

# Classification of acid sulphate soils of Finland according to Soil Taxonomy and the FAO/Unesco legend

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In order to place acid sulphate soils (a.s. soils) of Finland in an international context, five pedons from cultivated a.s. soils from Liminka, Ylistaro and Laitila on the western coast of Finland were analyzed and classified according to Soil Taxonomy and the revised legend of the FAO/Unesco Soil Map of the World. Three of the pedons (Liminka 1 and 2, Laitila 1) had sulfuric horizons within 50 cm of soil surface and qualify as Typic Sulfaquepts. One pedon (Ylistaro) had a sulfuric horizon at the depth of 100–150 cm and was classified as a Sulfic Cryaquept. The fifth pedon (Laitila 2) did not have either a sulfuric horizon or sulfidic materials, but it had a  $\text{pH} < 4.0$  and enough  $\text{SO}_4\text{-S}$  to be classified as a Sulfic Cryaquept. According to the FAO/Unesco legend, all pedons were classified as Thionic Gleysols. Thus Typic Sulfaquepts and Sulfic Cryaquepts (Soil Taxonomy) and Thionic Gleysols (FAO/Unesco classification) occur commonly on the western coast of Finland. As a result of artificial drainage and leaching, they gradually fail to meet the requirements of a.s. soil classes and will be classified as Typic Cryaquepts. In terms of the FAO/Unesco nomenclature, Thionic Gleysols become Dystric Gleysols or Gleyic Cambisols over time.

*Key words:* FAO/Unesco Soil Map of the World, pedogenesis, soil morphology, soil pH, soil survey, Soil Taxonomy, sulphur content

## Introduction

Acid sulphate soils (a.s. soils) are soils in which, “as a result of processes of soil formation, sulphuric acid either will be produced, is being produced or has been produced in amounts that have a lasting effect on main soil characteristics” (Pons 1973). A more quantitative criterion, needed for soil classification, has been presented, e.g. by van Mensvoort and Dent (1997): In a.s. soils,

enough sulphuric acid is produced to bring soil pH below 4. In the revised legend to the FAO/Unesco Soil Map of the World (FAO 1988), these soils are called Thionic Gleysols, Thionic Fluvisols or Thionic Histosols. In Soil Taxonomy (Soil Survey Staff 1996), a.s. soils are dispersed through several taxa. The most coherent and detailed classification of a.s. soils by Dent (1986) makes the important distinction between ‘sulphidic soils’ (or potential a.s. soils), ‘raw a.s. soils’ that are actively generating sulphuric acid

and which, therefore, pose an environmental hazard, and 'ripe acid sulphate soils' that are still severely acid (pH 4 or less) but are no longer exporting acidity. The 1994 revision of Soil Taxonomy (Fanning and Witty 1993) seeks to distinguish the 'raw acid sulphate soils' as Sulfaquepts using a severe pH criterion (pH<3.5) for the diagnostic sulfuric horizon.

The a.s. soils of Finland, mainly located on the coast of the Gulf of Bothnia, have developed in sulfidic sediment accumulated during the Litorina period of the Baltic sea (7000 – 3000 yr B.P.). These soils were earlier studied mainly from the agricultural point of view (Kivinen 1938, Purokoski 1958, 1959, Erviö 1975, Erviö and Palko 1984). Since the 1980's, the emphasis has been in environmental aspects, particularly acid loading from these soils to surface waters (Palko et al. 1985, 1987, Palko and Saari 1987, Hartikainen and Yli-Halla 1986, Palko 1988, 1994, Erviö 1991, Palko and Yli-Halla 1993). Acid sulphate soils of Finland have not been classified according to international systems, but local criteria have been applied to identify a.s. soils in national soil surveys. In Finland, Erviö (1975) and Erviö and Palko (1984) called a soil an a.s. soil if the subsoil (40–60 cm or 50–70 cm) had a pH(H<sub>2</sub>O, 1:2.5) <5.0 and/or a SO<sub>4</sub>-S content >100 mg l<sup>-1</sup> of soil, determined in air-dried samples. More recently (Palko and Saari 1987, Palko et al. 1987), the use of SO<sub>4</sub>-S content as the criterion for classification was discontinued and the

pH was determined in the field in a moist soil. The minimum pH (<5.0) of the profile was the principal criterion in the classification, and redox potential was a secondary variable.

The purpose of this paper is to place the a.s. soils of Finland in an international context. Five representative pedons from three a.s. soil areas on the western coast of Finland are classified according to Soil Taxonomy and the revised legend to the FAO/Unesco Soil Map of the World.

## Acid sulphate soils in Soil Taxonomy and FAO/Unesco legend

A sulfuric horizon and sulfidic materials (Table 1) are essential in the classification of a.s. soils. In Soil Taxonomy (Soil Survey Staff 1996), the determination of sulfidic materials is based on soil pH before and after aerobic incubation. Sulfidic materials are stable in anaerobic environments. A sulfuric horizon develops when sulfidic materials are oxidized to sulfuric acid, resulting in a sufficient decrease of pH. In Soil Taxonomy, evidence that the acidity is caused by sulfuric acid is required. Accepted evidence is at least one of the following: 1) presence of jarosite, 2) high content of water-soluble SO<sub>4</sub>-S in the horizon concerned and 3) sulfidic materi-

Table 1. Characteristics of sulfidic materials and the sulfuric horizon.

Taxonomic feature	Soil Taxonomy	FAO/Unesco Soil Map of the World
Sulfidic materials	pH > 3.5. After incubation pH decreases by at least 0.5 units and reaches a pH<4.	Total S >0.75% mostly in the form of sulfide and a pH > 3.5. After drainage pH decreases below 3.5.
Sulfuric horizon	pH ≤ 3.5 and thickness at least 15 cm and one or more of the following: – jarosite concentrations – directly underlying sulfidic materials – water-soluble SO <sub>4</sub> -S >0.05%	pH < 3.5 and thickness at least 15 cm and generally jarosite mottles

Table 2. General requirements of some acid sulphate soil units according to Soil Taxonomy (Soil Survey Staff 1996) and the legend of the FAO/Unesco Soil Map of the World (FAO 1988).

Soil unit	Description
Soil Taxonomy:	
Sulfaquents	Entisols with aquic soil moisture regimes and sulfidic materials within 50 cm of soil surface
Sulfaquepts	Inceptisols with aquic soil moisture regimes and sulfuric horizons within 50 cm of soil surface
Sulfic Cryaquepts	Inceptisols with aquic soil moisture regimes and cryic temperature regimes and with one or more of the following: <ul style="list-style-type: none"> <li>– a sulfuric horizon between 50 and 150 cm from soil surface</li> <li>– sulfidic materials within 150 cm of soil surface</li> <li>– within 150 cm of soil surface a horizon which has all the characteristics of a sulfuric horizon except pH which is between 3.5 and 4.</li> </ul>
FAO/UNESCO Soil Map of the World:	
Thionic Gleysols	Gleyic properties within 0.5 m of soil surface. Sulfuric horizons or sulfidic materials within 125 cm of soil surface

als below the acidic horizon. A sulfuric horizon must have a  $\text{pH} \leq 3.5$ . This requirement attempts to include horizons where sulfide is presently oxidizing (raw acid sulphate soils in Dent's classification) and to exclude horizons where all sulfide has already disappeared (Fanning and Witty 1993). The legend of the FAO/Unesco Soil Map of the World (FAO 1988) uses merely the oxidized pH value which must be  $<3.5$ .

The essence of the taxonomic definitions of the a.s. soils is to include soils which have enough sulfuric acid to exhibit a  $\text{pH} <3.5$  (FAO 1988) or  $<4.0$  (Soil Survey Staff 1996), or enough sulfide to produce, upon oxidation, a pH below these values. In Soil Taxonomy, a.s. soil units include great groups in Entisols, Inceptisols and Histosols, e.g. Sulfaquents, Sulfaquepts and Sulfohemists, respectively, and Sulfic subgroups in Entisols and Inceptisols, e.g. Sulfic Endoaquents and Sulfic Cryaquepts, respectively. In that system, soils in which sulfide is oxidizing and reduced soils which contain sulfidic materials but not an acidic horizon are classified into different units. In the revised legend of the Soil Map of the World (FAO 1988), thionic units are recognized in Histosols, Fluvisols, Gleysols and soils with a sulfuric horizon and

those with only sulfidic materials are classified in the same taxa. The requirements of some relevant a.s. soil units are summarized in Table 2.

## Material and methods

Five pedons representative of the range of a.s. soils in Finland were described from Liminka (two pedons), Ylistaro and Laitila (two pedons) in Northern and Southern Ostrobothnia and Southwestern Finland, respectively (Fig. 1).

In Liminka, the study area ( $64^{\circ}50'N$ ,  $25^{\circ}24'E$ ) is flat and about 1 m above the level of the Gulf of Bothnia. It rose above the sea level 100–150 years ago. The Liminka 1 pedon (Fig. 2) has been cultivated for grass and small grains for about 15 years, but was fallowed at the time of inspection. Initially, the field had open drains, but it was pipe-drained 8 years prior to inspection. The ground water was not encountered within 1 m of soil surface on August 13, 1992 (sampling). The Liminka 2 pedon comes from an experimental polder (described in detail by Palko 1988) which was constructed 8 years be-



Fig. 1. Locations of the pedons.

fore sampling. At the same time, the sampled plot was pipe-drained to the depth of 113 cm and limed (15 tons dolomitic limestone ha<sup>-1</sup>). Oats had been grown in the field for three years, after which cropping was abandoned and the area was now covered with a grassy vegetation. Ground water was at 95 cm below the soil surface on August 14, 1992.

The Ylistaro pedon (62°55'N, 22°29'E) represents the major acid sulphate soil area of Finland (Purokoski 1958, Erviö 1975). The pedon (Fig. 3) is located on a flat coastal plain with an elevation of 26 m asl. The area had been cultivated for about 100 years but has been fallow since 1991. Different grasses grow on the area now. Pipe drainage has been installed. No water table was encountered above 150 cm on October 3, 1996.

The Laitila pedons (60°53'N, 21°41'E) are located in a cultivated Valkojärvi polder (1000 ha) 10 m asl. The a.s. area, described by Palko

et al. (1985), is drained to the River Sirppujoki by pumping. During the Litorina period the area was a gulf of the sea and later it became a lake. Lake Valkojärvi was drained for agricultural use piecemeal between the 1930's and 1966. Small grain and sugarbeet have been grown. The area of the Laitila 1 pedon was drained about 30 years ago. The site is the lowest-lying spot of the Valkojärvi polder. No groundwater was encountered on September 24, 1996. The Laitila 2 pedon is about 200 m away from the Laitila 1 pedon. Ground water (pH 3.5) was 95 cm below the soil surface on September 15, 1992.

In all pedons, moist Munsell colours were recorded. Where mollic/umbric epipedons were considered, also dry colours were determined. Each horizon was sampled, and samples air-dried and ground to pass a 2-mm sieve prior to analysis. In the Liminka 1 and 2 and Laitila 2 pedons, redox potential and soil pH were determined in the field in the soil pit at intervals of 10 cm by inserting electrodes directly into the soil. A small amount of deionized water was added to allow proper contact between the soil and the electrode (Puustinen et al. 1994). The samples from the Laitila 1 and Ylistaro pedons were transported to the laboratory in plastic bags, and the pH(1:1) of the moist samples was determined the day after sampling. The pH of all soil samples was also measured after aerobic incubation and drying. Particle size distribution of mineral material was determined by a pipette method. The total contents of C, N and S were determined using a Leco dry combustion apparatus (CNS-1000). Because the samples were acid, all C was assumed to be organic. After incubation for 2 months, SO<sub>4</sub>-S was extracted with 0.01 M CaCl<sub>2</sub> and determined by Inductively Coupled Plasma Emission Spectrometry (ICP). Exchangeable cations (Ca, Mg, K, Na) were extracted with 1 M NH<sub>4</sub>-acetate at pH 7. Acidity released from the soil was determined by titrating the soil extract back to the original pH with 0.02 M NaOH. The sum of K, Na, Ca, Mg and acidity was taken as the cation exchange capacity (CEC) and the base saturation was calculated as the percentage of Ca+Mg+K+Na of CEC. Free acid, present



Fig. 2. The Liminka 1 pedon.



Fig. 3. The Ylistaro pedon from 0.80 m below.

originally in the soil or formed upon drying and partial oxidation of sulfide, probably results in a slight overestimation of CEC and underestimation of base saturation in the most acid ( $\text{pH} < 3.5$ ) horizons and in the horizons containing sulfidic materials. Possible presence of free sulphate salts also adds to the overestimation of CEC. Poorly crystalline Fe and Al (hydr)oxides were extracted with 0.2 M  $\text{NH}_4$ -oxalate ( $\text{pH} 3.0$ ) in the dark (McKeague and Day 1966). Iron and Al were determined by ICP.

## Results

All the soils were mineral soils. The organic C content was usually highest in the Ap horizons (Table 3), but the deeper layers were also richer in organic C than mineral soils in general, par-

ticularly in the Laitila pedons. The Laitila 1 pedon had the highest C content at the depth of 35–50 cm, presumably inherited from the initial sediment. The pedons represent the following particle size classes:

Pedon	Soil Taxonomy	FAO/Unesco legend
Liminka 1 and 2	coarse silty	medium textured
Ylistaro	fine silty	medium textured
Laitila 1 and 2	fine	fine textured

Based on the morphological descriptions (Table 4), it can be concluded that all pedons had ochric epipedons. Relatively high pH values in the Ap horizons of all pedons except Ylistaro (Table 5) are attributable to liming. All pedons had cambic B horizons (as indicated by the development of structure) and aquic moisture re-

Table 3. Selected physical and chemical properties of the pedons.<sup>1)</sup>

Depth cm	Clay %	Silt %	C %	S <sub>tot</sub> %	N <sub>tot</sub> %	CEC cmol(+)/kg	Base satu- ration, %	Fe <sup>2)</sup> g/kg	Al <sup>2)</sup> g/kg
<b>Liminka 1</b>									
0-25	10	82	2.9 <sup>b</sup>	0.19 <sup>a</sup>	0.19 <sup>b</sup>	17.5	89	10.1 <sup>d</sup>	1.7 <sup>d</sup>
25-35	8	86	0.4 <sup>a</sup>	0.17 <sup>a</sup>	0.04 <sup>a</sup>	7.1	53	4.8 <sup>ab</sup>	0.5 <sup>a</sup>
35-45	10	86	0.4 <sup>a</sup>	0.27 <sup>b</sup>	0.04 <sup>a</sup>	8.8	46	3.8 <sup>a</sup>	0.5 <sup>a</sup>
45-65	10	85	0.6 <sup>a</sup>	0.26 <sup>b</sup>	0.06 <sup>a</sup>	13.1	44	6.0 <sup>b</sup>	0.5 <sup>a</sup>
65-85	12	86	0.7 <sup>a</sup>	0.45 <sup>d</sup>	0.06 <sup>a</sup>	15.5	48	6.0 <sup>b</sup>	1.1 <sup>c</sup>
85-100	13	86	0.7 <sup>a</sup>	0.36 <sup>c</sup>	0.06 <sup>a</sup>	13.7	80	8.0 <sup>c</sup>	0.6 <sup>b</sup>
<b>Liminka 2</b>									
0-25	11	83	6.0 <sup>b</sup>	0.29 <sup>a</sup>	0.28 <sup>b</sup>	29.6	81	8.5 <sup>b</sup>	1.6 <sup>c</sup>
25-65	9	85	0.5 <sup>a</sup>	0.24 <sup>a</sup>	0.05 <sup>a</sup>	11.6	41	5.7 <sup>a</sup>	0.6 <sup>a</sup>
65-72	10	80	0.6 <sup>a</sup>	0.66 <sup>b</sup>	0.06 <sup>a</sup>	18.2	32	6.0 <sup>a</sup>	1.2 <sup>b</sup>
72-85	11	86	0.6 <sup>a</sup>	0.73 <sup>b</sup>	0.06 <sup>a</sup>	14.1	59	7.9 <sup>b</sup>	1.1 <sup>b</sup>
<b>Ylistaro</b>									
0-30	24	64	4.6 <sup>d</sup>	0.17 <sup>a</sup>	0.40 <sup>d</sup>	20.5	9	10.5 <sup>b</sup>	3.4 <sup>b</sup>
30-52	28	64	1.1 <sup>ab</sup>	0.19 <sup>a</sup>	0.19 <sup>ab</sup>	12.3	13	7.9 <sup>ab</sup>	1.1 <sup>a</sup>
52-70	27	67	1.0 <sup>a</sup>	0.17 <sup>a</sup>	0.18 <sup>a</sup>	9.5	13	6.1 <sup>a</sup>	0.9 <sup>a</sup>
70-100	26	67	1.0 <sup>a</sup>	0.21 <sup>a</sup>	0.18 <sup>a</sup>	11.1	17	5.7 <sup>a</sup>	0.9 <sup>a</sup>
100-125	28	65	1.2 <sup>bc</sup>	0.22 <sup>a</sup>	0.22 <sup>bc</sup>	12.1	16	8.5 <sup>ab</sup>	1.0 <sup>a</sup>
125-150	26	65	1.3 <sup>c</sup>	0.31 <sup>b</sup>	0.24 <sup>c</sup>	13.2	29	7.8 <sup>ab</sup>	1.0 <sup>a</sup>
<b>Laitila 1</b>									
0-25	43	53	6.6 <sup>c</sup>	0.22 <sup>a</sup>	0.72 <sup>c</sup>	27.3	75	7.3 <sup>c</sup>	3.0 <sup>f</sup>
25-35	51	46	6.6 <sup>c</sup>	0.53 <sup>b</sup>	0.87 <sup>d</sup>	30.4	13	17.8 <sup>f</sup>	1.5 <sup>b</sup>
35-50	48	46	7.6 <sup>d</sup>	0.77 <sup>c</sup>	1.08 <sup>e</sup>	34.2	15	16.5 <sup>e</sup>	1.6 <sup>c</sup>
50-90	49	49	3.0 <sup>a</sup>	1.72 <sup>e</sup>	0.44 <sup>a</sup>	49.7	25	8.6 <sup>d</sup>	3.5 <sup>e</sup>
90-125	50	48	3.0 <sup>a</sup>	1.54 <sup>b</sup>	0.44 <sup>a</sup>	51.2	55	7.1 <sup>c</sup>	2.4 <sup>d</sup>
125-150	49	49	3.7 <sup>b</sup>	1.68 <sup>c</sup>	0.54 <sup>b</sup>	51.2	61	5.9 <sup>b</sup>	1.4 <sup>b</sup>
150-180	53	46	3.6 <sup>b</sup>	1.45 <sup>d</sup>	0.58 <sup>b</sup>	34.5	84	2.6 <sup>a</sup>	1.2 <sup>a</sup>
<b>Laitila 2</b>									
0-25	48	50	4.3 <sup>b</sup>	0.24 <sup>a</sup>	0.39 <sup>c</sup>	23.6	53	8.7 <sup>b</sup>	1.6 <sup>c</sup>
25-35	53	44	2.6 <sup>a</sup>	0.38 <sup>b</sup>	0.33 <sup>a</sup>	19.4	18	10.7 <sup>c</sup>	1.2 <sup>a</sup>
35-55	48	49	2.7 <sup>a</sup>	0.43 <sup>b</sup>	0.35 <sup>b</sup>	20.2	16	12.0 <sup>de</sup>	1.2 <sup>a</sup>
55-85	48	50	2.5 <sup>a</sup>	0.44 <sup>b</sup>	0.32 <sup>a</sup>	20.1	18	13.5 <sup>e</sup>	1.3 <sup>b</sup>
85-100	52	46	2.7 <sup>a</sup>	0.82 <sup>c</sup>	0.35 <sup>b</sup>	23.6	25	4.0 <sup>a</sup>	2.7 <sup>d</sup>

<sup>1)</sup> Results of each pedon and soil characteristics were tested separately. Means marked with the same superscript do not differ at P = 0.05. Results without superscripts were not tested, owing to too few replicates.

<sup>2)</sup> NH<sub>4</sub>-oxalate extraction, pH 3.0

gimes. Gleyic properties, as indicated by iron (hydr)oxide cutans on ped faces, were exhibited within 50 cm of soil surface, meeting the requirements of Gleysols of the FAO/Unesco legend. The high contents of oxalate extractable Fe (Table 3) are in accordance with the thick Fe hydroxide coatings on ped faces occurring in most investigated pedons.

According to Soil Taxonomy, the pedons belong to the aquic suborder of Inceptisols, Aquepts. Throughout Finland, the mean annual soil temperature at the depth of 50 cm is between 0 and 8°C, and the mean summer temperature is below 15°C (Table 6). Thus the entire country has a cryic temperature regime (Soil Survey Staff 1996).

Table 4. Morphological characteristics of the pedons.

	Horizon	Depth cm	Matrix colour	Mottles and cutans <sup>1)</sup> colour	Texture <sup>2)</sup>	Structure <sup>3)</sup>
Liminka 1	Ap	0–25	5Y 4/2	c 7.5YR 3/4	si	gr
	Bgj1	25–35	5Y 5/2	c 7.5YR 3/4 <sup>4)</sup> , f 2.5Y 7/6 <sup>4)</sup>	si	1f sbk
	Bgj2	35–45	5Y 5/2	m 2.5Y 7/6 <sup>4)</sup> , m 7.5YR 3/4 <sup>4)</sup> , c 7.5YR 4/6 <sup>5)</sup>	si	2f sbk
	Bg	45–65	5YR 5/2	c 7.5YR 3/4 <sup>5)</sup> , f 2.5Y 7/6	si	1m sbk
	CB	65–85	10YR 4/1	f 10YR 3/6 <sup>5)</sup>	si	2m sbk
	Cg	85–100	2.5Y 2.5/1	f 10YR 3/6 <sup>5)</sup>	si	
Liminka 2	Ap	0–25	10YR 2/2 <sup>6)</sup> , 5Y 5/2 <sup>7)</sup>	c 7.5YR 3/4	si	gr
	Bgj1	25–65	5Y 5/2	c 7.5YR 3/4 <sup>4)</sup> , c 2.5Y 7/6 <sup>4)</sup> , c 10YR 3/6 <sup>5)</sup>	si	1m sbk
	Bgj2	65–72	10YR 4/1	c 2.5Y 7/6 <sup>5)</sup> , c 7.5YR 3/4 <sup>5)</sup>	si	1m sbk
	CBg	72–85	2.5Y 2.5/1		si	2c sbk
Ylistaro	Ap	0–30	7.5YR 2/2, 10YR 6/2 <sup>8)</sup>		sil	1m sbk
	Bw	30–52	5Y 5/1	c 7.5YR 4/4 <sup>4),5)</sup>	sil	2m sbk
	Bgj1	52–70	5Y 5/1	m 7.5YR 3/4 <sup>4),5)</sup> , c 2.5Y 8/4 <sup>4),5)</sup>	sil	2m sbk
	Bgj2	70–100	5Y 5/1	m 5YR 3/3 <sup>4),5)</sup> , 2.5Y 8/4 <sup>4),5)</sup>	sil	2c pr
	Bgj3	100–150	5 Y 5/1	m 7.5YR 3/4 <sup>4),5)</sup> , m 2.5Y 8/4 <sup>4),5)</sup>	sil	2vc pr
Laitila 1	Ap	0–25	2.5Y 3/2, 2.5Y 6/2 <sup>8)</sup>		sic	1m sbk
	AB	25–35	2.5Y 4/2	m 10YR 3/4	sic	2m pl
	Bg1	35–50	2.5Y 4/2	m 7.5YR 4/6 <sup>5)</sup> , m 5YR 3/4 <sup>5)</sup>	sic	3m pr
	Bg2	50–90	2.5Y 4/2	m 7.5YR 4/6 <sup>5)</sup> , m 5YR 2.5/2 <sup>5)</sup>	sic	3c pr
	BCg	90–125	2.5Y 4/1	c 7.5YR 4/6 <sup>5)</sup>	sic	2c pr
	C	125–180	2.5Y 4/1		sic	massive
Laitila 2	Ap	0–25	2.5Y 3/2, 2.5Y 6/2 <sup>8)</sup>		sic	1m sbk
	AB	25–35	2.5Y 4/2	m 10YR 3/4 <sup>4),5)</sup> , vf 2.5 Y 7/6	sic	2m sbk
	Bg1	35–55	2.5Y 4/2	m 7.5YR 4/6 <sup>5)</sup> , m 5YR 3/4 <sup>5)</sup> , vf 2.5 Y 7/6	sic	3m pr
	Bg2	55–85	2.5Y 4/2	m 7.5YR 4/6 <sup>5)</sup> , m 5YR 2.5/2 <sup>5)</sup>	sic	3c pr
	BCg	85–100	2.5Y 4/1	c 7.5YR 4/6 <sup>5)</sup> , f 2.5Y 2.5/1 <sup>9)</sup>	sic	3c pr

<sup>1)</sup> m=many, >20%; c=common, 2–20%; f=few, <2%

<sup>2)</sup> si=silt, sil=silt loam, sic=silty clay

<sup>3)</sup> 1=weak, 2=moderate, 3= strong, f=fine, m=medium, c=coarse, vc=very coarse  
gr=granular, sbk=subangular blocky, pl=platy, pr=prismatic

<sup>4)</sup> around previous root channels, yellow zone between dark brown zone

<sup>5)</sup> on ped faces

<sup>6)</sup> organic matter and <sup>7)</sup> mineral material not completely mixed

<sup>8)</sup> dry color

<sup>9)</sup> interiors in peds

Both Liminka pedons had horizons that had a pH≤3.5 (Fig. 4), a SO<sub>4</sub>-S content above 0.05% (Table 5) and yellow jarosite mottles at the 30–65 cm depth (Table 4), which are the criteria of sulfuric horizons. Because they occurred within

50 cm of soil surface, these pedons classify as coarse silty, cryic Typic Sulfaquepts (Soil Survey Staff 1996) and medium-textured Thionic Gleysols (FAO 1988). Both Liminka pedons also have sulfidic materials below the acidic horizons

Table 5. Soil pH and SO<sub>4</sub>-S content of the pedons.<sup>1)</sup>

Depth cm	pH		SO <sub>4</sub> -S <sup>2)</sup> mg/kg
	moist	dried	
<b>Liminka 1</b>			
0–25	6.5 <sup>c</sup>	6.1 <sup>a</sup>	623 <sup>c</sup>
25–35	4.7 <sup>abc</sup>	4.0 <sup>b</sup>	271 <sup>a</sup>
35–45	3.9 <sup>ab</sup>	3.6 <sup>d</sup>	323 <sup>b</sup>
45–65	3.4 <sup>a</sup>	3.4 <sup>e</sup>	655 <sup>d</sup>
65–85	5.3 <sup>bc</sup>	3.5 <sup>e</sup>	1325 <sup>f</sup>
85–100	6.5 <sup>c</sup>	3.9 <sup>c</sup>	1106 <sup>e</sup>
<b>Liminka 2</b>			
0–25	5.6 <sup>b</sup>	5.7 <sup>a</sup>	854 <sup>b</sup>
25–65	3.4 <sup>a</sup>	3.4 <sup>b</sup>	661 <sup>a</sup>
65–72	4.6 <sup>ab</sup>	2.9 <sup>c</sup>	2442 <sup>d</sup>
72–85	5.4 <sup>b</sup>	3.4 <sup>b</sup>	1496 <sup>c</sup>
90	6.0 <sup>b</sup>	n.d.	n.d.
<b>Ylistaro</b>			
0–30	4.3 <sup>e</sup>	4.2 <sup>d</sup>	29 <sup>a</sup>
30–52	3.9 <sup>d</sup>	3.7 <sup>c</sup>	42 <sup>b</sup>
52–70	3.8 <sup>c</sup>	3.5 <sup>c</sup>	60 <sup>c</sup>
70–100	3.5 <sup>b</sup>	3.3 <sup>ab</sup>	112 <sup>d</sup>
100–125	3.4 <sup>a</sup>	3.3 <sup>a</sup>	156 <sup>e</sup>
125–150	3.4 <sup>a</sup>	3.4 <sup>abc</sup>	480 <sup>f</sup>
<b>Laitila 1</b>			
0–25	5.9 <sup>c</sup>	5.7 <sup>e</sup>	222 <sup>a</sup>
25–35	3.5 <sup>ab</sup>	3.3 <sup>c</sup>	413 <sup>b</sup>
35–50	3.3 <sup>a</sup>	3.0 <sup>b</sup>	1410 <sup>c</sup>
50–90	3.8 <sup>b</sup>	2.8 <sup>a</sup>	5777 <sup>f</sup>
90–125	6.0 <sup>c</sup>	3.1 <sup>bc</sup>	4329 <sup>e</sup>
125–150	7.6 <sup>d</sup>	3.0 <sup>ab</sup>	4250 <sup>e</sup>
150–180	7.5 <sup>d</sup>	3.7 <sup>d</sup>	3394 <sup>d</sup>
<b>Laitila 2</b>			
0–25	5.3 <sup>c</sup>	5.1 <sup>a</sup>	61 <sup>a</sup>
25–35	3.7 <sup>b</sup>	3.8 <sup>b</sup>	156 <sup>b</sup>
35–55	3.4 <sup>ab</sup>	3.5 <sup>c</sup>	227 <sup>c</sup>
55–85	3.2 <sup>a</sup>	3.4 <sup>c</sup>	462 <sup>d</sup>
85–100	3.6 <sup>b</sup>	3.3 <sup>c</sup>	2069 <sup>e</sup>

<sup>1)</sup> Results of each soil and soil characteristics were tested separately. Means marked with the same superscript do not differ at P = 0.05.

<sup>2)</sup> Incubated samples, 0.01 M CaCl<sub>2</sub> extraction  
n.d. = not determined

(below 65 cm), as indicated by the drop in pH upon drying (Table 5). These black layers had negative redox potentials (Fig. 2) and the colour of iron monosulfide although these layers did not

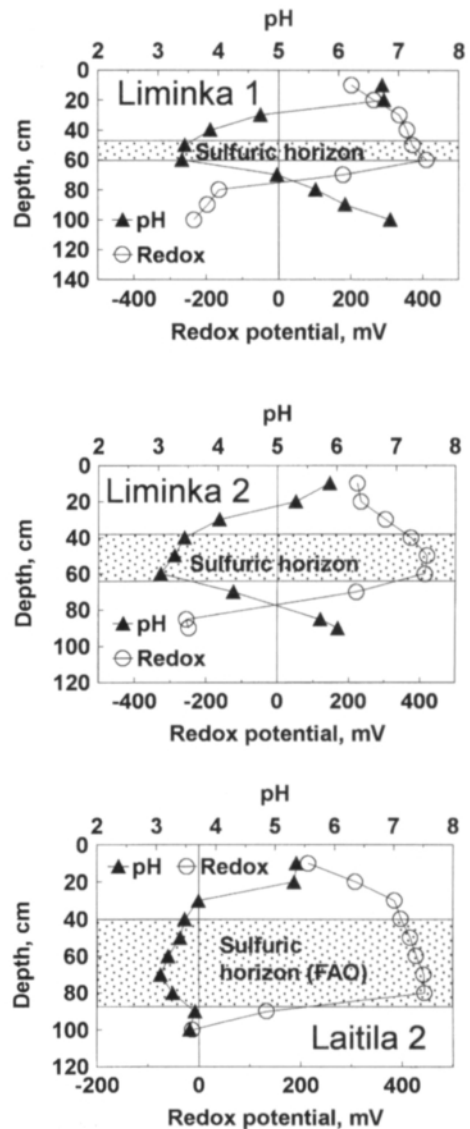


Fig. 4. Soil pH and redox potential of the Liminka 1 and 2 and Laitila 2 pedons, measured in the soil pit.

meet the total S requirement (0.75%) of sulfidic materials in the FAO/Unesco legend.

The Ylistaro pedon was oxidized throughout the sampling depth as indicated by the low pH



Table 6. Soil temperatures in Finland, measured at the depth of 50 cm.

Location		Period	Mean annual °C	Mean summer °C
Jokioinen	60°49'N, 23°30'E	1957–1970	5.9 <sup>1)</sup>	12.7 <sup>1)</sup>
Ylistaro	62°57'N, 22°31'E	1968–1980	5.5 <sup>2)</sup>	13.1 <sup>2)</sup>
Sodankylä	67°22'N, 26°39'E	1963–1970	3.0 <sup>1)</sup>	11.8 <sup>1)</sup>
Utsjoki	69°45'N, 27°02'E	1964–1970	1.9 <sup>1)</sup>	6.2 <sup>1)</sup>

<sup>1)</sup> Finnish Meteorological Institute (1979)

<sup>2)</sup> Agricultural Research Centre of Finland, unpublished data

which did not change upon aerobic incubation (Table 5). Long-term drainage has led to leaching of  $\text{SO}_4\text{-S}$  to below the requirement for the sulfuric horizon in Soil Taxonomy. However, below 52 cm, jarosite was present (Table 4), an alternative criterion of the sulfuric horizon, and below 100 cm the pH was  $<3.5$  (Table 5). Thus a sulfuric horizon was present at 100–150 cm. The Ylistaro pedon is classified as a fine silty Sulfic Cryaquept (Soil Survey Staff 1996). In the FAO/Unesco legend, the  $\text{pH}<3.5$  is sufficient to identify a sulfuric horizon, and this pedon classifies as a medium-textured Thionic Gleysol (FAO 1988).

The Laitila 1 pedon had a  $\text{pH}<3.5$  and a high content of  $\text{SO}_4\text{-S}$  in the 35–50 cm layer, which qualifies as a sulfuric horizon (Table 5). Very little or no jarosite was observed. At 50–150 cm there were sulfidic materials according to the requirements of both classification systems (Table 2). The pedon classifies as a fine, cryic Typic Sulfaquept (Soil Survey Staff 1996) and a fine textured Thionic Gleysol (FAO 1988).

In the Laitila 2 pedon there was a layer at 40–85 cm which had a  $\text{pH}<3.5$  in moist soil (Fig. 4). None of the other requirements of a sulfuric horizon of Soil Taxonomy were fulfilled: neither jarosite nor sulfidic materials occurred within the sampling depth, and the content of  $\text{SO}_4\text{-S}$  was too low. However, at 85–100 cm there was a  $\text{SO}_4\text{-S}$  content  $>0.05\%$  and a  $\text{pH}<4.0$  (Table 5), allowing the soil to be classified as a fine Sulfic

Cryaquept (Soil Survey Staff 1996). Moreover, the redox potential reached a value of 0 mV at approximately 100 cm (Fig. 2). Sulfidic materials can be expected below this depth, supporting the above classification. According to the FAO/Unesco legend, a sulfuric horizon occurs at 40–85 cm in this soil. Therefore, Laitila 2 is a fine-textured Thionic Gleysol.

## Discussion

Major processes after drainage of soils formed in sulfidic sediments include 1) oxidation of sulfidic materials to sulfuric acid with a consequent decrease of pH and 2) leaching of water-soluble components (sulphate accompanied by acid and base cations), resulting in the decrease of base saturation. The pedons of this study can be arranged according to decreasing base saturation and decreasing contents of sulfidic materials and sulphate as follows:

Laitila 1 > Liminka 2 > Liminka 1 > Laitila 2 > Ylistaro

The Liminka 1 and 2 and Laitila 1 pedons (Typic Sulfaquepts/Thionic Gleysols) contained sulfidic materials and sulfuric horizons with high contents of easily soluble  $\text{SO}_4\text{-S}$ . The Laitila 1

pedon is placed first because it is the only pedon which contained sulfidic materials also according to the criteria of the FAO/Unesco legend. The sulfuric horizon was closer to the soil surface in the Liminka 2 pedon than in the Liminka 1 pedon and therefore it has more pronounced a.s. characteristics than the Liminka 1 pedon. The Ylistaro and Laitila 2 pedons (Sulfic Cryaquepts/Thionic Gleysols) were oxidized and leached to greater depths, resulting in lower base saturation. The Laitila 2 pedon had a sulfuric horizon only according to the criteria of the FAO/Unesco legend. It was much more oxidized and leached than the Laitila 1 pedon nearby, because the Laitila 2 pedon was slightly higher in the landscape while the Laitila 1 pedon was taken from the more poorly drained deepest point of the polder. However, owing to the lower base saturation and  $\text{SO}_4\text{-S}$  content, the Ylistaro pedon can be considered the most leached one and is placed last in the sequence.

According to this investigation, cultivated a.s. soils along the western coast of Finland commonly qualify as Typic Sulfaquepts (Soil Survey Staff 1996). The soils of Mälsör (Koivulahiti), Bäckby (Ähtävä) and Vaasa in Southern and Central Ostrobothnia (Hartikainen and Yli-Halla 1986, Palko et al. 1987, and Erviö 1991, respectively) probably also meet the requirements of Typic Sulfaquepts. The present study and previous investigations suggest that the soils of Storsjö (Lapväärtti) in Southern Ostrobothnia (Hartikainen and Yli-Halla 1986, Palko and Saari 1987) and many soils in the Sirppujoki catchment in Southwestern Finland (Palko et al. 1985) can be classified as Sulfic Cryaquepts. The occurrence of Sulfic Cryaquepts in Finland, in addition to the Swedish soils (Öborn 1989), justifies the recognition of this taxon which was added only in 1992.

Pedogenesis results in gradual changes in the soils formed in sulfidic sediments. Besides artificial drainage, pedogenic transformations in a.s. soils are promoted also by the postglacial land uplift which continues at the annual rate of 4–8 mm on the western coast of Finland. The present pedons constitute a sequence exemplifying dif-

ferent stages of pedogenesis of a.s. soils. Initially, all of them were probably Sulfaquents, developing into Sulfaquepts when drained for agriculture. Over time the sulfuric horizon moves downwards and a Sulfaquept is transformed into a Sulfic Cryaquept like in the Ylistaro pedon which exhibits a sulfuric horizon below 100 cm. That soil probably once had a sulfuric horizon below 50 cm because there was still abundant jarosite at that depth. The Ylistaro pedon resembles the two Sulfic Cryaquepts (Ängesby and Ersnäs) from Northern Sweden (Öborn 1989) which contained jarosite but were low in  $\text{SO}_4\text{-S}$  and had the most acidic horizons at the depth of 70–110 cm.

Principally, a similar sequence as described above was presented by Fanning and Fanning (1989) in an East-Texas environment where a Sulfaquent developed into a Sulfaquept and further into a Sulfic Endoaquept and finally into a Haplustalf and a Vertic Albaqualf. In the cool and humid climate of Finland, cultivated a.s. soils are eventually transformed from Sulfic Cryaquepts to Typic Cryaquepts (Soil Survey Staff 1996). In terms of the FAO/Unesco system, Thionic Gleysols become Dystric Gleysols or Gleyic Cambisols. The Härkmeri soil (Lapväärtti) in Southern Ostrobothnia (Yli-Halla and Hartikainen 1984) represents this final stage. It had a  $\text{pH}(\text{CaCl}_2)$  of 3.5 in aerobic subsoil, but none of the other requirements of the a.s. soils were met. Typically, low pH is a more persistent soil characteristic than a high  $\text{SO}_4\text{-S}$  content.

In a recent survey (Puustinen et al. 1994), approximately 300,000 ha of cultivated soils in Finland with a minimum  $\text{pH}<5$  in subsoil were recognized as a.s. soils. This estimate is certainly much greater than the area of soils meeting the requirements of a.s. soils as stated in Soil Taxonomy or the FAO/Unesco Soil Map of the World. The national criteria can also be questioned from the environmental point of view. Based on the above results, it can be concluded that soils with subsoil pH values of 4–5 (a.s. soils according to the national criteria) do not contain actively oxidising sulfide or appreciable

quantities of acidic solutes. These soils may have passed the raw, acid-generating phase or their sulfide content was too low in the first place to produce sufficient sulfuric acid to lower the pH below 4.0. Therefore, soils with subsoil pH values between 4 and 5 do not present a hazard of acid loading to the recipient water courses. If these soils are included in a.s. soils, the environmental problems caused by a.s. soils in Finland are apparently overemphasized and may draw attention of authorities away from the re-

mediation of the acid loading in areas with the highest loading potential.

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## SELOSTUS

### Suomen happamien sulfaattimaiden kansainvälinen luokittelu

Markku Yli-Halla

*Maatalouden tutkimuskeskus*

Suomessa luokitellaan happamiksi sulfaattimaiksi sellaiset maat, joissa kuivaamattomasta näytteestä mitattu maaprofiilin minimi-pH on alle 5 ja maan hapetus-pelkistyspotentiaali ensin nousee ja sitten laskee mentäessä maaprofiilissa alaspäin. Kansainvälisiä maaperän luokitusjärjestelmiä ovat FAOn/Unescon järjestelmä ja Yhdysvalloissa kehitetty Soil Taxonomy -järjestelmä. Jotta maa olisi sulfaattimaa, sen pH:n on oltava Soil Taxonomy-järjestelmässä alle 4,0 ja FAOn/Unescon järjestelmässä alle 3,5. Vaihtoehtoisesti pelkistyneessä maassa on oltava niin paljon sulfidia, että hapettuvan maan pH laskee alle e.m. raja-arvojen. Luokittelurajojen tarkoituksena on, että (happamiksi) sulfaattimaiksi nimettäisiin vain sellai-

sia maita, joissa on tai joissa voi kehittyä runsaasti happamuutta. Tällaiset maat voivat tuottaa ympäristöönsä merkittävää happamoittavaa kuormitusta.

Tässä tutkimuksessa Limingasta, Ylistarosta ja Laitilasta otettuja happamia sulfaattimaita luokiteltiin kansainvälisten kriteerien mukaan. Maaprofiilien tutkimus osoitti, että maamme länsirannikolla esiintyy yleisesti Soil Taxonomy -järjestelmän Typic Sulfaquepts- ja Sulfic Cryaquepts- luokkiin ja FAOn/Unescon luokituksen Thionic Gleysols- luokkiin kuuluvia viljelymaita. Sellaiset Suomessa happamiksi sulfaattimaiksi nimitetyt maat, joiden pH on 4–5, eivät kansainvälisten kriteerien mukaan kuitenkaan ole happamia sulfaattimaita.