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ACID SULPHATE SOIL IN FALKENBERG ON THE WEST COAST OF SWEDEN - THE FIRST DISCOVERY OF ACTIVE ACID SULPHATE SOIL OUTSIDE THE BALTIC BASIN

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Abstract

Active AS soil has several negative impacts on the environment due to their ability to severely decrease pH-values and mobilize metals bound in the soil. The negative impacts can especially be seen in aquatic environments that drains an active AS soil. Active AS soil creates difficulties to reach the environmental goals that were set by the Swedish Parliament in 1999. Investigations of the distribution of AS soil in Sweden have chiefly been done along the northern coast, Västerbotten, and Norrbotten, but discoveries have also been done in Mälardalen and Skåne. During a construction work in Falkenberg 2019, water pumps corroded and the presence of yellowish drainage water with low pH-values and high sulphate concentrations led to the conclusion that AS soil exists in the area. The focus of this project was to determine the distribution and existence of AS soil in Falkenberg, on the west coast of Sweden, to shed light on their formational environment, and to evaluate the suitability of ERT methods as an identification tool for these soils on the Swedish west coast. The project was carried out from September 2019 to June 2020 as a master thesis at the University of Gothenburg in collaboration with SGU. Soil sampling was done during the autumn of 2019 with an extendible Edelman auger. Soil sampling was carried out in areas where earlier soil-type mapping showed occurrence of organic-rich sediments. The soil samples were collected for oxidation and further laboratory analyses, including metal and S analyses at an accredited laboratory. After the oxidation of the soil samples, it was concluded that both active and potential AS soil exists in Falkenberg. Four sites were classified as active AS soil sites and one was classified as a potential AS soil site. This is the first discovered active AS soil outside of the Baltic Basin in Sweden. All the observations of AS soil sites were done below 13 m.a.s.l., in clay gyttja, gyttja clay, and sand. When the location of these sites was established, ERT measurements were done at one of the sites, H19001, during November 2019 and February 2020. The results showed that differentiation of the AS soil from surrounding sediments was possible at this site. The formation of the AS soil on the west coast of Sweden differs from that along the Swedish north coast and is thought to have taken place in shallow protected lagoons and bays during Tapes transgression.

Keywords: Acid sulphate soil on the Swedish west coast, formational environment, Tapes transgression, Resistivity measurements, Baltic Basin

Sammanfattning

Aktiva SSJ har flertalet negativa konsekvenser på miljön på grund av deras förmåga att kraftigt sänka pH-värden i både jord och vatten samt att mobilisera metaller som finns bundna i jorden. De negativa effekterna ses framförallt i vattenmiljöer som dränerar en aktiv SSJ. Aktiv SSJ innebär svårigheter att uppnå de svenska miljömålen som beslutades av den svenska regeringen 1999. Undersökningar om utbredningen av SSJ i Sverige har framförallt gjorts längs den norra kustremsan, Västerbotten och Norrbotten, men upptäckter har även gjorts i Mälardalen och Skåne. Under ett byggnadsprojekt i Falkenberg år 2019, ledde eroderade vattenpumpar, närvaro av gulaktigt vatten med lågt pH och höga koncentrationer av svavel till slutsatsen att SSJ finns i området. Syftet med denna studie var att undersöka utbredning och förekomst av SSJ i Falkenberg, på Sveriges västkust, att klargöra dess bildningsmiljö, samt att utvärdera möjligheten att använda ERT metoder som en identifikations metod för dessa jordar på den svenska västkusten. Projektet utfördes från september 2019 till juni 2020 i from av en masteruppsats på Göteborgs Universitet, i samarbete med SGU. Provtagning av jord utfördes under hösten 2019 med en förläggningsbar Edelmann borr. Prover togs i områden som under tidigare jordarskartering konstaterats utgöras av sediment med hög organisk halt. Jordprover togs för oxidering och vidare analyser i laboratoriet, inkluderat metall och S analyser. Efter oxidering av jordproverna kunde det konstateras att både aktiv och potentiell SSJ förekommer i Falkenberg. Fyra lokaler klassades som aktiva SSJ och en lokal klassades som potentiell SSJ. Detta är den första upptäckten av aktiv SSJ utanför den baltiska bassängen i Sverige. Alla observationer av SSJ gjordes nedanför 13 m.ö.h., i lergyttja, gyttjelera och sand. När platserna för dessa lokalerna var fastställda utfördes ERT mätningar på en av dessa, H19001, under november 2019 och februari 2020. Resultaten visade att det var möjligt att skilja SSJ från omgivande sediment på denna lokal. Formationsmiljön för SSJ på den svenska västkusten skiljer sig från den längs norra Sveriges kustremsa, och tros ha utgjorts av grunda skyddade laguner och havsvikar under Tapes transgression.

Nyckelord: Sura sulfatjordar på den svenska västkusten, formationsmiljö, Tapes transgression, Resistivitetsmätningar, Baltiska bassängen

Abbreviations and terminology used for soil type description

Cl – Clay

Cl sagr – Clay with a layer of sand and gravel

gyCl – gyttja clay, a clay with high organic content and ‘yeast’ structure

grsasiCl – gravely sandy silty Clay where clay is the dominating soil type

gyCl – gyttja Clay where clay is the dominating soil type

safCl – fine sand in Clay where clay is the dominating soil type

sagr – sandy gravely thinner layer

saSi – sandy Silt where silt is the dominating soil type

sasiCl – sandy, silty Clay where the clay is the dominating soil type

siSa – silty Sand where sand is the dominating soil type

siclSa – silty clayey Sand where sand is the dominating soil type

Glossary

Dry crust clay/soil – is present in the uppermost clay/soil layers and is caused by drying, ground frost, and weathering. The weathering can result in ion exchange and alteration of the clay mineral. The cracks in the dry crust clay/soil affect the microstructure so that drainage goes faster than the permeability of the soil would allow. (Larsson, 2008)

Fennoscandian ice sheet – The ice sheet that, during the Weichselian glaciation (c. 115,000 – c. 11,700 years ago) reached out from the Scandinavian mountains to the east-coast of Schleswig-Holsten, the March of Brandenburg and Northwest Russia (Weichselian glaciation. (n.d.) From Wikipedia. Retrived 2020-04-09 https://en.wikipedia.org/wiki/Weichselian_glaciation).

Holocene – a warm period (interglacial) with its onset app. 11 ka y. B.P. (Harff, Björck, & Hoth, 2011)

Hydraulic conductivity – is a coefficient that describes the speed at which a fluid can flow through a medium (Fetter, 2014).

ICP – SFMS – An isotope analysis method in which a magnetic sector is used as the mass analyzer (SF = sector field). This method gives a high mass resolution. Under optimum conditions the precision in isotope ratio measurements is better than 0,05 % relative standard deviation (ALS, (n.d.). Isotope laboratory. From ALS. Retrieved 2020-05-31 from https://www.alsglobal.se/en/isotope-analysis/laboratory)

Littorina Sea stage – A brackish stage of the Baltic Sea basin, 8500-3000 ^{14}C y.B.P. that had a salinity about twice as high as today (Ekman, 1953; cited in Sohlenius, Sternbeck, Andrén, & Westman, 1996). When mentioning the Littorina stage in Denmark it refers to the highest elevation of the sea 5750 – 2650 y. B.P((Christensen & Nielsen, 2008).

Oxidized zone – The oxidized zone is the zone above the ground water table where oxygen has entered the soil pores. The oxidized zone can again become reduced when saturated so that reducing reactions initiate.

Postglacial isostatic rebound – During the Pleistocene, the weight of the ice sheet pressed the bedrock downwards by several 100 m. When the ice sheet melted, a pressure release occurred. The equalization of this pressure difference is continuing today causing an uplift of the crust. After the ice sheets retreat, the rebound of the bedrock was in an initial state rapid but has today tapered off to around 9 mm/year (Johansson et al, 2004; Eronen, 2005).

Reduced zone – The reduced zone is the zone in the soil that is situated below the ground water table and where oxygen has not entered hence no reactions between elements bound in the soil and oxygen have taken place.

Regression - (marine) regression occurs as submerged seafloor or land surface is lifted above sea level. (marine regression. (2018). From Wikipedia. Retrieved 2020-05-20 https://en.wikipedia.org/wiki/Marine_regression

Tapes transgression – is the maximum transgression that followed the initial post-glacial regression. In Falkenberg it reached a maximum around 6500 y. B.P. and then reached a level of 12 - 13 m.a.s.l. (Påsse, 1988 unpublished). The transgression was initiated around 8500 y. B.P.

and led to the opening of Öresund and Great Belt, and the formation of the Littorina Sea (Lundqvist, Lundqvist, Lindström, Calner, & Sivhed, 2011).

Transgression – a (marine) transgression is a geological event when the sea level rises and the shoreline therefore moves landwards, to higher elevations. This results in the land surface being flooded by ocean water. Transgressions can be caused by (1) land subsidence, (2) a larger volume of water in the ocean or (3) the ocean basins capacity (volume) is decreasing. (Marine transgression. (2019). From Wikipedia. Retrieved 2020-05-20 https://en.wikipedia.org/wiki/Marine_transgression

Contents

1. Introduction

Acid sulphate soil (AS soil) exists in many places in the world including Southeast Asia, West Africa, eastern Australia, Latin America, and Europe (read in Boman, 2008 from Andriesse & van Mensvoort, 2006), and is common along coastal areas that once were covered with saline/ brackish water or in anoxic wetlands, tidal swamps, and sometimes in lake sediment (Dent & Pons, 1995; Becher, Sohlenius, & Öhrling, 2019; Åbjörnsson & Stenberg, 2017). The sediment in which AS soil develop is usually originally deposited as organic-rich, fine grained material. Following deposition, degradation of the organic material generates an anoxic environment where sulphate-reducing-bacteria decompose the organic matter. This process forms iron sulphide, resulting in sulphide-bearing sediment (parent material for AS soil). Sulphide-bearing sediment constitute no harm in waterlogged condition; and is in this state termed 'potential acid sulphate soil' (potential AS soil). Problems arise when the sediment are exposed to oxygen, especially in soil that lacks adequate buffering capacity. When iron sulphide oxidize, sulphuric acid is created, resulting in an acidic environment. The chemical reaction leads to pH values as low as 3 or even 2 (Pousette, 2010; Dent & Pons, 1995). In oxidized condition the soil is termed 'active AS soil'. The acidification entails negative environmental effects as it releases metals that prior to acidification had been bonded in the soil particles. The release of metals can kill or harm vegetation and aquatic organisms as well as pollute ground- and surface water bodies (Dent & Pons, 1995). Furthermore, AS soil have low stability and can be problematic during construction work (Pousette, 2010).

As the Fennoscandian Ice Sheet retreated, many coastal parts of Sweden were covered with water because the crust had become isostatically depressed beneath the ice sheet. The highest elevation reached by these former seas is referred to as the 'marine limit' or the 'highest coastline'. The Baltic Basin went through a series of stages and the saline concentration of the water fluctuated with them. During the stage of the Littorina Sea (Fig. 1) salty, nutrient-rich ocean water entered the Baltic Sea through Öresund and Great Belt (Westman & Sohlenius, 1999). The highest elevation reached during this stage is called the 'Littorina limit' (Lindqvist, Lindqvist, Lindström, Calner, & Sivhed, 2011). During this stage, organic-rich sediment was deposited at depth on the seafloor and in bays where little mixing of the water occurred. This implies an environment conducive for the formation of sulphide soil, as small amounts of oxygen are supplied to the bottoms and the lack of mixing allows for deposition of the organic matter before complete degradation. The reducing condition is also caused by oxygen consuming bacteria during the degradation of the organic material. Today, many areas whit this sediment are situated above (present) sea-level due to the post-glacial rebound.

AS soil is common on the west coast of Finland and in the northern coastal parts of Sweden, where they mainly have been observed under the Littorina limit. This, because of the history of the Baltic basin and the higher rate of the post-glacial rebound in the northern parts of the Fennoscandian shield that caused a larger area of Littorina-Sea sediment uplifted above sea-level. Earlier studies on AS soil has chiefly been focused on the northern coastlines of Sweden, and consequently, the distribution in other parts of Sweden is not well known. Nonetheless, some studies have discovered AS soil in other parts of Sweden. Areas with AS soil have been found in Mälardalen, and a recent discovery of active AS soil was found in paleo lake sediments in a region close to Kristianstad, Skåne (Åbjörnsson, Stenberg, & Sohlenius, 2018). AS soil is also rather common in Denmark, predominantly in wetlands (Beucher, Adhikari, Breuning-Madsen, Greve, Österholm, Fröjdö, Jensen, & Greve, 2016). In both Sweden and Finland, it is common to find potential AS soil underneath peat layers, because peat covered areas has such a groundwater table that hinders oxidation of the sulphide. To be able to cultivate crops on such land, drainage is needed (Boman, Becher, Mattbäck, Sohlenius, Auri, Öhrling, & Eden, 2018). When peatlands are drained, the peat layer will slowly disappear as it is oxidized, and further drainage is necessary. This can lead to oxidation of underlying potential AS soil and lead to the formation of active AS soil (Becher, Sohlenius, & Öhrling, 2019). It has been estimated that approximately 5 %, or 140 000 hectares, of agricultural land in Sweden is situated on AS soil (Åberg, 2017, Öborn, 1994), although this number may be a low estimate considering the new findings in Mälardalen and Skåne.

To avoid the problems that arise when a potential AS soil is oxidized, it is of importance to identify the distribution and status of the soil. Often, it is possible to get a hint of their presence by certain field characteristics like the colour (section 2,5). Geophysical investigations using resistivity (ERT) have been a successful identification tool of sulphide soils in earlier studies on the Swedish north coast, in Mälardalen and in Finland. This method can enable identification of AS soil over a large area in less time than traditional drilling. Drilling will still be needed together with ERT methods. This, because the ERT values of AS soil vary largely. It is unknown if it is possible to use this method for identification on the Swedish west coast. Due to the occurrence of marine and quick clays being more frequent on the west coast, it might not be possible to distinguish sulphidic soils from these clays. This, because the resistivity decreases as the salinity in the sediment increases (Rankka, Andersson-Sköld, Hultén, Larsson, Leroux, & Dahlin, 2004).

AS soil has a large part to play in Sweden's environmental goals. The Swedish Parliament established 16 environmental goals in 1999 for a more sustainable ecological future (Sveriges miljömål, 2019). Active AS soil create difficulties to reach the goals that refer to; good quality on groundwater, a living aquatic environment in streams and lakes, an environment free from pollutants, natural acidification only, a sea in balance and a living archipelago, swarming wetlands, and a multitudinous vegetation- and animal life (Åberg, 2017). This is because active AS soil affects water bodies with heavy metals, harms vegetation and microbiota, and in several cases have led to fish populations being killed. Active AS soil leads to impairment of spawning grounds for fish (Åström, & Björklund 1995), thus resulting in a decline in these fish populations. Additionally, the acidification seen in water and soil caused by active AS soil is (almost) solely a result from anthropogenic activity like lowering of the groundwater (Åberg, 2017), even if the formation and uplift of AS soil is a natural process.

The marine history of Sweden's west coast and the Kattegat Sea, where the study area Halland is situated (Fig. 1), differs from that of the Baltic Sea's. Parts of Sweden's west coast was also covered by water at several different stages (Fig.1). But the Kattegat Sea was never isolated from the ocean, and hence the supply of salty- organic-rich water was not as limited. Following deglaciation, the maximum marine limit varies between the southern and northern parts of Halland due to differences in the crustal rebound. The area also has a history of regressions and transgressions that have influenced the sediment today situated on land. The Tapes transgression is the highest of these transgressions (also called the postglacial limit) and was initiated around 9.5 ka cal y.B.P. In the southern parts of Halland it reached a maximum of 10 m.a.s.l., while in the middle parts of Bohuslän it reached 30 m.a.sl. (Lundqvist, Lundqvist, Lindström, Calner, & Sivhed, 2011) (See section 3.1). Despite its marine history, the Swedish west coast has had no investigations of AS soil. The Geological Survey of Sweden (SGU) now wants to investigate the existence and possible extent of AS soil on the Swedish west coast, specifically in the areas Falkenberg and Viskadalen. This thesis is one of two parallel investigations on this topic and will focus on Falkenberg municipality and its vicinity, while the parallel investigation will focus on Viskadalen (Bergström, InPress). In Falkenberg, organic-rich, sulphide fetid soil samples have been observed in earlier investigations concerning the Quaternary development of the area carried out by Tore Påsse (1982 - 1983, geologist at SGU). More recently, during a construction in the city of Falkenberg, lowering of the groundwater led to corrosion of water pumps, precipitation of metals, and presence of yellowish water (S. Bjurström, personal communication, 2020-01-27, construction project manager at Falkenberg municipality). According to U. Hempel (personal communication, 2020-02-26, environmental consultant at WSP) measurements in the drainage water showed a sulphide concentration of 500 - 600 mg/l and a pH value of 3; this is a strong indication that AS soil exists in the area. Furthermore, if active AS soil is discovered in this project, an investigation about its influence on the aquatic environment in the area will be carried out by a fellow student at the University of Gothenburg (Lindgren, InPress).

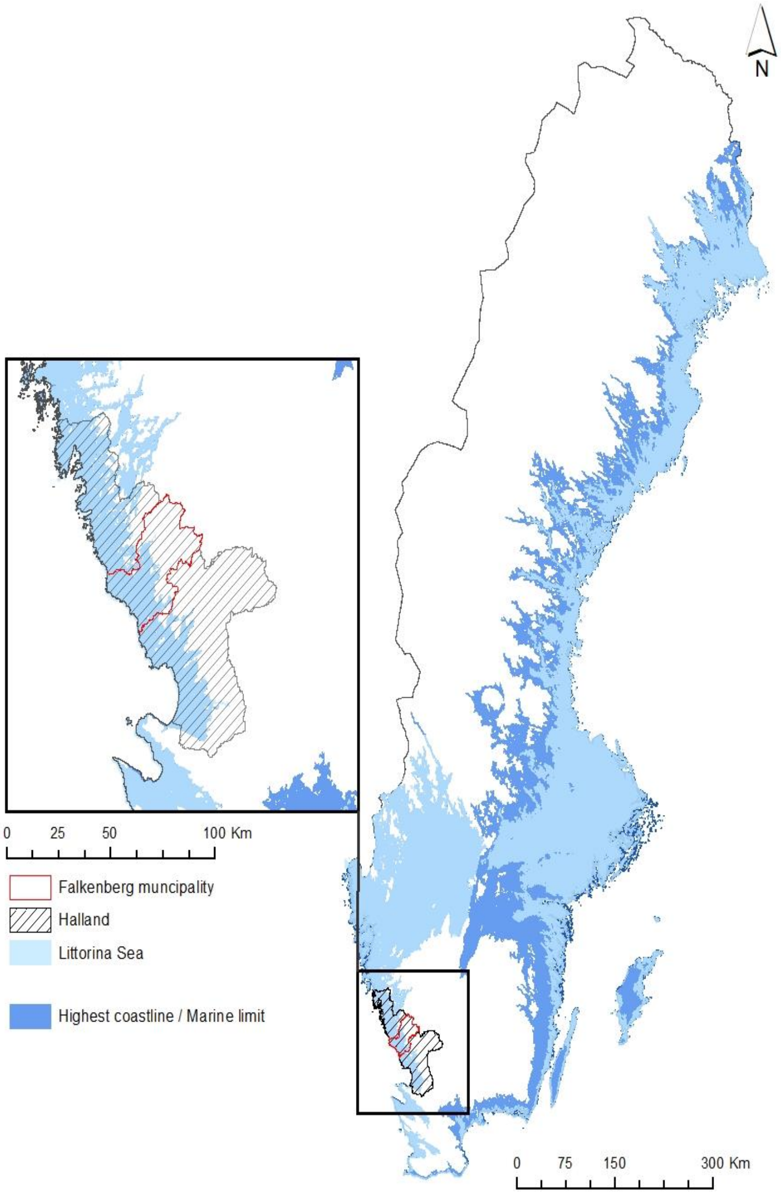


Figure. 1. The light blue area represents the highest elevation reached by the Littorina Sea in the Baltic Basin on the east coast of Sweden, also referred to as the marine limit in these parts; in the western parts it represents western sea extent (marine limit). The marine limit of the western sea equals the highest coastline (HK) on the west coast of Sweden. The darker blue area represents HK in the Baltic basin.. The study area Falkenberg is highlighted with red, and the county of Halland with lines. Data source: Sweden outline retrieved from DIVA-GIS ©; Halland and Falkenberg outline retrieved from DIVA-GIS ©; Highest coastline/Marine limit and Littorina Sea, retrieved from SGU© provided by Gustav Sohlenius.

1.2 Aim and research questions

This project aimed to investigate if AS soil occur on the Swedish west coast as well as to increase the knowledge of the extent and distribution of AS soil. In addition, it is thought that increased knowledge on their distribution will shed light on how sulphidic soils form. Drilling was performed with an extendible Edelman auger to collect soil samples for pH measurements and further laboratory analyses. To evaluate suitable geophysical identification methods for AS soil on the west coast, ERT measurements were carried out at selected sites where AS soil was discovered.

1.2.1. Specific research questions

- Is it possible to prove or discover the existence of AS soil in Falkenberg municipality? And in that case are they potential or active AS soil?

- If present, in what kind of environment did the AS soil in Falkenberg form? Is it possible to say anything about the characteristics of the soil in which they most commonly occur in? In what way do the findings correspond to the mapping data from Påsse?

- If AS soil is discovered, is it possible to differentiate them from their surrounding sediments by their ERT?

2. AS soil

AS soil is commonly associated with fine-grained, sulphide-bearing sediment (<63 µm), but a recent study by Mattbäck, Boman, and Österholm (2017) showed occurrence in coarser grain sizes (≥ 63 µm) in Finland. And in Australia, the presence of acidic properties in coarser grain-sized sediment has been known for long (Dear, Ahern, O'Brien, Dobos, McElnea, Moore, & Watling, 2014).

2.1. Formation of potential and active AS soil

The formation of a sulphide-bearing sediment occurs in the following way. Degradation of accumulated organic matter consumes oxygen, sometimes to such an extent that the environment becomes oxygen-free (anoxic). In an anoxic environment, the bacteria will reduce sulphate (SO_4^{2+}) to hydrogen sulphide (H_2S) and trivalent iron (Fe^{3+}) is oxidized to divalent iron (Fe^{2+}) allowing for the formation of iron sulphide. This is what constitutes a potential AS soil. Often iron monosulphides (FeS) is formed (eq. 1) (Becher, Sohlenius, & Öhrling, 2019). Under certain conditions the monosulphides can react with sulphur, and pyrite (FeS_2) is formed (Eq. 2) (Becher et al., 2019).

$$FeOOH \ + SO_4^{2+} + \frac{9}{4CH_2O} + \ 2H^+ \rightarrow \ FeS \ + \frac{9}{4CO_2} + \frac{15}{4H_2O} \qquad \text{(eq. 1)}$$

$$SO_4^{2+} + Fe^{3+} \rightarrow \ H_2S + Fe^{2+} \ \rightarrow FeS_2 \qquad \text{(eq. 2)}$$

When the sediment is exposed to oxygen both chemical and biological reactions are initiated, and an active AS soil is formed. The iron sulphides are then oxidized to sulphuric acid (H_2SO_4) and iron deposits like goethite (α-FeOOH↓) or jarosite ($KFe^{3+}{}_3(SO_4)_2(OH)_6$↓) through complex processes by different species of sulphur bacteria (Eq. 3 & 4). The oxidation process facilitates by cracks formed in the dry-crust soil as a result of the drainage, which allows for even more oxygen to enter (Becher, 2019). A result of the oxidation is that sulphate is produced, and the pH is decreased.

$$FeS_2 + \frac{15}{4O_2} + \ \frac{7}{2H_2O} \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \qquad \text{(eq. 3)}$$

$$2FeS + \frac{18}{4O_2} + \ 5H_2O \rightarrow 2Fe(OH)_3 \ + 2SO_4^{2-} + \ 2H^+ \qquad \text{(eq. 4)}$$

2.2. Acidifying potential

The amount of sulphur that an AS soil contains relates to its acidifying potential, and a sulphur content < 0,06% will not have a significant acidifying effect (Pousette, 2010).The Fe/S-ratio will also influence the acidifying effect, where a ratio < 3 generally give a high acidic effect (low pH values), and a ratio > 60 will give an insignificant acidifying effect according to Pousette (2010). The acidifying effect also relates to the organic content and buffering capacity of the soil, where a high organic content and a high buffering capacity will slow the acidic effect (Pousette, 2010). An oxidized active AS soil can again become reduced if being waterlogged and anoxic (Pousette, 2010).

2.3. Problems related to AS soil

2.3.1. Negative effects on the environment and human health

AS soil creates environmental and health concerns because a pH lower than 4 leads to chemical reactions that mobilizes metals bound in soil particles (Pousette, 2007). This leads to several negative effects in aquatic environments draining AS soil. The cracks seen in the dry-crust soil is an important cause for the elements being leached through runoff (Becher et al., 2019). Furthermore, a chronic exposure to elevated metal concentrations can pose an actual threat to human health (Fältmarsch, Åström, & Vuori, 2008).

In Finland, the total release of the metals Aluminum (Al), Cadmium (Cd), Cobalt (Co), Manganese (Mn), Nickel (Ni), and Zinc (Zn) into the environment and the Baltic Sea through runoff from AS soil, have been proven bigger than the total release of these metals from the Finnish industry (Sundström, Åström, & Österholm, 2002). Studies performed by SGU found that plants growing in streams connected to active AS soil contains high concentrations of metals (e.g. Lax, 2005). In Finland, it has been shown that sediment in bays where streams draining areas with active AS soil ends, likewise contain high amounts of metals (Nordmyr, Åström, Peltola, 2008). Österholm and Åström (2004) calculated that, after trenching of an area with AS soil, it takes nearly 30 years for the load of metals and sulphur to be halved, and even longer for the negative effects on the environment to reach acceptable values. A low pH and high metal concentration can affect many organisms in the soil and the aquatic environment, and drainage to nearby water streams can, in some cases lead to fish death. Trout and roach are very sensitive to low pH in water (Becher et al., 2019). In Finland, several cases of fish death led to an investigation of the extent of AS soil by the Finish geological survey (GTK) in 2009 (Sohlenius, Aroka, Whålen, Uhlbäck, & Persson, 2015).

Whether or not active AS soil harms human health is not well known, but according to Fältmarsch et al. (2008) the studies done are alarmingly few. A correlation between consumption of milk from cows grazing grass grown on AS soil, and multiple sclerosis (MS) has been demonstrated in a study by Alhonen, Mantere-Alhonen, and Vuorinen, (1997). The link between Parkinson's (PD) and Alzheimer's (AD) diseases and AS soil that has been demonstrated in several studies are discussed in a literature review from Fältmarsch et al. (2008). In their study, they found that iron (Fe) was enriched in oats grown on AS soil, and in cow milk from cows grazing grass grown on AS soil. Furthermore, Al showed high enrichment in cow milk, while Zn instead was found to be enriched in AS soil drainage-waters. Cornett, Markesbery, and Ehmann (1998) found a statistically significant link between AD and high amounts of Zn and Fe in the brain. Regarding PD, a link with continuing exposure to the individual metals Mn and copper (Cu), and the combined metals Fe-Cu, Lead (Pb)-Fe, Cu-Pb have been demonstrated in a study (Gorell, Peterson, Rybicki, & Johnson, 2004). Additionally, a significant association with Mn and PD was shown in a study performed by Gorell et al. (1997, 1998, & 1999). Mn is found in high concentrations in waters draining AS soil, as well as a widespread dispersion in crops grown on AS soil. In short, the links found between the metals and AD and PD and the fact that these metals are enriched in active AS soil landscapes should be a reason to study its influence on the human health, as well as its distribution.

2.3.2. Geotechnical properties of AS soil and its impact on the built environment

The problems related to AS soil is not restricted to the biosphere. The acidity can cause corrosion on pipes and other underground metal or concrete constructions (Dear, et al., 2014), which leads to a shorter life span and thus increased costs as replacement will be required. Additionally, the mobilization of Fe ions causes problem in drainage pipes as the Fe is precipitated in contact with alkaline water (Màcisk, 1994). Housing and infrastructure foundations risks being damaged by the corrosion that active AS soil is causing on concrete and metal reinforcement. This is because concrete breakdown can be accelerated by several minerals forming after FeS_2 oxidation (Dear et al., 2014). Additionally, AS soil have high water content and a high yield point, which in turn relates to their high compressibility, low undrained shear strength, and their vulnerability to creep deformation (Pousette, 2007). Soil with these characteristics show subsidence and low stability (Larsson, Westerberg, Albing, Knutsson, & Carlsson, 2007; Westerberg & Andersson, 2009). Traditional stabilization binders like cement and lime are less effective in AS soil, and other binders are thus needed to reach acceptable stability (Andersson, & Norrman, 2004).

2.4. Distribution and characteristics of AS soil in Sweden

2.4.1. Västerbotten and Norrbotten

Along parts of the northern coast of Sweden, the presence of AS soil has been known for a long time (see Sohlenius et al., 2015). The distribution of AS soil coincides with the distribution of silty and clay-rich soil (fine-grained soil) shown on SGUs soil-type maps (Sohlenius, Aroka, Wåhlén, Uhlbäck, & Persson, 2015). However, the most fine-grained sediments in this area of Sweden are often found superimposed by fluvial- or wave-washed sediments (Sohlenius, Persson, Lax, Andersson, & Daniels, 2004). The sedimentation of AS-soil parent material took place at depth during the time of the Littorina Sea (Sohlenius et al., 2004). Most observations of AS soil occur below 55 – 60 m a.s.l., which indicates sediment uplifted less than 5,0 ka y. B.P. (Sohlenius et al., 2015). Only a few observations have been made at 80 m.a.s.l. in sediment older than 6,5 ka years. However, only 7 investigations were made at this elevation, to compare with 300 investigations performed at 55 – 60 m.a.s.l. (Sohlenius et al., 2015). Most of the sites with observed AS soil were covered by water 3500 years ago and are today situated 35 – 40 m a.s.l. (Sohlenius et al., 2004). The total area with AS soil in Norrbotten and Västerbotten is estimated to be at least 600 km^2 (Sohlenius et al., 2015).

2.4.2. Mälardalen

The presence of AS soil in Mälardalen often coincides with the occurrence of 'gyttja clay' (organic-rich clay) on SGUs soil-type maps. Most observations in Mälardalen are from low-relief areas that 2000 years B.P. consisted of protected, shallow bays with a sea-level 10 m above present (Sohlenius, Persson, Lax, Andersson, & Daniels, 2004).

2.4.3. Skåne

Åbjörnsson et al., (2018) found 5 areas with active and potential AS soil in Skåne. The dominating soil type that active and potential AS soil was found in were gyttja, and gyttja clay. But AS soil was also found in coarse-, medium-, and fine-grained sand (Åbjörnsson et al., 2018). Three of the observed areas are situated in lake sediment. One of the two other areas consisted of a strait 2000 y. B.P. that connected Skälderviken to Öresund, and the other area consisted of a shallow bay surrounded by peatlands during the Littorina-Sea stage (Åbjörnsson, 2018).

2.5. Field characteristics of AS soil

Colour, thick rust/iron precipitates, smell of sulphur, and minerals such as $KFe^{3+}_3(SO_4)_2(OH)_6$, are characteristics that can be observed in field and hint that the soil could be an AS soil. The colour of AS soil differs between the north and the south of Sweden. The AS soil of northern Sweden generally have a black colour and is hence given the name '*Svartmocka'* (English translation: Black 'suede' soil*)*. The black colour is caused by the dominating sulphide mineral being FeS (Sohlenius et al., 2004). In Mälardalen, the dominating sulphide mineral is FeS_2 and the colour is instead influenced by the gyttja content of the soil, hence the typical colour is slightly green (Sohlenius, 2011). The sandy AS soil can however be difficult to identify by colour, although they occasionally can have a dark grey colour (Becher et al., 2019).

A typical AS soil generally consists of three zones; one unsaturated zone, a transition zone, and a saturated zone situated below the lowest groundwater table. The unsaturated zone can have a pH-value of < 4, which then successively increases downwards the profile to reach a pH-value > 7 in the saturated zone (Pousette, 2010; Becher et al., 2019). This pattern will give a typical look to a pH curve plotted against depth (Åström, 2001 Fig. 2). The unsaturated zone (the dry-crust soil) usually has substantial amounts of rust precipitates in the cracks; this is generally more common in the northern parts of Sweden (Becher et al., 2019). Occasionally, these rust precipitates can be seen in waterways that stand in hydraulic connection to active AS soil. At times the water can be clear due to the acid condition causing particles to flocculate and settle (Becher et al., 2019). At other times Al is precipitated in waterways, consequently giving the water a cloudy character (Becher et al., 2019).

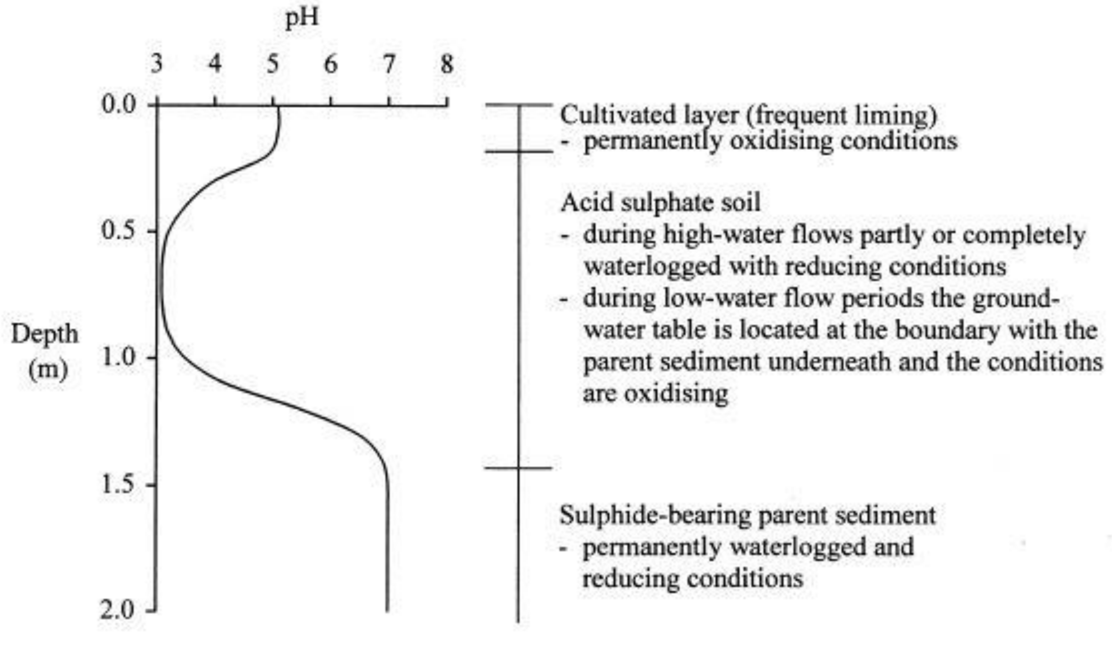
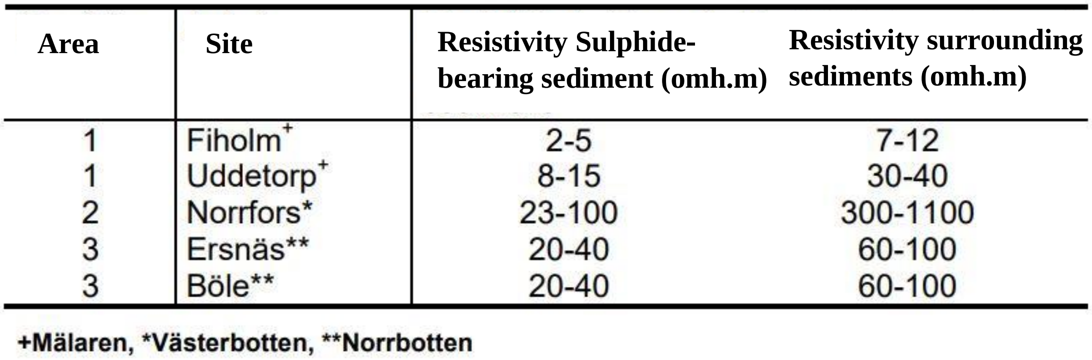


Fig. 2. An illustration of the typical pH curve plotted against soil depth for an active AS soil, where the pH in the upper part of the soil horizon have a slightly higher value caused by liming. The pH-value is then decreasing in the oxidized zone, and increasing again in the reduced, waterlogged zone. Picture from Åström, 2001.

2.6. Geophysical measurements as an identification tool for AS soil

ERT measurements at AS soil sites in Sweden have been performed in Norrbotten, Västerbotten, and Mälardalen in 2007 as an evaluation of the suitability of geophysical methods to differentiate AS soil in the field (Sohlenius, Persson, & Bastani, 2007). The measurements showed that AS soil has a lower resistivity than surrounding fine-grained sediment and hence, can be distinguished from the surrounding fine-grained non-sulphide sediment (Sohlenius et al., 2007). The lower resistivity that AS soil exhibit is thought to be caused by the relatively high concentration of chloride and sulphide in the soil, as these elements cause low resistivity (Sohlenius et al., 2007; Suppala, Lintinen, & Vanhala, 2005). The study also found that the AS soil along the northern coast of Sweden (Västerbotten and Norrbotten) have a higher resistivity than in Mälardalen (table 1, from Sohlenius et al., 2007). This could relate to the occurrence of AS soil in Mälardalen (gyttja clay), as clay have a lower resistivity than silt, in which AS soil often occur in along the northern coast (Sohlenius et al., 2007).

Table 1. Resistivity values of AS soil sites investigated by Sohlenius et al., 2007. Table from Sohlenius et al., (2007), modified to English.



Area	Site	Resistivity Sulphide-bearing sediment (omh.m)	Resistivity surrounding sediments (omh.m)
1	Fiholm+	2-5	7-12
1	Uddetorp+	8-15	30-40
2	Norrfors*	23-100	300-1100
3	Ersnäs**	20-40	60-100
3	Böle**	20-40	60-100

+Mälaren, *Västerbotten, **Norrbotten

3. Quaternary history

3.1. Deglaciation processes in Halland and Quaternary development of Falkenberg

Halland was deglaciated between 15-17 cal ka B.P. (Stroeven et al., 2016) (Fig. 4 from Dahlqvist et al., 2019). C^{14} dating of shells found in glacial clay in the Falkenberg region suggests that the ice left the coastal plain around 17.0 ka cal y.B.P. (14.0 ka ^{14}C y. B.P.) (Påsse, 1988 unpublished). Several findings of Foraminifera have been observed in the glacial clay that reveals an arctic depositional environment with high salinity (Påsse, 1988). The topographic character of Halland consists of a bedrock dominated landscape with valleys (*sprickdaler*) that follow bedrock fractures. These fractures were deeply weathered during the Mesozoic and excavated during the Cenozic (Lidmar-Bergström, 1996). During deglaciation in Halland, the ice margin formed calving bays in the fracture valleys and fjords, evidence that relatively deep water existed (Hillefors, 1979). The dominating ice-flow direction during the deglaciation was from N 50°E (Påsse, 1988 unpublished). As the ice retreated portions of the land surface in Halland was situated below sea level, the marine limit, because of the isostatic depression. The marine limit in northern Halland reached a maximum level of 90 m.a.s.l. while in the more southern parts, Falkenberg included, the marine limit reached app. 55 – 65 m.a.s.l. (Länsstyrelesen Hallands län, 2011; SGU, n.d.; fig. 3 from Påsse, 1988 unpublished). The differences between the northern and southern parts is a result from the isostatic pressure differences of the ice. The coastal flexure being larger to the west, also caused the sea to reach larger depths at the coastal plains as compared to the inlands. Portions of the bedrock uplands in northern Halland were drowned by the late-glacial sea where water depths of about 10 – 20 m occurred (Hillefors, 1979). An approximation of the ice-margin retreat for the total area (map sheet Ae nr 86) is 500 years, and the deglaciation rate has been calculated to 65 m/year for the same area (Påsse, 1988 unpublished). From app. 17.0 ka cal y.B.P. to app. 10.3 ka cal y.B.P. a relative fast regression took place in Falkenberg and its vicinity caused by the isostatic rebound (Fig 3. from Påsse, 1988 unpublished). Following the post glacial regression, a protected bay evolved around 13.7 ka y. B.P. in the area of Ätran valley (area contoured with black in Fig. 4, from Dahlqvist et al., 2019). A transgression was initiated around 9.5 ka cal y.B.P. (8.5 ka ^{14}C y.B.P.) with smaller regression-phases . It reached a maximum of 12 – 13 m.a.s.l. in Falkenberg around 10.3 ka cal Y.B.P. (6.7 ka ^{14}C y.B.P.) (Påsse, 1998). This transgression is called the Tapes transgression (Lundqvist et al., 2011). Following the Tapes transgression, a regression to the present shore level took place (Fig. 3, Påsse, 1988 unpublished).

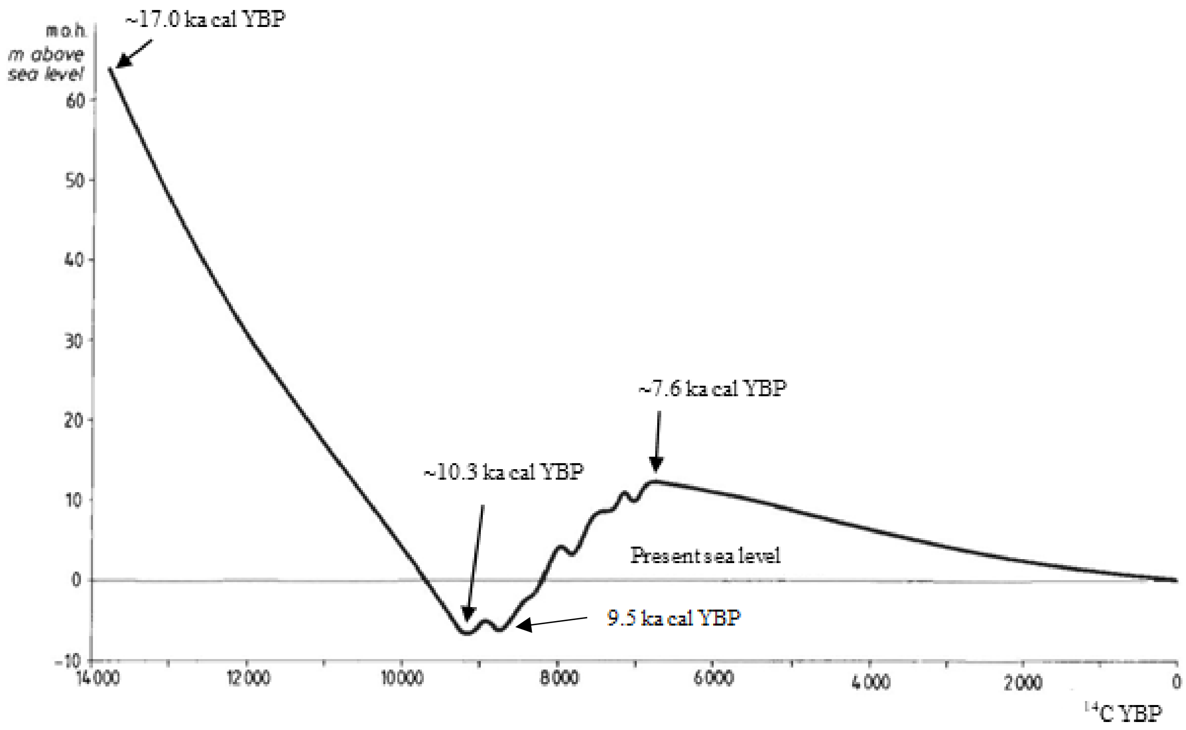


Figure 3. The shore-level displacement in the Falkenberg region from deglaciation till today, where the zero-line represent the present sea level (from Påsse, 1988 unpublished)The ^{14}C dates shown on the axis have been calibrated using the interface Oxcal 4.3 (Bronk Ramsey, 2020) and IntCal13 curve (Reimer et al., 2013). The transgression was initiated around 10.3 ka cal YBP (9.2 ka .^{14}C YBP), the Tapes transgression that reached its maximum level of 12 – 13 m.a.s.l. around 7.6 ka cal YBP (6.7 ka ^{14}C YBP) in the Falkenberg region.

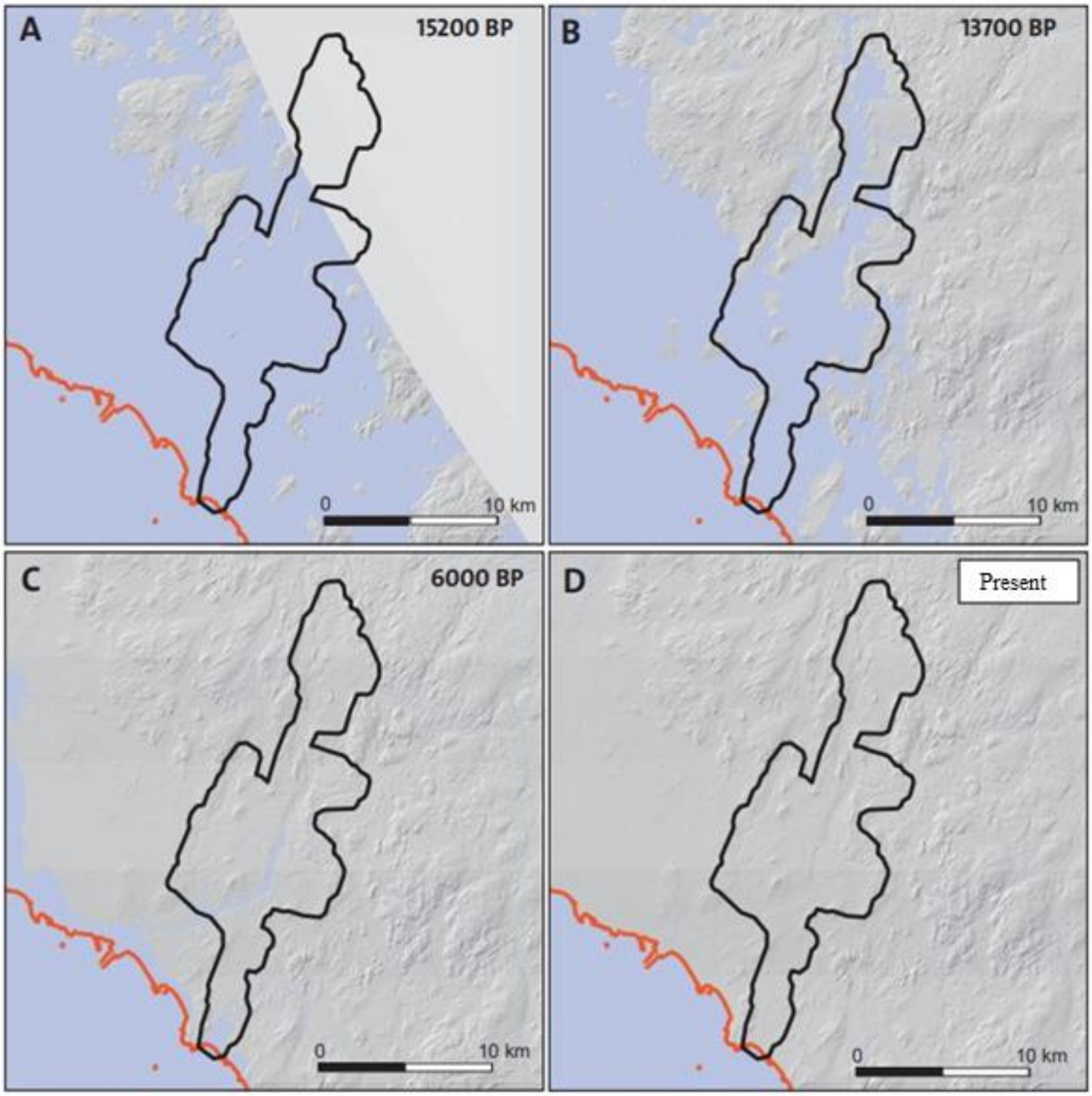


Figure 4. A reconstruction of the isostatic rebound in the Falkenberg region from the deglaciation till today (from Dahlqvist et al., 2019). The light grey area in A illustrates the ice margin. The red line represents the present shoreline, and the area inside the black line was examined with Airborne geophysics by Dahlqvist et al. (2019). Ätran valley are situated within this area and parts of it was investigated in this study.

4. Methods

4.1. Classification of AS soil

The Swedish-Finnish classification system for AS soil as described in *Klassificering av sura sulfatjordar I Finland och Sverige* (Boman et al., 2018) is applied to the classification of the locations as far as is possible. This classification defines an AS soil as a soil that contains sulphides (reduced condition/potential AS soil) or sulphates (oxidized condition/active AS soil) with a pH-value below 4 or prone to a decrease below 4. However, if the pH in field measures between 4 and 4,5 and this soil is underlain by a potential AS soil, the soil will still be classified as an active AS soil. The Swedish-Finnish classification also includes soil with a high organic content, such as peat and mire, but these need a decrease in pH to below 3 to be considered an AS soil (Boman et al., 2018). The system divides the soil into 7 different diagnostic materials (Table 2). The localities are then divided into 3 different types depending on what type of diagnostic material the soil constitutes (Table 3).This study will not investigate the diagnostic material of the sites (Table 2), but will solely use the pH measured in field and pH measured after oxidation of the soil samples for classification (Table 4).

Table 2. The Swedish-Finnish classification system will be applied to the classification of the locations in this study. The system divides the soil into 7 different diagnostic materials depending on the amount of sulphide content, water-soluble sulphate, and pH-value in field and after oxidation.

Soil material	[%]	Field pH	pH after oxidation
Sulphide material	≥ 0,01% dry weight sulphidecontent		
Hyper sulphide material		<4 (minerogenic soils) <3 (organic soils)	< 4 /< 3
Pseduo hyper sulphide material		<4 (minerogenic soils) <3 (organic soils)	< 4 - 4,5 / < 3 - 3,5
Hypo sulphide material		>4 (minerogenic soils) >3 (organic soils)	≥ 4,6 / ≥ 3,6
Mono sulphide material	≥ 0,01% dry weight acid volatile sulfide		
Sulphate material	≥ 0,05% water soluble sulfate	<4 (minerogenic soils) <3 (organic soils)	
Psedudo sulphate material		4 - 4,5 (minerogenic soils) 3 - 3,5 (organic soils)	

Table 3. Classification of sites based on soil material.

Classification of sites	Field pH
Acid sulphate soil	Soil with either sulphate- or hyper sulphide material, or pseudo material underlain by hyper sulphide material
Active acid sulphate soil	Soil with sulphate- and hyper sulphide material or pseduo sulphate material underlain by hyper sulphide material
Potential acid sulphate soil	Soil with hyper sulphide material

Table 4. Classification of sites based on their field pH and pH after oxidation as described above. The classification follows that of the Swedish-Finnish classification scheme.

Classification	Description
Active acid sulphate soil	Oxidized horizon with a field pH < 4 or a horizon with field pH < 4,5 underlain by a sulphide soil with a oxidized pH < 4
Potential acid sulphate soil	Reduced horizon where field pH is > 6 and after oxidation < 4
Non acid sulphate soil	Oxidized horizon with a field pH > 4
Non potential acid sulphate soil	Reduced horizon with a oxidized pH > 4

4.2. Calibration of ^{14}C dates

All radiocarbon dates retrieved from Påsse (1988 unpublished), or stated together with the abbreviation cal and given in this report, have been calibrated in this study with the interface OxCal (Bronk Ramsey, 2020) and Intcal13 curve (Reimer et al., 2013). The calibrated BC ages with the highest probability was used to calculate an average cal BC age. To retrieve calibrated ages in y.B.P. 1950 (present) was added to the calculated cal BC average.

4.2. Selection of sampling sites

Suitable sites for soil sampling were mainly located with the help of field observations of sulphide fetid soil made by Påsse (1986) that performed soil type mapping in the area. These observations are marked with a G on SGUs map sheet Ae nr 86 (Lantmäteriverket today Lantmäteriet, 1986) (appendix 1). The markings were made to show where in the area peat and clay gyttja were overlain by earlier (older) flood plain sediment. The map sheet was georeferenced in ArcGIS (Version 10.3.1; ESRI, 2016) and thereafter used in the selection. The following data was downloaded from SLUs download service 'geodata extraction tool': Jordartskartan (SGU), Höjddata_2M (Lantmäteriet), Orthophoto (Lantmäteriet), and Terrängkartan (Lantmäteriet). This data was used together with the observations from Påsse (1986) in the selection of suitable sampling sites in ArcGIS (Version 10.3.1; ESRI, 2016). The criteria for suitable sampling sites was based on the accessibility by car, the proximity to the markings on the map sheet, and located in low-lying terrain below the marine limit. Initially the sampling sites were planned to be carried out in different soil types to include coarser grain-sizes in the analysis (Fig. 5). This plan was later discarded as drilling in sandy soil types made it difficult to reach deep.

4.3. Site description

The study area is situated in Falkenberg municipality in the county of Halland. All the sampled sites are situated below the marine limit (Fig. 6). South of Falkenberg, the marine limit was situated 60 – 61 m.a.s.l., and north of Falkenberg at 63 – 64 m.a.s.l. (Påsse, 1998). Most of the sampled sites are located on cultivated fields and selected to be a minimum of 10 meters distance to waterways. A few samples were taken in central Falkenberg. A total of 15 sites were sampled.

The Quaternary sediments in the area of Falkenberg are a result of the earlier-mentioned deglaciation (section 3.1) together with the distribution and depth of the marine waters (Påsse, 1988 unpublished). The sediments are dominantly post-glacial in age, although some glacio-fluvial deposits, glacial clay, and till exists (Fig. 5). The dominating post-glacial sediment is wave-washed material up to a level of 15 m.a.s.l. The distribution of glacial clay in the region generally coincides with the valley of the river Ätran. In the outlet area of Ätran sand and silt have accumulated to a fluvial delta. The highest observed deltaic deposits are found at 15 m.a.s.l. (Påsse, 1988 unpublished). Excavations in the deltaic deposits have shown embedded layers with organic material, including peat. C^{14} dating of the peat layers gave an age of 7,5 ka cal y.B.P. (6,6 ka ^{14}C y. B.P.) (Påsse, 1988 unpublished). C^{14} dating have also been done north of Falkenberg in marine clay from two different transgression-phases, which have given an age of 8,0 ka cal y.B.P. and 7,6 ka cal y.B.P. (7,2 ka and 6,8 ka ^{14}C y. B.P) (Påsse, 1988 unpublished).

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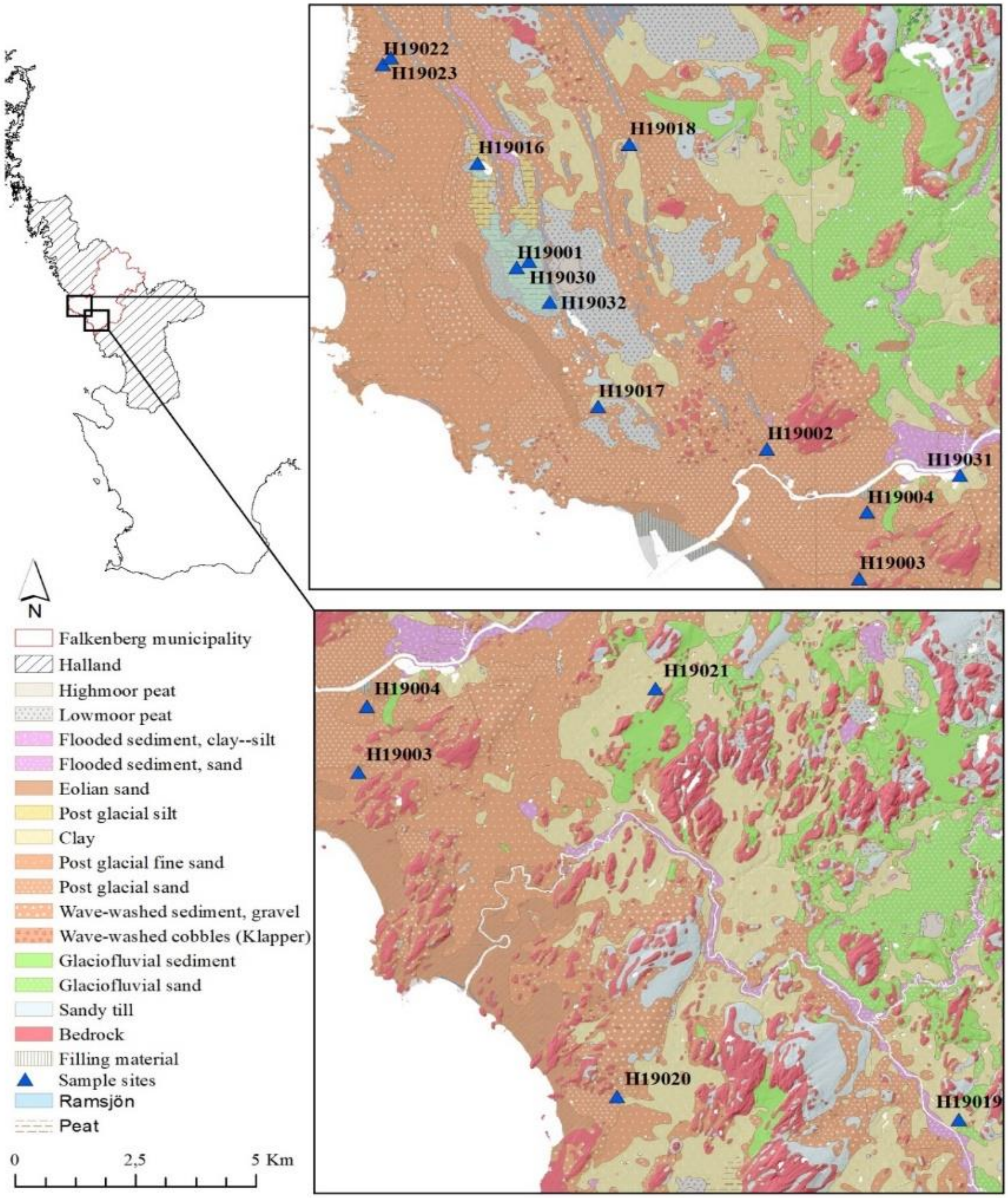


Figure. 5. The map illustrates the distribution of the sampled sites in Falkenberg. Ramsjön, the blue transparent area seen in the map, was a former lake that was drained in the 1900's in order to cultivate the land. The area of Ramsjön was retrieved from Ecknell C©. Data source: GSD Höjddata, grid 2+, retrieved from Lantmäteriet©; Sweden outline retrieved from DIVA-GIS ©; Halland and Falkenberg outline retrieved from DIVA-GIS ©; and Jordarter_25_100_jk2, retrieved from SGU©.

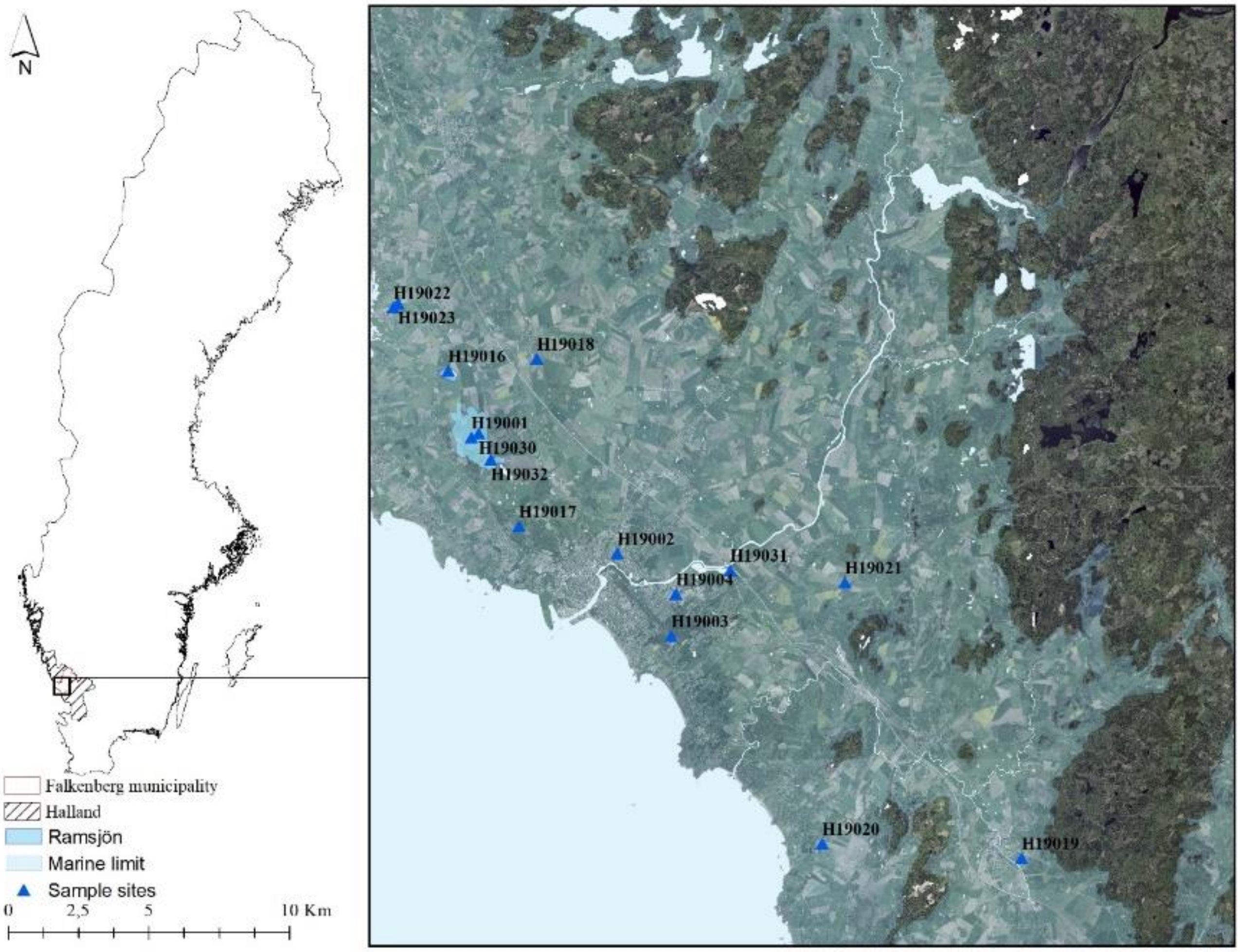


Figure. 6. All the sampled sites are situated below the marine limit as seen in the map. The marine limit is marked with transparent blue and represents the highest level reached by the seas on what today is land. A total of 15 sites were sampled in Falkenberg. Data source: Orthophoto, retrieved from Lantmäteriet©; Sweden outline retrieved from DIVA-GIS ©; Halland and Falkenberg outline retrieved from DIVA-GIS ©; and Högsta kustlinjen, retrieved from SGU© provided by Gustav Sohlenius.

4.4. Field work

During the period from the 26th of September 2019 to the 22nd of January 2020, soil sampling was conducted in both Falkenberg and Viskadalen. A total of 35 sites were sampled in both Viskandalen and Falkenberg, 15 of these located in Falkenberg and are a part of this study (Fig. 6). The elevation for the sample sites were retrieved in ArcMap (Version 10.6; ESRI 20) from a DEM-raster. Geophysical measurements were performed during 2019-11-20 and 2020-02-19 at one site in Falkenberg (Fig. 7).

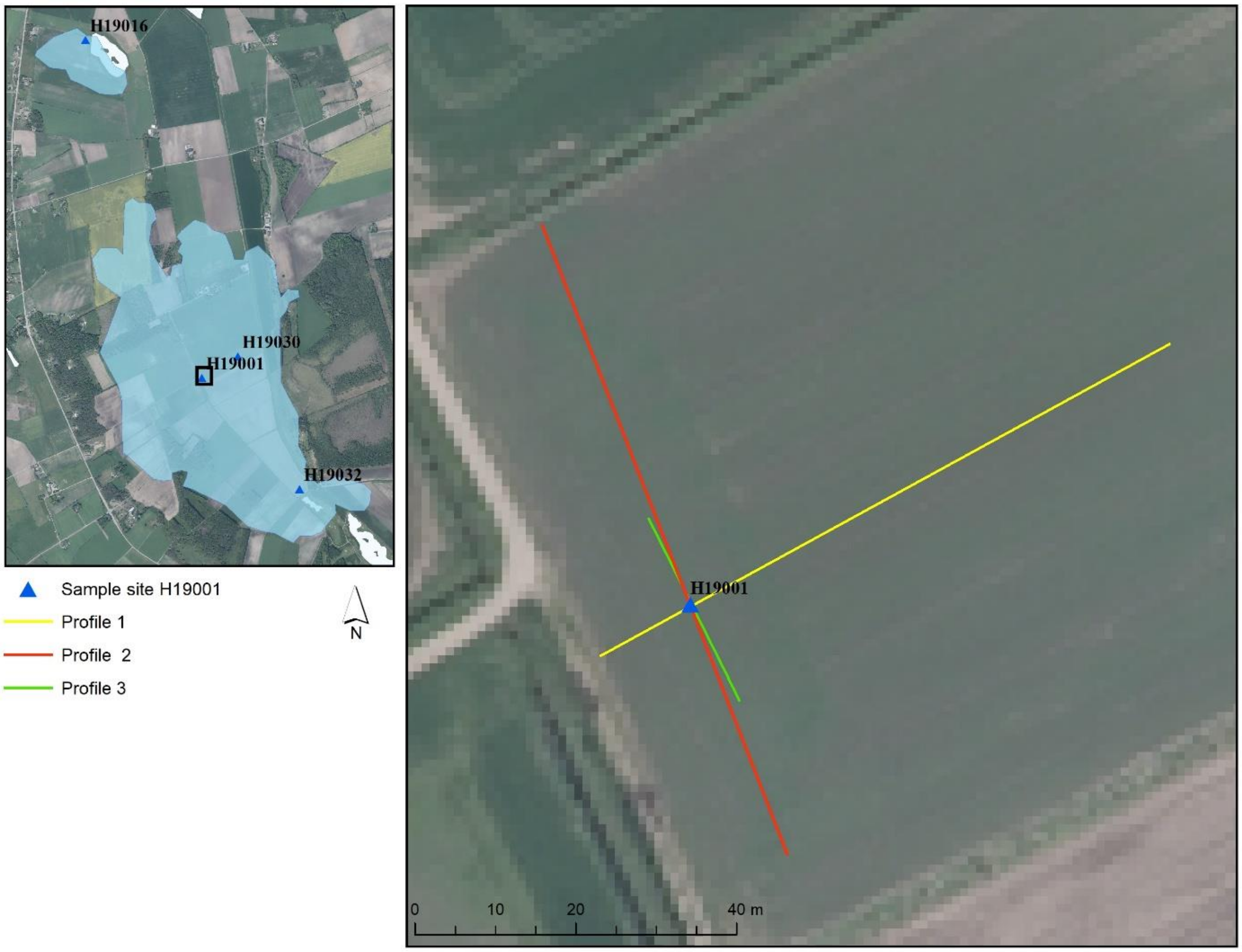


Figure 7. The yellow and red line represents the geophysical profiles that were made in 2019-11-20 at site H19001 after a 9 weeks oxidation period of the collected soil samples. The green line represents the geophysical profile that was made in field 2020-02-19. Data source: The area of Ramsjön was retrieved from Ecknell C©. Data source: Orthophoto retrieved from Lantmäteriet©.

4.4.1. Soil sampling

Soil samples were collected with an extendible Edelmann auger with a full length of 3,20 m. Soil was collected every 10 cm downwards in each hole as far as was possible. The soil was then placed along a folding rule next to the representing sampling depth, where pH-measurements were done with a WTW 340i (©Weilheim, 2004) directly, and thereafter soil type determination was done. Occasionally, soil colour was determined with a Munsell chart. Soil samples for oxidation in laboratory, grain-size analysis, and metal and sulphur analysis were collected for those samples that had (1) soil from the oxidized horizon (a pH close to 4,5 or below this), (2) soil from the reduced horizon overlain by an oxidized horizon (a high pH but below a soil with pH 4,5 or lower), (3) a dark coloured soil, (4) a soil that was identified as gyttja clay, or (5) a soil with rust precipitates. The soil samples were put in airtight plastic bags and stored in a refrigerator at the Department of Earth sciences in Gothenburg, Västra Götaland.

4.4.2. Geophysical measurements

ERT is an electric surveying method where electrical currents are induced into the ground to reveal the changes in resistance, which can help identify ground material. Different soils and sediments have a high range of and relatively characteristic electric conductivities, thus it is possible to distinguish different materials with ERT measurements.

Choice of locations for geophysical profiles was based on the sub-samples that had a pH below 4 after 9 weeks of oxidation in the lab. The geophysical data was acquired with ERT with a set-up of 1 m electrode-distance, 4 measurements per electrode, and roll-along layout. Profile 1 and profile 2 (Fig. 7) were done with this layout. A measurement with a setup of 0,25 m electrode-distance, 4 measurements per electrode, and a roll-along layout was later done to get a higher resolution in the data (Profile 3, fig. 7).

4.5. Laboratory analyses

Oxidation of soil samples is the main method to determine if the soil is an AS soil. Soil samples for oxidation were therefore sub-sampled from all the investigated sites. Samples for grain size distribution, Loss On Ignition (LOI), Inductively Coupled Plasma Sector Field Mass Spectrometry (ICP-SFMS) analyses were sampled from the locations listed in Table 3. Samples for metal and S analyses were collected form the sites listed in table 3 and for site H19001 soil from the chip tray were sent for analysis at an accredited laboratory. Due to the prevailing circumstances during the year 2020, no grain-size analysis was made in the laboratory but was instead determined in field.

4.5.1. Oxidation of soil samples

Soil samples for oxidation were stored in a chip tray in a laboratory environment (Fig. 8). The soil samples were sprayed with deionized water to keep them under field capacity (moist). These samples were taken both from the reduced- and oxidized zone. This was done to see if the pH would have a dramatic drop to < 4 for minerogenic soil organic content < 20%, and < 3 for organic soil, organic content ≥ 20% (Larsson, 2008) when exposed to oxygen. The first pH measurements on the soil samples were carried out after 6 weeks for the first eight sample locations (H19001 – H19008). For the rest of the samples, pH measurements were carried out after nine weeks. For the samples that could not be classified as a potential or active AS soil at this time, new pH measurements were carried out every 14 day until the pH showed a value below 4 or was stabilized. A stabilized pH is thought to be reached when the decrease is less than 0,1 pH units during a 14 days period (Boman et al., 2018).

Figure. 8. The chip trays in which the soil samples were stored and oxidized. The soil samples were sprayed with deionized water to keep them under field capacity during the 9 weeks oxidation time.

4.5.2. LOI

To be able to classify the soil based on organic content (percentage/dry weight), loss-on-ignition (LOI) measurements were carried out. The sites chosen were those that were already classified as an active AS soil or suspected to be a potential AS soil in field (table 5). The samples were first air dried for 5 days, then ground with a porcelain pestle. 5 g of the ground samples were then dried in a drying cabinet at 105 °C for 1 hour in a crucible that prior to this were dried in the drying cabinet at 105 °C for 15 minutes. The samples were then cooled in a desiccator and weighed. After this the samples were put in a cool muffle oven set to 550 °C. When this temperature was reached, the samples were left in the oven for 2 hours. When cooled for 20 minutes the samples were put in a desiccator for approximately 45 minutes for further cooling and then weighed. LOI were calculated with the equation:

$$LOI = 100 - \left(\left(\frac{Weight\ after\ 550°C}{Weight\ after\ 105°C}\right) * 100\right) \tag{eq. 5}$$

Table 5. List over sites where LOI-analyses were carried out.

LOI- analyses Sample site	Sampling depth [m]
H19016	1,4
H19017	0,4
H19018	2,3 + 2,4
H19019	1,8
H19022	0,8
H19022	1,3
H19030	0,7 + 0,8
H19031	0,9 + 1,0
H19032	0,6

4.5.3. ICP-SFMS analyses

Metal and Sulphur analyses were conducted at the accredited laboratory ALS Global in Umeå, Västerbotten, with the analys package M1-c/LE. The elements analyzed were Arsenic (As), Barium (Ba), Beryllium (Be), Cd, Co, Chromium (Cr), Cu, Fe, Pb, Mercury (Hg), Mn, Ni, Phosphorus (P), Sulphur (S), Strontium (Sr), Vanadium (V), and Zn.

4.6. ERT data analyses

Processing and analysis of the ERT data was done in the inversion software RES2DINV version 3.57 (Loke, 2004). The inversion creates a model of the ground, where the resistivity in each cell is adjusted to the measured values. A correction for the topography is an initial step before processing the data, that were done in ArcMap (Version 10.6; ESRI 20) with a DEM-raster, and the text file created from this correction were inserted in the DAT-file containing the ERT data.

5. Results

The results are reported based on the classification that was made after the oxidation of the soil samples. Only sites that could be classified as a potential or active AS soil site are presented here, for results from all sites see appendix 2. Of the 15 locations in this study, 4 were classified as active AS soil sites and 1 as a potential AS soil site.

5.1. Active AS soil

Out of the 15 sampled locations in Falkenberg 4 had a field pH below 4.5 and were underlain by a potential AS soil, hence these sites are classified as an active AS soil site (Table 4 & fig. 9). All these locations coincide with the area of the now drained lake Ramsjön (Fig. 9). Ramsjön was an inland lake that formed as the speed of the isostatic land rise overtook the postglacial transgression. It was surrounded by smaller lakes and peatlands (Rosenberg, 2005, July). In May 1852 the 6 km long *Ramsjökanal* (English: Ramsjö canal) was dug by hand to drain Ramsjön for agricultural purposes. Since the *Ramsjökanal* did not drain *Ramsjön* fully, another excavation was done again in 1909 (Rosenberg, 2005, July).

The soil type of all 4 sites is postglacial silt and peat according to the soil-type map, and its surroundings constitutes of highmoor (*mossetorv*) and lowmoor (*kärrtorv)* peat (SGU, Jordarter 1:25000-1:100000) (Fig. 5). According to the map sheet used in the delineation of the sample sites, the soil type is ‘marsh’ peat within coarse silt (appendix 1). An estimation of the area containing active AS soil was drawn from the area of the soil type marsh peat within fine silt to 2,9 km^2(Fig. 5). The drillings done during fieldwork showed a stratigraphy of sandy silt, then a gyttja clay layer overlying a peat layer at site H19001 (Fig. 10). The soil samples taken for oxidation at site H19001 consists of gyttja clay (Fig. 10). At H19016 the oxidized samples consist of sandy silty clay and gyttja clay (Fig. 11), and at site H19030 they constitute clay (Fig. 12). At site H19032 a peat layer was observed at a depth of 0,7 m, and both below and above this AS soil was observed (Fig. 13). Sample H19032: 3 consists of silty sand with a pH of 2,75 after a 9-week oxidation period (Fig. 13). As also can be seen in figures 10, 11, 12, and 13 the measured field pH in the top layer is above 5 or 6, and then drops below 4,5, to then rise above 6 or 7 deeper in the horizon. This pattern is typical for an active AS soil as described by Pousette (2010), Becher et al., (2019), and Åström (2001). The elevations for the sites are app. 10 – 13 m.a.s.l (Fig. 10, 11, 12, & 13).

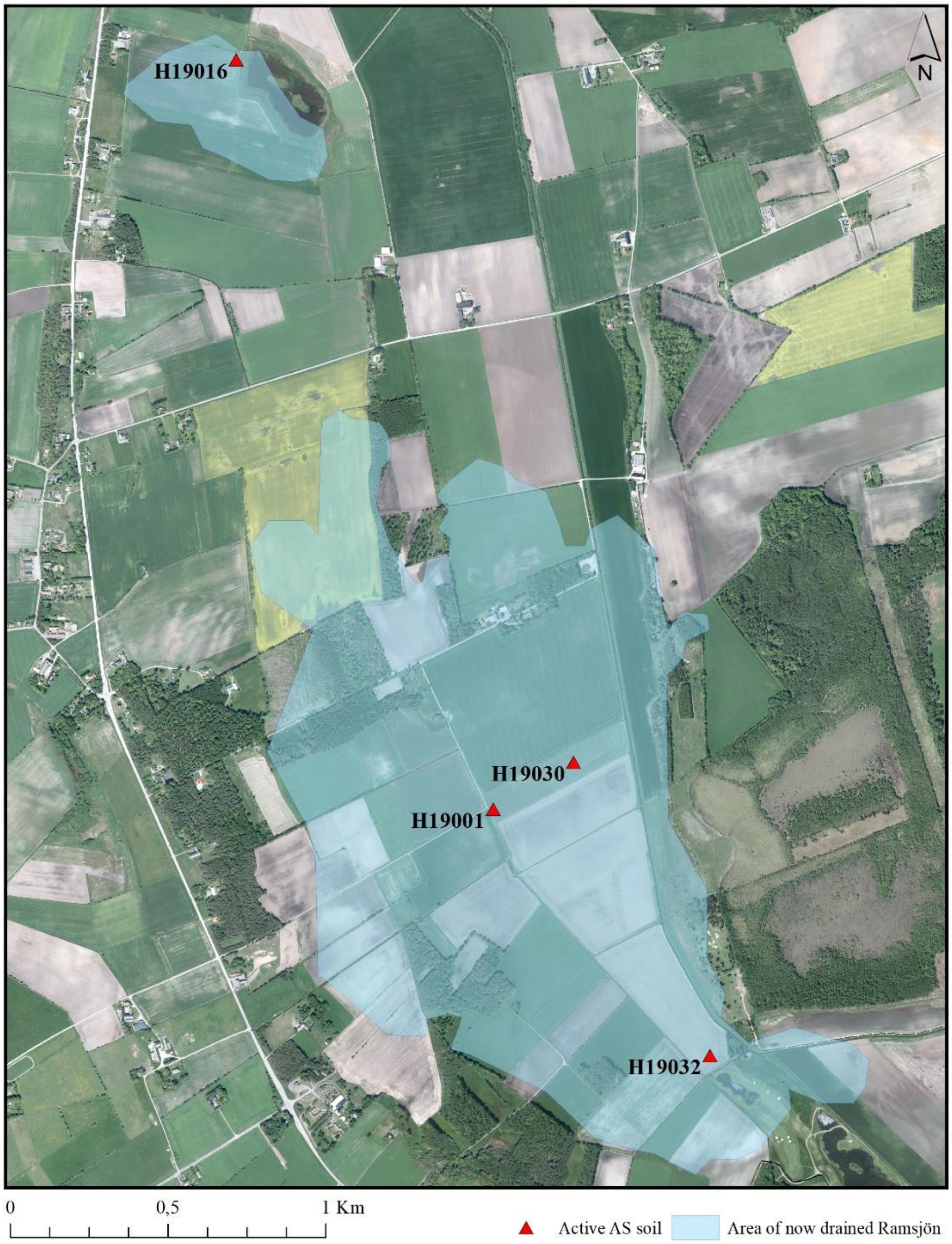
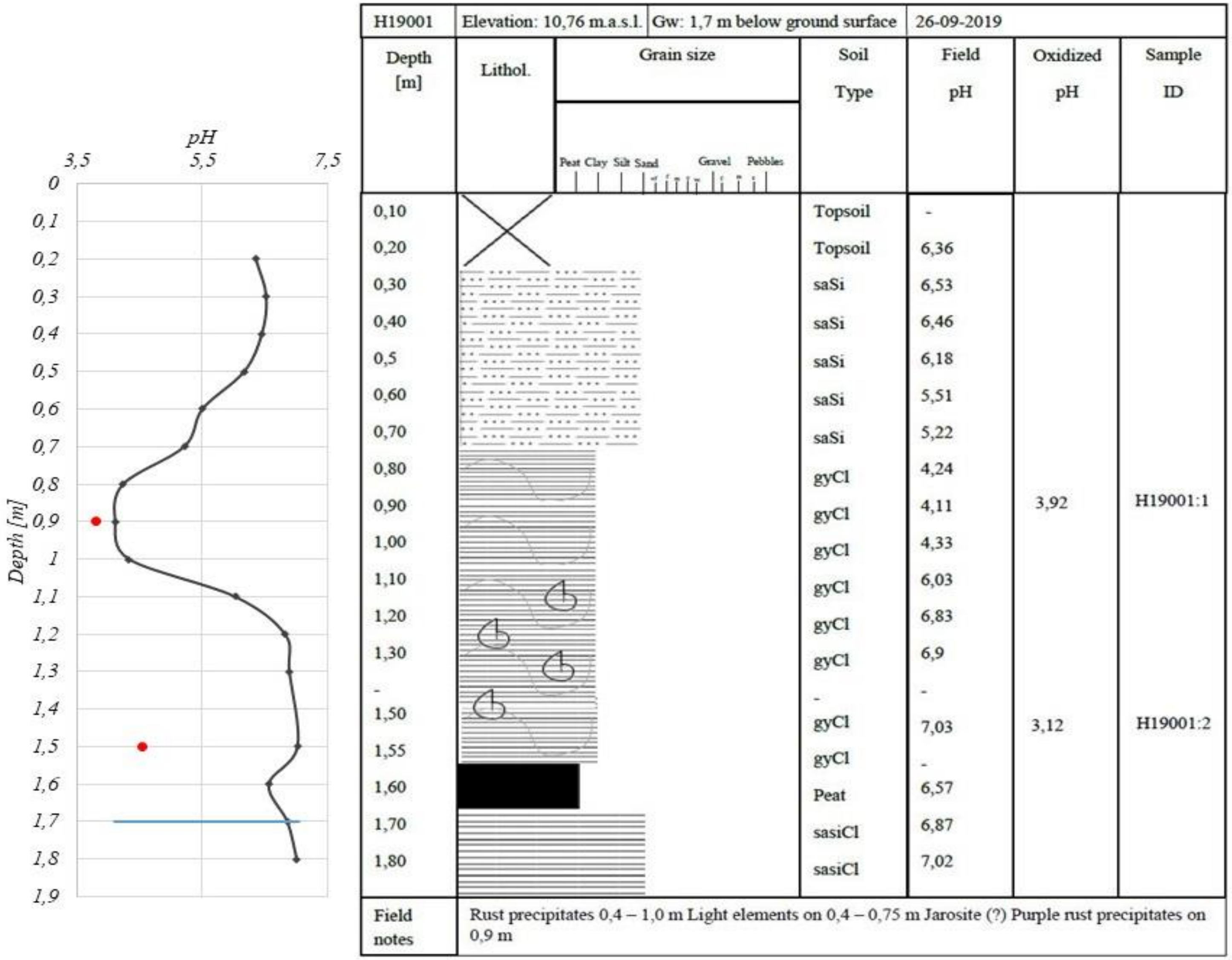


Figure 9. The figure illustrates the distribution of the four sites classified as active AS soil sites. Also seen is that all the four sites are situated in the former lake Ramsjön. Data source: The area of Ramsjön was retrieved from Ecknell C©. Data source: Orthophoto retrieved from Lantmäteriet©.

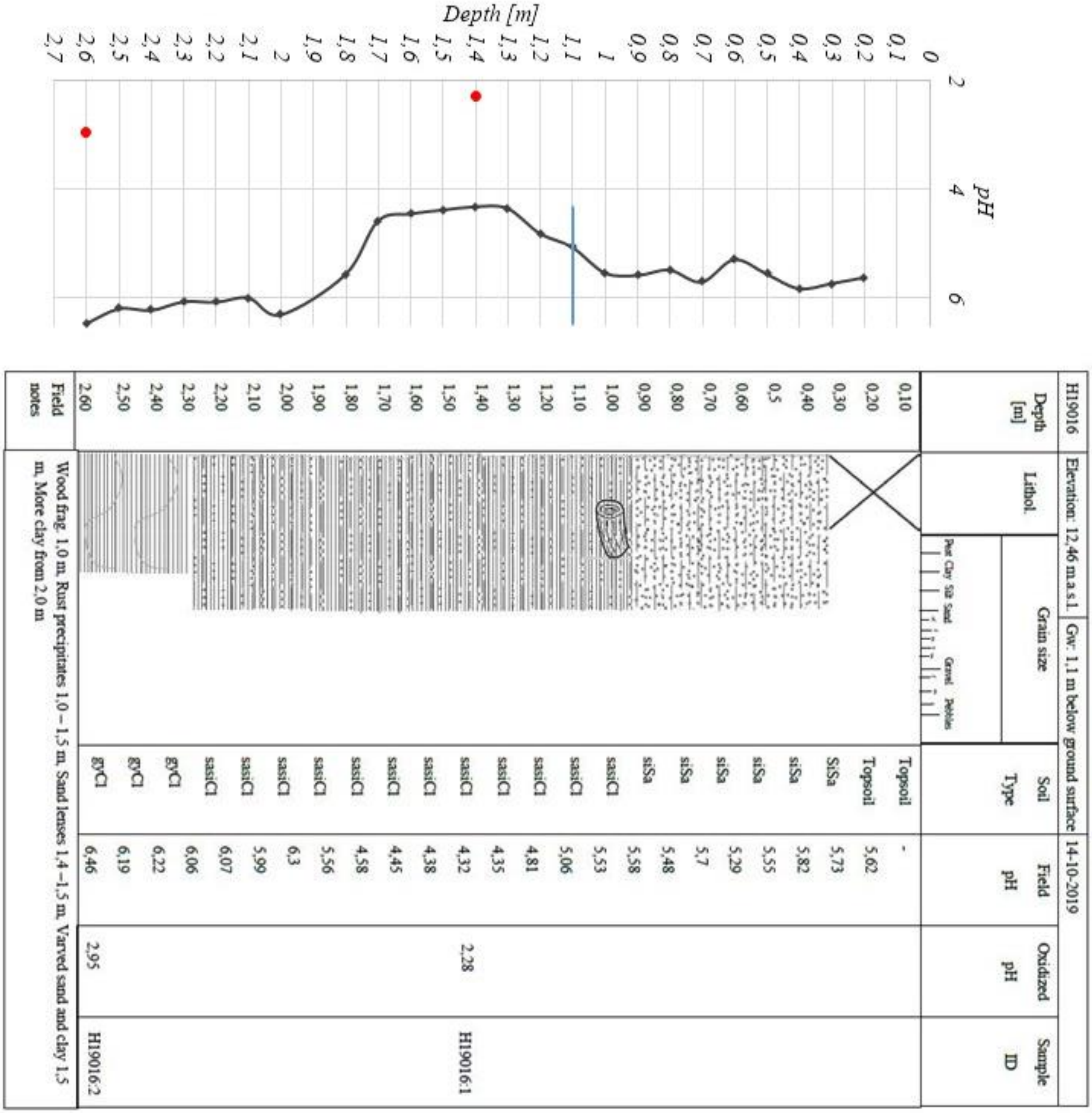
Sample site ID: H19001



H19001	Elevation: 10,76 m.a.s.l.	Gw: 1,7 m below ground surface		26-09-2019		
Depth [m]	Lithol.	Grain size	Soil Type	Field pH	Oxidized pH	Sample ID
0,10			Topsoil	-		
0,20			Topsoil	6,36		
0,30			saSi	6,53		
0,40			saSi	6,46		
0,5			saSi	6,18		
0,60			saSi	5,51		
0,70			saSi	5,22		
0,80			gyCl	4,24		
0,90			gyCl	4,11	3,92	H19001:1
1,00			gyCl	4,33		
1,10			gyCl	6,03		
1,20			gyCl	6,83		
1,30			gyCl	6,9		
-			-	-		
1,50			gyCl	7,03	3,12	H19001:2
1,55			gyCl	-		
1,60			Peat	6,57		
1,70			sasiCl	6,87		
1,80			sasiCl	7,02		
Field notes	Rust precipitates 0,4 – 1,0 m Light elements on 0,4 – 0,75 m Jarosite (?) Purple rust precipitates on 0,9 m					

Figure 10. The pH measurements carried out in field are illustrated by the black line, and the oxidized samples are illustrated by red dots. The groundwater level is illustrated by the blue line. For explanation of the sediment log see soil type in log and description for soil type abbreviations.

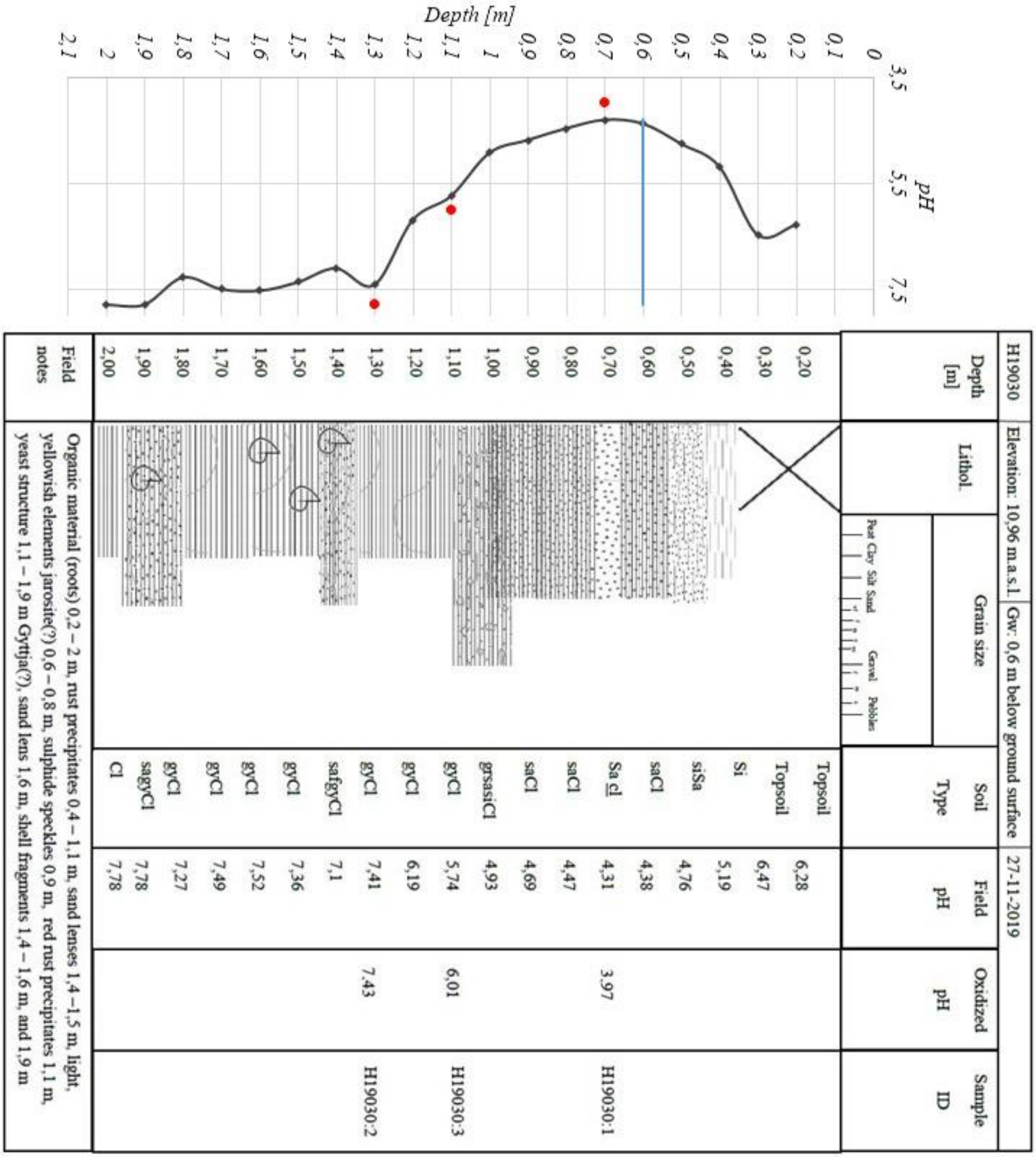
Sample site ID: H19016



H19016	Elevation: 12,46 m.a.s.l	Gw: 1,1 m below ground surface	14-10-2019		
Depth [m]	Lithol. / Grain size	Soil Type	Field pH	Oxidized pH	Sample ID
0,10		Topsoil	-		
0,20		Topsoil	5,62		
0,30		SiSa	5,73		
0,40		siSa	5,82		
0,5		siSa	5,55		
0,60		siSa	5,29		
0,70		siSa	5,7		
0,80		siSa	5,48		
0,90			5,58		
1,00		sasiCl	5,53		
1,10		sasiCl	5,06		
1,20		sasiCl	4,81		
1,30		sasiCl	4,35		
1,40		sasiCl	4,32	2,28	H19016:1
1,50		sasiCl	4,38		
1,60		sasiCl	4,45		
1,70		sasiCl	4,58		
1,80		sasiCl	5,56		
1,90					
2,00		sasiCl	6,3		
2,10		sasiCl	5,99		
2,20		sasiCl	6,07		
2,30			6,06		
2,40		gyCl	6,22		
2,50		gyCl	6,19		
2,60		gyCl	6,46	2,95	H19016:2
Field notes	Wood frag. 1,0 m. Rust precipitates 1,0 – 1,5 m. Sand lenses 1,4 –1,5 m. Varved sand and clay 1,5 m. More clay from 2,0 m				

Figure 11. The pH measurements carried out in field are illustrated by the black line, and the oxidized samples are illustrated by red dots. The groundwater level is illustrated by the blue line. For explanation of the sediment log see soil type in log and description for soil type abbreviations.

Sample site ID: H19030



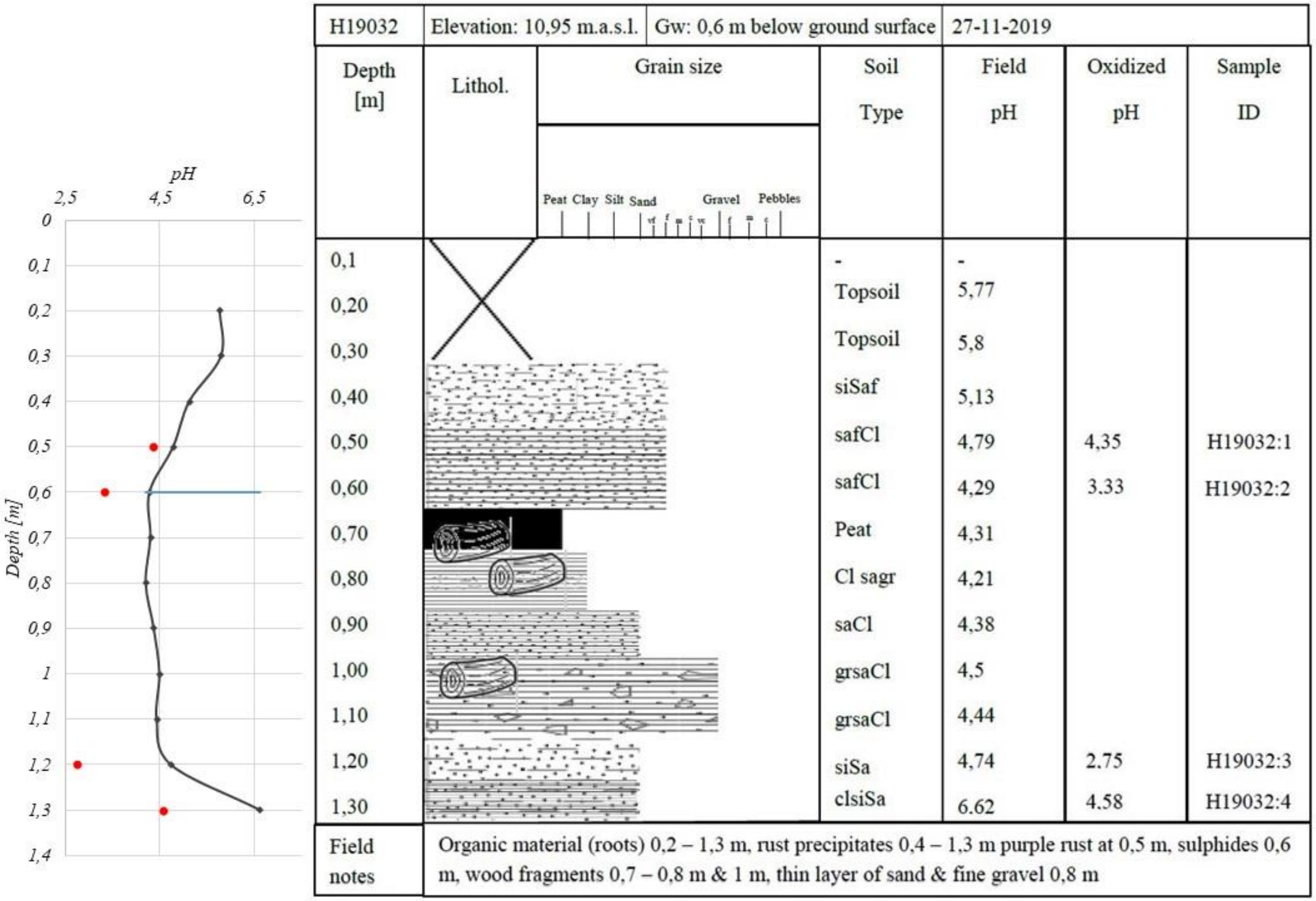
H19030 | Elevation: 10,96 m.a.s.l. | Gw: 0,6 m below ground surface | 27-11-2019

Depth [m]	Lithol.	Grain size	Soil Type	Field pH	Oxidized pH	Sample ID
0,20			Topsoil	6,28		
0,30			Topsoil	6,47		
0,40			Si	5,19		
0,50			siSa	4,76		
0,60			saCl	4,38		
0,70			Sa cl	4,31	3.97	H19030:1
0,80			saCl	4,47		
0,90			saCl	4,69		
1,00			grsasiCl	4,93		
1,10			gyCl	5,74	6,01	H19030:3
1,20			gyCl	6,19		
1,30			gyCl	7,41	7.43	H19030:2
1,40			safgyCl	7,1		
1,50			gyCl	7,36		
1,60			gyCl	7,52		
1,70			gyCl	7,49		
1,80			gyCl	7,27		
1,90			sagyCl	7,78		
2,00			Cl	7,78		

Field notes: Organic material (roots) 0,2 – 2 m, rust precipitates 0,4 – 1,1 m, sand lenses 1,4 –1,5 m, light, yellowish elements jarosite(?) 0,6 – 0,8 m, sulphide speckles 0,9 m, red rust precipitates 1,1 m, yeast structure 1,1 – 1,9 m Gyttja(?), sand lens 1,6 m, shell fragments 1,4 – 1,6 m, and 1,9 m

Figure 12. The pH measurements carried out in field are illustrated by the black line, and the oxidized samples are illustrated by red dots. The groundwater level is illustrated by the blue line. For explanation of the sediment log see soil type in log and description for soil type abbreviations.

Sample site ID: H19032



H19032	Elevation: 10,95 m.a.s.l.	Gw: 0,6 m below ground surface	27-11-2019		
Depth [m]	Soil Type	Field pH	Oxidized pH	Sample ID	
0,1	-	-			
0,20	Topsoil	5,77			
0,30	Topsoil	5,8			
0,40	siSaf	5,13			
0,50	safCl	4,79	4,35	H19032:1	
0,60	safCl	4,29	3.33	H19032:2	
0,70	Peat	4,31			
0,80	Cl sagr	4,21			
0,90	saCl	4,38			
1,00	grsaCl	4,5			
1,10	grsaCl	4,44			
1,20	siSa	4,74	2.75	H19032:3	
1,30	clsiSa	6.62	4.58	H19032:4	

Field notes: Organic material (roots) 0,2 – 1,3 m, rust precipitates 0,4 – 1,3 m purple rust at 0,5 m, sulphides 0,6 m, wood fragments 0,7 – 0,8 m & 1 m, thin layer of sand & fine gravel 0,8 m

Figure 13. The pH measurements carried out in field are illustrated by the black line, and the oxidized samples are illustrated by red dots. The groundwater level is illustrated by the blue line. For explanation of the sediment log see soil type in log and description for soil type abbreviations.

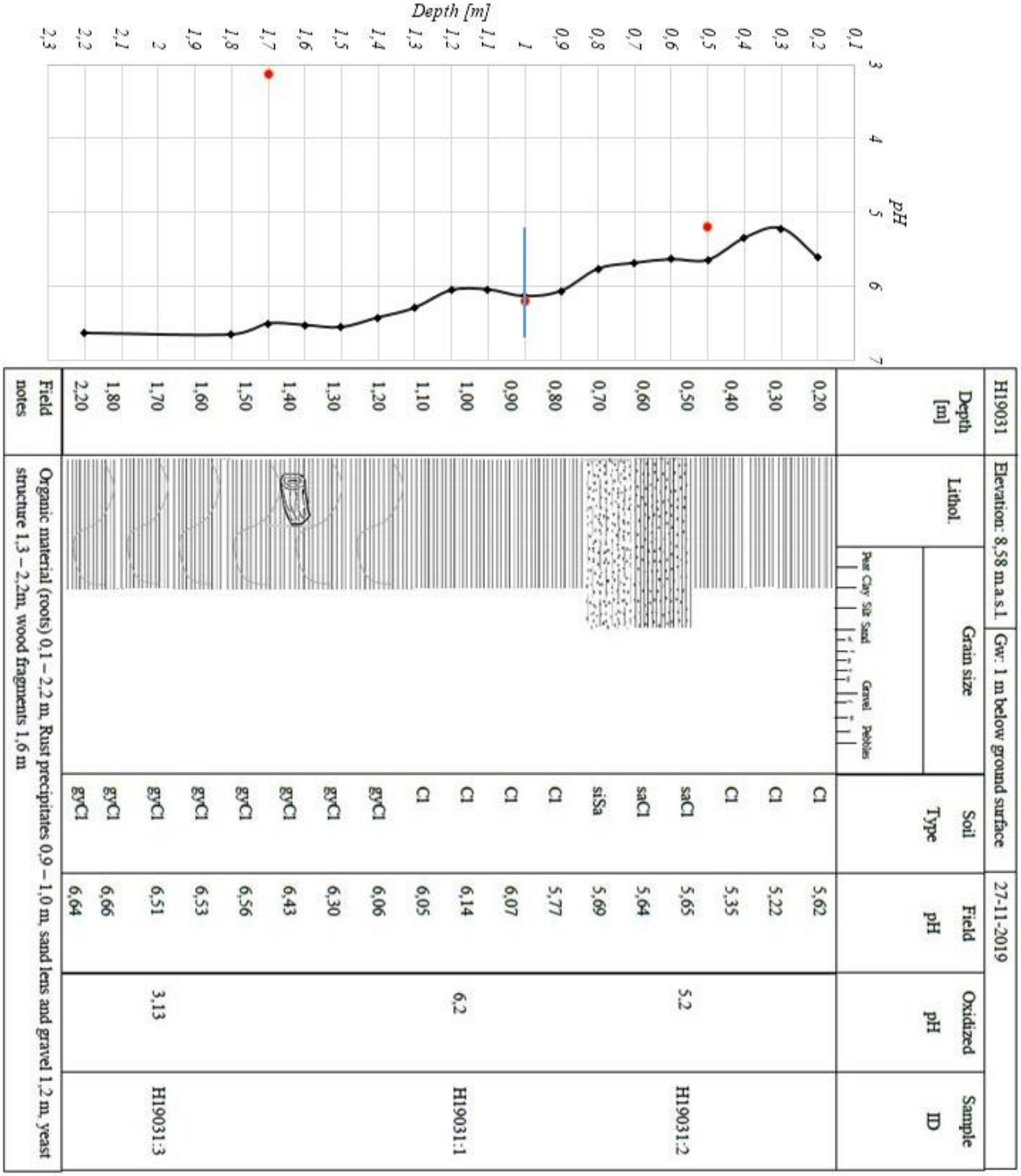
5.2. Potential AS soil

At the location H19031, one of the samples were measured to have a pH of 3,13 after 9 weeks of oxidation. In the field, the pH value was 6,51, and thus this site is classified as a potential AS soil. The site is situated in between an area of wetlands, the river Ätran, and cultivated land (Fig. 14). The soil type consists of clay as reported by the soil type map (SGU, Jordarter 1:25000-1:100000). The drilling from the fieldwork confirms this classification (Fig., 15). The measured pH-values in field and the oxidized pH-values can be seen in figure 15.

The environment at site H19031 where the potential AS soil was encountered, today consists of restored wetlands and smaller ponds. According to I. Danielsson (personal communication 2020-03-23, ecologist at Falkenberg municipality) the restoration was initiated in 1984, before this the site was used as a clay quarry (appendix 3, fig 35). The site is situated in the valley of the river Ätran, and the riverbanks consists of floodplain sediments. The area where the drilling was performed consist of a relatively thick clay layer interbedded with thinner silty sandy layers (Fig. 15). The last meter of the observed stratigraphy seems to be gyttja clay, and the whole sequence contains organic material. At a depth of 1,6 m remnants of wood was observed (Fig. 15). Precipitates of iron were observed at app. 1 m depth, and a smaller amount of sulphides at 0,5 – 0,6 m (Fig. 15). The elevation for the site is 8,66 m.a.s.l (Fig. 15).

Figure 14. Orthophoto over the site where potential AS soil was found, the location for the drilling is marked with a green triangle. The wetlands and ponds seen in the map was initially restored in 1984 and onwards (personal communication, 2020-03-23, with I. Danielsson, ecologist at Falkenberg municipality). The location is situated in the valley of the river Ätran, seen in the upper part of the map. Data source: Orthophoto retrieved from Lantmäteriet©.

Sample site ID: H19031



H19031	Elevation: 8,58 m.a.s.l.	Gw: 1 m below ground surface		27-11-2019		
Depth [m]	Lithol.	Grain size	Soil Type	Field pH	Oxidized pH	Sample ID
0,20			Cl	5,62		
0,30			Cl	5,22		
0,40			Cl	5,35		
0,50			saCl	5,65	5.2	H19031:2
0,60			saCl	5,64		
0,70			siSa	5,69		
0,80			Cl	5,77		
0,90			Cl	6,07		
1,00			Cl	6,14	6,2	H19031:1
1,10			Cl	6,05		
1,20			gyCl	6,06		
1,30			gyCl	6,30		
1,40			gyCl	6,43		
1,50			gyCl	6,56		
1,60			gyCl	6,53		
1,70			gyCl	6,51	3,13	H19031:3
1,80			gyCl	6,66		
2,20			gyCl	6,64		
Field notes	Organic material (roots) 0,1 – 2,2 m, Rust precipitates 0,9 – 1,0 m, sand lens and gravel 1,2 m, yeast structure 1,3 – 2,2m, wood fragments 1,6 m					

Figure 15. The pH measurements carried out in field are illustrated by the black line, and the oxidized samples are illustrated by red dots. The groundwater level is illustrated by the blue line. For explanation of the sediment log see soil type in log and description for soil type abbreviations.

5.4. Summarized results

5.4.1 Observed characteristics of AS soil in Halland, western Sweden

The AS soil of western Sweden have rust precipitates in the oxidized horizon. These precipitates occur in cracks, but also seem to occur sporadically in the oxidized part of the horizon. They often occur in the soil type gyttja clay but was also observed in sand. They often have a gray colour in reduced condition. At site H19001 at 1,5 m depth the colour was identified with the Munsell chart to 5y3/1. The sediments are made up of transgression sequences that at times are interrupted by a regression sequence made up of peat. All sites classified as AS soil sites were located beneath the limit for Tapes Transgression, in Falkenberg below 13 m.a.s.l. A lot of large wood remnants have been observed in the stratigraphy of the AS soil, and sometimes shell remnants. Pictures from the active AS soil sites can be seen in figure 16, 17, and 18, and from the potential AS soil site in figure 19.

Figure 16. Pictures from site H19001 where the active AS soil layer can be seen in the top picture (a), and the peat layer can be seen in the bottom picture (b). Photo: Christian Öhrling, SGU.

Figure 17. Pictures from site H19030 where the sample just above the oxidized sub-sample can be seen in a, and the sample below can be seen in b. In the lower picture, c, a part of the horizon from the top can be seen, and the oxidized sub-sample from the depth 0,7 can be seen.

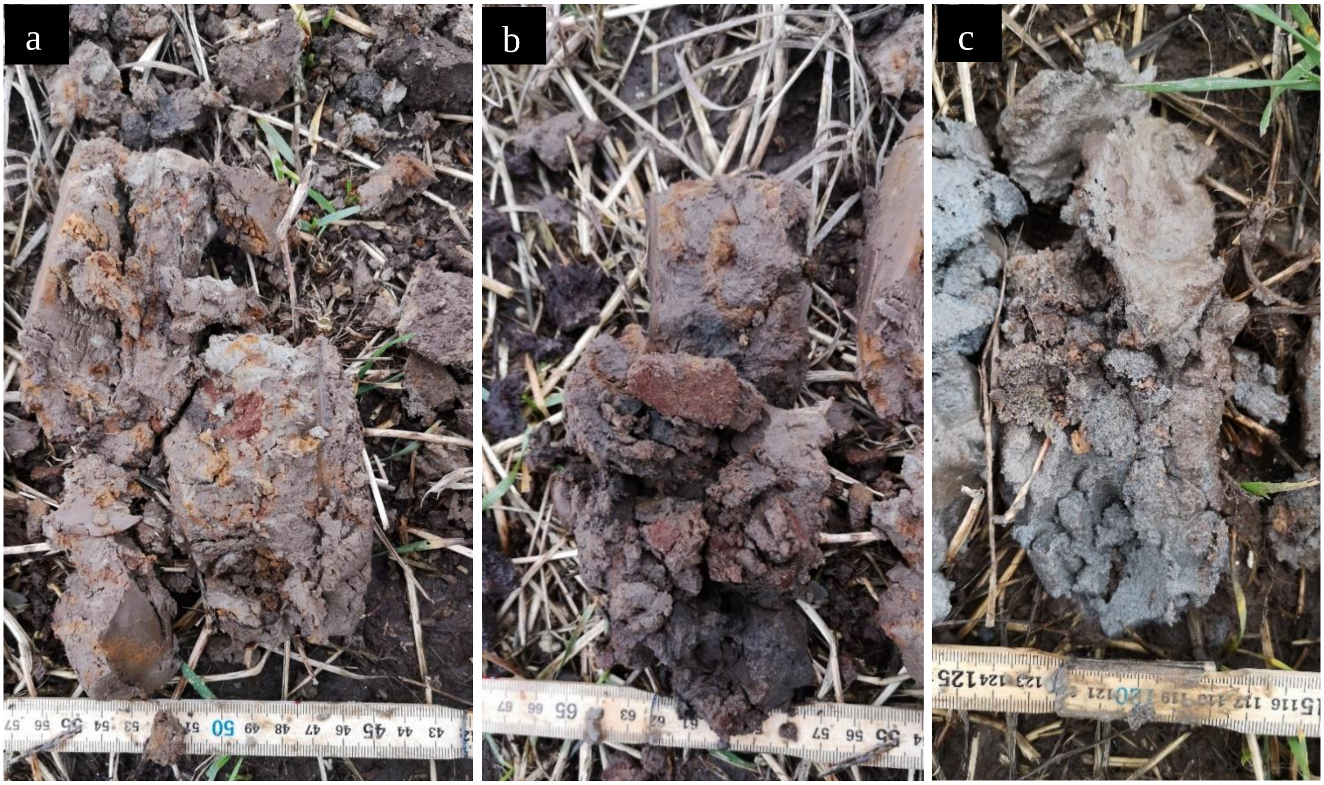

a
b
c

Figure 19. The sub-sample from site H19031 that had a pH-value of 3,13 after oxidation can be seen in picture a. The rust precipitates can be seen in picture b, and a part of the horizon can be seen in picture c.

5.4.2. Laboratory analyses

No high organic content was found in any of the samples where LOI-analyses were carried out (table 6). LOI-analyses were carried out at 3 of the four AS soil sites (table 6). The Fe/S-ratio for all the sites classified as an AS soil site are below 60. Two samples at two different sites had a ratio above this and a pH of 7,78 (H19030, 1 m) and 6,2 after 9 weeks oxidation period (table 7). The sites with a Fe/S-ratio below 3 showed the lowest pH-values, although sites with a ratio above 3 also showed low pH-values. The site with the lowest Fe/S-ratio did not show the lowest pH value. The lowest pH-value measured was at site H19016 with a Fe/S-ratio < 3 and a pH value < 3. A Fe/S-ratio < 3 did not always give a pH-value < 3 (table 7).

Table 6. Shows the results from the LOI-analys. LOI is an analytic way of determining the organic content in a soil

LOI- analyses				
Sample site	Depth [m]	LOI [%]	Sample	Classified as AS soil & LOI in same layer
H19016	1,4	0,9	H19016:1	Yes
H19017	0,4	0,1	H19017:1	No, but close to limit
H19018	2, 3 + 2,4	0,9	H19018:2	no
H19019	1,8	0,1	H19019:2	No, but close to limit
H19022	0,8	0,4	H19022:4	No
H19022	1,3	0,4	H19022:3	No
H19030	0,7 + 0,8	0,4	H19030:1	Yes
H19031	0,9 + 1,0	1,1	H19031:1	No, different soil type from H19031:3
H19032	0,6	0,0	H19032:2	Yes

Table 7. The table shows some summarized results from the analyses carried out in the laboratories.

Sample site	Depth [m]	Field pH	Oxidized pH	Fe/S	S [mg/kg DS]	Fe [mg/kg DS]	LOI [%]
H19001	0,9	4,11	3,92	7,97	3690	29400	-
	1,5	7,03	3,12	0,96	29000	27700	-
H19016	1,4	4,32	2,28	1,42	7200	10200	-
	1,8	5,56	-	2,06	1410	2910	-
	2,6	6,46	2,95	1,54	12300	19000	-
H19030	0,7	4,31	3,97	5,27	2390	12600	0,4
	1	4,93	-	50,66	381	19300	-
	1,3	7,41	7,78	95,52	335	32000	-
H19031	1	6,14	6,2	338,52	135	19300	1,1
	1,5	6,56	-	35,67	684	24400	-
H19032	0,6	4,29	3,33	8,59	1840	15800	0
	1,3	6,62	4,58	2,35	4980	11700	

The analyses for metal and S showed that at site H19001 and H19030 an enrichment of metals can be seen in the horizon underlying the active AS soil horizon (table 8 & 9).

Table 8. The results from the metal and Sulphur analyses done at ALS Global in Umeå, Västerbotten.

	Sample site	H19001	H19001
	Sample depth [m]	0,9	1,5
		Active AS soil	Potential AS soil
ELEMENT			
As, arsenic	mg/kg DS	6.04	7.64
Ba, barium	mg/kg DS	55.9	48.3
Be, beryllium	mg/kg DS	0.640	0.813
Cd, cadmium	mg/kg DS	0.150	0.424
Co, cobalt	mg/kg DS	5.74	9.74
Cr, chromium	mg/kg DS	31.6	25.8
Cu, copper	mg/kg DS	24.8	20.6
Fe, iron	mg/kg DS	29400	27700
Hg, mercury	mg/kg DS	<1	<1
Mn, manganese	mg/kg DS	209	542
Ni, nickel	mg/kg DS	14.6	22.1
P, phosphorus	mg/kg DS	597	552
Pb, lead	mg/kg DS	9.04	8.39
S, sulfur	mg/kg DS	3690	29000
Sr, strontium	mg/kg DS	17.3	77.8
V, vanadium	mg/kg DS	74.3	45.4
Zn, zinc	mg/kg DS	48.7	83.5
Dry substance at 105°C	%	65.8	61.8

Table 9. The results from the metal and Sulphur analyses done at ALS Global in Umeå, Västerbotten.

	Sample site	H19030	H19030	H19030
	Sample depth [m]	0,7	1	1,3
		active AS soil	no AS soil	no AS soil
ELEMENT				
As, arsenic	mg/kg DS	<3	<3	4.75
Ba, barium	mg/kg DS	22.5	51.3	114
Be, beryllium	mg/kg DS	0.125	0.736	1.33
Cd, cadmium	mg/kg DS	<0.1	<0.1	<0.1
Co, cobalt	mg/kg DS	1.41	7.13	13.0
Cr, chromium	mg/kg DS	6.50	17.0	27.5
Cu, copper	mg/kg DS	2.31	16.1	21.8
Fe, iron	mg/kg DS	12600	19300	32000
Hg, mercury	mg/kg DS	<1	<1	<1
Mn, manganese	mg/kg DS	71.8	187	1080
Ni, nickel	mg/kg DS	2.82	13.4	25.5
P, phosphorus	mg/kg DS	459	589	748
Pb, lead	mg/kg DS	2.76	7.19	12.4
S, sulfur	mg/kg DS	2390	381	335
Sr, strontium	mg/kg DS	20.5	14.1	56.3
V, vanadium	mg/kg DS	21.2	44.7	61.1
Zn, zinc	mg/kg DS	9.45	45.8	76.2
Dry substance at 105°C	%	84.4	80.9	78.1

The concentrations for site H19016 and H19032 however do not follow the pattern seen at sites H19001 and H19030. At site H19016 the highest metal concentrations were found in the active AS soil layer (table 10). And at site H19032 an enrichment can be seen in the underlying horizon for 5 metals (Be, Co, Mn, Ni. S, & Sr), while 12 metals were instead found at higher concentrations in the active AS soil layer (table 11). To see concentrations for analyzed metals at site H19031 see appendix 4.

Table 10. The results from the metal and Sulphur analyses done at ALS Global in Umeå, Västerbotten.

	Sample site	H19016	H19016
	Sample depth [m]	1,4	1,8
		Active AS soil	not classified
ELEMENT			
As, arsenic	mg/kg DS	<3	<3
Ba, barium	mg/kg DS	19.0	6.59
Be, beryllium	mg/kg DS	0.260	0.120
Cd, cadmium	mg/kg DS	0.499	<0.1
Co, cobalt	mg/kg DS	7.02	1.32
Cr, chromium	mg/kg DS	13.4	1.80
Cu, copper	mg/kg DS	7.56	0.862
Fe, iron	mg/kg DS	10200	2910
Hg, mercury	mg/kg DS	<1	<1
Mn, manganese	mg/kg DS	95.5	47.8
Ni, nickel	mg/kg DS	11.2	3.05
P, phosphorus	mg/kg DS	268	400
Pb, lead	mg/kg DS	4.27	<1
S, sulfur	mg/kg DS	7200	1410
Sr, strontium	mg/kg DS	6.52	3.93
V, vanadium	mg/kg DS	16.6	5.09
Zn, zinc	mg/kg DS	19.0	19.8
Dry substance at 105°C	%	62.5	78.5

Table 11. The results from the metal and Sulphur analyses done at ALS Global in Umeå, Västerbotten.

	Sample site	H19032	H19032
	Sample depth [m]	0,6	1,3
		Active AS soil	
ELEMENT			
As, arsenic	mg/kg DS	5.10	<3
Ba, barium	mg/kg DS	36.8	35.5
Be, beryllium	mg/kg DS	0.330	0.355
Cd, cadmium	mg/kg DS	<0.1	<0.1
Co, cobalt	mg/kg DS	2.71	3.70
Cr, chromium	mg/kg DS	21.1	10.7
Cu, copper	mg/kg DS	15.2	8.10
Fe, iron	mg/kg DS	15800	11700
Hg, mercury	mg/kg DS	<1	<1
Mn, manganese	mg/kg DS	112	147
Ni, nickel	mg/kg DS	6.16	6.36
P, phosphorus	mg/kg DS	558	485
Pb, lead	mg/kg DS	4.27	3.24
S, sulfur	mg/kg DS	1840	4980
Sr, strontium	mg/kg DS	11.8	28.6
V, vanadium	mg/kg DS	32.2	27.4
Zn, zinc	mg/kg DS	23.8	23.0
Dry substance at 105°C	%	61.4	82.9

5.3. Geophysical profiles

The ERT measurements showed that a layer with low resistivity is situated at the depth of the AS soil horizon. This layer has a resistivity of 25 ohm m (Fig. 20, 21, and 22). The location of the borehole is marked in the profiles. The depth of the oxidized sub-samples is marked with red lines (see fig. 10 for depths). In profile 1 the borehole is situated at 10 m into the profile. (Fig. 20). In profile 2 the borehole is situated app. 29 m into the profile (Fig. 21), and profile 3 the borehole is situated at 10 m into the profile (Fig. 22). When profile 3 was measured the ground water level was situated at 0,45 m under the ground surface.

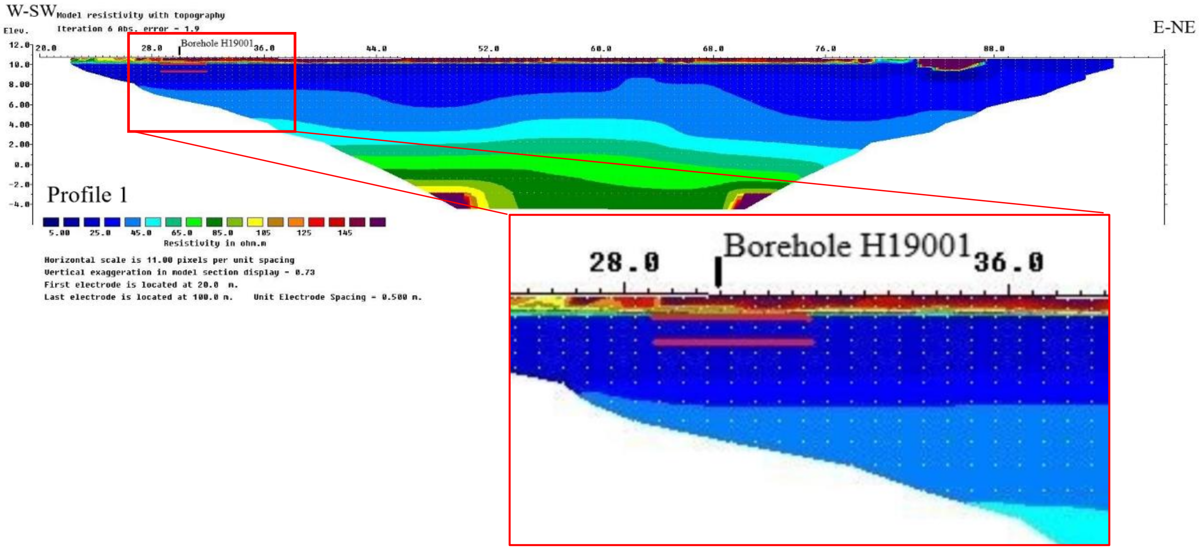


Figure 20. The figure shows the inversed data from the resistivity measurements carried out at site H19001 for profile 1 with a set-up of 1 m electrode spacing. The borehole at the site are marked out with a black line, and the sampling depths of the oxidized sub-samples are marked out with red lines in the figure.

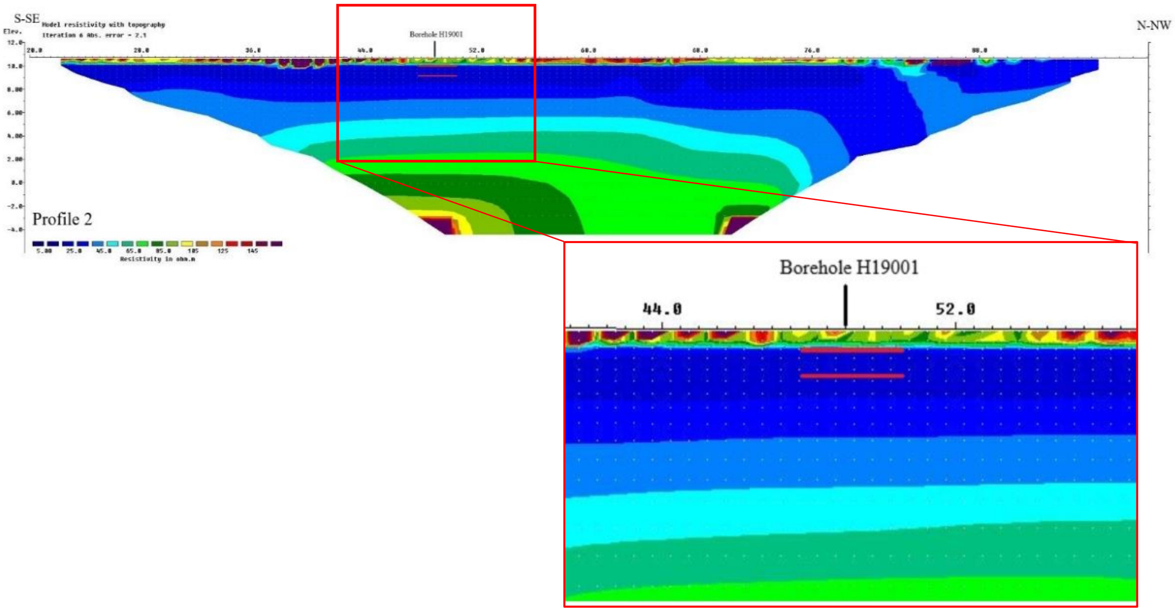


Figure 21. The figure shows the inversed data from the resistivity measurements carried out at site H19001 for profile 2 with a set-up of 1 m electrode spacing. The borehole at the site are marked out with a black line, and the sampling depths of the oxidized sub-samples are marked out with red lines in the figure.

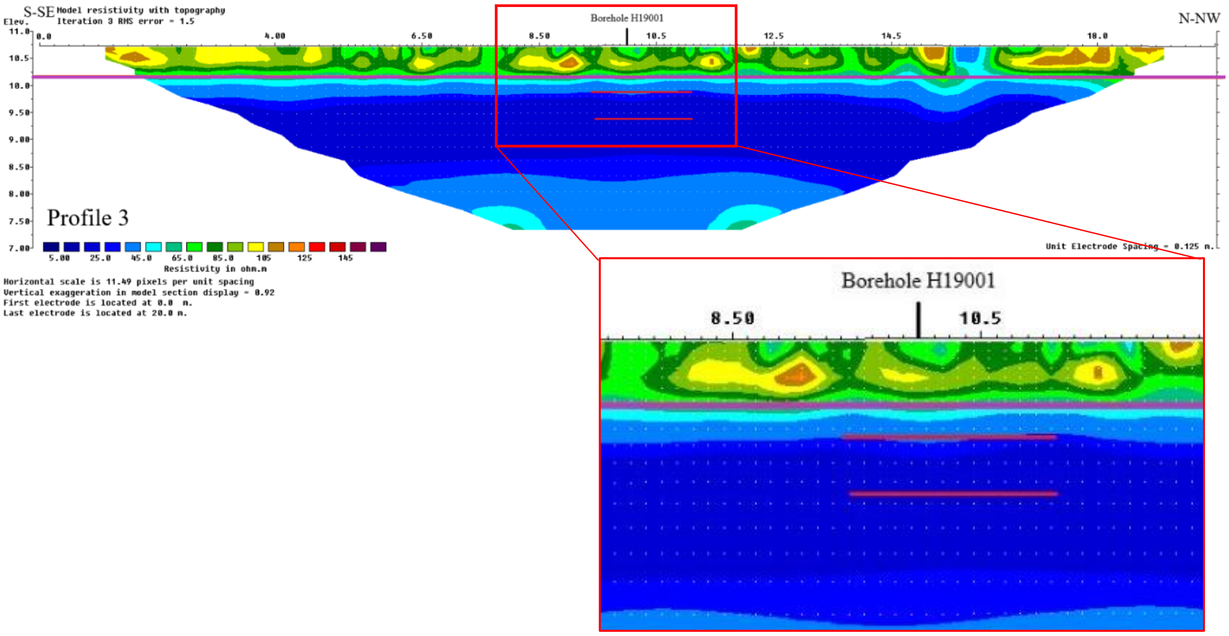


Figure 22. The figure shows the inversed data from the resistivity measurements carried out at site H19001for profile 3, with a set-up of 0,25 m electrode spacing. The borehole at the site are marked out with a black line, and the sampling depths of the oxidized sub-samples are marked out with red lines in the figure. The purple line represents the groundwater level at the time for the resistivity measurements.

6. Discussion

The following discussion will cover the specific research questions of this study and will cover sites where AS soil could be proved, but also sites that fall close to the limit of an AS soil site. The metal concentrations and the Fe/S-ratio will also be discussed.

6.1. Discussion based on the research questions

6.1.1. Existence of AS soils in Falkenberg municipality, on the west coast of Sweden

The existence of active and potential AS soil on the west coast of Sweden, in Falkenberg and Viskadalen, have through this study together with the parallel investigation by Bergström (InPress) been discovered. This is the first discovery of active AS soil outside of the Baltic Basin in Sweden. A total of five sites can be classified as AS soil sites in Falkenberg, where four of these sites were classified as an active AS soil. The land use at these sites is agricultural and probably an indirect cause of the oxidation of the iron sulphides (the direct cause being lowering of the groundwater). One site was classified as a potential AS soil. Even so, observations of iron precipitates in the stratigraphy indicate that the site was once exposed to oxygen and hence active AS soil likely existed at this site prior to the restoration of the wetlands (see chapter 5.2.). Studying historical orthophotos shows the historical land use being agricultural which surely means a lowering of the ground water have been done at the site recently, and hence could be a possible explanation concerning the observations of rust precipitates (appendix 3).

The area of active AS soil in Falkenberg, estimated to app. 2,9 km^2, is just an estimation and the total area of active AS soil is still unknown. At some sites where no AS soil was encountered, rust precipitations above the groundwater level and lower pH values closer to the ground surface was observed (appendix 2, & 5), being characteristics for AS soil sites (Pousette, 2010; Becher et al., 2019), and this indicates that the applied drilling method may have influenced the number of sites being classified as AS soil sites. This, as failure to reach deep enough could mean that analyses only were performed on layers overlying the AS soil. At these locations, the drilling was hampered by sand that can be overlying deeper AS soil, as is the case in Västerbotten and Norrbotten (Sohlenius et al., 2004). At site H19001 the active AS soil layer was also superimposed by sand with rust precipitations, which adds to the argument above.

The time for when the sulphates were initially oxidized can also influence the acidification that can be seen in the soil today. The grain size and the grain-size distribution of the sediment will further influence the leaching process of the sulfuric acid, which in turn will affect the pH measurements. Moreover, a well sorted sand (i.e. a sand with mainly one grain size) will have a quicker leaching process than an unsorted sediment (i.e. a sediment with clay, sand and silt) or a clay. This is caused by the pores being larger in a sorted sediment without finer sediment particles blocking the pore spaces.

6.1.2. Formational environment and characteristics of soil type

All the locations where active AS soil was found in Falkenberg, H19001, H19016, H19030, and H19032, are located in the former, now drained, Ramsjön. These sites are also situated in a soil type called marsh peat within coarse silt, being silt with a varying content of organic material. The formational environment of this soil type is thought to originate in protected, shallow lagoons. Diatomaceous analyses done on the sediments showed a marine depositional environment (Påsse, 1988 unpublished). Most likely, the water in Ramsjön kept the sulfides under reduced condition and the drainage evoked the oxidation reaction of these soils. This is the case for most of the discovered active AS soil in Sweden, where observations have been done in areas of drained lake sediments or drained wetlands (Sohlenius et al., 2015). Although the initial formation of the sulphides took place in lagoons as the land rose out of the sea, further formation might have taken place in Ramsjön after isolation.

Påsse (1988 unpublished) writes about a gyttja clay and peat superimposed by sand south of Backhult (4i) situated in the same area as the sites H19001, H19016, H19030, and H19032 (Fig. 5 & appendix 1). Shell fragments of *Cardium eduele, Littorina littorea,* and, *Bittium reticulatum* was found in the gyttja clay, being remnants of marine mollusks requiring higher water temperatures (Påsse, 1988 unpublished).The same stratigraphy as described above was observed at site H19001, where shell fragments were encountered at a depth of 1,1 – 1,5 m (Fig. 10). This depth also corresponds to the layer with encountered AS soil. A similar stratigraphy was observed at site H19030 with gyttja clay at 1,1 – 2,0 m depth, and shell fragments at 1,4 – 1,6 m depth (Fig. 12). No samples for oxidation was taken at the same depth as the shell fragments at H19030 and the grain size differs between the depths, hence it is unknown if this depth contains AS soil. At site H19016 and H19032 no shells were encountered. However, at site H19032 a peat layer was encountered in between the AS soil. No analyses of the observed shell fragments at site H19001 and H19030 were done. Påsse (1988 unpublished) dated shells found north (Munkagård 4i) of the AS soil sites to 15.2 ka cal y.B.P. (12.8 ka ^{14}C y.B.P) and 16.0 ka cal y.B.P. (13.4 ka ^{14}C y. B.P). (Bänared 4i), these shells are said to be different species from the ones found south of Backhult (Fig. 16 in Påsse, 1988 unpublished). Furthermore, these sites are situated above 13 m.a.sl., i.e. at a higher elevation than the active AS soil sites. Nevertheless, the consistent stratigraphy between the active AS soil sites allows for a conclusion that the depositional environment for the active AS soil in fact is marine, and the silty marsh peat indicates a shallow, protected lagoon environment. Although there are internal differences in the stratigraphy of the sites H19001, H19016, H19030, and H19032 (Figs. 10, 11, 12, and 13) their proximity and the overall similar stratigraphy allows for a conclusion that the formational environment is the same for all four sites.

The stratigraphy at site H19001 with peat underlying marine gyttja clay marks a time of a terrestrial environment followed by a marine transgression. The site is situated at a level of 10,7 m.a.s.l., hence the peat was probably formed around 11.4 – 8.3 ka cal y.B.P. (10.0 – 7.5 ka ^{14}C y.B.P.) when this elevation was raised above sea level (Fig. 3). This leads to the conclusion that the marine gyttja clay was deposited after 7500 y B.P. and hence, during the Tapes transgression. At site H19032 a peat layer was encountered at a depth of 0,7 m, in between the oxidized samples with a pH < 4 (0,5 m, 0,6 m, and 1,2 m). Diatomic analyses in marine gyttja (layer E and C, appendix 6) carried out by Påsse (1988 unpublished) at a site east of the AS soil sites (Lismossen (3i – 3j), appendix 1) give ages of 8,0 ka cal y.B.P. and 7.6 ka cal y.B.P. (7.2 ka ^{14}C y.B.P. & 6,8 ka ^{14}C y.B.P.). These ages represent two separate transgressions as the dated marine gyttja are interbedded with a peat layer (appendix 6, layer D). The ages given of the marine gyttja also corresponds to the time of Tapes transgression. Furthermore, the marine mollusks *Cardium eduele, Littorina littorea,* and, *Bittium reticulatum* found by Påsse (1988 unpublished) in the marine gyttja clay indicates a time with warmer temperatures (Påsse, 1988 unpublished). The shells are remnants from the Holocene and likely the Tapes transgression that reached its maximum at the same time as the Holocene Climatic Optimum (Lindqvist et al., 2011). The maximum level, 12 - 13 m.a.s.l., for the transgression was reached around 7.6 ka cal y.B.P. (6.7 ka ^{14}C y. B.P.) in Falkenberg (Fig. 3 from Påsse, 1988 unpublished). The discovered AS soil in Falkenberg are all situated below 13 m.a.s.l. (Fig. 10, 11, 12, and 13), hence these sites were drowned with water during the Tapes transgression. In the parallel investigation conducted by Bergström (InPress) in Viskadalen, AS soil were found below the maximum level for the Tapes transgression in this area (18,5 m at Veselången). This allows for the conclusion that the AS soil found in Halland, at least in Viskadalen and Falkenberg, were formed during the Tapes transgression (9,5 – 7,6 ka cal y.B.P).

The area just west of where site H19031 is located, is described by Påsse (1988 unpublished) as fluvial deltaic deposits with an elevation at 10 m.a.s.l. (2j, appendix 1)~~.~~ Excavations done in the deltaic deposits showed interbedded layers of peat at the elevation 11,80 – 11,78 m.a.s.l. and 10,05 – 10,00 m.a.s.l., with an age of 7,5 ka cal y.B.P. (6.6 ka ^{14}C y.B.P), corresponding to Tapes transgression. He also writes that organic deposits of gyttja and peat are superimposed by sand in another location west of H19031 (Kristineslätt), at an elevation of 9 – 10 m.a.s.l, with an age of 7.9 – 9.5 ka cal y.B.P. (7.1 – 8.5 ^{14}C y. B.P.). Around this time, the shoreline was raised in a fluctuating trend to 12-13 m.a.s.l.(Tapes Transgression) (Fig.

3, Påsse, 1988 unpublished). The paleogeographic history illustrated in figure 4 (Dahlqvist et al., 2019) shows that the environment constituted a marine bay at 13.7 ka y. B.P., and at 6.0 ka y. B.P. a river valley existed. In between this time the deltaic plain described by Påsse (1988 unpublished) was deposited. The elevation of site H19031 are app. 8,60 m.a.s.l. Hence the site is protected by the deltaic deposits when these rose above sea level, and surrounding hills probably protected the location before this. In a study of the late- and post-glacial geological evolution of the southern Kattegatt's connection to the Great Belt, the writers found indications of a tidal environment (Bendixen, Jensen, Boldreel, Clausen, Bennike, Seidenkrantz, Nyberg, & Hübscher, 2017). The formation of the sulphides at site H19031 most likely has its origin from the Tapes transgression like the active AS soil sites discussed above. The formational environment of the sulphides at site H19031 most likely constituted of a protected bay where the calm conditions allowed for deposition of the clay. The formation of the sulphides can also have taken place in a distal tidal delta plain. In a study of the late- and post-glacial geological evolution of the southern Kattegatt's connection to the Great Belt, the writers found indications of a tidal environment (Bendixen, Jensen, Boldreel, Clausen, Bennike, Seidenkrantz, Nyberg, & Hübscher, 2017). Considering the paleogeographic history seen in figure 4 (Dahlqvist et al., 2019), and that a large portion of the Ätran valley once was situtated below the limit for Tapes transgression, it is not unlikely that sulfides formed further up the river valley as well (Fig. 45, appendix 8).The floodplain sediments on the banks close by the site H19031 resembles the environment next to large rivers in north of Sweden that Sohlenius et al. (2015) describes, where these sediments are thought to superimpose potential AS soil and hinder oxidation and thus, formation of active AS soil. It is likely that the flooded sediments of Ätran are overlying potential AS soil.

The observed AS soil in Falkenberg were found in areas that rose from the sea around 4,5 ka cal y.B.P. (4.0 ^{14}C y.B.P.) and at elevations of 8 – 12,5 m.a.s.l. (Fig. 3, from Påsse, 1988 unpublished,).The formational environment of the AS soil on the Swedish west coast differs from that on the northern coastlines of Sweden (Sohlenius et al., 2004). The formation of AS soil on the west coast, at least in Halland, has taken place in shallow, protected lagoons and protected bays, and resembles the formational environments in Mälardalen and Skåne (Sohlenius, et al., 2004; Åbjörnsson et al., 2018). Differences between the formational environment on the east coast (Västerbotten, Norrbotten, Mälardalen, and Skåne) and the west coast is that the latter have had a more marine character because the Kattegat sea have never been isolated from the ocean, and therefore most likely higher saline concentrations in the water at the time for formation.Observations of AS soil in Falkenberg was mainly done in fine-grained material, the dominating soil type being gyttja clay. However, at site H19032 the sub-sample H19032:3 of silty sand had a pH value of 2,75 after oxidation (Fig. 13), and at site H19030 a pH of 3,97 was measured in sand with a thin clay layer, however this sample is situated in between sandy clay (Fig. 12). Due to the hampering of drilling in sandy soil, a smaller portion of this soil type was sampled, hence the results of this study could be biased and are not enough to conclude in what soil type the AS soil most often occur in the area. However, what can be concluded is that it exists in both fine-grained sediments as well as coarser-grained sediments like sand.

The findings of AS soil in Falkenberg did not correspond to the G marked on the map sheet Ae nr 86 (appendix 1). However, since these markings are mainly done in sand, the drilling was hampered so that the underlying clay gyttja and peat layers were not reached. With this said, the stratigraphy at site H19001 do correspond to the stratigraphy described above and Påsse (1988 unpublished) states that these deposits likely have a wider extent than marked on the map. Site H19001 was sampled nearby one of these markings and hence it is possible that the sites with these markings also located at an elevation below 13 m.a.s.l. contains AS soil. Some of these sites were situated above 13 m.a.s.l. and it is possible that AS soil can exist at these sites as well.

6.1.3. Identification of AS soil with ERT methods on the west coast of Sweden

From the ERT data some conclusions can be drawn first after a presumption of the AS soil layer at site H19001 have been made. The oxidized samples H19001:1, and H19001:2 are situated on 0,9 m and 1,5 m depth, the soil type between 0,8 m and 1,5 m depth are gyttja clay. Hence the assumption is that the AS soil layer extends from 0,8 m to 1,5 m depth. If this is true, the AS soil layer was possible to differentiate from the surrounding sediments at the site. An interpolated thickness of the AS soil layer can be made to 1,5 m (Fig 20, 21, & 22). It can be concluded that ERT can be used as a tool for identification of AS soil sites on the Swedish west coast. However, the ERT profiles in Viskadalen are a bit more difficult to interpret. Bergström (InPress) discuss that the identification may be possible, but the drilling with the Edelmann auger only reached the top of a highly conductive layer. One sub-sample that was collected at the top of this highly conductive layer did show the existence of potential AS soil (Bergström, InPress). Hence, identification of AS soil with ERT seems possible both in Falkenberg and in Viskadalen. It is possible that the formational environment of the AS soil on the west coast can influence the possibility to identify them with ERT methods. If the formational environment allowed for deposition of more marine clay it may make the differentiation of AS soil more difficult.

6.2. Discussion about the metal-, sulfur and laboratory analyses

Since an active AS soil is leached on metals, they generally show lower concentrations relative to the underlying reduced soil layers (Sohlenius & Öborn, 2004). The mobilization can also cause a leakage of metals downwards into an underlying reduced horizon, where the metals may become stabilized and again binds to the soil particles and hence an enrichment can be seen in underlying horizons (Sohlenius & Öborn, 2004). The results of the metal analysis revealed that site H19030 follows this pattern, where a depletion is seen in the active AS soil layer when compared to the underlying reduced layer (Appendix 4). The adjacent site H19001 shows similar pattern as H19030, with an enrichment for most of the metals in the underlying potential AS soil layer. Site H19032 shows a somewhat enriched concentration of 5 metals (Be, Co, Mn, Ni, S, & Sr) in the underlying soil layer, while 12 of the metals instead are elevated in the overlying AS soil layer. Further, site H19032 shows overall lower metal concentrations in the soil underlying the AS soil layer, as compared to site H19030. One possibility is that the higher amount of sand in the soil at site H19032 has affected the leaching process to a higher enrichment in the aquatic environment instead. According to Lindgren (InPress) the aquatic environment adjacent to H19032 did not show high metal concentrations as compared to other watercourses in the area at the time for the measurement. Considering that the concentrations in the aquatic environment fluctuates relatively quickly it is possible that an enrichment once existed. The water samples collected by Lindgren (InPress) were taken at the same time and hence, it is possible that the development of the AS soil at the sites differs. H19032 is located at the edge of Ramsjön while H19030 and H19001 are located in the center, consequently H19032 could have been oxidized earlier. The drainage of Ramsjön that was done in two steps with a 60-years gap could help explain the differences in development of the AS soil (Rosenberg, 2005, July). Further, the Fe/S-ratio at site H19032 is somewhat larger than at site H19030 (table 11). Sohlenius et al. (2017) states that the sulphur is leached out from the layers situated above the groundwater table, and hence a higher Fe/S-ratio could be a sign for a more developed AS soil. As the Fe/S-ratio affects the acidic effect of the soil (Pousette, 2010), and hence affects the pH, it is likely that it also will influence the leakage of metals. At site H19030 the highest enrichment of metals was found in the clay layer. Another possible explanation can therefore be that the higher amount of clay at site H19030 is the reason for the higher metal concentrations. This, since high clay concentration in a soil relates to a higher adsorption of metals and cations that is caused by the high cation exchange capacity of clay (Cronan, 2017).

According to Pousette (2010) the sulphur content in a soil relates to how large the acidic effect will be, where a sulphur content below 600 mg/kg DS will not have a significant effect the on the pH-value. The results found in this study supports this, as all samples with a concentration below 600 mg/kg DS did not show a large acidic effect after oxidation. And samples with a concentration exceeding 600 mg/kg DS had pH values < 4 (table 7, and figs. 10, 11, 12, 13, & 15). Another trend of the soil samples showing pH-values < 4 is that the Fe/S-ratio are < 9 and generally < 3 (table 7, and figs. 10, 11, 12, 13, & 15). Pousette (2010) states that a Fe/S-ratio < 3 relates to a larger acidic effect of the soil. The acidic effect is also affected by the soils organic content and carbonate concentrations. The LOI-percentage was analyzed at 3 of the 4 active AS soil sites and none of these showed a large organic content, why this cannot be considered to have influenced the soils acidifying effect (table 6).

6.4. Discussion about sample sites falling close to the limit of an AS soil site

Sites H19017 and H19019 both had pH values < 4,5 after a 9 week oxidation period, and site H19017 had a field pH of 4,66 (appendix 2).) During field work observations of rust precipitates and black sulphide spots were done at both sites (appendix 5). Collection of sub-samples for oxidation should have been done with a denser span, especially at site H19017. The pH-curve at site H19019 do not follow the trend as described in section 2.5, the rust precipitates and sulphide spots are not alone enough to suspect an AS soil, AS soil that are not an AS soil still can have black spots (SGU, 2019), and rust precipitates occur, to some extent, in dry-crust clays everywhere (personal communication 2020-06-02, Mark Johnson, professor at the Department for Earth Sciences). The pH curve for site H19017 shows the trend described in section 2.5, and the site is situated at 13,35 m.a.s.l. (above Tapes limit) and surrounded by lowmoor peat that are situated below the Tapes limit (appendix 7 & 8). The elevation of site H19019 are above that of Tapes transgression and may be an explanation why no AS soil was encountered. The acidifying effect might not have been large enough for a drop in pH at site H19017 to be considered an AS soil site, which may be related to the buffering capacity of the soil at the sites. However, no high organic content was found in any of the samples where LOI was conducted and at site H19017 the organic content were calculated to be 0,1 %, and hence the organic concentration cannot have acted as a buffering agent at the site.

At the sites H19003, and H19004 only sand was encountered and hence the drilling could not be executed deeper. Both sites had pH values close to the limit 4,5 after a 9 weeks oxidation time, site H19004 being closest (appendix 2). The pH-curve do not have the typical look as described in section 2.5 (appendix 7. Further site H19004 is situated below the Tapes transgression, but at a more exposed area as compared to the AS soil sites (appendix 8). At site H19022, and H19023 rust precipitates was observed in the stratigraphy, and both sites are situated below the limit for Tapes Transgression. The drilling was hampered by sand at site H19023 and by a big block at site H19022 why no samples could be collected deeper in the horizon. Lindgren (InPress) collected water samples in *Ramsjö kanal* next to the sites H19022 and H19023 and could see an increased metal concentration along with slightly decreased pH-values. Although the effect seen here is not as evident as in the watercourses next to H19001, H19016, H19030, and H19032. An explanation is that the sites H19022 and H19023 had a more exposed environment during the Tapes transgression and hence the conditions for formation of iron sulphides were not meet (appendix 8). Furthermore, the pH-curves of these sites do not follow the typical trend of a pH-curve at an AS soil site (appendix 7). The elevated metal concentrations and slightly decreased pH-value in the watercourses could be an influence seen from the active AS soil sites upstream.

7. Conclusions

- Both active and potential AS soil exists in Falkenberg. This is the first proven active AS soil outside the Baltic basin on the Swedish west coast.

- The formational environment of the active AS soil observed at the sites H19001, H19016, H19030, and H19032 consisted of a shallow, protected lagoon with a marine aquatic environment.. The formational environment at site H19031, where the potential AS soil was observed, most likely consisted of an inland distal delta basin in a protected, shallow bay, where the calm water allowed for deposition of the clay and formation of the iron sulphides.

- The formation took place during the Tapes transgression, around 9,5 – 7,6 ka cal y.B.P. The same transgression that also opened the Great belt and Öresund and initiated the Littorina stage in the Baltic basin.

- The formational environment of the AS soil on the west coast of Sweden differs from that in the north of Sweden. On the west coast, the formation of iron sulphides took place in shallow lagoons, and in deltaic environments in a protected bay.

- AS soils on the Swedish west coast occur in fine-grained soils, the most common being gyttja clay, but also occur in silty sand.

- The results from the geophysical measurements that was carried out in this study and the study done in Viskadalen suggests that these methods can be used in differentiating AS soil from surrounding sediments on the Swedish west coast. However, the formational environment or the type of surrounding sediments may make the data more or less difficult to interpret.

8. Future studies

The problems related to AS soil range over several societal interests as mentioned in section 2.3. However, Åberg (2017) states that the biggest influence of an active AS soil is seen in the aquatic environment (streams, lakes, and bays) in hydro- and hydrogeological connection to these soils. Hence, actions regarding these environmental issues should be a priority. In the study area of Falkenberg evidence of metal leakage to the adjacent watercourses has been seen by Lindgren (InPress). Considering these findings together with the discovery done in this study, further mapping of AS soil should be done in the area. The links that have been seen between metals leached from AS soil to adjacent watercourses and to crops gown on these soils and AD and PD are a reason to map the area, especially when considering that the Active AS soil sites were discovered on cultivated fields. The geotechnical and constructional problems these soils mean is a further reason why it is important. The difficulties active AS soil creates to reach the environmental goals decided by the Swedish Parliament together with the requirements that came along with the Weser judgement also make this discovery highly relevant for the municipality of Falkenberg. The Weser judgement is a preliminary judgement from the European Court of Justice that concerns work performed in the river Weser. The judgement has influenced the Swedish authorities' application of environmental quality standards for water. The European court of justice deemed that an activity causing a deterioration of the ecological- or chemical status of the water, or that in any way will hinder the attainment of the environmental objectives of water, must not be allowed (Havs- och Vattenmyndigheten [HaV], 2016). The ecological status of Ramsjökanal is rated as 'moderate' and the chemical status is rated as 'not good' (Viss, n.d.). Further oxidation of the already established active AS soil sites or sites with potential AS soil could risk a deterioration of the ecological status of Ramsjökanal and Ätran valley as well as other watercourses in the municipality. To avoid this, it is important to localize areas with AS soil. During a visit to the site H19001 an excavation was being made west of the area, and groundwater was being pumped out of the pit. The soil horizon in the pit had the typical rust precipitates of an AS soil and the same stratigraphy that was observed at site H19001 (appendix 9, & fig. 10). This is an indication for a more extensive area with active AS soil than could be established with soil sampling in this study, and why further investigations are needed. Suggestions are that more samples should be taken in the silty marsh peat of sites H19001, H19016, H19030, and H19032, and in the lowmoor peat east of this (Fig. 23). The area surrounding Ätran that once consisted of a shallow protected bay, the area east of the deltaic deposits, should also be prioritized in an initial state of a mapping project, and other areas with similar features (Fig. 23). Further drilling in areas where the markings G at the map sheet (appendix 1) should be carried out at sites where the drilling was hampered by sand, so that the peat and gyttja clay layers can be analyzed. This should also be carried out at sites situated above 13 m.a.s.l. since the stratigraphy of site H19001 do correspond to the stratigraphy described by Påsse (1988).

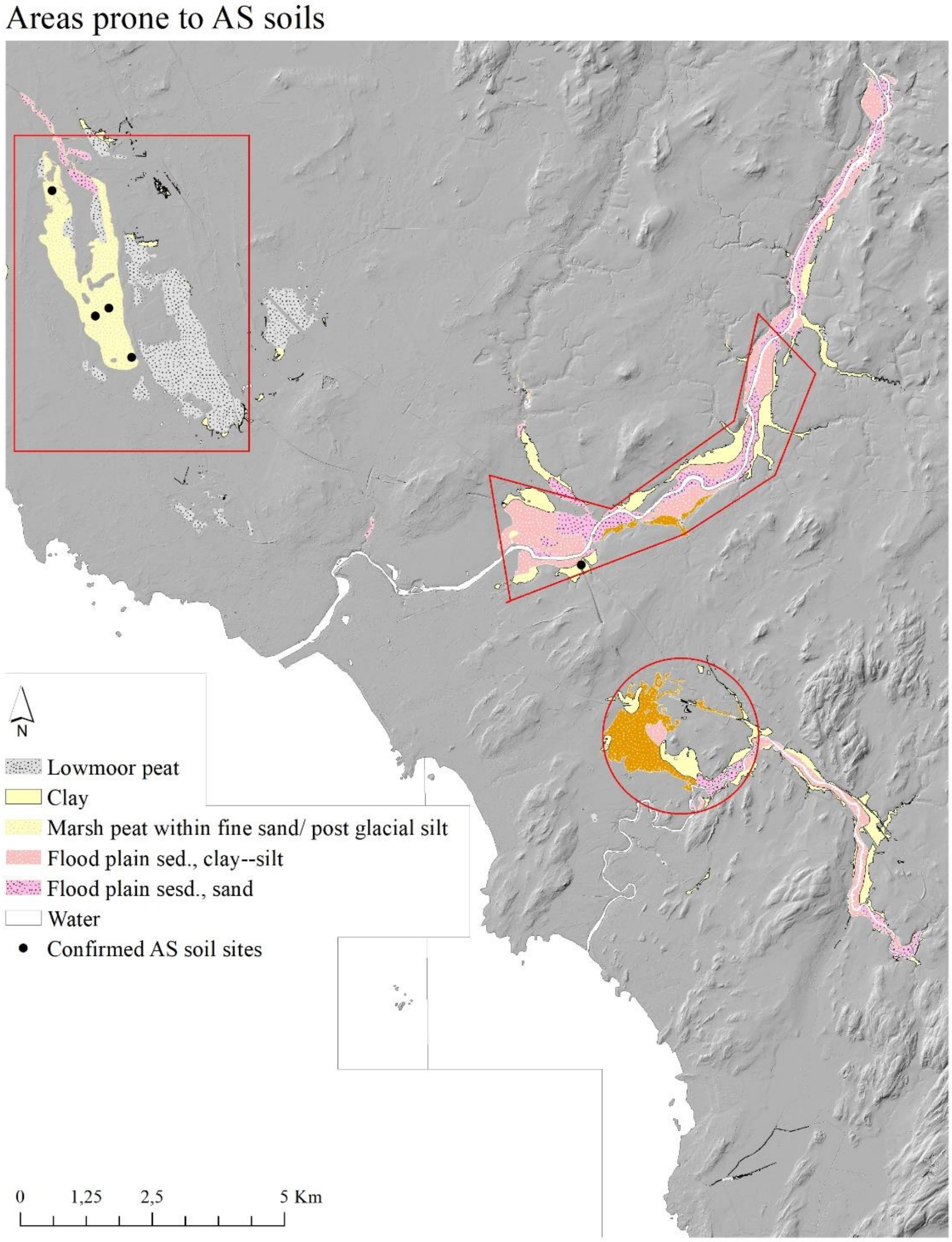


Figure 23. The map shows areas that have similar features, soil type, elevation, and formational environment, as the active and potential AS soil sites (marked with black icons). The areas are marked with soil type and the areas encircled with red are areas with a high risk of AS soil. Data source: GSD Höjddata, grid 2+, retrieved from Lantmäteriet©; and Jordarter_25_100_jk2, retrieved from SGU©.

9. Sources of error

Because the organic content of the soil was less than 20% the chosen method of analysis has large sources of error. This is due to that the grain-size analysis could not be conducted, hence the percentage of clay and the factor for correction could not be calculated. A better method for the analysis should instead have been with a carbon analyzer (Larsson, 2008).

The species of the shells observed in the stratigraphy of site H19001 used in the discussion about the formational environment were not identified and can therefore be of another species than the ones Påsse (1988 unpublished) observed.

Instrumental errors, procedural, and human errors have most likely influenced the results randomly to some extent. The pH-measurement device had to be stabilized before the pH-value was noted. Because the measurements were conducted by several different people at different times this may not have been done with consistency, although this may not affect the measurements to such an extent that it may matter for the classification of the sites. Furthermore, the pH-measurement device normally has an error range of +-0,2 units (personal communication, C. Öhrling). Further, the sub-samples were not homogenized and there can be differences ranging over small areas in a heterogeneous soil. The drilling also has some uncertainties regarding the procedure of deciding the depth for the sample. The auger does not have a fixed marking of the depth, and hence this was manually marked by the person conducting the drilling. Although a consistent procedure was used for this, the depth may vary to some extent from site to site as caused by human and procedural error.

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Appendix 1

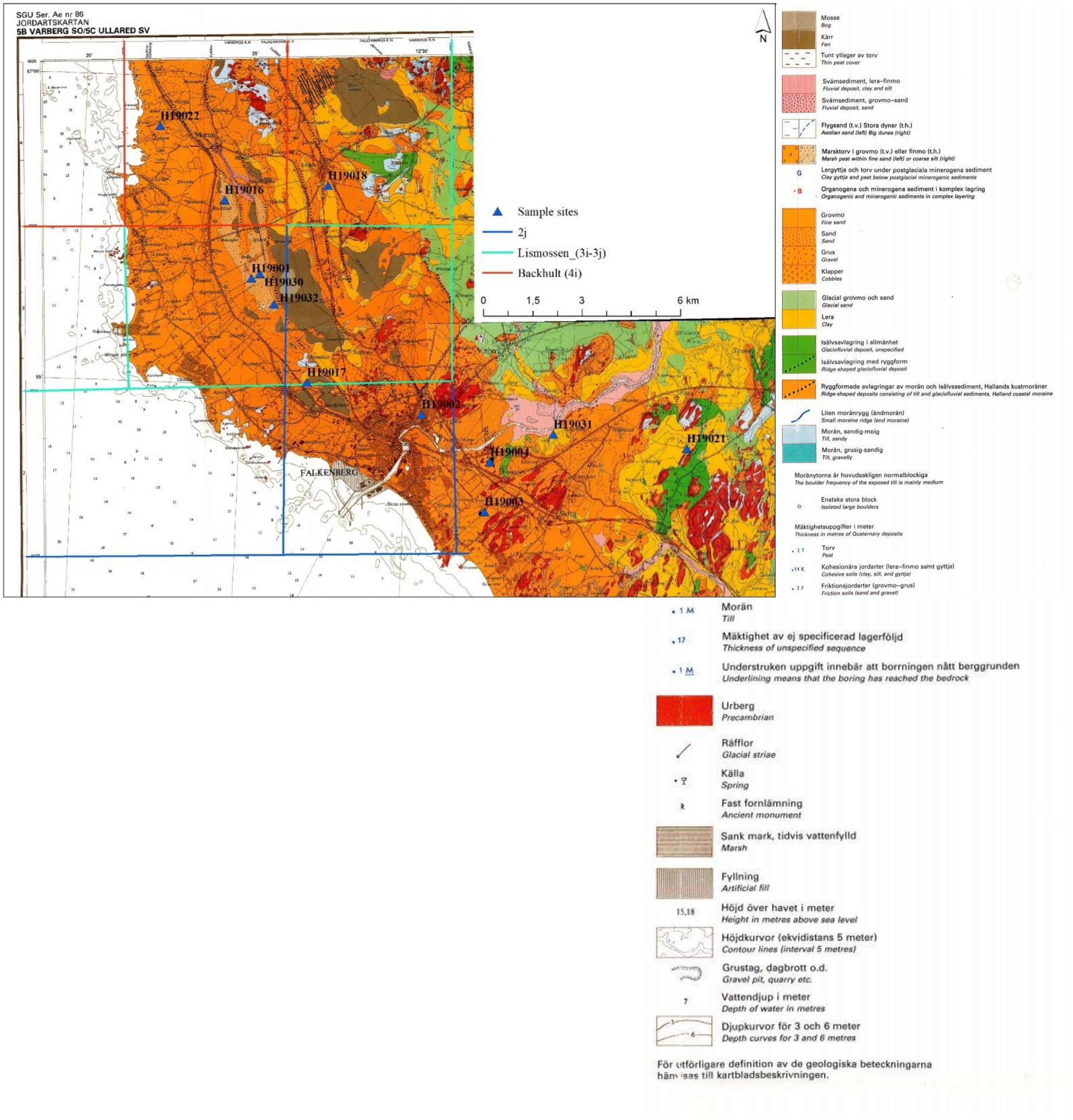

Figure 24. Map sheet Ae nr 86, with the areas mentioned in the discussion marked out by lines.

Appendix 2

Table 12. The results from field work and the oxidized pH for site H19002.

H19002				
Depth	Field pH	pH, oxidation 9 weeks	Sample	Soil type
0,3	6,38			Cl
0,4	6,37			Cl
0,5	6,16			Cl
0,6	6,37			Cl
0,7	6,42			Cl
0,8	6,48			Cl
0,9	6,56			Cl
1	6,45			Cl
1,1	6,74			Cl
1,2	6,65			Cl
1,3	6,76	6,34	H19002:1	Cl
1,4	6,72			Cl
Ground water at site: -				

Table 13. The results from field work and the oxidized pH of site H19003.

H19003				
Depth	Field pH	pH, oxidation 9 weeks	Sample	Soil type
0,15	4,87			Sa
0,2	5,76			Sa
0,3	5,77			Sa
0,4	6,06			Sa
0,5	5,7			Sa
0,6	5,84			Sa
0,7	5,78	4,74	H19003:1	Sa
0,8	5,85			Sa
0,9	6,01			Sa
1	5,82			Sa
1,1	6,14			Sa
1,2	5,94			Sa
1,3	5,71			Sa
1,4	5,92			Sa
1,5	5,95			Sa
1,6	5,94	4,91	H19003:2	Sa
Ground water at site: 0,4 m below ground surface				

Table 14. The results from field work and the oxidized pH of site H19004.

H19004 Depth	Field pH	pH, oxidation 9 weeks	Sample	Depth	soil type
0,2	4,83			0,2	Sa
0,3	5,18			0,3	Sa
0,4	5,27			0,4	Sa
0,5	5,33			0,5	Sa
0,6	5,12			0,6	Sa
0,7	5,78			0,7	Sa
0,8	5,69			0,8	Sa
0,9	5,46			0,9	Sa
1	5,76			1	Sa
1,1	5,86			1,1	Sa
1,2	5,87			1,2	Sa
1,3	5,87			1,3	Sa
1,4	6,38	4,92	H19004:1	1,4	Sa
1,5	6,17			1,5	Sa
1,6	6,03			1,6	Sa
1,7	5,84			1,7	Sa
1,8	5,51	4,55	H19004:2	1,8	Sa
Ground water at site: 1,3 m below ground surface					

Table 15. The results from field work and the oxidized pH of site H19017.

H19017 Depth	Field pH	pH, oxidation 9 weeks	pH 25/2	Sample	Soil type
0,2	5,05				Topsoil
0,3	4,94				Topsoil
0,4	4,66	4,26	4,29	H19017:1	Cl
0,5	4,86				siSa
0,6	4,73				saCl
0,7	4,99				siSa
0,8	4,96				saCl
0,9	5,56				lesaSi
1	6,52				saSi
1,1	6,64				siSa
1,2	6,62				siSa
1,3	6,32				siSa
1,4	7,01	5,1		H19017:2	siSa
1,5	6,99				siSa
1,6	7,03				siSa
Ground water at site: 0,4 m below ground surface					

Table 16. The results from field work and the oxidized pH of site H19018.

H19018 Depth	Field pH	pH, oxidation 9 weeks	Sample	Soil type
0,2	5,25			Topsoil
0,3	5,7			siCl
0,4	6,06			siCl
0,5	6,08			siCl
0,6	6,07			siCl
0,7	7,05			siCl
0,8	6,94	7,65	H19018:1	sasiCl
0,9	7,09			siCl
1	7,1			siCl
1,1	7,13			siCl
1,2	7,17			siCl
1,3	7			sasiCl
1,4	6,93			sasiCl
1,5	7,4			sasiCl
1,6	7,12			sasiCl
1,7	7,27			clsiSa
1,8	7,5			sasiCl
1,9	7,42			siCl
2	8,17			siCl
2,1	8,05			siCl
2,2	8,29			siCl
2,3	7,97			sasigyCl
2,4	8,23	7,69	H19018:2	sasigyCl
2,5	8,11			sasiCl
2,6	7,87			sasiCl

Ground water at site: 0,9 m

Table 17. The results from field work and the oxidized pH of site H19019.

H19019 Depth	Field pH	pH, oxidation 9 weeks	pH 25/2	Sample	Soil type
0,2	6,1				Topsoil
0,3	5,99				Topsoil
0,4	6,2				siSa
0,5	6,2				siclSa
0,6	6,34				siclSa
0,7	6,01				siclSa
0,8	6,04				siSa
0,9	6,12				siSa
1	5,38				siclSa
1,1	5,24				siSa
1,2	5,06	4,37	4,24	H19019:1	siSa
1,4	5,33				sasiCl
1,5	6,24				sasiCl
1,6	5,54				sasiCl
1,7	5,57				sasiCl
1,8	5,5	4,48	4,1	H19019:2	siCl
1,9	5,22				Peat
2	5,42				Peat
2,1	6,11				Peat
2,2	5,64				siCl
2,3	5,75				siCl
2,5	6,18				siclSa
2,6	6,89				siclSa
2,7	6,22				siSa
2,9	6,58				Cl
Ground water at site: 1,1 m below ground surface					

Table 18. The results from field work and the oxidized pH of site H19020.

H19020 Depth	Field pH	pH, oxidation 9 weeks	Sample	Soil type
0,2	4,9			Topsoil
0,3	5,18			Topsoil
0,4	5,5			saCl
0,5	5,42	5,73	H19020:1	saCl
0,6	5,81			saCl
0,7	5,86			Cl
0,8	6,06			Cl
0,9	6,34			Cl
1	6,51			Cl
1,1	6,83			Cl
1,2	7,13			Cl
1,3	7,07			Cl
1,4	8,29			Cl
1,5	7,79	7,76	H19020:2	Cl
1,6	7,83			Cl
1,7	8,39			Cl
1,8	8,14			Cl
1,9	7,82			Cl
2	8,1	7,47	H19020:3	Cl
Ground water at site: 1,2 m below ground surface				

Table 19. The results from field work and the oxidized pH of site H19020.

H19021 Depth	Field pH	pH, oxidation 9 weeks	Sample	Soil type
0,2	4,89			Topsoil
0,3	6,01			Cl
0,4	6,37	6,37	H19021:1	Cl
0,5	6,53			Cl
0,6	6,58			Cl
0,7	6,7			Cl
0,8	6,71			Cl
0,9	6,93			Cl
1	7,19	7,68	H19021:2	Cl
1,1	7,42			Cl
1,2	7,11			Cl
1,3	7,21			Cl
1,4	7,19			Cl
1,5	7,24			Cl
1,6	7,28			Cl
1,7	7,17			Cl
1,8	7,16	7,69	H19021:3	Cl
Ground water at site: -				

Table 20. The results from field work and the oxidized pH of site H19022.

H19022 Depth	Field pH	pH, oxidation 9 weeks	Sample	Soil type
0,2	4,78			Topsoil
0,3	5,77			Topsoil
0,4	5,39			Topsoil
0,5	5,07			Humus
0,6	4,93	5	H19022:1	saCl
0,7	5,6	5,43	H19022:2	Peat
0,8	5,3	5,48	H19022:4	clsiSa
0,9	6,47			siSa
1	6,1			siSa
1,1	6,14			siSa
1,2	5,81			siSa
1,3	5,45	5,58	H19022:3	siSa
Ground water at site: 1,0 m below ground surface				

Table 21. The results from field work and the oxidized pH of site H19023.

H19023 Depth	Field pH	pH, oxidation 8 weeks	pH, oxidation 9 weeks	Sample	Soil type
0,2	5,2				Topsoil
0,3	6,02				Topsoil
0,4	6,16	6,25	6,07	H19023:1	siSa
0,5	6,52				siSa
0,6	6,36				siSa
0,7	6,4				siSa
0,8	6,19				siSa
0,9	6,08				Sa
1	5,91				Sa
1,1	5,89				Sa
1,2	6,22	5,94	5,35	H19023:2	siSa
1,3	5,75				siSa
1,4	5,76				siSa
1,5	5,73				siSa
Ground water at site: 1,0 m below ground surface					

Appendix 3

Figure 25. Orthophoto over site H19031, marked with a green triangle, from year the 1960.

Figure 26. Orthophoto over the area H19031, marked with a green triangle) from the year 1975 before the restoration.

Appendix 4

Table 21. The results from the metal and Sulphur analyses done at ALS Global in Umeå, Västerbotten.

	Sample site	H19031	H19031
	Sample depth [m]	1	1,5
		potential AS soil	potential AS soil
ELEMENT			
As, arsenic	mg/kg DS	6.69	8.14
Ba, barium	mg/kg DS	81.7	54.5
Be, beryllium	mg/kg DS	0.990	0.697
Cd, cadmium	mg/kg DS	<0.1	<0.1
Co, cobalt	mg/kg DS	7.60	5.56
Cr, chromium	mg/kg DS	31.3	24.2
Cu, copper	mg/kg DS	17.1	13.6
Fe, iron	mg/kg DS	45700	24400
Hg, mercury	mg/kg DS	<1	<1
Mn, manganese	mg/kg DS	392	247
Ni, nickel	mg/kg DS	16.6	13.6
P, phosphorus	mg/kg DS	548	625
Pb, lead	mg/kg DS	10.5	10.1
S, sulfur	mg/kg DS	135	684
Sr, strontium	mg/kg DS	22.8	21.0
V, vanadium	mg/kg DS	64.6	58.6
Zn, zinc	mg/kg DS	55.1	48.0
Dry substance at 105°C	%	72.1	56.5

Appendix 5

Table 22. Field notes from sites that had a pH value close to the limit for an AS soil site.

Site	Field notes for sites falling close to AS soil
H19017	Rust grains 0,4 - 0,7 m
	Organic content 0,4 - 1 m
	Black sulphide speckles 0,4 - 1,2 m
	Black elements in sand on 0,5 m
	Some sand at 0,5 - 0,9 m
H19019	Rust percipitates 0,4 - 0,9 m
	Organic material 0,4 - 0,7 m and 1,1 m
	Black mineral grains 0,5 m
	Peat from 0,95 - 1,05 m
	Organic material (peat, wood) 1 - 1,2 m
	Peat layer 1,3 - 1,35 m
	Yeast structure and organic material 1,5 - 1,8 m
	Black sulphide speckles 1,8 m
	Peat content 2 - and 2,5 m? Silty sand to 2,85 m

Table 23. Field notes from sites that were not classified as an AS soil site.

Site	Field notes non-AS soil
H19002	Sporadic elements of sand Granular
H19003	Deciduous forest Marshy
H19004	Sand througout the whole horizon Seemingly high organic content with good cohesion Oxidized color until 1 m Transition zone ~10 - 20 cm, thereafter reduced
H19018	Organic material 0,3 - 2,6 m Rust percipitates 0,3 - 1,5 m Lime fragments 0,5 m Sporadic fine sand on 0,5 - 0,7 and 1,3 m Organic material (wood) 1,2 - 1,5 m Clayey peat from 1 - 2,6 m?
H19020	Rust percipitates 0,4 - 1,3 m Organic material 0,4 m - 2,0 m Yeast structure 0,7 - 2,0 m Sporadic sand lenses 0,9 and 1,1 - 1,2 m, 1,4 m, 1,6 - 1,7 m, 1,9 m Organic material wood 1,4 - 1,6 m and 2 m Yeast structure, clayey peat?
H19021	Organic material 0,3 - 1,8 m Yeast structure 0,3 - 1,8 m Rust percipitates 0,3 - 1,8 m, bigger at 0,9 m Small sand lenses 0,9 - 1 m and 1,5 m
H19022	Dark color from 0,2 - 0,5 m. Black at 0,7 m and rust percipitates peat? Organic material 0,8 - 1,3 m, purple red elements at 0,9 m Black speckles at 0,6 and 0,8 m, rust percipitates 1,3 m
H19023	Rust percipitates 1,2 - 1,3 m

Appendix 6

Fig. 25. Pollendiagram från Lismosse (3i-3j).
Pollen diagram from Lismosse (3i-3j).

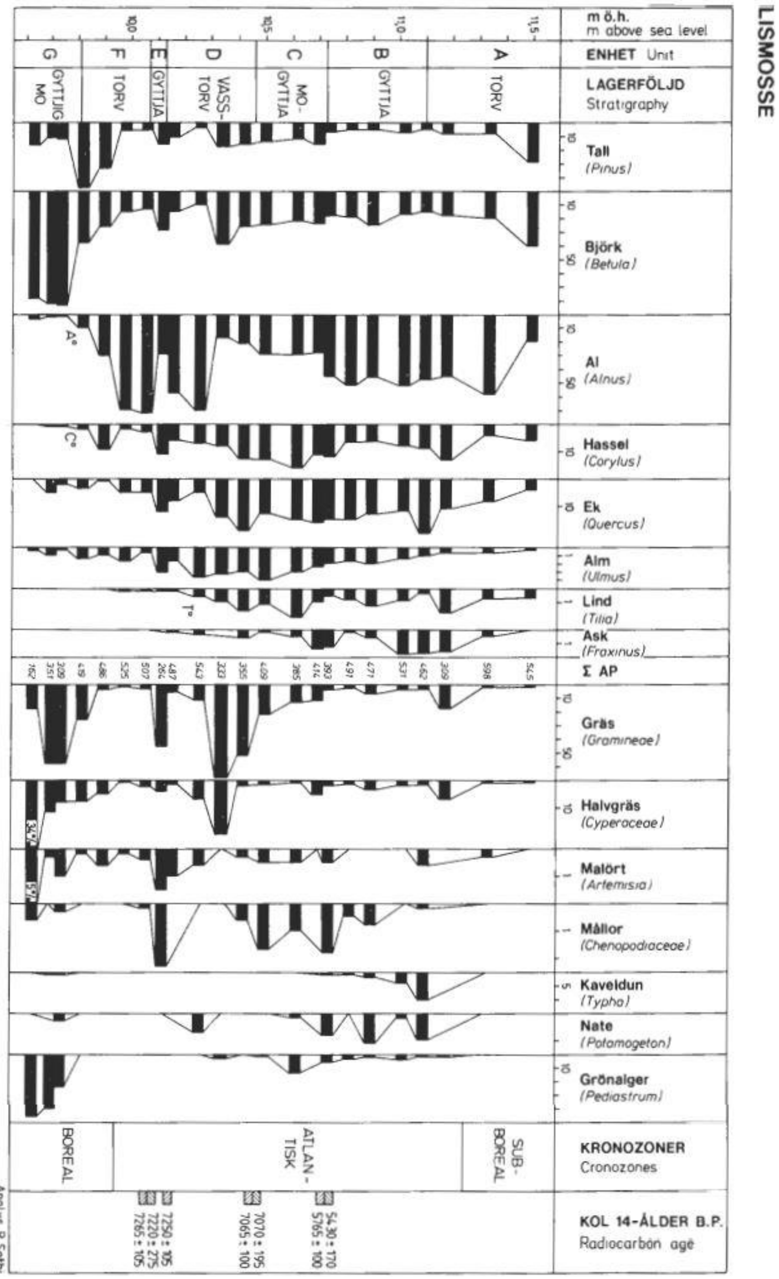

Figure 27. Pollen diagram from Lismosse (3i – 3j) from Påsse (1988 unpublished).

Appendix 7

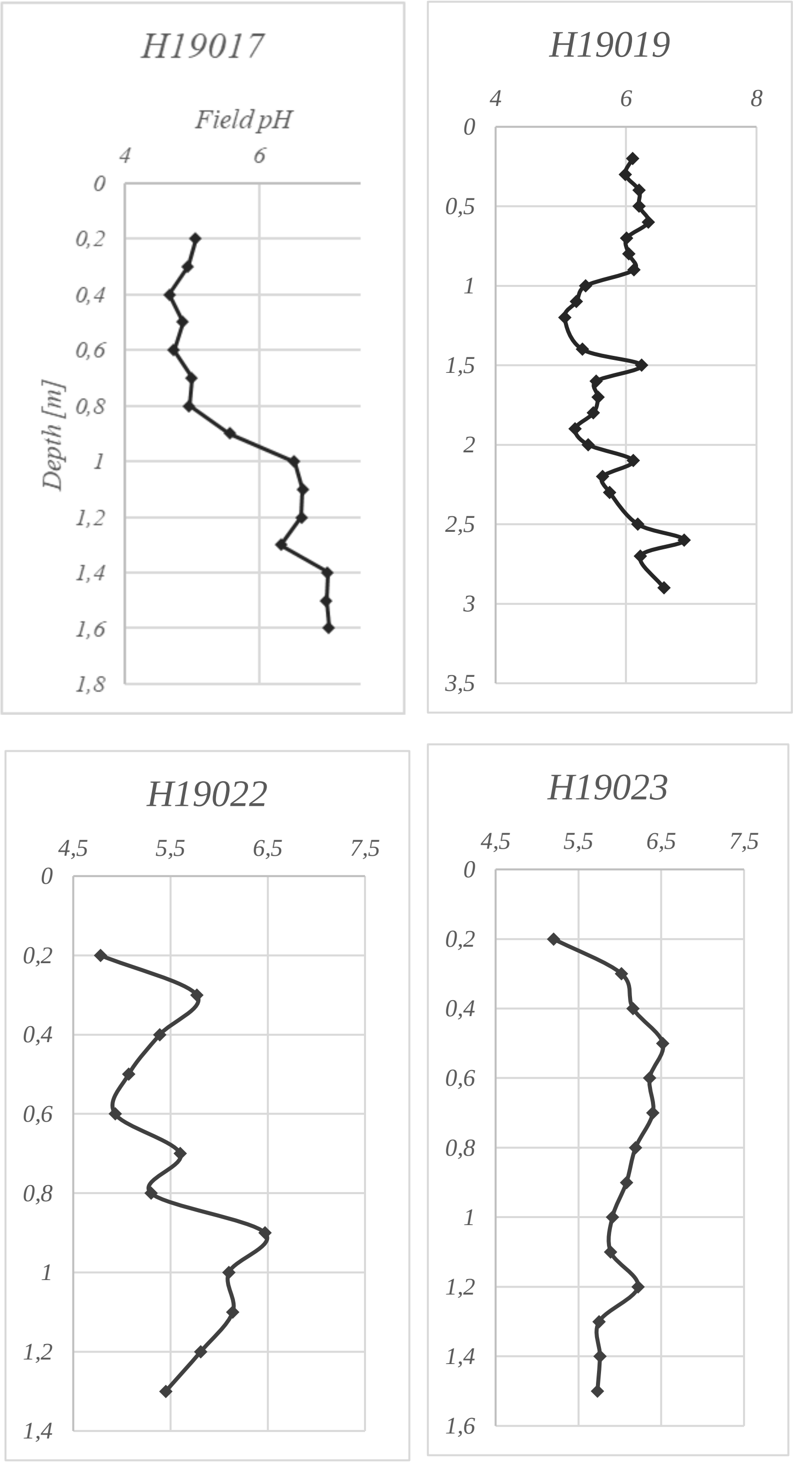

Figure 28. pH curves of the sites H19017, H19019, H19022, and H19023.

Appendix 8

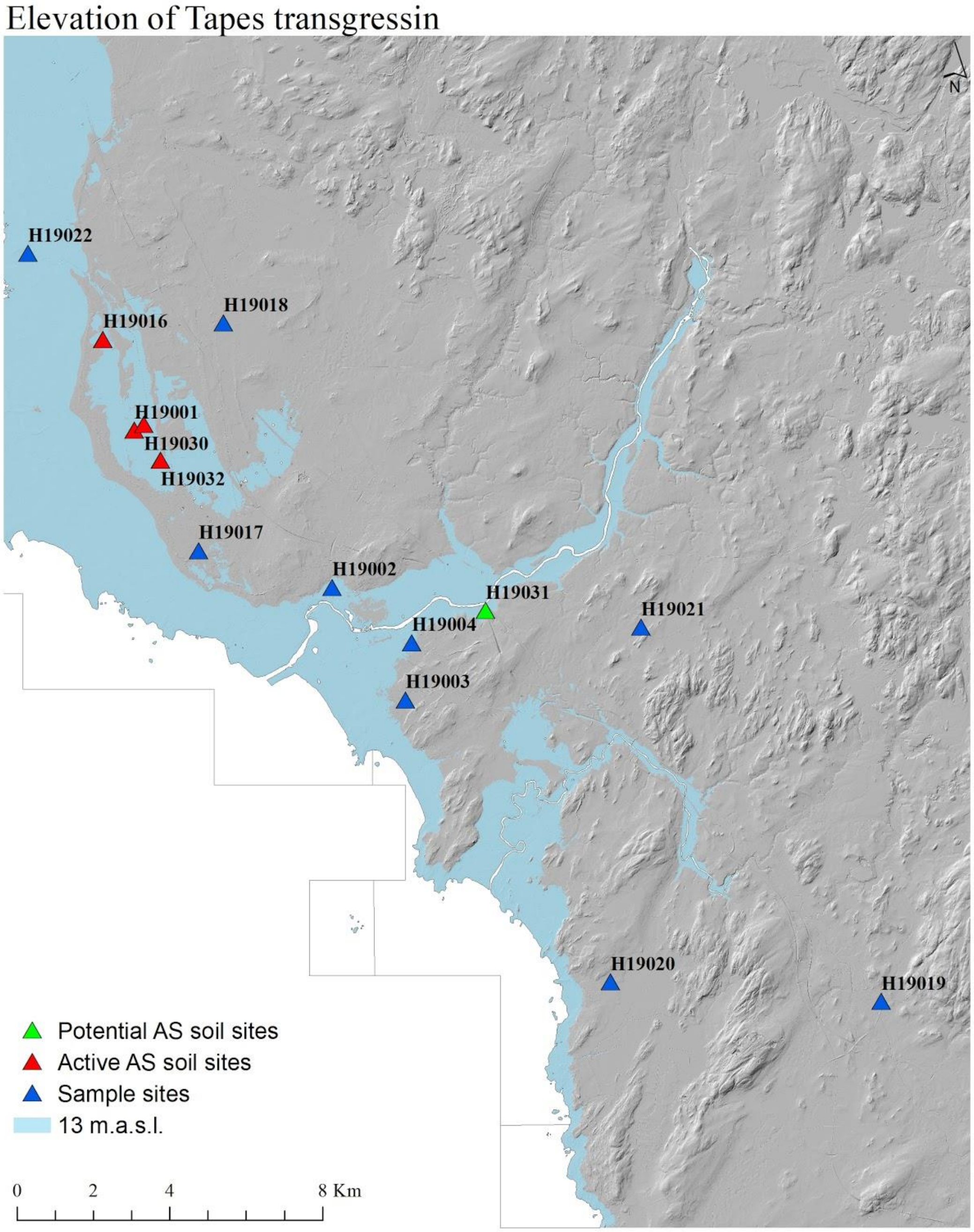

Figure 29. The blue line marks the maximum elevation, 13 m.a.s.l. of Tapes transgression in the study area Falkenberg. Data source

Appendix 9

Figure 30. An excavation done west of the location for site H19001, the same stratigraphy was observed at the excavation as the one at site H19001. Rust precipitates can be seen in the sand.