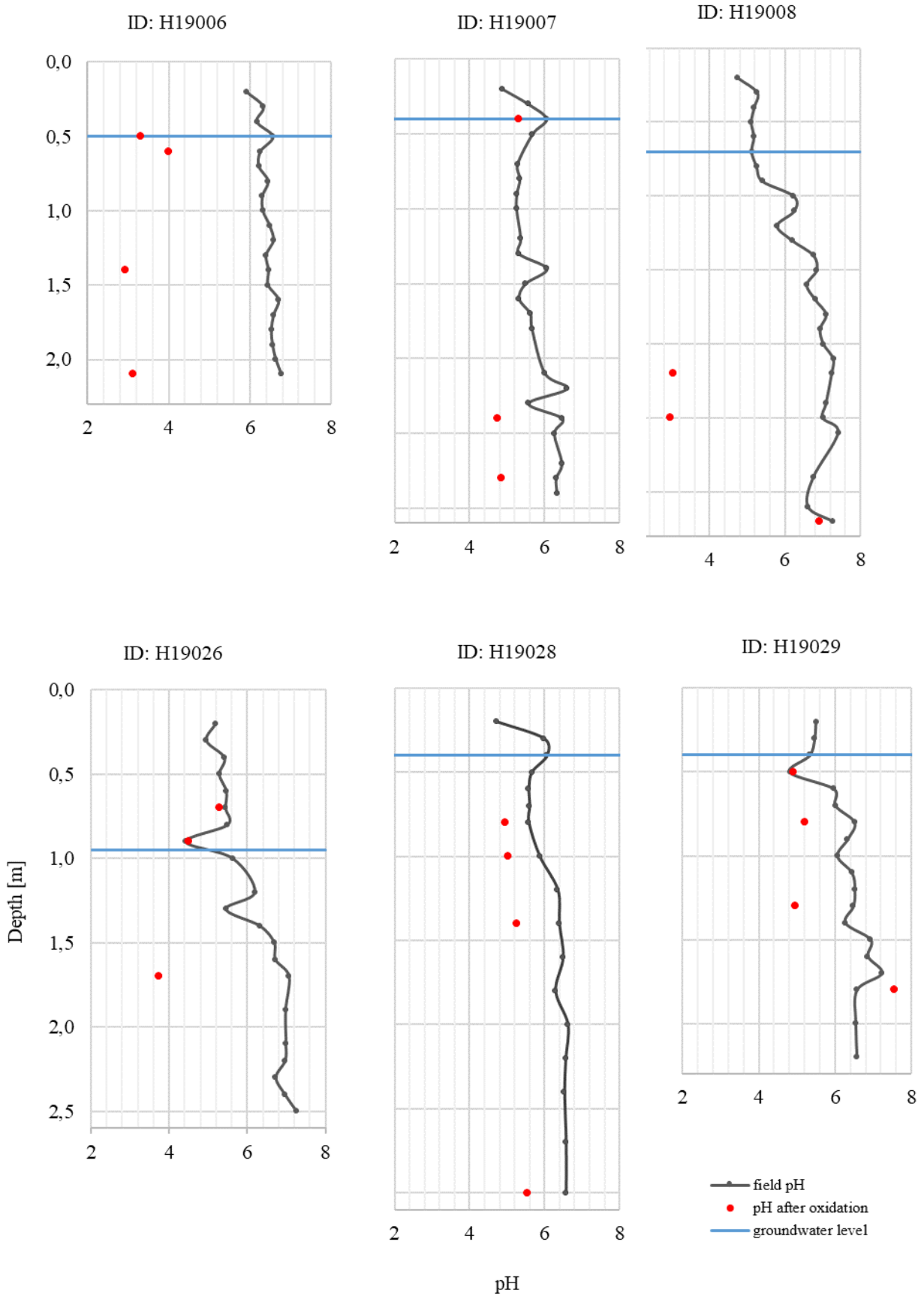


Figure 7. The graph is showing the field pH with depth and the pH on collected samples after oxidation in laboratory. H19006 and H19008 are potential AS soil. H19026 is active AS soil.



Figure 8. A) Sample site H19026. Rust colored mottles found at depths of 0.6 meter down to 1.0 meter. At 0.9 meter the field pH is 4.42 and classified as active AS soil, located just above the reduced zone. B) & C) comparison between H19026 (B) and H19008 (C) (Fig. 6). The two sample sites differ in soil composition, color and oxidation. H19026 is classified as active AS soil, and H19008 as a potential AS soil.

5.3.2. H19006. H19006B

These two sites are located close to von Post's profile S23, *Segerstad väst* (Fig. 6 and 11) between Horred and Björketorp. The area is cropland, and both sampling sites are located in the slope down to Viska River. The first 1.8 meters consisted of sandy clay and the lower part clay only. The samples did not show any noteworthy characteristic features except for rust nodules at 1.20 meters and some darker sulfide spots at 1.40 meters (Fig. 9). The drilling

depth was 2.10 meters. The variation of pH measured in field was not significant and varied between 5.92 and 6.78 with a general trend of an increasing pH with depth. All samples collected (at 0.5, 0.6, 1.4 and 2.1 meters) displayed a significant drop ($2 <$ units) in pH after oxidation in laboratory, which means the thickness of the sulfide layer must be a minimum of 1.60 meters (Fig. 7).

H19006B was sampled right next to H19006 (ca. 3 meters) but closer to the river with 0.5-meter lower elevation. Only one field measurement was made at a depth of 0.9 meters and showed a pH of 5.92. After 9 weeks oxidation in laboratory the pH dropped to 2.92 that corresponds with the pH at 1.9 meters depth at H19006.

5.4. Description of other sites of interest

In total 18 sites studied were classified as neither active nor potential AS soils. Some of them did not display any characteristic features or pH drop. Sites that showed interesting features, were near classification limits or displayed elevated concentrations in the metal analyses are presented here.

5.4.1. H19007

The site is located not far from the active and potential AS soil (H19008 and H19026) found in the area, and it is on the line of von Post's profile *S115*, which shows a 2-meter-thick sulfide layer (Apx. 3). The area is cropland and close to the river. This site displayed a fairly low pH after oxidation in lab (4.75) on the sample taken at 2.4 meters depth (Fig. 7). The whole profile is quite homogenous and consists of sandy silty clay. Rust nodules and organic residues are found in the whole profile. Shell fragments are present from 1,7 meters and deeper.

5.4.2. H19015

The site is located near von Post's profile *S51*, *Hulta* (the location of this profile is not digitalised and can only be found in von Post's report). H19015 differs a little from the other sites since it is in a deciduous forest and not cropland. This site is not classified as an AS soil, but it displayed a fairly low pH after oxidation in lab (4.6) on the sample taken at 2.4 meters depth (Fig. 7). Unfortunately, no samples were taken deeper than this. The groundwater level was never reached, and the field pH was stable throughout the profile. The upper 1.8 meters of the profile consists of layers with fine grained and medium grained sand and the rest down to 3.2 meters consists of gyttja clay with some silt and sand. At a depth of 1-1.1 meters smaller black sulfide spots can be seen (Fig. 9). The gyttja-clay layer contains fractures with iron- oxide coating at a depth of 2.1-2.2 meters.

5.4.3. H19029

This site is located in the same slope as H19006, around 50 meters away and with 3.5 meters lower elevation. The upper 0.6 meters consists of sand. The following meter varies between sandy clay and clay-rich sand and finally gyttja clay only at 1.6 meters and down. Despite the small distance to H19006, the site is not classified as AS soil. However, the pH after oxidation is rather low at 1.3 meters (1.5-unit drop). The general trend is an increasing pH with depth. From 0.6-1.6 meters organic material is found. Fractures with iron-oxide coating is found at 0.6-0.7 meters. Between 1.3 and 1.5 meters the color of the soil's changes to more orange.

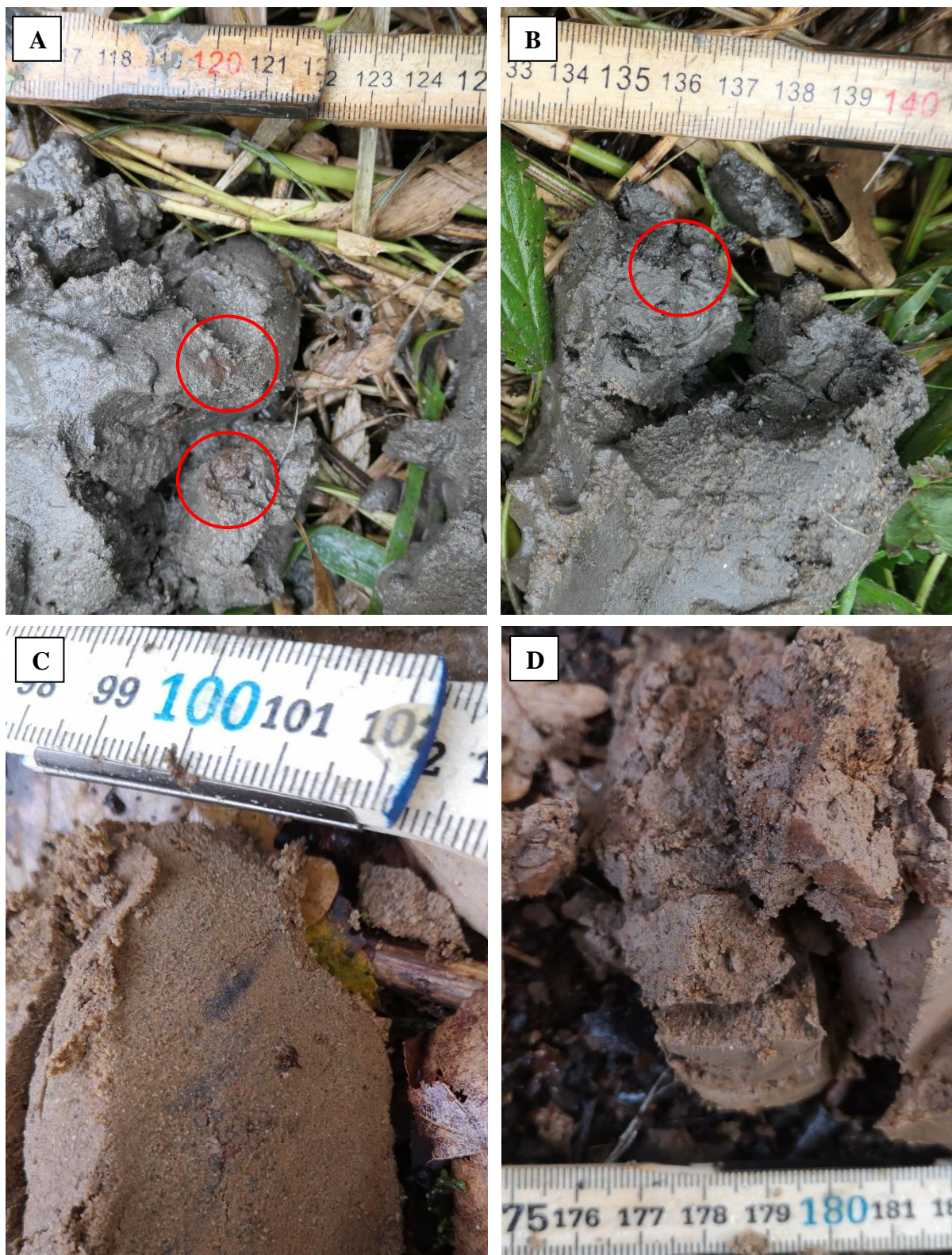


Figure 9. A) Small rust nodules of iron oxides at site H19006 (red circles). B) Dark sulfide spots (red circle), barely noticeable, at site H19006. Both in sandy clay. C) Sulfide spots in sand at H19015. D) Rust mottles/coating in sand at site H19015.

5.5. Organic content (LOI) and grain-size distribution

Since no sample sites in the Viska valley showed significant low pH-values in field, the samples for grain-size analysis and LOI were collected based on observations and suspicions of AS soil (Tab. 3). Unfortunately, not all the analyses match the sites that were classified as AS soil. In general, all the samples are very fine-grained and clay rich. The organic content varies between 0.80 up to 5.61 %. The highest organic content was found at site H19010 and H19027 in the gyttja clay that also displayed a larger amount of visible organic content. The sites with the lowest organic content are found in the sandy sample from H19015.

The wet sieving also showed that the same site (H19015) has the lowest proportion of fractions smaller than 63 μm (67.35 %) together with sample site H19026 (33.65 %) (Tab. 3). In the fine-grained portion, the SediGraph analysis revealed a clay content of around 30 % in both samples. The rest of the samples mostly contain fine fractions (<63 μm) and around 40-50% clay. The most clay-rich sample was H19013 (Fig.10).

Table 3. Grain size, organic content, and field-soil classification for selected samples

ID	Depth [m]	Grains finer than 63 μm [wt%]	Organic content [%]	Field soil classification
H19010	1.2	98.74	5.61	Cl
H19013	2.1 + 2.2	99.02	2.76	Cl
H19015	2.4	67.35	0.80	saSi
H19026	0.9	33.65	2.54	saCl
H19027	0.8 + 0.9	92.82	4.33	Cl
H19028	1.0	96.86	-	Cl
H19028	2.0	98.52	-	Cl
H19029	1.7	95.05	3.74	Cl
H19029	1.8	95.89	2.06	Cl

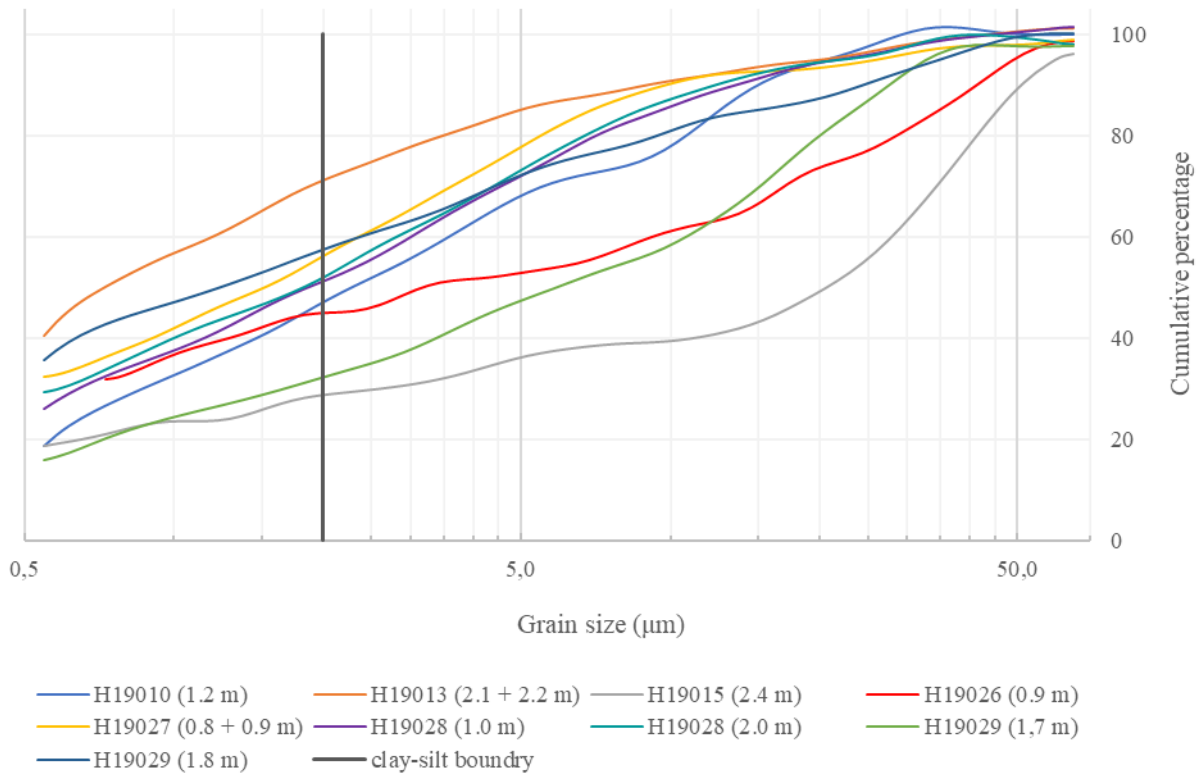


Figure 10. The grain-size distribution in samples from Table 3. The analysis is made on the finer fractions, ranging from silt-sized particles and smaller (63-0.5 μm). The samples have a clay content that ranges from 38 to 84 %.

5.6. Resistivity measurements

Resistivity measurements were performed in the field next to sample site H19006 where one of the potential AS soils are found. The area is currently used as arable land (Fig. 11). One of von Posts drilling profiles is located next to the sample site, which indicates that a sulfate layer might be found at a depth of 6 meter (Fig. 12). To cover as much as possible of von Posts section, two 80-meter-long profiles were made. Because of the heavily trafficked road that is cutting through the section, the two profiles had to be positioned with a 100-meter distance in order to overlap.

The resistivity measurements at profile 1 display a dry ~1.5-2-meter-thick surface layer with higher resistivity on top of a highly conductive layer. The conductive layer shows a very low resistivity of 5 Ωm . About 16 meters in the profile, the model displays another layer (~2-meter thick) with slightly higher resistivity, around 15 Ωm which reaches all the way to the end of the profile. At profile 2, the dry high-resistivity surface-layer is around 1 meter thick and underlain by a low resistivity layer (15 Ωm). The depth of von Post's drilling profile is marked in the two resistivity profiles (Fig.12).



Figure 11. Top: Resistivity was measured along two 80-meter-long profiles. The profiles were placed next to the sample site H19006 (classified as potential AS soil) and von Post’s (1968) drill profile S23. The profiles were placed with 100-meter distance in order to overlap and cover as much as possible of S23. Bottom: the two measured resistivity profiles marked in von Post’s “Section 23”. The purpose was to see if it was possible to see one of von Posts interpolated sulfide layers or the sulfide layer found in this study with the help of geophysics. Orthophoto 4 band 0.16 m 2019 © Lantmäteriet. Drilling profiles by von Post (1968) digitalized by Elin Norström, SGU.

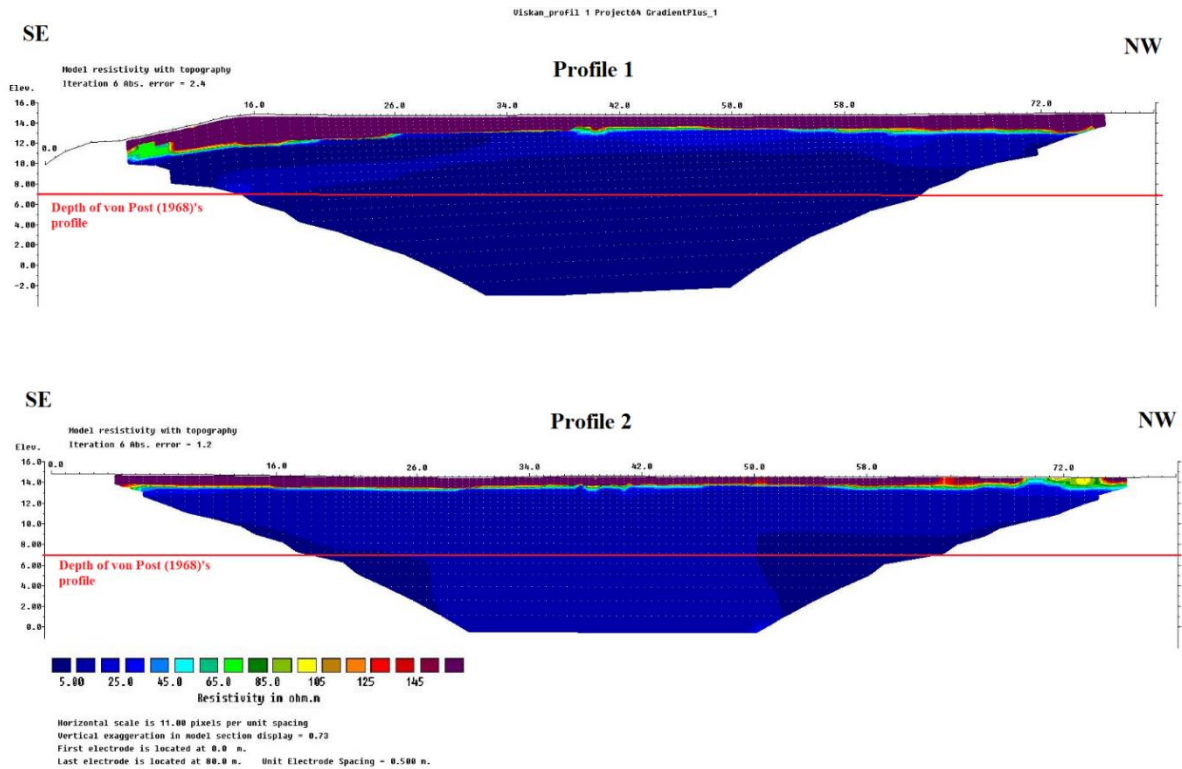
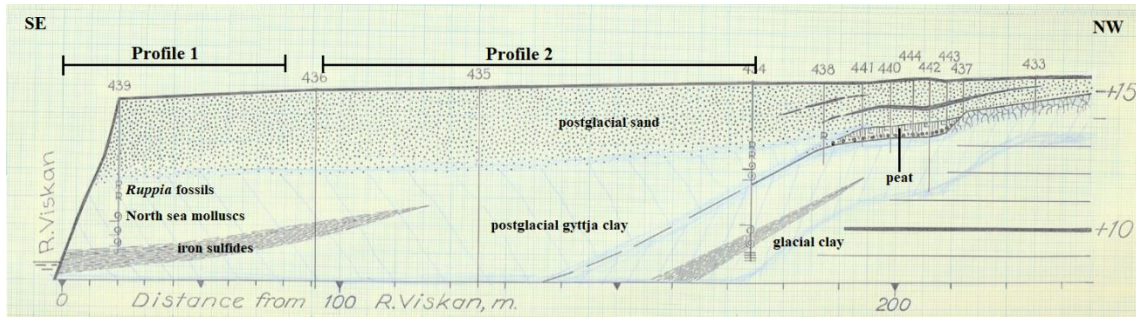


Figure 12. Top: The two measured resistivity profiles marked in von Post's drilling profile S23. The purpose was to see if it was possible to see one of von Posts interpolated sulfide layers or the sulfide layer found in this study with the help of geophysics. Bottom: Resistivity models made in Res2Din. Profile 1 is located closest to sample site H19006 and Viska River where a layer of potential AS soil is found. Profile 1 displays a highly conductive layer (5 Ω m) from about 1.5 meters depth and deeper. Within the layer, some differences can be seen with slightly higher resistivity (15 Ω m). Bottom: The model made from Profile 2 as well, reveals a highly conductive layer under the dry surface layer (15ohmm). The two red lines in the resistivity models is marking out the depth of von Post's (1968) profile.

5.7. Total metal and sulfur content

The content of sulfur and metals in the sites classified as active AS soil or potential AS soil will be presented in this section. For sample sites not classified as AS soil, only the total concentration of iron (Fe) sulfur (S) will be presented since these elements can be a crucial to the acidification potential. For a complete list of element concentration of all samples, see Appendix 3.

The results from H19026 show a higher total concentration of S and metals in the reduced zone, compared to the shallower oxidized zone (Tab. 4). In general, no concentrations are significantly high (compared to SGU's analyses), however the total concentration of S is quite high in the reduced layer, 11 800 mg/kg (dry matter) which is over 1%. When classifying sulfide sediments, $\geq 0,01\%$ (dry matter) is used as a limit value to be considered as a sulfide sediment (Boman et al., 2018).

In sample site H19008, the metal and S concentrations decrease in the middle sample at 2.5 meter where the soil is sandier, and then increases again in the deeper more clay-rich soil. The total S concentration is high in the shallow (2.2 meter) and the deep (3.2 meter) sample. 9950 and 10000 mg/kg (dry matter) respectively. The total metal concentration follows the same pattern as the S and no significantly high concentrations are observed. (Tab. 5) All sample sites show high S content (>1000) in at least one sample. The only site with quite low S through the profile is H19024.

The Fe/S ratio is low in both the active AS soil and the potential AS soil. At sample site H19026, it is under 1.9 in the potential AS soil. And between 1.9 and 3.3 in the potential AS soil at H19008. Most of the sites that is not AS soil have a higher ratio, often over 100. An exception is H19029, which shows a low ratio of 4.08 at a depth of 1.8 meter together with a high S content. H19033 also displayed a rather low ratio of 7.42 as the lowest at 1.7 meters (Tab. 5).

Table 4. Metal and sulfur concentrations [mg/kg dry matter].

ID	Depth [m]	As	Ba	Be	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	P	Pb	S	Sr	V	Zn
H19008	2.20	6.19	36.60	0.59	0.10	7.03	16.10	10.90	19000	<1	413	12.00	591	6.35	9950	26.60	33.9	48.1
	2.50	<3	13.00	0.25	<0.1	3.09	5.92	2.96	6070	<1	205	5.27	505	2.27	1840	8.60	14.1	19.4
	3.20	7.47	55.00	0.85	0.22	13.70	20.20	15.90	22800	<1	995	19.90	596	7.36	10000	50.90	43.2	63.3
H19026	0.90	6.88	53.60	0.35	<0.1	3.66	8.48	3.55	14100	<1	172	7.25	629	4.24	703	13.10	23.2	19.7
	1.70	8.15	42.00	0.78	0.13	8.94	16.60	9.31	22400	<1	697	17.00	597	7.17	11800	29.70	38.6	56.9
H19029	0.5	<3	24.8	0.23	<0.1	2.72	6.71	5.45	5510	<1	105	4.50	508	5.30	251	7.18	15.1	31.4
	1.8	9.74	85.3	1.32	<0.1	13.9	34.1	21.8	37500	<1	868	30.2	870	14.20	9190	41.1	74.8	84.2
H19033	0.6	15.8	84.6	1.32	<0.1	14.8	31.8	19.3	40000	<1	471	26.7	571	14.9	69.80	33.3	82.0	69.6
	1.4	6.14	98.0	1.51	0.12	15.0	37.8	35.7	46900	<1	1290	37.8	1050	16.7	122	34.6	89.6	92.7
	2.8	12.4	103	1.51	<0.1	15.6	40.8	27.2	36700	<1	843	34.2	916	15.5	2200	57.5	87.5	96.1

Table 5. Total S and Fe concentration and Fe/S ratio presented in all the analyzed sample sites. Fe/S ratio act as a factor with respect to acidification potential. The Lower the ratio the higher acidification potential (Pousette, 2010).

ID	Depth [m]	pH in field	pH after oxidation	S [mg/kg dry matter]	Fe [mg/kg dry matter]	Fe/S	Field soil classification
Active AS soil							
H19026	0.9	4.42	4.5	703	14100	20.06	clSa
	1.7	7.07	3.74	11800	22400	1.90	siCe
Potential AS soil							
H19008	2.20	7.25	3.05	9950	19000	1.91	siCl
	2.50	7.01	2.96	1840	6070	3.30	saCl
	3.20	7.28	6.91	10000	22800	2.28	saCl
Not AS soil							
H19024	0.6	4.46	5.29	55.10	28000	508.17	siCl
	1.6	6.79	6.73	79.40	38000	478.59	siCl
	3	7.35	7.68	133	40900	307.52	siCl
H19029	0.5	4.82	4.79	251	5510	21.95	Sa
	1.8	6.57	7.56	9190	37500	4.08	Cl
H19033	0.6	5.93	6.57	69.8	40000	573.07	siCl
	1.4	7.43	7.1	122	46900	384.43	siCl
	2.8	8.05	8.11	2200	36700	16.68	siCl
H19034	1	6.23	6.21	120	25600	213.33	Cl
	1.7	8.14	7.88	5140	38200	7.43	Cl
	4.6	8.47	7.96	1520	38400	25.26	Cl
	5.2	8.59	7.79	1620	37000	22.84	Cl

6. Discussion

The main goal with this study was to investigate if AS soil is present in western Sweden. To achieve this, we used appropriate and well-known methods as well as trying to apply a method that is new on the west coast, resistivity measurements. The resistivity data have been used to interpret if found a potential AS soil can be visualized but also to compare with the historic drilling data from von Post. The information collected in field and in laboratory have contributed to the understanding of the formational environment of AS soils. The following discussion will be based on the research questions and the results.

6.1. Does AS soil exist in western Sweden?

With the knowledge obtained from this study together with the work made by Kling Jonasson (2020) in Falkenberg, it is now possible to state that AS soils exist in Halland, western Sweden. These studies are the first to find active AS soil located outside the Baltic basin in Sweden. Fieldwork, including pH measurements, soil observations and soil sampling as well as lab work and sample oxidation, showed that at least one area in the Viska Valley has active AS soil and one area potential AS soil.

The layer with active AS soil is 0.1 meters thick and located on top of a potential AS soil. If it would not be overlaying a potential AS soil, the site would be classified as potential AS soil only, since the field pH was >4 . Together with the pH results from H19008, we can conclude that under the active AS soil is there is a 1.7 meters thick layer with potential AS soil.

H19008 and H19026 are only separated with 25 meters distance, thus the two sites will be discussed with the assumption that they are situated in the same stratigraphic unit. This area, classified as potential AS soil (H19006), is found 2 meters below surface on the slope to the Viska River next to von Posts profile s23. The layer is at least 2 meters thick but given that the deepest oxidation sample is from 2.1 meters, we cannot exclude the possibility that the layer might be greater than so.

Both sites are located within 200 meters of the river and situated on arable land that is under use. The sediment has been uplifted to higher elevations due to isostatic rebound. However, clues of former ditching can be shown on the hillshade map that could have led to oxidation at H19026. Older orthophotos of the valley show that the area has been used for agriculture for a long time and ditching around the croplands is common. Many of the sample sites display precipitation of iron oxides in the profile (regardless of classification) even in the reduced zone, which can be an indication of a fluctuating groundwater table.

The groundwater-level change can be from ditching but also a naturally fluctuation with seasonal variation. However, iron oxidation can occur in soil that is not AS soil as well, so it does not necessarily mean that it has been an AS soil. According to von Post (1968), a large part of the area between Veddige and Björketorp was covered by the ancient lake Veselången for some time (until mid-18th century). This would allow the AS soil in that area to be kept in reduced conditions, protected from oxidation during a longer period of time than the other sites. It is also known that the area around Veselången gets flooded every spring.

Similar to Kling Jonasson (2020)'s investigation in Falkenberg, all the sample sites where active and potential AS soil are found in the Viska valley are located under the limit of the Tapes transgression ca. 11-13 m.a.s.l (appx. 2). The Tapes sediment is commonly clay, but the AS soils are situated in gyttja clay with various amounts of clay, silt, and sand, mapped as sandy floodplain sediment by SGU. Floodplain sediments are younger than the Tapes sediment and form when streams flood the surrounding low-lying areas and deposit the material that the water brought with it where the current velocity decreases. The floodplain sediments usually consist of sand, silt and gyttja clay, mixed with organic residues in different stages of decomposition.

H19008 and H19026 are situated in a higher surface around 3 m.a.s.l., higher and further away from the river than the surrounding sites with non-AS soils, which are located in more fine-grained floodplain sediments (appx. 2). These two sites are developed in glacial, marine clay. Most likely, the AS soil is post-glacial gyttja-clay (Appx 3; section 3) covered by a layer of floodplain sediment. von Post (1968) describe the layer as lake sediment, but as (Påsse, 1983) suggests, it is more likely floodplain sediment. Floodplain sediment often cover older post-glacial sediments where you have a river Sohlenius et al (2015).

It is possible that these higher-situated sites (H19008 and H19026) have been protected from erosional action of the river. When looking at one of von Post's profile *S3 Albäck* (Fig. 2 & appx. 3) at the same elevation as H19006 and H19026, the post-glacial gyttja clay seems to be overlain by sand (mapped as floodplain sand by SGU) which can work as a protecting layer. The AS-soil perhaps originally covered the whole flat area around the river but have been replaced/covered by younger floodplain sediments and thus, be the reason for the undiscovered AS soil in the sites around. However, since the low-lying area gets flooded every spring, the most realistic explanation is that it is covered with a thick layer of floodplain sediment and thus the AS-soil layer is not reachable with the Edelman drill. It should be mentioned that there is a risk that the AS-soil layer has been overlooked because oxidation samples were not collected at every depth. For example, at H19007 there is a 2-meter gap where no oxidation samples were collected, where the deepest sample showed a significant drop in pH which can be a sign of AS-soil. The same regarding site H19010 where the deepest samples were collected only at 1.2 meters.

However, shells were found at site H19007 and H19010, and the organic content was rather high at H19010 and these factors can act as buffering agents.

6.2. Formation environment

During the time of deposition, the valley most likely consisted of a protected, elongated sea bay with calm water connected to Kattegat with sufficient saltwater supply. Considering the location and the fact that it is a valley, the area is well protected from wind and sea currents by the surrounding bedrock hills. The area where the AS soil is deposited consisted during Tapes maximum of a basin connected with a narrower passage to the other waterbodies south of Veddige (Appendix). When looking at von Post (1968)'s profile *S23 Segerstad väst* (appx 3, section 23), a peat layer is present over the glacial clay but under the post-glacial sand and post-glacial gyttja clay. This implies that the peat layer was formed

after the deglaciation in the stage when the water level was low in the valley (Fig. 3B). The younger, post-glacial gyttja clay and sand found at H19006 was deposited later during the post-glacial Tapes transgression when the sea level rose once again. The soil observations at H19006 showed a sandy gyttja clay that gradually changes to gyttja clay downwards in the profile. This indicates that the AS-soil layer is deposited as post-glacial gyttja clay. The sand that is mixed in the gyttja clay might originate from the upper sand layer or, the layer is river and floodplain sediments.

In von Post's investigation, he observed fossils of *Ruppia Maritima* in the post-glacial clay at around 11 m.a.s.l. This is a widgeon grass that grows in marine brackish to saline waters. It prefers semi-exposed to sheltered locations on soft and muddy bottoms. It is found mainly in waters shallower than half a meter but can appear in considerably deeper waters as well (källa). Deeper in the same stratigraphy, von Post (1968) also found mollusks of the species *Mytilus* and *Cardium*, which are marine mollusks. This indicates that deposition occurred during the post-glacial Tapes transgression, at a time when the water was saline and still connected to Kattegat. The *Ruppia* on the other hand, might have been growing when the area had been disconnected from the water or when it started to be cut off, and was shallower. It is not specified by von Post (1968) the exact depth where he found the *Ruppia* and the molluscs, but by the look of his drawing, the upper layer of the AS-soil in this study appears to coincide with the *Ruppia*. This area is located rather high up in the valley, in the outer margin of the Tapes maximum, where the deeper water would have met the fresh river water. This suggests a smaller estuarial environment with slightly lower salinity than closer to Kattegat. von Post (1968) describes the area found in the narrow valley between Horred and Björketorp as a 'delta' with the mouth around profile S23. The delta/estuary can also be an explanation to the sand found in the clay at H19006, which might have been transported to the river outlet.

As previously mentioned, von Post discovered several sulfide-rich layers as he drilled along the valley. These sulfide-rich layers can be seen in many of his interpolated profiles (Appendix. 3). It is reasonable to believe that these layers represent the seabed in the protected bay at different times when the conditions for sulfide formation were optimal (i.e., sufficient organic matter and minimal circulation). With this assumption, it is reasonable to assume that more potential AS soils exist at different depths elsewhere in the valley. The AS soil in this case is post-glacial gyttja clay just as in the study in Mälardalen (Bayard & Mood, 2014), but according to von post (1968) there are also sulfide-rich layers in the glacial clay that perhaps has AS soil potential (Appx. 3, Section 23).

6.3. Resistivity measurement on the west coast and correlation with von Post's drilling profiles

The surface layer on the top of the profile with the higher resistivity (Fig. 12) is most likely the dry surface layer above groundwater level in both profiles. It is in the thicker more conductive clay layer underneath that the potential ASS should be located. It is difficult to determine if the precise location and thickness of the sulfide layer can be seen in the ERT measurement data, since the models only display one single conductive layer with very little

differentiation within the stratigraphy in both profiles. However, when looking at the results from the pH measurement at site H19006, the potential AS soil found is present already at a depth of 2 m.a.s.l., which is much shallower than von Posts interpretations. Unfortunately, the resistivity data do not cover the first meters of the profile, but, a dark low resistivity area can be discerned just under the dry surface-layer, southeast in profile 1 and appears to coincide where the AS soil is found. The low resistivity (5ohmm) is within the zone of sulfide-rich clays (2-10 ohmm) (Suppala et al (2005)) and therefore it is a reasonable assumption to believe that it can be the potential AS-soil seen in the profile.

However, the low-resistivity layer does not occur where von Post (1968) mapped the sulfide layer in his profile (appx. 3, section 23). One explanation for this could be that the AS soil-layer continues down to where von Posts sulfide layer is. However, another sampling was made, H19029, with the intention to reach the sulfide layer and no AS soil was discovered. Nevertheless, the sulfur analysis reveals high levels of sulfur (~1%), which indicate that there is another sulfide-rich layer but possibly not enough to be picked up by the ERT.

Further northwest in von Post's profile, he found another sulfide layer but in the glacial clay, but with no AS-soil sample as a reference and no differentiation in the low-resistivity layer, it is not possible to evaluate if there is a sulfide layer located in profile 2 or not.

In the study from Falkenberg by Kling Jonasson (2020), the same electrode spacing (1.0 meter) was used as in the Viska valley. The results were difficult to interpret, and it was not possible to discern the AS soil. In a second measurement on the same profile, an electrode spacing of 0.25 meters was used instead, this gave a better resolution and this time it seemed possible to distinguish the AS soil. With this information, it might be possible to get better results from Viska Valley with the same approach as in Falkenberg.

In short, the ERT method does display some anomalies where the AS soil is found but not in all cases. However, it is not possible to say with certainty that it is AS soil or something else but more measurements and experimenting with different electrode distances might give more reliable results.

6.4. Metal and sulfur

Previous studies have shown that metals can be mobilized from active AS soil (Nordmyr et al. 2008, Åström 2001b). The analyses performed in this study show similar results. Although only one site with active AS soil was found, the Viska Valley is no exception; the typical leaching pattern can be observed here as well. The oxidized horizon at site H19026 show lower concentrations of metals and significantly lower sulfur content, whereas the reduced horizon shows elevated concentrations. This is a consequence of oxidation and the formation of sulfuric acid and further the associated mobilization and leaching of metals. The sulfur content is generally significantly higher in the AS soils. However, there are a few sites (H19029, H19033 & H19034) that show elevated concentrations of sulfur. In H19029 is the concentration is as high as in the AS soils, but the pH did not drop after oxidation which shows that sulfur content is not the only factor controlling the acidification properties.

As mentioned, Fe/S ratio have been used as a parameter to determine the acidification effect in AS soils (Mácsik, 2000; Pousette, 2010). This would mean that the soil where H19026 and H19008 is situated has very high acidification effect since the Fe/S ratio is < 3 . Furthermore, H19024, the upper part of H19033 and H19034 do not fulfil the conditions to be classified as sulfide sediments since the ratio is < 60 , this corresponds well with the conditions presented by Boman et al., (2018) of a sulfur content of 0.01 % needed to be classified as a sulfide sediment.

6.5. Limitations of study

As in many other studies, one of the major limitations of this study has been time and equipment; time to do as many samplings and laboratory work as possible to get a qualitative and comparable study. One thing that time affected was the fact that the metal analyses had to be sent in before all the oxidation in laboratory was done, which in turn lead to analyses on some samples that was not necessary. Another important factor is accumulated knowledge; you learn more as the work goes on and you are much wiser in the end of your study than you were when you started. This is shown in the sample collecting (for oxidation, LOI and grain-size analysis), a better approach would be to collect samples from all the sites and store them while waiting for the oxidation results, and then do analyzes on interesting samples. Additionally, oxidation samples for the ships tray should have been collected with a denser interval since it would give a better overview of what is happening with the pH through the whole profile. And also minimizing the risk of overlooking potential AS soil.

Furthermore, the Edelmann drill, available for this study, only allows you to drill down to 3.2 meters depth, which also limited the number of von Post's profiles that could be investigated. Another factor is the weather, since large parts of the croplands got flooded during spring it was not possible to make another resistivity measurement that was planned.

6.6. Future aspects

As mentioned, most of the investigations of AS soil in Sweden has been done on the east coast. This new discovery of AS soil the west coast has contributed to the understanding of the extent of AS soils and the fact that they can occur in areas that are still not investigated. But, also in areas that may not be the most obvious. And since AS-soil can be an environmental hazard, it is of great importance to continue the work of mapping this type of soil. The Viska valley is a large area and there is still much to discover regarding AS soils.

In many parts of the valley, the potential for landslides is high, which is why SGU made the survey of describing the geological conditions that affects the ground stability. The cost of landslide prevention is significant, which is why good knowledge about the geological conditions is central in spatial planning (SGU, 2019); building and excavating in an AS soil landscape comes with great responsibility. Trafikverket (2018) is building a new road in the valley, and as the soil stability is crucial in the construction of roads, it is suggested to investigate more extensively where there is a risk that AS soils or sulfide-rich sediments may occur since sulfide-sediments have poor stability. When building and excavating in an AS-

soil landscape it is also important to be aware of the oxidation process. Excavated AS soil needs to be handled appropriate to minimize the risk of oxidation and acid leakage to water streams.

Furthermore, in future studies it is suggested that von Post's drill sections should be investigated more closely as they contain tremendously amount of detailed information that can help locate possible AS soil in the valley. They can also be used (as in this study) as a reference when measuring resistivity. Continued resistivity measurements should be made to get more data to evaluate and this in conjunction with drilling data, preferably where a known area with potential AS soil. Since the resistivity measurements results from Falkenberg by Kling Jonasson (2020) have given optimistic results, measurement with smaller electrode spacing should be used in Viska valley as well. Shallower high-resolution profiles together with deeper measurements might give good results.

Another interesting aspect would be to investigate if AS soil can be found above Tapes

7. Conclusions

- The most important conclusion in this study is that both active and potential AS soil exist in Western Sweden. At least 2 areas (2 km apart) in Viska valley have a >2-meter thick AS-soil layer. Together with Kling Jonasson (2020), this is the first discovery of active AS soil in Sweden outside the Baltic basin.
- The AS-soil in Viska Valley is organic rich and consist of post-glacial gyttja clay covered by floodplain sediments. All the sites where AS soil is found is located 11-13 m.a.s.l and below the Tapes transgression's maximum.
- The formation took place during Tapes transgression (9200 – 7000 BP), when the valley most likely consisted of a fjord-like bay, protected from wind and currents but still connected to Kattegat allowing saltwater input.
- The data from the resistivity measurements displayed anomalies where the AS soil is found, but the information is not sufficient to determine with certainty whether the layer of AS soil can be discerned or if there is something else. However, more measurements and with denser placement of the electrodes may provide better resolution and thus give higher chances of detecting the AS soil.

- The time and equipment available for this study has covered only a small area of the Viska valley and most likely it is possible to find more AS-soil in the area. Probably there are large undiscovered areas of AS soil on the entire west coast in areas that were below the highest coastline.

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10. Appendices

Appendix 1 – pH

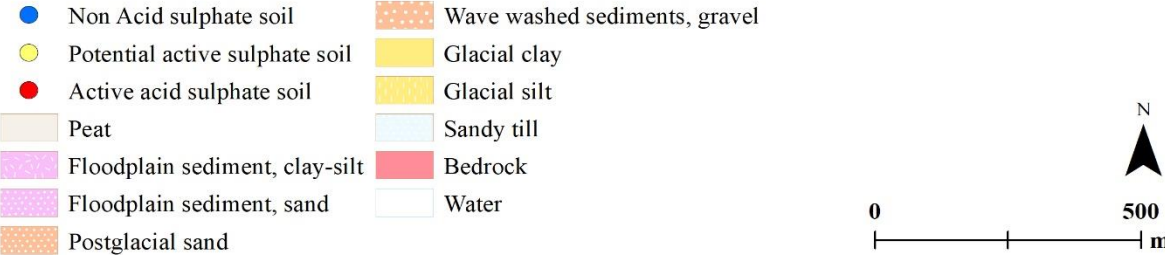
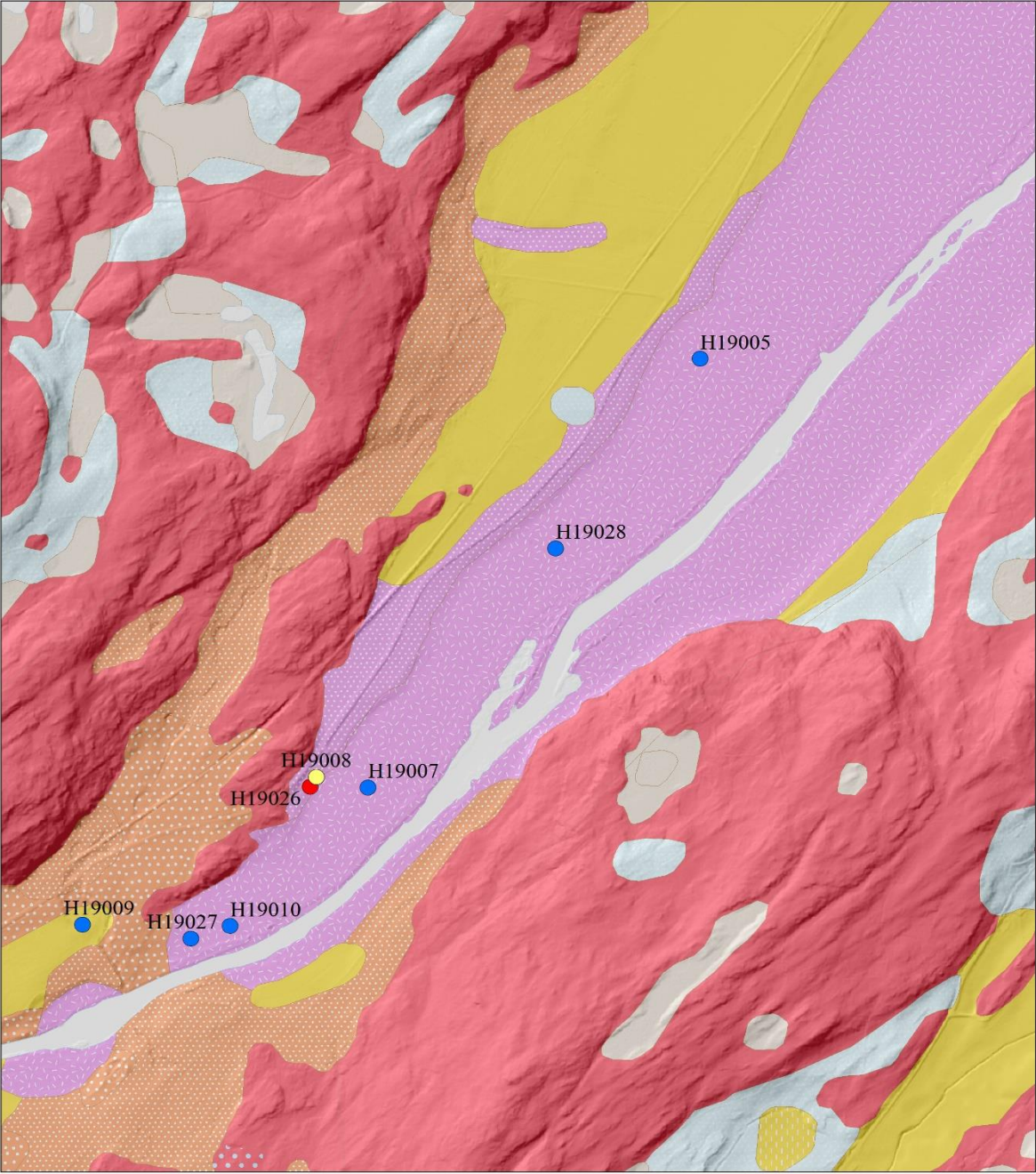
Tabell 1. pH in field and after oxidation.

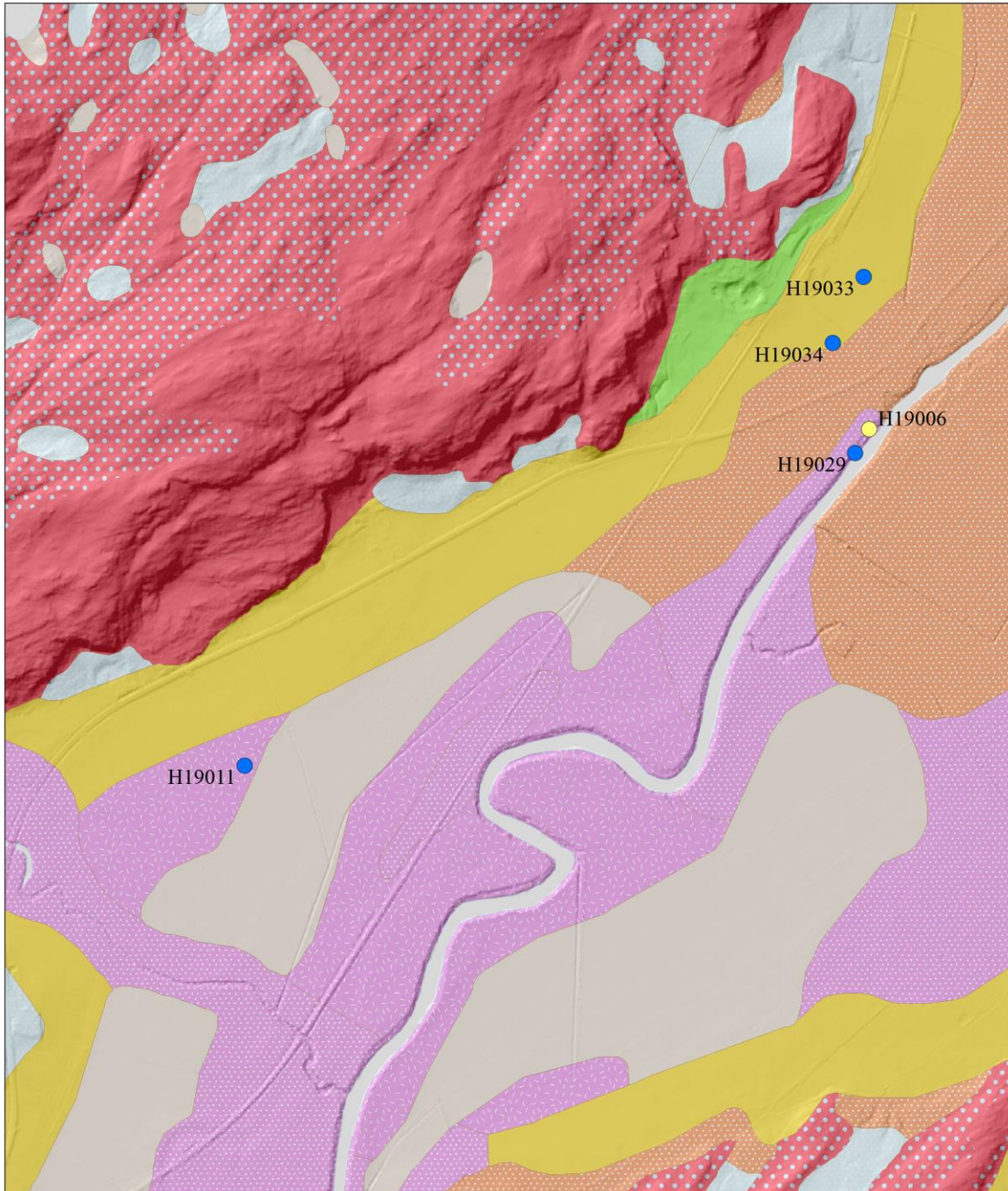
ID	Depth [m]	pH in field	Lowest pH after oxidation	soil classification
H19005	0,90	6,33	5,09	Cl
	1,00	6,76	5,79	Cl
	2,20	7,09	5,46	Cl
H19007	0,40	6,05	5,31	sasiCl
	2,40	6,47	4,75	sasiCl
	2,80	6,31	4,85	sasiCl
H19009	0,60	5,68	5,45	Sa
	1,50	6,29	5,92	Cl
H19010	0,60	5,25	5,50	Cl
	1,20	6,48	5,24	Cl
H19011	0,50	5,90	6,02	Cl
	2,40	7,82	7,64	Cl
H19012	1,50	5,82	6,17	Sa
H19013	0,80	5,96	7,70	Cl
	1,80	7,54	7,77	Cl
	2,10	7,49	7,59	Cl
H19014	2,00	6,34	6,35	clSa
H19015	1,60	5,45	5,18	Sa
	2,40	5,81	4,60	saSi
H19025	2,40	7,40	7,75	Cl
	3,20	7,88	7,73	Cl
H19027	0,70	6,50	6,40	Cl
	0,90	6,81	6,68	Cl
H19028	0,80	5,58	4,95	Cl
	1,00	5,87	5,02	Cl
	1,40	6,39	5,27	Cl
	3,00	6,57	5,54	Cl
H19029	0,50	4,82	4,79	Sa
	0,80	6,51	5,20	clSa
	1,30	6,48	4,96	clSa
	1,80	6,57	7,56	Cl
H19033	0,30	6,94	5,73	siCl
	0,60	5,93	5,57	siCl
	1,40	7,43	6,85	siCl
	2,80	8,05	8,11	siCl
H19033B	5,10	7,50	7,78	Cl
H19034	1,00	6,23	6,21	Cl

1,70	8,14	7,88	Cl
2,30	8,20	7,20	Cl
3,50	8,15	7,95	Cl
4,60	8,47	7,96	Cl
5,20	8,59	7,79	Cl

Appendix 2 – Maps

Closeup of the found AS soil in the soil classification map

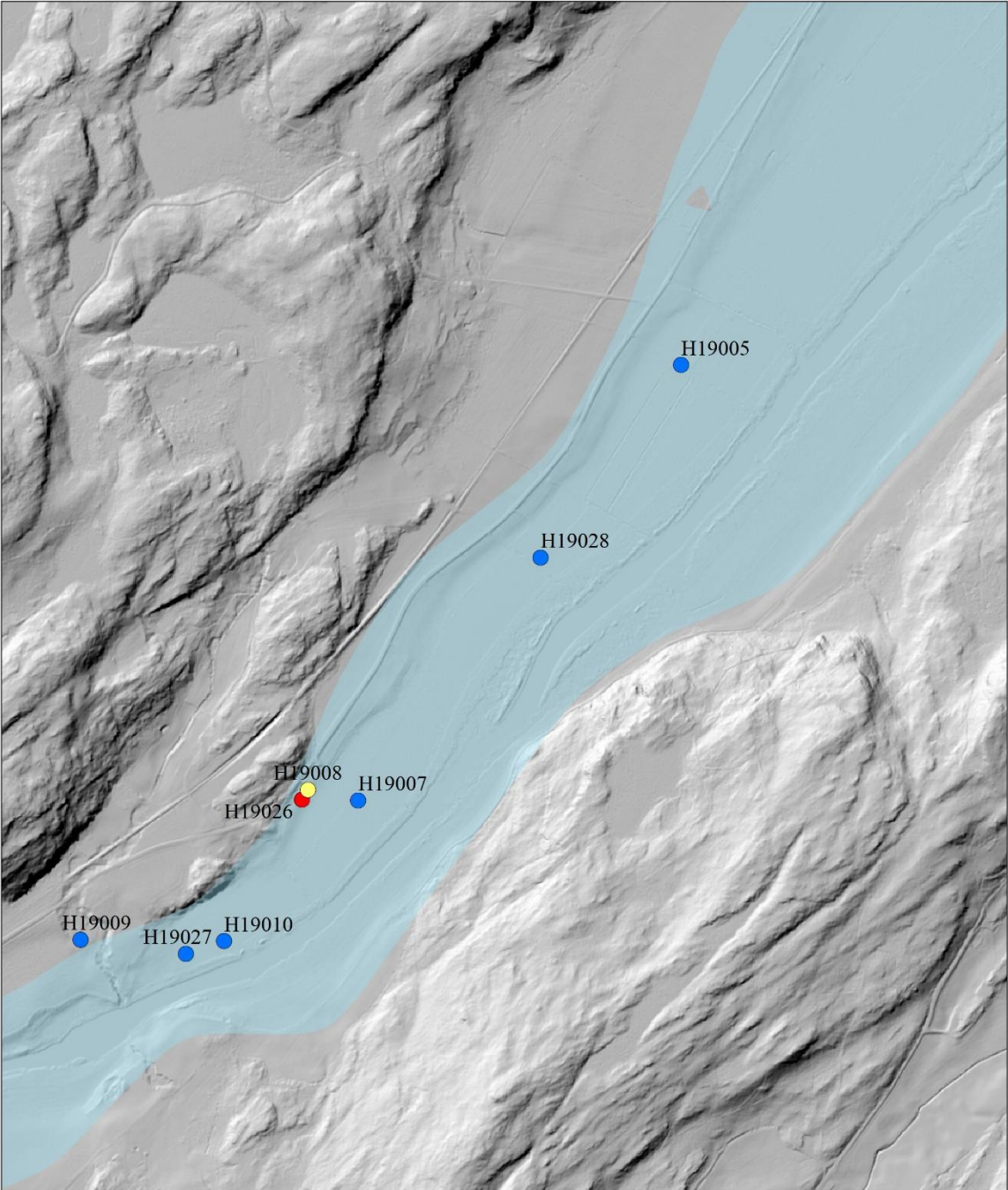




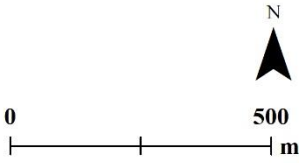
- | | |
|----------------------------------|--------------------------|
| ● Non Acid sulphate soil | ■ Glacial clay |
| ● Potential active sulphate soil | ■ Glaciofluvial deposits |
| ■ Peat | ■ Sandy till |
| ■ Floodplain sediment, clay-silt | ■ Bedrock |
| ■ Floodplain sediment, sand | ■ Water |
| ■ Postglacial sand | |

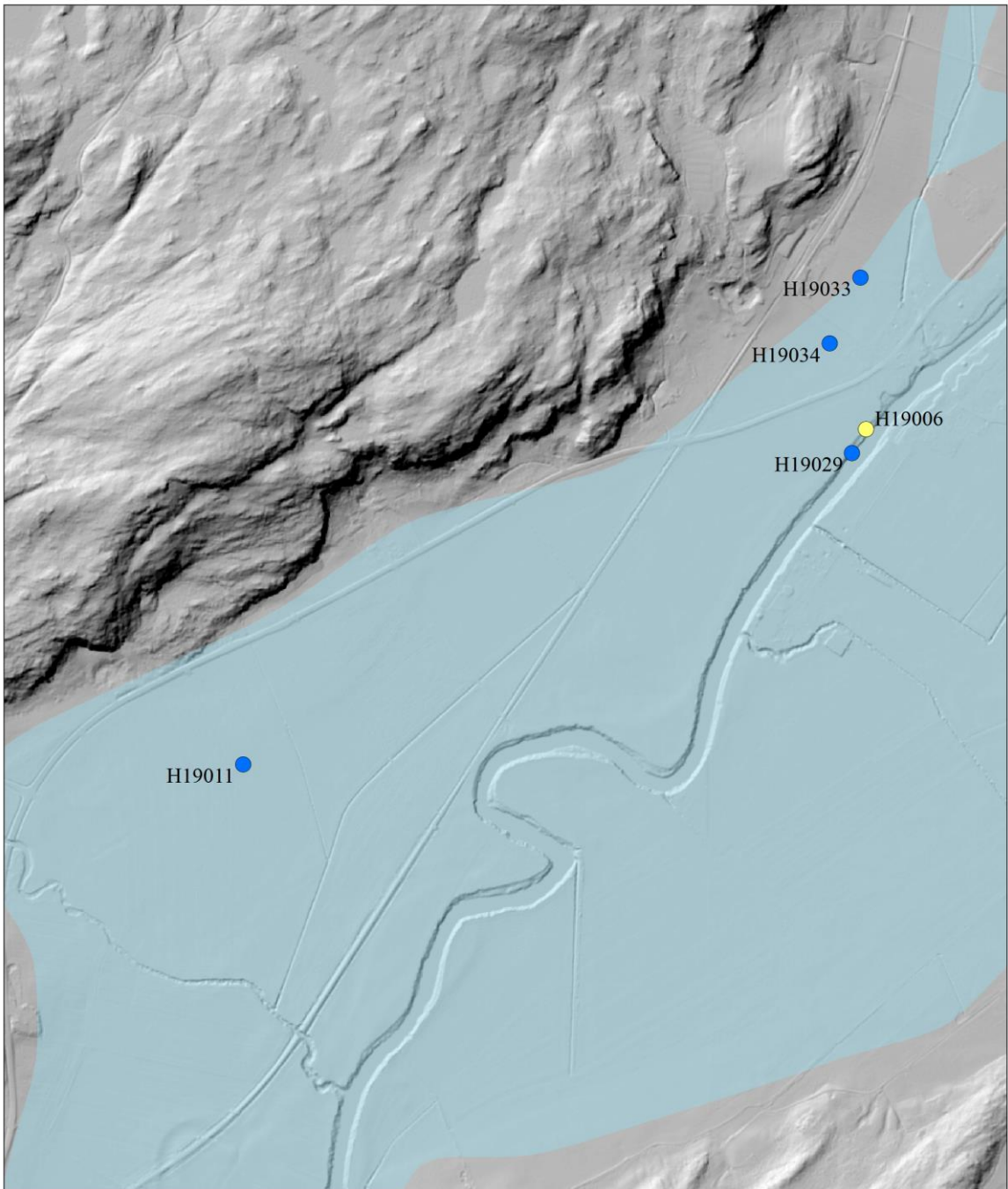


Closeup of the found AS soil and Tapes maximum



- Non Acid sulphate soil
- Potential active sulphate soil
- Active acid sulphate soil
- The post glacial transgressions maximum (PG)





- Non Acid sulphate soil
- Potential active sulphate soil
- The post glacial transgressions maximum (PG)



Appendix 3 – Drilling profiles by von Post

