Accumulations of soluble salts and gypsum in soils of the Central Region, Spain

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ABSTRACT

In this work, mineralogical, macro and micromorphological aspects of soils with gypsic and salic horizons are studied, in order to establish the characteristics of secondary enrichments in gypsum and soluble salts.

For this study four soil profiles of central region of Spain have been selected as representatives of soils with gypsic or salic horizons in the region.

Thenardite, bloedite, polyhalite and small amounts of eugsterite characterize the mineralogical composition of salic horizon. In hot dry periods massive formation of thenardite gives rise to loss of structure and consistence in this horizon. Salt efflorescences, microcrystalline salts embedded in a clay matrix, and small saline aggregates filling voids in the structure, are characteristics of secondary enrichment in soluble salts in the salic horizon.

Gypsum is the main component in soil with gypsic horizon. Secondary enrichment in gypsum is characterized by :
— both large and small lenticular gypsum crystals, are distributed with no apparent direction in the s-matrix. They are frequently altered and partially replaced by calcite ;
— small crystals of gypsum, generally lenticular with clean sections, partially or totally fill voids, channels, cracks and in some cases form mosaics of crystals with differents shapes : lenticular, more or less perfect and granular ;
— lenticular gypsum crystals form coatings on the surfaces of voids, channels and plant remains.

Processes affecting the formation of studied gypsic horizons are : the gradual refilling of the s-matrix by gypsum ; cristalline growing in voids and channels ; the progressive tendency to fill empty spaces in the soil structure and the evolution towards more massive structures.

KEY WORDS : Salic horizon — Gypsic horizon — Soil Mineralogy — Soil Micromorphology.

RÉSUMÉ

ACCUMULATIONS DE SELS ET DE GYPSE DANS LES SOLS DE LA RÉGION CENTRALE DE L'ESPAGNE

Au cours de ce travail, on étudie les aspects minéralogiques, macro et micromorphologiques de sols présentant des horizons gypsiques et salins afin d'établir les caractéristiques des enrichissements secondaires en gypse et sels solubles.

Pour cette étude on a sélectionné quatre profils de sols de la région centrale espagnole, estimés représentatifs de sols à horizons gypsiques et salins.

La thénardite, la bloedite, la polyhalite et de faibles quantités d'eugstérite caractérisent la composition minéralogique de l'horizon salin ; en périodes chaudes et sèches, la formation massive de thénardite conduit à une perte de structure et de consistance de cet horizon.

Des efflorescences salines, des sels microcristallins imprégnant la matrice argileuse, et de petits agrégats salins remplissant les vides structuraux traduisent les enrichissements secondaires en sels solubles de l'horizon salin.

Le gypse est le principal constituant des sols à horizon gypsique. Les enrichissements secondaires en gypse se caractérisent par :
— des cristaux lenticulaires de gypse, de diverses dimensions, distribués sans direction apparente dans la matrice, fréquemment altérés et partiellement remplacés par la calcite ;
— des petits cristaux de gypse de sections nettes et généralement lenticulaires, remplissant partiellement ou totalement les vides, les chenaux, les fissures et formant parfois des mosaïques avec des cristaux de différentes formes : lenticulaires, subeuhedraux et grenus ;
— des cristaux lenticulaires de gypse formant des revêtements sur la surface des vides, des chenaux et des résidus végétaux.

Les processus qui interviennent lors de la formation des horizons gypsiques sont le remplissage graduel de la matrice par le gypse, les phénomènes de croissance cristalline dans les vides et les chenaux et la tendance au comblement progressif des vides structuraux.

MOTS-CLÉS : Horizon salin — Horizon gypsique — Minéralogie du sol — Micromorphologie du sol.

RESUMEN

ACUMULACIONES DE SALES SOLUBLES Y YESO EN SUELOS DE LA REGION CENTRAL DE ESPANA

En este trabajo se estudian aspectos mineralógicos, macro y micromorfológicos de suelos con horizontes de diagnóstico gypsic y salic, en orden a establecer las características de los enriquecimientos secundarios en yeso y sales solubles.

Para este estudio se han seleccionado cuatro perfiles de suelos de la región central española, juzgandose representativos de suelos con horizontes gypsic y salic.

Thenardita, bloedita, polihalita y pequeñas cantidades de eugsterita caracterizan la composición mineralógica del horizonte de diagnóstico salic ; en periodos calidos y secos, la formación masiva de thenardita conduce a una perdida de la estructura y consistencia en este horizonte. Eflorescencias salinas, sales microcristalinas impregnando la matriz arcillosa y pequeños agregados salinos rellenando espacios vacios en la estructura, son caracteres de los enriquecimientos secundarios en sales solubles del horizonte salic.

El yeso es el principal componente en los suelos con horizonte gypsic. Los enriquecimientos secundarios en yeso se caracterizan por :
— cristales lenticulares de yeso, de tamaños variables distribuidos sin direccion preferente en la s-matrix, frecuentemente alterados y parcialmente reemplazados por calcita ;
— pequeños cristales de yeso de secciones limpias y generalmente lenticulares rellenando parcial o totalmente huecos, canales, grietas y que en ocasiones forman mosaicos de cristales de diferentes formas : lenticulares, subeuhedrales y granulares ;
— cristales lenticulares de yeso formando revestimientos sobre la superficie de huecos, canales y residuos de plantas.

Procesos que afectan a la formación de los horizontes gypsic son : el relleno gradual de la s-matrix por el yeso ; fenómenos de crecimiento cristalino en huecos y canales ; y tendencia a la colmatación progresiva de los espacios vacíos de la estructura.

PALABRAS CLAVES : Horizonte salic — Horizonte gypsic — Mineralogia de los suelos — Micromorfologia de los suelos.

INTRODUCTION

Gypsiferous soils occupy large areas in central Spain ; they are generally very rich in gypsum and also have small amounts of soluble salts and carbonates. These components occasionally display significant accumulations forming gypsic, salic or calcic horizons.

These soils usually develop from alluvial sediments with a high gypsum content, which sometimes makes it difficult to distinguish between pedogenic gypsum and the gypsum from underlying material.

Interesting aspects of secondary enrichment of gypsum and soluble salts stand out as a result of the study of their mineralogical composition and macro-micromorphological and submicroscopic observations. Several authors : KOOISTRA (1978) ; TURSINA *and al.*, (1980) ; ESWARAN *and al.*, (1980) ; NETTLETON *and al.*, (1982) ; ALLEN (1985) ; HALITIM and ROBERT (1987) and HERRERO and PORTA (1987), reported evidences of pedogenic forms of gypsum and soluble salts in different soils and horizons.

The aim of this work is the study of salic and gypsic horizons in order to determine the characteristics of secondary enrichments in soluble salts and gypsum. Probably this aspect is not explicit enough in the definition of these horizons given in the Soil Taxonomy (Soil Survey Staff, 1975).

GENERAL OCCURRENCE

The profiles (fig.1) have been selected from series studied by the authors (GUMUZZIO *and al.*, 1981 ; GUMUZZIO *and al.*, 1982 ; GUMUZZIO y ALVAREZ, 1984 and GUMUZZIO *and al.*, 1986). They were judged to be representative of the soils presenting salic or gypsic horizons in central Spain, in such a way that it was possible to study the most relevant aspects of the gypsum and soluble salts secondary enrichments.

FIG. 1. — Map of Spain with location of profiles (▲). *Carte d'Espagne et localisation des profils (▲)*

The general climate is typically Mediterranean with moderately humid winters and hot dry summers. Mean monthly temperatures range from 3.5°C to 24.2°C. The maximum monthly temperature mean in summer is 38°C and the minimum during December and January is — 5°C. Annual precipitation is about 450 mm, being the periods February-April and October-November those with the highest precipitation (110 mm). The annual potential evapotranspiration is 750 mm, July and August present the highest potential evapotranspiration (about 280 mm) as well as the lowest precipitation of the year (Fig.2).

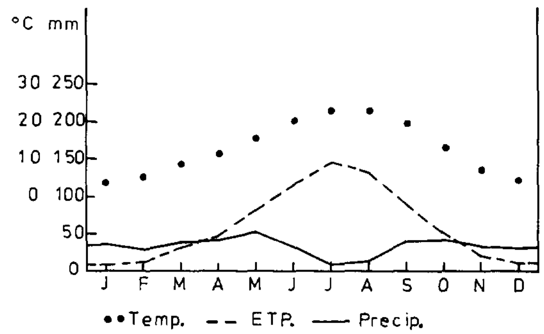

FIG. 2. — Climatic data in the meteorological station of Ocaña (near profile ▲ 1 of the fig.1). *Données climatiques de la station météorologique d'Ocaña (près du profil 1 de la fig.1)*

Profile 1 is classified as a Typic Salorthid (Soil Survey Staff, 1975). It is formed in a Quaternary alluvial plain with a slight slope with restrictions in runoff and internal drainage. A miocene formation of vindobonian age with evaporite facies, consisting mainly of gypsum and gypsum marls, borders the alluvial plain. This soil has salt efflorescences on the surface and a highly saline permanent water table fluctuates during the year between the surface (in wet periods) and a depth of 90 cm., (in dry periods). The typical vegetation is halophytic : Suaeda splendetis, Salicornietum ramosissimaee, Atriplex polula, Limonium.

Profiles 2, 3 and 4 are classified respectively as : Calcic Gypsiorthid, Cambic Gypsiorthid and Typic Gypsiorthid (Soil Survey Staff, 1975). These soils are found in alluvial plains with slight slopes and high gypsum contents. Profile 3 displays salt efflorescences in dry periods and is temporally affected by the presence near the surface of a saline water table. Saline-gypsum crusts with very weak laminar structure are found on the surface of profiles 2 and 4. These soils become flooded during the wettest months of the year but they have no permanent water table. Some characteristics of these soils are described in Table I.

MATERIAL AND METHODS

The samples were taken from different horizons (overall samples) and transported to the laboratory in hermetically sealed containers, in an attempt to preserve field conditions. Undisturbed samples of soil horizons, in Kubiena boxes, were used for micromorphological and submicroscopic studies.

Samples of salts from voids and channels were also taken and transported in hermetically sealed containers for subsequent study. Evaporation tests, carried out in

TABLE I

Abreviated profile descriptions. *Descriptions abrégées des horizons*

Profile	Horizont	Depth (cm).	Colour	Texture	Structure	Consistence (moist)	Carbonates	Salts	Roots	Boundary
1	Salt Effl.	0 - 5	white (dry)	-	structureless	loose	c	many	-	abrupt
	A11sa	5 - 8	10YR4/2	silt loam	weak fine granular	friable	c	many	common	abrupt
	A12sa	8 - 21	10YR5/2	clay	structureless	loose	c	many	common	gradual
	A13sa	21 - 49	10YR5/3	clay	moderate medium(sb)*	friable	c	many	few	diffuse
	C1sa	49 - 90	2.5Y6/4	clay	structureless	firm⁻	c	many	very few	
2	Salt crust	0 - 5	10YR6/2	-	weak medium platy	very friable	c	few	-	abrupt
	A11ca	5 - 11	10YR6/2	sandy clay loam	moderate medium(sb)*	friable	c	few	many	clear
	A12ca	11 - 14	10YR7/3	" " "	moderate medium(sb)*	friable	c	few	many	clear
	A13ca	14 - 25	10YR4/3	sandy loam	moderate medium(sb)*	friable	c	common	few	gradual
	A14ca	25 - 38	10YR4/4	" "	weak fine (sb)*	friable	c	many	few	gradual
	AC ca	38 - 53	10YR5/4	-	weak fine (sb)*	firm	c	many	few	abrupt
	C1cs	53 - 66	10YR8/2	-	weak fine (sb)*	firm	s.c.	few	-	gradual
	C2cs	66 - 75	10YR8/2	-	massive	very firm	s.c.	few	-	abrupt
	C3cs	75 - 108	10YR8/4	-	massive	very firm	s.c.	few	-	gradual
	C4	> 108	10YR7/3	-	massive	very firm	s.c.	-	-	-
3	Salt Effl.	0 - 3	white	-	structureless	very friable	c	many	-	abrupt
	A11	3 - 11	10YR7/2	sandy loam	weak fine (sb)*	firm	c	few	common	clear
	A12	11 - 29	10YR7/3	" "	moderate medium(sb)*	firm	c	few	few	gradual
	A13	29 - 53	10YR5/2	sandy clay	weak fine (sb)*	firm	c	many	few	gradual
	ACcs	53 - 66	10YR7/4	-	weak fine (sb)*	firm	c	many	-	gradual
	C1cs	66 - 77	10YR8/2	-	massive	very firm	s.c.	few	-	gradual
	C2cs	> 77	10YR8/6	-	massive	friable	s.c.	-	-	-
4	Salt crusts	0 - 5								
	A11cacs	5 - 11	10YR7/2	sandy loam	moderate medium(sb)*	friable	c	few	common	clear
	A12cacs	11 - 27	10YR4/3	" "	moderate medium(sb)*	firm	c	few	few	gradual
	A13cacs	27 - 43	10YR5/3	" "	weak fine (sb)*	firm	c	many	few	diffuse
	AC cacs	43 - 51	10YR6/2	" "	weak fine (sb)*	friable	c	many	few	gradual
	C1 cacs	51 - 56	10YR7/2	sandy clay loam	weak fine (sb)*	very firm	c	many	-	clear
	C2 cs	56 - 71	10YR8/4	" " "	weak fine (sb)*	very firm	s.c.	common	-	abrupt
	C3 cs	71 - 87	10YR8/3	-	massive	very firm	s.c.	few	-	diffuse
	C4 cs	87 - 120	10YR8/1	-	massive	very firm	s.c.	few	-	abrupt
	C5	> 120	10YR7/6	-	massive	firm	s.c.	few	-	abrupt

*(sb) = Subangular blocky.
c = With carbonates in field test.
s.c. = No carbonates or only traces in field test.

bolls under atmospheric conditions and using water extract from saturated paste allowed various crystallized salts to be obtained for the mineralogical study.

The mineralogical study was carried out by X-ray diffraction using a Phillips PW 1140 diffractometer, with Cu Kα radiation and a Ni filter working at 20 mA and 40 KV. A petrographic microscope was used on thin sections of samples embedded in resins. For the micromorphological study the binocular lens and the Philipps scanning electron microscope (SEM), equipped with an EDAX microanalysis device, were also used. The chemical and physico-chemical analysis were performed in the laboratory following the methods proposed by the Soil Conservaton Service (1972) and RICHARDS (1954).

RESULTS

a) Soils with salic horizons

Data obtained from the analysis of the saturation extracts of these soils (Table III) show the existence

TABLE II
Analytical results
Résultats analytiques

Soil Profile	Depth (cm).	pH in saturated paste	Organic matter (%)	CEC (me/100g soil)	Carbonates (%)
1 A11sa	5 - 8	8.6	2.2	20.6	16.2
A12sa	8 - 21	8.5	1.0	21.5	18.4
A12sa	21 - 49	8.5	0.7	21.7	19.6
C1sa	49 - 90	8.4	0.7	26.1	21.1
2 A11ca	5 - 11	7.9	4.8	22.0	20.1
A12ca	11 - 14	8.1	2.2	21.3	16.1
A13ca	14 - 25	8.1	1.5	19.2	22.4
A14ca	25 - 38	8.3	1.2	18.7	30.1
ACca	38 - 53	8.3	0.7	13.1	26.1
C1cs	53 - 66	8.4	0.5	7.2	9.3
C2cs	66 - 75	8.2	-	6.3	3.2
C3cs	75 -108	8.1	-	9.4	3.4
C4	> 108	8.1	-	-	4.4
3 A11	3 - 11	7.9	3.3	27.2	13.1
A12	11 - 29	8.1	0.8	29.1	10.1
A13	29 - 53	8.3	0.7	20.7	13.6
ACcs	53 - 66	8.3	0.4	-	12.5
C1cs	66 - 77	8.3	-	-	9.3
C2	> 77	8.5	-	-	7.5
4 A11cacs	5 - 11	7.8	3.0	14.9	18.9
A12cacs	11 - 27	8.1	1.2	16.1	21.2
A13cacs	27 - 43	8.2	0.7	12.1	27.0
ACcacs	43 - 51	8.3	0.7	-	21.0
C1cacs	51 - 56	8.3	0.6	-	31.6
C2cs	56 - 71	8.3	0.5	-	2.6
C3cs	71 - 87	8.2	-	-	4.9
C4cs	87 -120	8.3	-	-	5.2
C5	> 120	8.3	-	-	9.3

TABLE III

Analytical results. *Résultats analytiques*

Soil Profile	Depth (cm)	Electrical conductivity (mmhos/cm)	Water extract from saturated paste, me/100g soil: Cations				Anions			E.S.P.	Gypsum (%)	Salt (%)
			Ca	Mg	K	Na	HCO_3^-	$SO_4^=$	Cl^-			
1. A11sa	5 - 8	69.1	1.1	25.2	0.1	61.9	0.3	78.3	1.7	47	12.1	5.1
A12sa	8 - 21	58.0	1.2	19.2	0.0	62.6	0.3	75.5	2.3	58	13.2	4.8
A13sa	21 - 49	50.3	0.9	12.1	0.0	40.7	0.2	46.6	1.8	45	9.8	3.1
C1sa	49 - 90	54.1	1.8	31.5	0.0	67.3	0.4	87.8	5.6	70	9.6	5.9
2. A11ca	5 - 11	4.6	1.3	0.8	0.1	0.2	0.3	1.4	1.0	0	11.7	0.1
A12ca	11 - 14	11.7	3.5	1.8	0.0	1.0	0.2	3.6	2.0	3	35.0	0.4
A13ca	14 - 25	18.3	1.0	3.0	0.0	10.2	1.2	3.4	2.9	31	34.1	0.8
A14ca	25 - 38	36.9	1.1	10.9	0.1	12.4	0.1	16.0	6.6	26	27.8	1.4
ACca	38 - 53	12.5	1.1	3.2	0.0	2.8	0.1	4.1	2.7	6	21.1	0.4
C1cs	53 - 66	26.2	1.3	7.7	0.0	4.5	0.1	6.7	5.3	13	61.3	0.7
C2cs	66 - 75	17.3	1.4	3.6	0.0	2.8	0.1	2.9	3.3	11	56.1	0.4
C3cs	75 - 108	14.2	1.3	2.1	0.0	1.9	0.1	1.5	3.8	8	51.0	0.3
C4	>108	22.7	1.0	3.2	0.0	3.3	0.1	2.2	4.7	10.	40.8	0.4
3. A11	3 - 11	57.7	0.5	35.0	0.2	21.5	0.1	15.3	35.3	22	33.3	3.4
A12	11 - 29	53.4	1.6	15.7	0.9	10.9	0.1	6.5	22.0	21	39.6	1.7
A13	29 - 53	36.0	1.0	6.6	0.3	5.0	0.1	3.0	9.6	17	53.5	0.7
ACcs	53 - 66	47.5	1.0	18.4	0.8	11.0	0.1	8.0	21.5	20	61.1	1.8
C1cs	66 - 77	38.8	0.7	14.1	0.5	8.2	0.3	12.3	13.8	18	64.5	1.4
C2	> 77	38.3	1.1	14.2	0.6	7.2	0.3	11.9	13.4	16	50.8	1.3
4. A11cacs	5 - 11	14.9	1.1	3.8	0.1	1.9	0.1	3.2	3.5	4	22.4	0.4
A12cacs	11 - 27	13.3	0.3	1.2	0.0	0.7	0.1	1.2	1.0	6	19.8	0.3
A13cacs	27 - 43	38.2	1.9	31.5	0.9	20.7	0.3	27.6	29.3	21	19.6	1.5
ACcacs	43 - 51	18.1	0.6	2.4	0.0	1.7	0.1	2.7	1.8	10	27.5	0.6
C1cacs	51 - 56	16.3	0.4	1.8	0.0	1.3	0.1	2.6	1.2	10	54.2	0.4
C2cs	56 - 71	13.2	0.3	1.3	0.0	0.5	0.1	1.2	0.9	6	51.2	0.3
C3cs	71 - 87	24.3	1.1	8.7	0.2	6.0	0.1	2.6	10.5	7	35.7	0.6
C4cs	87 - 120	7.9	0.2	0.4	0.0	0.2	0.1	0.5	0.2	3	36.5	0.1
C5	> 120	18.0	0.4	2.4	0.0	1.3	0.1	3.1	1.3	10	12.0	0.3

of highly soluble salts. The most abundants consist of combinations of sulphate and chloride anions and sodium and magnesium cations. These make it possible for a wide variety of minerals to be formed.

Profiles 1 and 3 are the most saline, with important accumulations of soluble salts forming salic horizons, although in profile 3 this horizon is not permanent.

Salt accumulation can be directly seen in field observations in dry periods generally consisting of white coloured salts filling voids and channels. They are abundant in surface horizons (A horizons). In cold periods the profile 1 displays structure and consistence ; but in hot dry periods the horizons are structureless and of loose consistency giving rise to a great number of small saline microaggregates. During dry periods, they are found in surface salt efflorescences whose composition is similar to that studied by GUMUZZIO *and al.*, (1982).

Fluctuation in the maximum accumulation of soluble salts has been observed with stational field tests. It can be found at different depths in different times of the year ; however, the salts frequently show a tendency to accumulate in two depths : the surface or near surface and down near the groundwater table.

Salic horizon in profile 1, is associated with the presence, at a shallow depth, of a very saline water table, with high contents in sulphates (1390 mé/l) and sodium (1430 me/l). This water table during wet periods attains the surface, redissolving the salts and swamping the soil. The water table in profile 3 only exists temporally, linked to wet conditions, and no permanent salic horizon has been formed.

The results of the X-ray diffraction analysis (XRD) on overall samples of salic horizon from profile 1 (Table IV), show a predominance of gypsum and calcite. In addition to these minerals, quartz, illite, kaolinite and traces of palygorskite were also identified. Thenardite and bloedite were detected amongst the soluble salts.

TABLE IV
Mineralogical composition of profile I
Composition minéralogique de l'horizon I

Horizon	Gypsum	Calcite	Quartz	Clay Minerals	Thenardite	Bloedite	Polyhalite	Eugsterite
OVERALL SAMPLES								
A 11	xxx	xx	x	x	t	-	-	-
A 12	xxx	xx	xx	x	t	-	-	-
A 13	xxx	xx	xx	x	-	-	-	-
C 1	xxx	xxx	xx	x	t	-	-	-
SALT ACCUMULATIONS								
Efflores-cences	xx	xx	-	-	xxx	x	t	t
A 11	xx	xx	x	x	x	xx	t	t
A 12	xx	xx	x	x	x	x	t	t
A 13	xx	xx	x	x	x	x	t	t
C 1	xx	xx	t	x	xx	x	t	t

(Crosses indicate relative abundance, t = traces)
(Les croix indiquent l'abondance relative, t = traces)

The XRD study of samples taken from salt accumulations filling voids and channels (Table IV) also shows the presence of several soluble minerals. In profile 1, thenardite is the most abundant, specially in horizons near the surface and in salt efflorescences. Bloedite, polyhalite, and small amounts of eugsterite have also been detected. In cold dry periods mirabilite crystals have been identified a few centimeters down in the soil. In the surface horizons of profile 3 the presence of halite was detected (Table VI).

TABLE V
Mineralogical composition of overall samples in gypsic profiles
Composition minéralogique des échantillons globaux dans les horizons gypsiques

PROFILE II	GYPSUM	CALCITE	QUARTZ	CLAY MINERALS	HALITE
A 11	xxx	x	x	x	-
A 12	xxx	x	x	x	-
A 13	xxx	xx	x	x	-
A 14	xx	xxx	x	x	-
A C	xx	xxx	x	x	-
C 1	xxx	-	-	x	-
C 2	xxx	-	-	x	-
PROFILE III					
A 11	xxx	x	x	x	x
A 12	xxx	t	t	x	t
A 13	xxx	t	x	x	t
AC	xxx	t	x	x	t
C 1	xxx	-	-	t	-
C 2	xxx	-	-	t	-
PROFILE IV					
A 11	xxx	t	x	x	-
A 12	xxx	xx	xx	x	-
A 13	xxx	xx	xx	x	-
C 1	xxx	t	t	x	-
C 3	xxx	-	-	x	-
C 4	xxx	t	t	t	-
C 5	xxx	-	-	-	-

(Crosses indicate relative abundance, t indicates traces)
(Les croix indiquent l'abondance relative, t indique les traces)

Evaporation experiments with water extract from saturated paste from salic horizon (profile 1) allowed two types of salt accumulations to be identified : one was white in color and powdery in appearance, mainly consisting of thenardite with some bloedite, and the other was formed of mirabilite crystals up to 1 cm in size, which alter rapidly to thenardite.

Optical microscope observations (in a range of magnification from 25 to 500 X) show that the salts in the salic horizon (profile 1) are organized in two forms : one is composed of microcrystalline salts embedded in a clay matrix, and the other of salt microaggregates which fill voids, channels and cracks. Calcite and gypsum were also identified in this horizon, with lenticular habits being predominant in the latter.

In the deepest horizons of salorthid soil, the presence of gypsum crystals is the dominant feature, of around 1 mm in size, anhedral in shape and with parallel cleavage lines on the sections.

The submicroscopic study of the salic horizon (profile 1) with the SEM show globular-shaped thenardite with dissolution marks on surface of crystals and reprecipitation phenomena in the voids of crystals (photo 1). Small lenticular crystals of gypsum were also found coating roots and filling voids.

b) **Soils with gypsic horizons**

Gypsiferous soils (profiles 2, 3 and 4) have a high gypsum content throughout the profiles. Gypsic horizons are recognized by the content and distribution of gypsum with depth in the soil profiles (Table III) according to the Soil Taxonomy definitions.

TABLE VI
Mineralogical composition of salt accumulations in gypsic profiles
Composition minéralogique des accumulations de sel dans les horizons gypsiques

PROFILE II	GYPSUM	CALCITE	QUARTZ	CLAY MINERALS	HALITE
Efflorescences	xxx	-	-	-	-
A 11	xxx	t	x	x	-
A 12	xxx	x	x	x	-
A13	xxx	xx	t	x	-
A14	xxx	xxx	x	x	-
AC	xxx	x	t	x	-
C1	xxx	-	-	x	-
C2	xxx	-	-	x	-
PROFILE III					
A 11	xxx	x	t	x	x
A 12	xxx	t	t	x	t
C 1	xxx	-	-	x	-
C2	xxx	-	-	x	-
PROFILE IV					
Efflorescences	xxx	-	-	-	-
A11	xxx	t	t	t	-
A 12	xxx	x	x	x	-
A13	xxx	x	x	x	-
C1	xxx	t	t	x	-
C 3	xxx	-	-	x	-
C 4	xxx	t	t	x	-
C 5	xxx	-	-	-	-

(Crosses indicate relative abundance, t indicates traces)
(Les croix indiquent l'abondance relative, t indique les traces)

In profile 2, the gypsic horizon lies at a depth between 53 and 108 cm. In profil 3 this horizon is located between 53 and 77 cm., and in profile 4 there is a gypsic horizon between 5 and 120 cm., in depth. The maximum content of gypsum is found in the subsurface horizons and these are generally massive and hard in dry periods. Accumulations of gypsum can be directly seen in field observation. In general they consist of small voids and channels filled in with gypsum crystals which are more abundant in the roots zone of the soil profile (A and AC horizons). Structure in this zone is generally better and its consistence softer than in deepest horizons.

Carbonates are recognized through field test together with gypsum and soluble salts in filling voids and channels. Carbonate accumulations occur above the zones with maximum gypsum content (Table II) and there is a clear boundary between them. In profiles 2 and 4, these accumulations form calcic horizons at a depth between 5 and 53 cm., and 5 and 56 cm, respectively, while in profile 3 a Ca horizon is formed between 3 and 66 cm.

There are certain similarities in the mineralogical composition of gypsiferous soils. The X-ray diffraction study of overall samples (Table V) shows a predominance of gypsum in the subsurface horizons, while in the surface horizons this mineral is present together with similar amounts of calcite and appreciable quantities of quartz. A11 the horizons contain small amounts of clay minerals, mainly illite and kaolinite.

The mineralogical compositions of samples obtained from voids and channels fillings (Table VI) do not differ significantly from overall samples, although the gypsum content is higher.

PHOTO 1. — Dilution-recrystallization in thenardite crystal (bar = 10μm). — *Dilution-recristallisation dans les cristaux de thénardite (bar = 10μm)*

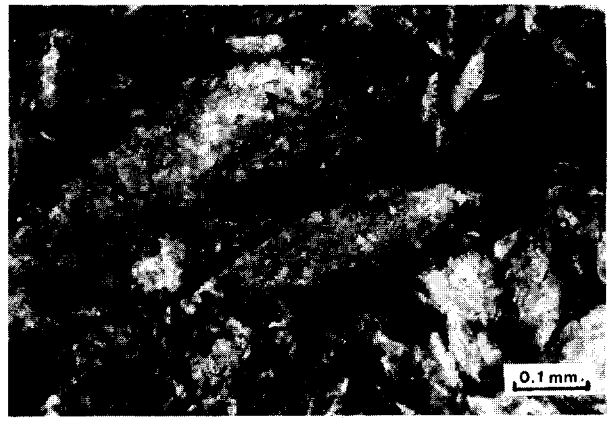

PHOTO 2. — Carbonated lenticular gypsum (crossed polarizers). — *Cristaux lenticulaires de gypse carbonaté (polariseurs transversaux)*

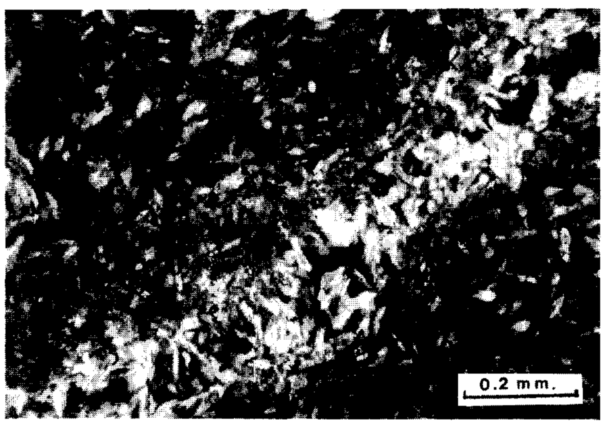

PHOTO 3. — Interlocking of microcrystals of gypsum (crossed polarizers). — *Mosaïque de petits cristaux de gypse (polariseurs transversaux)*

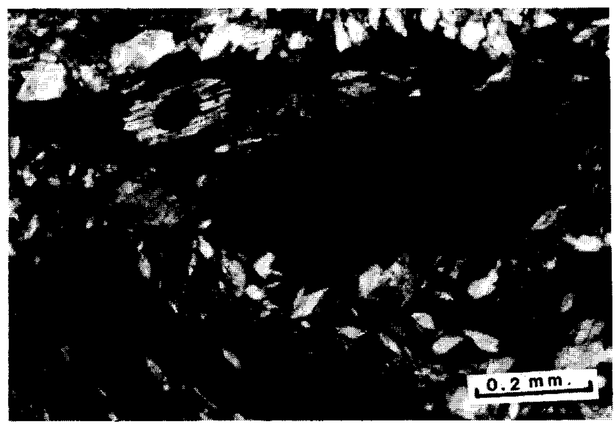

PHOTO 4. — Gypsum crystals coating organic residues (crossed polarizers). — *Cristaux de gypse formant des revêtements sur la surface des résidus organiques (polariseurs transversaux)*

PHOTO 5. — Gypsum crystals filling channels (crossed polarizers). — *Cristaux de gypse remplissant les chenaux (polarisseurs transversaux)*

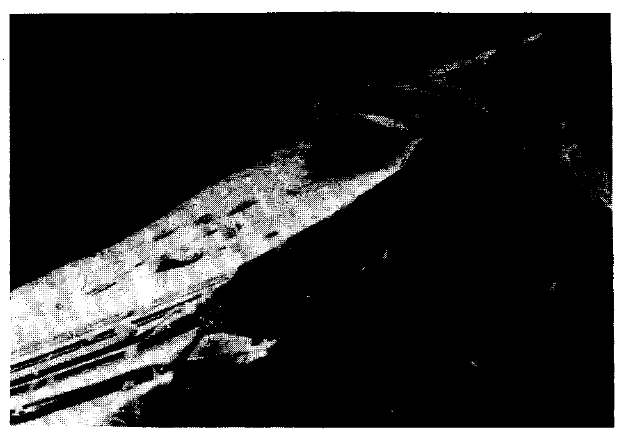

PHOTO 6. — Tabular forms of gypsum (bar = 10μm). — *Formes tabulaires de gypse (bar = 10μm)*

Evaporation tests on these soils using water extract from saturated paste allow different soluble minerals to be identified by XRD : halite, epsomite, thenardite and bloedite.

Optical microscope observations of samples from gypsic horizons and from gypsum accumulations in voids and channels of the upper horizons (A and AC horizons) show the following types of pedogenic features :

— lenticular gypsum crystals, both large (> 0.5 mm) and small (about 0.05 mm), not distributed in any apparent direction in the s-matrix, frequently altered and partially replaced by calcite (photo 2) ;

— small crystals of gypsum, generally lenticular with clean section, partially or totally filling voids, channels, cracks and which in some cases form mosaics of crystals with different shapes : lenticular, subeuhedral or granular (photo 3) ;

— lenticular gypsum crystals forming coatings on the surfaces of voids, channels and plant ramains (photo 4). Sometimes the coatings and fillings are associated, but while the gypsum crystals in the coatings tend to be aligned parallel to the coated surface, there is generally no discernible alignment in the fillings (photo 5).

The forms of gypsum found in the deeper horizons (the levels underlying the gypsic horizon), which are considered to have a geological origin, have large anhedral crystals with platy cleavage and tabular habit.

Irregular shaped quarz particles and clays have been identified in the basal mass. The calcite does not show euhedral crystals but generally takes the form of disseminated micrite.

The SEM study confirmed the predominance of the lenticular gypsum in the gypsic horizons and in the pedogenic accumulations in the surface horizons. Coatings of calcite were also observed on this type of gypsum. In the deepest horizons tabular gypsum (photo 6) was found, sometimes with surface dissolution phenomena and flakes opening up.

DISCUSSION

The semiarid climate, landscape position and the existence of a very saline water table at shallow depth contribute to the confinement of the salts and allow them to remain in the salic horizon from profile 1, while in profile 3, the water table is not permanent preventing the soil from evolving towards more saline phases.

Analytical data from salorthid soil show high amount of easy soluble salts in agreement with mineralogical composition. The main associations of soluble minerals identified in this soil correspond to the system mirabilite-thenardite-bloedite, although not all minerals are necessarily present in both summer and winter. Mirabilite has been identified during cold dry periods, whereas thenardite is predominant in summer. The presence of these minerals in salic horizon was according with the results of evaporation experiments.

Climate conditions cause important changes in the structural properties of salorthid soil. In dry hot periods, mineralogical transformations with massive formation of thenardite cause loss of structure and consistency of soil. In wet periods the soil are swamping and the salts are redisolving.

Differences in the mineralogical composition from summer to winter (thenardite/mirabilite) are attributed to the variations in moisture and temperature from one season to other and differences in the solubilities of salts (BRAITSCH, 1962).

Evidences of secondary enrichment in soluble salts are remarkable in the salic horizon from salorthid soil. At macroscopic level they consist in surface efflorescences and voids and channels filled with soluble salts. At the microscopic level we can observe microcrystalline salts embedded in a clay matrix and saline aggregates filling the voids and channels of the salic horizon.

Gypsiorthid soils have high gypsum contents with accumulations which form gypsic horizons. Macroscopic and microscopic features have been observed in gypsic horizons and in upper horizons. The most significant ones are associated with the presence of lenticular gypsum crystals filling and/or coating voids, channels, plant remains and even forming mosaics of gypsum crystals with differents shapes and sizes. STOOPS and ILAIWI (1981) ; NETTLETON *and al.* (1982) ; ALLEN (1985) ; and HALITIM and ROBERT (1987), consider the gypsum accumulations in voids and channels as pedogenic gypsum and they can be identified as pedogenic features. On the other hand, we have observed that gypsum of geological origin takes usually the form of large anhedral crystals with platy cleavage and tabular habit.

The forming of the gypsic horizons was explained by NETTLETON *and al.*, (1982) by feedback processes with characteristics similar to those described by TORRENT and NETTLETON (1978).

Gypsic horizons from studied soils show some similarity with NETTLETON'S theory. Crystal growth in voids and channels is very frequent with lenticular forms being dominant in the crystals. Voids and channels partially filled with gypsum crystals (gypsans) coexisting with other voids and channels totally filled indicate a gradual process of secondary enrichment.

Growth of gypsum crystals in voids and channels continues until space becomes limiting causing crystals to interlock and lose some of their form. Mosaics of crystals in some voids indicate a progressive colmatation process which characterises some of the studied gypsic horizons.

Slight amounts of soluble salts are also frequently identified in all gypsic horizons probably due to the temporary presence of a water table and the low permeability of subsuperficial horizons. Furthermore, evaporation tests with water extract from saturated paste show the presence of soluble minerals (halite, epsomite, thenardite and bloedite) in these soils, and this leads us to think that they may be present as function of the saline concentration, but only under limited conditions and in very small proportions.

Gpysic horizons usually form abrupt boundaries with overlying calcic horizons. Carbonates are recognized in upper horizons mainly filling voids and channels. This fact, and partial replacements of gypsum by calcite appear to indicate that these carbonates are of a secondary origin.

As conclusion we think in agreement with others authors (STOOPS and ILAIWI, 1981 ; HERRERO and PORTA, 1987) that there is a relation between the morphology of the accumulation type and its genesis. Evidences of secondary enrichment in salts or gypsum can be confirmed with morphological observations, and it is necessary to consider these aspects as possible criteria in definitions of gypsic and salic horizons in Soil Taxonomy System.

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