10th International Acid Sulfate Soils Conference

15–17 September 2025 Luleå, Sweden

Post-Conference Excursion GUIDEBOOK

18–20 September 2025 Finland & Sweden

GTK

Acid Sulfate Soil Working Group
International Union of Soil Sciences

LULEÅ UNIVERSITY OF TECHNOLOGY

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Cover photos: Anton Boman

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GTK

SGU
Geological Survey of Sweden

Acid Sulfate Soil Working Group
International Union of Soil Sciences

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Programme

Note: There is a one-hour time difference between Sweden and Finland. An asterisk (*) indicates when the time changes from Finnish to Swedish time or vice versa.

Day 1: Thursday 18 September 2025

07:30	Start from Luleå, Sweden and travel to Gammelgården (45 min)
08:15-09:00	**Site 1 – Gammelgården:** Learn about acid sulfate soils in Northern Sweden (45 min).
09:00-09:50	Travel to the Finnish/Swedish border (50 min). Possible border control.
11:00*-12:40	Travel to Kupsussuo (including a short break) (1h 40 min).
12:40-13:40	**Site 2 – Kupsussuo:** Learn about peat harvesting. Presence of acid sulfate soils. (1 h)
13:40-14:10	Travel to Välimaa (30 min).
14:10-14:40	**Site 3 – Välimaa:** Sulfidic material in the peat, mineral soil, and glacial till (30 min).
14:40-15:00	Travel to Jääli (20 min).
15:00-15:35	**Site 4 – Jääli:** Learn about iron contamination from black schists. Presence of black schist boulders area (35 min).
15:35-16:15	Travel to Nenänperä, Oulu (40 min).
16:15-17:15	**Site 5 – Nenänperä:** A typical acid sulfate soil in the Oulu region will be studied in a soil pit. Discussions about corrossion in infrastructure (1 h).
17:45	Arrival at Hannuksen Piilopirtti, where we will spend the night, enjoy a nice dinner, and experience a traditional Finnish sauna.

Day 2: Friday 19 September 2025

07:45	Start from Hannuksen Piilopirtti and travel to Turpeenperä (55 min).
08:40-09:20	**Site 6 – Turpeenperä:** Study of a hypersulfidic coarse-grained soil containing black monosulfidic sand and fine sand (40 min).
09:20-11:50	Travel to Kokkola (2h 30 min). There will be a short break in Kalajoki.
11:50-12:10	**Site 7 – Kokkola:** Acidic sand pits within a sand and gravel extraction area (20 min).
12:10-12:45	Travel to a sand and gravel extraction area in Socklot (35 min)
12:45-13:25	**Site 8 – Socklot:** Sand and gravel extraction area with hypersulfidic and sulfuric material in littoral deposits (40 min).
13:25-13:30	Travel to Plottret in Socklot (5 min).
13:30-14:10	**Site 9 – Plottret:** Visit to a sulfuric wetland and exploration of Fe and SO_4 precipitates (40 min).
14:10-15:00	Travel to Vassorfjärden Bay (50 min).
15:00-16:00	**Site 10 – Vassorfjärden Bay:** Discussion on the impact of land uplift on oxidation processes and the development of future sulfuric soils. Fika break at Tesses Café (1 h).
16:00-16:45	Travel to Söderfjärden (45 min).
16:45-18:00	**Site 11 – Söderfjärden:** Study of a typical sulfuric fine-grained soil (soil pit) within the Söderfjärden impact crater. We will learn about acid sulfate soil management practices in this region. The visit also includes a stop at the Meteorian Visitor Centre (1h 15 min).
18:15	Arrival at Scandic Waskia, where we will enjoy a pleasant dinner together and stay the night.

Day 3: Saturday 20 September 2025

07:45	Start from Scandic Waskia to the Vaasa harbor from where we will cross the Kvarken Archipelago to Umeå, Sweden.
09:00-12:00*	We are enjoying the Kvarken Archipelago while learning about metal leaching into the Baltic Sea **("Site 12")**. Lunch will be served in the cafeteria, and participants will have the opportunity to visit the ferry's observation room during the 4-hour crossing.
12:00-12:30	Travel to Envix sulfide soil treatment facility (30 min).
12:30-13:45	**Site 13 – Envix Nord:** Facility for the treatment of contaminated soils (1h 15 min).
13:45-14:30	Travel to Västervik (45 min).
14:30-15:00	**Site 14 – Västervik:** We will visit a formerly drained lake that is leaching acid and metals into the surrounding stream waters (30 min).
15:00-17:45	Travel back to Luleå, where the excursion ends at Clarion Hotel Sense (2h 45 min). One minibus will return to Umeå to drop off participants at their destinations.
17:45	Arrival at Clarion Hotel Sense and end of post-excursion.

Map of the excursion tour

Overview

Over the course of three days, we will travel to various acid sulfate soil sites in Sweden and Finland in four minibuses, accompanied by a support vehicle for field equipment and excess luggage. In total we will cover more than 1000 km by road, plus approximately 80 km across open water in the Kvarken Archipelago (Figure 1). The journey begins and ends in Luleå, Sweden, and is divided into into the following legs:

- Day 1, Thursday 18 September 2025: Luleå – Oulu
- Day 2, Friday 19 September 2025: Oulu – Vaasa
- Day 3, Saturday 20 September 2025: Vaasa – Umeå – Luleå

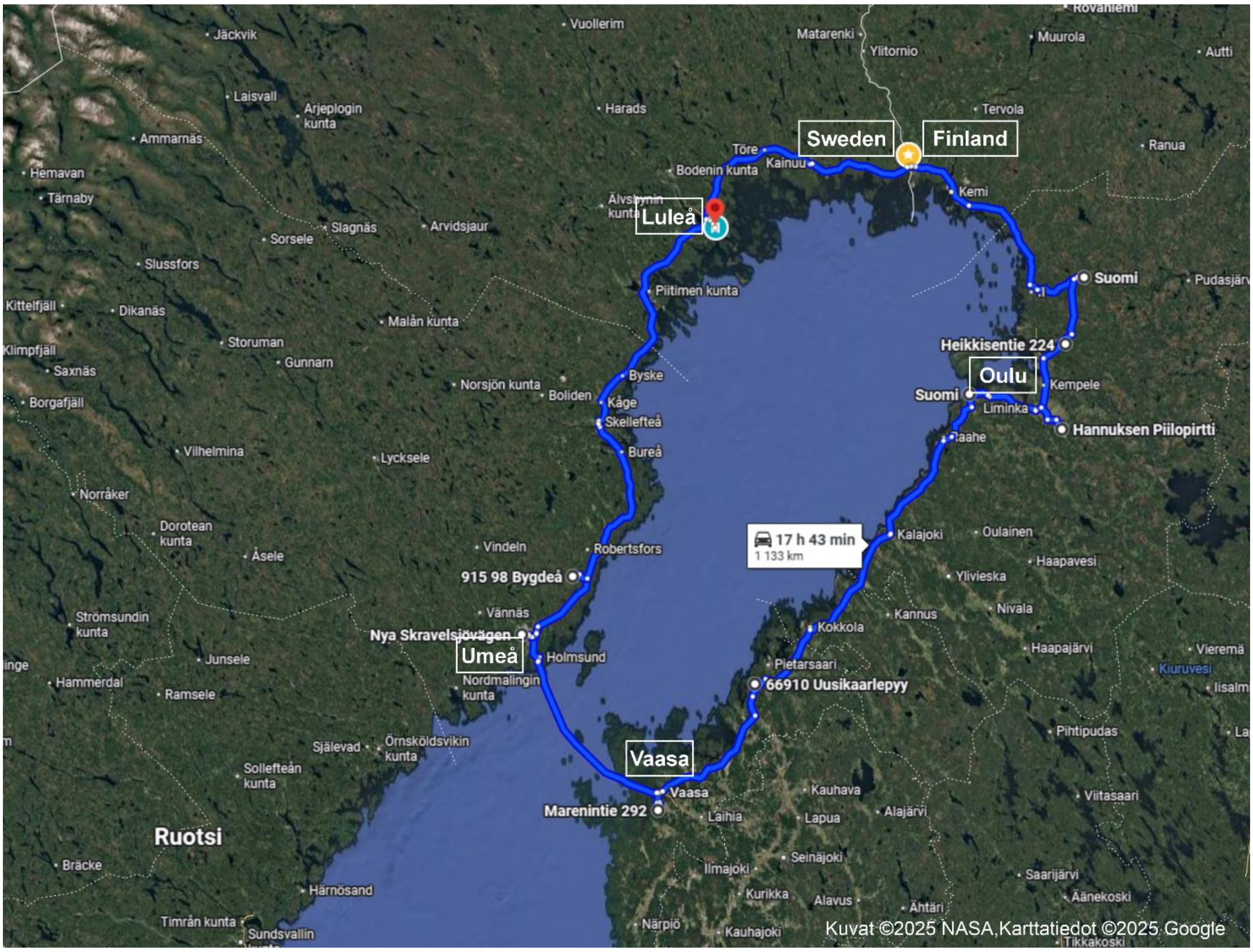


Figure 1. Map of the excursion tour.

Preface

Welcome to this field excursion exploring the diverse and geochemically fascinating acid sulfate soils (ASS) found in the coastal areas of Northern Sweden and of Northern and Western Finland, set within a landscape shaped by the last glaciation. During the "7th IASSC" in Vaasa, Finland (2012), participants became acquainted with typical Finnish ASS, which are commonly fine-grained (clay and silt), contain organic matter, and often display a black colour in reduced hypersulfidic material due to the presence of metastable iron sulfides (mackinawite and greigite). These are called ***fine-grained ASS*** in the unified Finnish-Swedish ASS classification and are also common in the coastal areas of Northern Sweden. During this excursion, we will also visit such sites, but this time the focus will also be on less common or less studied types of ASS, such as ***coarse-grained ASS*** (containing sandy ASS materials), ***organic ASS*** (containing organic ASS materials such as peat), and ***unsorted ASS*** (containing ASS materials in glacial till).

The journey begins in Luleå, Northern Sweden, where we will drive through typical ASS landscapes. From there, we continue into the coastal peatlands of Northern Finland, passing through black schist areas and glaciofluvial and littoral sand deposits in Northern Ostrobothnia (Oulu region). The route then leads southward along the coastal plains to Central Ostrobothnia (Kokkola region), where we will visit acidic sand pit lakes, and further south to Ostrobothnia (Socklot and the Vaasa region) in Western Finland. In Ostrobothnia we will visit a sand and gravel extraction area with hypersulfidic and sulfuric ASS materials, slog through a sulfuric wetland, observe the effects of isostatic land uplift, and examine traditional agricultural ASS within an impact crater, along with current ASS management practices. From Ostrobothnia, we cross the Kvarken Archipelago to Umeå in Sweden to visit a facility specializing in the treatment and neutralization of sulfidic soil materials. After this, the journey continues to a formerly drained lake that releases acid and metals into the environment. The excursion concludes with a return northward to Luleå, completing a circular route through some of the most geochemically and environmentally significant ASS regions in Finland and Sweden.

The content of the post-excursion guidebook has been developed by several contributors and compiled by Anton Boman. The guidebook includes, among other things, descriptions of field sites, as well as overviews and maps of the geology, Quaternary geology (including superficial deposits), and the occurrence of acid sulfate soils in the area. It also provides an overview of how acid sulfate soils are classified in Finland and Sweden.

We are delighted to have you join us on this journey and hope you will find it an interesting and memorable experience.

On behalf of the 10th IASSC Organising Committee

Anton Boman

Geological Survey of Finland

Chair of the International Acid Sulfate Soil Working Group

1. Introduction

Anton Boman

This guidebook provides descriptions of the sites we will visit during the field excursion. A total of 14 sites will be visited, 3 in Sweden and 11 in Finland. These are described in Section 6.

An introduction to the classification of acid sulfate soils (ASS) in Finland and Sweden is provided in Section 2. Since most of the sites are located in Finland, we have included a more detailed description of the distribution of ASS in Finland (Section 3), as well as the bedrock and Quaternary geology of the coastal areas of Lapland, Northern Ostrobothnia, Central Ostrobothnia, and Ostrobothnia (Sections 4 and 5). In Sweden, these conditions will be addressed in connection with the field visits.

Links to useful soil maps, as well as other geology-related maps, in Finland and Sweden can be found through the GTK and SGU map services. A selection of these includes:

Acid sulfate soils in Finland: https://gtkdata.gtk.fi/hasu/

Soil maps in Finland: https://gtkdata.gtk.fi/maankamara/

Acid sulfate soils in Sweden: https://www.sgu.se/produkter-och-tjanster/kartor/kartvisaren/jordkartvisare/sur-sulfatjord/

Soil maps in Sweden: https://www.sgu.se/produkter-och-tjanster/kartor/kartvisaren/jordkartvisare/jordarter-125-000-1100-000/

2. Classification of acid sulfate soils in Finland and Sweden

Anton Boman, Stefan Mattbäck & Jaakko Auri

Introduction and overview

International soil classification systems have struggled to accommodate acid sulfate soils (ASS) in Finland and Sweden due to: (1) diagnostic features often occurring below required depths, and (2) the absence of criteria for acidic or potentially acidic materials that do not meet the strict pH < 4.0 threshold. To address these issues, the Finnish-Swedish ASS classification (Boman et al., 2023) removes depth requirements for diagnostic ASS materials and introduces two new materials: ***parasulfuric*** (oxidized) and ***parahypersulfidic*** (reduced), with diagnostic pH ranges of 4.0–4.5 for mineral soils and 3.0–3.5 for organic soils. The term ***para-acid sulfate soil*** (*para-ASS*) material is introduced for soil materials which may have a considerable environmental impact due to mobilization of acidity and dissolved metals. For organic soil materials, a pH < 3.0 is used to classify hypersulfidic material, accounting for the influence of organic acids. These updates also slightly adjust the pH thresholds for existing terms such as hypersulfidic and sulfuric material.

Classification of acid sulfate soil materials

Diagnostic ASS materials significantly influence pedogenetic processes in ASS and para-ASS or are indicative of them and include all soil materials (and parent sediment) containing sulfidic and sulfuric material as well as their para-variants (i.e., parasulfuric and parahypersulfidic material). To fulfill classification as an ASS material, the diagnostic criteria (i.e., certain numerical values such as pH and sulfide concentration) need to be within the given threshold values. An overview of diagnostic ASS materials and their diagnostic criteria (sulfur and pH) is presented in Table 1 and described in detail in Boman et al. (2023). Examples of ASS materials are presented in Figure 1. Whereas the procedure for classification of ASS materials using pH and the soil incubation method is illustrated in Figure 2.

Table 1. Overview of diagnostic acid sulfate soil (ASS) materials and their classification criteria. The limits for sulfidic-S, AVS-S, and SO4 are presented as mass fraction (%) of total dry weight. Note that for sulfuric and parasulfuric material, ≥ 0.05% water-soluble sulfate do not need to be fulfilled if there are other signs of sulfide oxidation (from Boman et al., 2023).

Diagnostic ASS material	Diagnostic criteria								Comment
	Sulfur (%)			pH					
				Field		Incubation			
	Sulfidic-S	AVS-S[a)]	SO_4	Mineral	Organic	Mineral	Organic	Drop	
Sulfidic	≥0.01	-	-	-	-	-	-	-	Same criteria as in[b), c), d)]
Hypersulfidic	≥0.01	-	-	≥4.0	≥3.0	<4.0	<3.0	≥0.5	Modified criteria compared to[b), c), d)]
Parahypersulfidic	≥0.01	-	-	>4.5	>3.5	4.0-4.5	3.0-3.5	≥0.5	New term
Hyposulfidic	≥0.01	-	-	≥4.0	≥3.0	>4.5	>3.5	-	Modified criteria compared to[b), c), d)]
Monosulfidic	-	≥0.01	-	-	-	-	-	-	Same criteria as in[b), c)]
Hypermonosulfidic	-	≥0.01	-	≥4.0	≥3.0	<4.0	<3.0	≥0.5	Modified criteria compared to[b)]
Parahypermonosulfidic	-	≥0.01	-	>4.5	>3.5	4.0-4.5	3.0-3.5	≥0.5	New term
Sulfuric	-	-	≥0.05	<4.0	<3.0	-	-	-	Modified criteria compared to[b), c)]
Parasulfuric	-	-	≥0.05	4.0-4.5	3.0-3.5	-	-	-	New term

[a)] AVS = Acid volatile sulfide

[b)] Sullivan et al. (2010)

[c)] Isbell & NCST (2021)

[d)] IUSS Working Group WRB (2022)

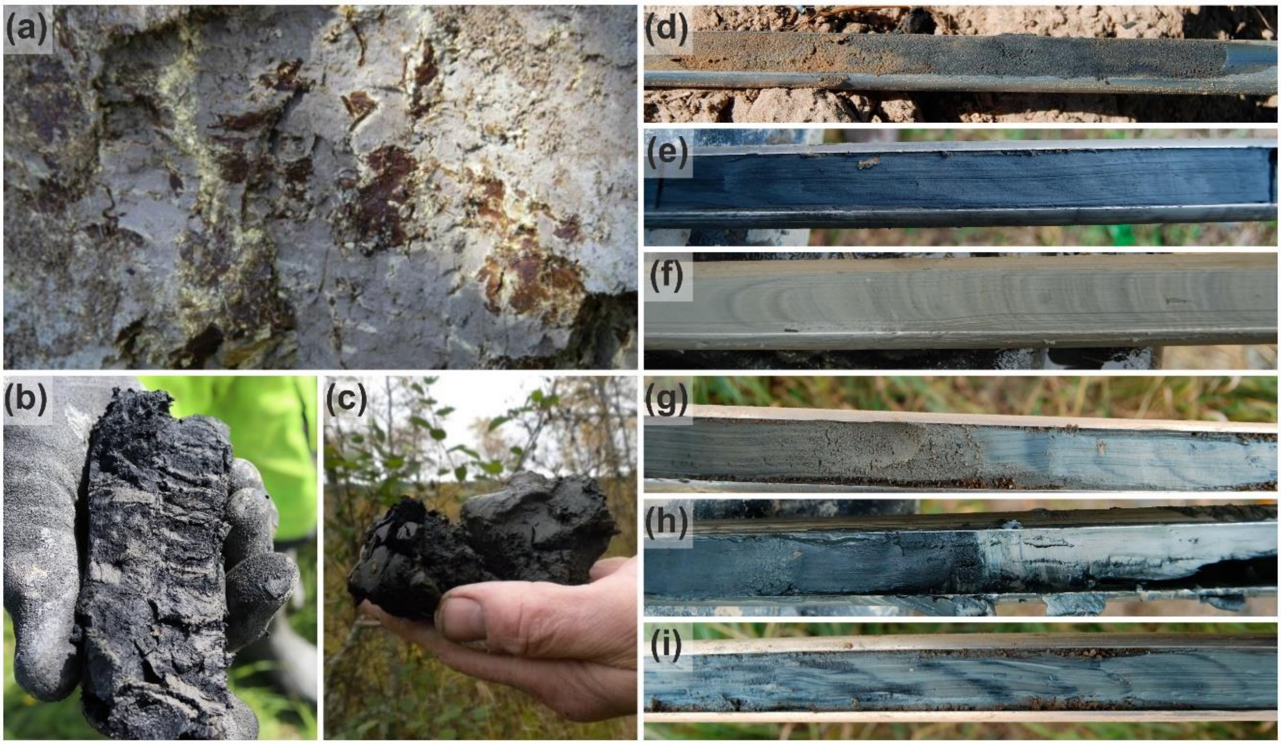
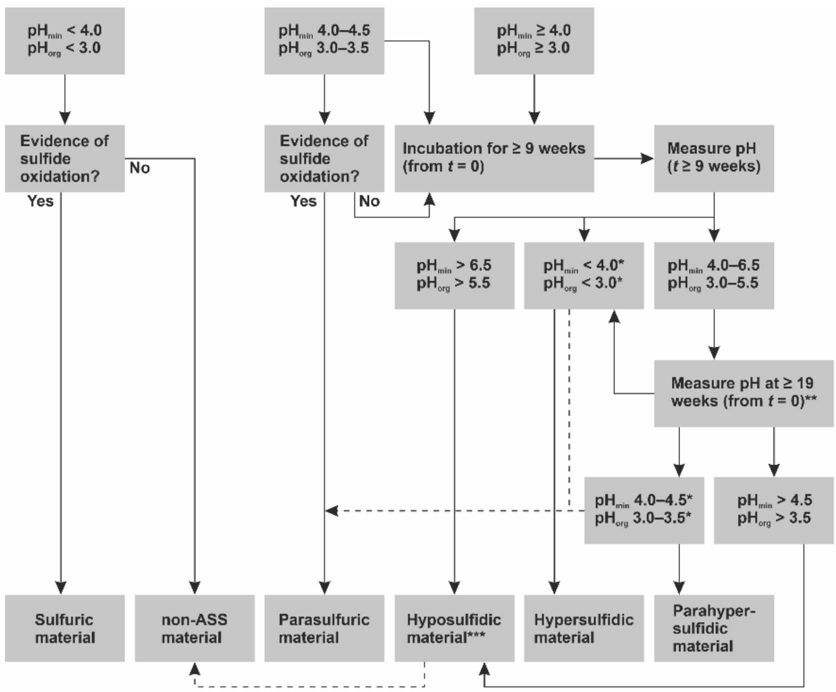


Figure 1. Examples of various types of acid sulfate soil (ASS) materials commonly found in Finnish and Swedish ASS. **(a)** Sulfuric material containing jarosite (yellow mottles) and iron hydroxides in gyttja-containing silt (oxidized). **(b)** Clayey hypersulfidic material with monosulfidic bands. **(c)** Black coloured hypermonosulfidic material (similar to the material in Fig. e). **(d)** Hypermonosulfidic black sand, upper part (left) oxidized. **(e)** Weakly stratified gyttja-containing hypermonosulfidic silt. **(f)** Stratified gyttja-containing hypersulfidic silt. **(g)** Gyttja-containing hypersulfidic silt on top (left) of bluish-gray clay with black monosulfidic bands (deposited in the Ancylus Lake; often classified as hyposulfidic or parahypersulfidic material) with an erosional contact (thin sandy layer) in-between. **(h)** Sharp erosional contact between gyttja-containing black hypersulfidic silt (left) and underlying gray massive hyposulfidic clay (right). **(i)** Massive bluish-gray clay with black monosulfidic bands (similar to the material in the lower part in Fig. g) (from Boman et al., 2023).



* Parasulfuric material if the ΔpH between t = 0 weeks and t ≥ 19 weeks is < 0.5 pH-units.
** The incubation may be stopped if the pH is stable (pH-change < 0.1 pH-units) over a period of ≥ 14 days or if the pH has started to increase.
*** May also be classified as non-ASS material.

Figure 2. Procedure for classification of acid sulfate soil (ASS) materials (from Boman et al., 2023).

Classification of the acid sulfate soil profile

The umbrella terms acid sulfate soil (ASS) and para-acid sulfate soil (para-ASS) are broad and encompass soils where sulfuric material, hypersulfidic material, and/or hypermonosulfidic material, including their para-variants (parasulfuric and parahypersulfidic material), occur in the soil profile. In many international soil taxonomy systems, typical ASS properties in Finnish and Swedish ASS are commonly located too deep to fulfill the depth criteria set for various soil types. Earlier versions of WRB also had depth requirements, but updates in recent editions (IUSS Working Group 2015, 2022) now allow recognition of soil properties deeper in the profile. The current WRB uses the prefix "*bathy*" (from Greek bathus, meaning "deep") to classify ASS features, such as *bathyhypersulfidic*, even several meters below the surface. In "Keys to soil taxonomy" (Soil Survey Staff 2022), there is still a depth criterion for ASS properties (e.g., sulfuric and sulfidic materials within 50–150 cm of the soil surface depending on soil type), which are often not met in many Finnish and Swedish ASS.

While WRB no longer imposes depth limits for ASS classification, moderately or potentially moderately acidic materials, such as ***parasulfuric*** and ***parahypersulfidic***, can still pose environmental risks despite not meeting the pH < 4.0 criterion. In Finland and Sweden, organic soils with naturally low pH due to humic acids often contain sulfidic materials, emphasizing the need for adjusted pH thresholds. The Finnish-Swedish classification responds to these challenges by removing depth requirements and focusing on environmental impact.

The Finnish-Swedish ASS classification provides a systematic approach for assessing the entire soil profile, without depth restrictions for diagnostic materials. The following sections describe how ASS and para-ASS, which is the main group, are classified and divided into two main soil types, four soil subtypes and four diagnostic soil subtypes (Table 2).

Classification of ASS types

To classify as an ASS, the soil must have a direct (active) or indirect (potential) acidifying impact on soil or water due to diagnostic ASS materials, and contain at least one of the following:

1. ***Sulfuric material*** with a combined thickness of ≥ 15 cm; ***and/or***
2. ***Parasulfuric material*** with a combined thickness of ≥ 15 cm **AND** ***hypersulfidic material*** (incl. monosulfidic material) with a combined thickness of ≥ 15 cm within 1 m of the oxidation depth, and/or the lowermost part of organic soil materials such as peat and gyttja; ***and/or***
3. ***Hypersulfidic material*** with a combined thickness of ≥ 15 cm within 1 m of the oxidation depth, and/or the lowermost part of organic soil materials such as peat and gyttja.

Acid sulfate soils are further divided into ***sulfuric soils*** (acid-producing; synonym "active or actual ASS") and ***hypersulfidic soils*** (potentially acid-producing; synonym "potential ASS") based on whether acidity has already been released or may form upon oxygen exposure (Table 2).

Classification of para-ASS types

To be classified as a para-ASS, it must contain at least one of the following:

1. ***Parasulfuric material*** with a combined thickness of ≥ 15 cm; and/or
2. ***Parahypersulfidic material*** with a combined thickness of ≥ 15 cm within 1 m of the oxidation depth, and/or the lowermost part of organic soil materials such as peat and gyttja.

Para-ASS thus do not contain either sulfuric or hypersulfidic material and can further be divided into ***parasulfuric soils*** (moderately acid producing) and ***parahypersulfidic soils*** (potentially moderately acid producing, containing only parahypersulfidic material), depending on whether they are active or not (Table 2).

Acid sulfate soil and para-acid sulfate soil subtypes

ASS and para-ASS types are further divided into four broad soil subtypes based on their organic matter content and the presence of certain mineral soil materials, which can in turn be subdivided into specific subtypes indicating diagnostic ASS/para-ASS properties (Table 2).

Table 2. Acid sulfate soils (ASS) and para-acid sulfate soils (para-ASS) are classified into two main soil types (bold), four soil subtypes (bold italics), and further into four diagnostic soil subtypes (italics) based on ASS/para-ASS properties (from Boman et al., 2023).

Acid sulfate soils (ASS)		
Sulfuric soils		**Hypersulfidic soils**
Sulfuric organic soil	***< Organic ASS >***	*Hypersulfidic organic soil*
Sulfuric fine-grained soil	***< Fine-grained ASS >***	*Hypersulfidic fine-grained soil*
Sulfuric coarse-grained soil	***< Coarse-grained ASS >***	*Hypersulfidic coarse-grained soil*
Sulfuric unsorted soil	***< Unsorted ASS >***	*Hypersulfidic unsorted soil*
Para-acid sulfate soils (para-ASS)		
Parasulfuric soils		**Parahypersulfidic soils**
Parasulfuric organic soil	***< Organic para-ASS >***	*Parahypersulfidic organic soil*
Parasulfuric fine-grained soil	***< Fine-grained para-ASS >***	*Parahypersulfidic fine-grained soil*
Parasulfuric coarse-grained soil	***< Coarse-grained para-ASS >***	*Parahypersulfidic coarse-grained soil*
Parasulfuric unsorted soil	***< Unsorted para-ASS >***	*Parahypersulfidic unsorted soil*

Classification of the acidifying potential

Based on titratable incubation acidity (TIA), a method developed by Österholm and Nystrand (2016), acid sulfate soil (ASS) materials are classified into three categories indicating the magnitude of their acidifying potential: large, medium, and small (Visuri et al., 2021). This classification uses different threshold values for TIA depending on the type of material: **peat** (>40% organic matter), **gyttja** (20–40% organic matter), **fine-grained materials** (<0.06 mm; clay and silt), and **coarse-grained materials** (>0.06 mm; often sand) (Table 3). The rationale is that these materials, although exhibiting similarly low incubation pH values, may have very different acidification impacts (Figure 3; Visuri et al., 2021). This variation is largely related to differences in sulfur content, which vary substantially between these materials (Figure 4). For peat, the influence of humic acids must also be considered when assessing acidifying potential, as the goal is to quantify the acidity released specifically from sulfides. For coarse-grained materials, the poor buffering capacity allows for a substantial pH drop during incubation, even when the sulfur content is low (<0.1%). However, the total amount of acidity formed is often small in this type of material.

Table 3. Classification of acidifying potential (After Visuri et al. (2021).

Soil material	**Acidifying potential (mmol H+ / kg, pH 6.5)**		
	Small	**Medium**	**Large**
Peat (>40% LOI)	<250	250 - 600	>600
Gyttja (20-40% LOI)	<100	100 - 200	>200
Fine-grained material (<0.06 mm)	<20	20 - 100	>100
Coarse-grained material (>0.06 mm)	<6	6 - 20	>20

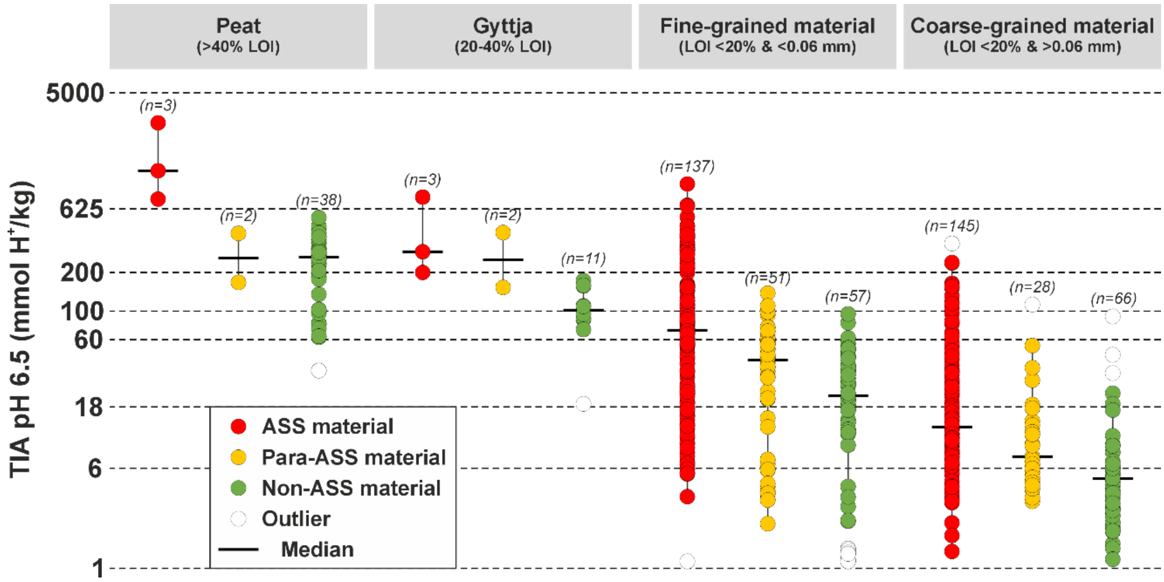


Figure 3. Distribution of titratable incubation acidity (TIA) in acid sulfate soil (ASS) materials (hypersulfidic material), para-acid sulfate soil (para-ASS) materials (parahypersulfidic material), and non-ASS materials based on grain size and organic matter content (loss on ignition, LOI). The classification of soil materials follows the current Finnish-Swedish ASS classification. Both fine- (clay and silt) and coarse-grained (e.g., sand and gravel) materials include gyttja-containing materials (2–20% LOI). TIA was determined on incubated (at least 19 weeks) soil samples using procedures based on KCl extraction followed by titration with NaOH, as described in Österholm and Nystrand (2016) and Mattbäck et al. (2017). Slightly modified after Visuri et al. (2021).

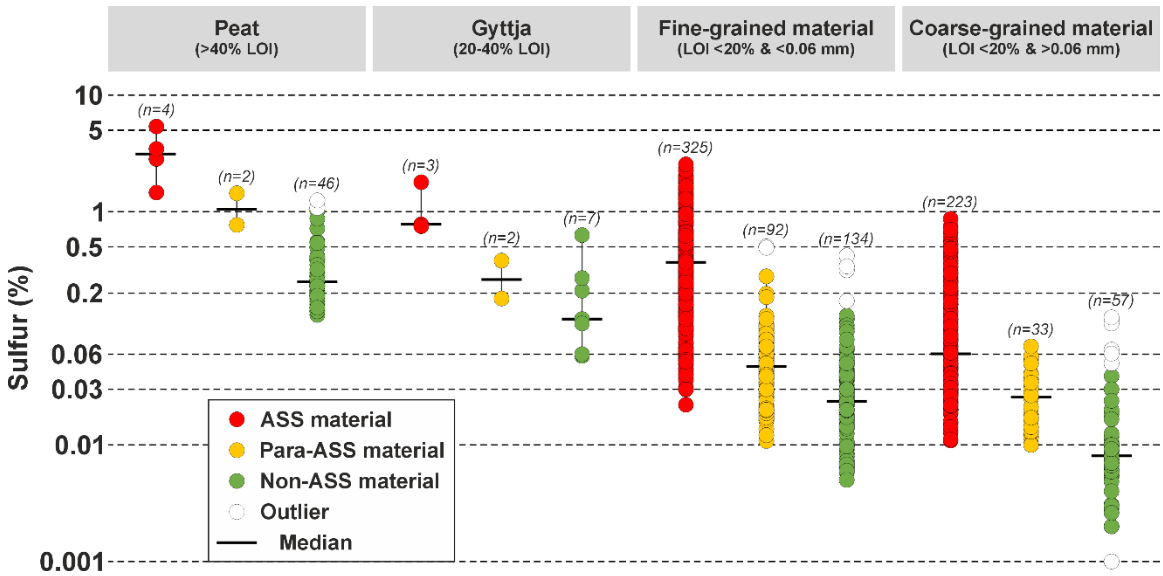


Figure 4. Distribution of total sulfur in reduced acid sulfate soil (ASS) materials (hypersulfidic material), para-acid sulfate soil (para-ASS) materials (parahypersulfidic material), and non-ASS materials based on grain size and organic matter content (loss on ignition, LOI). The classification of soil materials follows the current Finnish-Swedish ASS classification. Both fine- (clay and silt) and coarse-grained (e.g., sand and gravel) materials include gyttja-containing materials (2–20% LOI). Total sulfur concentrations were determined by dissolution with aqua regia followed by IPC-OES for quantification. Slightly modified after Visuri et al. (2021).

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3. Distribution of acid sulfate soils in Finland

Anton Boman, Jaakko Auri, Jukka Räisänen & Stefan Mattbäck

Overview of acid sulfate soil occurrences globally

Acid sulfate soils (ASS) are commonly associated with low-lying coastal areas in relatively warm climate zones. Their global extent is currently estimated at approximately 50 million ha (Michael et al., 2017) (Figure 1). However, this figure should not be considered definite, as ongoing surveys and mapping in previously unmapped regions and evolving ASS classification approaches may lead to changes in estimated extent (e.g., Edén et al., 2023; Boman et al., 2023a). More information about global extent of coastal ASS can be found in Andriesse and van Mensvoort (2006).

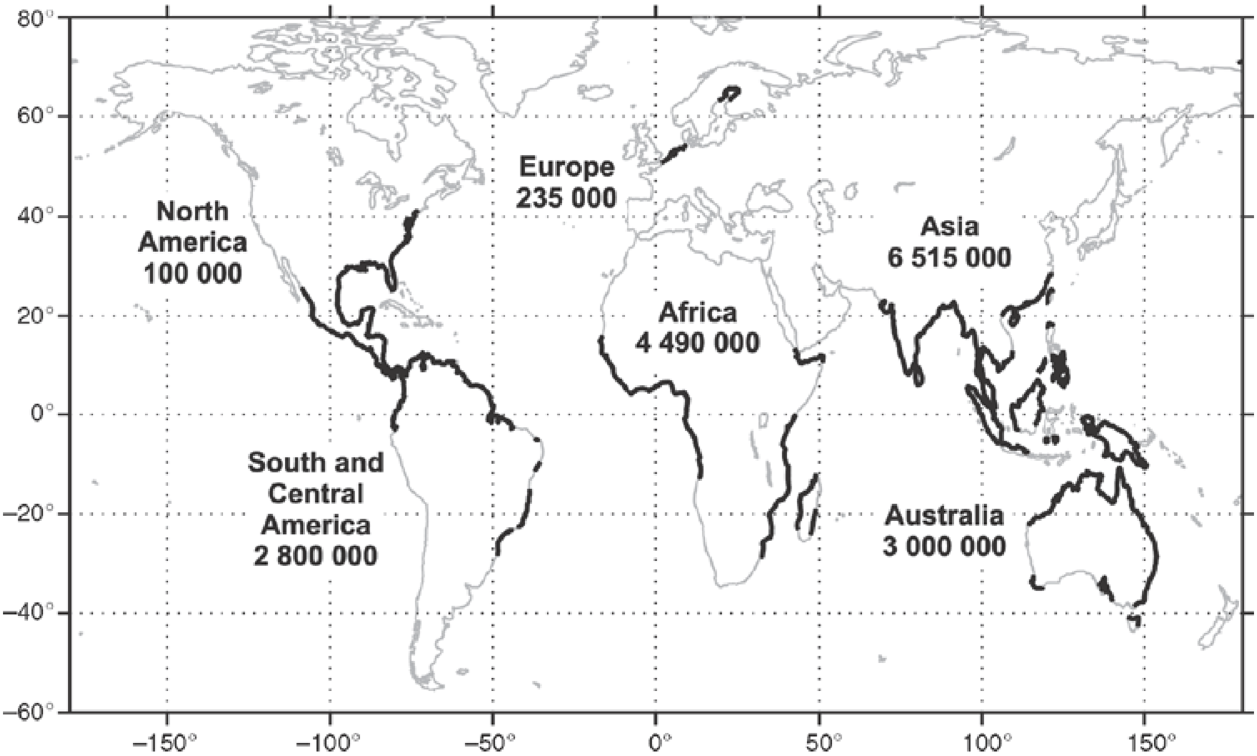

Figure 1. Global distribution of acid sulfate soils (ASS). Note that the figures are not up to date and that inland ASS are not shown (from Proske et al., 2014).

In Europe, the largest and most studied ASS occurrences are found in Finland, Sweden and Denmark (Edén et al., 2023: Figure 2). In Finland the extent is estimated to 1,000,000 ha (Edén et al., 2023), in Sweden 50,000–140,000 ha (Öborn, 1994) and in Denmark 140,000 ha (Madsen et al., 1985). It is suspected that all of these figures, particularly for Finland and Sweden, will increase as more unified classification approaches are applied and also inland ASS occurrences are accounted for. In addition to these three countries, considerable occurrences are described from northern Germany (Gröger, 2011) and the Netherlands (Westerveld and van Holst, 1973). In Russia, ASS have been described from the eastern parts of the Gulf of Finland (Kivinen,1944), from the White Sea region (Putkinen pers. comm., 2012), Karelia (Krasilnikov and Volodin, 1996), and the St Petersburg area (Krasilnikov pers. comm., 2018). Acid sulfate soils occur in East Anglia in England in former tidal fens and marshes, now agricultural land (Dent et al., 1976). Some ASS sites have recently been described from the coast of Poland (Hulisz, 2016; Hulisz et al., 2017; 2020), and from Spain (Catalán et al., 2019). Moreover, ASS were recently identified near Alta in Northern Norway (Andersson and Hansen, 2024), and most likely also exist in the Baltic states.

Besides the coastal ASS occurrences, it is now recognized that these soils can also occur away from immediate coastal zones. For example, in Australia, inland ASS are estimated to cover about 16 million ha (Michael et al., 2017). In Finland, ASS have been observed inland in association with peatlands and black schist formations (Edén et al., 2023). Moreover, ASS have recently been identified in cold climate zones, including the Arctic, such as Northern Norway (Andersson and Hansen, 2024) and Northern Finland (Boman et al., 2023b), and even in Antarctica (Siqueira et al., 2022). This highlights the importance of considering ASS across all climate zones, and that inland ASS must not be overlooked in land use and infrastructure planning.

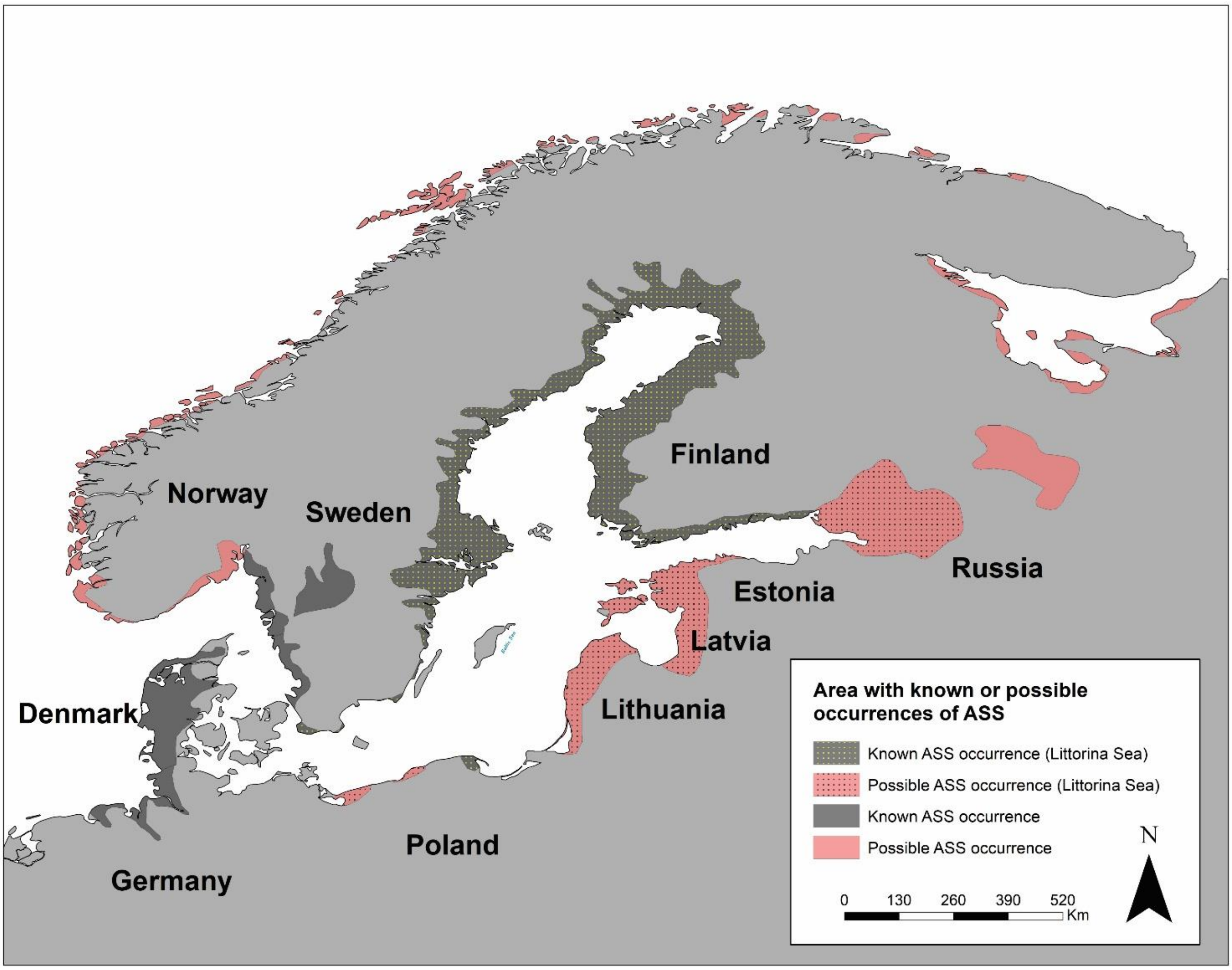

Figure 2. Area with known and possible acid sulfate soils (ASS) in Northern Europe. This map includes both sulfuric and hypersulfidic soils. Note that inland ASS, as well as those in the Arctic, are excluded (map created by Jaakko Auri, GTK.).

Overview of acid sulfate soil occurrences in Finland

Finland has the largest occurrences of acid sulfate soils (ASS) in Europe, mainly along the coast of the Baltic Sea. A 10-year-long ASS mapping programme, led by the Geological Survey of Finland (GTK) and in cooperation with the geology and mineralogy department at Åbo Akademi University, began in 2009, and fieldwork was completed in 2021. The mapping was initiated in response to environmental concerns, particularly the leaching of acid and metals, following major fish kills in 2006–2007 and implementation of EU directives. Mapping was concentrated in a 5,010,000-ha large coastal area corresponding to the maximum extent of the Littorina Sea (Figure 3). This area was chosen because previous surveys indicated that most ASS in Finland is present there. During the mapping programme, observations, pH-measurements, sampling, and analyses were conducted at 23 000 sites across the study area. The results of the mapping have been published in Edén et al. (2023) and Auri et al. (2022) and the ASS map is available via the GTK map service: https://gtkdata.gtk.fi/hasu/.

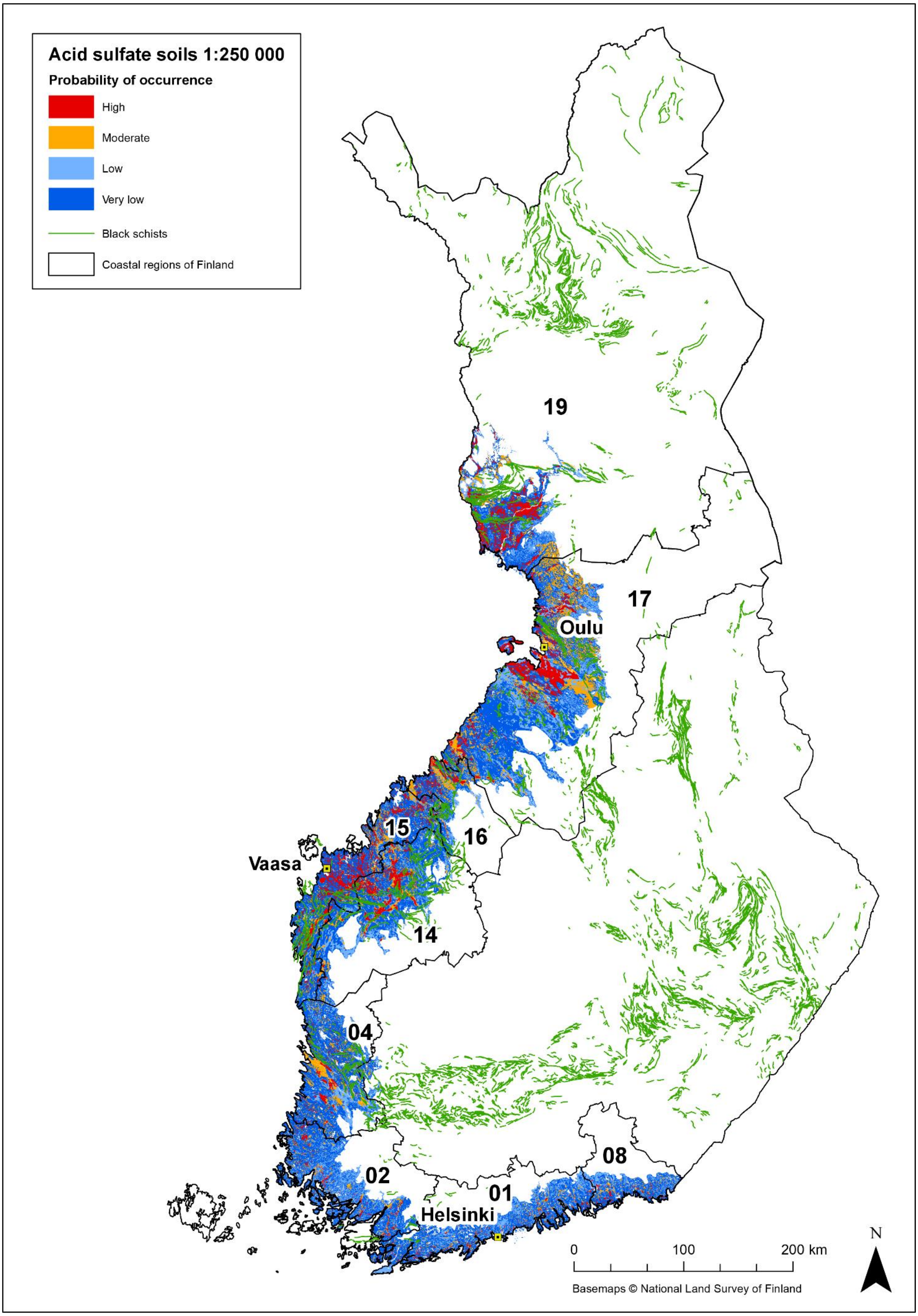

Figure 3. Occurrence of acid sulfate soils (ASS) in Finland within the maximum extent of the Littorina Sea. Coastal Regions of Finland are indicated by their corresponding numbers (see Table 2). Black schist areas are shown in green. Map created by Jaakko Auri, GTK.

Traditionally, ASS in Finland have been considered to consist of fine-grained sulfidic sediments and/or their oxidized layers, typically found on agricultural land along the coast below the highest shoreline of the Littorina Sea transgression. These are classified as “fine-grained ASS” according to Boman et al. (2023a). During the mapping programme, new types of ASS were identified and classified. Following the classification by Boman et al. (2023a), Finnish (and Swedish) ASS currently include:

1. Fine-grained ASS (clay and silt, often gyttja-containing)
2. Coarse-grained ASS (fine sand - gravel)
3. Organic ASS (mainly peat)
4. Unsorted ASS (glacial till material)

Typical ASS landscapes in Finland are shown in Figure 4 and 5. It has also become evident that bedrock plays a role in the regional distribution of ASS, and that these soils are not necessarily confined to the maximum extent of the Littorina Sea. Certain rock types and minerals can increase the sulfur content of soil layers (e.g., black schist and volcanic rocks), while others can help neutralize acidity (e.g., dolomite and other carbonates). In particular, in areas with black schist (Figure 3), weathered shale material, as well as other sulfide-bearing bedrock, may be incorporated into glacial till, where they become a source of acidification in so-called unsorted ASS.

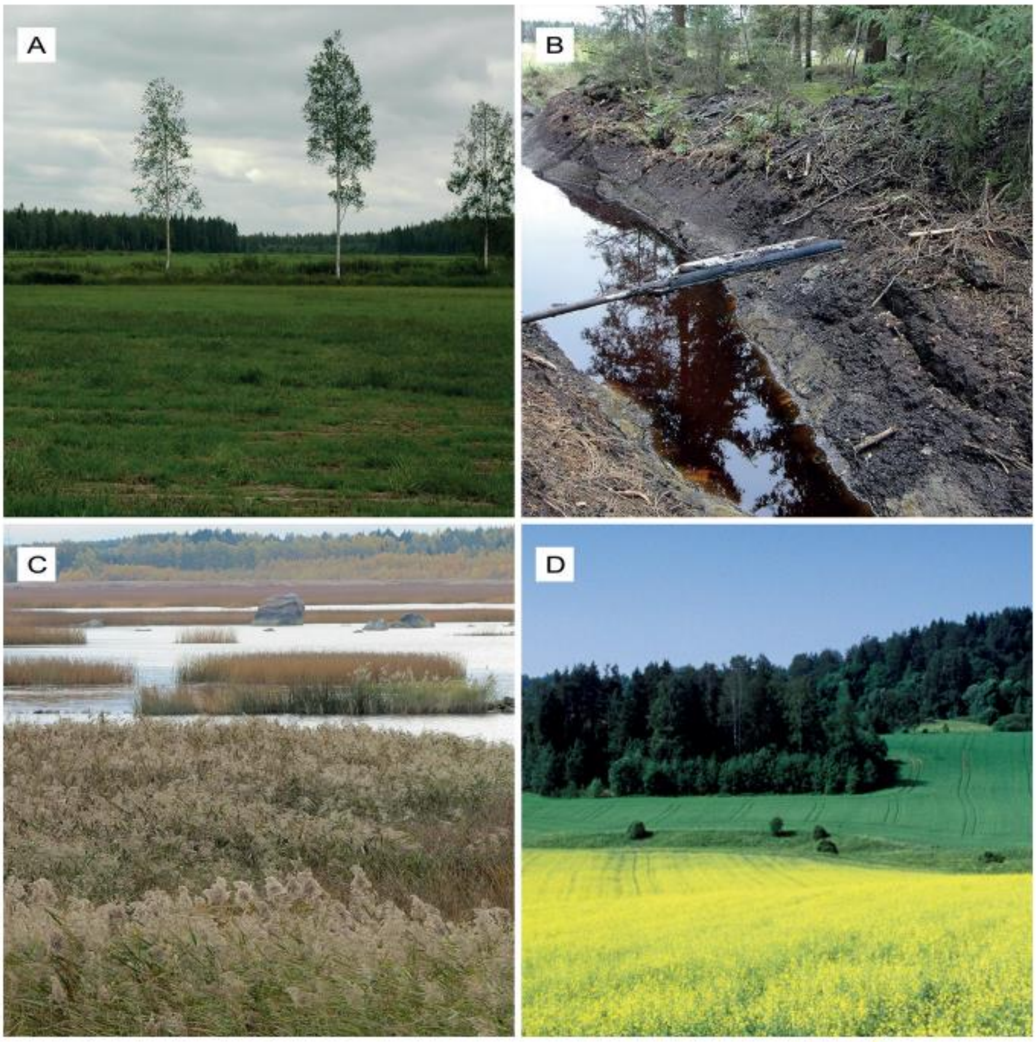

Figure 4. Typical acid sulfate soil (ASS) landscapes in Finland. **A.** Flat river-valley landscape in Siikajoki, western Finland. **B.** Peat covering sulfidic material in a swampy forest, cleared for agriculture in the background, Kokkola, western Finland. **C.** Sulfidic sediments forming today in a shallow bay with common reed (phragmites australis) and common club-rush (Schoenoplectus lacustris) in Vaasa, western Finland. **D.** Rolling landscape with a small brook, southern Finland. Photos: GTK / Olli Breilin, Jaakko Auri, Peter Edén and Jari Väätäinen (Edén et al., 2023).

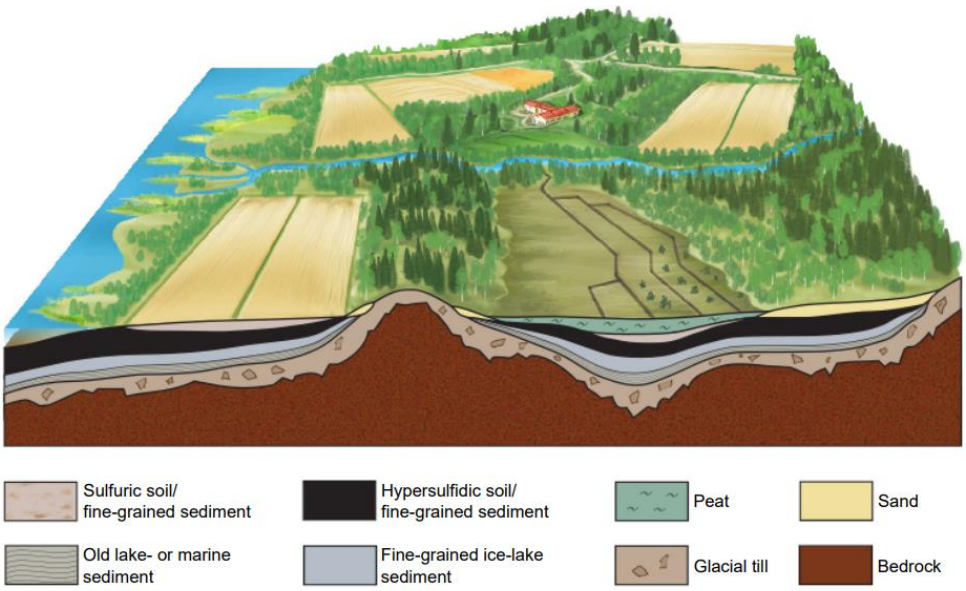

Figure 5. Conceptual model (not to scale) of typical acid sulfate soil (ASS) landscapes and profiles in Finland. Drawing by Harri Kutvonen, GTK.

Extent and regional distribution of acid sulfate soils in Finland

The final ASS map of Finland (1:250 000; Figure 3), compiled in this project, contains information on the distribution and properties of ASS in c. 23 000 observation sites in the study area. On the publicly available ASS map available at GTK´s map service (https://gtkdata.gtk.fi/hasu/), fine-grained and organic ASS are marked as ASS, while coarse-grained ASS are indicated on the map with a dot pattern. Unsorted ASS and inland ASS are not shown on the map and are not included in the calculated extent. It should be noted that ASS encompasses both sulfuric and hypersulfidic soils.

The extent of ASS was calculated based on the approach previously used in Denmark (Madsen and Jensen, 1988) using the following formula:

Area of ASS = *[area of the high probability class]* **x** *[the probability % of the high probability class]* **+** *[area of the moderate probability class]* **x** *[the probability % of the moderate probability class]* **+** *[area of the low probability class]* **x** *[the probability % of the low probability class]* **+** *[area of the very low probability class]* **x** *[the probability % of the very low probability class]*

Overall, the extent of ASS along the coast is estimated to be about 1,000,000 ha (Table 1), corresponding to 21% of the area previously covered by the Littorina Sea. This figure includes both sulfuric and hypersulfidic soils. Comparing the final map with data from Corine Land Cover (Finnish Environment Institute, 2022), reveal that about 41% of the ASS in Finland are agricultural land, c. 55% are forests, drained peaty forests, drained forested peatland and open peatland (open bog and marsh). A small proportion occurs in urban environments (Auri et al., 2022).

Table 1. Probability of encountering acid sulfate soils in four probability classes within the Littorina area in Finland (Edén et al., 2023).

	Probability class			
	High	**Moderate**	**Low**	**Very low**
Probability	93%	56%	5%	3%
Extent, ha	486,390	365,091	58,410	92,649
Total extent, ha				**1,002,539**

However, the occurrence may vary significantly at both local and regional scales (Table 2). For example, in the Pyhäjoki catchment area in Northern Ostrobothnia, located below the highest shoreline of the Littorina Sea, an estimated 6% of the area consists of ASS. In contrast, in the Vöyri River catchment area in Ostrobothnia, the proportion of ASS is estimated at 40%. The most extensive ASS occurrences in Northern Finland are found in the valley areas surrounding the Kemijoki River. In Northern Ostrobothnia, ASS are abundant in the surroundings of Oulu and on Hailuoto Island. Elsewhere, the most significant occurrences are found along the coastal areas of Central Ostrobothnia, Ostrobothnia, and in the Kokemäenjoki River catchment area in Satakunta. In Southern Finland, the proportion of ASS in the mapped areas is relatively lower. In addition to coastal ASS, inland occurrences have also been identified, mainly associated with black schists and sulfidic ores.

Table 2. Distribution of acid sulfate soils (ASS) by Region in Finland, presented in north–south order (Auri et al., 2022). The Region number is shown in parentheses. See also Figure 3 for geographical context.

Region	ASS (ha)	ASS % of area
Lapland (19)	151,958	29
Northern Ostrobothnia (17)	316,460	22
Central Ostrobothnia (16)	50,695	24
Ostrobothnia (15)	162,329	24
Southern Ostrobothnia (14)	117,123	18
Satakunta (4)	84,390	15
Southwest Finland (2)	53,494	10
Uusimaa (1)	48,891	10
Kymenlaakso (8)	19,265	12

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4. Geological overview of the coastal areas of Lapland, Northern Ostrobothnia, Central Ostrobothnia, and Ostrobothnia in Finland

Jaakko Auri, Jukka Räisänen & Anton Boman

Introduction

This section provides a brief overview of the bedrock and Quaternary geology of the coastal areas of Lapland, Northern Ostrobothnia, Central Ostrobothnia, and Ostrobothnia in Finland. A more detailed overview of the Oulu region in Northern Ostrobothnia is presented in Section 5.

Bedrock geology

Finland is a part of the ancient Fennoscandian shield, which is one of the oldest parts of the Eurasian continent. The bedrock in Northern and Eastern Finland was formed during Archean time, more than 2,500 million years ago. The Archean bedrock was in many places covered by younger rocks of sedimentary and volcanic origin 2,500–1,890 million years ago. The Southern and Western parts of Finland consist of 1,930–1,890 million year old volcanic rocks and marine sediments that have been folded and metamorphosed and intruded by different granitic magmas between 1,890 and 1,820 million years ago. Together with areas in central Sweden they make up the Svecofennian bedrock. After this, there was a long, calm geological period that ended with the formation of the rapakivi granites 1,650–1,540 million years ago and diabase dykes c. 1,270 million years ago.

Approximately 600–500 million years ago, layers of sediments were deposited on the already weathered and leveled surface, but these sediments have also been eroded by later geological processes. Traces of these sediments have been preserved in the meteorite impact crater (520 million years old) at Söderfjärden (one of the excursion stops) in Vaasa and Korsholm, where they form layers more than 200 meters thick. These are overlain by 80 meters of unlithified and postglacial deposits. The sediments have remained at the bottom of the crater, protected from erosion and weathering to this day, and are unique within the extensive Svecofennian province. Practically no new bedrock has been formed in Finland during the last 500 million years.

The Precambrian bedrock of Finland consists of approximately 50% various types of granite, 20% migmatites (gneisses), and the remainder is made up of schists, volcanic rocks, gabbro, quartzite, and limestone. The bedrock is very difficult to examine, as only about 3% is exposed at the surface. The rest is covered by till, sand, clay, peat, and vegetation.

The rocks of Ostrobothnia are part of the Svecofennian bedrock and were mostly formed between 2,000 and 1,800 million years ago. The formation began with the sedimentation of sand and clay on the seafloor around 2,000 million years ago, with volcanic rocks intercalated within the sediments. During the Svecofennian orogeny, approximately 1,885 million years ago, the sediments sank 15 km into the crust and were metamorphosed under high temperatures and pressures into mica gneiss (recrystallization), veined gneiss (partial melting), and, in extreme cases, completely melted into a granodioritic melt that later solidified into diatexite (known as Vaasa granite). Around 1,270 million years ago, a basic melt intruded near the Earth's surface, forming olivine diabases in the western part of the archipelago. These represent the final components of the Ostrobothnian basement. Due to hundreds of millions of years of weathering and erosion, these rocks are now exposed at the Earth's surface.

The bedrock of the coastal areas in Northern Ostrobothnia and Lapland differs somewhat from that of the Vaasa and Kokkola region. The bedrock in Ostrobothnia and Central Ostrobothnia is younger and more granitic due to Svecofennian metamorphism and intrusions, whereas the coastal areas of Lapland and Northern Ostrobothnia are geologically older, dominated by Archean rocks and more deeply metamorphosed formations, including black schists that represent ancient organic-rich sediments. The coastal geology of Lapland and Northern Ostrobothnia is shaped by ancient bedrock and more recent Quaternary processes. The bedrock belongs to the Karelian domain and consists mainly of Archean and Paleoproterozoic rocks, including granite, gneiss, and greenstone belts, formed over 2,500 million years ago. However, the most visible geological features in the coastal zone are related to glacial and post-glacial activity. The bedrock of the Oulu region is described in more detail in Section 5.

Quaternary geology

The Earth's youngest period, the Quaternary (approximately 2.5 million years), is characterized by alternating glacial and interglacial stages. The term Quaternary deposits refers to the loose overburden on the Earth's surface, and these deposits are classified according to their genesis and the environment in which they were formed. They consist of two main groups: glacial and postglacial. Glacial deposits were formed by an ice sheet or its meltwater and include till, glaciofluvial sediments, and glacial clay. Postglacial deposits formed independently of the melting ice sheet and include, for example, marine, fluvial, alluvial, and peat deposits.

Scandinavia and the coastal areas of Ostrobothnia, Central Ostrobothnia, Northern Ostrobothnia, and Lapland in Finland were glaciated multiple times during the Quaternary Period (the last 2.5 million years) and were located at the center of the Late Weichselian glaciation, which occurred approximately 28,000–10,000 years ago (Figure 1) (e.g., Donner, 1996; Svendsen et al., 2004).

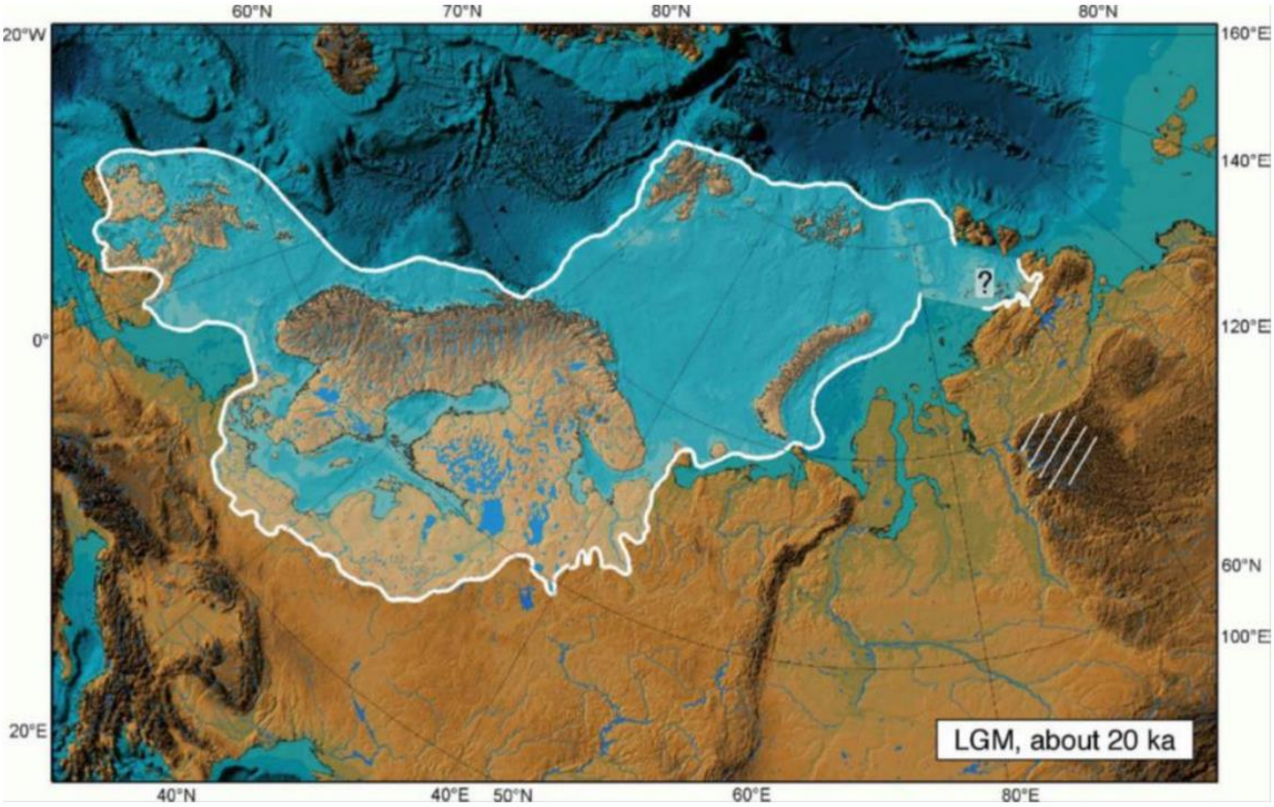

Figure 1. Extent of the Eurasian ice sheet during the Late Weichselian glacial maximum (from Svendsen et al., 2004).

The features of glaciation are clearly visible in the Finnish landscape. Continental ice sheets have carved and ploughed the bedrock, depositing an average of 7 meters of till that now covers most of the land area. They also created various moraine and glaciofluvial formations, as well as lakes. In subaquatic areas where the rock surfaces have been cleaned by wave action, striations are clearly visible. These markings make it easy to determine the direction of ice movement. In many places, large erratic boulders, transported by the ice, can also be found.

Most of the Finnish and Swedish Quaternary deposits were formed during and after the latest (Weichselian) glaciation. At the final stage of this deglaciation, beginning around 10,500 years ago, the glacier terminated in a freshwater body known as the Ancylus Lake, a precursor to the Littorina Sea and the present-day Baltic Sea. The Earth's crust was depressed by the weight of the glacier, and as a result, the ancient coastline of the Ancylus Lake in this area is now located more than 200 meters above the current level of the Baltic Sea at its highest point. During the late-glacial and subsequent post-glacial periods, fine-grained water-lain sediments were deposited over former sea bottoms, bays, and river mouths.

Deglaciation of the Scandinavian Ice Sheet during the Late Weichselian is relatively well studied (e.g., Lundqvist, 2007; Lunkka, 2004). During the Last Glacial Maximum (LGM), around 21,000 years ago, the Eurasian Ice Sheet covered all of Scandinavia (Figure 1), and its center was located approximately 100 km west of the Gulf of Bothnia (Lundqvist, 1969). From there, the ice margin retreated toward the north or northwest (Lundqvist, 2002; 2007). The retreat in the Kvarken area was rapid (Lindén et al., 2006; Lindén and Möller, 2005), and the eastern region (Ostrobothnia) was deglaciated around 10,500 years BP (Lundqvist, 2002; Wohlfarth et al., 2008).

According to LGM models and other studies, the maximum thickness of the ice sheet was estimated to be 2.5–3 km (Svendsen et al., 2004; Fjeldskaar, 1994; Peltier, 1994). The thickest parts of the ice were located over the Bothnian Sea due to the depth of the basin (Lundqvist, 2007). The calculated total depression of the Earth's crust caused by the weight of the ice is 800–1,000 meters (Kakkuri and Virkki, 2004; Eriksson and Henkel, 1994; Taipale and Saarnisto, 1990). Rebound began during the melting and thinning of the ice in the Baltic area around 15,000 years ago. During the first thousand years, the land uplift rate in deglaciated areas was estimated to be up to 10 meters per 100 years (Saarnisto, 1981). The highest shoreline is located at 286 meters above sea level (m.a.s.l.) in the High Coast area on the Swedish east coast. Based on these observations, the water depth in the Kvarken (Vaasa) region immediately after deglaciation was approximately 250–280 meters. The current relative uplift rate is about 8.0 mm/year on the Finnish side of the Kvarken area. It is assumed that land uplift will continue for another 10,000 to 12,500 years in the region, potentially resulting in an additional 100–125 meters of isostatic uplift (Ekman, 1996; Mäkinen and Saaranen, 1998). The uplift will continue until the depression of the geoid is reversed or until a future glaciation begins to load and submerge the Earth's crust once again.

Due to post-glacial isostatic rebound (land uplift) and marine regression, these areas are now located on dry land, in some places extending more than 100 km inland. After the emergence of the flat coastal area from the sea, the moist climate and soil conditions have been favorable for mire development. Today, mires cover about 17% of the land area in Ostrobothnia, 34 % in Central Ostrobothnia, with even higher percentages in Northern Ostrobothnia, and Lapland (Virtanen et al., 2003).

Quaternary sediments

The present-day Baltic Sea has evolved through several distinct stages following deglaciation: the Baltic Ice Lake (c. 13,000–11,600 BP), the Yoldia Sea (c. 11,600–10,700 BP), the Ancylus Lake (c. 10,700–9,800 BP), the Littorina Sea (c. 9,800–4,000 BP), and the Limnea Sea, which gradually became less saline and eventually developed into the modern Baltic Sea (Wohlfarth et al., 2008; Björck, 1995). Due to persistent ice coverage during the early deglaciation, the Baltic Ice Lake and Yoldia Sea stages are not represented in the geological evolution of the present-day Gulf of Bothnia, which is the northernmost extension of the Baltic Sea and covers approximately 30% of its total area. The present Baltic Sea is the world's largest brackish water body. It is highly enclosed and relatively shallow, with a maximum depth of 459 meters. The only straits connecting it to the ocean are located between Sweden and Denmark. Salinity ranges from approximately 1‰ in the northern parts to 6–8‰ in the central Baltic Sea (Björck, 1995).

The onset of the Littorina Sea stage (Figure 2) is clearly defined across the Baltic Sea region in the sedimentary record. In clay strata, the arrival of brackish water at the transition to the Littorina Sea stage is marked by a sharp lithostratigraphic boundary (e.g., Breilin et al., 2004; Saarnisto, 1974). Widely distributed greenish mud, rich in organic matter, sulfur, and saline diatom flora, was deposited on the bottom of the Littorina Sea. Today, these sediments (often classified as hypersulfidic sediments) form the most fertile agricultural areas along the coast of the Bothnian Bay, but they also pose a potential environmental risk, as they can easily transform into sulfuric soils due to artificial lowering of the groundwater level. All ancient shorelines and beach deposits in the coastal areas of Ostrobothnia, Central Ostrobothnia, Northern Ostrobothnia, and Lapland date back to the Littorina Sea stage and are less than 8,000 years old (Winterhalter et al., 1981). A map showing the distribution of Quaternary sediments in the coastal areas of Lapland, Northern Ostrobothnia, Central Ostrobothnia, and Ostrobothnia is presented in Figure 3.

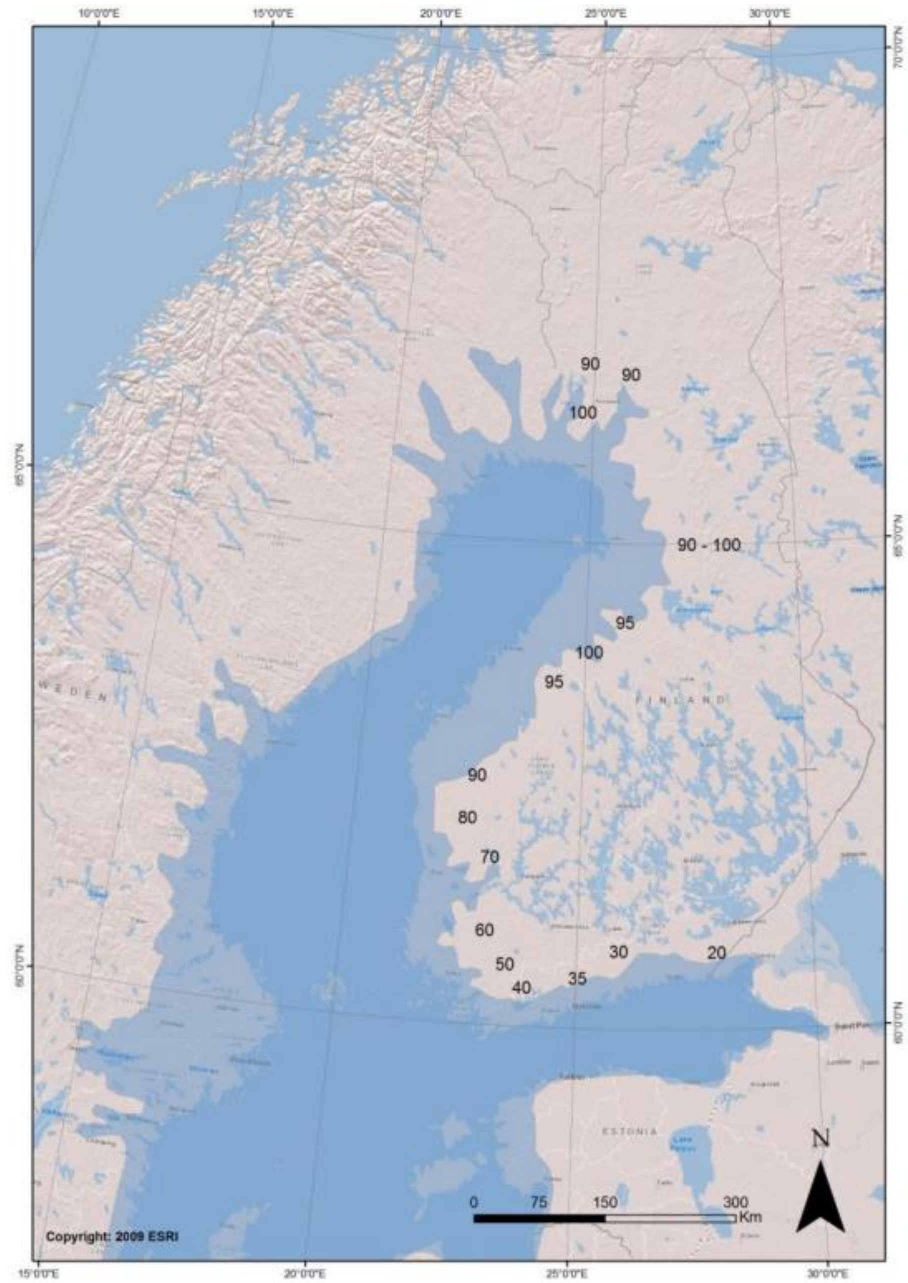

Figure 2. Extent of the Littorina Sea about 8000 years ago (Tikkanen and Oksanen, 2002). The number values indicate the highest shorelines (meters above present sea level) during the Littorina Sea stage (Eronen, 1974).

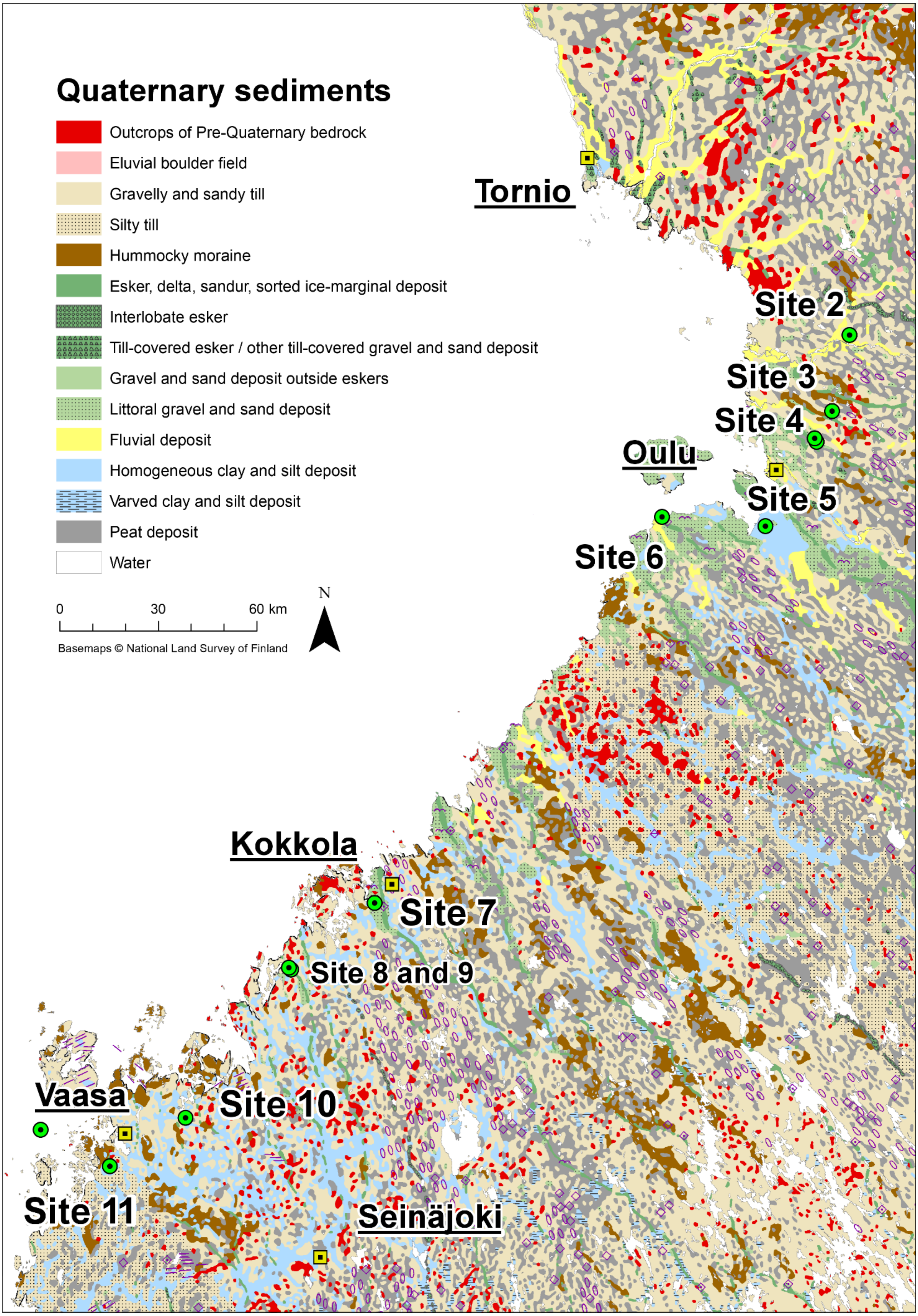

Figure 3. Quaternary sediments in the coastal areas of Lapland, Northern Ostrobothnia, Central Ostrobothnia, and Ostrobothnia. Excursion sites in Finland are labelled Site 2 to Site 11.

Till is the most common sediment type in the area and was deposited mainly during the last glaciation. It is a poorly sorted sediment, consisting of material ranging from boulders to clay, and forms laterally alternating stratigraphic units throughout the region. Till typically covers and smooths the bedrock surface. However, in many places, especially in the Kvarken region outside Vaasa, it occurs as distinct moraine formations. The most common of these are drumlins, hummocky moraines, De Geer moraines, and ribbed moraines. Glacier-polished and eroded crystalline bedrock outcrops are also found in many locations where wave action has removed the loose overburden.

Sand and gravel deposits in the area are mainly of glaciofluvial or littoral origin. Glaciofluvial deposits typically form eskers, which have often been reshaped and flattened by wave action, and may be covered by fine-grained postglacial sediments. In some cases, eskers deposited before the last glaciation are found beneath a cover of till. Beach sands, beach ridges, and dunes commonly occur along the flanks of these eskers. The most prominent eskers and extensive sand accumulations are located in the regions of Kokkola, Lohtaja, Kalajoki, and Oulu (Figure 3), where they also serve as important groundwater reservoirs for society.

Fine-grained sorted sediments (clay and silt) cover large areas, especially in ancient river valleys, but are also found in smaller topographic depressions. The oldest clays are typically glacial clays, which may exhibit annual varve structures. These glacial clays are usually overlain by younger postglacial sediments from the Ancylus, Littorina, and Post-Littorina stages. Ancylus sediments are typically light gray clays deposited in freshwater environments and are commonly overlain by Littorina and Post-Littorina clays and silts, which were deposited in saline and brackish waters. These younger sediments generally contain higher levels of organic matter and sulfur compared to older deposits. They often form the parent material (hypersulfidic sediments) for acid sulfate soils (ASS), which are abundant in the coastal areas of Finland (Figure 4).

At higher elevations and along the margins of river valleys, the thickness of fine-grained sediments typically ranges from less than one meter to a few meters, whereas in the river valleys, thicknesses can reach several tens of meters. In many locations, fine-grained sediments are overlain by peat or younger littoral, fluvial, or alluvial deposits. Especially the Oulu region exhibits a complex depositional history, including prograding deltaic sedimentation from the Oulunjoki River. A more detailed description of the geology of the Oulu region is provided in Section 5.

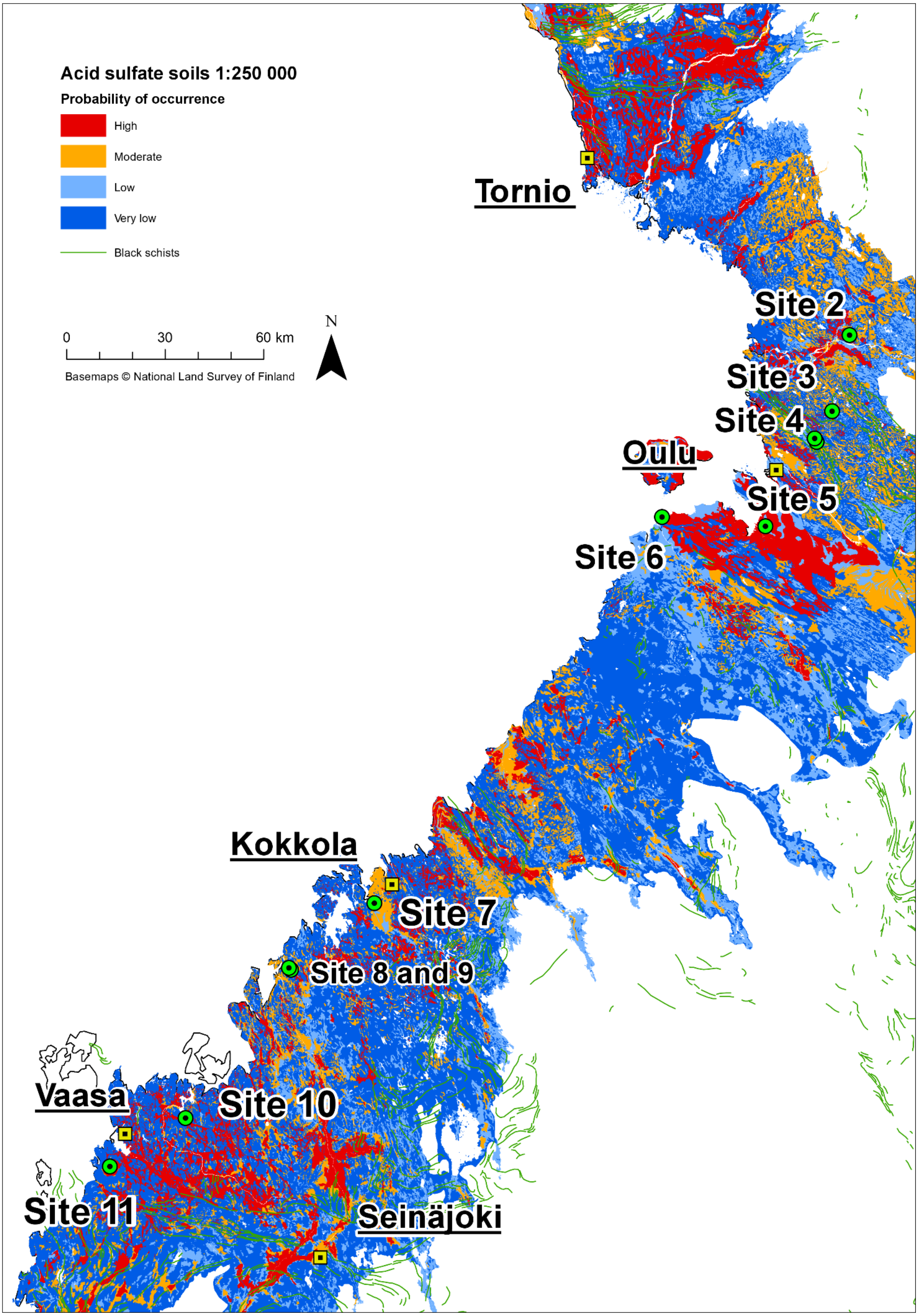

Figure 4. Occcurrence of acid sulfate soils (ASS) in the coastal areas of Lapland, Northern Ostrobothnia, Central Ostrobothnia, and Ostrobothnia. Excursion sites in Finland are labelled Site 2 to Site 11.

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5. Geology of the Oulu region

Jukka Räisänen, Jaakko Auri & Anton Boman

Introduction

This section provides a detailed overview of the bedrock and Quaternary geology of the Oulu region. The Oulu region is characterized by a diverse and structurally complex bedrock geology, including granitoids, metasedimentary rocks, and Jotnian sediments in the Muhos Formation, and exhibits a complex depositional history, including prograding deltaic sedimentation from the Oulujoki River.

Bedrock in the Oulu region

The occurrence of acid sulfate soils (ASS) in Finland is typically associated with sediments deposited during the Littorina Sea phase along coastal areas. However, bedrock composition also influences the regional distribution of ASS. Certain rock types and minerals can increase the sulfur content of soil layers (e.g., black schist, pyrite, pyrrhotite, and volcanic rocks), while others can help neutralize soil acidity (e.g., dolomite and other carbonates).

The bedrock of the Oulu region is shown in Figure 1. The northern and northeastern parts of the region belong to the Kiiminki schist belt, part of the Northern Ostrobothnia schist zone, where rock types include volcanic rocks, mica schist, greywacke, quartzite, and sulfur-rich black schist. The black schist mapping data from GTK, included in the bedrock map is primarily based on interpretations of aerogeophysical (electrical and magnetic) data and provides a rather coarse depiction of black schist occurrences. The map shows a dense distribution of black schist zones between Oulu and Kiiminki.

Black schists are metamorphic rocks typically found in schist belts as thin, elongated zones. They originate from organic-rich marine sediments and typically contain high levels of carbon and sulfur, along with other elements such as arsenic, cobalt, nickel, copper, zinc, lead, and uranium. Black schists weather easily and can locally cause environmental issues related to soil acidification. They are relatively common in Finland and are increasingly considered in various land use studies.

To harmonize and improve the quality of these studies, a guide on assessing and managing the environmental impacts of black schists was published in Finland in 2023 (Loukola-Ruskeeniemi et al., 2023). The greatest environmental risk arises when black schists occur in association with volcanic rocks (Loukola-Ruskeeniemi et al., 2022). Such rock associations are present in the Kiiminki area.

The quartzite area east of Kiiminki Church belongs to the Koiteli quartzite–conglomerate formation. Quartzite bedrock is prominently exposed in the well-known Koiteli Rapids area (Kananoja, 2004). The volcanic rocks of the Kiiminki schist belt are mainly massive mafic lava flows and pillow lavas. Calcium-rich dolomite commonly occurs as thin, lens-shaped interlayers within these volcanic rocks.

The western part of the region belongs to a sedimentary rock zone, better known as the Muhos Formation, estimated to be about 1,300–1,400 million years old (Simonen, 1990). It formed in a subsiding bedrock fault zone filled with sedimentary rocks. The main rock type is shale, with interlayers of sandstone. Deeper layers contain conglomerates formed from ancient gravel. The shale and sandstone contain abundant iron hydroxide, giving the rocks a reddish hue. Calcite is also present. Due to the softness of the rock material, the Muhos Formation has eroded more than the surrounding harder rocks.

The chemical composition and mineralogy of the local bedrock are clearly reflected in the region's soil, especially in till and esker deposits. High sulfur contents in these soils often result from the presence of black schist and volcanic rocks. The reddish hue caused by the high iron content of rocks from the Muhos Formation is also frequently visible in the soil. The significance of the Muhos Formation in the occurrence of acid sulfate soils (ASS) is complex: material derived from its rocks may neutralize soil acidity due to the presence of calcite, but its deep erosion basin may also have accumulated sulfide-rich marine sediments and black schist-bearing material that increase soil acidity. The direction of glacial flow is crucial in determining where bedrock-derived acidity or alkalinity is reflected in the soil.

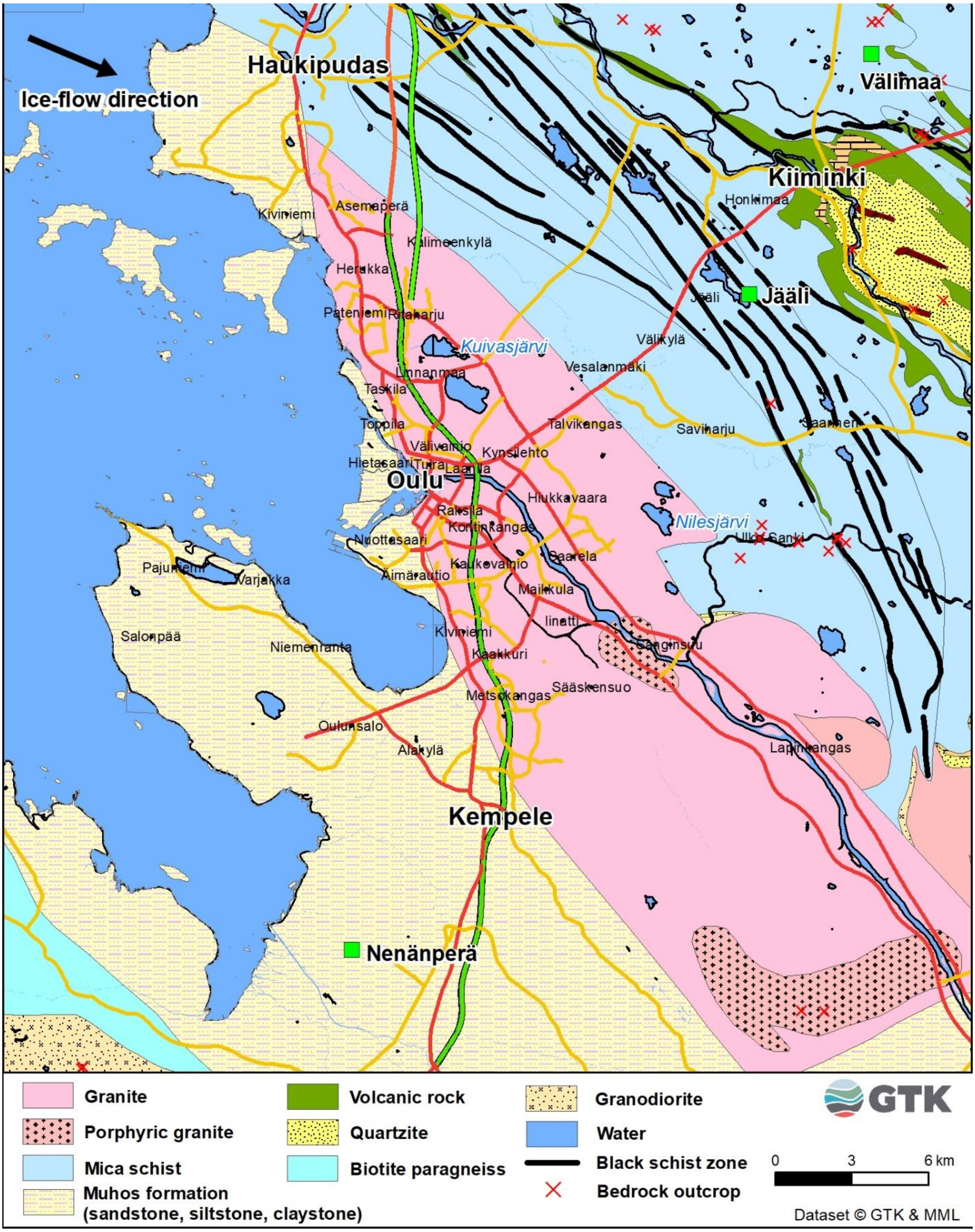

Figure 1. Bedrock of the Oulu region. The locations of Välimaa (Site 3), Jääli (Site 4), and Nenänperä (Site 5) are shown as green squares.

Quaternary sediments in the Oulu region

The most recent glaciation, known as the Weichselian glaciation, began about 120,000 years ago and ended around 10,000 years ago. It consisted of three glaciation phases. The soil in the Oulu region was mainly formed during and after the last glaciation. The soil map of the Oulu urban area and its surroundings is shown in Figure 2, based on GTK's 1:20,000 scale soil maps and the superficial deposits and formations database.

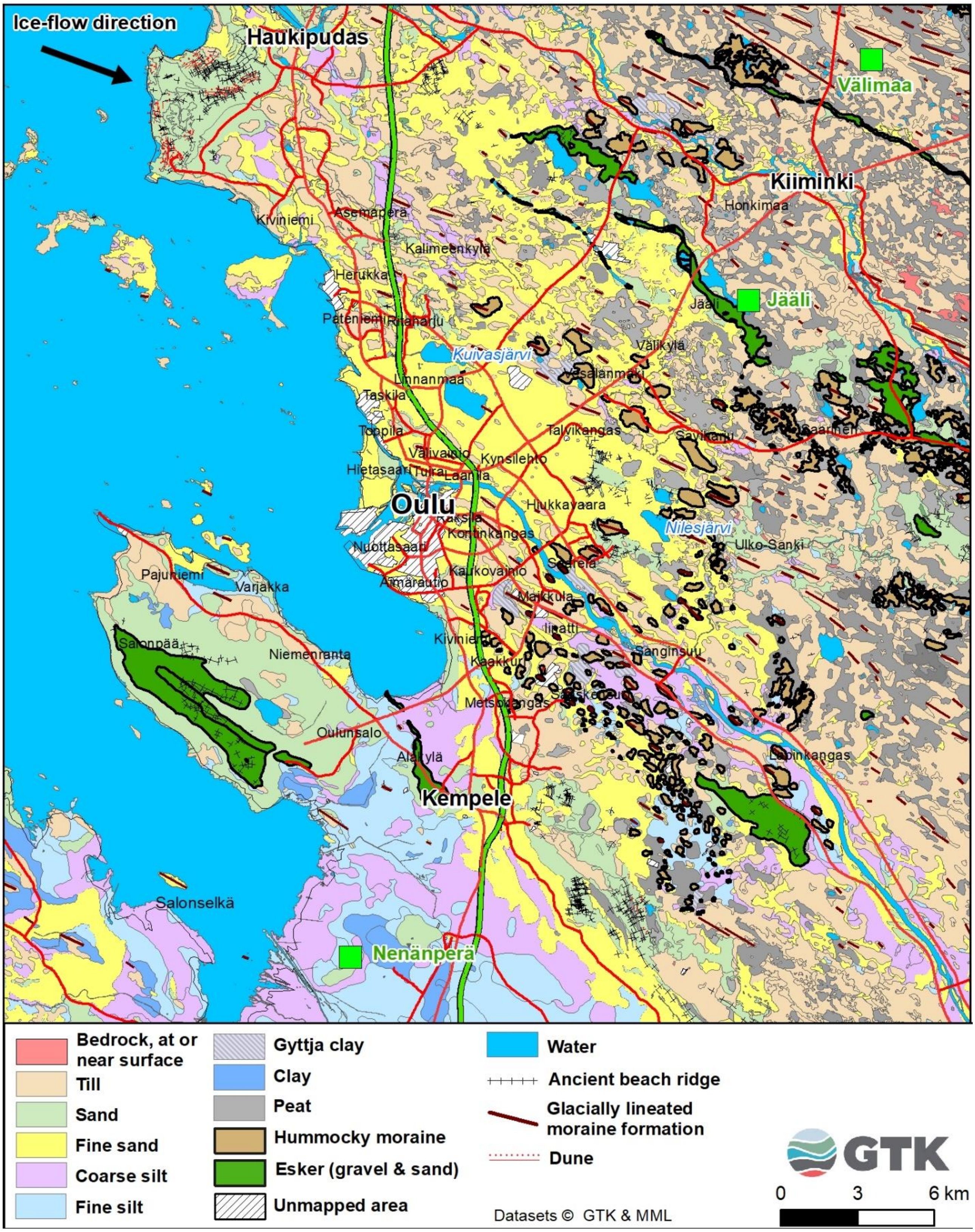

Figure 2. The soil map / Quaternary sediments in the Oulu region.

As the continental glacier melted, massive meltwater streams carved various channels and deposited sorted gravel and sand into glacial tunnels or crevasses as eskers or in front of the glacier as delta formations. In the southern part of the Oulu region, wide delta eskers (Salonselkä, Kempeleenharju, and Hangaskangas) belong to the broader Oulunsalo-Rokua esker zone. The sediment thickness in these delta eskers can be substantial; for example, over 100 meters have been observed in the southeastern parts of Kempeleenharju (Breilin et al., 2006). Another significant esker zone starts in Haukipudas and extends all the way to Kuhmo. Meltwater streams also deposited fine-grained sediments in submerged areas, often referred to as glacial clays or silts.

After the retreat of the continental glacier, the entire Oulu region lay beneath the waters of Ancylus Lake. Around 9,000 years ago, the Littorina Sea phase began in the Baltic Sea basin. During this time, the climate was about two degrees warmer than today, and the water was saltier. These conditions led to eutrophication and increased biological productivity. Sediments deposited during the Littorina Sea phase commonly contain abundant sulfidic material. The sediments deposited in the Oulu region during various marine phases are mainly silt or fine sand, rarely clay, and often rich in organic matter (over 2%).

At the end of the Littorina Sea phase, about 4,000 years ago, the Oulujoki River flowed along a more southern route, from Liminka and Tyrnävä to Muhos, into a marine bay (Ylimannila, 1970). The river carried large amounts of sediment, forming a wide delta at its mouth. The deeply eroded Muhos Formation area was largely filled with these river deposits along the early route of the Oulujoki. Later, wave action leveled the old river deltas, making it difficult to distinguish them from coastal deposits (Figure 2). Esker material and older sediments, such as pre-glacial marine deposits, fill the deeper parts of the Muhos Formation valley. Observations of up to 140 meters of continuous unconsolidated cover have been made in Liminka's Vesikari area (Breilin and Putkinen, 2012), which is exceptional considering the average thickness of soil cover in Finland is 7 meters.

The lower course of the Oulujoki River shifted to its current path about 2,500 years ago (Ylimannila, 1970). Sediment carried by the river was deposited over a wide area surrounding the lower course. These river deposits in the Oulu region are mainly fine sand or coarse silt, but grain size can vary from silt to gravel. Since these deposits formed in a delta advancing slightly below sea level due to land uplift, they often contain sulfidic material from the Littorina Sea phase. This material serves as the parent material for acid sulfate soils (ASS), which are abundant in the area (Figure 3). The erosional and depositional activity of the Oulujoki continues today.

The highest points in the soil map area are located along the eastern edge, where elevation exceeds 70 meters above sea level. These areas emerged from the sea about 5,500 years ago due to land uplift (cf. Räsänen, 2015). About 3,500 years ago, the sea level was at 40 meters, and the retreating shoreline reached the 20-meter elevation approximately 2,000 years ago. Land uplift continues today at a rate of about 7 mm per year in the Oulu region.

As the shoreline retreated, wave action strongly eroded previously formed deposits, such as eskers and till mounds. The dominant feature of the coastal section of the soil map is the extensive, flat areas of sand and fine sand, formed by wave-distributed coastal and/or riverine deposits. The flatness of the eskers is also attributed to their deposition into the deep waters of the Ancylus Lake, where sediment was widely spread during the sedimentation process.

The soil map area contains many ancient beach ridges, formed from sand accumulated by wave-wash currents and aligned with the ancient shoreline. These ridges are especially common in Salonselkä, the Haukipudas coastal area, and east of Hiukkavaara. After the shoreline retreated, and while the land was still devoid of vegetation, wind-blown dunes formed, most commonly in the Haukipudas coastal area.

Especially in central Oulu, the surface soil has been modified for centuries, so the topsoil often does not represent natural deposits but is human-altered or imported material. Aside from human activity, the most recent geological process affecting the soil has been peat formation. Since the Oulu region has only recently emerged above sea level, peat layers have not had time to become very thick. In the urban area, peat occurs mainly as thin layers (a few tens of centimeters) covering mineral soils in depressions. Inland from the coast, peat thickness increases, and in the Kiiminki area, there are many peatlands with depths of 2 to 3 meters.

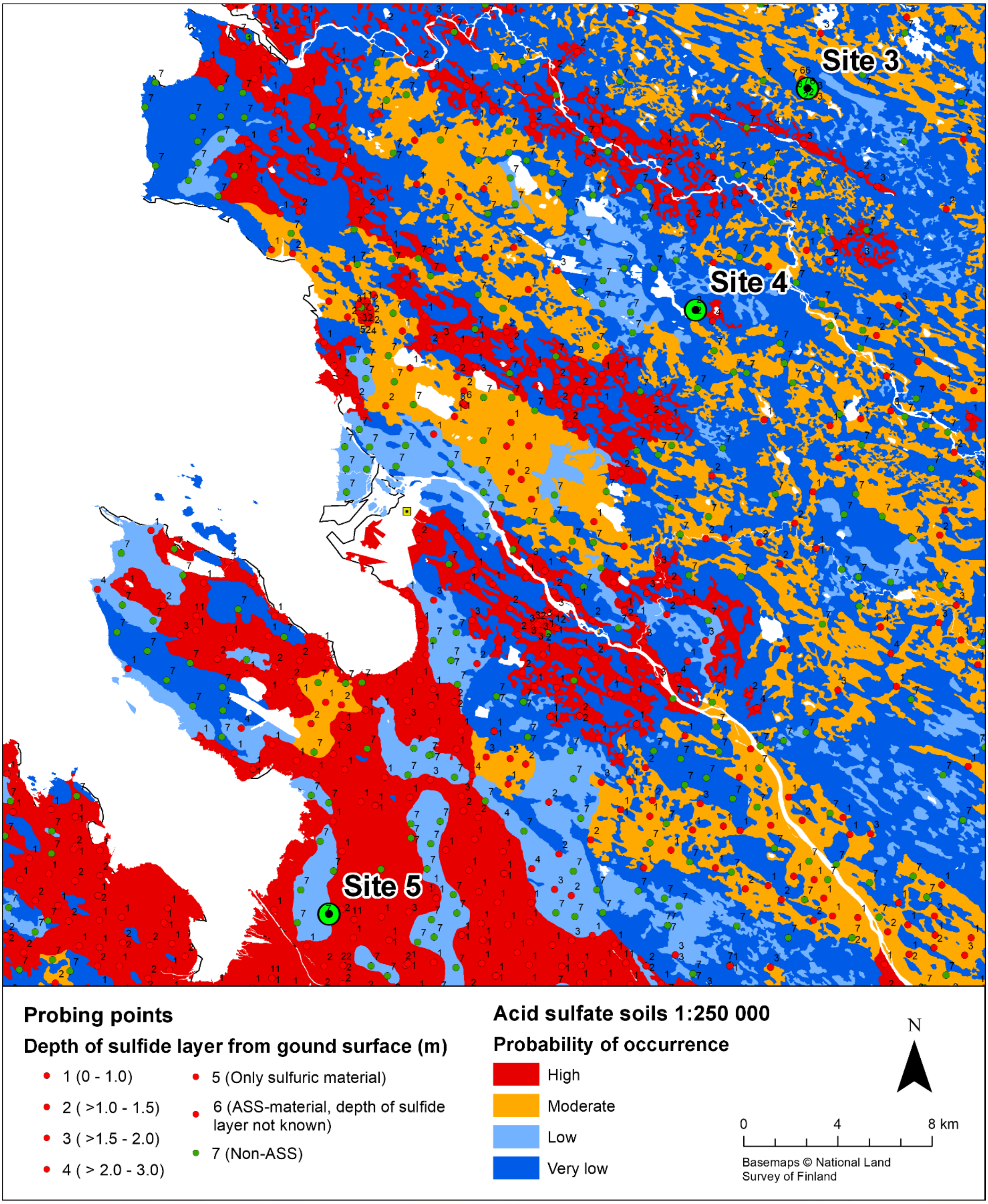

Figure 3. Acid sulfate soils (ASS) in the Oulu region. Site 3 = Välimaa, Site 4 = Jääli, and Site 5 = Nenänperä.

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6. Description of field sites

Overview

Over the course of three days, we will visit a wide range of acid sulfate soil (ASS) environments and localities, primarily in Finland, but also in Sweden (Figure 1). In total, we will explore 14 field sites, each of which is described in the following sections.

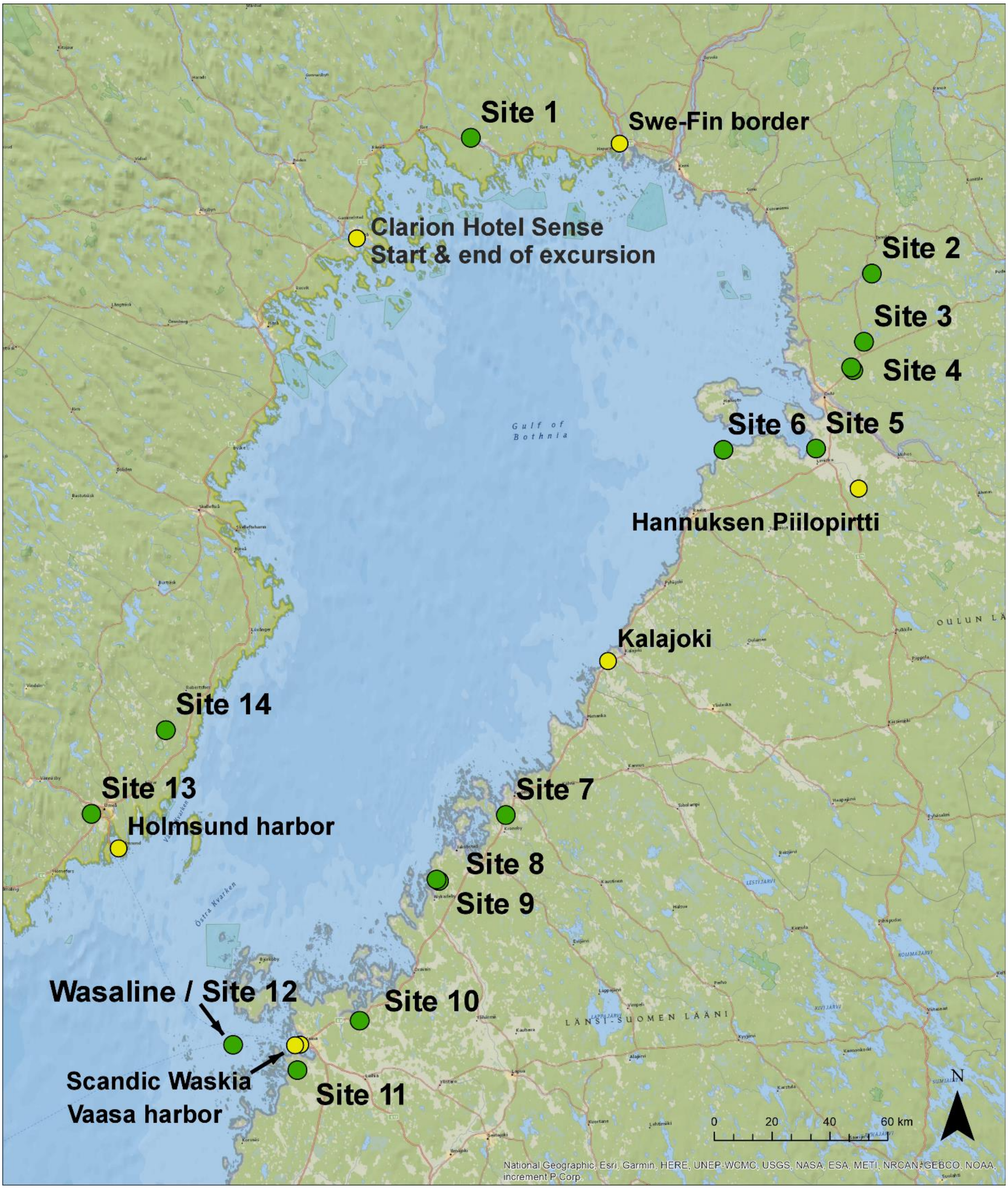

Figure 1. Overview of the field sites (1–14, marked in green) and other stops (start and end of the excursion, accommodation, breaks, etc., marked in yellow).

Site 1: Gammelgården – Acid sulfate soils in Northern Sweden

Gustav Sohlenius & Anton Boman

Location

Google maps: https://maps.app.goo.gl/gRmeCNHGP3PWWuPk7

Coordinates: 65°53'19.1"N 22°55'17.2"E

Figure 1. Location of the field visit at Gammelgården (Site 1). The soil core studied by Georgala is indicated by a blue point.

Purpose of the visit

We will visit a classic site, where sulfidic sediments were studied in detail by Danai Georgala in 1980. Here we will learn about typical acid sulfate soils in Northern Sweden.

Quaternary deposits in the area

The Quaternary deposits (Figure 2) in the area were deposited during the latest glaciation and the following postglacial period. The highest topographical areas are dominated by glacial till and exposed outcrops. In the valley, the till is largely covered by partly sulfidic clay and silt. These deposits are often overlain by peat and postglacial sand/gravel. Along the rivers, fluvial sediments cover parts of the fine-grained deposits.

Occurrence of acid sulfate soils

The occurrence of acid sulfate soils (ASS) has been documented along the coast of northern Sweden. The observations have been used together with other geographical data to produce a map showing the distribution of ASS. These soils commonly occur in flat areas with clay and silt situated at low altitudes. Active ASS, or sulfuric soils, have often formed in areas where the groundwater table has been artificially lowered. Potential ASS, or hypersulfidic soils, are common in areas covered by peat. In Figure 3, ASS occurrences in the surroundings of Gammelgården are shown.

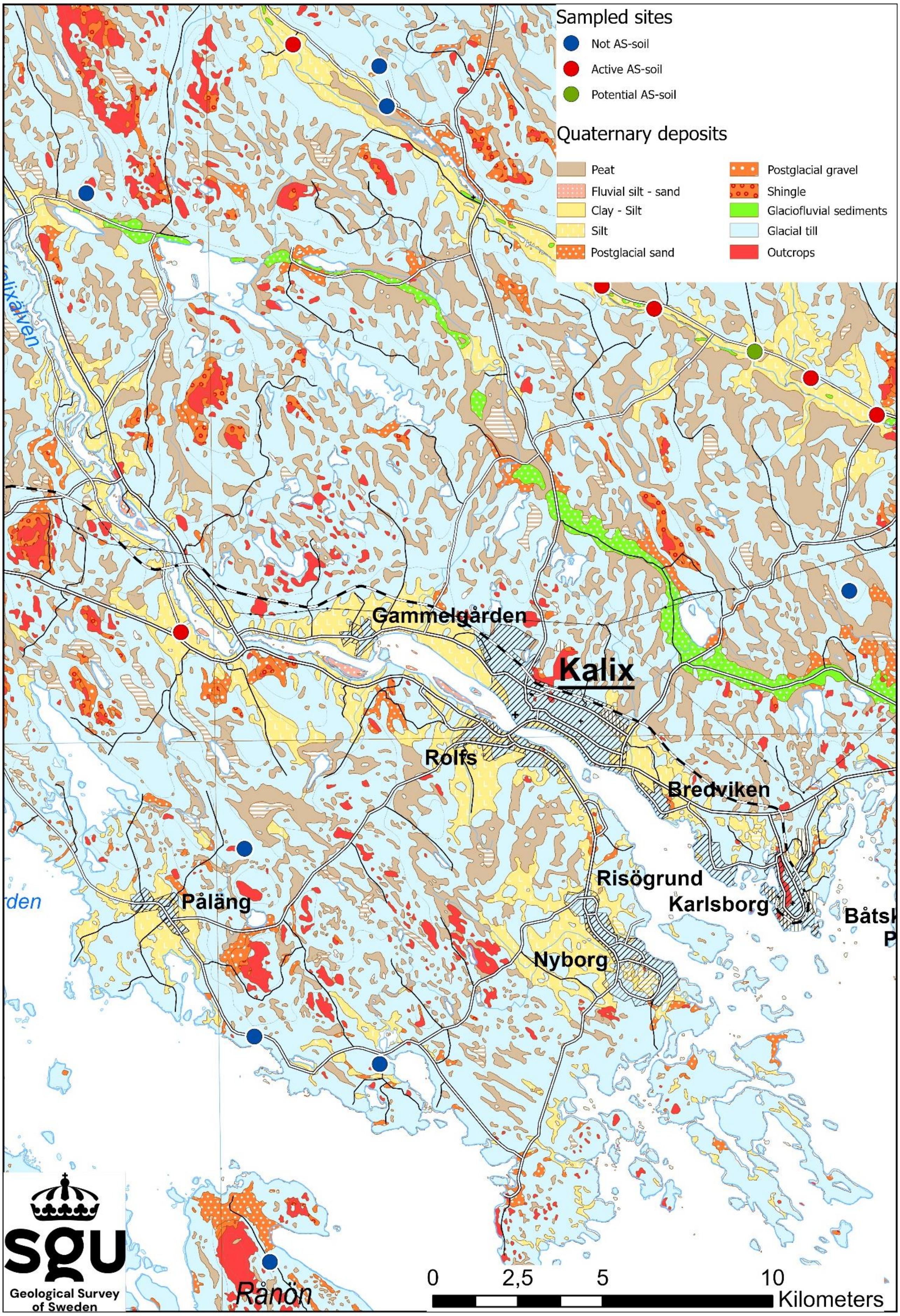

Figure 2. Distribution of Quaternary deposits in the surroundings of Gammelgården (Site 1). Green points = hypersulfidic soils, red points = sulfuric soils, and blue points = non acid sulfate soils (ASS).

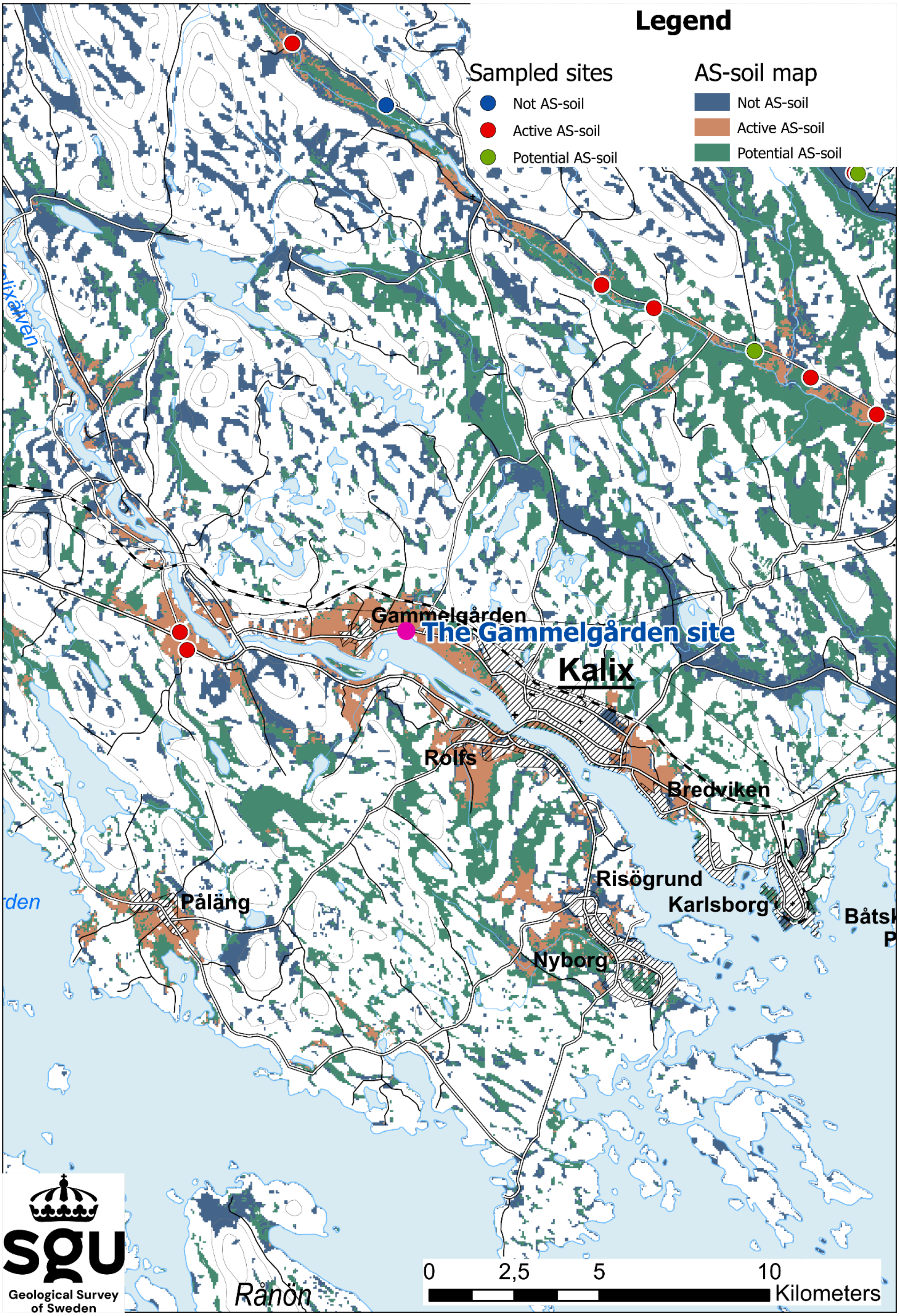

Figure 3. Acid sulfate soil (ASS) occurrences around Gammelgården. Green points and areas = hypersulfidic soils, red points and orange areas = sulfuric soils, and blue points and areas = non-ASS.

Soil core from Gammelgården

Gammelgården is a classic site where Danai Georgala studied a nearly 12 m deep soil core in 1980 (Georgala, 1980; Figure 4). The location liex approximately 2 km east of the village of Gammelgården. The planned field visit is situated a few kilometers west of the site where Georgala's a soil core was collected (Figure 1).

The soil core studied by Georgala (1980) had a 2.5 m thick red-brown top layer, which was apparently oxidised. Below this layer, the sediments were black, silty and very homogenous throughout the core. The sediments of the core originates from the Littorina Sea stage and were deposited in a relatively deep basin under anoxic conditions, which were favoured by the presence of a distinct halocline. Sulfur species (FeS and pyrite) were analysed along with several other parameters. The content of acid volatile sulfides (AVS; i.e., FeS) ranged from 0.04 to1.82 wt% (Figure 4). It is obvious that the black colour of the sediment is due to presence of FeS. The pyrite content was calculated as the difference between total S and AVS and ranged from 0 to 1.15 wt%. Unfourtunately, focus seem to have been on the unaffected (unoxidised) part of the profile, so no analytical data is available for the upper 3 m (Figure 4).

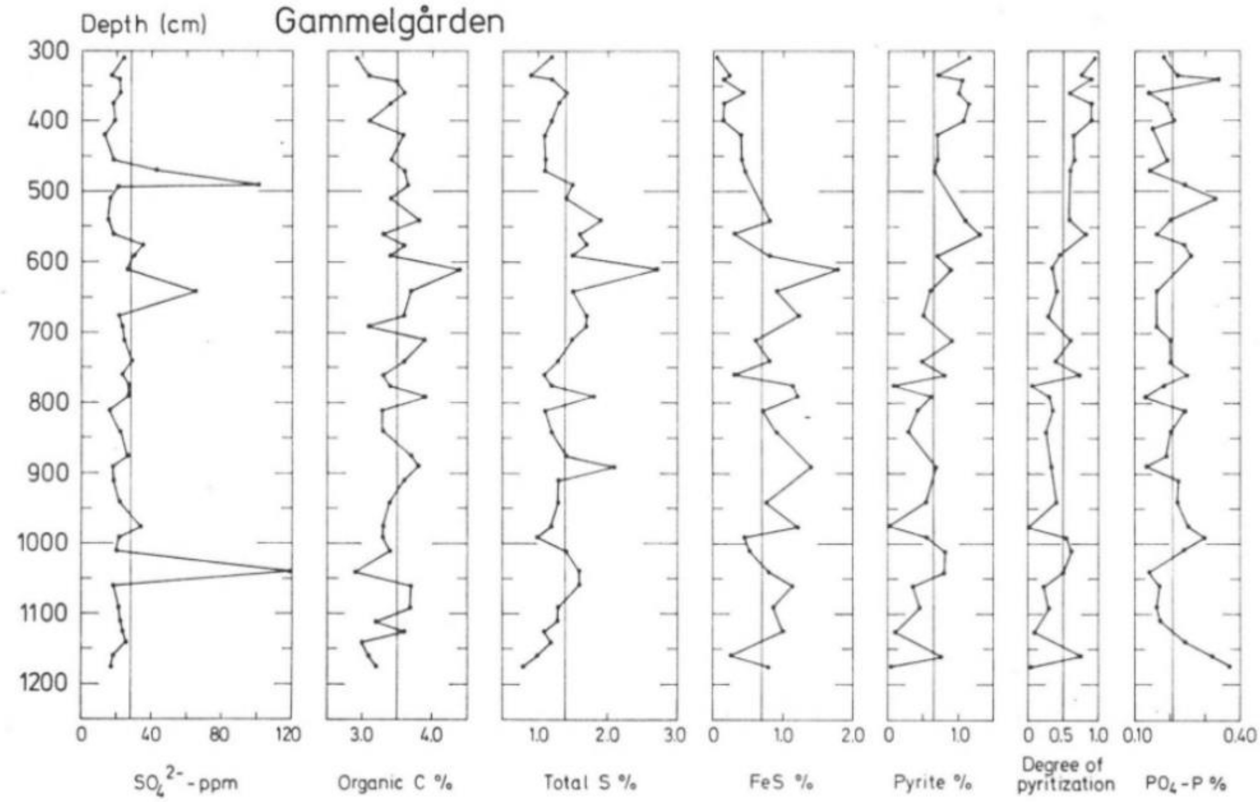

Figure 4. Analytical data from a soil core in Gammelgården. Iron monosulfides (FeS) and pyrite is present in elevated confentrations throughout the profile. From Georgala (1980).

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Site 2: Kupsussuo – Peat harvesting area containing hypersulfidic material

Anton Boman, Jukka Räisänen & Jaakko Auri

Location

Google maps: https://maps.app.goo.gl/EcpSP5wg5FfVrRgGA

Coordinates: 65°22'56.5"N 25°56'00.6"E

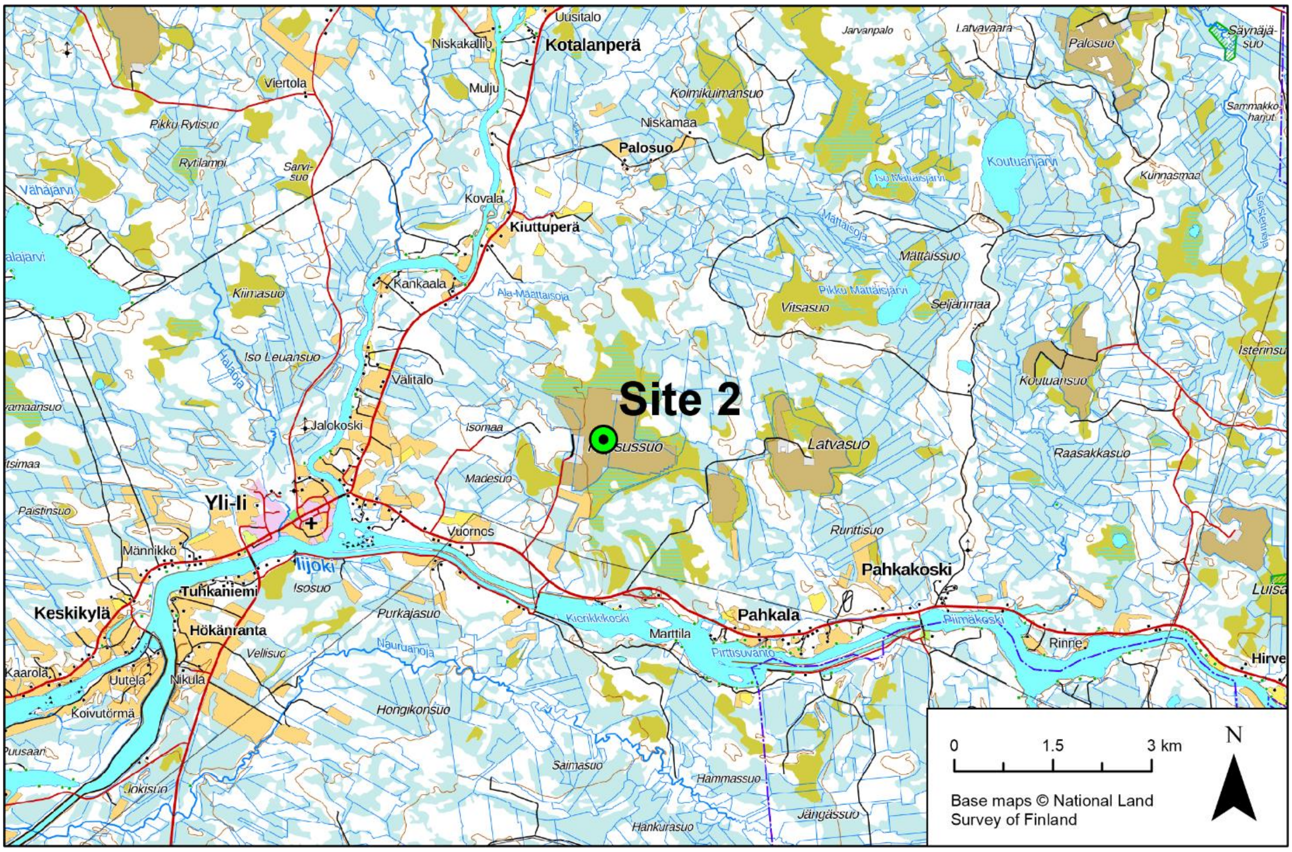

Figure 1. Location of Kupsussuo (Site 2).

Purpose of the visit

To learn about peat harvesting in Finland and problems associated with acid sulfate soils (ASS). Representatives from Neova, the owner of the area, will be present to provide more information about their operations. The Geological Survey of Finland (GTK) has done surveys in the area in 2015 and 2020 and revisited the area in May 2025 for additional soil sampling.

Background and description of the area

The Kupsussuo peat harvesting area is located in Oulu, Northern Ostrobothnia, approximately 4 kilometers northeast of the Yli-Ii urban area (Figure 1). The area covers approximately 166 hectares and lies at an elevation of about 60–62 meters above sea level, which is clearly within the area covered by the maximum extent of the Littorina Sea, estimated at around 100 meters in this region. Maps of acid sulfate soil (ASS) occurrences and the presence of superficial deposits in the area are presented in Figure 2.

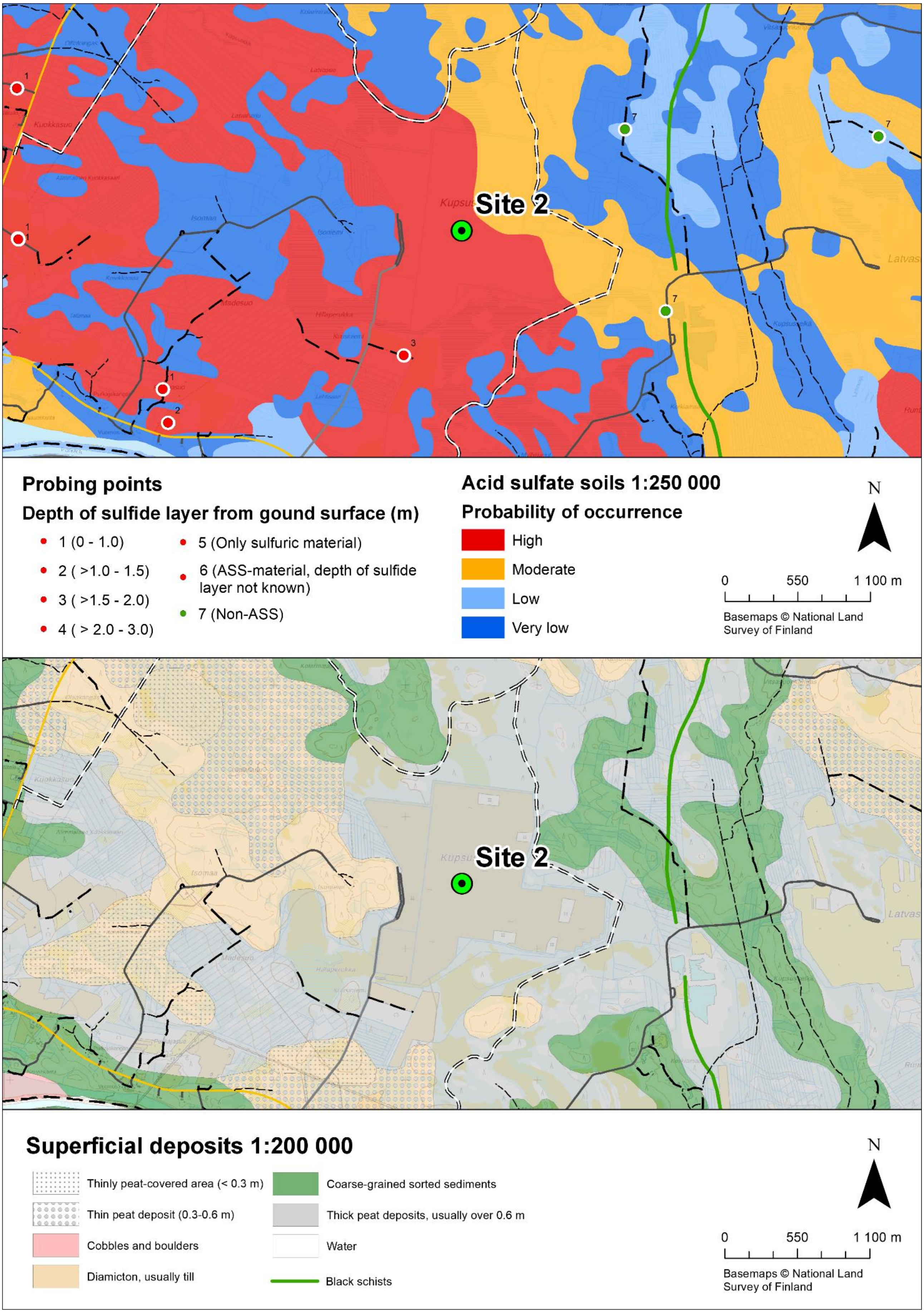

Figure 2. Occurrences of acid sulfate soils (ASS) and the distribution of superficial deposits in the Kupsussuo area. The probing points are derived from the national ASS mapping conducted by the Geological Survey of Finland (GTK).

During the GTK survey in 2020, the thickness of the peat layer varied between 50 and 140 cm. Beneath the peat, there was usually a thin layer of silty fine sand or gyttja (>20% organic matter), which may partly represent a transitional layer between the peat and the mineral soil (Figure 3). At greater depths, the mineral soil was typically coarse silt, sand, or fine sand, where the soil coring usually ended. In two cases, the bottommost soil type was clay (Räisänen and Auri, 2020).

Figure 3. The uppermost one meter of the soil profile collected in May 2025, showing peat down to 70 cm, and underlain by brown-grayish and gyttja-containing silt. Photo: Jukka Räisänen, GTK.

Based on the GTK surveys in 2015 (Boman, 2015) and 2020 (Räisänen and Auri, 2020), it can be estimated that more than half of the Kupsussuo area falls into the high probability class for ASS occurrence (Figure 4). In total, ten soil profiles were taken in the GTK surveys 2015 and 2020, of which nine revealed subsoil layers containing ASS materials. Two of these profiles, 1045 and 1049, are presented in Figures 5 and 6, respectively, and their locations are indicated in Figure 4. Of the collected soil profiles, two were classified as having a medium acidifying potential due to relatively low total sulfur content. The thickness of the acidifying soil layers observed in the studies varied between 20 and 100 cm.

Acid sulfate soil materials (hypersulfidic materials) were found in all soil materials beneath the peat. These showed total sulfur contents exceeding 0.2%, especially in silty fine sand and coarse sand. The highest sulfur content was 1.1% in silty fine sand. Slight acidification was observed in one basal peat layer. Weak sensory indicators (smell and visually) of sulfides were commonly observed in the soil layers. One sampling site (1049; Figure 5) contained black/gray-coloured fine sand with a very strong sulfide odor. All ASS in the area are classified as hypersulfidic soils, indicating that no oxidized soil with a pH below 4 (in mineral soils and gyttja) or below pH 3 (in peat) was found at any site.

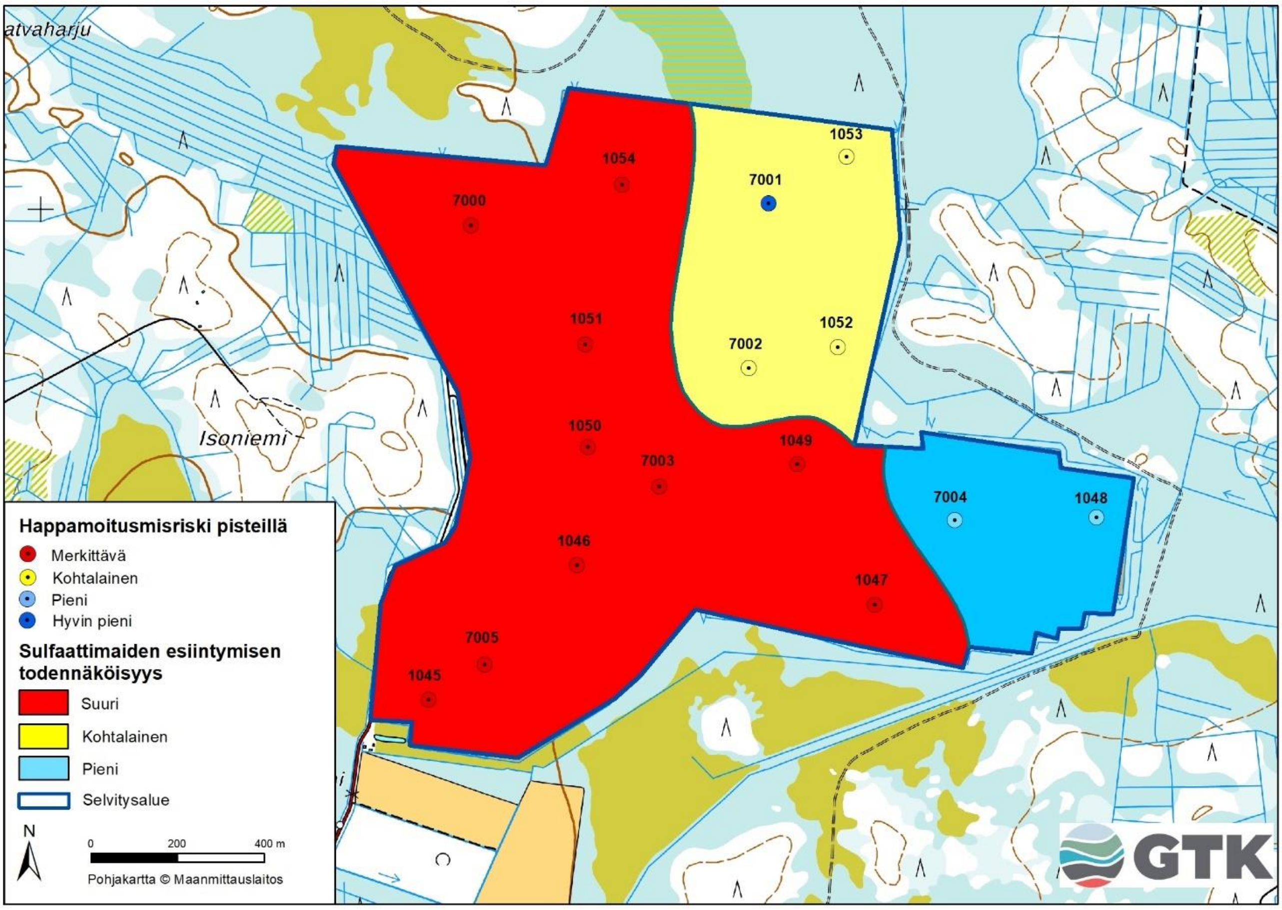

Figure 4. Occurrence of acid sulfate soils (ASS) at Kupsussuo. Red circles and areas indicate a high probability of ASS occurrence; yellow circles indicate a moderate probability; light blue circles and areas indicate a low probability; and dark blue circles indicate a very low probability (Räisänen and Auri, 2020).

In May 2025, the area was revisited by GTK, and soil samples were collected from a location near profile 1045. These samples were incubated, and pH, titratable incubation acidity (TIA), and sulfur speciation (AVS and CRS) were analysed. The results are presented in Table 1. Low concentrations of AVS (i.e., metastable iron sulfides; mackinawite and greigite) were present in both the peat and the underlying silt. CRS (i.e., pyrite fraction) was also low in the peat but showed higher concentrations in the silt. Hypersulfidic materials are present in the silt but not in the peat. The acidifying potential of the silt is classified as large, following the recommendations by Visuri et al. (2021).

Table 1. Field- and analytical data from a profile collected in May 2025 near profile 1045 (see Figure 4). The profile is classified as a hypersulfidic fine-grained soil with a large acidifying potential.

Depth	Soil type	Colour	pH		LOI	TIA, pH 6.5	AVS	CRS	Total S	ASS	Acidifying
Meter			Field	Incubation	%	mmol/kg	mg/kg	mg/kg	mg/kg	material	potential
0-0.5	Peat	Brown	4.8	4.0	82.5	535	207	285	1330	Non-ASS	-
0.5-0.7	Peat	Brown	5.3	4.4	77.5	429	<100	172	1930	Non-ASS	-
0.7-0.9	Silt	Black-gray	5.9	2.9	5.4	122	105	3172	2850	Hypersulfidic	Large
0.9-1.1	Silt	Black-gray	5.9	2.1	6.4	297	106	7444	6240	Hypersulfidic	Large
1.1-1.3	Silt	Black-gray	6.1	2.4	4.5	188	161	7303	9860	Hypersulfidic	Large
1.3-1.5	Silt	Black-gray	6.4	2.7	2.1	68	432	4668	5240	Hypersulfidic	Medium

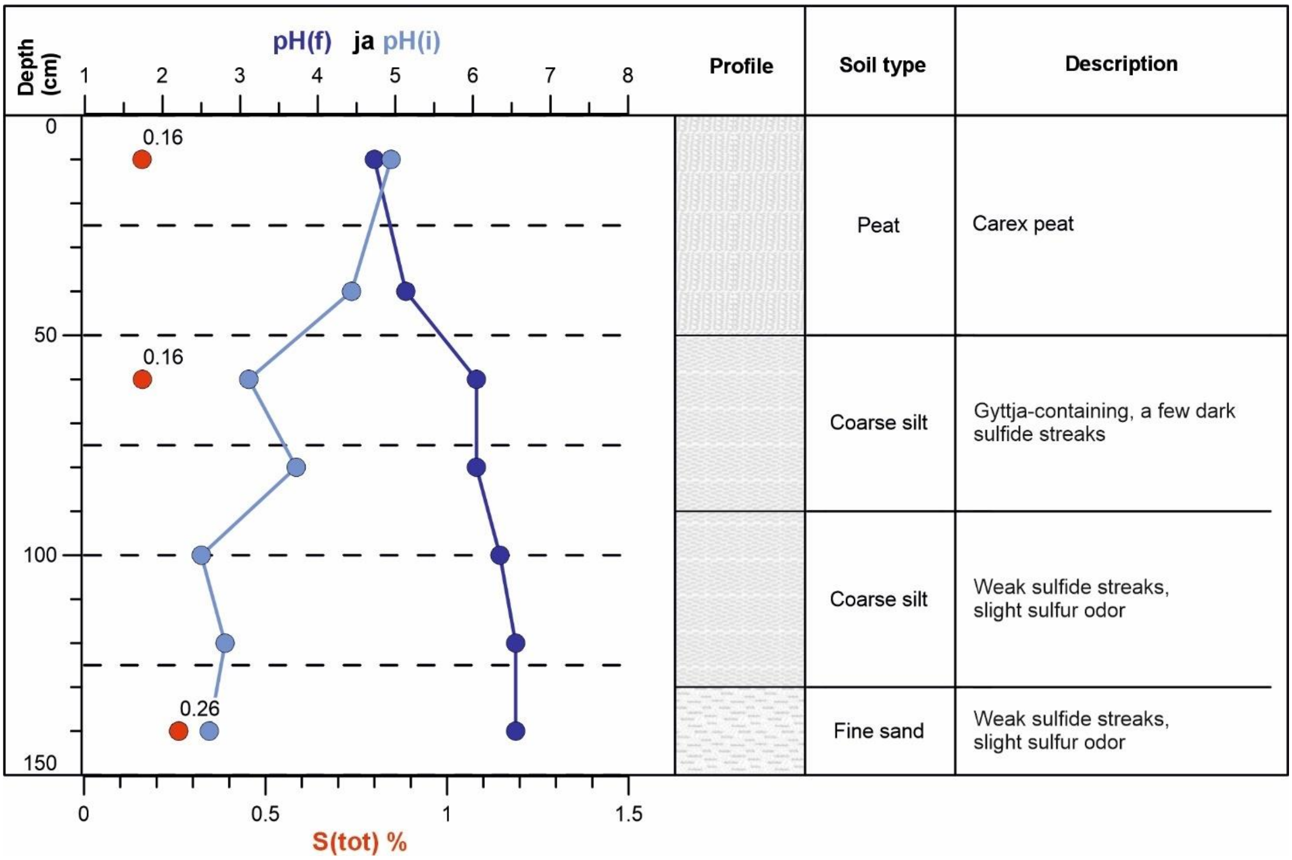

Figure 5. A soil profile (1045 in Figure 4) classified as a hypersulfidic fine-grained soil (Boman et al., 2023) (modified after Räisänen and Auri, 2020).

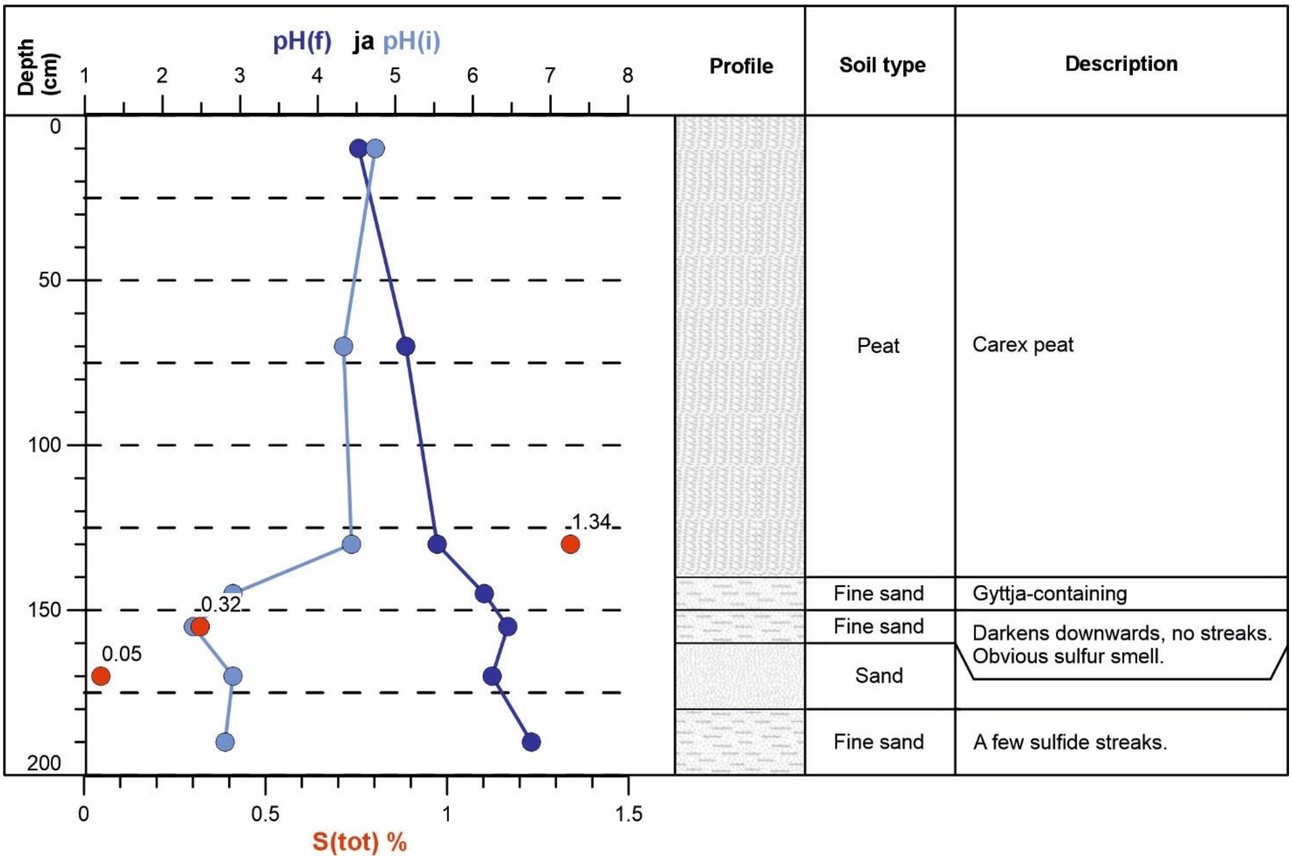

Figure 6. A soil profile (1049 in Figure 4) classified as a hypersulfidic fine-grained soil (Boman et al., 2023) (modified after Räisänen and Auri, 2020).

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Site 3: Hypersulfidic organic soils at the Välimaa circular economy area

Jukka Räisänen, Anton Boman & Jaakko Auri

Location

Google maps: https://maps.app.goo.gl/rhzv4aDxfufDNBvH8

Coordinates: 65°10'25.5"N 25°49'41.4"E

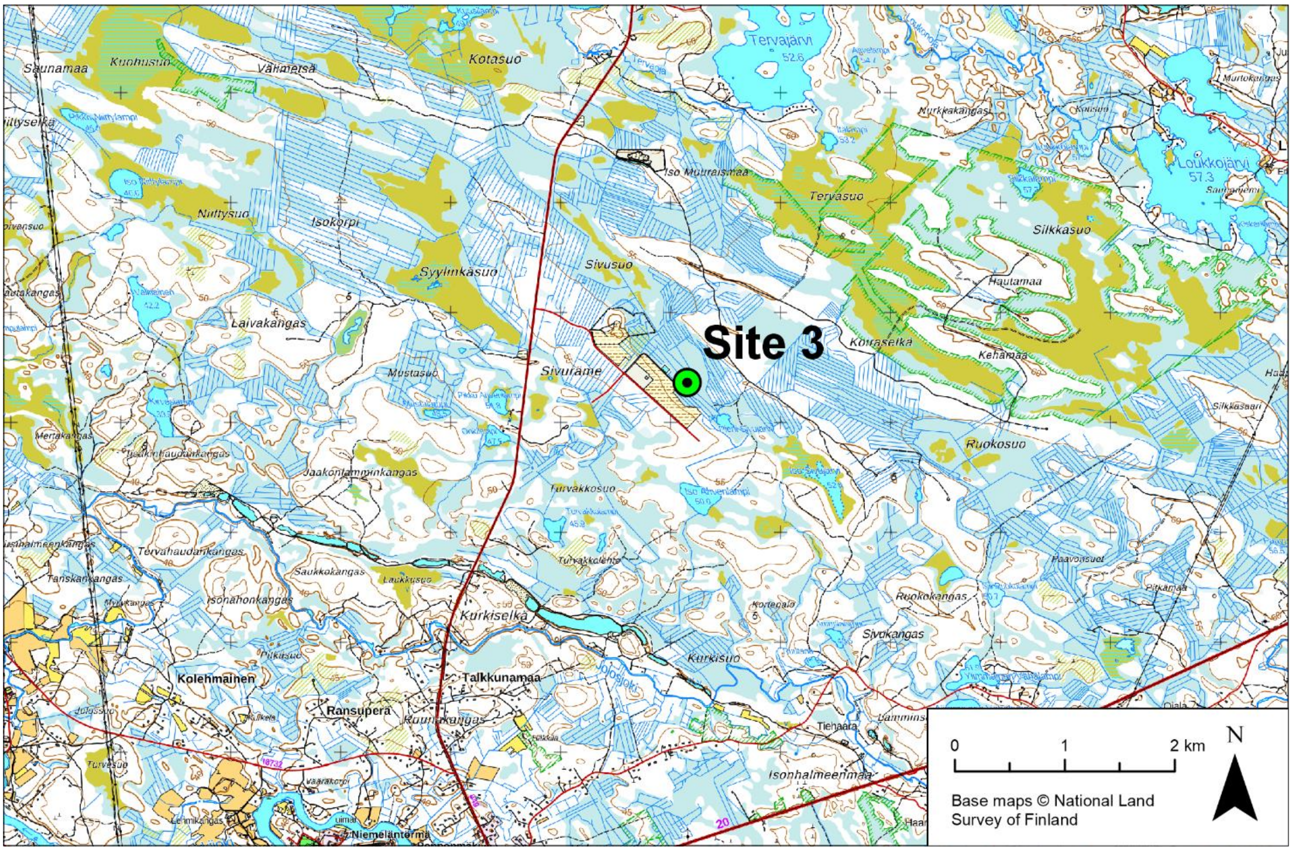

Figure 1. Location of Välimaa circular economy area (Site 3).

Purpose of the visit

We will study an acid sulfate soil (ASS) profile in a peatland. The ASS is classified as a hypersulfidic organic soil and comprises hypersulfidic materials within the peat, the underlying mineral soil, and the glacial till.

Description of the site

The site is located within the Välimaa circular economy area (Figure 1), which was established to meet the recognized need for a location where circular economy actors can utilize high-volume side streams and excavated soil masses. Water discharge from the site is regularly monitored by Lassila & Tikanoja, a key player in the circular economy sector. The Välimaa circular economy area is located in Oulu, about 6 km north of the Kiiminki urban area and approximately 28 km from the center of Oulu.

For the CircVol project, the Geological Survey of Finland (GTK) investigated the soil at the Välimaa circular economy area. A total of eight soil profiles were collected (P1–P8; Figure 2). The results, presented in Auri et al. (2022), show that hypersulfidic materials are present in the peat and gyttja, as well as in the mineral soil and glacial till. Maps of ASS occurrence and superficial deposits in the area is found in Figure 3.

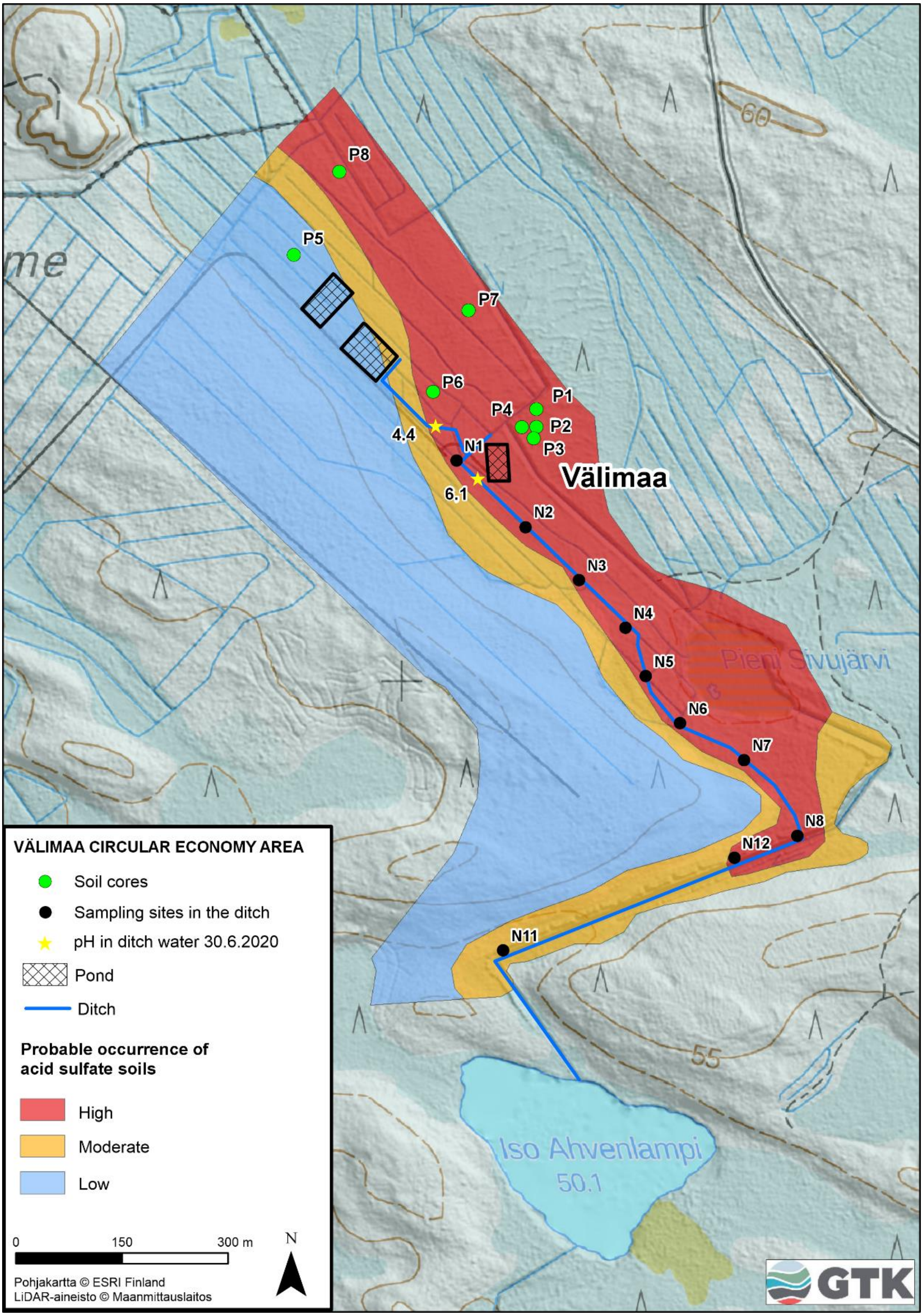

Figure 2. Occurrence of acid sulfate soils (ASS) and sampling sites at Välimaa. P1-P8 indicates where soil profiles were taken. N1-N11 indicates where samples were taken from the ditch. Yellow stars show the pH of the ditch water 30 June 2020. Modified after Auri et al. (2020).

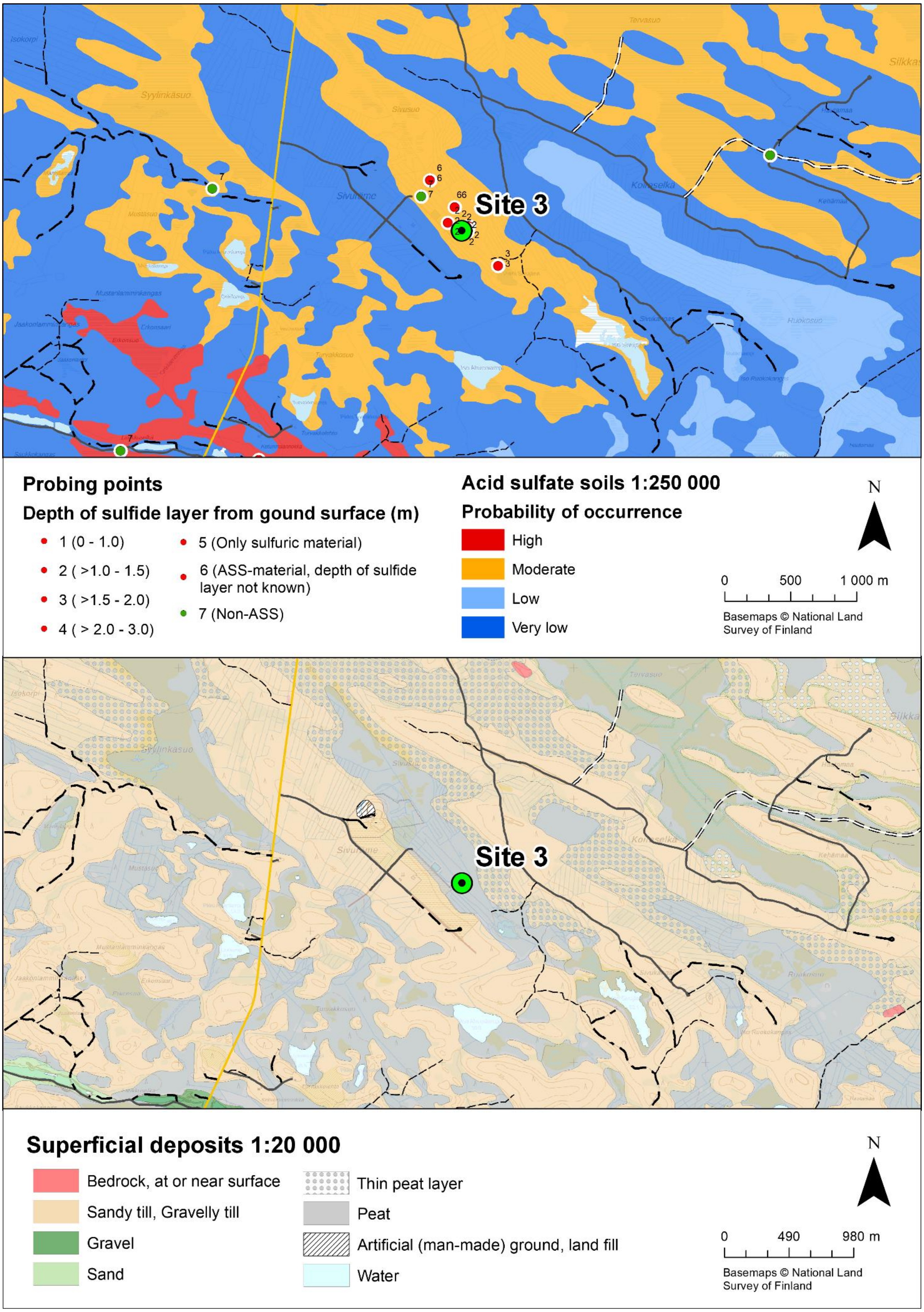

Figure 3. Occurrences of acid sulfate soils (ASS) and the distribution of superficial deposits in the Välimaa area. The probing points are derived from the national ASS mapping conducted by the Geological Survey of Finland (GTK).

Lithology of the soil at Välimaa

In the CircVol project (Auri et al., 2020), eight soil profiles were collected (P1-P8 in Figure 2). In general, the soil at these locations exhibited the following lithological strata from the surface downward:

1. **Peat layer**, with a thickness ranging from 1.1 to 1.8 meters. The peat was mainly *Carex* peat, with common additions of common reed (*Phragmites australis*) and horsetail (*Equisetum*) in the lower part. The incubation pH of the basal peat was generally above 4.0, except at points P7 and P8, where the incubation pH was below 3.0 (i.e., classified as ***hypersulfidic organic material***; Boman et al., 2023).
2. **Gyttja layer**, with a thickness of 10–25 cm (Figure 4). The gyttja consisted of an upper, thinner layer of coarse detritus gyttja and a lower, thicker layer of fine detritus gyttja. The colour of the gyttja was greenish brown. This deposit formed in a shallow freshwater basin that existed in the area after the retreat of the Littorina Sea. The gyttja oxidized strongly during incubation, with the lowest incubation pH recorded at 1.8 (i.e., classified as ***hypersulfidic organic material***; Boman et al., 2023).
3. **Gyttja-containing fine sand / sand**, with a thickness of 5–10 cm. This layer formed at the end of the Littorina Sea phase, when wave action washed mineral material from surrounding moraine areas into the valley. This layer also oxidized strongly during incubation, with the lowest incubation pH recorded at 2.5 (i.e., classified as ***hypersulfidic coarse-grained material;*** Boman et al., 2023).
4. **Glacial till**, with a leached surface containing only a small amount of fine material. Beneath the leached surface was gray or dark gray basal till, which was visually assessed to possibly contain black schist material. The moraine samples used for pH measurements were mostly taken from the surface layer, as the available drilling equipment did not allow deeper sampling. The pH of the till also generally dropped below 4.0 during incubation (i.e., classified as ***hypersulfidic unsorted material;*** Boman et al., 2023). This is probably due to the presence of black schist material. However, framboidal pyrite has also been detected by FE-SEM, which may indicate *in situ* formation as well.

Figure 4. The gyttja layer appears as a greenish-brown layer between the peat and the mineral soil. Photo: Jukka Räisänen, GTK.

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Site 4: Jääli – Iron contamination in a black schist area

Anton Boman, Elina Niemelä, Jukka Räisänen & Jaakko Auri

Location

Google maps: https://maps.app.goo.gl/ddSmMANs9W5Y6wWJ6

Coordinates: 65°05'19.9"N 25°43'54.0"E

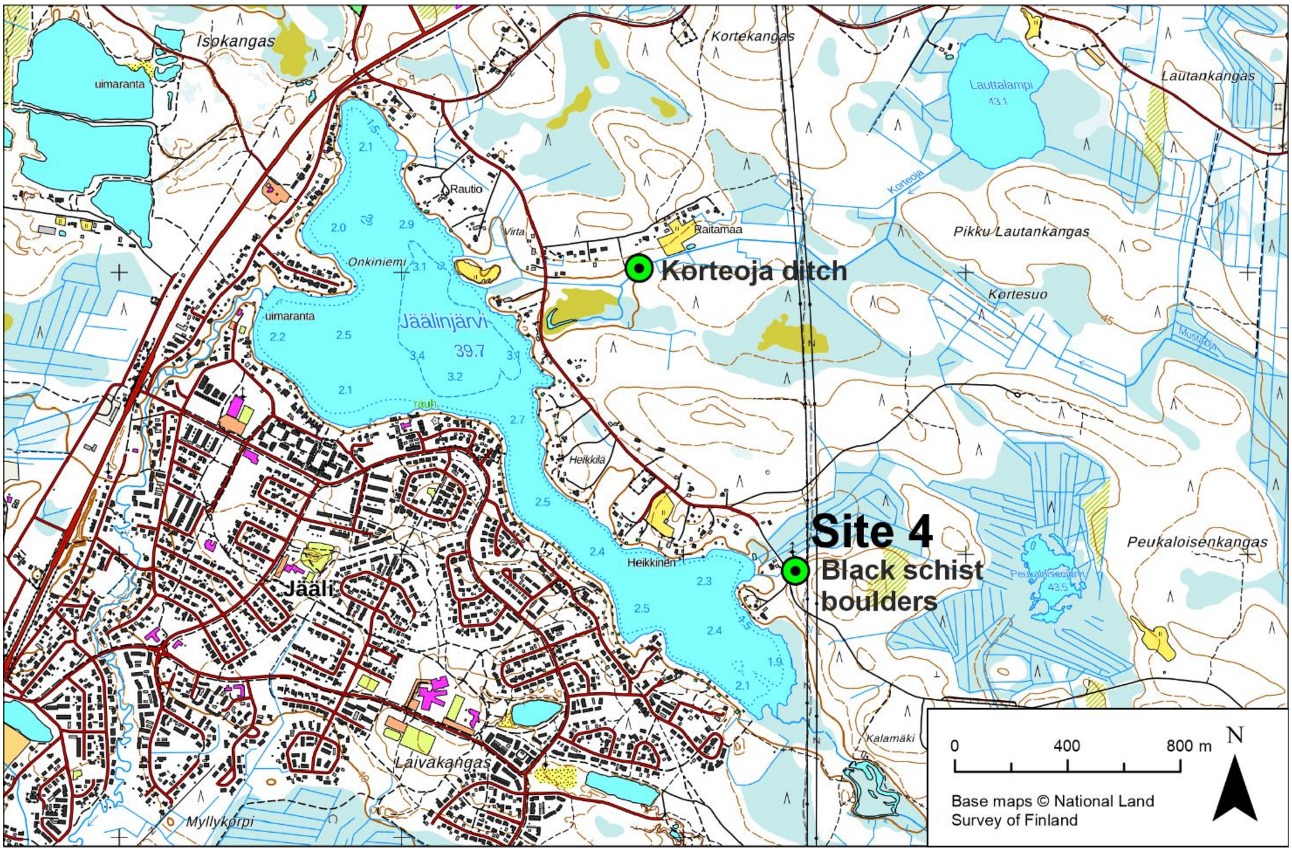

Figure 1. Location of Jääli and stop 1 (black schist boulders) and stop 2 (iron precipitates at Korteoja ditch).

Purpose of the visit

To study the issues related to iron contamination in the Jääli area, with a particular focus on Lake Jäälinjärvi (Figure 1). The first stop will be at a site where sulfide-bearing boulders (black schist) are located (Figure 2), and the second stop will be at the Korteoja ditch, near a constructed wetland (Figure 1), where a regulating dam has been built by the “Kiiminki-Jääli Water Management Association” (Kiiminki-Jääli vesienhoitoyhdistys in Finnish) to mimimize nutrients (N, P) from entering Lake Jäälinjäärvi. At this site, also iron precipitates are usually very well visible in the ditch (Figure 2). Representatives from the “Kiiminki-Jääli Water Management Association” will be present and inform us of their activities in the area and explain how iron leaching impacts the Lake Jäälinjärvi.

Figure 2. Black schist boulders in Jääli (left; Photo: Jukka Räisänen, GTK) and iron precipitates at the Korteoja ditch (right; Photo: Birger Ylisaukko-Oja).

Background and area description

The geology and Quaternary geology of the area are descibed in Section 4 (Geology of the Oulu region). The Lake Jäälinjärvi catchment area covers 36 km^2 and is dominated by forestry (87% forested, of which 40% consists of peatlands). Extensive forest ditching has been carried out in the area, and only a few small untouched peatland areas remain. One of the most striking features of the Jääli area is the presence of black schists (Figure 3; Figure 1 in Section 5). Black schist material has ended upp in the glacial till due to glacial erosion and sediment transport and black schist boulders are a common sight in the area (Figure 2). When this sulfide bearing glacial till is exposed to oxygen, the pH often drops during incubation to below 4, meaning that the material is classified as hypersulfidic unsorted ASS material (Boman et al., 2023). It has been shown that glacial till having at least 0.06% total S often becomes acidic, displaying an incubation-pH of <4 and thus classified as hypersulfidic material (Visuri et al., 2021; Boman et al., 2023).

Superficial deposits mainly include sand and fine sand,and glacial till, which are often covered by peat (Figure 3; Figure 2 in Section 5). Acid sulfate soils (ASS) are also present in the area (Figure 3). Elemental analyses of peat from the Saarisenojanniitty area (Figure 4) have revealed high concentrations of iron and sulfur (Fe 11.5% and S 9.9%), approximately three times higher than typical peatland levels (Raumanni et al., 2024). The highest concentrations are found in the bottom layers of the peat and at the contact between peat and mineral soil (Raumanni et al., 2024). About three-quarters of the water entering Lake Jäälinjärvi flows through the Saarisenoja ditch into the southern part of the lake, while roughly one-fifth comes from the northern part via the Korteoja ditch.

The "Kiiminki Jääli Water Management Association" has been working to improve water quality for over 10 years. Several water protection structures have been built, resulting in significant improvements in water quality, with reductions in algae and nutrients. However, the iron problem persists. Hundreds of kilograms of iron flow daily into the lake via Saarisenoja. In July – August, total iron concentrations in the lower reaches of Saarisenoja can reach nearly 30 mg/l. Iron darkens the water significantly and causes sediment accumulation on the lake bottom. Iron is poorly retained by water treatment structures. Only the large sedimentation basin (3.5 ha; Figure 5) separated from Lake Jäälinjärvi effectively settles iron (14%), thanks to a sufficiently long retention time (4 days at base flow). Wetlands, wood bundles, and vortex basins are ineffective at retaining iron.

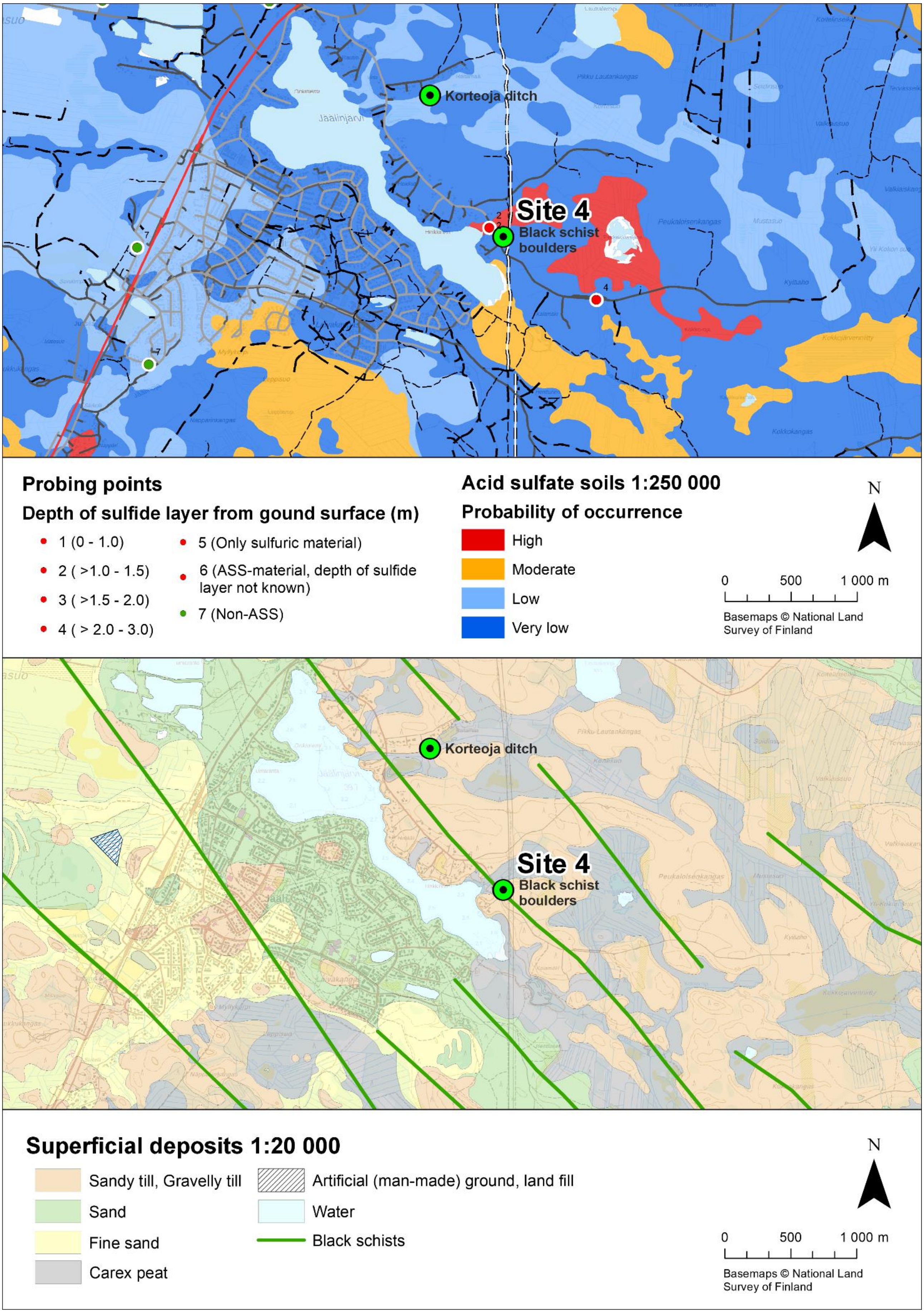

Figure 3. Occurrences of acid sulfate soils (ASS) and the distribution of superficial deposits in the Jääli area. Black schists are abundant throughout the region. The probing points are derived from the national ASS mapping conducted by the Geological Survey of Finland (GTK).

Higher iron concentrations appeared to be somewhat associated with black schists and peatland drainage, with the latter having a clearer impact (Raumanni et al., 2024). For instance, peat located on top of black schists have shown elevated iron concentrations (Raumanni et al., 2024). It cannot, however, be excluded that ASS, especially unsorted ASS (i.e., containing hypersulfidic material in glacial till) in the area (Figure 3), also contribute to the iron problem.

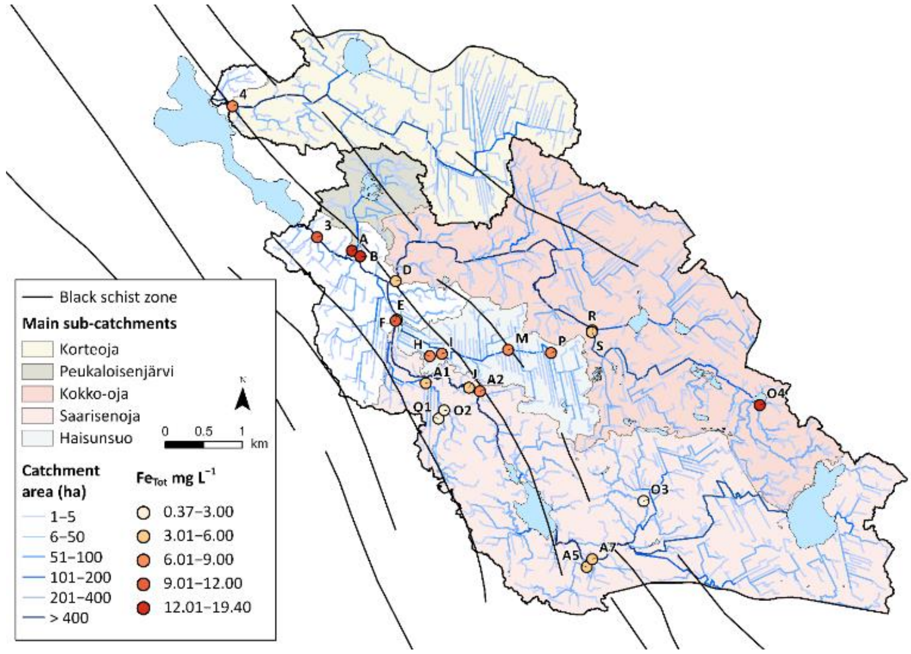

Figure 4. Lake Jäälinjärvi catchment area and its sub-catchments, black schist zones, drainage systems, and the average iron concentrations (from 2023). The map has been created by Petra Korhonen (University of Oulu).

Figure 5: A 3.5 ha sedimentation basin separated from Lake Jäälinjärvi. Photo: Birger Ylisaukko-Oja.

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Site 5: Nenänperä – Corrosion in infrastructure

Jukka Räisänen, Mirkka Visuri, Anton Boman, Hannu Hirvasniemi & Jaakko Auri

Location

Google maps: https://maps.app.goo.gl/85SJynjAZ1mRRSXJ6

Coordinates: 64°51'19.7"N 25°24'51.4"E

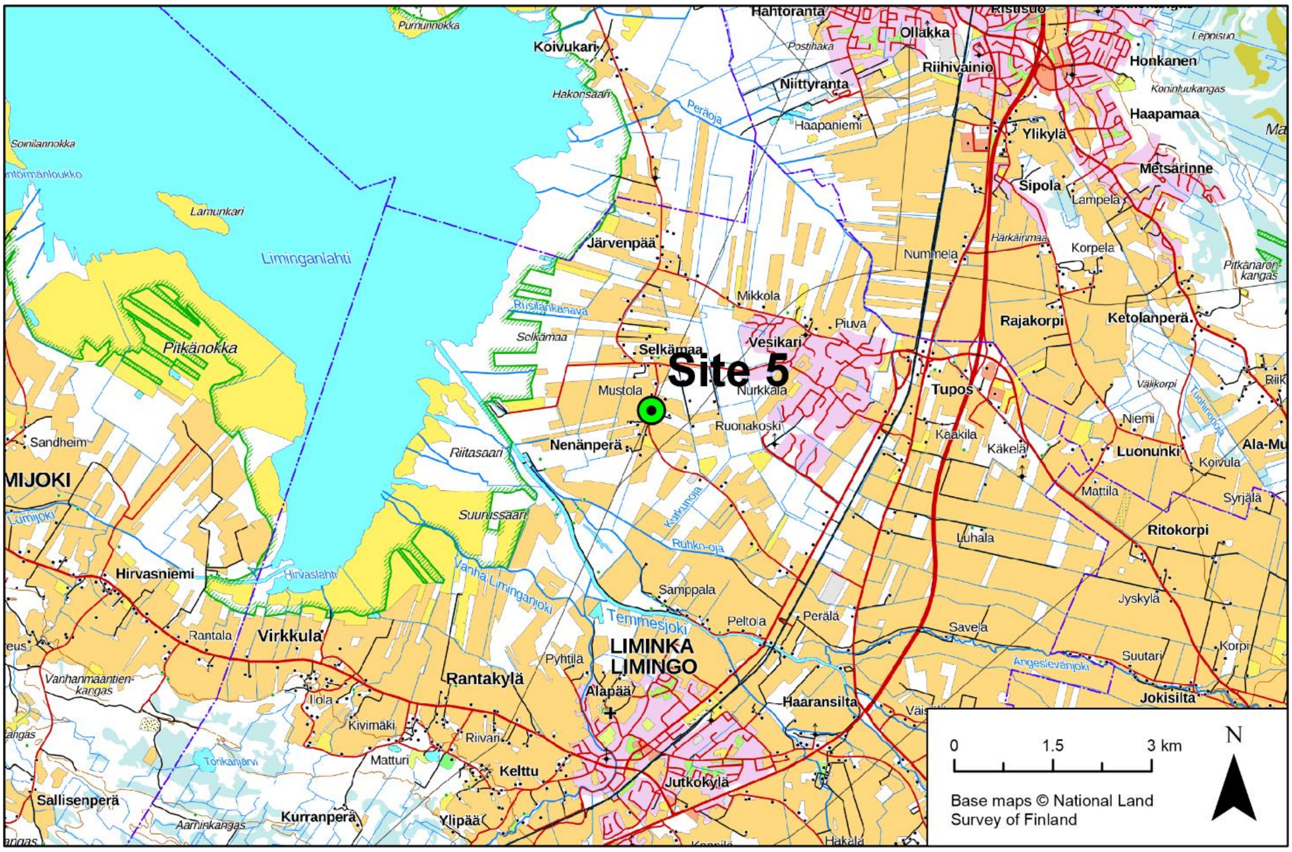

Figure 1. Location of Nenänperä (Site 5).

Purpose of the visit

The aim is to study a typical acid sulfate soil (ASS) profile in a soil pit representative of the region. The profile is characterized by black, fine-grained hypersulfidic material. We will also discuss corrosion-related issues that affect infrastructure in such environments.

Site description

The Nenänperä site is located on a former agricultural field that has since become forested. Its elevation is 5 meters above sea level, meaning it has been on dry land for approximately 700 years. Acid sulfate soils are present in the area, where the superficial deposits typically comprise fine sand and sand overlying finer sediments, such as clay and silt (Figure 2).

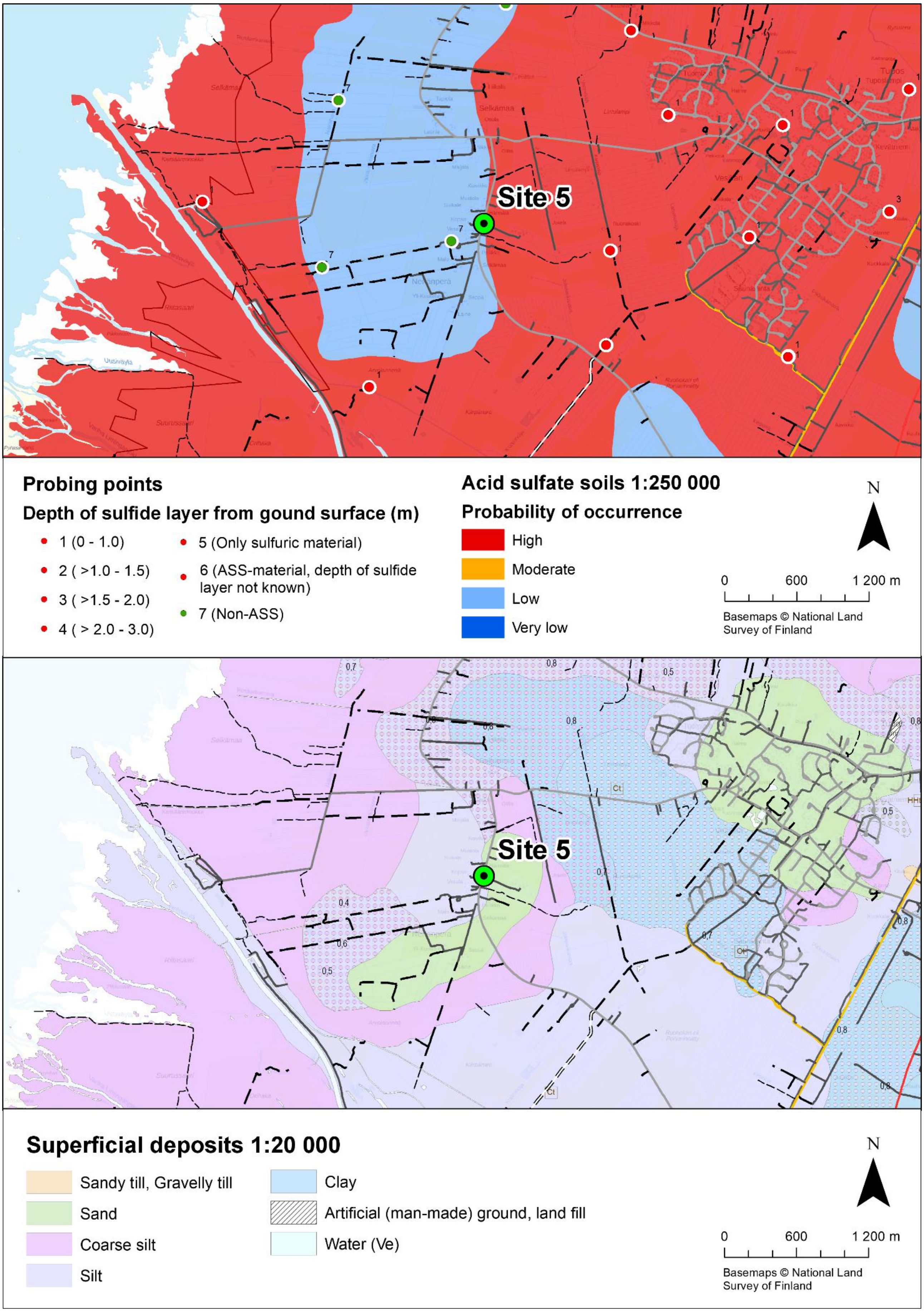

Figure 2. Occurrences of acid sulfate soils (ASS) and the distribution of superficial deposits in Nenänperä. The probing points are derived from the national ASS mapping conducted by the Geological Survey of Finland (GTK).

Profile description and analytical data

The soil in the Nenänperä area consists of fine sand in the surface layer (Figure 3). This material is oxidized (pH around 5.3) beach deposits, originally derived from the Kempele esker formation located to the north. The oxidtion depth is located at about 1.1 m. At greater depths, the material transitions into silt, with colours ranging from dark gray to nearly black (Figure 3). This silt layer was formed during the Littorina Sea phase. The colour variations are clearly visible and can be observed in a soil pit excavated at the site. The black colour indicates the presence of metastable iron sulfides (i.e., AVS in Table 1). The field pH for the black sulfidic materials is quite high at 8.3 (Table 1), indicating strongly reducing conditions. During incubation, pH dropped considerably for all reduced soil samples (silt) (Table 1). Also total S and the sulfide content is elevated in the reduced samples, and the acidifying potential has been classified as large according to the guidelines in Visuri et al. (2021). Data from soil samples collected in May 2025 is presented in Table 1. Based on the pH-measurements and sulfide content, the soil is classified as a ***hypersulfidic fine-grained soil*** (Boman et al., 2023). It is important to note that this soil is not a so-called "active ASS" (i.e., sulfuric soil), as it has been leached to the extent that the pH has increased. Consequently, no sulfuric or parasulfuric materials are present (Table 1). If the groundwater table is lowered, the soil will likely transition into a sulfuric soil.

Figure 3. Soil profile at Nenänperä showing oxidised orange-brown fine sand with iron precipitates extending down to approximately 1.1 m (oxidation depth). Below this depth, the reduced material becomes finer, transitioning into silt, and the colour gradually changes from dark gray to black (>1.9 m depth), indicating the presence of metastable iron sulfides (i.e., AVS in Table 1). The organic topsoil layer (approx. 0–0.3 m) is not visible in the picture but can be observed in the soil pit at the excavation site. Photo: Jukka Räisänen, GTK.

Table 1. Field- and analytical data from the Nenänperä profile. LOI = loss on ignition, TIA = titratable incubation acidity, AVS = acid volatile sulfides, CRS = Chromium reducible sulfur, and ASS = acid sulfate soil.

Depth	Soil type	Colour	pH		LOI	TIA, pH 6.5	AVS	CRS	Total S	ASS	Acidifying
Meter			Field	Incubation	%	mmol/kg	mg/kg	mg/kg	mg/kg	material	potential
0.9-1.2	Fine sand	Orange-brown	5.3	4.4	0.4	7	<100	<100	109	Non-ASS	-
1.3-1.7	Silt	Dark grey	6.4	2.4	2.8	164	<100	10145	10400	Hypersulfidic	Large
1.9-2.0	Silt	Black	8.3	2.5	3.1	132	1173	3867	4730	Hypersulfidic	Large

Acid sulfate soils and corrosion in infrastructure

In Finland, ASS have been found to affect, among other things, the corrosion of guy anchors for power poles, steel piles and sheet piles, as well as reinforced concrete. The soil material from this site is included in corrosion studies conducted as part of the FiksuHasu (SmartASS) project. Acid sulfate soils are recognized in construction as a soil type with exceptional corrosion risk, and they can cause significant damage to steel and concrete structures (Figure 4). Corrosion of steel structures in ASS is primarily an electrochemical process, whereas in concrete, damage is caused by degrading chemical reactions.

Figure 4. Corrosion of steel can be quite severe in areas underlain with acid sulfate soils. Photos: ©Fingrid.

Corrosion in ASS is accelerated especially by low pH, high electrical conductivity, high sulfate concentration, and microbial activity (e.g., sulfate reducing bacteria). Sediments from the ancient Littorina Sea, commonly recognized as ASS material, may also contain high levels of chloride, increasing soil conductivity and corrosion risk. The oxidized and reduced layers of ASS typically form two distinctly different corrosion environments. Corrosion in soil is usually most intense at the interface between oxidized and reduced layers. In construction, this risk can be mitigated proactively, for example, by adjusting the drainage depth. Other risk management methods include using corrosion-resistant materials, increasing corrosion allowance in materials, neutralizing or stabilizing the soil, and replacing soil masses.

In Finland, soil corrosion risk is generally assessed according to the corrosion investigation program presented in Table 2 (Väylävirasto, 2023). Additionally, the risk can be evaluated based on water samples, including both surface and groundwater. The risk of microbiological corrosion is assessed based on the results of the basic investigation program, as there is currently no suitable procedure available for its evaluation. Chemical stress on concrete in ASS is assessed based on sulfate concentration and the Baumann-Gully acidity index.

Table 2. Corrosion investigation program for soil samples (modified after Väylävirasto, 2023).

Measured Property	Method	Quantity	Threshold
soil type	sieving and areometer or sedigraph CEN ISO/TS 17892-4	during geotechnical investigations, layer order is determined	most significant are fine-grained and gyttja containing soil types
water content, w	oven drying at 105°C SFS-EN ISO 17892-1	during geotechnical investigations.	If $w > w_l$, corrosion is slow
electrical conductivity or resistivity	air-dried, <2 mm fraction, filtered from 1:5 water solution with electrode ISO 11265:1994/Cor 1:1996	two parallel samples, samples from different depths	>50 mS/m²
	resistivity measurement in situ	during geotechnical investigations, from ground surface to the pile penetration depth	p<20 Ωm in fine-grained soil, p<50 Ωm in coarse-grained soil
humus content	loss on ignition SFS 3008	during geotechnical investigations.	>6%
pH	ISO 4316 ISO10390 air-dried or <40°, <2 mm fraction filtered from 1:5 water solution with electrode	two parallel samples, samples from different depths	pH<4.5 pH>9
sulfate SO_4^{2-}	SFS-EN196-2 (ISO11048, for rock sample)	samples from different depths and layers	SO_4^{2-}>500 mg/kg or SO_4^{2-}>200 mg/l in water solution
chlorides Cl^-	e.g water extraction, SFS-EN196-2 (ISO11048, for rock sample)	samples from different depths and layers, groundwater sample taken separately if chloride concentration is suspected.	Cl^- > 500 mg/kg or Cl^- > 300 mg/l in aqueous solution"

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Väylävirasto, 2023. Eurokoodin soveltamisohje – Geotekninen suunnittelu - NCC17, Siltojen ja pohjarakenteiden suunnitteluohjeet.

Site 6: Black hypersulfidic sand at Turpeenperä

Jukka Räisänen, Anton Boman, Hannu Hirvasniemi & Jaakko Auri

Location

Google maps: https://maps.app.goo.gl/UGdNBqHTC7s8B7CJ7

Coordinates: 64°52'19.9"N 24°44'55.5"E

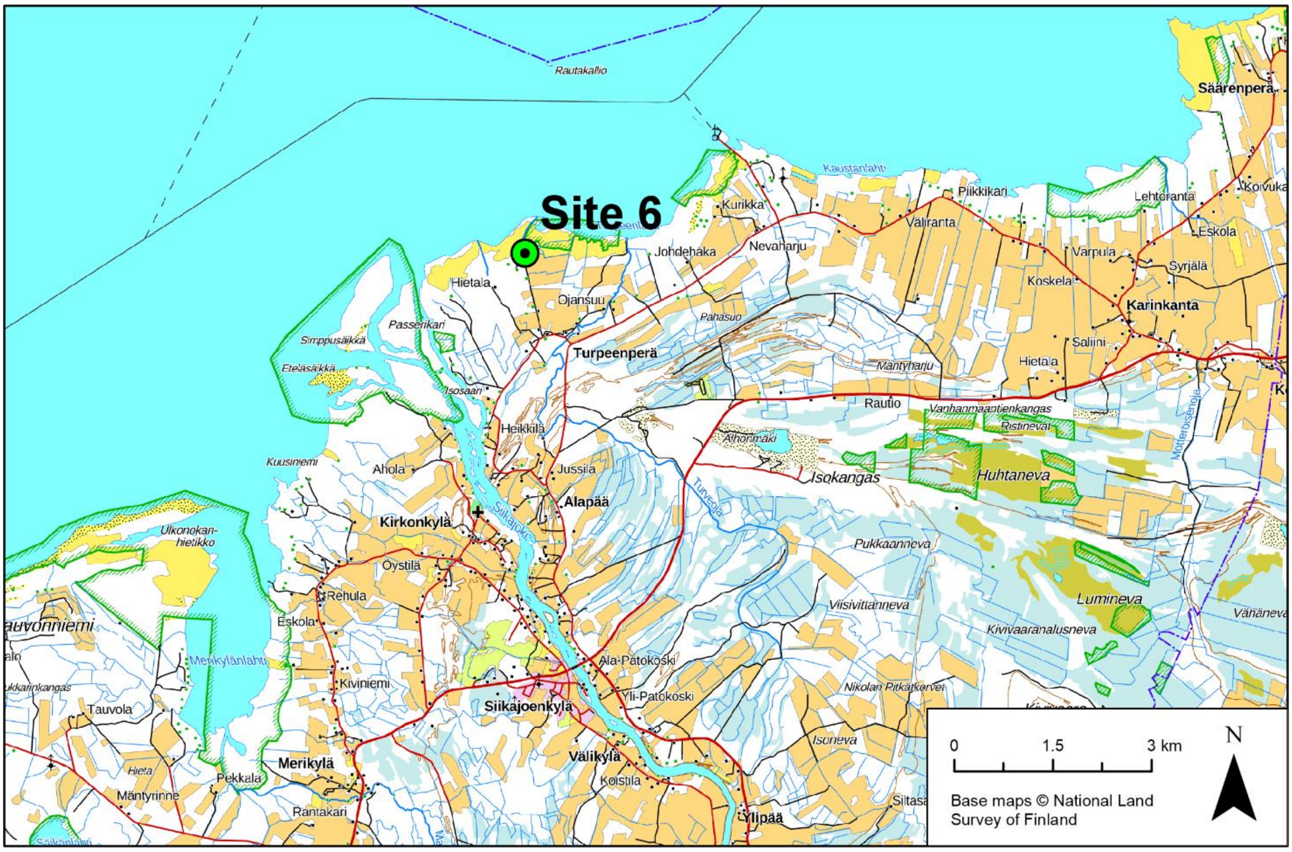

Figure 1. Location of Turpeenperä (Site 6).

Purpose of the visit

In Finland, acid sulfate soils (ASS) are commonly, or historically, considered to consist mainly of fine-grained materials such as clay and silt. At this site, we will examine a black, hypersulfidic, coarse-grained ASS, which represents a less typical but scientifically and environmentally significant variant.

Site and soil description

Turpeenperä is located in an agricultural area, approximately half a kilometre from the coast of the Bothnian Bay. Its elevation is only 1.5 metres above sea level, meaning it has been dry land for just about 200 years. The soil in the Turpeenperä area consists mainly of sand (Figure 2). The material is a beach deposit, originating primarily from the esker formation that runs south of Turpeenperä (Figure 3 in Section 4). Over time, the retreating sea has spread this material into flat marginal sand plains. Numerous beach ridges found in the area, visible along the road leading to the site, also testify to the action of the retreating sea. The site is located near the Simo River delta, meaninf that the uppermost soil layer partly consists of flood deposits carried by the river.

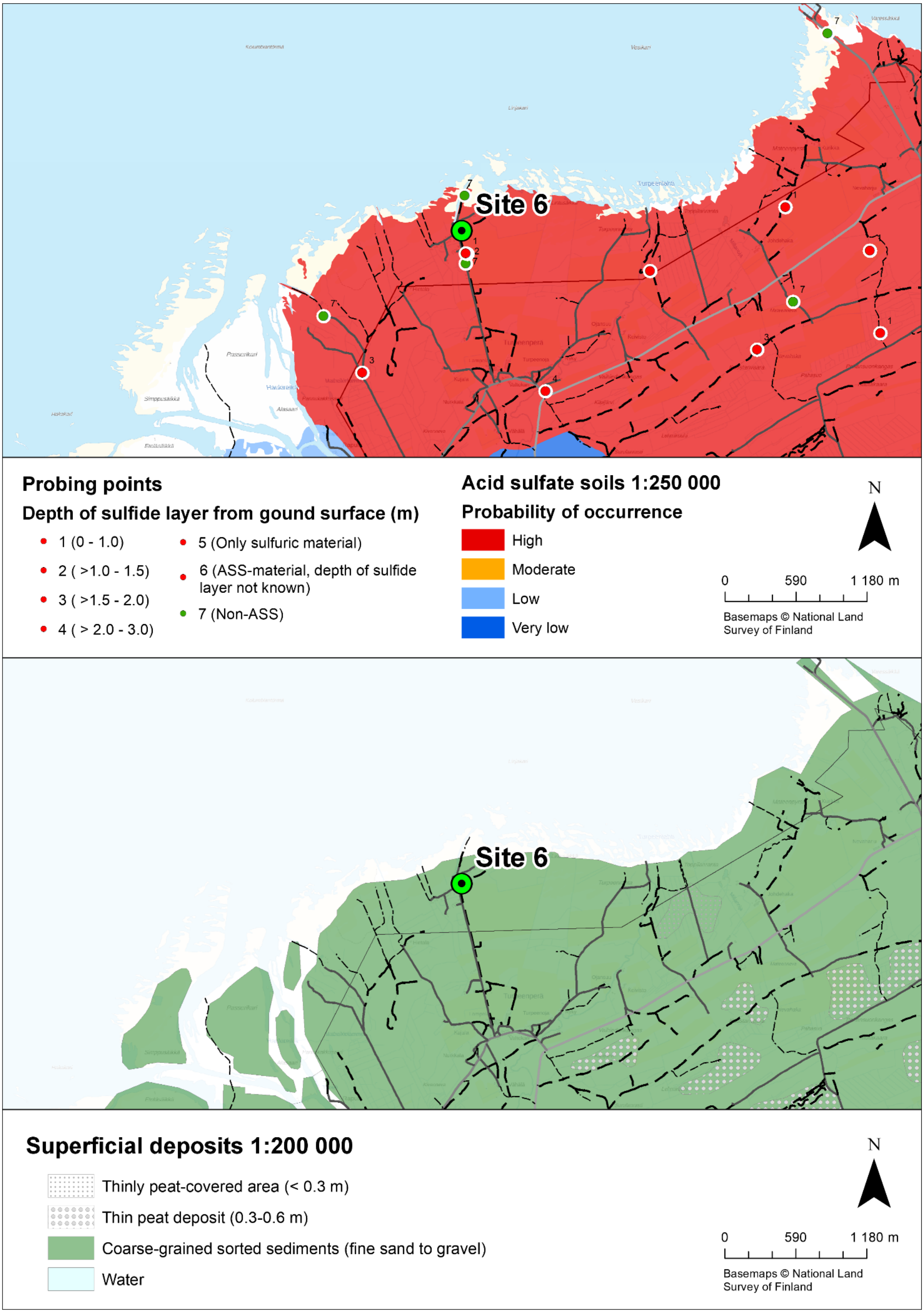

Figure 2. Occurrences of acid sulfate soils (ASS) and the distribution of superficial deposits in Turpeenperä. The probing points are derived from the national ASS mapping conducted by the Geological Survey of Finland (GTK).

In many places near the coast of the Bothnian Bay, and particulraly in this region, almost black, coarse-grained sulfide-rich soil layers are found. This can be observed in the soil coring conducted at the site. The surface layer consists of oxidised fine sand, coloured orange by iron precipitates. This material may partly be flood deposits brought by the river. Below the oxidation boundary, at about one metre depth, the fine sand quickly turns black, and the presence of sulfidic material can be detected not only by its colour but also by its smell. Acid sulfate soils (ASS) occur frequently in the area (Figure 2).

Soil description and analytical data

Sulfur speciation (AVS and CRS) conducted on samples collected in May 2025 revealed that the sulfide concentration was quite low, despite the black colour and noticeable smell (Table 1). The total sulfur (S) concentration was also low (Table 1; Figure 3). AVS was present in all analysed samples, but in concentrations below the detection limit, indicating strong pigmentation from iron monosulfides. It is also likely that some of the AVS oxidised during transportation to the laboratory and subsequent freezing, and thus ended up in the CRS pool. In any case, the main sulfide species was likely CRS, corresponding to the pyrite fraction.

Table 1. Field- and analytical data from the Turpeenperä profile. LOI = loss on ignition, AVS = acid volatile sulfides, CRS = Chromium reducible sulfur.

Depth	Soil type	Colour	pH		LOI	TIA, pH 6.5	AVS	CRS	Total S	ASS	Acidifying
Meter			Field	Incubation	%	mmol/kg	mg/kg	mg/kg	mg/kg	material	potential
0-0.4	Organic topsoil	Brown	6.1	5.8	1.1	0	<100	<100	225	Non-ASS	-
0.4-0.7	Sand	Orange-brown	6.4	5.6	0.4	0	<100	<100	53	Non-ASS	-
0.7-1.1	Sand	Orange-brown	6.5	5.8	0.2	0	<100	<100	51	Non-ASS	-
1.1-1.4	Sand/Fine sand	Black-gray	6.6	3.1	0.1	6	<100	223	216	Hypersulfidic	Small
1.4-1.7	Sand/Fine sand	Black-gray	6.6	3.2	0.2	7	<100	173	208	Hypersulfidic	Small
1.7-2.1	Sand/Fine sand	Black-gray	6.7	3.3	0.2	7	<100	301	198	Hypersulfidic	Small
2.1-2.5	Sand/Fine sand	Black-gray	7.2	3.1	0.2	6	<100	309	302	Hypersulfidic	Small

The generally low sulfide, and sulfur concentrations (Table 1; Figure 3), combined with the low incubation pH, show that the buffering capacity of coarse-grained materials is very poor (Table 1; Figure 3). This has been shown in several previous studies (e.g., Mattbäck et al., 2017; 2022). Correspondingly, the acidifying potential is small, and this type of ASS is not expected to have a long-lasting negative effect on the environment.

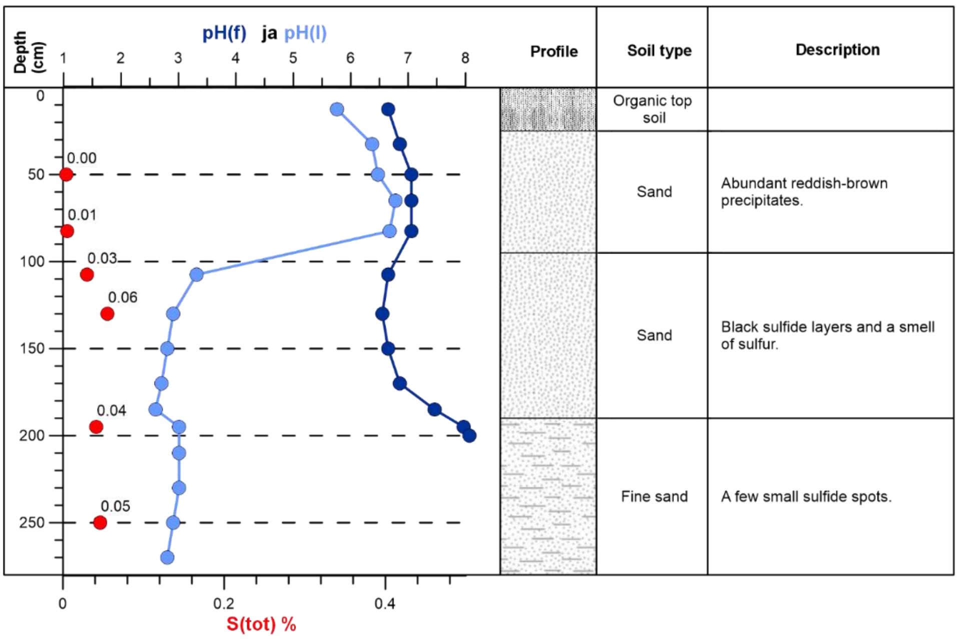

Figure 3. Field and incubation pH, and sulfur concentrations in a soil profiles (the red point beneath the site label in Figure 2) from Turpeenperä, collected in 2015 during GTK's mapping programme.

References

Mattbäck, S., Boman, A. & Österholm, P., 2017. Hydrogeochemical impact of coarse-grained post-glacial acid sulfate soil materials. Geoderma 308, 291–301. https://doi.org/10.1016/j.geoderma.2017.05.036

Mattbäck, S., Boman, A., Sandfält, A. & Österholm, P., 2022. Leaching of acid generating materials and elements from coarse- and fine-grained acid sulfate soil materials. Journal of Geochemical Exploration 232, 106880. https://doi.org/10.1016/j.gexplo.2021.106880

Site 7: Acidic sand pit lakes in Kokkola

Stefan Mattbäck, Anton Boman & Jaakko Auri

Location

Google maps: https://maps.app.goo.gl/6NQwf8g8rLAgQVAU6

Coordinates: 63°46'55.0"N 23°02'59.8"E

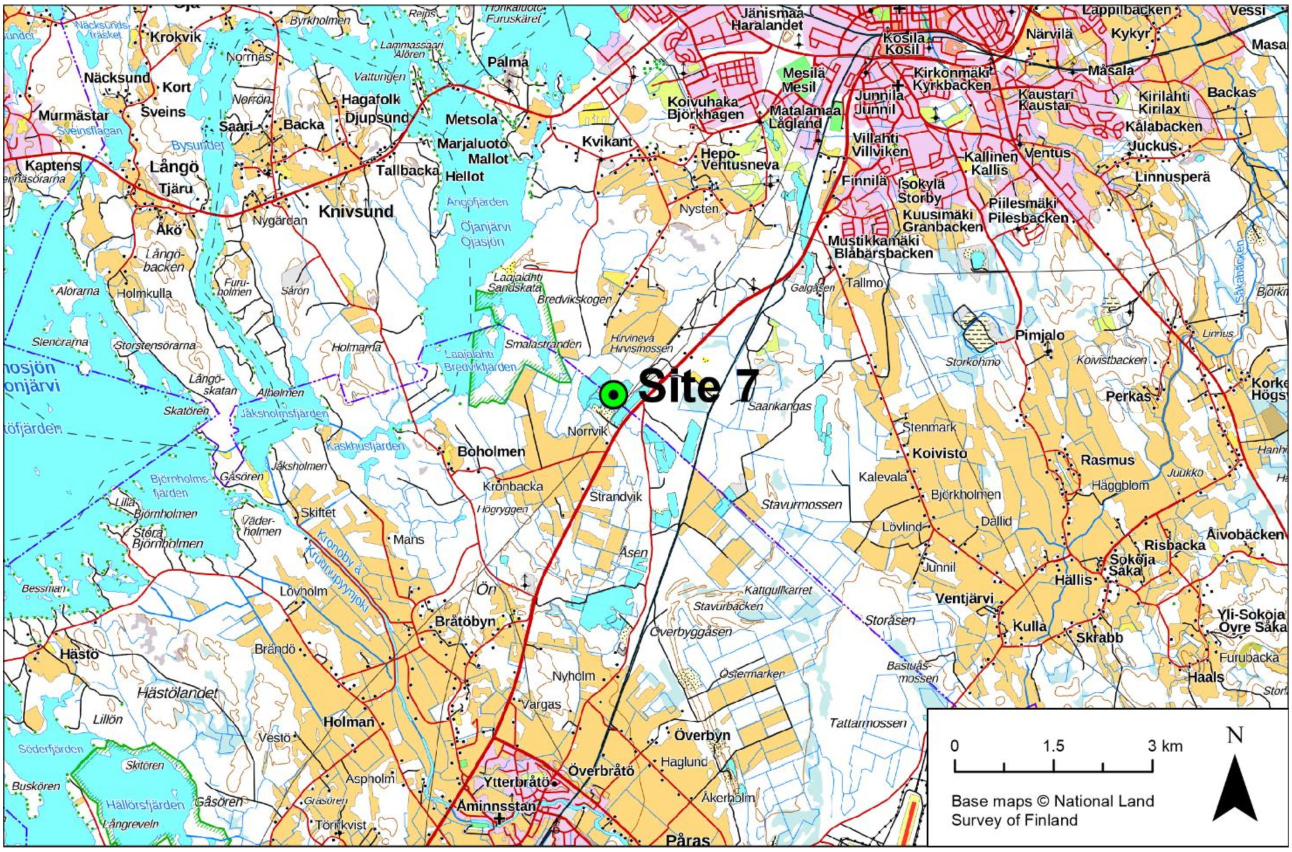

Figure 1. Location of acidic sand pit lakes in Kokkola (Site 7).

Purpose of the visit

At this site we will study acidic sand pit lakes that have formed in a sand and gravel extraction area in Kokkola. During the retreat of the ice sheets, long winding ridges known as eskers formed from deposits of sand, gravel, and boulders left behind by glacial meltwater. Today, these geological features serve dual purposes: they are vital groundwater reservoirs and a key source of construction materials, particularly sand and gravel. However, sand extraction has led to the formation of acidic sand pit lakes.

Background and site description

Our excursion site lies in an uplifted Holocene terrain near Larsmo-Öja Lake, south of the city of Kokkola in midwestern Finland. The landscape is dominated by alluvial sandy deposits and a prominent glaciofluvial esker (Figure 2), which serves as a crucial drinking water source for Kokkola. The nearby lands are actively used for sand extraction, forestry, and agriculture. The ares is also known for ASS-related issues, including recurring acidity and metal contamination in nearby water bodies (Figure 2). Acid sulfate soils are abundant in the region, but the actual site is located in an area with a low probability of ASS occurrence (Figure 2). This is because coarse-grained soil materials were largely excluded in the early stages of the national ASS mapping by the Geological Survey of Finland (GTK).

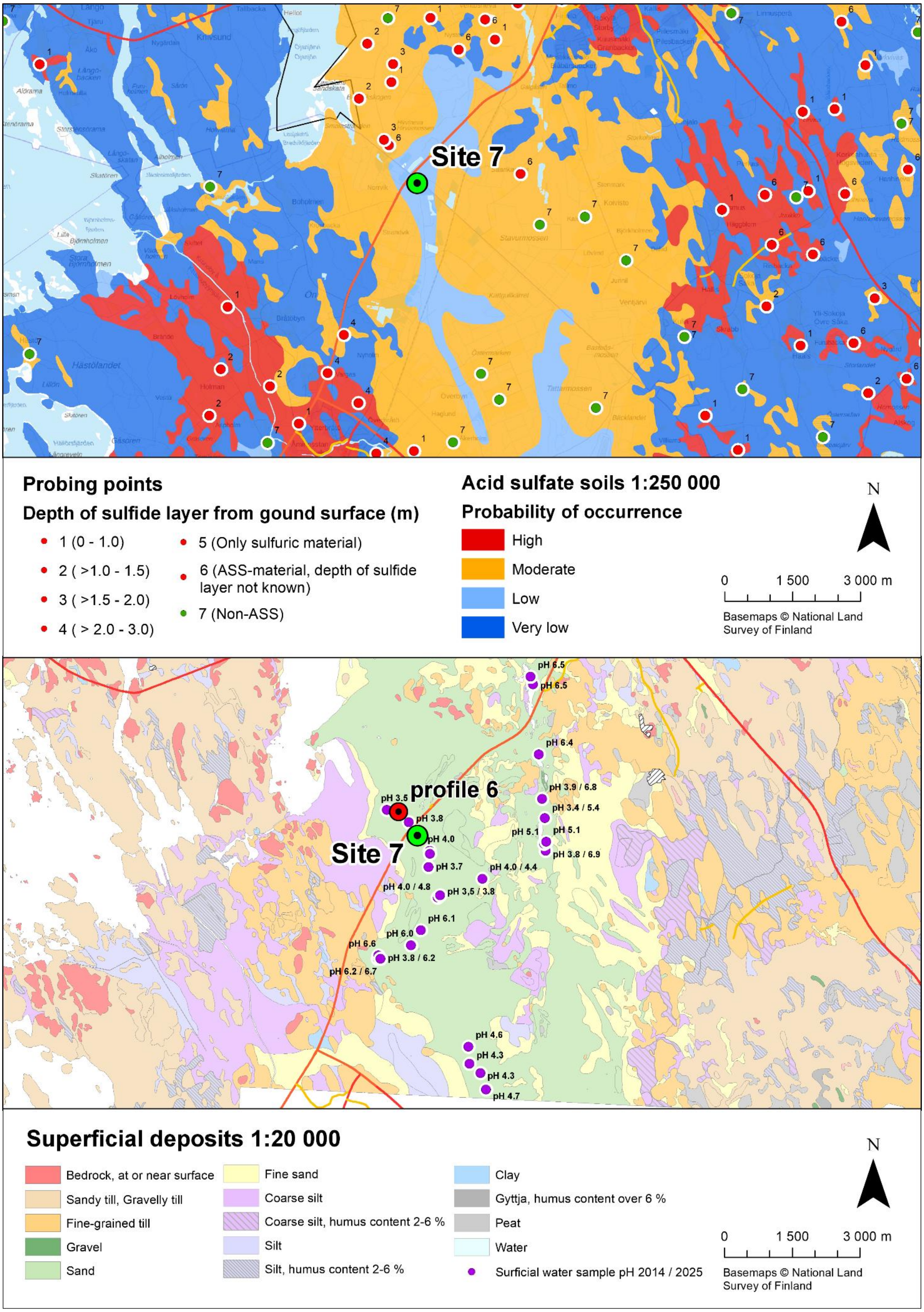

Figure 2. Occurrences of acid sulfate soils (ASS) and the distribution of superficial deposits in Kokkola. The probing points are derived from the national ASS mapping conducted by the Geological Survey of Finland (GTK). Surficial water samples, collected during 2014 and 2025, from ditches and sand pit lakes are marked with a purple point. Profile 6 is the location of a 10 m soil profile studied by Mattbäck et al. (2017).

Acidified sand pit lakes are common in this area (Figures 2 and 3) and are believed to result from the oxidation of coarse-grained ASS materials with low sulfide content. Interestingly, these soils release less acid and metals into the environment compared to their fine-grained counterparts, with the exception of iron, which is leached in significant quantities (Figure 4).

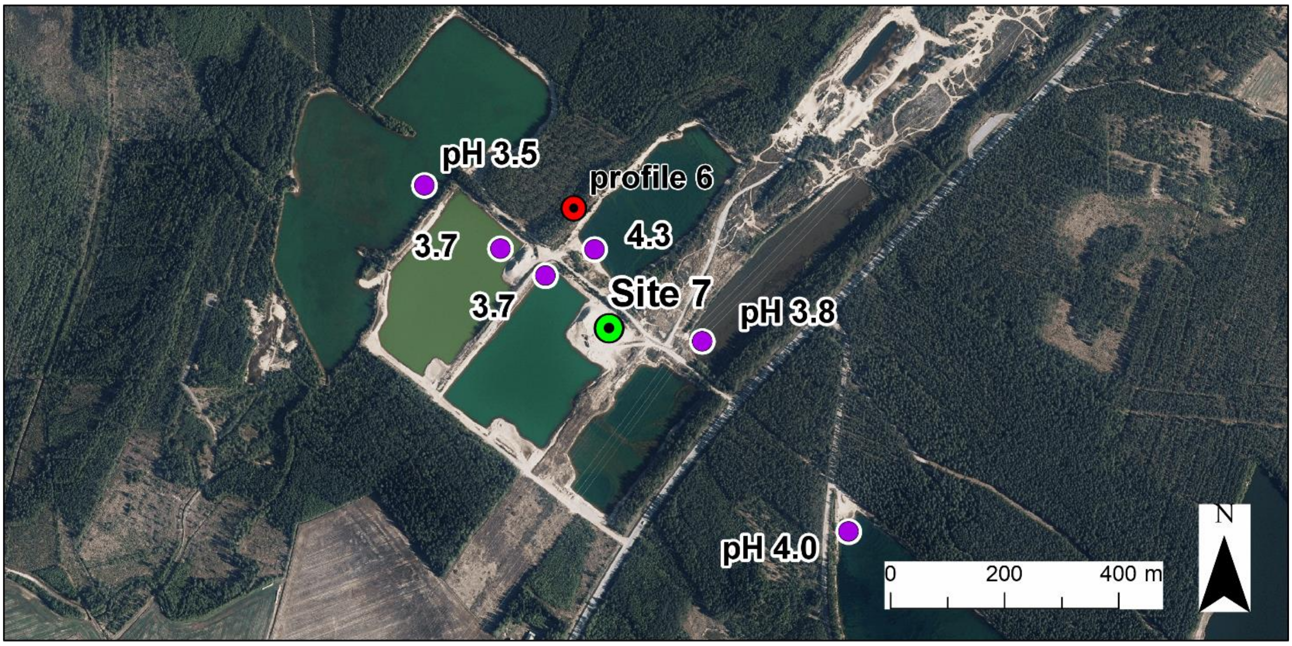

Figure 3. pH measurements from 2025 in the acidic sand pit lakes near site 7. See also Figure 2 for an overview of pH measurements conducted in the area in 2014 and 2025.

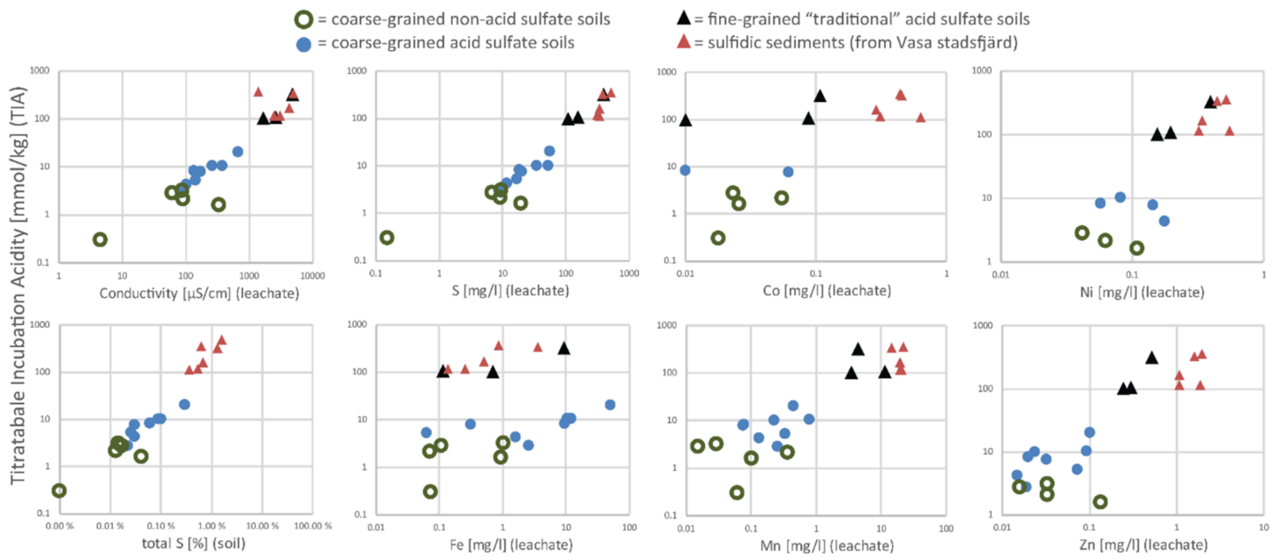

Figure 4. Several types of acid sulfate soil (ASS) materials were leached (ratio 1:10) with de-ionized water after a 16-week oxidation (incubation) period. The leachates were analyzed for acidity, electrical conductivity and several elements by ICP-OES (from Mattbäck et al., 2022).

The sulfides responsible for the acidity may have originated from pyrite-bearing black schists, or they could have formed *in situ* in littoral environments. The latter is the more probable cause, since sulfides from black schists would likely have eroded and possibly oxidized during the littoral stage. In shallow coastal zones, wave action erodes fine materials and redistributes them across the sea bottom and beach areas. These are ideal conditions for sulfidization. Due to rapid shoreline changes caused by wave erosion and post-glacial rebound (land uplift), *in situ* formed iron sulfides are likely mixed with sandy materials or buried beneath layers of sand. This dynamic landscape complicates the understanding of sulfide distribution and its environmental impact.

Recent studies have shown that the leaching of elements such as aluminum, cobalt, copper, lithium, nickel, zinc etc. from coarse-grained acid sulfate soils (ASS) is 1–2 orders of magnitude lower than from fine-grained ASS (Figures 4 and 5; e.g., Mattbäck et al., 2022). These levels are only slightly higher than those from non-ASS. Iron is the only metal leached in comparable or greater amounts from coarse-grained soils than from fine-grained ones. Due to their lower sulfur content, coarse-grained ASS pose less environmental risk in terms of acid generation and metal mobilization (Figure 5), but may be of a big concern locally.

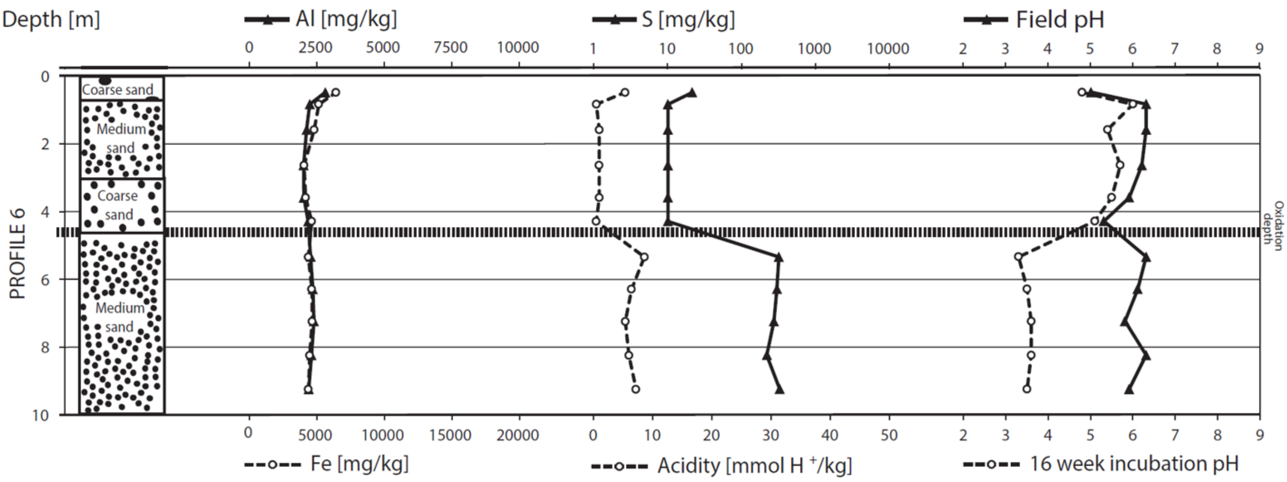

Figure 5. A typical coarse-grained soil profile with an oxidation depth deeper than 4m (Profile 6 in Figures 2 and 3). From Mattbäck et al., 2017).

References

Mattbäck, S., Boman, A., Sandfält, A. & Österholm, P., 2022. Leaching of acid generating materials and elements from coarse- and fine-grained acid sulfate soil materials. Journal of Geochemical Exploration 232, 106880. https://doi.org/10.1016/j.gexplo.2021.106880

Mattbäck, S., Boman, A. & Österholm, P., 2017. Hydrogeochemical impact of coarse-grained post-glacial acid sulfate soil materials. Geoderma 308, 291–301. https://doi.org/10.1016/j.geoderma.2017.05.036

Site 8: Sand and gravel extraction area containing sulfuric and hypersulfidic material

Anton Boman, Jaakko Auri & Stefan Mattbäck

Location

Google maps: https://maps.app.goo.gl/5V9MPr4qrWsoNYaEA

Coordinates: 63°34'57.9"N 22°34'24.5"E

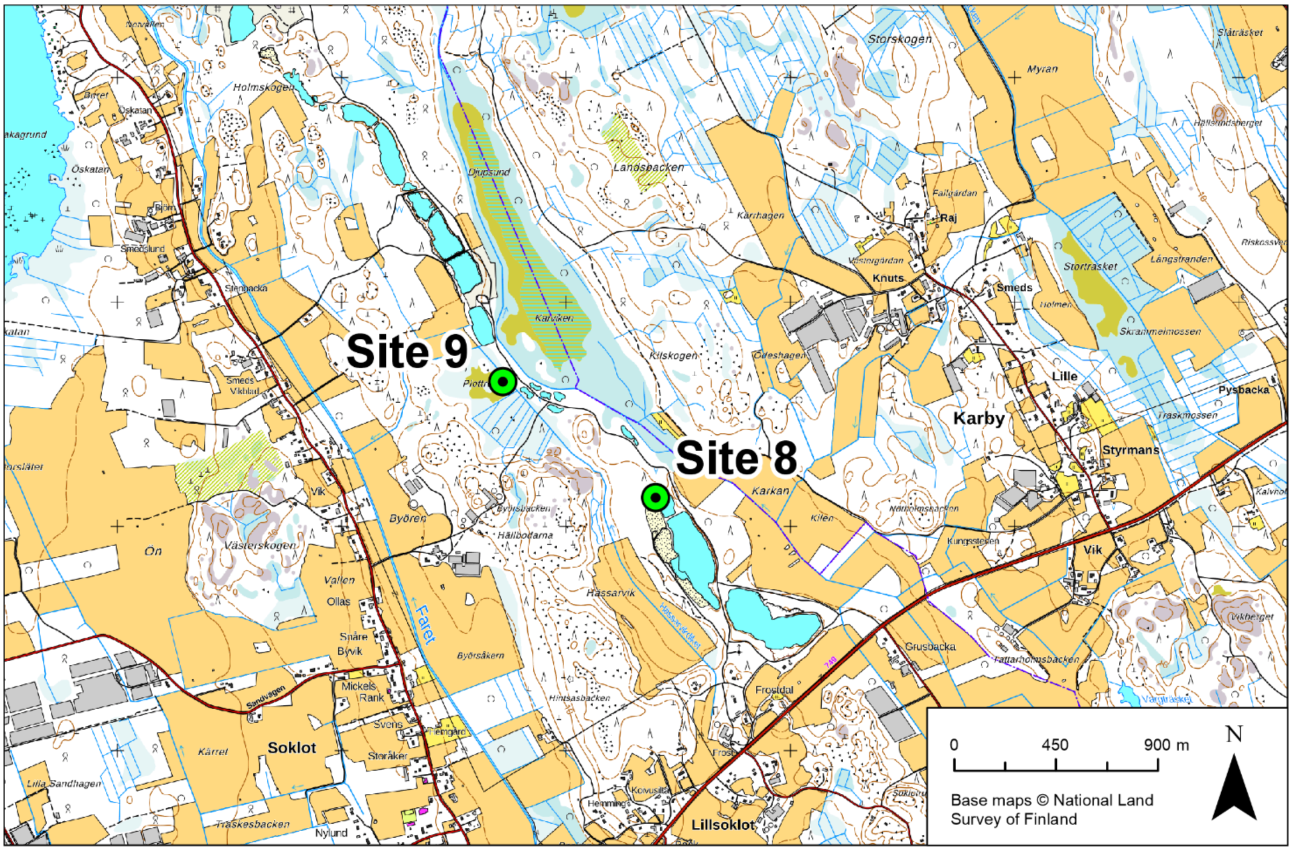

Figure 1. Location of the sand and gravel extraction area (Site 8) and the sulfuric wetland at Plottret (Site 9), located approximately 1 km apart.

Purpose of the visit

At the sand and gravel extraction site, hypersulfidic materials are present in both coarse- and fine-grained littoral deposits. These materials are occasionally disturbed during extraction activities, which leads to their transition into sulfuric material. We will examine this in an exposed section at the edge of the sand and gravel extraction area and in the surrounding area. We will also discuss the importance of having different risk assessment classes for different types of ASS materials

Background and site description

The sand and gravel extraction area is located in Socklot, between the towns of Jakobstad and Nykarleby (Figure 1). The site has been in active use for the past 10–15 years. This area, comprising Sites 8 and 9, serves as a pilot area in the MASSIW project, funded by Interreg Aurora. The aim of the study site within this project is to investigate the suitability of various geophysical methods for mapping acid sulfate soil (ASS) properties, such as differences in grain size. For this purpose, a soil profile was obtained in June 2025 from littoral sand deposits in close proximity to the sand and gravel extraction area (Figure 2).

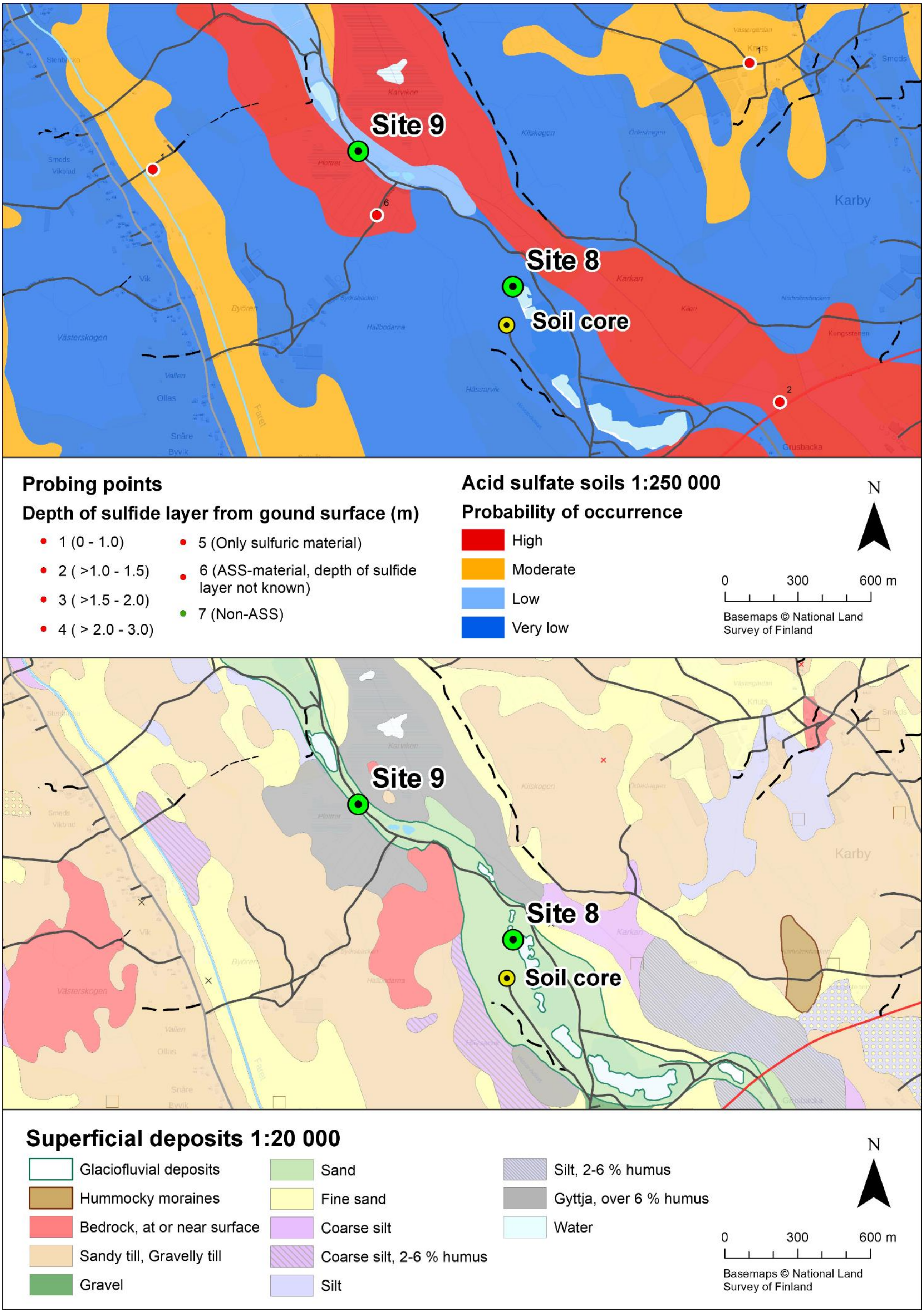

Figure 2. Occurrences of acid sulfate soils (ASS) and the distribution of superficial deposits in Socklot. The probing points are derived from the national ASS mapping conducted by the Geological Survey of Finland (GTK).

The site lies within an esker zone, where glaciofluvial deposits are accompanied by littoral and beach sediments (Figure 2). Wave action has smoothed the original shapes of the eskers, resulting in relatively flat terrain. Beneath the beach sands, fine-grained sediments deposited in deeper water environments can be found in some places. Acid sulfate soils are present in the region (Figure 2), but this type of area was excluded from the national ASS mapping conducted by GTK. As a result, the occurrence map is not up to date and shows a very low probability (blue colour) of ASS occurrence at the site. During excavation, hypersulfidic materials (sand and clay; Table 1) have been exposed, leading to the formation of sulfuric materials (Figure 3).

Figure 3. A cross-section at the edge of the sand and gravel extraction area showing conditions on 2 June 2025. Oxidized sand (rust-brown colour transitioning into pale-yellow colours) overlies dark-coloured hypersulfidic clay. Jarosite precipitates are clearly visible in a nearly 1-meter-thick layer above the clay. Photo: Anton Boman, GTK.

Soil description and analytical data

A soil profile (Figure 4) was obtained from the littoral sand deposits located a few tens of meters northwest of the sand and gravel extraction area (Figure 2). A description of the profile, along with data on pH (field and incubation), titratable incubation acidity (TIA), loss on ignition (LOI), and sulfur content (AVS and CRS for selected samples, and total sulfur for all samples), is presented in Table 1. The vertical distribution of sulfur and pH is illustrated in Figure 5. The uppermost 2.6 meters of the profile consisted of sand stained with iron precipitates. The sand colour is orange-brown in the oxidized section (down to approximately 1.6 meters), transitioning to gray below that depth. A gradual change from sand to fine sand occurs between 2.6 and 2.8 meters, followed by coarse silt from approximately 2.8 to 3.4 meters. From about 3.4 meters to the bottom of the profile at 4 meters, clay is present. The clay is dark gray and has a sulfur smell, indicating the presence of sulfidic material. The presence of sulfides was confirmed through sulfur speciation. Pyrite (CRS) was the dominant sulfide fraction in the reduced material, while metastable iron sulfides (AVS) were detected in only one sample (Table 1). Total sulfur increased gradually from the surface, where very low concentrations indicate leaching, down to the bottom of the collected profile (at 4 m depth), where concentrations exceeded 1% (Table 1).

It is worth noting that although hypersulfidic materials are present in both the coarse-grained and fine-grained fractions, and the incubation pH values are similar, the amount of acidity formed during incubation (TIA) is significantly higher in the finer material (Table 1). However, since the acidifying potential is based on soil type (Visuri et al., 2021), both materials are classified as having medium acidifying potential.

Figure 4. A 4 m deep soil profile collected in June 2025. The transition into reduced hypersulfidic material at approximately 1.6 m is quite noticeable. Photo: Anton Boman, GTK.

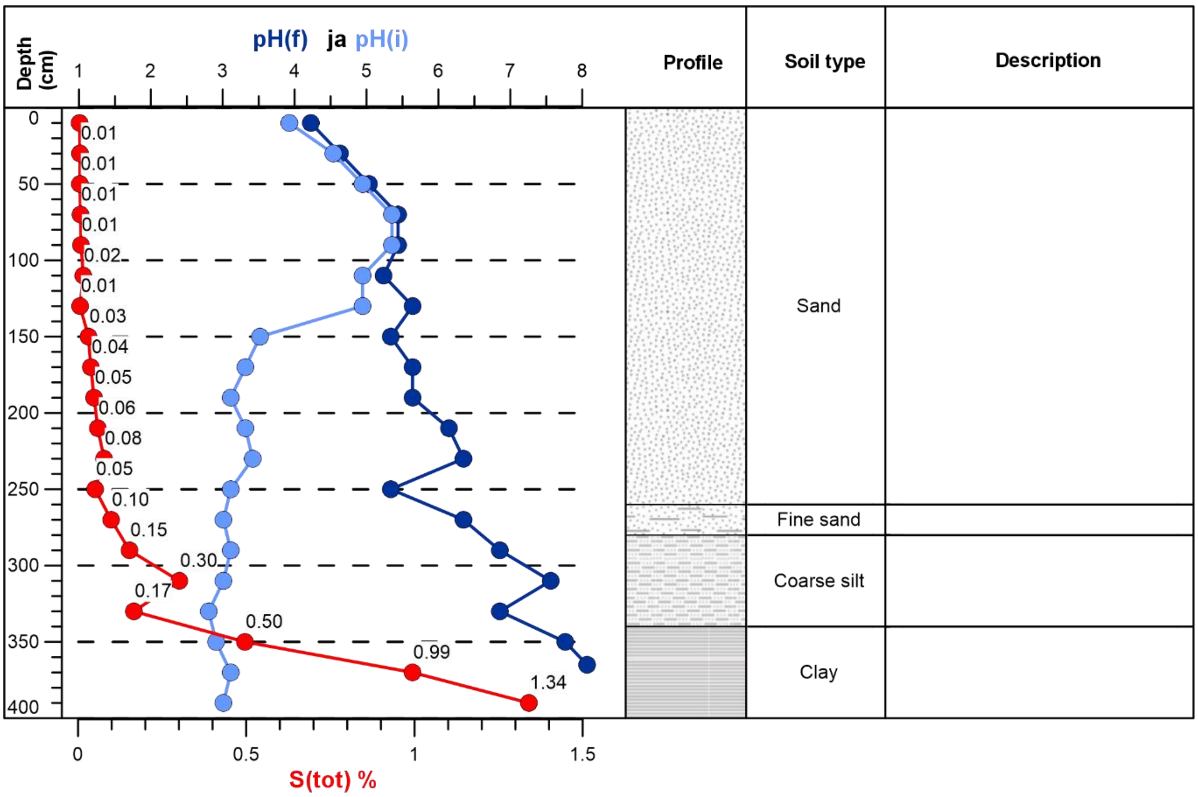

Figure 5. Field pH (f), incubation pH (i), and total sulfur (S) from a 4-meter-deep soil profile collected from the sand and gravel extraction area in Socklot in June 2025. The location of the soil profile is found in Figure 2.

Table 1. Field- and analytical data from the soil profile obtained at the sand and gravel extraction area in Socklot.

Depth	Soil type	Colour	pH		LOI	TIA, pH 6.5	AVS	CRS	Total S	ASS	Acidifying
Meter			Field	Incubation	%	mmol/kg	mg/kg	mg/kg	mg/kg	material	potential
0-0.2	Sand	Orange-brown	4.2	3.9	2.3	20			47	Non-ASS	-
0.2-0.4	Sand	Orange-brown	4.6	4.5	0.9	13			58	Non-ASS	-
0.4-0.6	Sand	Orange-brown	5	4.9	0.7	9			55	Non-ASS	-
0.6-0.8	Sand	Orange-brown	5.4	5.3	0.5	5			72	Non-ASS	-
0.8-1	Sand	Orange-brown	5.4	5.3	0.7	8			88	Non-ASS	-
1-1.2	Sand	Orange-brown	5.2	4.9	1.1	10			156	Non-ASS	-
1.2-1.4	Sand	Orange-brown	5.6	4.9	0.5	5			61	Non-ASS	-
1.4-1.6	Sand	Orange-brown	5.3	3.5	0.6	15	0	330	311	Hypersulfidic	Medium
1.6-1.8	Sand	Gray	5.6	3.3	0.5	16			380	Hypersulfidic	Medium
1.8-2	Sand	Gray	5.6	3.1	0.5	15			476	Hypersulfidic	Medium
2-2.2	Sand	Gray	6.1	3.3	0.5	14	0	619	589	Hypersulfidic	Medium
2.2-2.4	Sand	Gray	6.3	3.4	0.6	14			773	Hypersulfidic	Medium
2.4-2.6	Sand	Gray	5.3	3.1	0.5	16			509	Hypersulfidic	Medium
2.6-2.8	Fine sand	Gray	6.3	3	0.6	28	0	1091	985	Hypersulfidic	Medium
2.8-3	Coarse silt	Gray	6.8	3.1	0.7	22	0	1481	1530	Hypersulfidic	Medium
3-3.2	Coarse silt	Gray	7.5	3	0.8	24	0	2918	3010	Hypersulfidic	Medium
3.2-3.4	Coarse silt	Gray	6.8	2.8	0.5	27			1660	Hypersulfidic	Medium
3.4-3.6	Clay	Gray	7.7	2.9	1.2	52	0	3787	4960	Hypersulfidic	Medium
3.6-3.8	Clay	Dark gray	8.1	3.1	5.3	92	119	9364	9940	Hypersulfidic	Medium
3.8-4	Clay	Dark gray	8.1	3	5.3	83	0	7345	13400	Hypersulfidic	Medium

References

Visuri, M., Nystrand, M., Auri, J., Österholm, P., Niilivaara, R., Boman, A., Räisänen, J., Mattbäck, S., Korhonen, A. & Ihme, R., 2021. Maastokäyttöisten tunnistusmenetelmien kehittäminen happamille sulfaattimaille. Technical report 43. Finnish Environmental Institute, 111 p. https://helda.helsinki.fi/bitstreams/6b35df04-aac1-41c1-a259-bc42cfbe7258/download

Site 9: The sulfuric wetland at Plottret

Anton Boman, Jaakko Auri & Stefan Mattbäck

Location

Google maps: https://maps.app.goo.gl/BTXD7TPKjdRyPjqi9

Coordinates: 63°35'12.9"N 22°33'33.0"E

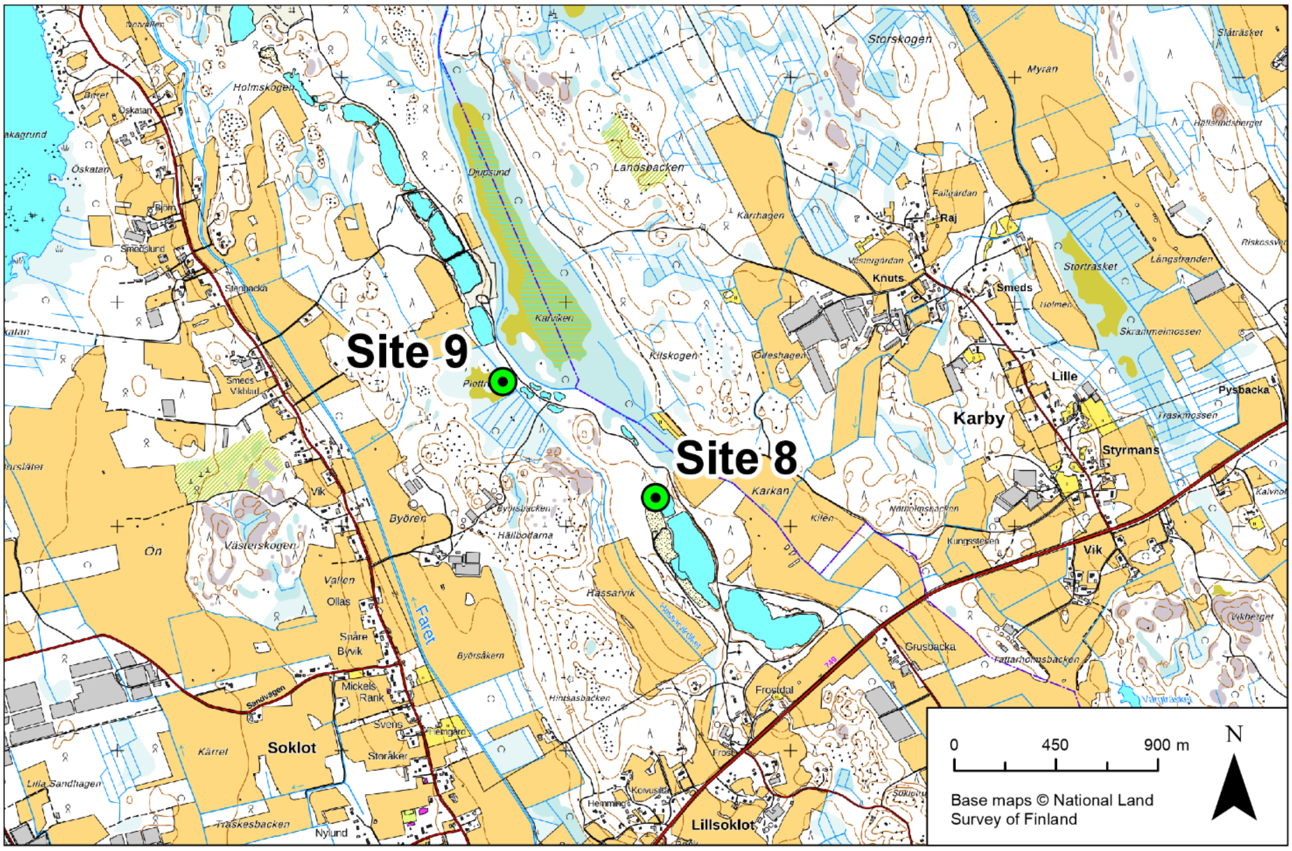

Figure 1. Location of Plottret (site 9). Location of the sulfuric wetland at Plottret (Site 9) and the sand and gravel extraction area (Site 8), located approximately 1 km apart.

Purpose of the visit

This site is a unique feature in Finland, and no other similar location is currently known. We will discuss how the sulfuric wetland developed and how this type of environment affects forestry. Furthermore, we will study the presence of iron and sulfate precipitates, which are abundant at the surface.

Background and site description

The study site, Plottret, is located in the small village of Socklot, Ostrobothnia, western Finland (Figure 1). The name “Plottret” comes from the local Swedish dialect and refers to an area that is very muddy and difficult to traverse. There is limited documentation on the development of the sulfuric wetland at Plottret, and this description is based on interpretations of local historical narratives and old maps. In the 1950s, Plottret was a glo lake located near Karviken (Figures 1 and 2), which at the time was a freshwater lake. Plottret and Karviken were once part of a bay connected to the nearby sea, but due to postglacial land uplift, both areas gradually became cut off from the sea. During the 1960s, Karviken was drained to reclaim new land. This likely also affected the nearby Plottret by lowering the water table and exposing hypersulfidic sediments to the elements. This presumably led to oxidation of hypersulfidic materials and the formation of a sulfuric wetland. Under normal conditions, a peat layer would most likely gradually have developed on top of the hypersulfidic sediments, thus preventing oxidation.

However, due to the lowered water table and prolonged exposure to oxygen, peat formation was likely inhibited. Instead, the oxidation of sulfides led to the accumulation of sulfuric compounds and the development of a sulfuric wetland.

The area is surrounded by shallow ditches which, however, are very ineffective at transporting away the formed acidity, thereby promoting the build-up of extremely acidic conditions (pH 3). Signs in the area indicate that cattle were once present, most likely for grazing. Currently, wildlife such as moose and deer frequently visits the area. Pugging caused by the cattle and wildlife has likely further contributed to the acidification process (Figure 3). Cattle-induced sulfide oxidation has also been reported in similar settings on Norfolk Island, Australia (Fitzpatrick et al., 2023). The extremely acidic and wet conditions have inhibited forest development in the area, as clearly seen in aerial photos (Figure 2).

Figure 2. Aerial photo of Plottret. Karviken is located in the upper right corner of the image.

Figure 3. Iron and sulfate precipitates (orange-brown-yellow colours) at the surface of Plottret. Pugging from moose is clearly visible at the site. Photo: Anton Boman, GTK.

Soil description and analytical data

From the study site, one profile down to 300 cm was obtained using a D-section peat corer. pH was measured every 10 cm in the field by inserting the electrode (Hamilton Flatrode) directly into the fresh sediment (Table 1). The entire soil profile is very fine-grained (mainly clay) and gyttja-containing (2–20% organic matter, determined as loss on ignition; LOI) throughout (except for the sandy layer at 120–127 cm containing 1.1% organic matter). The uppermost 10 cm is technically defined as gyttja due to having >20% organic matter (Boman et al., 2023). The brownish-coloured oxidised horizon in the upper 70 cm is characterized by low pH and the presence of jarosite and possibly schwertmannite. The presence of jarosite has been confirmed by XRD analysis, while the presence of other Fe/SO_4 minerals remains to be verified. Between 70–120 cm, the sediment colour is black, indicating the presence of metastable iron sulfides (Figure 4). This was also confirmed by sulfur speciation (Table 1). At 120–127 cm, a sandy layer is present, indicating an erosional event. Below this depth and down to 300 cm, the sediment colour is gray, with streaks of black bands.

Figure 4. Black monosulfidic material at 70-100 cm depth. Photo: Anton Boman, GTK.

The soil is extremely acidic, with a pH of 2.9–3.0 in the uppermost 20 cm (Table 1; Figure 5), and is oxidised to about 80 cm depth, where the pH gradually increases with depth. A thin transition zone between the oxidised and reduced materials is present between 70–80 cm (pH 4.4). Below this depth, pH gradually increases from 6 to over 8 at around 300 cm. For the reduced samples, incubation pH was low, ranging between 2.3–3.1, indicating. hypersulfidic material.

The organic matter content, determined as loss on ignition (LOI), was highest in the uppermost 20 cm (LOI >20%) and remained between 5.7–10.2% down to 300 cm (end of the collected profile), except for a thin section at 110–130 cm, where LOI was lower (1.1–2.0%) due to the presence of a sandy layer (120–127 cm) (Table 1).

Titratable actual acidity (TAA) was determined on oxidised samples (0–70 cm), while titratable incubation acidity (TIA) was determined on the reduced samples (70–300 cm), following the procedures described in Mattbäck et al. (2022). Both TAA (93–141 mmol H+/kg) and TIA (77–268 mmol H+/kg) were generally high, except in the sandy layer, where TIA was lower (26–28 mmol H+/kg) (Table 1; Figure 5).

All collected samples were also analyzed for total sulfur (S) and 30 elements using aqua regia extraction followed by ICP-MS. Data for total S, aluminum (Al), iron (Fe), and nickel (Ni) are presented in Figure 5. Iron concentrations were generally high, with a maximum of nearly 18% in the top layer. Total S followed a similar pattern to Fe, with a maximum of just above 4% in the top layer (Table 1; Figure 5). Aluminum and nickel showed a similar trend, with concentrations increasing toward the transition zone (0.7–0.8 m), after which they decreased toward the sandy layer at 1.2–1.3 m. Below this depth, concentrations of both Al and Ni increased again toward the bottom of the collected profile. Total S and Fe also showed lower concentrations in the sandy layer.

Acid volatile sulfide (AVS) and chromium reducible sulfur (CRS) were analysed using a slightly modified procedure described in Dalhem et al. (2021). AVS was not present in the upper part of the oxidised horizon, but small concentrations (0.02%) were detected right above the transition zone. CRS was present in low concentrations throughout the oxidised horizon (around 0.02–0.03%) and increased considerably toward the transition zone (0.24%), matching the AVS concentration (0.24%). In general, AVS dominated over CRS in the black sediment, whereas CRS was dominant in the gray sediment. Sulfate was likely the dominant form of sulfur in the uppermost 0.6 m, as total S was present in much higher concentrations than AVS and CRS (Table 1).

Table 1. Field description and analytical data from the sulfuric wetland at Plottret. TIA = Titratable incubation acidity, LOI = loss on ignition, AVS = acid volatile sulfides, CRS = Chromium reducible sulfur, TRS = AVS + CRS, ASS = acid sulfate soil.

Depth	pH		Dry weight	TIA, pH6.5	LOI	AVS	CRS	TRS	Total S	ASS	Field description
cm	Field	Incubation	%	mmol H+/kg	%	mg/kg	mg/kg	mg/kg	mg/kg	material	
0-10	2.9	3.0	40.0	119	28.9	0	204	204	40700	Sulfuric	**0–50 cm:** Clay is the dominant mineral (possibly presence of gyttja). High content of organic matter in the upper 40 cm. Gyttja content throughout. Some coarser material mixed in the upper 40 cm. Jarosite occurrences mainly at 10 cm. Slight sulfide presence at 45 cm.
10-20	3	3.2	39.7	100	20.0				21700	Sulfuric	
20-30	3.1	3.1	47.5	134	14.0	0	<100	<100	8240	Sulfuric	
30-40	3.3	3.2	46.6	93	11.3				6190	Sulfuric	
40-50	3.1	3.2	50.7	103	8.9	0	302	302	4010	Sulfuric	
50-60	3.5	3.1	56.5	119	7.7				4910	Sulfuric	
60-70	3.5	3.4	54.0	141	8.1	160	3146	3306	4870	Sulfuric	
70-80	4.4	3.1	52.4	153	7.8	2838	2445	5283	7520	Sulfuric	**50–100 cm:** Gyttja-containing clay. The transition zone lies at 70–80 cm and is characterized by equal parts monosulfide and pyrite. Below 70 cm, the soil is black in color due to the presence of monosulfides. Possibly some sand grains at the bottom.
80-90	6	3.0	57.1	122	7.0				6800	Hypersulfidic	
90-100	5.8	2.9	56.7	95	7.1	4063	1594	5658	8260	Hypersulfidic	
100-110	6	3.0	54.7	80	6.9				7140	Hypersulfidic	
110-120	6.1	3.0	71.8	26	2.0	1106	1046	2151	2910	Hypersulfidic	
120-130	6.1	2.8	79.7	28	1.1				2620	Hypersulfidic	
130-140	6.3	2.6	62.0	77	6.1	<100	10919	10942	13300	Hypersulfidic	
140-150	6.3	2.8	59.5	89	6.2				9990	Hypersulfidic	**100–150 cm:** Gyttja-containing clay. Monosulfides are present down to approx. 120 cm (black colour). A sand layer is present between 120–127 cm. Possible transition to clay below. Black monosulfide bands and lower gyttja content.
150-160	6.4	2.8	59.2	92	6.6				13200	Hypersulfidic	
160-170	8.5	2.8	55.1	136	7.6				13000	Hypersulfidic	
170-180	6.8	2.8	51.9	148	9.2				13600	Hypersulfidic	
180-190	7.3	2.9	58.3	140	8.5				13800	Hypersulfidic	
190-200	7.5	2.7	58.8	244	9.2				12600	Hypersulfidic	
200-210	7.3	2.3	52.8	245	10.2				14500	Hypersulfidic	
210-220	7.5									Hypersulfidic	**150–200 cm:** Gyttja-containing clay with monosulfide bands.
220-230	7.6	2.5	52.2	267	8.8				20100	Hypersulfidic	
230-240	7.8									Hypersulfidic	**200–300 cm:** Gyttja -containing clay. Gray color down to 240 cm, followed by black monosulfide inclusions in the remaining section.
240-250	8.3	2.6	52.1	209	7.1				10600	Hypersulfidic	
250-260	8.3									Hypersulfidic	
260-270	8.2	2.7	50.6	268	8.8				13300	Hypersulfidic	
270-280	8.9									Hypersulfidic	**300–400 cm:** Gyttja-containing clay. Gray colour with black monosulfide inclusions. Harder bottom layer?
280-290	8.1	3.1	58.8	115	5.7				6540	Hypersulfidic	
290-300	7.8									Hypersulfidic	

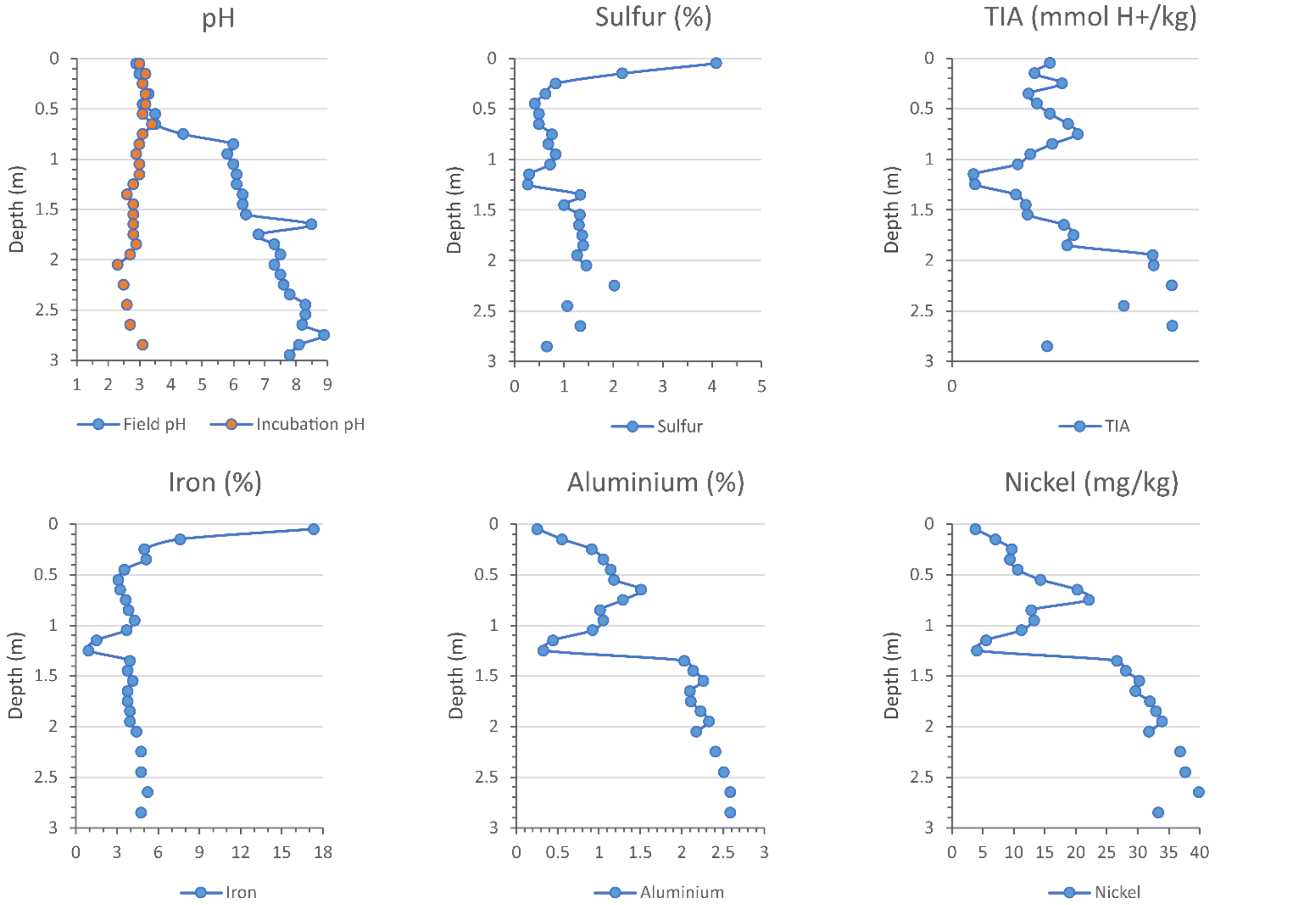

Figure 5. Vertical distribution of field and incubation pH, total sulfur (S), titratable incubation acidity (TIA), aluminium (Al), iron (Fe), and nickel (Ni).

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Site 10: Vassorfjärden Bay – Land uplift and future sulfuric and hypersulfidic soils

Anton Boman & Jaakko Auri

Location

Google maps: https://maps.app.goo.gl/uXgnKXwFcT6B5jHw5

Coordinates: 63°09'27.4"N 21°59'54.6"E

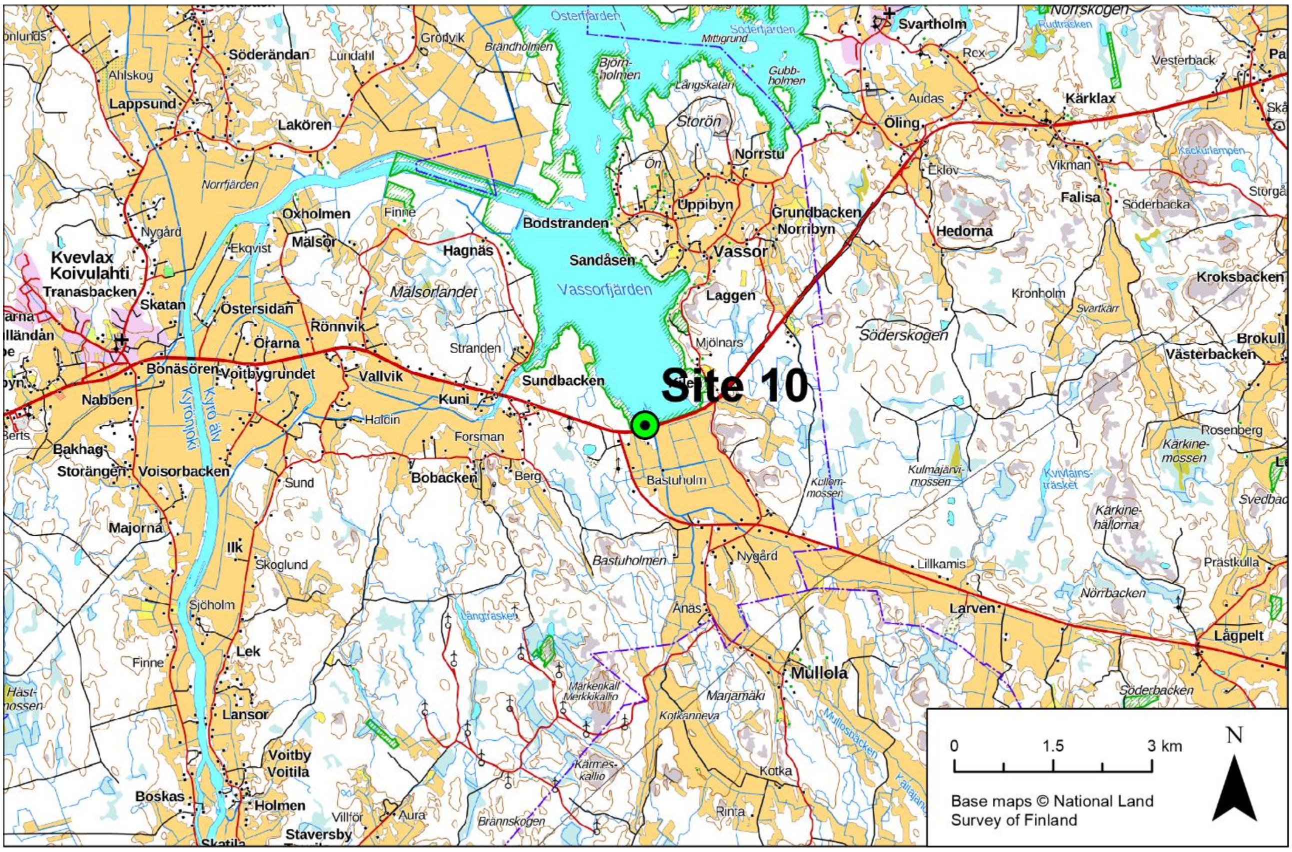

Figure 1. Location of Vassorfjärden Bay (Site 10).

Purpose of the visit

At this site, we will learn about land uplift and how this ongoing geological process gradually brings subaqueous acid sulfate soils (ASS) closer to the surface. Several stages of ASS development can be observed here, from subaqueous hypersulfidic soils, through hypersulfidic soils where an organic topsoil helps minimise sulfide oxidation, to the formation of sulfuric soils resulting from anthropogenic drainage aimed at reclaiming farmland.

Background and site description

Vassorfjärden Bay (Figure 1) is located approximately 30 km northeast of Vaasa and is part of the delta of the river Kyrönjoki, which flows into the Gulf of Bothnia. A large part of the area surrounding Vassorfjärden Bay is underlain by ASS, which typically occur in low-lying regions dominated by fine-grained superficial deposits, often containing gyttja (Figure 2). In this area, postglacial land uplift is very pronounced, and sulfidic sediments are continuously being brought above the current sea level. Between 1953 and 1966, approximately 1.5 km^2 of the inner Vassorfjärden Bay, with water depths up to around 80 cm, was converted into farmland by embankment (Figure 3). Since then, the area has been efficiently drained using a pumping station and ditches up to 2 meters deep. The sediments in the area have a characteristic black colour (Figure 4) caused by metastable iron sulfides (Boman et al., 2008).

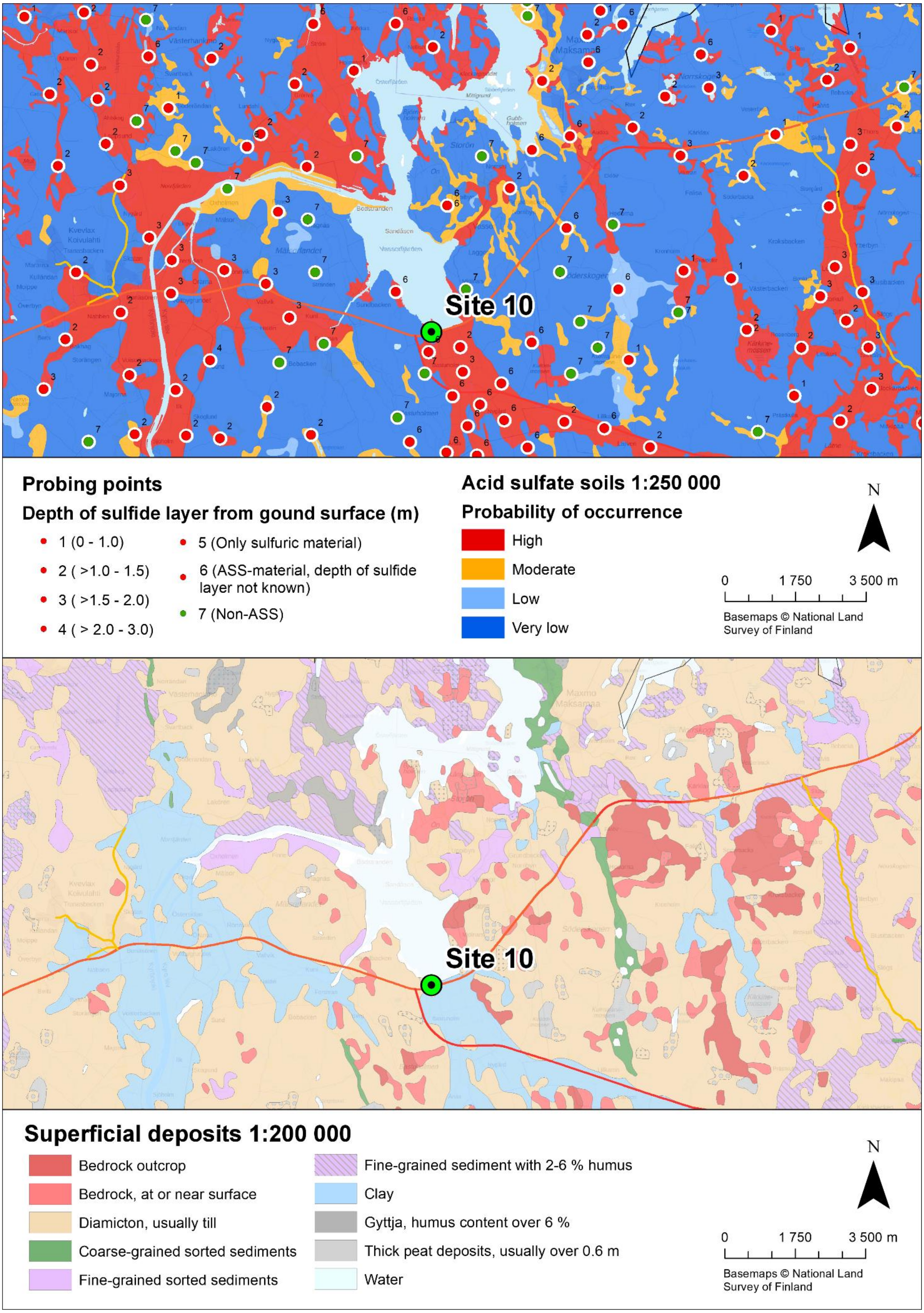

Figure 2. Occurrences of acid sulfate soils (ASS) and the distribution of superficial deposits in the surroundings of Vassorfjärden Bay. The probing points are derived from the national ASS mapping conducted by the Geological Survey of Finland (GTK).

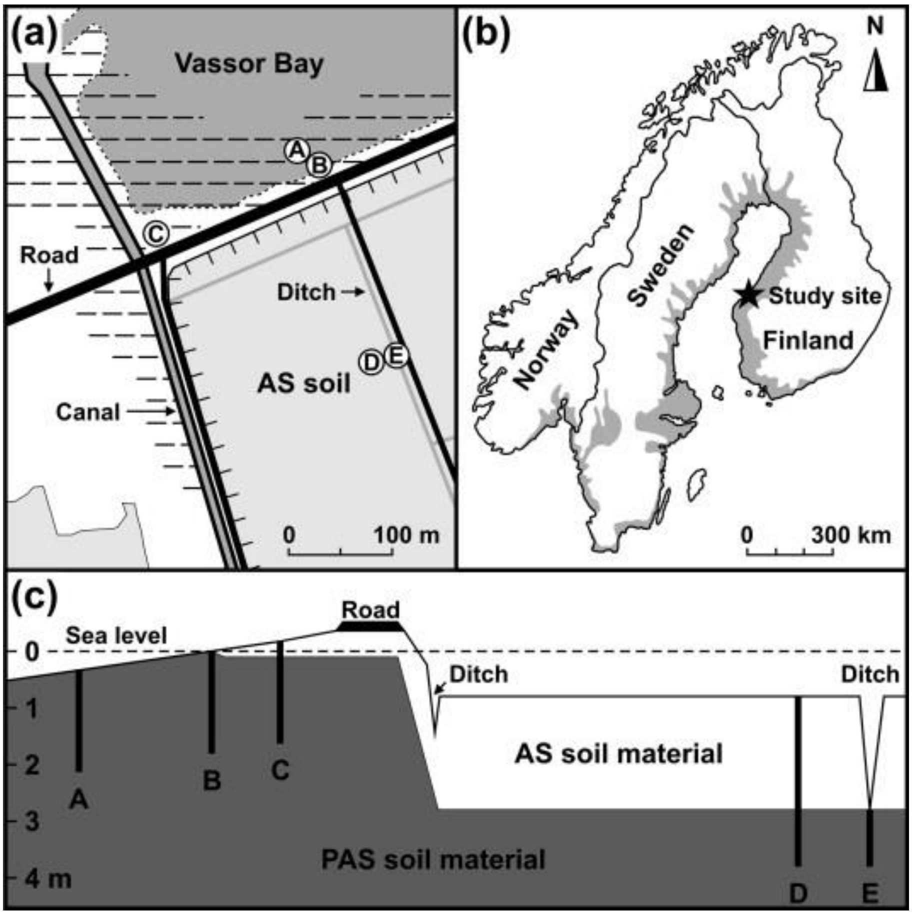

Figure 3. Vassorfjärden Bay showing the embanked area. Sites A–E show the locations of previously collected soil/sediment profiles in the study by Boman et al. (2010) and include **(A)** subaqueous hypersulfidic sediment, **(B)** shoreline hypersulfidic sediment, **(C)** peat covered sediment, **(D)** drained sediment (sulfuric soil), and **(E)** drain bottom sediment (hypersulfidic material). PAS soil material = hypersulfidic material; AS soil material = sulfuric material. From Boman et al. (2010).

Figure 4. Del Fanning sniffing at black monohypersulfidic material at Vassorfjärden Bay during the 7th International Acid Sulfate Soils Conference 2012. Photo: Peter Edén (retired from GTK).

Sulfur dynamics and impact of land uplift and anthropogenic drainage

The sulfur dynamics at the site, along a transect from subaqueous sediments to agricultural land (Figure 3), including the impact of land uplift and anthropogenic drainage, were studied by Boman et al. (2010). Field descriptions, stratigraphy, and data on sulfur speciation for five collected soil profiles are presented in Figures 5 and 6, respectively. The study by Boman et al. (2010) demonstrated, among other findings, that land uplift does not contribute to the formation of sulfuric soils. Furthermore, once hypersulfidic soils are drained and converted into farmland, the leaching of acids and metals increases significantly.

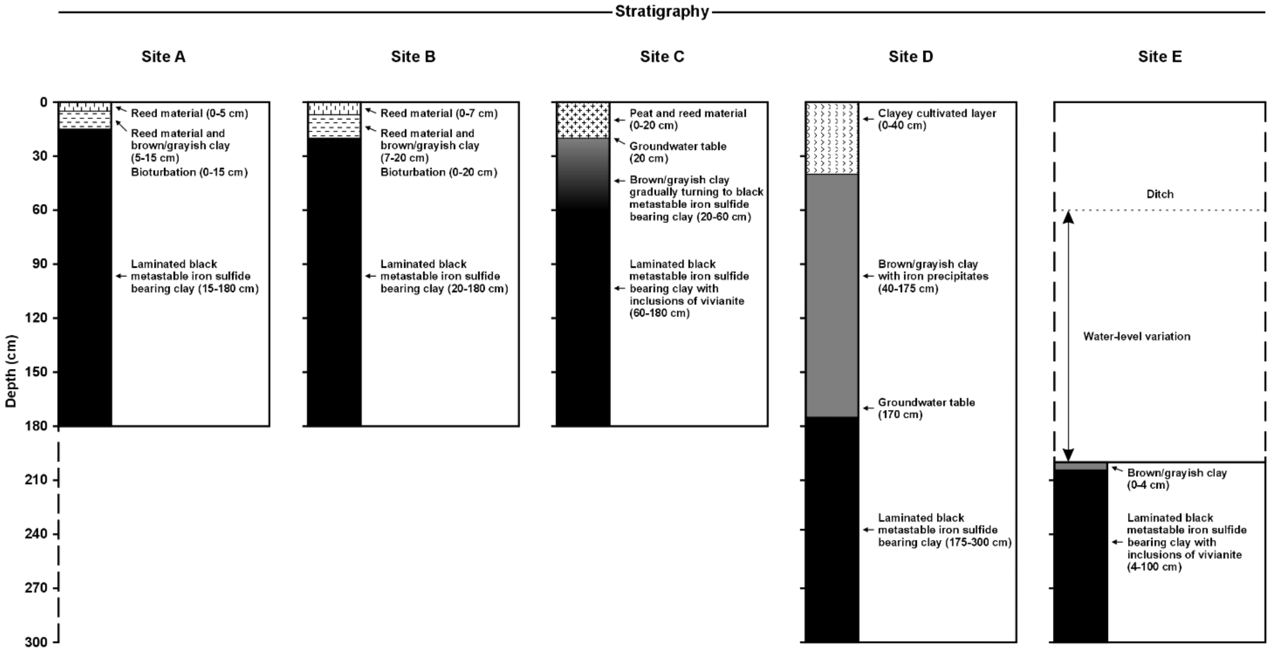

Figure 5. Field observations and stratigraphy at Vassorfjärden Bay. **(A)** subaqueous hypersulfidic sediment, **(B)** shoreline hypersulfidic sediment, **(C)** peat covered sediment, **(D)** drained sediment (sulfuric soil), and **(E)** drain bottom sediment (hypersulfidic material) adjacent to site D. From Boman et al. (2010).

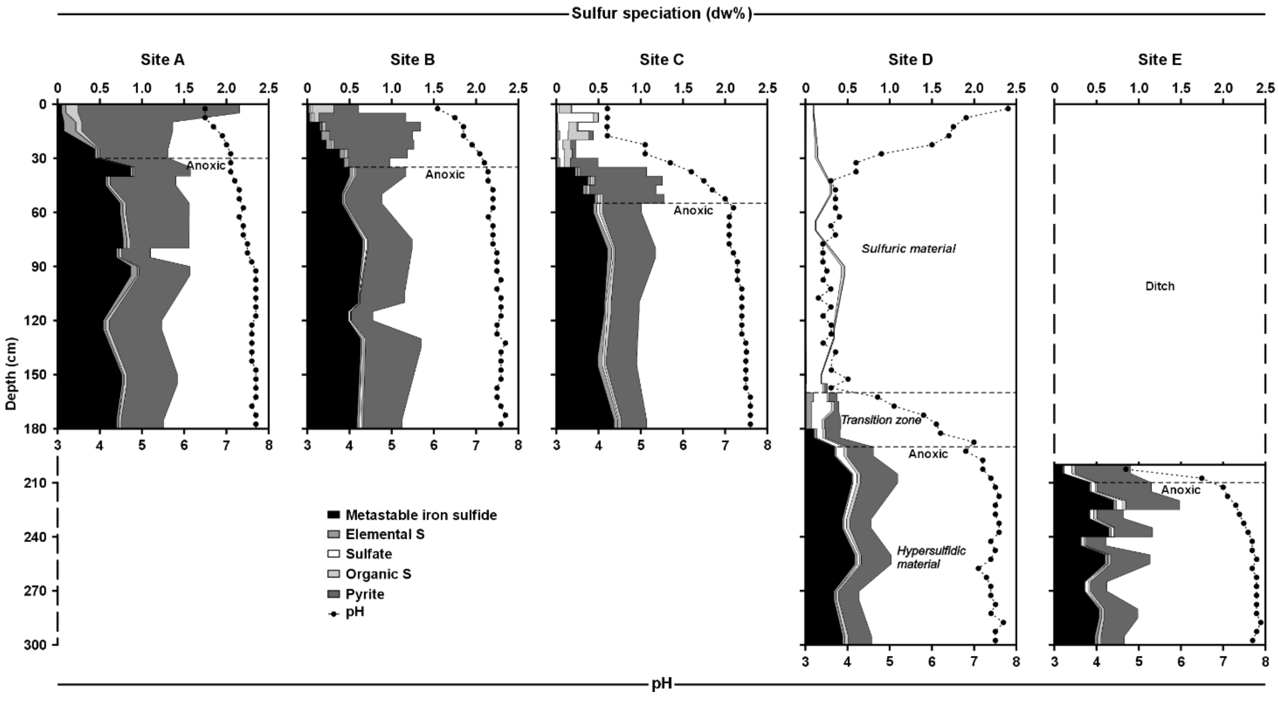

Figure 6. pH and sulfur speciation at Vassorfjärden Bay. **(A)** subaqueous hypersulfidic sediment, **(B)** shoreline hypersulfidic sediment, **(C)** peat covered sediment, **(D)** drained sediment (sulfuric soil), and **(E)** drain bottom sediment (hypersulfidic material) adjacent to site D. Modified from Boman et al. (2010).

Development of future sulfuric and hypersulfidic soils

Due to ongoing land uplift and sedimentation, Heikkilä (1999) estimated that the entire Vassorfjärden Bay would be filled by 2030, thereby exposing the hypersulfidic bottom sediments to the elements and creating new areas for agricultural land and other types of settlements. However, this prediction does not appear to be fulfilled. It is clear, though, that land uplift has brought hypersulfidic sediments closer to the sea surface over the past 20–30 years. It is very likely that within the next 50 years, the entire Vassorfjärden Bay, visible in the center of Figure 1, will be above sea level. If left undisturbed, these former subaqueous hypersulfidic soils will transition into hypersulfidic soils and pose no environmental threat. However, if the bottom sediments are drained and no measures are taken to prevent oxidation, sulfuric soils will form and continue to release acid and metals into the surrounding soil and water courses.

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Site 11: Management of acid sulfate soils in the Söderfjärden area

Miriam Nystrand, Sten Engblom, Eva Högfors-Rönnholm, Anton Boman, Jaakko Auri &
Peter Österholm

Location

Google maps: https://maps.app.goo.gl/CJ5Hjv7Tk2r5yrUZ8

Coordinates: 63°00'30.2"N 21°34'03.1"E

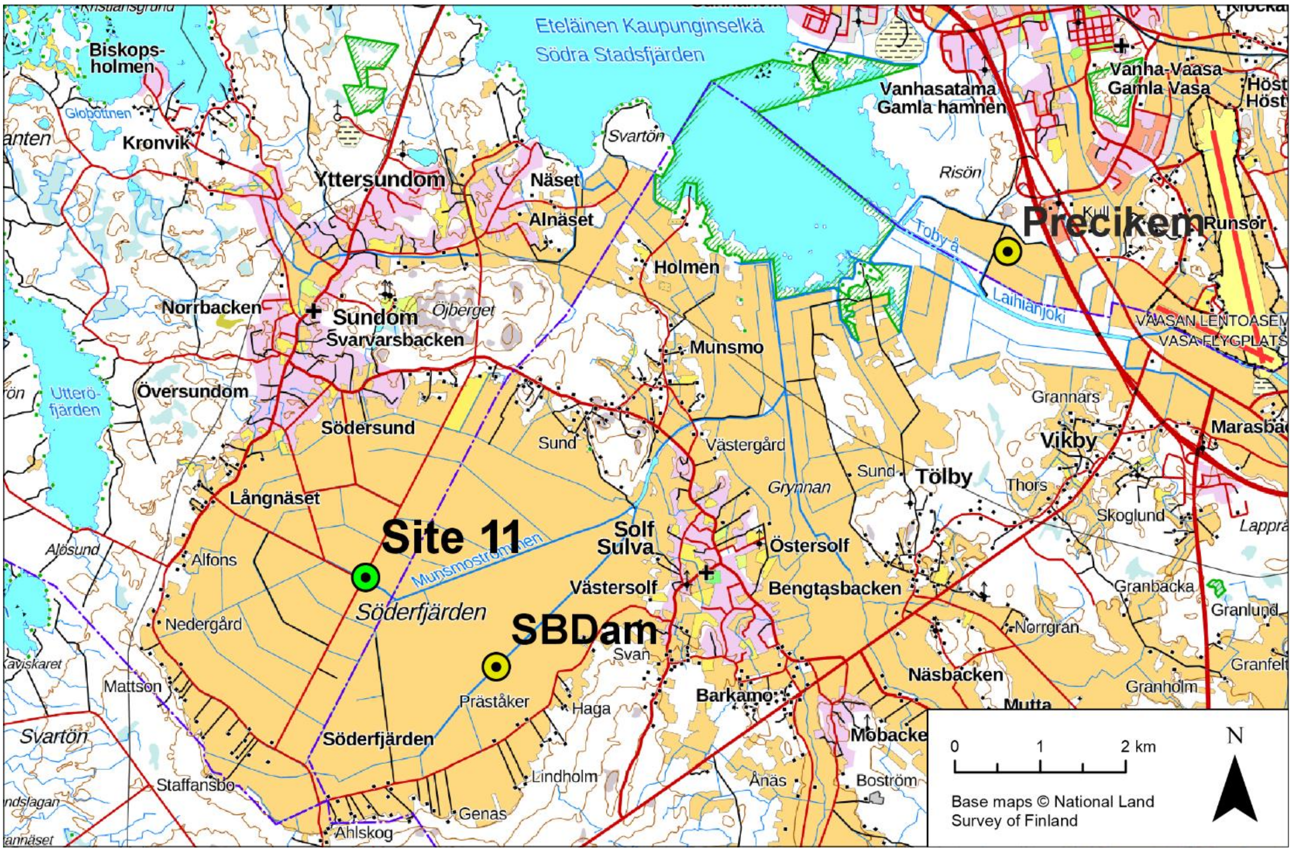

Figure 1. Location of Söderfjärden (Site 11), SBDam, and the PRECIKEM test site.

Purpose of the visit

At these sites, we will learn about water management to reduce sulfide oxidation and to promote the neutralization and immobilization of metals in hydrologically active macropores in farmland acid sulfate soils (ASS).

Background and description of the area

The impact crater in Söderfjärden is located in an low-lying area with abundant acid sulfate soil (ASS) occurrences, where the superficial deposits are predominantly fine-grained, consisting of clay and silt (Figure 2). A large part of the ASS in Finland, particularly in this area, is in agricultural use. These soils are very fertile once the plough layer has been limed. Liming of the plough layer does however not improve the pH of the soil layer below (see Figure 3) and is therefore not improving the quality of the drainage water. The challenge is to mitigate the environmental damage caused by the acidic and metal-rich drainage water, while allowing normal agricultural activities to be maintained.

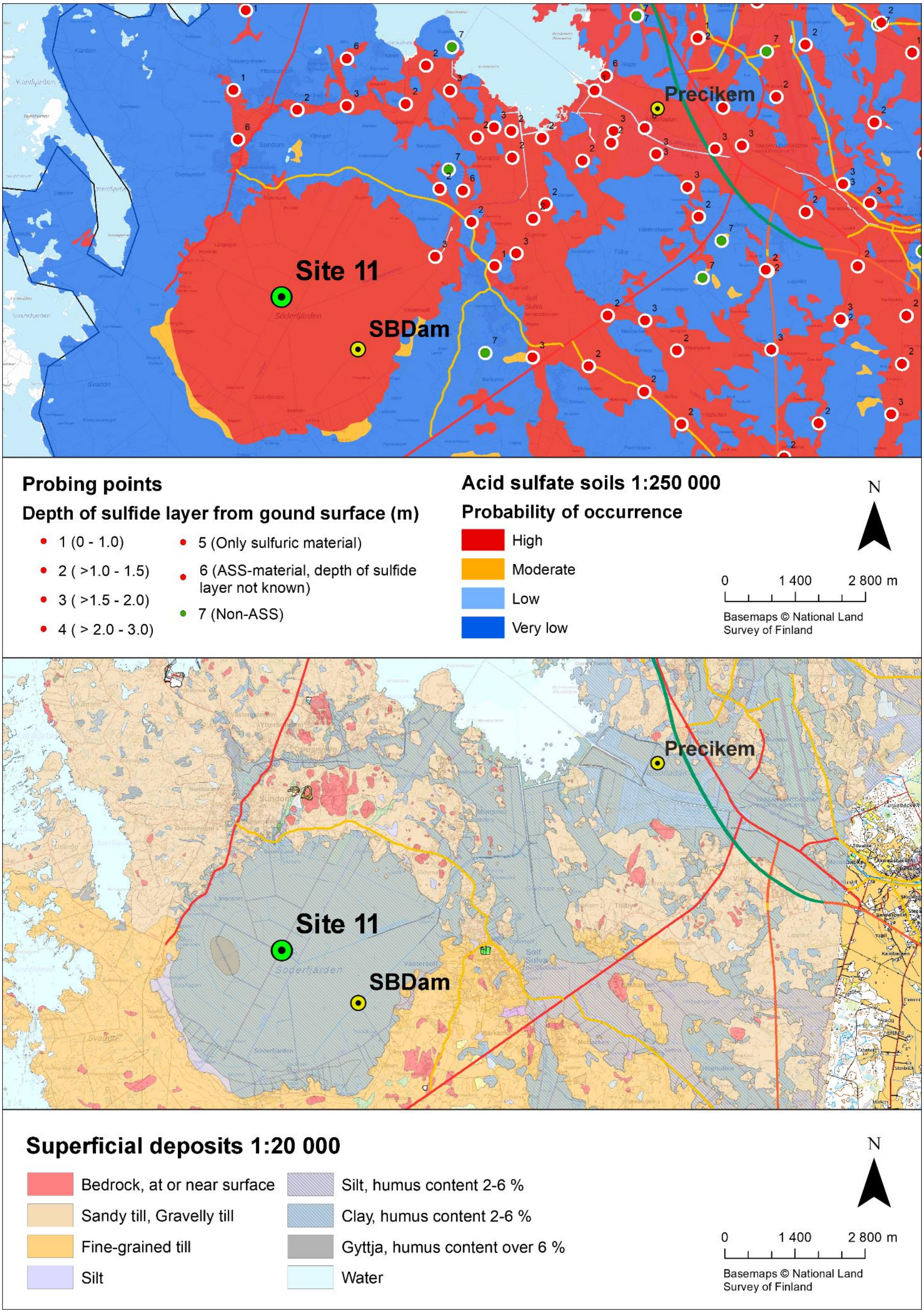

Figure 2. Occurrences of acid sulfate soils (ASS) and the distribution of superficial deposits in Söderfjärden and its surroundings. The probing points are derived from the national ASS mapping conducted by the Geological Survey of Finland (GTK).

To find and evaluate new mitigation methods, research groups were formed with members from among others Novia UAS, Vaasa UAS, Åbo Akademi University, Ely centre, GTK, and the Vocational College of Ostrobothnia from Finland, and Linnaeus University, SGU, and County administrative boards from Sweden. The group worked for more than 10 years in several projects, e.g., PRECIKEM projects (https://precikem.eu/en/home.html), and projects conducting various trials on agricultural fields in Söderfjärden, e.g., CATERMASS, VIMLA (https://vimlavatten.org/), and KLIVA (https://kliva.org/). The evaluation of the mitigation methods in Söderfjärden is now continuing within the MASSIW project (https://www.interregaurora.eu/approved-projects/massiw/) funded by Interreg Aurora (EU), Västerbotten County Council, the Swedish Agency for Marine and Water Management, and the Regional Council of Lapland.

Söderfjärden

The experimental agricultural boreal (18-hectare) field is located in western Finland (Figure 1) 6 km from the coastline (63°00'00.4"N 21°36'07.1"E) in the Söderfjärden meteorite crater (2,300 ha). This area consists of Holocene sulfide-bearing marine sediments about 2 m above the current sea level. In 1926, a large drainage ditch and pumping station were constructed to convert the area into arable land. Subsurface drainage pipes were added in the 1950s, and through reclamation and extensive surface liming, Söderfjärden has become one of Finland's most productive and valuable agricultural regions (Österholm et al., 2015).

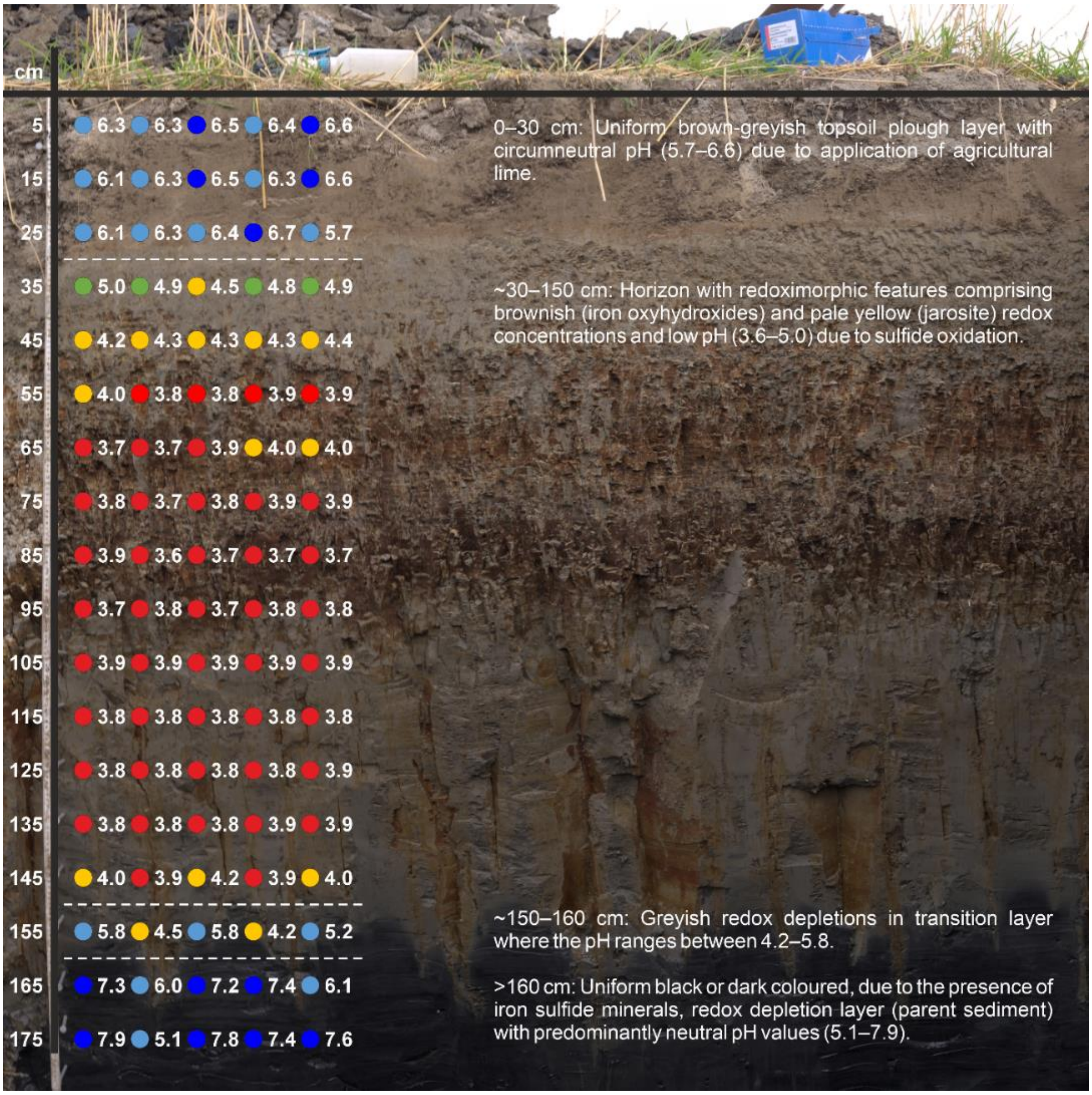

Figure 3. A "pH wall" and soil description from a soil pit excavated in 2018. The location is near the SBDam (see Figure 1). From Boman et al. (2023). Photo: Krister Dalhem.

The soil profile at the site is typical for ASS (Table 1 and Figure 3); the upper horizons (to a depth 1.5 m) have angular blocky aggregates with permanent shrinking cracks, allowing significant bypass flow of water. Sulfide oxidation is visible to a depth of 1.5 m (i.e., visible brown iron hydroxide and yellow jarosite coatings) with total sulfur concentrations ranging from 0.2-0.4%. Below a depth of 1.5 m the soil has a massive structure, with no rust mottles, and contains black sulfidic material inherent from the parent sediment (Yli-Halla et al., 2020) containing higher sulfur concentration (0.8%) (Österholm et al., 2015). The sulfides in the parent sediment materials contain nearly equal amounts of reactive metastable iron sulfides (mackinawite and greigite) and pyrite (Boman et al., 2008). According to Soil Taxonomy (Soil Survey Staff, 2014), the soil belongs to Sulfidic Cryaquepts and to Thionic Gleysols (drainic, humic, loamic/siltic) according to the WRB system (IUSS Working Group WRD, 2015).

Table 1. Field measurements and analytical data from a profile of a sulfuric soil at Söderfjärden located near the SBDam (see Figure 1). The soil profile was collected in 2021. LOI = loss on ignition, TIA = Titratable incubation acidity, AVS = acid volatile sulfides, CRS = Chromium reducible sulfur, TRS = AVS + CRS, ASS = acid sulfate soil.

Depth	Soil type	Colour	pH		LOI	TIA, pH 6.5	AVS	CRS	TRS	ASS	Acidifying
Meter			Field	Incubation	%	mmol/kg	mg/kg	mg/kg	mg/kg	material	potential
0-0.1	Organic top soil	Brown	6.6	6.1	4.8	12	0.0	<100	198	Non-ASS	-
0.1-0.2	Organic top soil	Brown	7.2							Non-ASS	-
0.2-0.3	Organic top soil	Brown	6.2	4.8	4.2	38	0.0	202	252	Non-ASS	-
0.3-0.4	Silt	Gray-brown	5.0							Non-ASS	-
0.4-0.5	Silt	Gray-brown	5.2	4.0	4.3	100	0.0	287	351	Non-ASS	Medium
0.5-0.6	Silt	Gray-brown	3.8							Sulfuric	Medium
0.6-0.7	Silt	Gray-brown	3.9	3.9	4.5	90	0.0	329	390	Sulfuric	Medium
0.7-0.8	Silt	Gray-brown	4.0							Parasulfuric	Medium
0.8-0.9	Silt	Gray-brown	3.9	4.1	4.3	107	0.0	424	426	Sulfuric	Large
0.9-1.0	Silt	Gray-brown	3.8							Sulfuric	Large
1-1.1	Silt	Gray-brown	4.1	3.9	4.8	97	0.0	365	362	Parasulfuric	Medium
1.1-1.2	Silt	Gray-brown	4.1							Parasulfuric	Medium
1.2-1.3	Silt	Gray-brown	4.1	3.9	5.2	95	<100	594	647	Parasulfuric	Medium
1.3-1.4	Silt	Gray-brown	4.0							Parasulfuric	Medium
1.4-1.5	Silt	Gray-brown	4.1	3.2	5.2	121	351	3463	3814	Parasulfuric	Large
1.5-1.6	Silt	Black	5.7							Hypersulfidic	Large
1.6-1.7	Silt	Black	6.8	3.0	4.8	129	365	4225	4590	Hypersulfidic	Large
1.7-1.8	Silt	Black	7.8							Hypersulfidic	Large
1.8-1.9	Silt	Black	8.0	2.7	5.2	183	586	5767	6353	Hypersulfidic	Large
1.9-2.0	Silt	Black	8.1							Hypersulfidic	Large
2-2.1	Silt	Black	8.2	2.6	5.5	165	1025	5717	6742	Hypersulfidic	Large
2.1-2.2	Silt	Black	8.2							Hypersulfidic	Large
2.2-2.3	Silt	Black	8.1	2.8	5.2	128	1941	4179	6119	Hypersulfidic	Large
2.3-2.4	Silt	Black	8.1							Hypersulfidic	Large
2.4-2.5	Silt	Black	8.1	2.7	5.3	141	1279	4927	6206	Hypersulfidic	Large
2.5-2.6	Silt	Black	8.1							Hypersulfidic	Large
2.6-2.7	Silt	Black	8.0	2.8	5.0	122	1269	5555	6823	Hypersulfidic	Large
2.7-2.8	Silt	Black	8.0							Hypersulfidic	Large
2.8-2.9	Silt	Black	8.0	2.9	4.4	78	1289	5195	6484	Hypersulfidic	Medium
2.9-3.0	Silt	Black	8.1							Hypersulfidic	Medium

Between 2010 and 2020, the effects of controlled subsurface drainage (CD) and controlled drainage with subsurface irrigation (CDI) were monitored on the experimental fields in Söderfjärden. Each field was divided into three sections owing to a control well for the regulation of groundwater for the whole field. In the adjacent reference field (REF) no regulation was applied. All three fields were hydrologically isolated with vertical plastic sheets extending to the depth of 1.8 m to prevent bypass flow. In late summers 2014 and 2017 the farmers dredged the main drain and in May 2018, a small dam (SBDam; Figure 4; see location in Figure 1) was built in the main drain to regulate the water flow. This could have an impact on the groundwater level, e.g., stronger fluctuation of groundwater level, and therefore on the water quality.

Soil profiles were sampled on four occasions (2009, 2011, 2017, and 2021) from every field and analysed for changes. Groundwater levels were continuously logged in the lowest field sections, and water flow was monitored at drainage outlets. During runoff periods, discharge water was sampled for acidity, pH, concentrations of SO_4, PO_4, EC and several metals (e.g., Al, Cd, Fe, Ni, and Zn) were taken from discharge water fortnightly during the runoff periods.

In CD, and especially in CDI, a groundwater level drop into the sulfidic layer was slowed down or prevented during normal weather conditions (i.e., normal precipitation rates and temperatures) and without dredging (Österholm et al., 2015; Virtanen et al., 2016; Yli-Halla et al., 2020; Nystrand et al., 2024). In CDI, a severe groundwater drop was, moreover, prevented during prolonged dryer spells in spring/summer. During the 11-year period, the drainage water quality improved considerably, e.g., several metal concentrations were halved in all fields, including the reference field with conventional subsurface drainage. The improvement may be due to changed water flow path caused by the isolating plastic sheets and/or a depletion of the acid soluble metal reserve after an extreme drought in 2006. While the differences between treatments were generally minor after two prolonged summer dry spells, the acidity and metal release increased in REF, whereas the impact of the drought was less pronounced in CD and nonexistent in CDI. Occasional spikes of dissolved Fe and PO_4 concentrations in CDI also indicate that this method creates more reducing conditions in the soil (Nystrand et al., 2024). Consequently, controlled subsurface pipe drainage with subirrigation and vertical plastic sheet around the field can prevent a groundwater drop into the sulfidic layer and prevent an enhanced leakage of acidic metal-rich drainage water during more extreme weather conditions that are predicted to occur in the future.

Figure 4. The SBDam, constructed to ensure access to irrigation water during the summer. Photo: Peter Österholm.

PRECIKEM projects

In the PRECIKEM projects, a new approach was introduced to treat the subsoil layers of the soil, in particular the hydrologically active macropores. A subsurface drainage system allows for subsurface irrigation. By mixing an ultrafine-grained powder of e.g., limestone ($CaCO_3$) with the irrigation water, the resulting suspension can be pumped through the drainage system and out into the partly oxidized soil layer at drainage depth, utilizing the soil's pores and cracks. A stable structure of macropores with a high hydrological conductivity is formed in these fine-grained soils as they are drained and dried. The treatment suspension can therefore be spread in to the soil via the macropores. To test the technique on a practical scale, an experimental field has been built as part of the PRECIKEM projects (see location in Figure 1).

In order to be able to simultaneously test the effects of several different treatments on drainage water and to make comparisons with drainage water from untreated soils, the field has in the first stage been divided into a number of subfields. Every subfield is surrounded by a plastic sheet extending from about 0.4 metres below the ground level down to a depth of 1.9 metres. At this depth, the soil material consists of a very dense clay with little or no hydrological conductivity. This sheet provides hydrological isolation between the subfields and between the subfields and the open ditches surrounding the experimental field.

Evaluation of the 2012–2014 field experiments showed that treatment suspensions spread most effectively near the control well, where flow and pressure were highest. Further along the drainpipes, flow decreased, and sedimentation in the pipes started to occur. This highlighted the need for a drainage system with uniform flow and pressure. In the second stage a modified system enabling circulating subirrigation was therefore planned, and build.

In the third stage of development, the experimental field was supplemented in two subfields where a separate irrigation pipe above the drainage system was added. The new system features a looped pipe placed about 60 cm below ground level (roughly 50 cm above the drainage pipes) within the upper part of the acidified soil layer. This pipe is connected to its own well, enabling circulating subirrigation with water or treatment suspension, which helps prevent sedimentation in the pipe. Both the outgoing and returning part of the loop lies between drainpipes. When treatment suspension is injected, it flows through cracks and macropores downward and sideways toward the drainpipes, allowing a larger soil volume to be treated.

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Yli-Halla, M., Virtanen, S., Regina, K., Österholm, P., Ehnvall, B. & Uusi-Kämppä, J., 2020. Nitrogen stocks and flows in an acid sulfate soil. Environ Monit Assess 192, 1-20.

Results from the PRECIKEM projects have been published in:

Högfors-Rönnholm, E., Stén, P., Christel, S., Fröjdö, S., Lillhonga, T., Nowak, P., Österholm, P., Dopson, M. & Engblom, S., 2023. Targeting oxidation sites on boreal acid sulfate soil macropore surfaces mitigates acid and metal release to recipient water streams. Applied Geochemistry. Volume 158.

Högfors-Rönnholm, E., Lundin, D., Brambilla, D., Christel, S., Lopez-Fernandez, M., Lillhonga, T., Engblom, S., Österholm, P. & Dopson, M., 2022. Gallionella and Sulfuricella populations are dominant during the transition of boreal potential to actual acid sulfate soils. Communications Earth & Environment volume 3, Article number: 304.

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Site 12: Ferry ride to Umeå through metal-rich waters

Anton Boman

Ferry ride to Umeå

We will cross the Kvarken Archipelago by ferry between Vaasa (Finland) and Umeå (Sweden). The islands and moraine formations in the area are remnants of the last ice age. Due to ongoing land uplift, it is estimated that it in approximately 2,000 years, it will be possible to walk from Vaasa to Umeå. Durning the journey, we will discuss leaching of metals from acid sulfate soils (ASS) and how these are transported into the Kvarken Archipelago and the Gulf of Bothnia.

Metal leaching into the Baltic Sea

Rivers draining ASS in western Finland are known to transport substantial amounts of trace metals, causing detrimental environmental effects in the recipient estuaries of the eastern Gulf of Bothnia, northern Baltic Sea (Nordmyr et al., 2008a; 2008b). Especially the Kvarken Archipelago, receiving discharge from the Laihianjoki and Sulvanjoki rivers, is notably impacted by ASS (Virtasalo et al., 2020). In the study by Virtasalo et al. (2020), it was shown that concentrations of Cd, Co, Cu, La, Mn, Ni, and Zn in seafloor sediments increased markedly during the 1960s and 1970s, coinciding with intensive artificial drainage of ASS (Figure 2). Since the 1980s, metal deposition has remained at elevated levels. Currently, metal enrichment in sediments is detectable at least 25 km seaward from the river mouths (Figure 1).

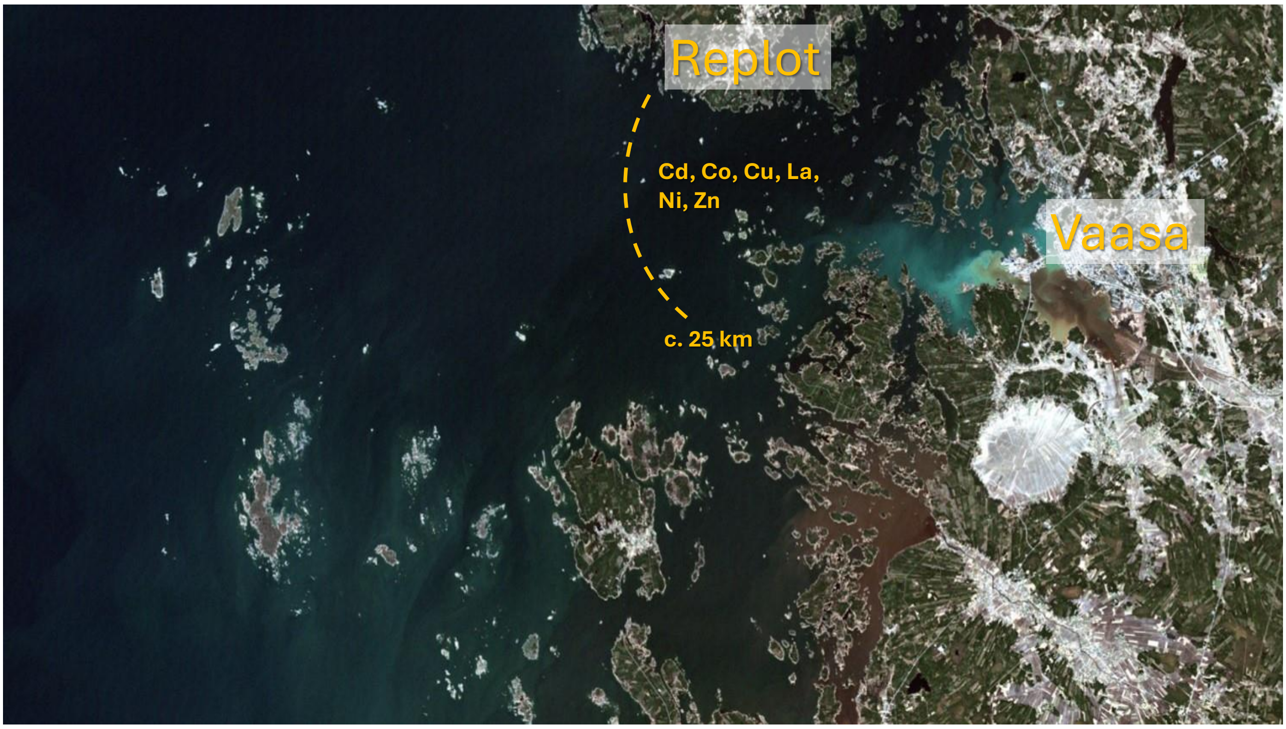

Figure 1. The turquoise-coloured plume indicates leakage and transport of acidic and metal-rich water from acid sulfate soils (ASS) into the Kvarken Archipelago, offshore from the town of Vaasa. The dotted orange line shows how far some metals are transported before being deposited in the seafloor sediment. The meteorite impact crater in Söderfjärden is clearly visible to the right of the image. The satellite image was compiled by Pasi Peltola.

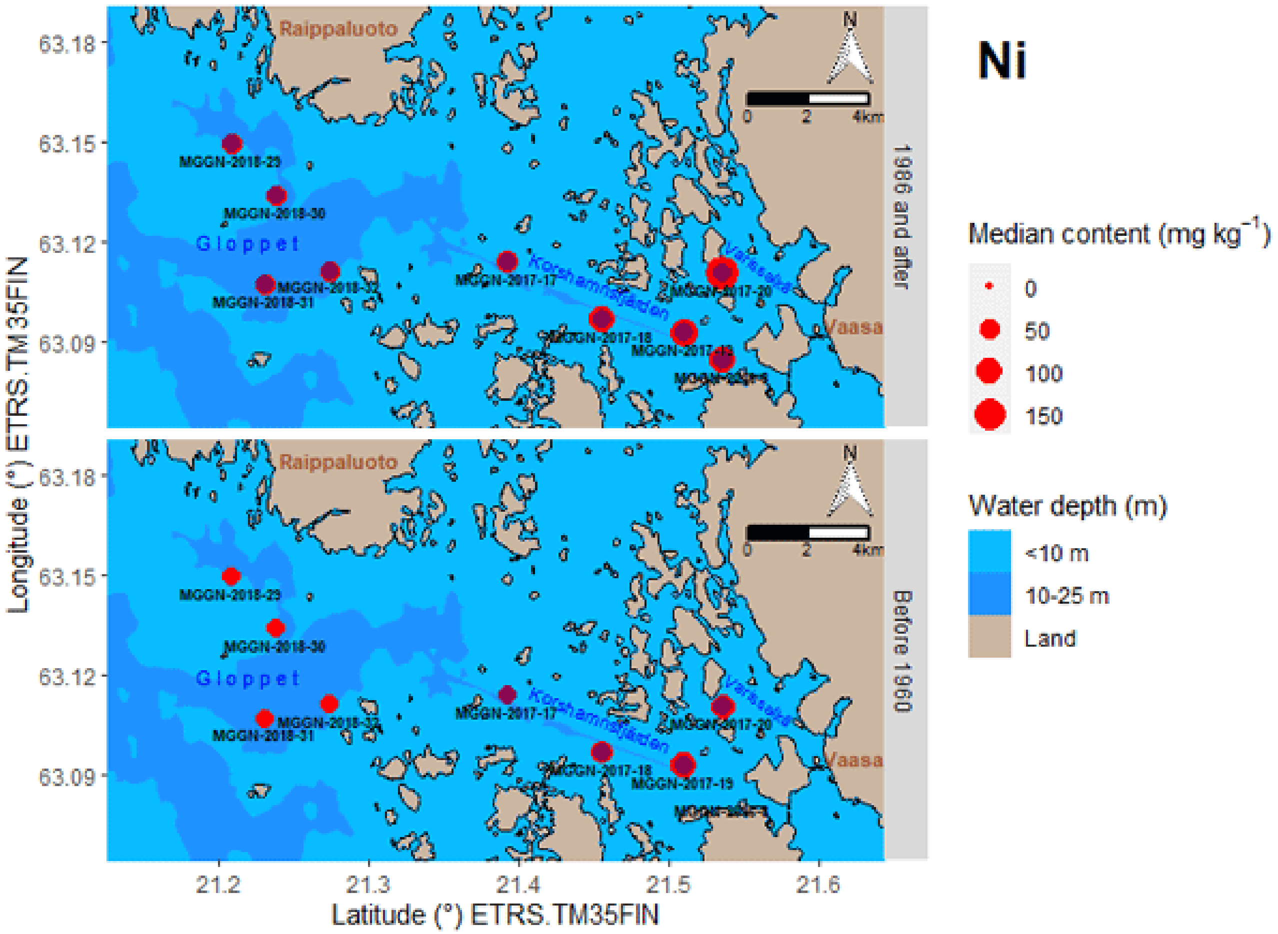

Figure 2. Map of the sea area off the town of Vaasa, with the median Ni contents in the <63µm grain size fraction of core sections deposited before 1960 (lower panels) and in 1986 and later (upper panels). Bright red dots indicate median contents, while dark red dots represent the mean of median values in the pre-1960 sections from four cores in the Gloppet area (MGGN-2018-29 to MGGN-2018-32) (from Virtasalo et al., 2020).

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Site 13: Envix Nord – Facility for treatment of sulfidic soils

Anton Boman

Location

Google maps: https://maps.app.goo.gl/br1ABPBHRTLs3L8M7

Coordinates: 63°48'44.0"N 20°10'38.4"E

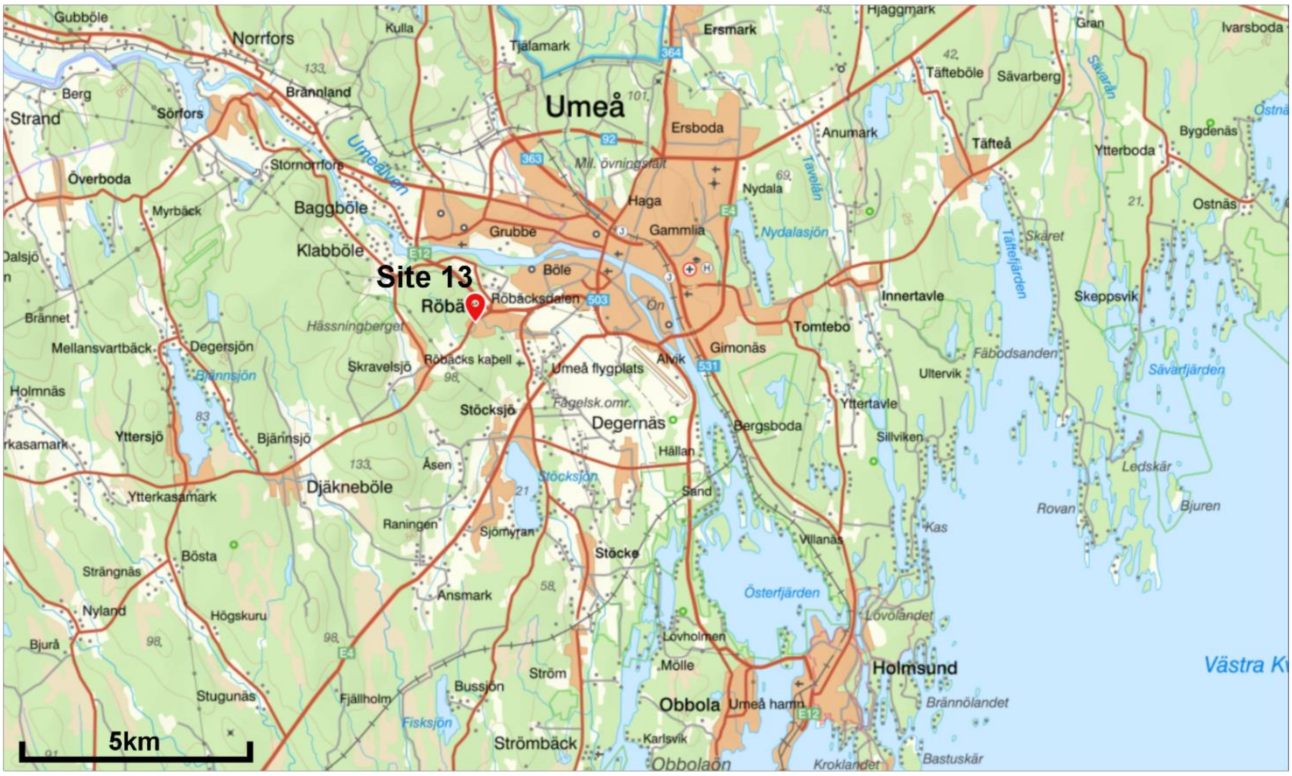

Figure 1. Location of Envix Nord (Site 13) in Umeå, where contaminated soil, such as acid sulfate soil (ASS) materials are neutralized and reused in various projetcs.

Purpose of the visit

We will visit Envix Nord's facility for the treatment of contaminated soils (Figure 1). Here we will learn how sulfidic soil is treated and neutralized and reused in various projects.

Envix treatment technology

Envix Nord's treatment technology transforms sulfidic soil material and rock into a usable resource. The method is equally effective for both sulfidic and oxidized acid sulfate soil (ASS) materials, enabling a circular and environmentally sound approach to managing these challenging materials. It reduces the need for landfill and minimizes environmental and health risks, while making the material reusable.

The Röbäck facility

Located in Umeå (Figure 1), the Röbäck facility, is a key hub for projects across Västerbotten. With high capacity and access to major transport routes, it handles sulfidic soil materials from projects of all sizes. The facility has been in operation since 2019, when it was the first officially permitted treatment and recycling facility for sulfidic soil materials in Sweden.

At the Röbäck facility, sulfidic soil materials are treated using a method developed through extensive research and experience, eliminating the environmental risks associated with untreated sulfidic soil materials. Once treated, the soil meets the criteria for “end of waste” and is no longer considered waste, but a reusable product. The final product can be used in construction projects and is sold directly at the Röbäck facility.

Figure 1. Envix Nord’s facility in Röbäck (Umeå) for the treatment of contaminated soils (source: www.envix.se).

Site 14: The drained Lake Västerviksjön – An acid sulfate soil hotspot

Jan Åberg & Anton Boman

Location

Google maps: https://maps.app.goo.gl/16w9BHjgJLQMkJhg7?g_st=ac

Coordinates: 64°04'16.0"N 20°42'03.0"E

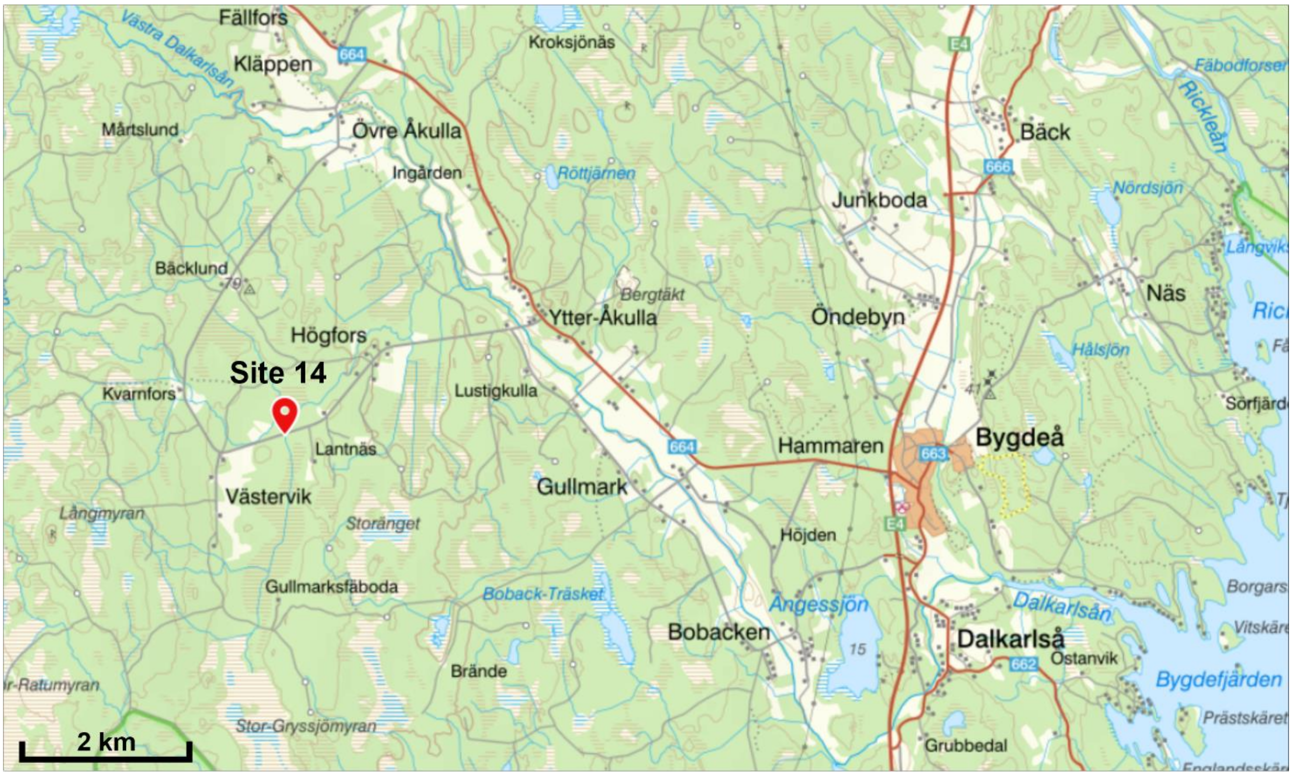

Figure 1. Location of the drained Lake Västerviksjön (Site 14).

Purpose of the visit

We will visit the formerly drained Lake Västerviksjön, which has become an acid sulfate soil (ASS) hotspot, releasing acid and metals into the environment.

The drained Lake Västerviksjön - an acid sulfate soil hotspot

For almost 5000 years, Lake Västerviksjön was a freshwater lake with an open water area of about 114 hectares (Figure 2). It was formed from a bay of the Littorina sea, due to post-glacial rebound. The total length was 2.7 km and the maximum depth was approximately 2.4 m. The area of the former Lake Västerviksjön mostly contains sulfidic sediments, making it an acid sulfate soil hotspot (Figure 3).

The vast littoral zone of Lake Västerviksjön was biologically rich, nourished by a lake bed of mostly fine grained, sulfide-rich, sediments. The fauna included among others: duck mussels and fish such as pike, roach, perch and trout; mammals such as otters, beavers and water voles; crustaceans, insects and many species of birds.

Lake Västerviksjön was a local source for hay-production already during medieval times (then called Gryssjön). Likely, the lake was harvested also in much earlier times. The practice of harvesting grass in shallow fresh waters is at least 1500 years old in northern Sweden, but the techniques were improved during the 19th century, with intentional regulation of the water levels to maximize sedimentation, minimize frost-damage of root-systems, and stimulate the growth of especially Carex grasses. In the early 20th century, about 40 hay barns were needed to store the hay-harvest from Lake Västerviksjön.

In 1956, Lake Västervikssjön was completely drained to gain tillable farmland. However, the attempts to cultivate the soils failed due to high soil acidity. Today, the former lake bed is instead covered with mostly deciduous forest and swamp-forest vegetation

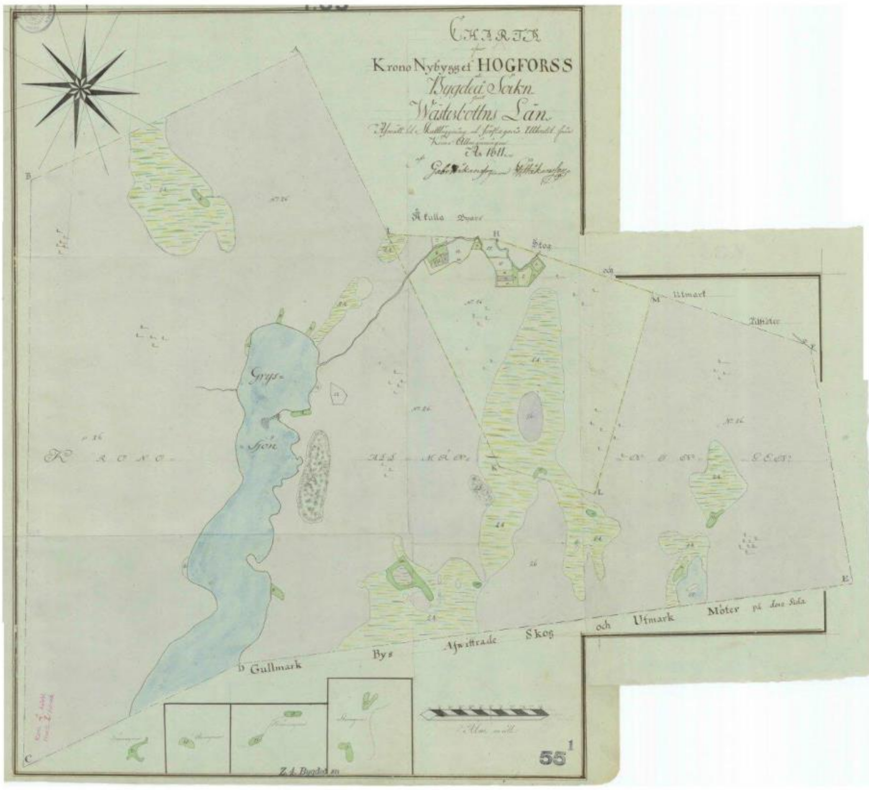

Figure 2. A map from 1811, covering the Northern part of Lake Västervikssjön.

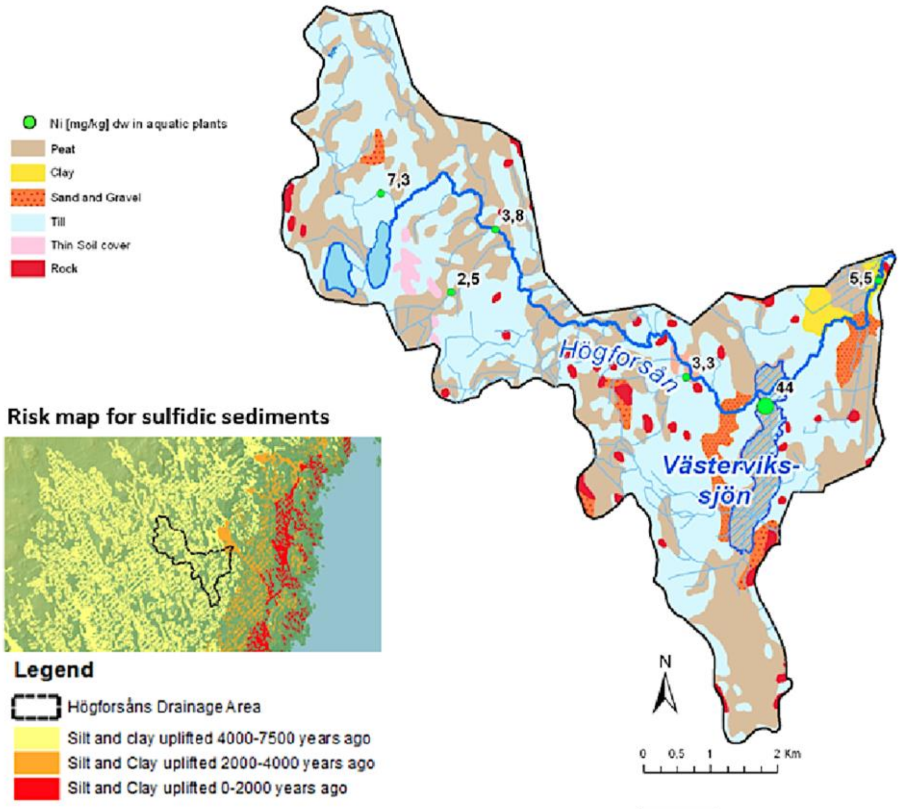

Figure 3. The soils of the Högforsån Creek catchment, with the former Lake Västervikssjön marked in the downstream part. The area of the former lake mostly contains sulfidic sediments.

The failed attempt to convert Lake Västervikssjön to productive farmland

In 1944, a "drainage-company" consisting of local farmers signed a legally binding contract to convert Lake Västervikssjön into 114 hectares of tillable farmland (Figure 4). This project, and many other similar projects in the region, were planned and coordinated by the government to increase the overall agricultural productivity in the region. Co-financing from the government was promised, but not until the project was completed and had been approved by the authorities.

Partly due to geological and hydrological challenges, the drainage company needed several years longer than expected to finish its task. Most of the money required during this phase had to be loaned from the state, and this debt was not fully paid back until several decades later. In 1956, six years later than planned, all water was drained from the lake, and the project was approved for co-financing (about half of the estimated cost).

Figure 4. Construction of the canal that drained Lake Västervikssjön. Photos from around 1956, by Abel Åberg.

The water decree was configured for the purpose of creating and maintaining dry soils and cultivatable fields across the entire area of the lake bed (114 hectares). However, when the lake bed finally dried up, several years later than planned, the soils turned out to be extremely acidic. Only a few hectares were ever cultivated, and when these small fields were planted, most crops failed completely. Liming was considered and attempted in some cases, but the much-needed long-term liming strategy was not economically viable due to the lack of nearby lime sources. In addition, the downstream part of the canal was narrow, leading to flooding of large parts of the former lake bed during periods of heavy precipitation.

Some socioeconomic perspectives on the draining of Lake Västervikssjön

The water decree itself did not include time limits. This means that, even today, about three generations later, the decree remains legally binding and is a shared responsibility among current landowners. The maintenance cost per hectare is high compared to the natural forests surrounding the lake, while the production of high-value wood crops is generally low. Additionally, the soft ground of the former lake bed often leads to extra costs for wood-harvesting operations. Still, some landowners are beginning to receive cash income from the former lake bed. In the lower parts, wetlands and swamp forests, the maintenance cost remains much higher per hectare than the achievable cash income.

There is a legal possibility to change or abolish ("kill") the water decree. These two types of actions are, however, complicated, involving high administrative costs, uncertain outcomes, and potentially challenging negotiations between landowners. Therefore, the incentives to change or abolish the water decree are weak.

Damages not considered in the water decree include, among others: the lost possibilities of living near the lake or waterfront, the missed opportunities for fishing (both in the lake and the acidified river system downstream), and the lost opportunities for various lake-related recreational activities.

Ecological effects after draining Lake Västervikssjön

Around the end of the 1950s, when the old lake bed had dried up, a notable mass fish kill occurred in River Dalkarlsån, about 5 km downstream of Lake Västervikssjön. Thousands of roaches gathered on the water surface of the river to gasp for air before they died and disappeared. Since then, the Högforsån Creek and the downstream River Dalkarlsån have suffered from recurring difficult chemical conditions for many aquatic organisms. Around the 2000s, roaches started to appear again in larger numbers in the main channel of the River Dalkarlsån (after more than 40 years of absence). This was probably mainly due to a combination of reduced acid rain and reduced ditching activities in the potentially acid sulfate soils within the catchment.

The latest major reduction of fish stocks in River Dalkarlsån occurred in late 2018, following a large-scale drought across Scandinavia. The resulting episode of highly acidic and chemically harmful leakage from acid sulfate soils (ASS), not least from Lake Västervikssjön, persisted for several years in River Dalkarlsån. In the summer of 2025, roaches in River Dalkarlsån were back in similar numbers to those before the 2018 event, reflecting a continuous period of wetter summers since 2020.

Chemical effects after draining Lake Västervikssjön

Högforsån Creek is the first recipient of water from Lake Västervikssjön. The lowest recently observed pH in the main channel of Högforsån Creek is 3.9 (just before it meets a tributary of River Dalkarlsån). There is no regular monitoring program for Högforsån Creek, which means that the pH may have been even lower after the drought in 2018. During normal hydrological conditions in ditches within the former lake bed, the pH values of the water can be as low as 3.5, with aluminum concentrations up to 50 mg/l (50,000 µg/l).

Figure 5. Peak flows can lead to the occasional return of the deeper parts Lake Västervikssjön. Photo: Jan Åberg.

Some chemical characteristics summarized

The Högforsån Creek (3,300 ha) receives water from the former Lake Västervikssjön (114 ha) (Figure 3).

Some chemical characteristics of the Högforsån Cree catchment outlet:

- TOCmax >45 mg/l
- Inorganic aluminum (Alimax) >1000 µg/l (about 10x the concentration needed for long term fish survival).
- pH_{min} <3.9
- EC_{max} >130 µS/cm
- Sulfate (SO_{4max}) >0.7 mekv/l (>30 mg/l, and about 15-20x local background level)

Some chemical characteristics of the 114 ha hotspot, in ditches (water-filled) in former Lake Västervikssjön:

- Inorganic aluminum (Ali_{max}) up to at least 34 000 µg/l (very toxic to most water life).
- pH_{min} ~3.5
- EC_{max} >1000 µS/cm
- SO_4 >13 mekv/l (>600 mg/l)

Chemical characteristics of the inlets upstream of Lake Västervikssjön:

- TOC from about 20 to 60 mg/l.
- EC-ranging between 5-60 µS/cm, usually around 20-30.
- Inorganic aluminum below 100 µg/l.
- SO_4 at background levels.
- pH-values in the range of 4-6, with low values due to organic acids.

Figure 6. Field measurements in one of the ditches within the former Lake Västervikssjön. pH 3.59. Electrical conductivity (EC) 595 µS/cm. Photo: Jan Åberg.

Example of seasonal chemical shifts

During snowmelt in spring, soft water containing high concentrations of organic acids flows into Lake Västervikssjön from upstream. A decrease in water colour and the formation of metal-humus precipitates can be observed as a layer of new sediments in the canal (Figure 7). During summertime, under low-flow conditions, deeper groundwater with higher pH flows into the former lake from upstream locations. The natural colour of the water increases dramatically when the high-pH incoming water reacts with the acidic water within the former lake.

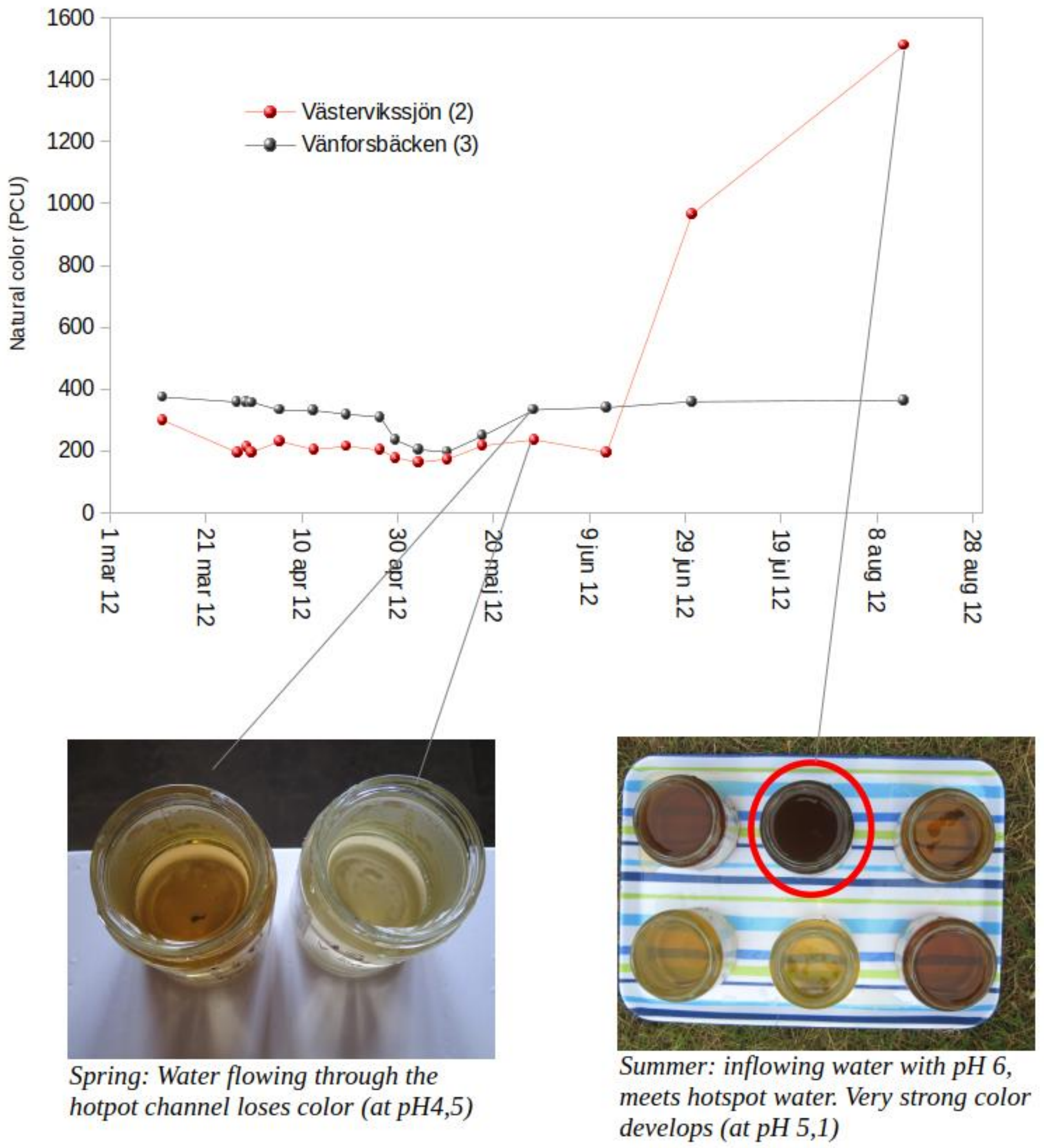

Figure 7. Colour changes in the water flowing through the acid sulfate soil (ASS) hotspot.

Irregular event: the hotspot gets water-filled and starts to produce sulfides

The acid sulfate soil (ASS) hotspot, the former Lake Västervikssjön (114 ha), became water-filled due to a heavy spring flood in 2012 (Figure 8). On that occasion, the outlet of the hotspot had higher pH than the incoming water. This suggests that reducing conditions may have been initiated, possibly leading to sulfide formation.

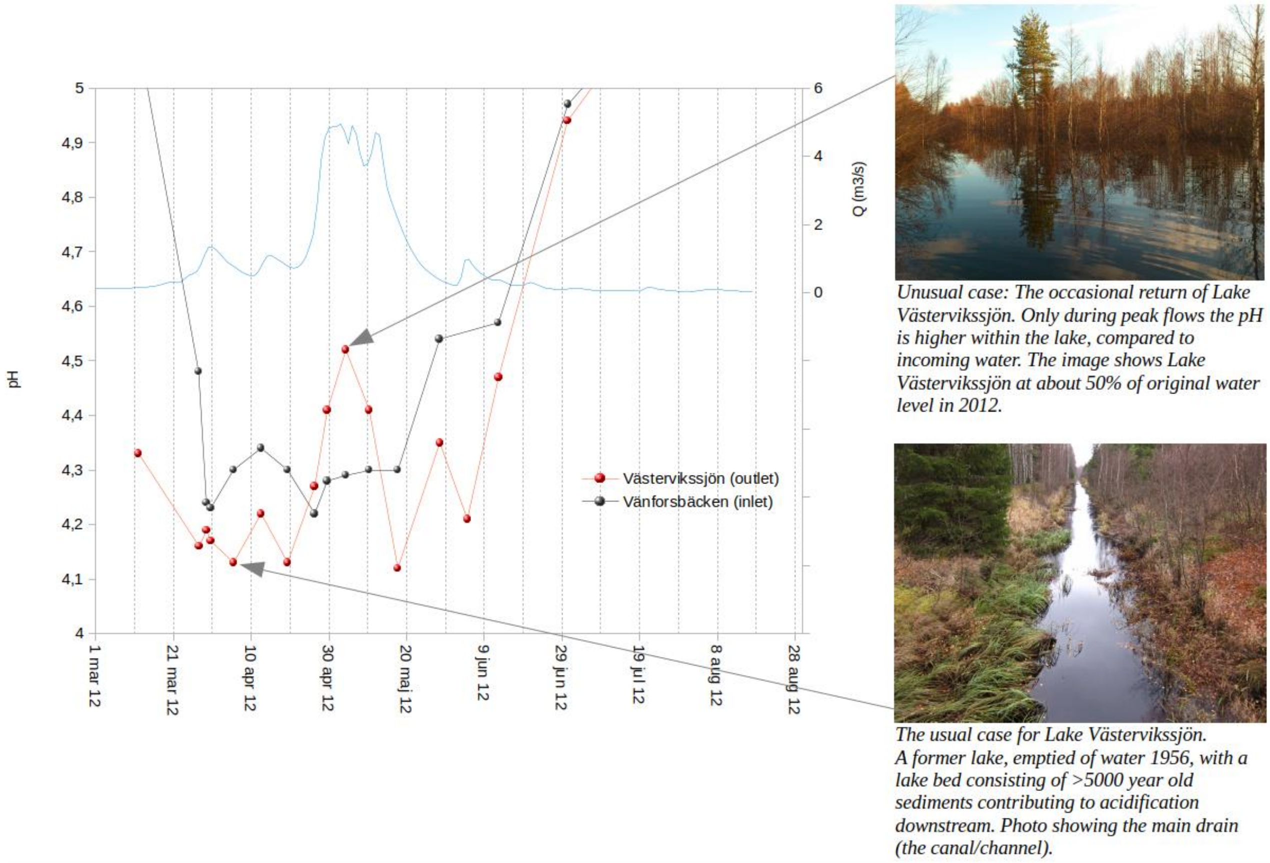

Figure 8. Data and photos from the spring flood in 2012, when Lake Västervikksjön became water-filled.

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