THE PEAT DEPOSIT OF THE SUBSIDING ZENNARE BASIN, SOUTH OF THE VENICE LAGOON, ITALY: GEOTECHNICAL CLASSIFICATION AND PRELIMINARY MINERALOGICAL CHARACTERIZATION

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1. *Abstract.*

This study is part of the VOSS Project (Venice Organic Soil Subsidence) and deals with the geotechnical classification and a preliminary mineralogical characterization of peat soils of the experimental site in the Zennare Basin. The scope is to better understand the correlation between peat oxidation and loss in ground elevation.

For the geotechnical characterization a visual classification and the von Post classification were used. A preliminary mineralogical characterization was done using an Environmental Scanning Electron Microscope (ESEM).

The peat in the experimental site is formed by vegetal deposits and can be distinguished in two levels: a completely decomposed amorphous granular top level and a slightly decomposed fibrous bottom level with a higher organic content. The limit between the two levels corresponds to the depth to which the plough furrows.

2. *Introduction.*

This study investigates the following: a) water content in peat layers, b) mineralization grade, c) type of minerals and their distribution, d) mineral zonations, e) structure of the organic components in the Zennare Basin.

Because of the high organic and moisture content in the soil, ad hoc analytical techniques and instrumentations had to be used. Textural, geochemical and mineralogical analyses of few peat samples have been obtained using an Environmental Scanning Electron Microscope (ESEM) equipped with an Energy Dispersive Spectrometer (EDS).

Furthermore, a geotechnical classification of the organic soil is proposed using different in situ and laboratory methods based on basic geotechnical properties such as structure, water content, ignition loss, humification grade.

3. *Geological-stratigraphycal setting.*

The analyzed peaty soil has been collected from one site in the Zennare Basin, a 23 Km^2 area which is part of the south catchment of the Venice Lagoon between the Adige and Bacchiglione rivers (Favero, Serandrei Barbero, 1978). At present the area is covered by alluvial sediments where sandy and silty soils represent the remnants of ancient fluvial ridges and peaty soils the interdistributary lowlands characterized by the presence of marshes and swamps. In the second half of the 19^{th} century reclamation works started for agricultural activities. The area was completely reclaimed in the first half of the 20^{th} century. Soil ploughing enhanced the oxidation of the peaty soil with consequent formation and emission of carbon dioxide, mass loss, and subsidence.

The outcropping peat deposit extends for many square kilometres with a thickness of 1-2 metres. It derives from the accumulation of reeds (*Phragmites australis*) living in wetlands before the reclamation. *Cupressus sempervirens*, *Sambucus nigra*, *Salix*, *Eriophorum* and *Carex* constitute the actual natural vegetation in addition to corn, the most important crop in the area.

According to the "Treatment of Organic Soils in the U.S.D.A. 7^{th} Approximation Soil Classification", the Zennare Basin soil is a *Histosol* (order soil number 10). It is defined as *soil with organic matter that does not contain mineral layers in the upper 40 cm.*

An experimental site has been selected within the study area to collect the samples for geotechnical and mineralogical analyses. The results show that there are two major levels of the same original peat (Tab. 1): the top layer, between 0 and 40 cm deep, is constituted by oxidized soil ploughed due to agricultural activities; the underlying layer between 40 and 100 cm deep, is constituted by fibrous peat with well-preserved fibres, in growing position between 50 and 90 cm deep. Furthermore, at a depth ranging between 100 to 110 cm there is a transition layer of clayey peat, and between 110 and 145 cm a clay unit with spread vegetable remains. Finally, between 145 and 200 cm of depth, a layer of gray silty medium sand is observed. Samples of the two peaty layers were collected by digging a 2 meters-deep trench and horizontally inserting a 15-cm diameter plastic tube. The G1 sample was cored at a depth of 22.5-37.5 cm, and the G2 at a depth of 92.5-107.5 cm. The water table depth ranges between 40 and 70 cm and is controlled by pumping stations.

4. *Historical data of reclamation.*

The study basin is the result of very deep transformations (Benincasa, 2001) caused by human intervention to reclaim large cultivable areas from marshes and swamps (Fig.1).

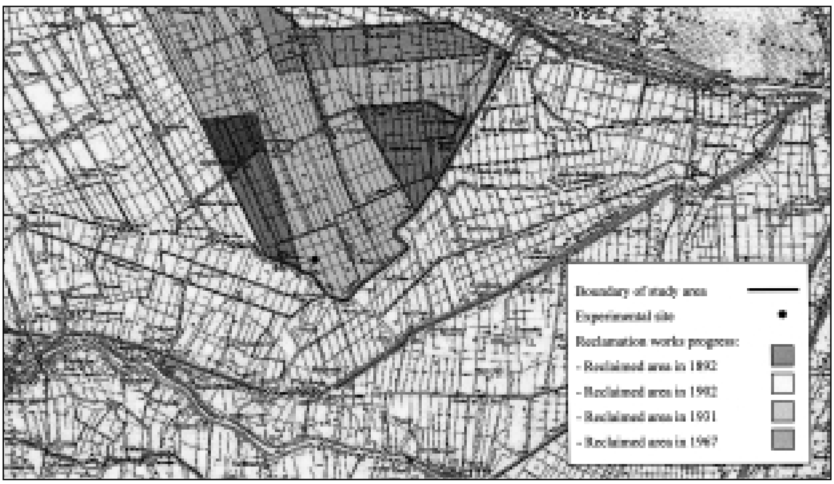

Fig. 1 - Historical reclamation data.

In 1833 (map of the Regno Lombardo Veneto, scale 1:86400, 1833) the area appeared as a bog including Valle Cordonazzo in the west, Valle Sista in the center and Valle Zenare in the east.

In 1892 (map I.G.M. - Brenta (F°. 65; IV SE), scale 1:25000) only the northern part started to be reclaimed.

In 1902 (map I.G.M.- Brenta (F°. 65; IV SE), scale 1:25000) most of

Tab. 1 - Description of the trench stratigraphy.

	Samples	depth, cm	Description
	G1 S2	0 - 40	*Black amorphous granular* peat with numerous remains of little brown roots, leaves, seeds and light olive green woody reed fragments. Size of fragments is from 1 mm to some centimeters. Small roots give some cohesion to the soil by keeping the grains of peat together. Slight smell.
		40 - 50	*Brown fibrous peat*, very moist, with a rather compact structure, prevalently consisting of light olive green soaked reeds, randomly arranged. Reeds are up to 3 cm long and 1 cm wide. Presence of several roots from 1 mm to some centimeters long. Slight smell.
		50 - 80	*Brown fibrous peat*, very moist, with a compact structure, prevalently consisting of light olive green intact soaked reeds, in growing position. Reeds are more than 10 cm long and some cm wide. Very strong smell.
	S5	80 - 90	*Brown fibrous peat*, more compact than the previous one and with abundant brownish dark gray clayey matrix. Reeds remains prevail over clayey components and have the same features as the previous ones. Very strong smell.
	G1	90 – 100	*Brownish gray fibrous peat*, very compact and with an increasing quantity of brownish medium gray clayey matrix. Reed remains prevail over clayey components and are arranged in horizontal layers. Very strong smell.
	S6	100 – 110	*Grayish-brown fibrous clayey peat*, very compact. The clayey component increases up to 50%. Reed remains are arranged in horizontal layers. Very strong smell.
	S8	110 – 145	*Light blue-grayish clay*, very compact with spread remains of dark brown-blackish roots and brownish green reeds. Strong smell.
		145 – 200	*Gray silty medium sand* with a lot of mica. Rare vegetal remains. No smell.

the study area started to be reclaimed except for the southern part of Valle Cordenazzo in the west as well as the southern part of Valle Zenare in the east.

In 1931 (map I.G.M. - Brenta (F°. 65; IV SE), scale 1:25000) only the northern part of Valle Cordenazzo was still wet.

In 1967 (map I.G.M. - Civè (F°. 65; IV SE), scale 1:25000) the overall study area has been reclaimed.

Interview to some local people has revealed that, farmers had to ameliorate a few areas of the basin for agricultural use due to acidity and salinity of soil even if no trace of salty environment was found by experimental studies. Up to the 1980's, they used to spread lime over these areas to reduce the acidity and to flood these fields with fresh water to reduce the salinity. They tried to cultivate crops different from corn, such as soybean, but return was not high enough.

5. *Visual Classification.*

A visual *in situ* classification (Muskeg Engineering Handbook, 1969) is fundamental to describe the peat state because some characteristics, i.e., the colour, can change rapidly on exposure to air as result of oxidation; within an hour the peat is coloured with a uniform dark brown or black.

Very high quality samples have been accurately collected for laboratory tests without disturbing the soil structure or changing the moisture content. The samples have been taken horizontally to avoid sediment compression and have been kept in a humidity and temperature controlled room.

To a visual analyses (Tab. 2), G1 sample structure appears amorphous granular and G2 structure appears fibrous. This is confirmed by the scanning electron microscope observation. The highly humified fibres have been totally reduced by agricultural machines.

While G1 contains just rare few millimetres fibres represented by little roots, G2 consists almost exclusively of reeds in growing position. Because of the nature of the reed stems, the remains are well-preserved and keep the peat very compact.

G1 sample is not too wet to the touch while G2 is.

The colour is black for G1 because of the oxidisation due to agricultural use of the soil. G2 sample is generally brown but reeds are greenish yellow because they are less decomposed than the matrix due to their siliceous content.

Due to the presence of H_2S, smell is very slight for G1 and very strong for G2 because anacronyc decomposition is proceeding.

Tab. 2 - Visual classification table.

sample name	**G1 (depth: 22.5-37.5 cm)**	**G2 (depth: 92.5-107.5 cm)**
sample dimension	L = 16 cm; Ø = 15 cm	L = 24.5 cm; Ø = 15 cm
sample direction	horizontal	horizontal
sample quality	Q5	Q5
peat structure	granular position and woody fibres	fibrous with reeds in growing
water content	not too wet	very wet
colour	black freshly exhumed reeds	brown with greenish yellow
smell	very slight	very strong

6. *Geotechnical Classification.*

6.1. *von Post Classification (1922).*

A common classification scheme used in Europe (Tab. 3) is that proposed by von Post (1922) based on a simple squeeze test for assessing the degree of humification on a scale from 1 to 10 (H_1 being the least humified). In addition to humification (H_n), the predominant plant is noted together with wetness (B), fine fibres (F), coarse fibres (R), wood and shrub remnants (V), organic content (N), smell (A), plasticity (P) and pH (Muskeg engineering handbook, 1969).

This is a simple and highly informative system which has the advantage of requiring only close scrutiny of the peat. It attempts to describe peat and its structure in quantitative terms and to provide the means with which to correlate the types of peat with their physical, chemical, and structural properties.

Another classification system "Treatment of Organic Soils in the U.S.D.A. 7th Approximation Soil Classification" is used to complete the von Post classification.

The botanical composition represents the principal vegetal component. It is not possible to identify it for the G1 sample because it is macroscopically invisible. G2 sample peat appears to consist mainly of the common reeds, Phragmites (symbol: Ph), a plant which is tolerant of brackish conditions (Hobbs, 1986). It is 1-4 m tall and it grows in up to 2 m deep water. It usually forms a densely packed closed reed swamp community. By preventing water circulation the clay and silt deposition is encouraged; the rich mineral nutrients and concomitant breakdown and humification of the newly dead plant detrital fragments produce a luxuriant emergent growth. Reeds are well preserved and in growing position because they are not oxidized and acid conditions have prevented the production of detrital mud. The basal reed peat is, however, more divided and reeds are in a horizontal position.

The degree of humification relates to the degree of biochemical decomposition of original plant components. This is a visual/manual method: a representative sample is picked by hand and squeezed firmly. A considerable difference appears between G1 and G2 samples with respect to the degree of humification: the highest grade (H_{10}) is evident for the first sample composed of little oxidized detrital fragments, while a very low grade (H_3) is present for the second sample composed of well preserved non-oxidized fibres. The G2 sample presents an H_3 degree as a general property but an H_2 degree is attributable to stronger parts of the reeds like stems.

For the "Treatment of Organic Soils in the U.S.D.A. 7th Approximation Soil Classification" the G1 sample represents a Histosol (organic soil) as order and Saprist (humification about H_9 to H_{10}) as sub-order; G2 represents a Histosol as order and Fibrist (humification about H_1 to H_5) as sub-order.

The water content of peat is estimated on a scale from 1 (dry) to 5 (very high, greater than 2000%), designated B_1 to B_5. It was calculated using ASTM Designation D 2974-87 test method: "Standard Test Methods for Moisture of Peat and Other Organic Soils". G1 sample presents a moisture content of 95% identified as B_2 degree ($w<500\%$) and G2 sample presents 629% that corresponds to B_3 degree ($500\% < w < 1000\%$).

Fine fibres are defined as less than 1 mm long. The content is graded on a scale from 0 to 3. G1 sample has a low visible content of fine fibre (F_1) while G2 has a moderate content (F_2). Coarse fibres are defined as more than 1 mm long. The content is graded on a scale from 0 to 3. G1 sample presents only visible fine fibers and no coarse ones (R_0); G2 total fiber content is mostly constituted by coarse fibres (R_3: high content).

Macroscopic wood content is graded on a scale from 0 to 3. G1 sample does not present it (W_0: no content), while G2 has a moderate content (W_2) if we consider reed stems as "woody" because of their strong siliceous composition.

Organic matter content (Andreiko et al., 1983) is calculated by subtracting percent ash content from one hundred determined by ASTM Designation D 2974-87 test method: "Standard Test Methods for Ash of Peat and Other Organic Soils" (Annual book of ASTM standards, 1996). G1 sample presents a 49% of organic matter; it corresponds to the N_2 class (40 %< N<60%). For G2 the organic content is 73% that corresponds to N_3 (60 %< N<80%). The smell, which is an indication of fermentation under anaerobic conditions, is graded on a scale from 0 to 3 in the von Post classification. It is very slight (A_1) for G1 and very strong (A_3) for the G2 sample. This is due to the differing degree of decomposition of the two peaty samples.

Regarding the plasticity index, if it is impossible to determine its value the sample is classified as P_0, if it is possible it is P_1. The Zennare Basin peats are classified as P_1.

The pH is evalueted by using ASTM Designation 2976-71: "Standard Test Method for pH of Peat Materials". G1 and G2 samples have the same pH=5 that in the von Post classification corresponds to index pHL. This acid reaction can be caused by the presence of carbon dioxide and humic acid arising from peat decay.

6.2. *ASTM Classification (1992): Standard Classification of Peat Samples by Laboratory Testing.*

ASTM classification (Tab. 4) is under the jurisdiction of the American Society for Testing and Materials Committee and has been approved by agencies of the American Department of Defence (Annual book of ASTM standards, 1996).

Comments regarding moisture, ash, organic matter content, degree of humification and pH are in the von Post classification paragraph.

Fiber content is determined using the standard test method D 1997-91 that covers the laboratory determination of the fiber content of peaty samples by dry mass. The description of the term "fiber" used in this method is fundamental: *a fragment or a piece of plant tissue that retains a recognisable cellular structure and is large enough to be retained on a 100-mesh sieve (openings 150 μm). Plant materials larger than 20 mm in smallest dimension are not considered fibers.*

G1 sample has a fiber content of 44 % and it is classified as hemic

Tab. 3 - von Post classification table.

sample name	**G1 (depth: 22.5-37.5 cm)**	**G2 (depth: 92.5-107.5 cm)**
botanical composition	---	Ph (Phragmites australis)
H: degree of humification or decomposition *	H_{10}: completely de-composed peat containing no discernible plant tissues. When squeezed, all of the peat releases through the fingers as a uniform dark paste.	H_3: Slightly decomposed peat that when squeezed, releases turbid brown water, but in which no amorphous peat passes between the fingers. Plant remains are still relatively intact. H_2 (for stronger part of reeds): almost completely undecomposed peat that, when squeezed, releases yellowish water. Plant remains are still relatively intact. No amorphous material present.
B: moisture content *	B_2: w<500%	B_3: 500%<w<1000%
F: fine fibres content (Ø <1 mm)	F_1: low content	F_2: moderate content
R: coarse fibres content (Ø >1 mm)	R_0: no content	R_3: high content
W: woody fibres content	W_0: no content	W_2: moderate content
N: organic matter content *	N_2: 40%<N<60%	N_3: 60%<N<80%
A: smell	A_1: very slight	A_3: very strong
P: plasticity	P_1: it's possible to determi-nate the plastic limit test	P_1: it's possible to deter-minate the plastic limit test
pH *	pH_L: pH<7	pH_L: pH<7

(fiber content between 33% and 67%). G2 sample results in a fiber content of 30% and it is classified as sapric (fiber content < 33%). Therefore, due to the definition of "fiber", G2 appears to be less fibrous than G1 only because it is composed almost exclusively by more than 2 mm long and wide coarse fibers (Gatti, 1997).

*determined by ASTM test.

Tab. 4 – ASTM classification table for the peat samples collected in the Zennare Basin.

sample	**G1 (depth: 22.5-37.5 cm)**	**G2 (depth: 92.5-107.5 cm)**
moisture content (85°C) (standard test method: D 2974-87)	95%	629%
ash content (440°C) (standard test method: D 2974-87)	51%	27%
organic matter content (440°C) (standard test method: D 2974-87)	49%	73%
fibre content (150 _m<fibre<20 mm) (standard test method: D 1997-91)	44% *(Hemic)	30% **(Sapric)
degree of humification (standard test method: D 5715-95)	H10	H3
pH (standard test method: D 2976-71)	5	5

7. *Geotechnical characteristics of peat of the experimental site within the Zennare Basin.*

The peat bulk density (Tab. 5) is very low. It is related to the organic content and influenced by the degree of saturation or gas content emitted by the humification process. Peats are generally under-saturated and are buoyant under water due to the presence of gas. G1 sample presents a bulk density (mass of oven dry soil per unit volume) equal to 0.302 g/cm^3 while G2 sample has a bulk density equal to 0.253 g/cm^3 due to its larger organic content and its decomposition in act (Landva, 1983).

* in the G1 sample there is no fibres >2mm.
** almost 70 % of the G2 sample is composed by fibres >2mm.

Water content of fibrous peat is almost five times higher than that of the amorphous peat, while the organic content is almost double. In general, the greater the organic content the greater the water content. The difference, however, is also due to the higher degree of decomposition of amorphous peat with respect to the fibrous peat. In fact, fibrous peat (low humification) has a higher total water content than the granular-amorphous peat (high humification). The amount of intracellular water generally exceeds the interparticle water in fibrous peat and the proportion declines with the increase in humification as the cellular structure is destroyed (Landva and Pheeney, 1980). The organic content has a considerable effect on the physical and mechanical properties of peat. In general, the greater the organic content the greater the void ratio and the compressibility of the peat.

The specific gravity of the solids (ratio between specific weight of solids and specific weight of water) in peat is usually between 1.1 and 2.5 but more frequently between 1.4 and 1.6. It is measured by using Kerosene with a known specific gravity. G1 specific gravity is 1.670 for G1 and 1.449 for G2, due to the higher fibre content of this latter.

Peat fibrous nature makes the consistency of limits test difficult. They can usually be carried out only if the von Post humification exceeds the H3 degree. It is important to realise that limit measurement requires to destroy not only the fabric and structure sample, as in a clay soil, but partly decomposed fibres are themselves broken down into very fine detritus, each particle being surrounded by a powerful adsorption complex. Consequently, the tested material bears little relation to the material sampled, except in the case of much humified peat, as the G1 sample, in which breakdown has been virtually completed in the mire. The forcible reduction leads to a very high liquid limit for peat in comparison with clay, due to its low specific gravity and high cation exchange; the higher the cation exchange ability, the stronger the adsorption complex and the greater the interparticle adherence. The observed decline in the liquid limit with increased humification is the evidence of the weakening of the adsorption complex, presumably due to the decomposers. G1 sample, which has a high degree of humification, has a resulting liquid limit of 142, almost four times less than the G2 sample liquid limit of 524. Therefore, the fibrous state would be expected to have a higher liquid limit than the amorphous state.

Plasticity index results from the difference between liquid limit and plasticity limit. It is 41 for sample G1 and 161 for sample G2. The numerical value of the plastic limit, however, appears to be of little interest as no correlation has so far been found between the plasticity index and other properties. This is presumably because the plastic limit is associated with strength, a property that can be highly erratic in peat that is highly frictional.

Tab. 5 - Geotechnical characteristics of the Zennare Basin peat.

sample	**depth cm**	**γ g/cm³**	**w %**	**O_C %**	**G_S**	**LL %**	**PL %**	**PI 150 to 20 mm, %**	**pH**	**fibres from**	**fibres >20mm %**
G1	22.5-37.5	0.302	95	49	1.670	142	101	41	5	44	0
G2	92.5-107.5	0.253	629	73	1.449	524	363	161	5	30	≈70

TABLE LEGEND
γ: Bulk Density
w: Moisture Content
O_C: Organic Matter Content
G_S: Specific Gravity of Soil Solids
LL: Liquid Limit
LP: Plasticity Limit
PI: Plasticity Index

8. *Analyses of peat using ESEM.*

ESEM (Environmental Scanning Electron Microscope) is a new type of scanning electron microscope, which allows the examination of specimens in the presence of gases without preparation. As a result, it is possible to identify vegetal structures which would be stressed by sample drying (Cohen, 1983). This is fundamental to a detailed examination of the fabric and structure of peat which is characterized principally by water content and porosity (presence of voids).

While ESEM identifies morphology of crystals and vegetal structures an EDX (Energy Dispersive X-ray) system is useful to recognize the mineral composition.

Tab. 6 – Description of samples used for ESEM analyses.

Depth, cm	**Stratigraphy description**	**Sample**
0-50	Amorphous granular peat	S2, 29-30 cm
50-100	Fibrous peat	S5, 83-84cm
100-110	Fibrous clayey peat	S6, 107-108 cm
110-120	Light blue grayish clay	S8, 119-120 cm

These systems have been used to analyze four samples (S2, S5, S6, and S8) selected as representative of the four layers, which characterize the first 120 cm-stratigraphy of the experimental site in the Zennare Basin (Tab. 6).

Figure 2 shows the results of ESEM analyses.

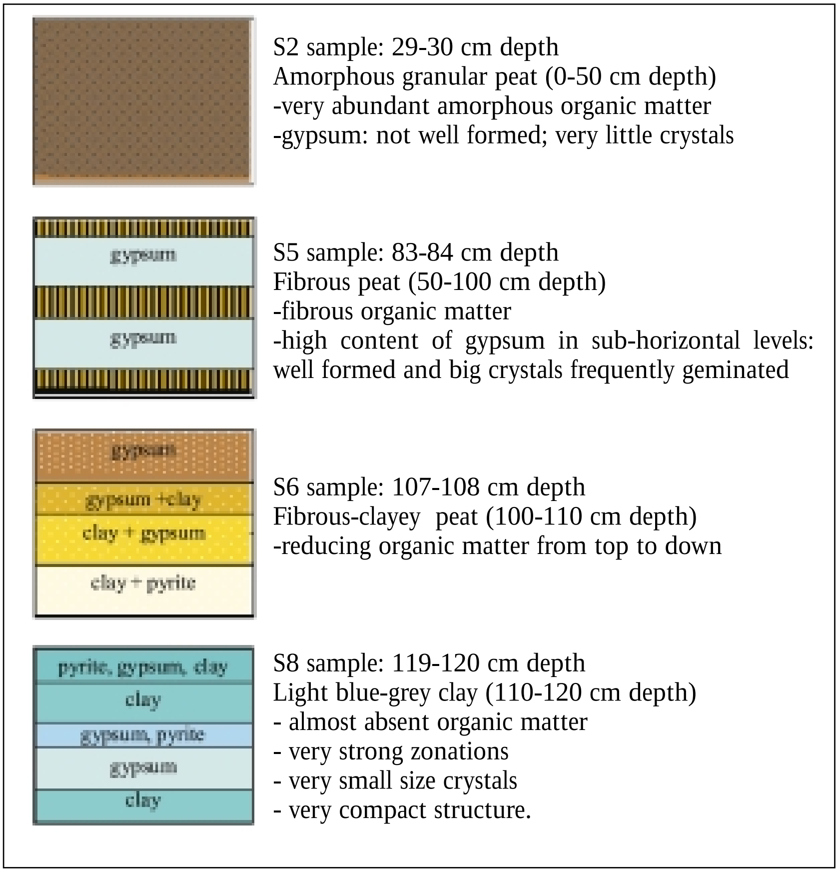

Fig. 2 – Mineral zonation of the four samples analyzed by ESEM.

The ploughed peat is very homogeneous and has a compact structure with pores smaller than the other peat levels due to lower decomposition gas content. The underlying peat level presents a strong zonation concerning the presence, size and shape of gypsum (Fig. 3).

The graph in figure 4 shows the general trend of main elements analyzed by he ESEM. The gypsum trend follows that of the organic matter while clay minerals and pyrite have an opposite behavior. The high gypsum content is probably due to the agricultural practice to spread lime on the fields to diminish the acidity of the soil in act until 1980's.

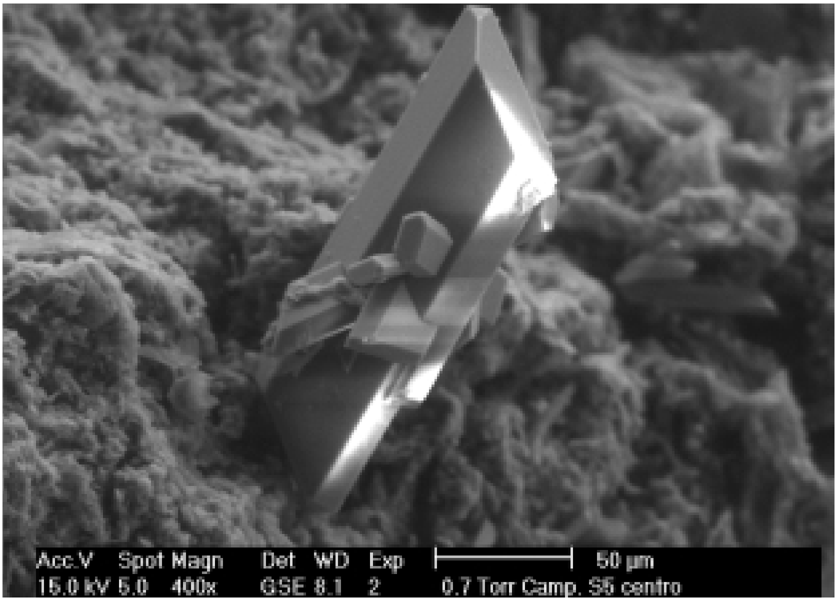

Fig. 3 – ESEM image of gypsum from S5 sample.

Figure 5 shows the results of some chemical analyses regarding the presence of sulphate, sulphide and total sulphur. Their trends are very similar: the content is very high in the fibrous peat level where there is a high gypsum content too.

9. *Conclusion.*

The peat deposit in the Zennare Basin can be divided into two levels (here referred to as top and bottom layers) based on their texture. The limit between them is defined by the depth to which the plough furrows (40-50 cm deep).

The top level consists of decomposed, oxidized homogeneous amorphous granular peat. It has lower liquid limit and water content and

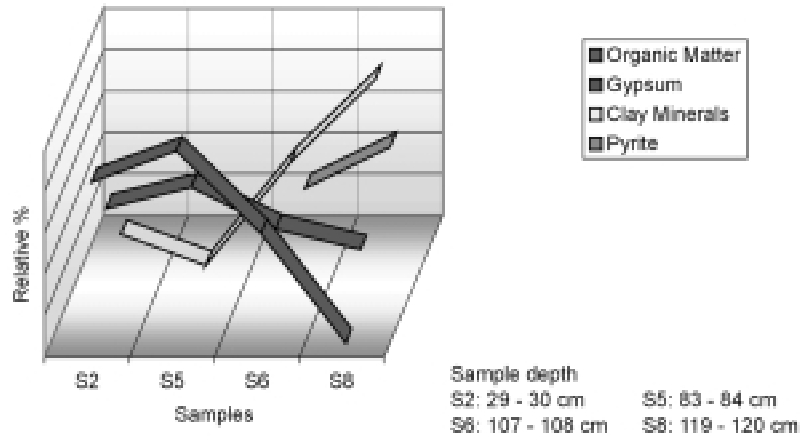

Fig. 4 - General trend of main ESEM analyzed elements from S2, S5, S6, S8 samples.

higher bulk density than the underlying peat level lying below it due to lower organic content. The top level has a higher specific gravity due to lower fiber content. The chemical analyses show that the top peat unit is characterized by a rich phosphorous content with elements suitable for agricultural practices, and the ESEM observation does not show any zonation. Moreover the structure appears more compact and with smal-

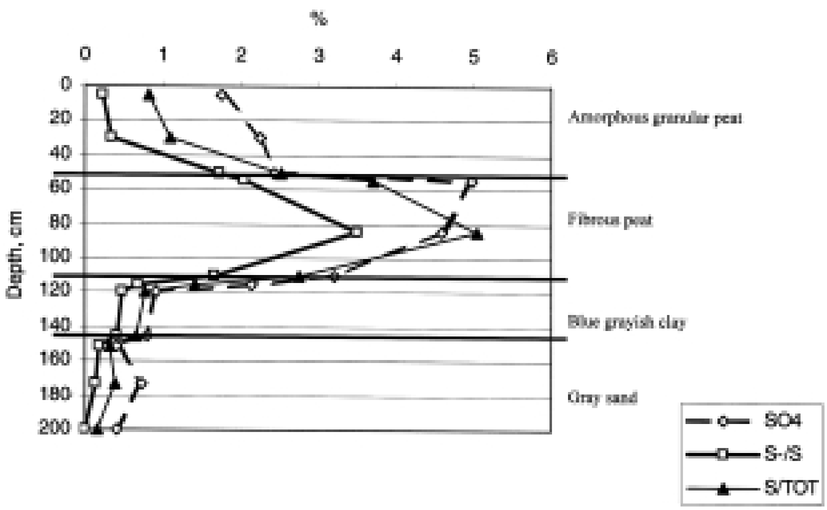

Fig. 5 - Sulphate, Sulphide and total sulphur content versus depth.

ler pores than that of the other level due to a lower content of decomposition gas.

The bottom level, which is not ploughed, is constituted by generally slightly decomposed fibrous peat with the presence of several almost completely undecomposed reed remains. It is very rich in sulphur because it is still decomposing. It has a very low bulk density because of the gas content emitted by the humification process in act. Fibers are still recognizable; the water content and the liquid limit are almost five times higher than the overlying ploughed peat and there is a higher organic content. Furthermore, the high liquid limit depends on the weakening of the adsorption complex due to the decomposition. The high water content occurs because the level is below the water table and because it contains a considerable amount of intracellular water inside the undecomposed fibers.

The bright colours and high content of undecomposed organic matter indicates that this level is poorly oxidized. ESEM observations show that the bottom level is well zoned with the presence of big crystals of gypsum, because the mineral growth is not disturbed. Porosity is very high and fibers are easily recognizable.

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