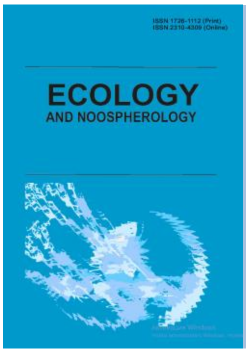

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Soil formation and hydrological evolution of Navazo del Toro small-lake ecosystem, Doñana National Park, Andalusia, Spain

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The wetlands on the quartz sands aeolian sheet make up one of the ecosystems most recognized and important of the Doñana National Park and Doñana Biological Reserve (South Spain). More than 650 temporal small-lakes have been surveyed in the abundant sand depressions of the aeolian sheet, the most are a hydro-geomorphological dune-small-lake system. This paper studies the pedological diversity around Navazo del Toro (NVT) wetland, one of the biggest temporal small-lakes, through a geopedological catena along 230 m with five soil profiles (NVT-1 to NVT-5). In this context a major focus is displayed on pedological processes and the current hydrological situation of the depression in the Middle-Upper Holocene. The main processes are: translocation of materials (silt and clay) from the Arenosols developed in the slope dune (sand washing processes), sediment accumulation on the dune depression (current wetland bottom), and the development of tirsificated and vertic Luvisols with a chronology of more than 4.255 BP (OSL dating). The water body of the geoecosystem has modified the horizons morphology, creating new hydromorphic (gleyic and stagnic) conditions that have incorporated abundant organic material (sediment of diatoms and sponge spicules) in the higher profile layer and generated an incipient podzolization processes.

Keywords: dunes; sand washing; small-lake; wetland evolution; Holocene; Navazo del Toro; Doñana; Spain

Introduction

The Navazo del Toro (NVT) small-lake is located in the Doñana Biological Reserve, settled at the Doñana National Park (Huelva, Spain), on El Abalario-Doñana Aeolian Littoral Sheet geomorphological unit (Fig. 1). This zone has been formed by a complex system composed by five morphosedimentary sheets whose the main parental material are quartz sands (>80%) (Borja, 1997; Borja, et al., 1999; Zazo et al., 2008). One of this five sheets is called "humid sheet" (High Aeolian Wet Sheet, AMEh), which is related to the existence of a large group of small sized wetland ecosystems (amongst 0.5–7 hec.) with a great biodiversity, geodiversity and ecological services and constituting one of the landscapes and environments more relevant of Doñana (Borja, 2011) (Fig. 1).

Except for one part of the active dune system (“active sheet”) (Fig.1), the rest of the aeolian units appears phyto-stabilised to a greater or lesser degree. The preferred landscapes of formation of wetland ecosystems are the aeolian sheet fronts, the dune depressions and the inter-dune valleys, as a result of reaching the aquifer the landscape topography.

As part of this zone, the results of the NVT small-lake reveal the existence of a hypogenic functioning, and during certain periods of the year the wetland presents a water layer disconnected of the hipogenic water table, configuring a systems of perched wetlands, similar to described by Brown et al. (2003), Schoeneberger and Wysocki (2005) and Melly et al. (2017). Other authors have denominated the hydrological functioning developed in the aeolian sheets’ mesogenic functioning with formation of their water body by direct retention of rainwater and the participation of subsurface waters that circulate through the interstices of sands under dry climate conditions (Borja, 2011; Recio et al., 2009, 2014 and 2019 (a)). Velasco et al. (2009) in 2003 wet winter and spring highlight through planktonic bacterias and sand transmissivity the hydrological connectivity between the surface waters and groundwaters in Toro-Dulce-Santa Olalla small-lakes ecosystem. Others important wetlands in Doñana National Park (Dulce or Santa Olalla ecosystem) its hypogenic formation is supplied permanently by hydrological groundwater (Suso and Llamas, 1993; Serrano and Serrano, 1996; García Novo (2000), Muñoz Reinoso, 2001; Manzano et al., 2002; Muñoz-Reinoso and Castro, 2005; Velasco et al., 2009).

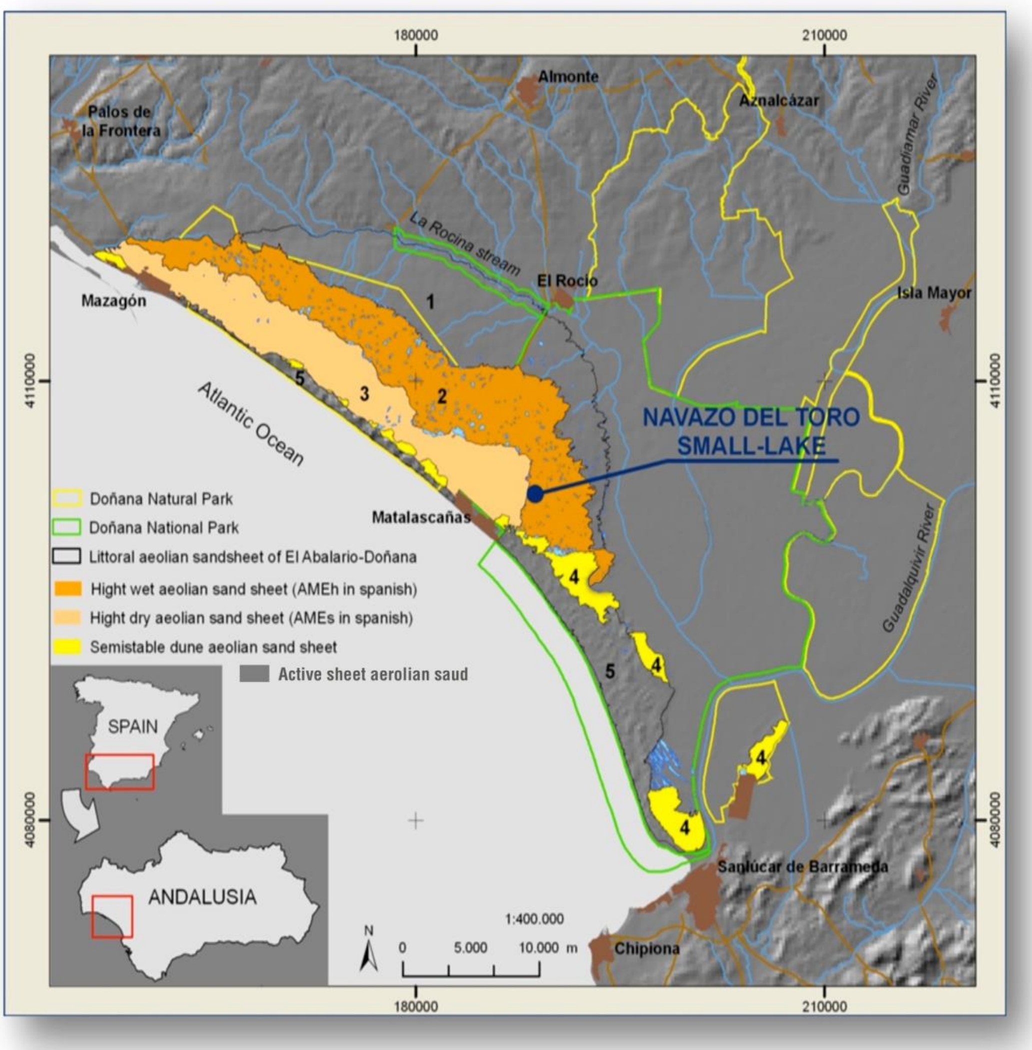


Fig. 1. Navazo del Toro small-lake location in Doñana National Park

Navazo del Toro small-lake is located on the limit between the High Aeolian Wet Sheet (AMEh, Middle Holocene) and the High Aeolian Dry Sheet (AMEs, Middle-recent Holocene), mainly associated with a system of phyto-stabilized parabolic sand dunes with a SW wind dominant direction (Borja, 1997; Borja, et al., 1999; Zazo et al, 2008) (Fig. 1). Doñana shows a average rainfall of 536 mm/y (series 1978-2017), whose 80% occurs from september to april, and a average temperature of 18ºC (maximum temperature are 41ºC and minimum annual average and -2ºC). For Capel Molina (1981) Doñana is part of the oceanic variety of the Mediterranean climate in Spain.

Nevertheless during wet periods with high rainfall (>536 mm/y) the groundwater of the regional aquifer floods all the sand depression. Whereas in dry years (<536 mm/y) it is possible to identify several water bodies in this ecosystem, disconnected of the groundwater levels.

This schedule constitute a "perched wetland" or “perched water tables”, where the pedological processes and the hydrological flows are conditioned by the hydrological cycle in the vadose zone, consequence of the soil horizons characteristics and in particular by the sand fraction size (Brown et al., 2003; Schoeneberger and Wysocki, 2005; Borja, 2011; Melly et al., 2017).

The NVT wetland extends over a sand depression of 4.5 ha (382 × 175 m). It topographic bottom basin presents a centimetric micro morphology in stepped holes called by us sectors: high, medium and low (Fig. 2). The higher sector lies at 21.80 m.a.s.l. and is flooded only in years with above-average precipitations; the medium sector lies from 21.80 to 21.50 m.a.s.l., and has a longer annual balance up to nine months in the rainy winters. Low sector constitutes the zones of less height than this last value flooded in the annual wet season (Fig. 2).

The juniper woodland (“bosque de Naves”) is a vegetal xerophytic formation characteristic of the High Aeolian Dry Sheet, forest which phytostabilize the aeolian-sheet dunes not affected by the groundwater fluctuation. The progressive fall of the littoral groundwater levels in Doñana during the last decades (urban and agrarian water extractions) have increased the colonization xerophytic species (*Juniper*, *Phillyrea*, *Pine*, etc.) (Muñoz Reinoso, 2001). Particulary in NVT ecosystem the vegetation mainly consists in *Juncus spp.* and *Scirpus spp.* in the lateral areas of the lower sectors, *Agrostis stolonifera* in the central area, including the lower and medium sectors, and *Pinus pinea, Erica spp.*, *Cistus* spp on the high sector and the contact among the sand depression with the dune.

Siljeström and Clemente (1987) and Siljeström et al. (1994) described the large environmental units of Doñana through geomorphology-soil-vegetation relationships, and provided some initial data on the types of soils developed in these ecosystems. They described the direct incorporation of sands into the small lake basin by aeolian processes, the existence of different sand fractions and the presence of lithologic discontinuities in different locations. According to these authors the formation of these small-lakes are resulted of the water table fluctuation, distinguishing among “permanent and temporal lagoons”, lowering of the sea level and climate changes leading to increasing aridity during the subboreal phase (Siljeström et al., 1994). The pedogenesis processes are conditioned by the geomorphological position and the organic matter accumulation, since quartz sands in the aeolian sheet and silt-clay in marshes (Clemente et al., 1988). The pedogenesis

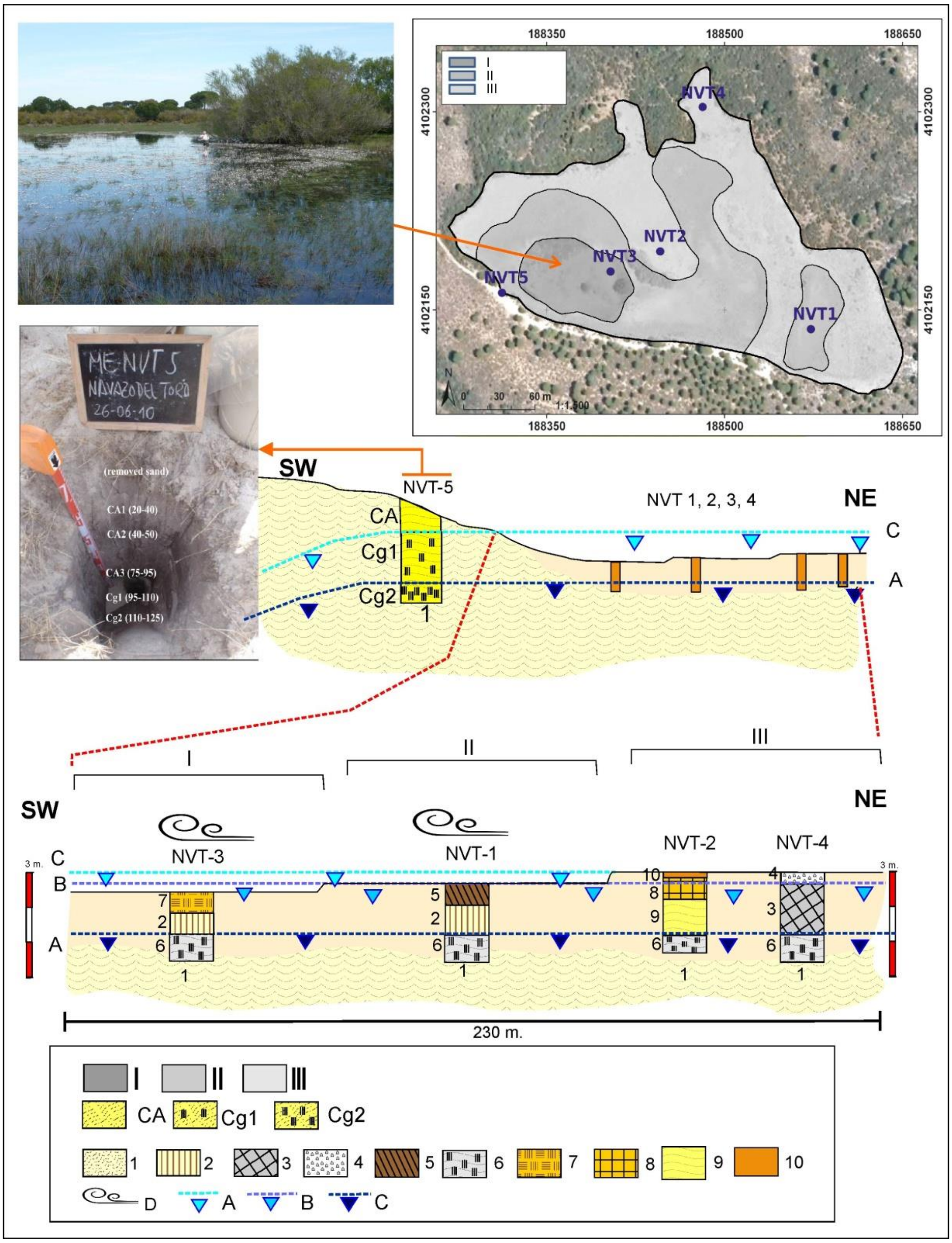


Figure 2. Navazo del Toro small-lake sectors, map and photo (November 2010): I. lower; II. medium; III. higher. Geopedological catena (NVT-1 to NVT-5): 1: sand dune depression; A: groundwater permanent level; B: water table medium oscillation; C: water table higher oscillation; D: aeolian processes; 2: smectites horizon; 3: tirsification soil process; 4: diatom layer; 5: brownish soil process; 6: clay layer; 7: gleycification soil process; 8: incipient podsolization; 9: Bsh horizon; 10: Apg horizon

relationed with these wetland was characterized as *Typic Humaquept*, with an epipedon umbric and aquic regimen (water table quasi on surface).

Cámara et al., 2013, Díaz del Olmo et al., 2010 and Recio et al., 2009, 2014 and 2019(a) have described new pedological processes in this ecogeographical context. These authors point out the importance of the lateral movement of clay and silts particles (sand washing processes) and their retention at depth by the water table, provoking a strong and rapid decrease in the hydraulic conductivity and the consequent small-lake water body formation (Torrent et al., 1980; Cámara et al., 2013; Casado Obrero, 2016).

The aim of this article is the study of pedo-sedimentary processes existing in the geosystem NVT's dune-wetland, the genesis and characteristics of the impermeable layers that allow episodes of "perched wetland", the bioclastic accumulations in superficial horizons and the different soil profile types evolved in the morphotopographic sectors mapped in the small-lake bottom.

Material and methods

The fieldwork has been based in a geopedological catena survey of 230 m in length, covering the three morphotopographic sectors of the small-lake basin and the dune slope into the sand depression (Fig. 2).

The water dynamics of the wetland, subsurface water levels, water column thickness and evolution of the regional aquifer level was previously described by Borja (2011). A georeferenced mapping of NVT small lake and nearby environment was obtained through a detailed altimetric survey using high-precision GPS techniques (TOPCON Hiper GD/ GPS L1), showing the, high, medium and low sectors.

Five profiles of 2–3 m depth (hand boreholes) have been described: profiles NVT-4 and NVT-2 were opened in the highest sector, NVT-1 and NVT-3 ones were in the medium and low sector respectively, and NVT-5 profile located in the dune slope which surrounds the small-lake, with the aim of analysing processes that are held out of the small-lake hydrologic functioning.

FAO (1977) was used to describe the soil profiles and FAO (2015) like the international soil classification system. In the laboratory were determined: color (Munsell Color, 1990); pH in water (Duchaufour, 1975); salinity (USDA, 1973); organic matter by calcination; particle size distribution by Robinson pipette (Soil Survey England and Wales, 1982); magnetic susceptibility with a Bartington MS2 (Dearing, 1999); hydraulic conductivity by M.A.P.A. (1986); X-ray diffraction analysis with Siemens D5000 diffractometer with CoKα radiation and a Fe filter (Brindley and Brown, 1980) and semi-quantitative determination of clays by Montealegre (1976); sand mineralogy by Parfenoff and Pomerol (1970) using NikonTipe 103 modele. Some horizons have been studied with more details, and showed the morphologic characteristics of soil profiles (Figures 4, 6 and 7).

Optically stimulated luminescence (OSL) dating was conducted in the Radiochemistry Laboratory of the University Autonoma of Madrid (LDR, Spain) (reference: MAD-5742SDA; equivalent dose (Gy): 6.17, annual dose (μGy/y): 1.45, supra-alignment (Gy): 0.0, K factor: 0.06, U (ppm): 1.05, Th (ppm): 2.41, K20 (%): 0.31, Cos. Rad. (μR/h): 0.70; wet sample (%): 0.36.

Results and discussion

A) Dune: NVT-5 (Haplic arenosol, FAO, 2015)

NVT-5 soil profile is located on the slope of the parabolic dune that limits and surrounds by the SW the wetland at 22.28 m height. NVT-5 is out of the hydrologic functioning of the small-lake, except in very wet winters where the lateral discharges and vertical fluctuation groundwater reaches the lower part of the profile.

This has been studied to a depth of 130 cm, it is brownish in surface but discoloured at a depth of 95–110 cm (white colour, 10YR 8/2 in Cg$_1$), and gray chroma in Cg$_2$) by the fluctuating vertical position of the regional aquifer (Table 1). It shows a pH close to neutral values, no salinity and low organic matter (OM) content, reaching values of 0.25% and 0.08% in the surface and Cg$_2$ horizon, respectively. Particle size distribution in CA$_1$, CA$_2$, and CA$_3$ horizons are bimodal (medium and fines size predominant) up to 95 cm depth, and a 5.4% correspond to fine particles (silts and clays). From here, the lower horizons are unimodal (53% of middle sands) and present a low percentage of fine sands (33% and 26%), lower of very fine sands (2,68% and 2,39% in Cg$_1$ and Cg$_2$ respectively) and the silt and clay fractions (1.80 and 1.95%, in Cg$_1$ and Cg$_2$ respectively) (Table 2, Fig. 2).

The soil profile has a strong hydraulic conductivity (HC), 130.8 cm/h in CA$_3$ horizont. Ilmenite ferric minerals constitute a 1.56% of the CA$_1$ horizon (Recio et al., 2009). So, the siliceous nature of the soil profile shows a very low signal of magnetic susceptibility (Table 1). Illite and kaolinite are the most abundant minerals in clays (57% and 34% respectively), compound of 8-9% of vermiculites synthesized within the profile under geoecological conditions of acidity, permeability, OM content and humidity (Table 3, Fig. 3).

Taking account of the physic-chemical and textural parameters of the NVT5 profile, we interpret the 130 cm thick of the profile there are two parts clearly differentiated: the lower one (95–130 cm), slightly hydromorphic and with predominance of middle (53%) and coarse (14%) sands; and the upper one (20–95 cm), with low organic matter (OM) content, bimodal texture of middle and fine sands, and a big percentage of silt and clay (predominant illites and kaolinites and neoformation of vermiculites). The high values of HC indicate that the whole profile presents an accentuated permeability and an excess drainage, faster on the upper level (130 cm/h) than in the bottom (81 cm/h), which favours the dune aridity and its colonization by pines and the xerophytic bush, similar condition described by Díaz del Olmo et al., (2010), Cámara et al. (2013) and Casado Obrero (2016). In consequence, the textural differentiation and the vermiculites presence show the importance of the leaching and sedimentary-inputs processes in the NVT-5, and on its upper part (0–95 cm)

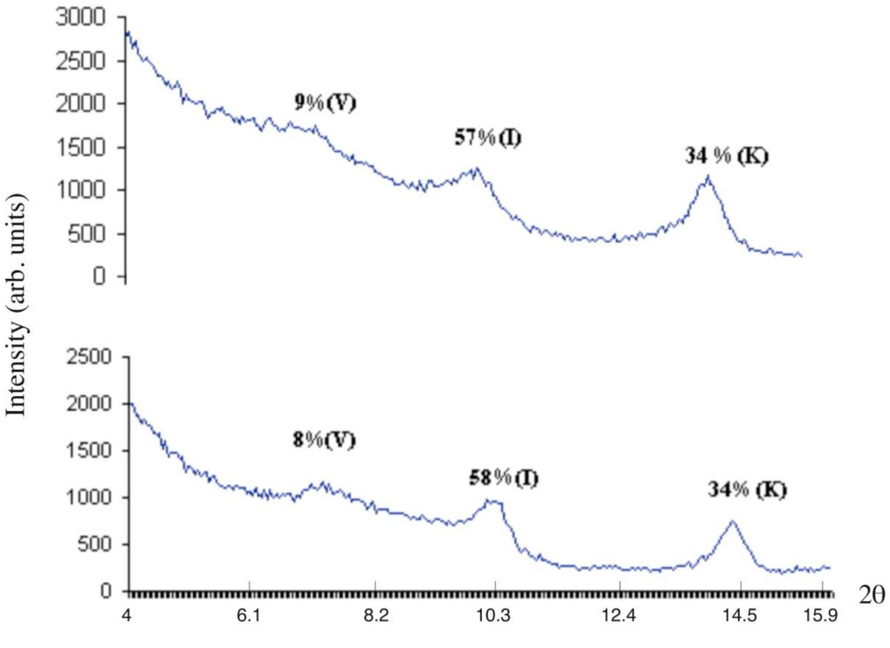


Fig. 3. Clay fraction mineralogy and semicuantitative analysis of CA$_1$ y CA$_2$ horizons of NVT-5 soil profile (V: vermiculite; I: illite; K: kaolinite)

Table 1
Physico-chemical characterization of studied soil profiles in the Navazo del Toro small-lake (E.C.: electric conductivity; O.M.: organic matter; H.C.: hydraulic conductivity; M.S.: magnetic susceptibility). (*): chronology determination (OSL)

Profile	**Horiz/Depth (cm)**	**Colour**		**pH**	**E.C.**	**O.M.**	**H.C.**	**Wet**	**M.S.**
		(d)	**(w)**	**(H_2O)**	**(mhs/cm)**	**(%)**	**(cm/h)**	**(%)**	**χ(10^{-9} m^3/kg))**
NVT-1 Stagnic luvisol	A/Bg1 (0-10)	10YR 6/1	10YR 3/1	8,30	0,24	2,29	0,01	0,86	16
	A/Bg2 (10-25)	10YR 7/1	2,5Y 4/2	7,65	1,50	0,75	–	0,79	16
	A/Bg3 (25-50)	10YR 7/1	2,5Y 5/2	8,09	1,30	0,44	0,01	0,73	16
	BAt (50-75)	2,5Y 5/2	2,5Y 4/2	8,10	0,69	1,68	0,00	3,96	68
	Cg1 (75-95)	10YR 7/2	2,5Y 6/3	8,71	1,03	0,23	0,80	0,44	12
	Cg2 (95-130)	2,5Y 8/2	2,5Y 7/2	8,81	0,49	0,11	–	0,05	4
	Cg3 (130-185)	10YR 6/2	2,5Y 5/2	8,19	0,92	0,30	–	0,16	4
	Cg4 (185-235)	2,5Y 6/2	5Y 5/2	7,97	1,29	0,39	30,00	0,28	4
NVT-2 Stagnic podsol	Apg1 (0-18)	10YR 6/1	10YR 2/2	6,75	0,93	0,00	14,02	2,13	20
	Apg2 (18-35)	2,5Y 6/2	2,5Y 4/3	7,60	0,47	0,04	–	0,50	20
	ABgs (35-75)	10YR 5/4	10YR 4/3	6,90	2,25	1,40	0,17	1,93	52
	BCsh (75-125)	10YR 6/8	10YR 5/8	6,20	3,69	0,83	–	1,08	36
	Cg1 (125-170)	10YR 7/3	2,5Y 5/3	5,26	3,46	0,00	92,53	0,81	16
	Cg2 (170-190)	10YR 7/1	2,5Y 6/0	5,04	2,59	0,00	71,23	0,92	20
NVT-3 Gleyic luvisol	B/Atg1 (0-10)	2,5Y 6/4	10YR 3/3	7,10	0,85	2,70	0,21	6,25	92
	B/Atg2 (10-45)	2,5Y 5/3	2,5Y 3/2	7,66	1,23	1,07	0,99	6,13	92
	BCt (45-60)	2,5Y 6/4	2,5Y 5/3	7,50	1,74	1,42	0,74	4,62	100
	Cg (60-70)	2,5Y 7/3	2,5Y 5/2	7,34	1,54	0,00	6,83	1,92	28
	Cgh1 (70-110)	2,5Y 6/2	2,5Y 5/2	7,56	0,66	0,48	4,58	0,21	4
	Cgh2 (110-125)	5Y 6/1	5Y 5/1	6,50	0,54	0,86	86,12	0,13	4
NVT-4 Vertic luvisol	A/Bg (0-15)	10YR 5/1	10YR 2/2	6,70	1,99	2,97	0,55	5,10	48
	BAt (15-50)	10YR4/1	10YR 2/1	6,70	2,04	4,98	0,53	7,21	100
	BCtg (50-80)	2,5Y 5/2	2,5Y 4/2	6,10	1,75	1,88	0,31	6,93	60
	Cg (80-100) **(*)**	10YR 8/2	10YR 6/2	6,34	0,55	0,00	93,65	0,48	12
NVT-5 Haplic arenosol	CA1 (20-40)	10YR 6/1	10YR4/2	7,2	0,05	0,25	98,0	–	0
	CA2 (40-50)	10YR 7/1	10YR 5/2	7,2	0,06	0,18	–	–	0
	CA3 (75-95)	10YR 7/2	10YR 6/3	7,6	0,21	0,17	130.8	–	0
	Cg1 (95-110)	10YR 8/2	10YR 6/3	7,3	0,19	0,08	–	–	0
	Cg2 (110-130)	10YR 7/2	10YR 6/2	7,3	0,13	0,17	81.2	–	0

we want to emphasise the lateral translocation of materials (silt and clay) from the dune slope to the bottom of the sand depression (sand washing) (Duchaufour, 1975; Nettleton et al., 1975; Torrent et als, 1980; Torrent and Gómez, 1985; Brown et al., 2003; Ibrahim and Lee Burras, 2013).

B) High sector botton: NVT-4 (Vertic luvisol, FAO, 2015)

The NVT-4 profile has a thickness of 100 cm and is located in the high sector of small-lake (Fig. 4). It is slightly acidic (pH 6.1–6.7) in all horizons, with a high amount of silt and clay in the first 80cm, with values among a maximum of 78.55% and a minimum of 40.45%, being equally high the OM contents (4.98% and 1,88%, in the 50–80 cm).

On the surface, the 15 cm hickness, A/Bg bleached horizon (10YR 5/1) consists in a layer rich in organic debris (45.15% silt), composed of diatoms and sponge spicules (Blanco et al., 2013; Espejo Alcaide, 2016). The whole profile is based on fine unimodal sands; it is impermeable to a depth of 80 cm (BCtg, 0.55–0.31 cm/h; Table 1), overlying to the presence of a great permeable Cg horizon (93.65 cm/h).

BCg horizon (50–80 cm), a strong layer of smectites clay (57.50%; 94%; Tables 1 and 3) and a 35 cm of thickness appears upwards in the profile. It presents intense dark gray chroma (10YR 4/1 (d), Table 1), high OM content (4.98%), and the magnetic susceptibility values (M.S., Table 1) are indicated the level of weathering of these horizons A/Bg, BA y BCg (Table 1). It has been included in Vertic luvisols group (FAO, 2015).

This discoloured Cg horizon at 80-100 cm, with a 1.7% of silt and clay particles, 0.0% OM content, 98.3% of middle and fine sands and with and a clear white chroma (10YR 8/2; 10YR 6/2, Table 1) would be consequence of groundwater fluctuation. OSL dating conducted at its lower sandy level (Cg) indicates a chronology of 4.255 + 438 BP.

The development of a tirsification process (NVT-4) (Díaz del Olmo and Recio, 1991; Moustakas, 2012; Recio et al., 1988; Recio et al., 2017 and 2019(b)) require in addition to alternating climatic conditions of dry-wet seasons and must be interpreted as a wetland different to the current NVT small-lake, correlative with the diatoms deposit (A/Bg) which is superimposed to the tirsification horizon BAt.

C) High sector botton: NVT-2 (Stagnic podsol, FAO, 2015)

The NVT-2 profile in the high sector (21.85 m.a.s.l.) of central area of the small-lake bottom is affected by very different current pedological processes from those in the previous profile NVT-4 (Fig. 7).

Table 2
Distribution particle size of soil samples studied

Profile	Horiz/depth (cm)	Sand fractions						Silt+Clay	Clay	Silt
		2-1	1-0,5	0,5-0,25	0,25-0,125	0,125-0,063	Total			
			mm (%)			(%)			(%)	
NVT-1 Stagnic luvisol	A/Bg1 (0-10)	0,07	0,91	14,42	58,54	26,03	65,50	34,50	12,50	22,00
	A/Bg2 (10-25)	0,14	1,25	16,06	53,20	29,33	67,85	32,15	7,50	24,65
	A/Bg3 (25-50)	0,21	0,93	12,00	52,98	33,86	69,55	30,45	5,00	25,45
	BAt (50-75)	0,00	0,46	10,68	60,77	28,08	54,30	45,70	32,98	12,72
	Cg1 (75-95)	0,00	0,36	8,48	66,54	24,60	81,90	18,10	–	–
	Cg2 (95-130)	0,00	0,00	1,85	65,29	32,85	86,30	13,70	–	–
	Cg3 (130-185)	0,00	0,87	17,24	69,40	12,47	91,35	8,65	–	–
	Cg4 (185-235)	0,16	1,34	23,11	67,29	8,08	92,80	7,20	–	–
NVT-2 Stagnic podsol	Apg1 (0-18)	0,00	0,67	14,72	65,40	18,34	81,5	18,5	–	–
	Apg2 (18-35)	0,22	0,87	24,45	62,95	11,52	92,45	7,55	–	–
	ABgs (35-75)	0,13	0,90	17,84	64,72	16,38	73,80	26,20	17,5	8,7
	BCsh (75-125)	0,63	1,14	29,35	64,33	4,66	87,90	12,10	–	–
	Cg1 (125-170)	0,62	4,61	24,18	52,31	14,17	88,90	11,10	–	–
	Cg2 (170-190)	0,11	3,11	49,95	43,18	3,65	93,10	6,90	–	–
NVT-3 Gleyic luvisol	B/Atg1 (0-10)	0,98	2,12	0,33	59,64	25,33	30,60	69,40	37,50	31,90
	B/Atg2 (10-45)	0,72	1,81	0,36	53,99	27,17	41,40	58,60	37,50	21,10
	BCt (45-60)	0,69	1,58	5,04	57,76	24,73	50,55	49,45	–	–
	Cg (60-70)	0,29	1,13	16,95	65,43	16,18	84,15	15,85	10,00	5,85
	Cgh1 (70-110)	0,37	2,51	25,33	61,97	9,80	93,35	6,65	–	–
	Cgh2 (110-125)	0,94	3,70	22,95	57,13	15,26	90,40	9,60	–	–
NVT-4. Vertic luvisol	A/Bg (0-15)	0,00	1,41	15,09	55,53	28,97	24,85	75,15	30,00	45,15
	BAt (15-50)	2,56	3,26	14,92	46,39	32,87	21,45	78,55	57,50	21,05
	BCtg (50-80)	0,42	1,93	23,76	55,08	18,56	59,55	40,45	–	–
	Cg (80-100) **(*)**	0,25	4,78	43,29	47,51	3,15	98,3	1,7	–	–
NVT-5 Haplic arenosol	5 CA1 (20-40)	0,97	8,63	45,53	38,04	6,80	94,60	5,40	–	–
	5 CA2 (40-50)	1,29	6,00	43,66	40,96	8,06	94,60	5,40	–	–
	5 CA3 (75-95)	0,42	1,85	44,24	47,16	6,31	94,60	5,50	–	–
	5 Cg1 (95-110)	0,82	9,64	53,63	33,21	2,68	98,20	1,80	–	–
	5 Cg2 (110-130)	2,70	14,95	53,15	26,78	2,39	98,05	1,95	–	–

It has not a accumulative clay-smectite B horizon in depth (Table 2), and the original surface horizon (ABgs, 17.50% of clay and 1.40% of OM) seem to be buried by 75 cm of fine unimodal anthropic removed sand horizons (Apg1 and Apg2), which have increased the thickness of the original soil (Legates et al., 2010; Ma et al., 2017; Schwen et al., 2014).

So, the decolorized Cg1 horizon appears at a greater depth than 125 cm (Table 1). There is a BCsh horizon (75–125 cm) with an intensely yellowish chroma (10YR 6/8), giving the morphological and chromatic contrast whith ABgs horizons (10YR 5/4, Table 1, Fig. 4), acidity of 6.20 and contents of OM (0.83%) and silt and clay that reach a 12.10%, respectively. In

Table 3
Some specific results of more significant horizons: silt and clay fraction and semiquantitative analysis of clay minerals
(V: vermiculite; Sm: smectite; I: illite; K: kaolinite)

Profile/ Horiz.	Depth (cm)	Silt + Clay (%)	Course silt (%)	Fine silt (%)	Clay (%)	(V) (%)	(Sm) (%)	(I) (%)	(K) (%)
1- Bat	50-75	45,70	7,80	20,04	72,16	0.00	88.00	9.00	3.00
2- ABgs	35-75	26,20	20,00	10,00	70,00	0,00	80.00	19.00	1.00
3- B/Atgs	10-45	58,60	16,66	20,82	62,50	0,00	90.00	7.00	3,00
4 –Bat	15-50	78,55	6,52	16,30	76,66	0,00	94,00	3,00	3,00
5- CA$_1$	20-40	5,40	30,.56	24,45	36,68	9.00	00,00	57,00	34,00
5- CA$_2$	40-50	5.40				8,00	00,00	58,00	34,00

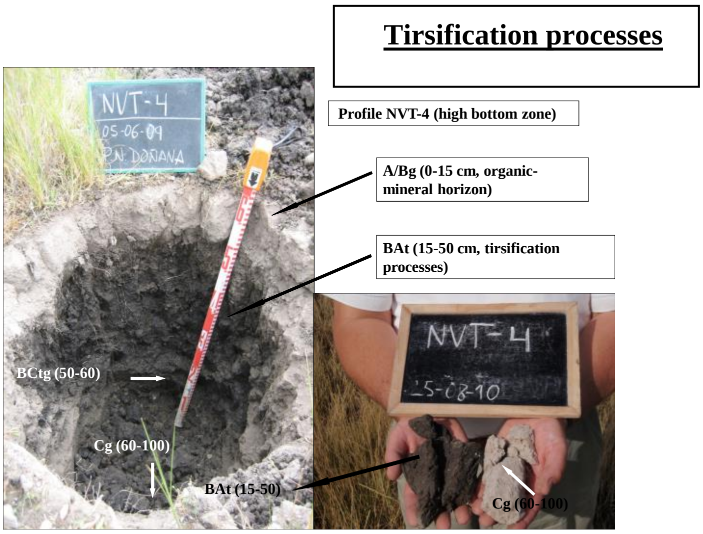


Fig. 4. Horizons morphology of NVT-4 soil profile (Vertic luvisol)

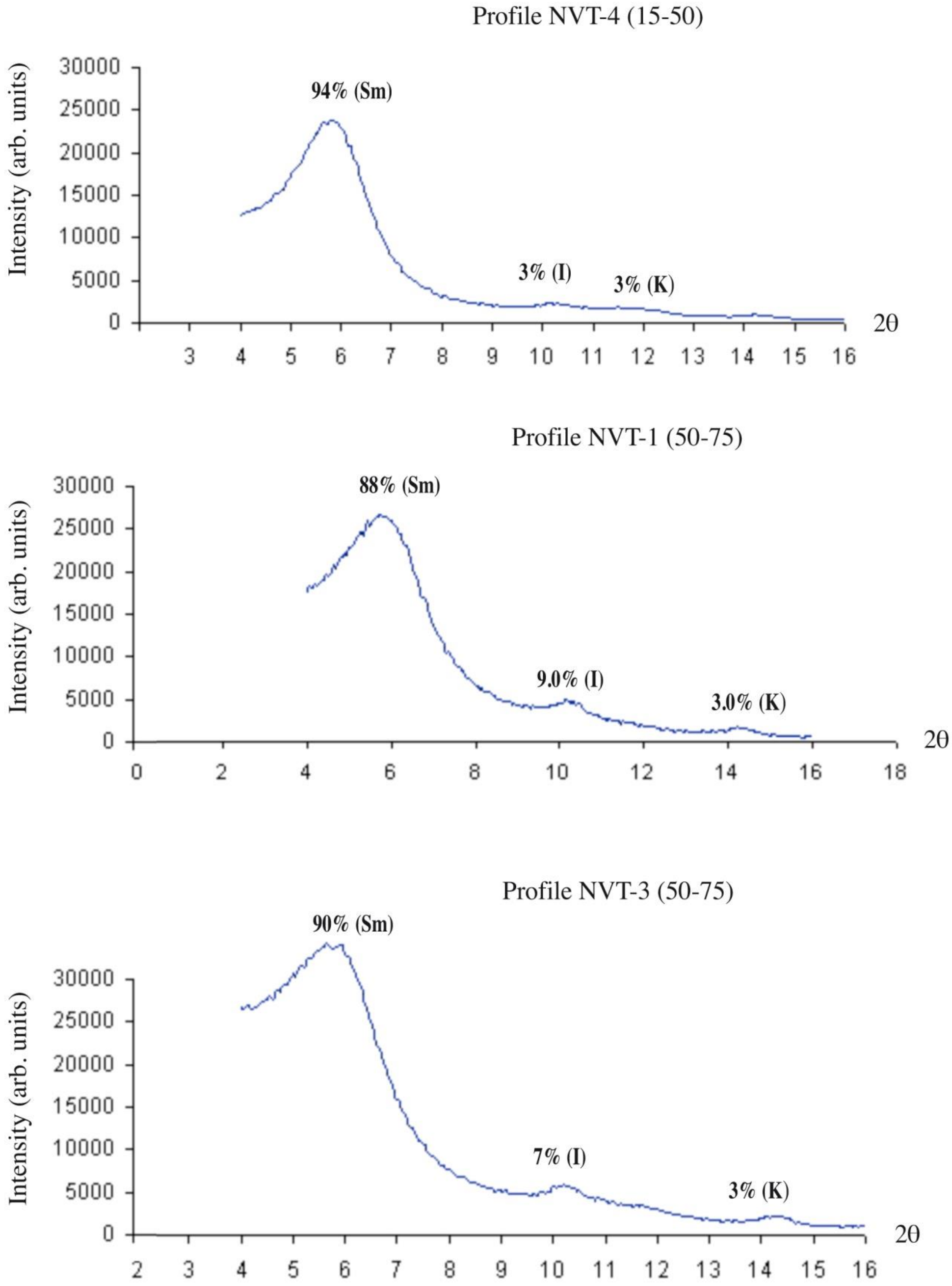


Fig. 5. Smectites presence in the Navazo del Toro small-lake bottom: horizons BAt and B/Atg2, of NVT-4, NVT-1 and NVT- 3 soil profiles (Sm: smectites; I: illite; K: kaolinite)

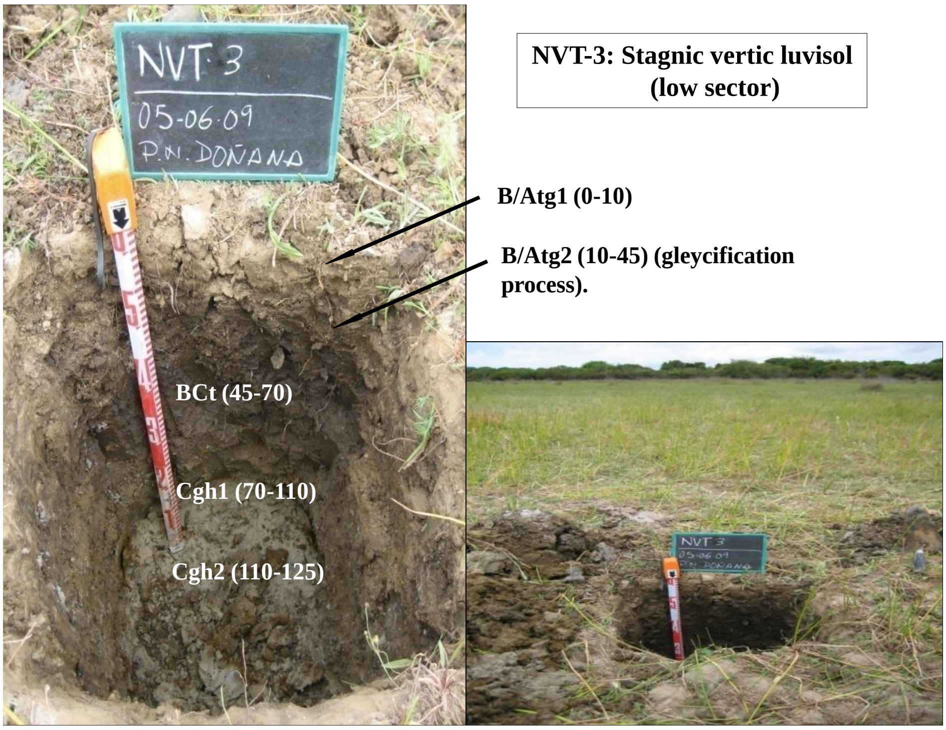


Fig. 6. Horizons morphology of NVT-3 soil profile (Gleyic luvisol)

addition, it has a high content of goethite in its colloidal fraction, which results mainly from the alteration of the ilmenite present in the sandy matrix (Table 3; Recio et al., 2009) (Fig. 8). This explains the relatively high values of its magnetic susceptibility (MS) compared to the other Cg horizons discussed above (Table 1; Fig. 7). The absence of clay horizon in deept and the high hydraulic conductivity of the all profile (Table 1) allow a downward movement of the acid waters of the current wetland towards the lower layers where the water table circulates.

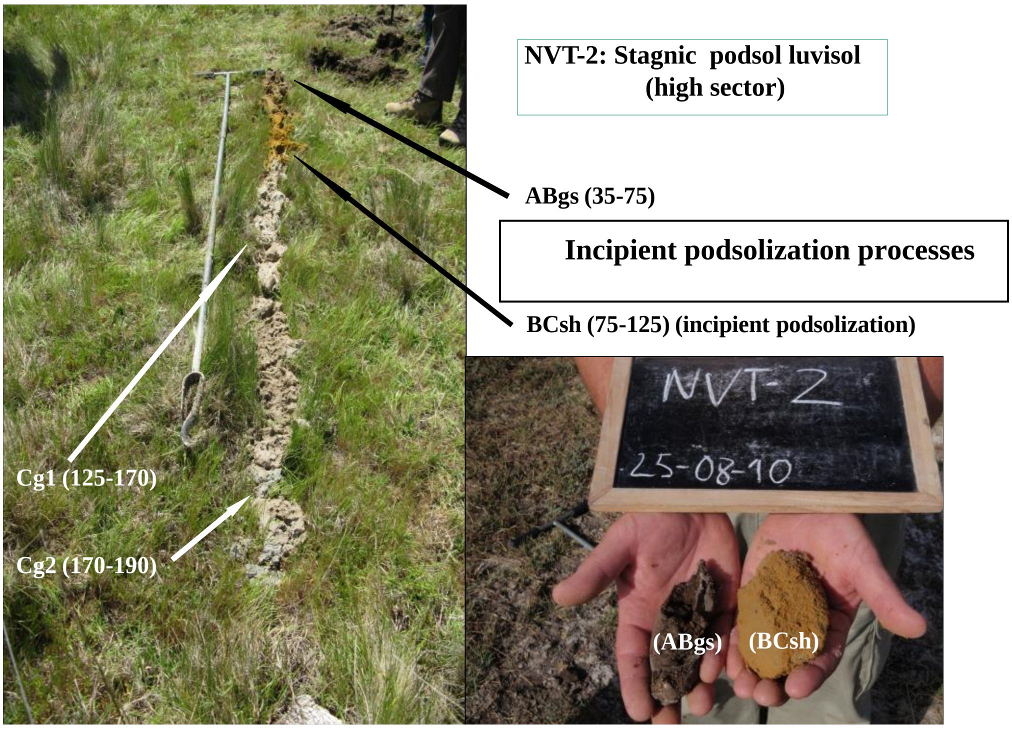
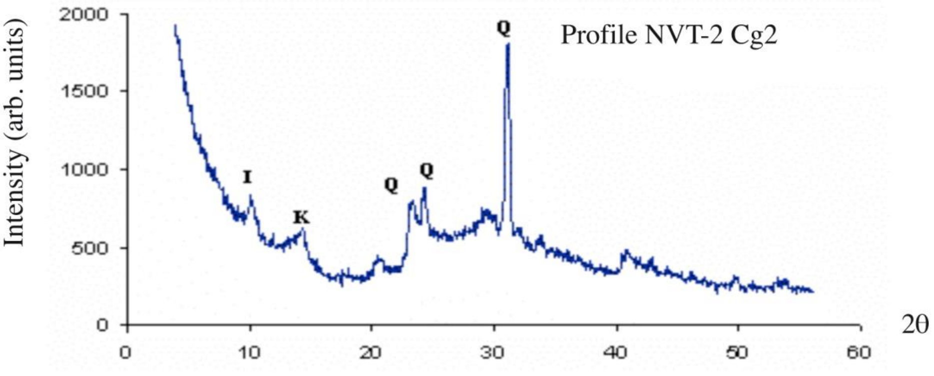


Fig. 7. Horizons morphology of NVT-2 soil profile (Stagnic podzol)

The existence of the current body of water would be the trigger factor of the most recent pedo-alterological processes identified in the wetland; filtration and vertical percolation of water and the presence of minerals rich in iron (ilmenite), seem to favour the formation of yellowish horizons, rich in goethite and organic matter, indicating an incipient podzolization process favored by well-drained quartz sands (BCsh horizon) (Robin et al.,1981, Torrent and Gómez, 1985 and Buurman and Jongmans, 2005). Based on its morphology and sequence of the horizons this profile has been classified as Stagnic podzols (FAO, 2015)

D) Medium sector bottom: NVT-1 (Stagnic luvisol, FAO, 2015)

The NVT-1 profile is located in the medium sector, show a thickness of 235 cm and presents a great predominance of fine and very fine sands (0.25–0.125 and 0.125–0.063mmØ), a higher silt content and low clay levels. On the top (10–50 cm) A/Bg1, A/Bg2 and A/Bg3 horizons are modified by the current



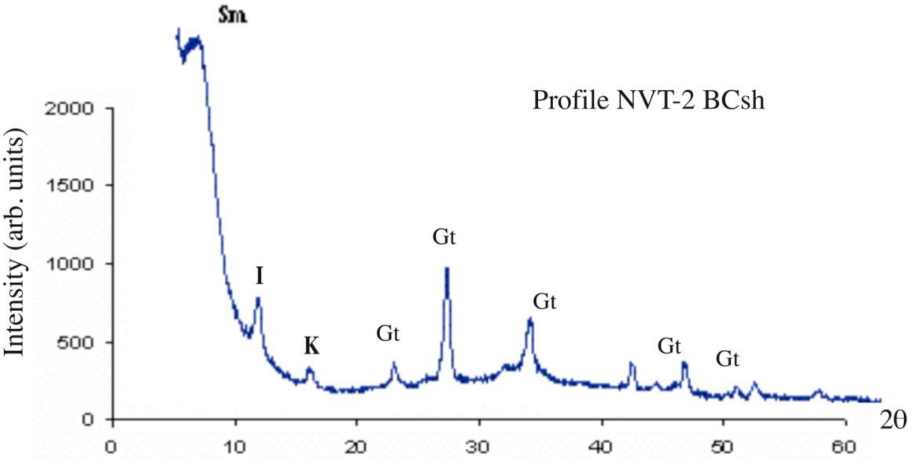


Fig. 8. Ray diffraction (2º – 60º) colloidal minerals of NVT-2 soil profile (Stagnic podsol) (Sm: smectites; I: illite; K: kaolinite; Q: quarz; Gt: gohetite)

water dynamics of the wetland, are of greyish chroma (10YR 6/1-7/1), brownish horizons affected by oxi-reduction processes and a matrix with high levels of OM in the surface (2.29%) derived from the presence of abundant bioclastic material, similar to NVT-4 soil profile (Tables 1 and 2) (Blanco et al., 2013; Espejo Alcaide, 2016).

Its most distinctive feature is the presence of clay-smectite horizon located to 50–75 cm (BAt horizon, 32.98% clays, 88% of these are smectites, Tables 1, 2 and 3), a extremely low hydraulic conductivity (HC, 0.0%, Table 1) and elevated value of M.S. (68×10^{-9} m^3/kg); the profile has a pH values from 7.5 and 8.8 and variable contents of organic matter (OM). The gleyic horizons began approximately to 75–95 cm deep (10YR 7/2), while the discoloured Cg2 horizon (2.5Y8/2) is located at a depth of 95–130 cm. It has low O.M. contents, pH 8.8 and 13.70% of fine particles (silt and clay) and fine unimodal sands (0.25–0.125 mm) (Table 1 and 3). Cg3 and Cg4 complete the horizons soil profile to 130–235 cm, with a very sandy texture and a high hydraulic conductivity (30 cm/h) (Table 1).

The soil profile shows a evolved hydromorphic phase subjected to a vertical fluctuation of the groundwater table. The lower horizon (75–235 cm) corresponds to the hydromorphic impermeable faded level (clay layer, Cg 1 to 4) which holds the water table during the wet periods. Its morphology and horizons sequence would allow him to be included in the group of Stagnic luvisol (FAO, 2015).

E) Low sector bottom: NVT-3 (Gleyic luvisol, FAO, 2015)

NVT-3 soil profile is developed in the lower and flooded sector in the annual wet season. This lower sector profile constitutes the domain of the small-lake's flooded area caused by the aquifer recharge happens during the winter and spring rainfalls, causing the water table rise until covering up the whole low sector of the small-lake.

Its higher horizon with fine unimodal sands show brown clays contents with predominance of smectites (horizons B/Atg1 and B/Atg2; 37.50% of clays, 90% are smectites) (Tables 2 and 3), with a thickness of 45 cm for both these and extend up to 125 cm depth (Table 2 and 3, Fig. 6). The smectites horizon favours the hydromorphic soil character, retaining the water sheet, coming to form for some weeks real "perched wetland" in the vadose zone (Brown et al., 2003; Schoeneberger and Wysocki, 2005; Borja, 2011; Melly et al., 2017). In this situation, the wetland's superficial water sheet is disconnected from the water table level of the aquifer.

It presents high OM content (2.70%), the highest levels of magnetic susceptibility observed ($92–100 \times 10^{-9} m^3$/kg) and very low permeability (0.21–0.99 cm/h) similar to soil profiles previously mentioned. The discoloured Cg horizon (2.5Y7/3) is founded at the depth of 60 cm, presents no OM content and a relatively fast hydraulic conductivity compared to levels observed in upper horizons (Table 1), maximum in Cgh2 horizon with values of 86.12 cm/h.

No surface bioclastic layers (diatoms and spicules) are identified in this soil profile and all lower sector. The subsequent wind erosion processes associated with deforestation have eroded these initial horizons, moved the sands and clays and formed a depressed area (lower sector) of very low permeability too. This soil type have been be included in the Gleyic luvisol group (FAO, 2015).

Conclusion

The hydro-pedological processes existing in El Abalario-Doñana Littoral Aeolian Sheet are decisive for the formation of Navazo del Toro ecosystems perched wetland. The translocation of fine particle, silt and clay, from the slope dune (sand washing) and its accumulation in the base of the sand depression in the boundary of water table position of the aquifer gives rise to the genesis of a non-permeable clay accumulative horizon with esmectites neoformation that serves as a supports the water mass of the wetland.

A permanent wetland with acidic and oligotrophic water provides an organic-mineral horizon containing diatoms and sponge spicules in high and medium sector bottom and the formation of tirsificated horizons processes with cronology before 4.255y BP.

The water body of the current geoecosystem has modified the surface horizons creating a new hydromorphic conditions. The acidity, organic matter contents, presence of ferric mineral and high permeability by absence in certain areas of this clay layer in depth facilitates a vertical infiltration and the genesis of certain podsolization processes.

In medium and lower sector the fault of drainage favour the appearance of stagnic and gleycification properties in the soil profiles depending of duration and extension of sheet of water. No surface bioclastic layers (diatoms) are identified in the lower sector, consequence by wind erosion.

The soils profiles studied have been included in Luvisols groups with principal qualifiers of vertic (tirsificated), gleyic, stagnic or podzolic properties depending of hydrological evolution of the small-lake ecosystem. Arenosols soils are developed in the surrounding dunes.

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