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Micromorphology of Gypsum Crystals in Southern Iranian Soils under Different Moisture Regimes

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ABSTRACT

Gypsiferous soils occur in xeric, ustic, and aridic moisture regimes. Environmental conditions affect the mode of gypsum formation. Gypsiferous soils in Fars Province, southern Iran, are found in piedmont plains, flood plains, and alluvial plains. The objective of this work was to investigate the micromorphology of gypsum crystals formed under different soil moisture regimes. The results indicate that lenticular crystals of gypsum have been frequently found in more developed soils, whereas under aridic soil moisture regime such form is rare and they are frequently found in the subsurface horizons. Columnar, prismatic, and blade forms of gypsum are found in areas with aridic moisture regime, where soils are highly leached. Formation of gypsum pendant under gravels is dominant in piedmont plains with limited moisture in the profile. Complex gypsum crystals were found in low rainfall regions. It seems that surface runoff, as well as hydrological system of the region, transfers gypsum from geological sediments in higher elevations to coarse-textured soils of flood plains. In landscapes with xeric and xeric-aridic soil moisture regimes, lenticular, euhedral and subhedral crystals of gypsum were abundant. The results of this study indicate that, in addition to soil moisture, texture and landscape position play a significant role in the formation of pedogenic gypsum. Well crystallized gypsum was observed in soils with silt loam, sandy loam, and loamy texture. Observation of gypsic horizons suggests that the accumulation of gypsum took place under *per descendum* process in the soils studied.

Keywords: Gypsiferous soil, Gypsum crystal forms, SEM analysis, Soils of Iran

INTRODUCTION

High amounts of gypsum are frequently found in soils of arid and semi-arid environments. Formation of gypsum in the soil is mostly associated with gypsiferous rocks and sediments of different origins, where leaching is insufficient to remove gypsum from the soil profile. Gypsum can also form on non-gypsiferous rocks, where $CaSO_4$ enters the soil by atmospheric deposition. Soils having undergone leaching processes reveal unusual increases of SO_4^{2-} at 40-50cm depth. This may be an indicator of more recent SO_4^{2-} input due to atmospheric deposition since the beginning of industrialization. It is supposed that gypsum is formed by the reaction of atmogenic sulfuric acid with different Ca sources in soils (Dultz and Kühn, 2005).

Worldwide, gypsiferous soils cover about 186 million ha, representing 1.5% of the world soil cover (FAO, 1993). Eswaran and Zi-Tong (1991) have estimated 207 million ha of soils with gypsic or petrogypsic horizons. Gypsum is the most common sulfate mineral in soils of arid and semi-arid areas (Doner and Warren, 1989), and is highly correlated with soil moisture regime. Although gypsum is found over a wide range of temperatures (Waston, 1988; FAO,

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1990), most gypsic soils are formed under xeric, ustic, and aridic moisture regimes (FAO, 1990).

Gypsum can accumulate in soils through the following four processes: (1) *In situ* weathering of existing parent material (Carter and Inskeep, 1988; Taimeh, 1992), (2) Sulfate-enriched precipitation from an oceanic source (Podwojewski and Arnold, 1994), (3) Aeolian or fluvial input of gypsum or sulfate-rich sediment (Van Hoesen, 2000; Buck and Van Hoesen, 2002) and (4) *In situ* oxidation of sulfide minerals (Podwojewski and Arnold, 1994).

Shape, size and position of gypsum crystals within the soil matrix have been used to determine their source and mode of formation (Buck and Van Hoesen, 2002). Pedogenic gypsum crystals can occur as individuals and as masses within the soil groundmass and pores (Eswaran and Zi-Tong, 1991). Previous studies have found that gypsum accumulates in the soil through time in a similar manner as calcium carbonate (Van Hoesen, 2000; Buck and Van Hoesen, 2002). Gypsum first forms thin filaments, then, small nodules, and, eventually, massive indurated horizons. Unlike calcium carbonate, however, gypsum also forms small snowballs in early pedogenesis (Van Hoesen, 2000; Buck and Van Hoesen, 2002). Pedogenic gypsum in gravelly soils mostly occurs as pendants bellow pebbles (Waston, 1985). In non-gravelly materials, pedogenic gypsum is observed as whitish, powdery or crystalline, soft masses, or diffused in the soil matrix. Rainfall and topographic setting strongly influence the quantity and the location of gypsum in the soil (Waston, 1985).

Diagenetic gypsum has been characterized by subhedral to anhedral crystals that completely filled voids (Carter and Inskeep, 1988). Pedogenic gypsum in soils exhibits a variety of crystal forms that may represent different environments of formation.

Lenticular disk, tabular pseudo-hexagonal, tabular hexagonal, microcrystalline, prismatic lath and fibrous gypsum crystals have been observed (Amit and Yaalon, 1996; Jafarzadeh and Burnham, 1992). Such diversity results from changes in micro-environmental condition in soils with time (Amit and Yaalon, 1996).

Buck and Van Hoesen (2002) describe a new morphology of pedogenic gypsum in soils of southern New Mexico as they call it snowball morphology. They noted that snowballs are composed of numerous small, euhedral gypsum crystals of different habits including tabular, pseudo-hexagonal, hexagonal, and lath.

Various methods have been used to study the micromorphology of gypsum crystals formed in soils, in the field as well as in the laboratory. Owliaie *et al.* (2006), Buck and Van Hoesen (2002), and Jafarzadeh and Burnham (1992) used scanning electron microscopy (SEM) analysis to study size and shape of crystals formed in soils on gypsiferous material. They reported different forms of gypsum crystals including pseudo-hexagonal, needle-like prismatic, lenticular, and columnar.

The objective of this study was to investigate the diversity of gypsum crystals in arid and semi-arid regions of southern Iran under different moisture regimes using analytical SEM analyses.

MATERIALS AND METHODS

Geomorphic Settings

The study sites are located in an area of about 132,000 km^2 in Fars province, southern Iran (Figure 1). The area has different soil moisture and temperature regimes including xeric, ustic and aridic soil moisture regimes and mesic, thermic and hyperthermic soil temperature regimes (Banaei, 1998). Precipitation ranges from 200 mm in the arid areas in the north, the south, and the southeast to 800 mm in the mountainous region of the northwestern area. However, a large part of the study area receives 200-300 mm, of rainfall. Potential evaporation ranges from 1100 mm in the east (Sarvestan Plain) with mesic

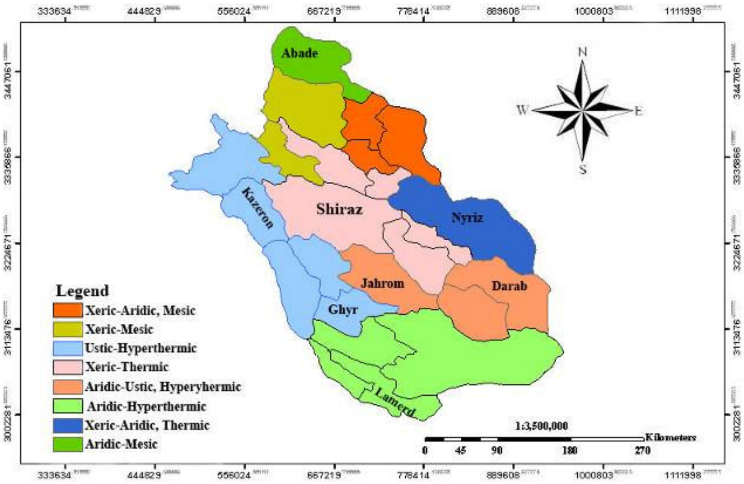

Figure 1. Soil moisture regimes in the area studied.

temperature regime to 1900 mm in the arid area with hyperthermic temperature regime.

The overall climate of the province is arid and semi-arid. The natural vegetation of Fars Province consist of: *Rose sulfurea, Malva sylvestris, Agropyrum ramousum, Alhagi camelorum, Glycyrrhiza glabra, Cartamus oxicanthus,* and *Brasica napus.*

The study area is a part of the post-Tethyan sea environment where sediments are rich in soluble salts and gypsum in most of the southern and southeastern parts (Zahedi, 1976). Results of sulfur isotope geochemistry of gypsiferous aridisols of central Iran strongly support the hypothesis that such areas were cut off from the Tethys Seaway at the end of Mesozoic era and, as a result, the lower Cretaceous sulfate has controlled the sulfur geochemistry of the younger sediments (Khademi, 1997).

The main geological units containing gypsum include Cambrian (Hormoz formation), Mid-Upper Cretaceous (Sachun formation), and Tertiary (Gachsaran and Razak formation) rocks. Hormoz formation consists mainly of salt, anhydrite, crushed dolomites, basic igneous rocks and red siltstones. Suchun formation consists of cherts marls, marlstones and silt, off-white limestones. These are followed by gypsum and dolomites that are overlain by off-white and brown-ochre marlstones and dolomites. The upper part is composed of massive gypsum, marls and ribs of dolomites. Gachsaran formation is one of the evaporitic kinds of sediments, showing thick-bedded alternating layers of anhydrite and marl (James and Wynd, 1965).

In the north and northeastern parts, aridic moisture regime is dominant. The temperature regime varies from mesic and thermic in the north and northeast, hyperthermic in the southern and the ustic and ustic-aridic prevail in the western and south-central parts. Xeric moisture regimes prevail in northwest and temperature regimes vary from mesic in the higher elevations to thermic toward the center of province (Figure 1).

Most gypsum-enriched soils in Fars province occur in alluvial plains, flood plains, and piedmont plains and are rarely found in younger lowlands.

Field Sampling and Laboratory Methods

Based on the soil survey and remote sensing reports (Hashemi *et al.*, 2007), there are seven major soil series in the study area, out of which only four are gypsiferous. Thirty five pedons were initially studied and then reduced to 12 pedons for detailed studies. Most pedons are located in flood plains and piedmont plains, in which different soil horizons were sampled for macro- and micromorphological studies. Pedons were described and classified according to the Soil Survey Manual (Soil Survey Staff, 1999) and Keys to Soil Taxonomy (Soil Survey Staff, 2006). The locations of the 12 pedons studied are shown in Figure 2.

Due to the high content of gypsum, the laboratory analyses of gypsiferous soil present some special problems. Particle size analysis was performed on each horizon in the 12 sampled soil profiles using the hydrometer method described by Gee and Bauder (1986). Organic carbon was measured by wet oxidation with chromic acid and back titration with ferrous ammonium sulfate (Nelson, 1982). Calcium carbonate equivalent (CCE) was measured by acid neutralization (Salinity Laboratory Staff, 1954).

Soil pH was measured with a glass electrode in a saturated paste (mixture of water and soil). Electrical conductivity (EC) was measured in the saturation extract (Salinity Laboratory Staff, 1954). Cation exchange capacity (CEC) was determined using sodium acetate at a pH of 8.2 (Chapman, 1965).

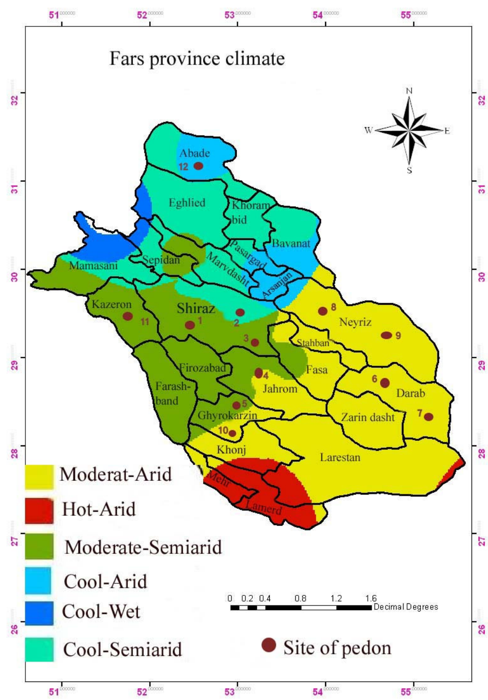

Figure 2. Climate map of the area studied showing the location of the profiles.

Gypsum was quantified with the revised acetone method (Soil Conservation Service, 1972) and corrected for hydration water (Nelson *et al*., 1978). This procedure involved changing soil/water ratio from 1/5 to 1/500, increasing the first shaking period from 0.5 to 24h and increasing the sedimentation period from 0.5 to 2h after adding acetone (Toomanian *et al*., 2001).

Electron microscopy: Soil aggregates separated from 27 dried samples of By and Bym horizons from 12 pedons were studied by scanning electron microscope (SEM). Samples were mounted on Al stubs using double-sided tape and carbon paste, then, coated with Au in a sputter coater (Cambridge, SC 7640) and examined using LEO SEM. Identification of the chemical composition of minerals was carried out using EDX analysis. SEM and EDX analyses were performed to characterize the micromorphology of gypsum crystals in the soil and to determine if the gypsum was formed during pedogenesis.

RESULTS

General soil properties: Selected properties of pedons including their parent material, location, precipitation, evaporation, elevation, and classification are presented in Table 1 and morphological and physicochemical properties are depicted in Table 2.

Since the parent material of the study area contains gypsum, the soils are also highly gypsiferous. Alluvial soils (Entisols) and moderately developed soils with gypsic and cambic horizons (Inceptisols and Aridisols), comprise about 95% of soils in the area. The soils rich in gypsum cover a large area in the flood and piedmont plains. These soils are in aridic and ustic moisture regimes in the southern, northwestern, and eastern parts with precipitation less than 300 mm and extremely high evapo-transpiration. They also occur in the vicinity of saline and alkaline lakes and are classified as Typic Haplogypsids, Typic Calcigypsids, Gypsic Haplustepts and Gypsic

Haplosalids. Gypsiferous and saline soils are mainly bare or under pasture. Those with very deep water table can partly be used for crop production.
As shown in Table 2, most of the soils have a texture of silt loam, clay loam, sandy loam, or sand. Textural analysis ternary diagrams of the 12 profiles indicate that silt loam textural class is dominant for soils textures. All soils are highly gypsic throughout containing, on the average, more than 35% $CaSO_4 \cdot 2H_2O$, increasing with depth. These fine (0.5-1mm) pedogenic gypsum crystals showed powdery spheres (snowball morphology), nodules and thin filaments.

With the exception of pedon number 9, all other soils were non-saline (EC<4 dS/m). It is interesting to note that even soils subjected to leaching processes show accumulation of SO_4^{2-} at 50 cm depth.

Morphology and composition of withish efflorescence: In this study, SEM analysis of soil gypsum crystals from 27 small soil aggregate samples indicates a pedogenic origin with no evidence of re-crystallizations, or detrital transport.
Element detection by EDX indicates that all of the B horizons of the pedons contain gypsum, the most common calcium sulfate mineral in soils. The EDX spectra recorded of the whole area indicates a clear enrichment of Ca and S. Al and Si, which are inherited by different silicates, especially feldspar, mica and clay minerals quartz (contains no Al), fade in the spectra. The presence of significant Au and Pd reflects the type of sputter coating used on the sample (Figure 3d, 4d, f; 6d; 7c). Gypsum crystals occur in different shapes and sizes such as euhedral lenticular, rosette-like, granular, rod-like, subhedral, hexagonal, columnar, tabular, prismatic, etc.

Habitus of Gypsum Crystals in Relation with Moisture Regimes

1. Xerix moisture regime: Abtahi (1977) suggests the geosynclinals of gypsum and anhydrite formation of the Mesozoic and Tertiary era, such as Sachun and Tarbur. Lenticular (Figure 3a1, a2, b) and lenticular-columnar crystals (Figure 3c) of gypsum were found in pedons 1, 2, 3. These forms occur where disk shaped lenticular crystals were developed in the soil matrices, in addition to the prismatic crystals observed. They also precipitate as 50-1000 µm sized individual crystals in the soil matrix. With increasing the soil depth the diversity of crystal forms were increased. Down in the lowest part of pedon 2 lenticular, rod like and subhedral forms of gypsum were clustered. While in its Byss1 horizon, only lenticular crystals and in the surface horizon rod like crystals were abundant. *Per descendum* is a dominant process and thus drying after rain is slow, this may result in greater length/width ratios and looser crystal packing like lenticular crystals and rod like crystals (Figure 3g, h, i). The relation between gypsum crystal forms and soil moisture regime is shown in Table 3.

Lenticular crystals are lozenge, half moon shaped in cross-section and resemble convex lens (Figure 3i). These are spar sized ranging between 50 and 1400 µm. Disk shaped crystals developed from 111 crystal faces and even so sometimes from 103 crystal faces.
2. Ustic moisture regime: Ustic regime is similar to xeric regime regarding the rainfall but its temperature is higher than 22˚C. Pedons 5 and 10 are classified as a hypergypsic Aridisols (Figure 4a, b). Comb-shape gypsum crystals of Bym horizon indicate that evaporation causes the water from underneath of the gravels to re-crystallize as vertically arranged columnar, cubic, and needle form apex crystals (Figure 4a, b). Gypsum leaching through coarse–textured soils leads to an increased accumulation of gypsum crystals in deeper parts of the profiles studied. Allabastrin gypsum crystals with white color, soft and smooth like flour could be seen in pedon 5 (Figure 4c). These gypsum crystals show frequent high super saturation and evaporation in the upper parts of the soil profile.

Table 1. Description of the pedons studied.

Pedon. No.	Location	Landform	Moisture-temperature regimes	Annual Potential Evaporation (mm)	Annual Precipitation (mm)	Elevation	Parent material
1	Gharehbagh (Shiraz)	Flood plain	Xeric-Thermic	1400	334	1429	Calcareous and Gypsiferous alluvium
2	Gharehbagh (Shiraz)	Flood plain	Xeric-Thermic	1400	334	1425	Calcareous and Gypsiferous alluvium
3	Sarvestan	Flood plain	Xeric-Thermic	1100	288	1507	Calcareous and Gypsiferous alluvium
4	Jahrom	Flood plain	Aridic-Ustic, Hyperthermic	1250	288	1047	Calcareous and Gypsiferous alluvium
5	Ghyr	Plateau	Ustic , Hyperthermic	1300	280	705	Calcareous and Gypsiferous alluvium
6	Darab	Piedmont plain	Aridic-Ustic, Hyperthermic	1900	275	1080	Calcareous and Gypsiferous alluvium
7	Darab	Alluvial plain	Aridic-Ustic, Hyperthermic	1900	275	1048	Calcareous and Gypsiferous alluvium
8	Nyriz	Flood plain	Xeric-Aridic, Thermic	1350	207	1586	Coarse gypsiferous alluvium
9	Nyriz	Low land	Xeric-Aridic, Thermic	1350	207	1561	Coarse gypsiferous alluvium
10	Ghyr	Piedmont plain	Ustic , Hyperthermic	1300	280	681	Gypsiferous alluvium
11	Kazeron	Piedmont plain	Ustic, Hyperthermic	1600	400	610	Calcareous and Gypsiferous alluvium
12	Abadeh	Piedmont plain	Aridic-Mesic	1500	136	2056	Gravelly sediment alluvium

Table 2. Physico-chemical properties of the pedons studied.

Horizon	Depth (cm)	Color (moist)	Sand (%)	Silt (%)	Clay (%)	pH	SO_4^{2-} (meq/L)	EC $dsSm^{-1}$	CEC (Cmolc kg^{-1})	Ca^{2+} (meq/L)	K^+ (meq/L)	Na^+ (meq/L)	CCE (%)	Gypsum (%)	OM (%)	Special features
							1.Gypsic Haploxerepts (Gharehbagh)									
A	0-30	10YR4/4	47.4	12	40.6	7.6	5	1.9	14.6	36	0.08	195.2	27	0.5	0.56	Fine root,
Bky1	30-70	5YR4/4	20.6	24	55.4	7.9	25	2.3	15.3	36	0.08	324	27	6.7	0.1	Few gypsum mycelium
Bky2	70-110	5YR4/6	20.7	50	29.3	7.9	31	2.8	17.4	39	0.08	348	26.5	5.7	0.1	Common gypsum mycelium
Bky3	110-150	5YR3/4	13.8	43.9	42.2	8.1	36	2.8	17.4	39	0.1	341	31	36.1	0.43	Many gypsum mycelium
							2.Aquic Haploxerets (Gharehbagh)									
A	0-15	7.5YR4/2	5.5	43.5	51.3	7.7	39	1.1	17.4	21	0.2	126	19	0.3	0.04	Many Fine root, cracking
Byss1	15-35	5YR3/4	26.44	26.44	63.32	8.2	46	2.7	14.6	38	0.1	344	25	13.4	0.4	Few gypsum (snowball)
Byss2	35-85	5YR4/4	5.24	30.72	64.04	8.2	17	0.8	17	7	0.1	71	37	9.4	0.5	Gelling, Few gypsum (snowball)
Cyg1	85-103	5YR4/4	13.24	19.44	67.32	8.1	21	5.2	19	19	0.06	61	39	6.4	0.6	Few gypsum mycelium
Cg2	>103	5YR5/2	11.24	15.44	73.32	7.9	26	0.5	20	21	0.03	58	39	0.3	0.7	Full gelling
							3. Gypsic Haploxerepts (Sarvestan)									
Ay	0-16	5YR2/7	58.12	38	3.88	7.7	26	0.2	7.3	24	0.05	2.7	9	80.4	1	Few gypsum powdery pocket
By1	16-34	5YR3/7	60.12	38	1.88	8.1	31	0.4	7.3	23	0.07	52	12	80.4	0.2	common gypsum powdery pocket
By2	34-77	5YR3/6	50.12	48	1.88	8.1	30	0.4	8.3	24	0.08	47.5	10	81.7	0.6	Many gypsum powdery pocket
By3	77-105	5YR3/6	50.12	48	1.88	8.0	28	0.5	9.4	23	0.08	60	15	79.1	0.1	Many gypsum powdery pocket
Cy	105-140	5YR6/6	48.12	51.34	.54	7.9	30	0.5	13.2	29	0.07	60	14	72.4	0.3	Many gypsum granular
							4. Gypsic Haploustepts (Jahrom)									
A	0-15	5YR5/3	44.68	42	13.32	7.5	20	0.2	41	26	0.3	3.0	49	1	0.6	Few gypsum granular
By1	15-53	5YR3/4	68.68	24	7.32	7.5	26	0.2	37	64	0.22	3.0	28	44.2	0.07	Many gypsum crystal
By2	53-80	10YR3/4	29.4	24	46.6	8.4	30	0.2	33	27	0.2	145	27	16.1	0.2	Few gypsum crystal
							5. Gypsic Calciustepts (Ghyr)									
Ay	0-11	7.5YR6/2	54.68	32.72	12.6	7.9	24	0.5	13	21	0.2	51	51	14.7	0.4	Few gypsum mycelium
Bky1	11-44	7.5YR5/2	44.88	42.72	12.6	7.9	18	0.3	9.5	28	0.2	32.5	49	31	0.5	Many gypsum crystal
Bky2	44-60	5YR6/3	32.68	50.72	16.6	8.1	32	1.7	23	29	1.25	191	48	40.3	0.2	Many gypsum crystal
Cy	60-110	7.5YR5/4	17.08	44.16	38.76	7.9	20	0.3	25	24	1.25	15	27	64	0.3	Few gypsum crystal
							6. Gypsic Calciustepts (Darab)									
A	0-18	10YR6/4	43.4	55.28	1.32	7.9	12	3.0	24	28	0.3	30	59	3.5	0.27	Fine root
Bw	18-51	7.5YR5.5/4	27.4	71.28	1.32	8.3	6	1.4	24	25	2.1	66	57	3.6	0.2	Very few gypsum on granular
Bky1	51-86	7.5YR6/4	39.4	59.28	1.32	8.4	13	0.6	24	24	1.5	482	49	7.0	0.3	few gypsum, fossil of carbonate
Ck	>86	7.5YR6/4	9.4	89.28	1.32	8.2	3	0.6	25	23	1.2	66	46	3.5	0.3	few gypsum, fossil of carbonate

Table2 continued. Physico-chemical properties of the pedons studied.

Horizon	Depth (cm)	Color (moist)	Sand	Silt	Clay	pH	SO_4^{2-} (meq/L)	EC dsm^{-1}	CEC ($Cmol_c$ kg^{-1})	Ca^{2+}	K^+	Na^+	CCE	Gypsum	OM	Special features
			(%)							(meq/L)			(%)			
							7.Ustic Haplogypsids (Darab)									
A	0-15	10YR4/3	30.68	67.28	2.04	8.2	30	5.0	9.4	42	2.0	1521	34	0.6	.05	No visible feature
By1	15-30	10YR4/4	54.68	43.28	2.04	8.4	21	2.5	8.3	35	0.88	1225	29	8.7	0.6	Few gypsum crystal
Bw	30-52	10YR5/3	26.68	71.28	2.04	8.5	25	2.6	6.3	34	0.7	1151	33	0.5	0.5	Many gypsum crystal
By2	52-85	10YR5/3	18.68	79.28	2.04	8.4	32	2.2	10.4	33	0.25	1040	32	5	0.78	Many gypsum crystal
By3	85-104	10YR5/4	46.68	51.28	2.04	8.3	36	2.0	12.5	30.2	0.2	379	23	12.7	0.45	Very little gypsum powdery
Cy	>104	10YR5/3	48.68	51.28	0.04	8.5	49	1.6	10.4	27	0.18	50	15	32	0.38	Very little gypsum powdery
							8.Chromic Gypsitorrert (Nyriz)									
Ap	0-20	10YR6/4	8.72	60	31.28	7.6	5	0.5	17.4	36	0.2	93.7	26	0.9	1.8	Few fine root, cracking
Byss	20-75	10YR6/4	7.5	42	50.5	7.7	16	1.5	18	66	0.2	155.5	31	6.4	1.28	Few gypsum (snowball)
Cy	>75	10YR4/4	0.72	43.28	56.0	7.4	23	1.5	18.1	76	0.2	159	25	9.7	0.45	Many gypsum (snowball)
							9. Gypsic Aquisalids (Nyriz)									
Azg	0-15	5YR6/2	51.96	37.28	10.76	7.8	27	38.0	14.6	67.2	3.5	4764.5	35	2.3	0.35	Full salt crystal
Byzg1	15-55	5Y5/2	19.96	73.28	6.76	8.1	37	38.0	14.6	100.6	2.5	3952.8	24	21.4	0.45	Many gypsum crystal (lath)
Byzg2	55-80	10YR4/4	35.96	59.28	4.76	7.9	40	38.0	15.3	88	2.8	4119.1	15	9.7	0.28	Many gypsum crystal (lath),gelling
Bg	>80	10YR4/3	37.8	58.2	4.0	8.0	35	8.0	13.2	91	2.8	3109.5	21	2.7	0.21	Gelling, no gypsum
							10. Gypsic calciustepts (Ghyr)									
A	0-15	10YR7/2	54.68	32.72	12.6	7.5	4	0.5	25.9	29	0.1	30.1	55	0.5	0.2	Few gypsum mycelium
Bky	15-60	10YR7/2	51.96	37.28	10.76	7.6	22	2.0	8.3	27	0.12	66.3	46	27	0.1	Many gypsum crystal
Bym	60-110	10YR6/4	32.68	50.72	16.6	7.6	35	2.0	4.5	28	0.29	483	21	68	0.1	Layer of gypsic
							11. Gypsic Haplustepts (Kazeron)									
A	0-30	10YR4/3	37.4	45.2	17.4	7.7	4	0.7	12	7.9	0.1	2.7	60	4	0.86	Few gypsum mycelium
Bky	30-50	7.5YR4/4	33.4	44.2	22.4	7.9	15	0.5	14	13	0.1	2.4	65	8	0.17	Gypsum crystal, lime powdery pocket
By1	50-80	10YR4/4	41.4	40.2	22.4	8.1	25	0.6	9	25	0.02	2.3	69	15	0.17	Gypsum crystal with gravel
By2	80-110	10YR4/4	68.4	20.2	11.4	7.9	32	0.4	8	27	0.02	2.7	70	19	0.17	Full gypsum crystal with gravel
							12. Typic petrogypsids (Abadeh)									
AP	0-19	10YR6/4	51.96	37.28	10.76	7.8	3	0.5	15	54	2.8	235	22	0.5	0.1	No visible feature
BK1	19-36		50.12	48	1.88	7.8	7	1.5	12	34	4.8	184	55	1.5	0.12	lime powdery pocket
BK2	36-52	10YR7/2	50.12	48	1.88	7.6	5	1.5	8.3	28	2.1	85	43	3.6	0.2	lime powdery pocket
Bym1	52-95	10YR6/4	60.12	36	3.88	7.9	31	0.7	5	28	2.1	73	20	63	0.01	Coarse pendant, many gravel
Bym2	95-125	10YR7/4	66.12	20	13.88	7.9	36	0.7	5.5	56	2.9	165	21	70	0.02	Coarse pendant, many gravel

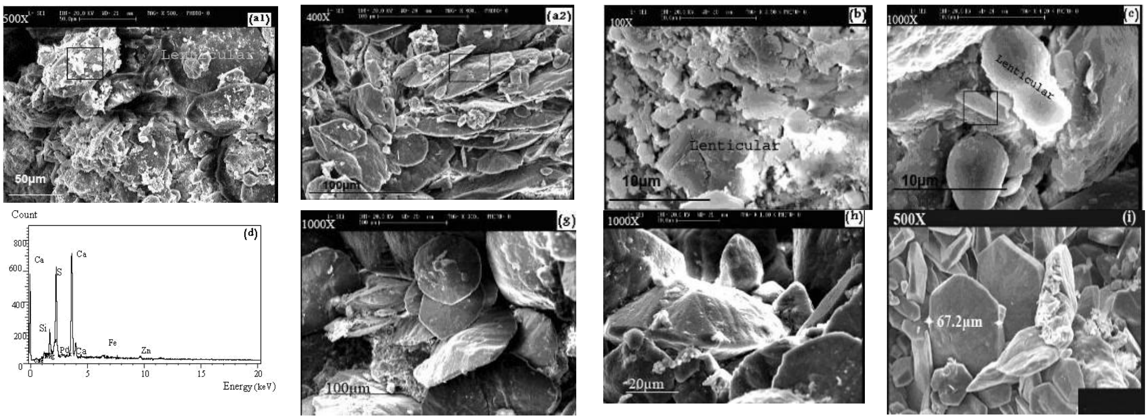

Figure 3. Back scattered electron images of the crystal habits of pedogenic gypsum in xeric moisture regimes together with EDX spectra of gypsum crystal, (a1, a2). Cluster of gypsum crystal, By1, By2 horizon of pedon 1 (b). Lenticular crystals from the By horizon, pedon 2 (c). Lenticular to columnar gypsum crystals, By1 horizon, pedon 3 (d). EDX spectra of lenticular crystal (a1 image) indicating a relative abundance of Ca and S (g). Lenticular gypsum crystals of the By1 horizon of pedon 3 (h). Lenticular gypsum crystal of a Byss horizon with a large thickness, pedon 2 (i). Subhedral to anhedral forms of gypsum, Cy horizon of pedon3.

In areas with ustic moisture regimes, evaporation occurring soon after sufficient rainfalls, therefore, rapid soil drying allows a short period for crystal growth and favors smaller length/width ratios and tight packing of more equant crystals. This type of gypsum crystallizes in a displaced way; either displacing the host soil material or forming shattered fragments inside the cracks of shattered gravel.

3. Aridic-ustic moisture regime: Euhedrals to sub-hedrals are the most common crystals observed in the aridic-ustic transitional regime (pedons 4, 6, 7). These crystals grow in-situ and do not undergo transportation or relocation. They are randomly oriented throughout the soil profile with transportation and re-crystallization rings associated with re-hydration of anhydrite or simple re-crystallization from alternating wetting and drying cycles. There is no evidence of corrosion or comb-shaped edges at the soil boundary, but suggest dissolution occurred on the irregular surfaces. There are solution pits on the surface of the crystal (Figure 5 a_1, a_2, b). Acicular to blade form of gypsum crystal of Cy horizon (Figure 5c) and Needle form with blade apex gypsum crystal of Ay horizon were observed in this regime. Pseudo-hexagonal tabular lath gypsum crystals are of microspar size, (ranging from 20 to 50µm); the six sided lath shaped crystals elongate to 101 and 111 where one axis of the hexagon is longer than the other (Figure 5h, i). This habit is exclusive to ustic moisture regime since, evaporation occurs soon after the rainfall, and thus small and thin crystals are produced. In pedon 4 with ustic moisture regime, crystals of blade, columnar, needle forms are dominant, while in pedon 6 and 7 with aridic- ustic moisture regime, subhedral, subhedral–hexagonal and associated lenticular shapes were observed (Figure 5h, i). This regime resembles the pervious regimes i.e. xeric and ustic regimes, and has *per descendum* mode. Gypsum crystal forms in relation to the respective soil horizon in this regime are shown in Table 3.

4. Xeric- Aridic moisture regime: Globular and tabular crystals are the most common shapes of gypsum crystals observed in the xeric-aridic transitional regime. Clusters of these crystals (Figure 6a, b, e) are found in soils with xeric and aridic moisture regimes. In these regions, as the soil depth increases, the presence of longer and thicker crystals of gypsum were found to be abundant. But, such a trend was not observed in pedon 9

Table 3. Morphology of gypsum crystals in relation with soil moisture regime.

Soil moisture regime	Symbol of horizon, Number of pedon	Gypsum crystals forms
Xeric	By1; pedon 1 By1; pedon 3 Byss1, pedon 2	Lenticular (aboundant)
	By2; pedon 1 Byss2; pedon2	Lenticular-columnar, Rod like
	Cy ; pedon 3	Cluster of Lenticular (superfluity)
Ustic	By; pedon 5	Cubic by needle form
	By; pedon 11	Lenticular (rarely)
	Bym, By; pedon 10	Comb-structure, Needle form
Aridic-Ustic	Ay; pedon 4	Needle form
	By; pedon 4	blade form
	Byz1; prdon 7	Cluster of lenticular,
	By; pedon 6	Pseudo-hexagonal to lenticular
	Byz2; prdon 7	Tabular
	Cy; pedon 4	Large blade form, Acicular
Xeric-Aridic	Byss; pedon 8	Globular
	Byg1; pedon 9	Tabular
	Byg2; pedon 9	Tabular-lenticular
Aridic	Byk ; pedon 12	Fibrous, Acicular
	Boundary of Bym1; pedon 12	Sheet of Rhombohedral, Blade form and fibrous
	Bym2; pedon 12	Prismatic, Interlocked plates

since this profile occurs near a lake. However, upward movement of water with capillary rise and subsequent evaporation has been suggested as the mechanism of generation and accumulation of gypsum in the soil surface around lakes. Contrary to the previous regimes, in areas close to the lake, especially pedon 9, gypsum crystals are located below the surface crust and are formed by the *per ascendum* mode in the presence of high amounts of sodium chloride. Macroscopically spear like morphology was observed at this condition.

5. *Aridic moisture regime:* Pedon 12, occurring in the piedmont plain with little progress in soil development, shows gypsum pedofeatures with speckled and pendants. Gypsum crystals increase in the groundmass of lower horizons (depth 50 to 125Cm). Gypsum enters the old gravelly alluviums through run off; evaporation causes this water from underneath the gravels to recrystalize as vertically arranged prismatic, columnar, blade form, interlocked plates and fibrous crystals (Figure 7). The gypsic prisms are euhedral and they crystallize perpendicular to the plane of fracture, shattered fragments or gravel surfaces (Figure 7b). As the process continues, neoformation of such crystals was occurred. The prominent cleavage of gypsum is accentuated by dissolution observed in the Bym horizon, pedon 12 (Figure 7f). This process forms gypsic fibers and eventually centimetric threads underneath gravels. These bearded gravels are called gypsic pendants.

Considering the soil data and taxonomic proposals (Eswaran and Zi-Tong, 1991) the soil could be classified as a hyper gypsic (profile 10 and 12). Under this condition, crystals grow happens in two directions whereby the third one is quite thin, resulting in platy crystals. However, most of the gypsum crystals such as prismatic, tabular lath, fibrous and blade have moderate length so that their size is more than 50 µm. Based on this observations concluded that the aridic regime has the *per descendum* mode. Since in the area with mesic soil moisture temperature regime, soil drying is slow the crystals growth is moderate and is long in

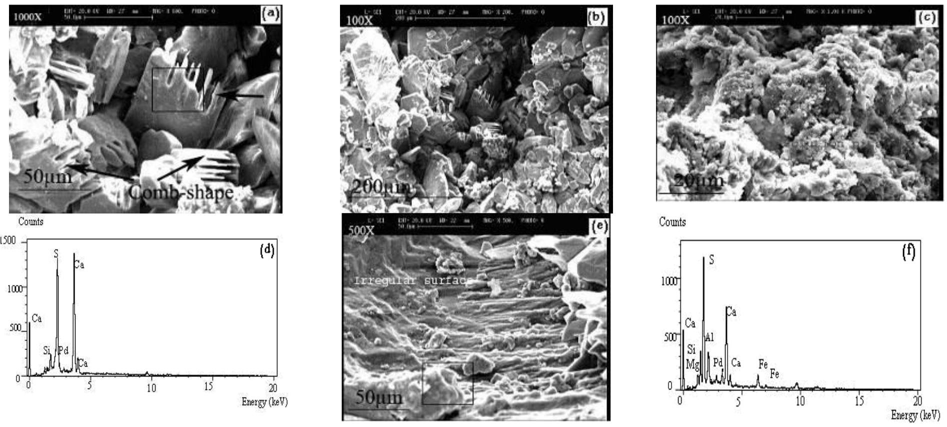

Figure 4. Back scattered electron images of the crystal habits of pedogenic gypsum in ustic moisture regimes together with EDX spectra of gypsum crystal (a). Cubic with needle form apex of gypsum crystal of Bym horizon of pedon 10 (b). Comb-shape gypsum crystal of Bym horizon of pedon 10 (c). Allabastrin gypsum crystal of the By horizon of pedon 5 (d). EDX spectra of gypsum crystal of Bym horizon of pedon 10 (e). Irregular surface of crystal affected by dissolution, By horizon of pedon 11 (f). EDX spectra of gypsum crystal of By horizon of pedon 11 (e).

length. Because pedons 10 and 12 don't have sufficient time (moderate developed soil) and have coarse texture; however, we couldn't observed lenticular, powdery and smooth crystals in aridic regime. A prismatic pseudo-hexagonal crystal can occur in gypsum crystals with strongly developed 100 and 110 faces, as suggested by Jafarzadeh and Burnham (1992). These investigators showed that in the *per ascendum* experiments larger lenticular crystals sometimes appear in corporation of matrix grains, especially with silt loam texture. Waston (1988) proved that massive crusts or subsurface petrogypsic horizons were characterized by large lenticular crystals whose formation has presumably taken a very long time. Our results also support this view. Due to the existence of gravel in this pedon with silt loam texture and rapid leaching we couldn't observe lenticular crystals.

DISCUSSION

Gypsum crystals in soils differ in shape and size. Distribution of these morphological forms has a relative relationship with soil depth and soil moisture regimes. This study shows gypsum crystals diversity in By and Bym horizons. The length and thickness of crystals varied in the different soil moisture regimes. We observed that gypsum crystals within developed soils and inmature soils are different. The transition from lenticular to allabastrine gypsum accumulation is a consequence of crossing an intrinsic threshold in soil development. In addition, gypsum crystal morphology is different in surface and subsurface horizons; as a result we concluded that subsurface horizons have more diversity of gypsum crystals than in surface horizons. In all pedons, together with soil depth the number of longer crystals of gypsum observes increased, for example in Ay horizon of pedon 4, needle form is dominant, while in By of pedon 4 has found blade form of gypsum crystal and in the Cy horizon of pedon 4 large blade form crystals have observed (Table 3). The results indicate that the formation of lenticular gypsum crystals needs a long time and is frequent in more developed soils (with more rainfall and low evaporation); thus they are found in aridic moisture regimes rarely. The conditions needed to form lenticular crystals are high ionic impurities and deposition in a

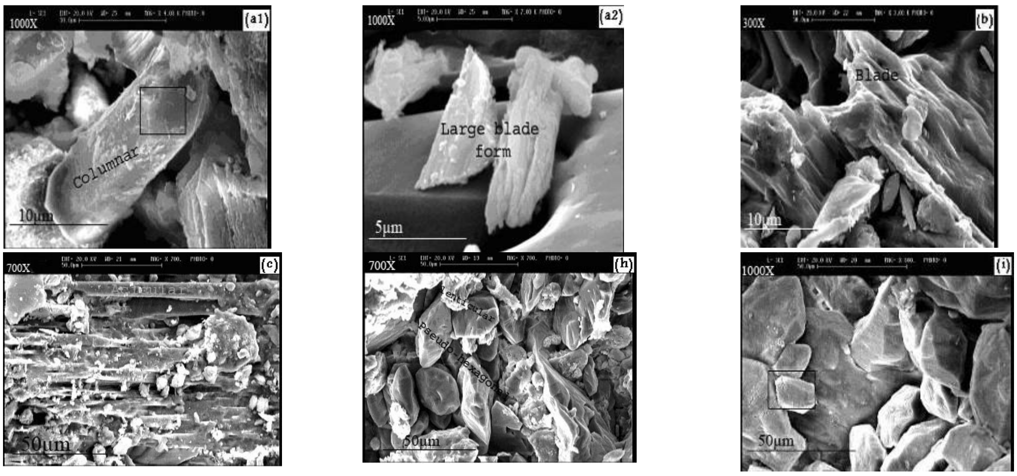

Figure 5. Back scattered electron images of the crystal habits of pedogenic gypsum observed in aridic-ustic moisture regimes (a1). Columnar gypsum crystal of the By horizon of pedon 4 (a2). Large blade form of gypsum crystal of the Cy horizon, pedon 4 (b). Blade form of gypsum crystal of the By horizon of pedon 4 (c). Acicular-blade form of gypsum crystal of Cy horizon, pedon 6, (h). Pseudo-hexagonal to lenticular gypsum crystals of the By horizon, pedon 6 (i). Tabular gypsum crystals of Byz2 horizon, pedon 7.

void system, where the space is not a limiting factor. Our results indicate that lenticular gypsum crystals are more abundant in subsurface horizons than in surface horizons. Jafarzadeh and Burnham (1992) have reported similar observations. Formation of prismatic, columnar and blade like crystals occur in soils with very low rainfall and short period of time such as in aridic moisture regime (Bym1 and Bym2, pedon 12). There are gypsic pendant in the profiles, crystal growth and length are moderate. The complex crystal habits of pedogenic gypsum are observed in soil moisture regimes, indicating that they may have been formed under slightly different environmental conditions. Subhedral, subhedral-hexagonal gypsum crystals are dominant in aridic-ustic moisture regime (pedon 6 and 7), but when soil moisture trend to xeric-aridic moisture regime globular (By, pedon 8) and tabular-lenticular (Byg1 horizon of pedon 8) are found. Our results showed that lenticular crystals are formed in the absence of organic matter, whereas curved faces are formed in the presence of sodium chloride. Furthermore, we observed that prismatic crystals are found at around pH 7.5 and higher, whereas previous studies had stressed that prismatic gypsum are mostly found in acidic conditions (Edinger, 1973; Carenas *et al.*, 1982). As can be seen in micrographs, some spaces are filled with anhedral crystals that are granular gypsum crystals. In natural crusts, the granular gypsum may infill the cracks in the crust (Figure 4a, b). In ustic moisture regime, similar to xeric regimes, sufficient rainfall occurs with relatively high evaporation. As a result, rapid soil drying that allows only short time for crystal growth, favors small length/width ratios and tight packing of equant crystals. Soils with high sodium chloride content in pedons near the lake, especially pedon 9, showed gypsum crystals under the surface crusts that have been formed by *per ascendum* process. Spear like form morphology is also noticed in this condition by naked eye. It seems that water tables can bring gypsum-saturated water near the soil surface and evaporation is high enough to elongate the crystals that are affected by soil moisture regime.

Moreover, the presence of high amount of salt plays an important role in curving crystal faces during their growth. Salts in the soil may affect dehydration and, consequently, gypsum crystal growth is rapid.

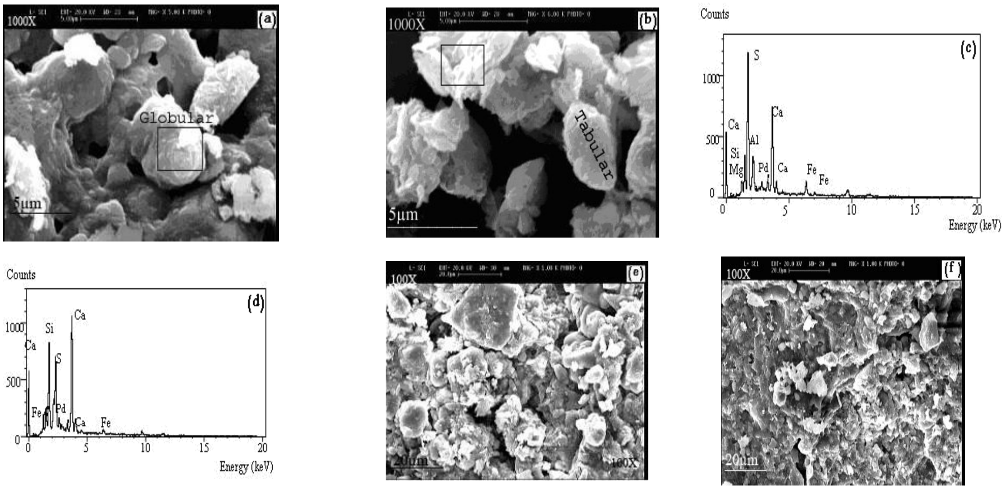

Figure 6. Back scattered electron images of the crystal habits of pedogenic gypsum xeric-aridic moisture regimes together with EDX spectra of gypsum crystal (a). Globular gypsum crystals of the Byss horizon, pedon 8 (b). Tabular gypsum crystals of the Byg1 horizon, pedon 9 (c). EDX spectra of gypsum crystal of the Byss horizon of pedon 8 (i.e a image), (d). EDX spectra of gypsum crystal of the Byg1 horizon, pedon 9 (i.e b image) (e). Cluster of gypsum crystal of the Byg2 horizon, pedon 9. (f) Hexzagonal in gypsum crystal matrix, Byss horizon, pedon 8.

In a previous study, an indication was obtained that the crystal habit of pedogenic gypsum can be linked to the presence of soil impurities and the degree of soil solution supersaturation with respect to gypsum (Jafarzadeh and Burnham, 1992).

The evaporation rate affects soil drying rate. Hence, in areas where temperature is low (pedon 12, Abadeh), soil drying will be slow. Therefore, the crystal growth is moderate as well as large in length. In case of rainfall, soil drying is rapid and crystals growing in a short period of time will produce morphologies with smaller length/width ratios. In addition to, evaporation helps the movement of water in *per ascendum* mechanism and causes rapid growth of gypsum crystal.

According to Sadeghi *et al.* (2002), the agroclimatological index (P/ET° i.e. ratio of mean annual precipitation to mean annual reference crop evaportranspiration) varies from less than 0.2 in arid areas of the north, east, and south to more than 0.6 in the mountainous regions of the northwest. This variation is also in accordance with the soil moisture and temperature regime map of Fars Province. This finding shows that $ET_\circ$ value in the aridic moisture regime is high and in the xeric moisture regime is low, confirming the discussion about evaporation rate and its effect on soil drying rate and gypsum crystal formation.

CONCLUSION

The amount of gypsum accumulation in soils of the study area depends on soil moisture regimes, but not on the soil temperature regimes. Gypsiferous soils occur more commonly in aridic moisture regimes. Micromorphology of gypsum crystals changes in different moisture regimes. In aridic moisture regime, interlocked plates, acicular, fibrous, prismatic and blade forms are more common, while, in xeric moisture regimes, lenticular crystals are dominant; but, in the subsoil, cluster of lenticular, rod like, and tabular subhedrals are observed. Under ustic soil moisture regime, evaporation induces water moving by capillary rise of the gravels to recrystalize vertically arranged columnar, cubic, and needle form crystals. In the intermediate moisture regimes, however, we observed gypsum crystals between either xeric

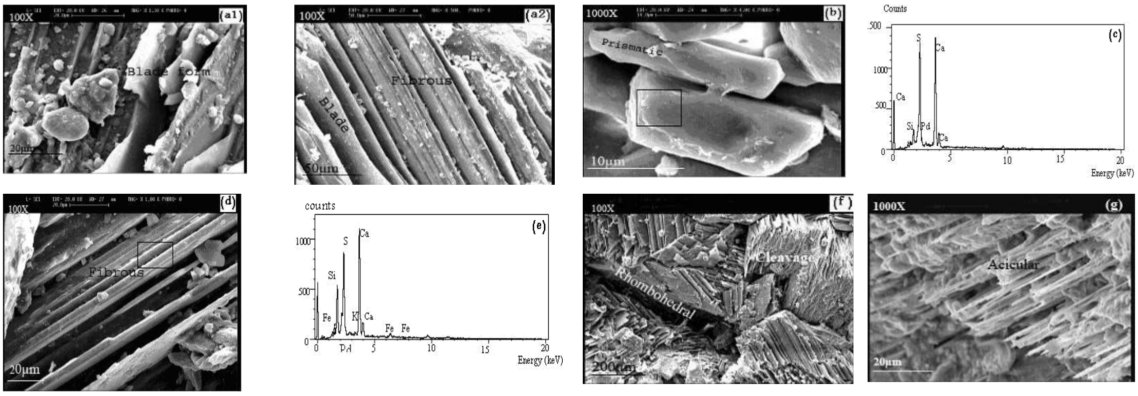

Figure7. Back scattered electron images of the crystal habits of pedogenic gypsum aridic moisture regimes together with EDX spectra of gypsum crystal (a1, a 2). Blade form and fibrous gypsum crystal of the Bym1 horizon, pedon 12 (b). Prismatic gypsum crystals of the Bym2 horizon, pedon 12 (c). EDX spectra of prismatic (i.e b image) gypsum crystals, (d) fibrous gypsum crystals, Byk horizon. .(e) EDS spectral images of blade form and fibrous gypsum crystals (d image). (f). Sheet of rhombohedral gypum in soil boundary of the Bym horizon, pedon 12 (occurrence of accentuated cleavage) (g). Acicular Gypsum crystal of the Bym1 horizon of pedon12.

and aridic moisture regimes or ustic and aridic. Therefore, near the aridic regimes, more crystals grow length wise with limited thickness (such as columnar, fibrous, perpendicular, blade and needle forms), while with increasing rainfall, like in xeric regime, more crystals grow in width with higher thickness (such as lenticular, globular, tabular and rosette-like forms). Indeed, as rain water becomes saturated with gypsum and continues to evaporate, successive phases of crystallization and renewed crystallization would constantly follow. Gypsum saturated runoff removes the soil materials from alluvial fans and plateaus towards the piedmont plains.

The textural analysis data reveals that the dominant classes are silt loam, sandy loam, and loam, respectively. In pedons with high clay content, the amount of gypsum is <15%. However, in other light textures, $CaSO_4{\cdot}2H_20$ content was ≥25%. SEM approved for studying the shape of gypsum crystals. For spatial determinations of gypsum crystals, the use of large thin sections and polarization microscopy would be promising.

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میکرومورفولوژی کریستالهای گچ در خاک‌های جنوب ایران تحت رژیم‌های رطوبتی متفاوت

س. س. هاشمی ، م. باقرنژاد و ح. خادمی

چکیده

خاک‌های گچی بیشتر در رژیم‌های رطوبتی زریک، یوستیک واریدیک دیده می‌شوند. شرایط محیطی در تشکیل گچ اثرگذار است. خاک‌های گچی استان فارس در جنوب ایران،بیشتر در دشتهای دامنه‌ای، سیلابی و آبرفتی یافت می‌شوند. هدف از این تحقیق بررسی میکرومورفولوژی کریستالهای گچ تشکیل شده تحت رژیم-های رطوبتی متفاوت است. نتایج نشان می‌دهد که کریستالهای عدسی گچ معمولا در خاک‌های توسعه یافته به وفور یافت می‌شوند، در حالی که تحت رژیم رطوبتی اریدیک کمیاب هستند. این کریستال‌ها در افق‌های زیر سطحی به وفور یافت می‌شوند. شکل‌های ستونی، منشوری و تیغه‌ای گچ در نواحی با رژیم رطوبتی اریدیک که خاکهای آنها شستشوی بالا داشته اند، یافت می‌شوند. تشکیل پندانت گچ در زیر سنگریزه‌ها در دشتهای دامنه‌ای، با رطوبت محدود فراوان است. در نواحی با بارندگی کم کریستالهای گوناگونی از گچ تشکیل شده است. به نظر می‌رسد که رواناب به عنوان یک سیستم هیدرولوژی منجر به انتقال رسوبات زمینی از ارتفاعات بالا به دشتهای سیلابی محتوی خاک‌های با بافت درشت، می‌شود. در نواحی با رژیم رطوبتی زریک و زریک مرز اریدیک، رشد کریستالهای عدسی، ائوهدرال و ساب هدرال گچ فراوان است. نتایج مطالعه نشان می‌دهد که علاوه بر رطوبت خاک، بافت خاک و موقعیت توپوگرافی، نقش مهمی در تشکیل کریستالهای گچ خاکساز دارند. تبلور خوبی از گچ در بافتهای سیلت لوم، شنی لوم و لوم دیده شد. مشاهده افق‌های جیپسیک پیشنهاد می-کند که تجمع گچ در خاکهای مورد مطالعه بیشتر تحت فرآیند *Per dscendum* صورت گرفته است.