Polygenetic saline gypsiferous soils of the Bam region, Southeast Iran

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Abstract

Gypsiferous and saline soils are among the major soils of arid and semi-arid regions of the world. Although numerous studies on salic, gypsic and petrogypsic horizons have been carried out, the co-occurrence of gypsum and halite and their morphological expression are still poorly documented. Eight pedons located on a co-alluvial fan (Bam area, southeast Iran) were described, sampled and analyzed for physico-chemical and micromorphological characteristics based on standard methods. The highest amounts of gypsum (≈ 60 %) comprising xenotopic gypsum and/or fibrous bassanite pseudomorph remaining behind after xenotopic gypsum dehydration were determined in the surface crust and in the underlying 2Byz horizon. At a depth of 15 cm, a horizon cemented by gypsum and halite was observed. The highest amount of gypsum was determined at the upper part of this horizon followed by a sharp decreasing trend towards the lower depth. The amount of halite increases with increasing depth towards the bottom of 3Byzm horizon. Deeper, in the 5Byz horizon the quantity of gypsum increases drastically and coarse elongated gypsum pendants dominate. Micromorphological observations demonstrate that the dominant cementing agent is halite rather than gypsum. However, due to inexistence of petrosalic diagnostic horizon in Keys to Soil Taxonomy, these soils are to be classified as Petrogypsic Haplosalids at subgroup level in Soil Taxonomy. In WRB Taxonomy, they are classified as Petrosalic Solonchaks. Co-occurrence of gypsum and halite in the same horizon, their specific layering and vertical distribution patterns in the studied pedons might be considered as indicators for polygenetic soils in this area.

Keywords: polygenetic soils, bassanite, gypsum, halite, Petrogypsic Haplosalids, Petrosalic Solonchaks.

1. Introduction

Among the countries in arid and semiarid regions, Iran seems to have the largest area of gypsiferous soils in world, covering about 27 to 28 Mha (Mahmoodi, 1994, Farpoor *et al*., 2004). Saline soils comprise around 16 to 23 Mha of arable lands in Iran (Siadat *et al*., 1997). As the accumulation of soluble salts in soil causes a sever decrease in soil quality, the study of the processes involved in salinization is essential for sustainable soil management (Farifteh *et al*., 2006). The factors and processes that determine the distribution and morphology of soluble minerals in these environments are poorly understood (Mees, 2003). Distribution of gypsum and/or halite-bearing soils is controlled by the geology of the parent materials (Eswaran and Zi-Tong, 1991) and/or mechanisms that introduce the required cations or anions (Buck *et al*., 2002; Herrero and Porta, 2000), such as a changing groundwater level (Mees, 2003). Distribution of gypsum and soluble salts within the profile depends on the prevailing climatic conditions. While in more arid climates ascending water is the dominant process and gypsum and soluble salts accumulation occur in the surface horizon, the descending process prevails in semiarid climates and accumulation occurs in the subsurface horizons (Dultz and Kühn, 2005). Owliaie *et al*. (2006) concluded that micromorphological observations and SEM analyses can help investigators as a useful tool to show variable habits of gypsum crystals in different physiographic units which demonstrate dynamic soil formation environment.

Hashemi *et al*. (2011) suggested that the amount of gypsum accumulation in their study area was depended on soil moisture regimes rather than soil temperature regimes. They also concluded that micromorphology of gypsum crystals varies at different moisture regimes. Interlocked plates, acicular, fibrous, prismatic and blade forms in arid zones and lenticular gypsum in semiarid zones are dominant; however, in the subsoil, clusters of lenticular, rod like, and tabular shapes observed. Under hot and dry conditions, due to more evaporation and capillary rise vertically arranged columnar, cubic, and needle shapes of gypsum were dominant. Toomanian *et al*. (2001) studied gypsum enriched soils of central Iran and showed that the distribution, arrangement and orientation patterns of the secondary gypsum crystals were largely depended to the physical environment. Soil fabric and microstructure, coarse to fine related distribution pattern and voids play a considerable role in formation of different gypsic pedofeatures.

Due to insufficient data on gypseous soils distributed in different environments around the world their classification process is very problematic. Coexistence high amounts of salts more soluble with gypsum especially as a cementing agent in soil horizons may cause strengthening the problem. A correct classification of gypsiferous soils commonly will require a careful morphological observation in order to identify the secondary gypsum accumulations (Florea and Al-Joumaa, 1998). According to Soil Survey Staff (2010), gypsiferous soils located at the regions with aridic soil moisture regime are classified as gypsids or great groups and subgroups of the other suborders aridisols. The other gypsiferous soils might placed in different categorical levels of soil orders related to their key identification. IUSS (2006), with introducing the petrosalic diagnostic horizon, has tried to tackle out the problems in classification of gypsiferous soils.

In the Bam region, southeast Iran, soils with a bimodal and combined distribution of both gypsum and halite are frequent. The objectives of this paper are discussing the genesis and classification of salic, gypsic and particularly petrogypsic/salic horizons in this region.

2. Materials and methods

2.1 The studied area

The Bam area is located between 58º, 35´-58º, 50´ Eastern longitudes and 28º, 50´-29º, 10´ Northern latitudes in southeast Iran (Figure 1A). Figure 1B, shows the location of the studied pedons and their geological context. Except pedon no. 8 they are situated on low level piedmont fan and valley terraces, with a slope < 5% and randomly distributed on different positions of the landscape. The parent materials are mostly derived from saliferous-gypsiferous marls of the Neocene, igneous rocks of the Palaeocene and some quaternary formations. Mean annual precipitation (from 1956 to 2005), is 61.3 mm, spread over winter (26.5 mm), spring (29.1 mm), summer (2.1 mm) and autumn (3.6 mm) rainfalls. Mean annual air temperature is about 23 ºC, with mean summer value of 33 ºC and mean winter value of about 12 ºC. The mean annual potential evapotranspiration exceeds 2880 mm, the highest and lowest means occurring in July (≈ 366 mm) and January (114 mm) respectively. The soil moisture and temperature regimes are aridic and hyperthermic respectively (Banaei, 1998). Except for a cover of *Salsola* species, limited to the narrow seasonal river beds (< 5 %), the soil surface is mostly covered by desert pavement (about 75-80 %) and gypsum crust (about 20 % respectively). These soils are part of the arid rangeland of the Bam region.

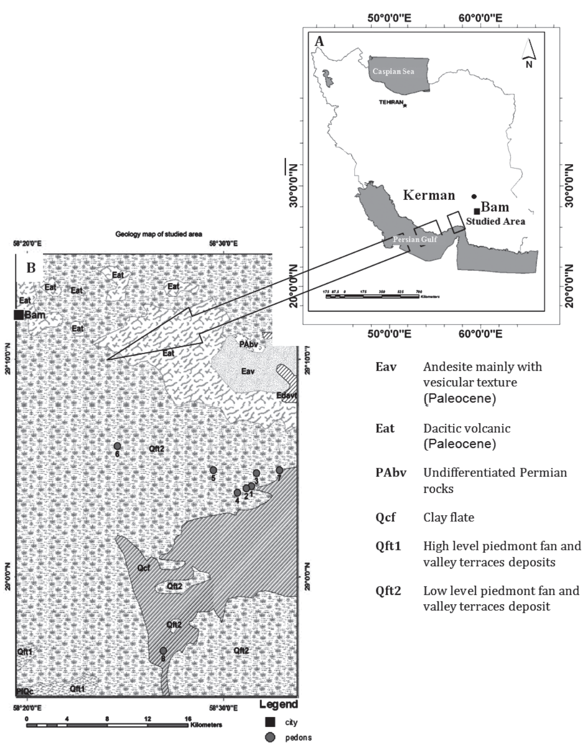

Figure 1. Location of the study area. A) Location of the Bam region (Southeast Iran); B) geological map of the studied area and location of the studied pedons.

2.2 Field and laboratory methods

Eight pedons, were randomly selected in a coalluvial physiographic unit and described according to USDA-NRCS (2002) guidelines and classified according to Keys to Soil Taxonomy (Soil Survey Staff, 2010) and correlated with World Reference Base for Soil Resources (IUSS, 2006). All horizons of the studied profiles were sampled, air-dried at room temperature, ground to pass through a 2-mm sieve prior to analysis. The EC and pH of the saturated extracts were measured with PW 9527 Philips EC meter and EYELA 2000 pH meter respectively. The gypsum content was quantified by aqueous extraction with a 1:500 soil:water ratio, precipitation in acetone, centrifuging, and re-dissolution in water for measuring electrical conductivity (USDA-NRCS, 2004). Organic carbon (Acid-Dichromate Digestion (6A1)), calcium carbonate equivalent (Carbonate and Gypsum (4E)), soluble anions and cations (procedures 4F2c1b1a1-8 and 4F2c1c1a1-2) were measured according to standard methods (USDA-NRCS, 2004). Twenty undisturbed oriented soil samples from gypseous and saline horizons (Table 1) were impregnated with polyester resin and thin sections prepared according to Murphy (1986), using kerosene as coolant. The thin sections were analysed and described according to Stoops (2003). Scanning electron microscopy observations (SEM) and Energy Dispersive Spectrometry (EDS) for Byz and Byzm horizons were performed on undisturbed soil samples mounted on aluminium stubs and coated with gold (USDA-NRCS, 2004) using a Philips SEM.XL30.

3. Results

3.1 Macro-morphology

Pedon 2 was taken as representative profile for description of macromorphological characteristics of the studied pedons. Abrupt changes in amount, shape, size and lithology of gravels in the horizons of the studied pedons (Table 1) point to the presence of several discontinuities (Figure 2).

Table 1. Some morphological characteristics of the representative pedons.

Pedon No.	Horizon	boundary	Depth (cm)	Soil Structure	Colour (moist)	Field Texture	Remarks
1	A	abrupt wavy	0-3	Granular	10YR7/2	Silt loam	Desert pavement, patches of gypsum crust
	2Byz	abrupt wavy	3-20	Massive	7.5YR7/2	Silt loam	Powdery and massive gypsum (many)
	3Byzm	abrupt wavy	20-40	Massive	7.5YR3/2		Powdery and massive gypsum (common), saline taste
	4Byz1	abrupt wavy	40-60	Single grain	7.5YR3/1	Sandy	Powdery and massive gypsum (common)
	4Byz2	abrupt wavy	60-80	Massive	7.5YR3/2		Powdery and massive gypsum (many)
	5Byz3			Single grain	10YR4/2	Sandy loam	Powdery and massive gypsum (few)

Pedon No.	Horizon	boundary	Depth (cm)	Soil Structure	Colour (moist)	Field Texture	Remarks
2	A	abrupt wavy	0-4	Granular	10YR5/4	Loamy silt	Desert pavement, patches of gypsum crust
	2Byz	abrupt wavy	4-15	Single grain	7.5YR8/1	Gravelly clay loam	Powdery and massive gypsum (many), saline taste
	3Byzm	clear wavy	15-37	Massive	7.5YR7/5	Gravelly sand	Gypsum and halite cement, saline taste (many)
	4Byz1	clear wavy	37-56	Apedal (Single grain)	10YR6/3	Gravelly sand	Powdery gypsum, saline taste (common)
	5Byz2	clear wavy	56-88	Apedal (Single grain)	10YR7/2	Gravelly silt loam	Gypsum pendants 0.5 – 3 cm length (many), saline taste
	6Cz1	clear wavy	88-108	Massive	10YR6/4	Loamy	Saline taste
	6Cz2		108-130	Massive	10YR5/4	Loamy	Saline taste
3	A	abrupt wavy	0-5	Granular+ Massive	10YR3/3	Clay loam	Desert pavement, patches of gypsum crust
	2Byz	abrupt wavy	5-20	Granular+ Massive	7.5YR6/2	Gravely clay loam	Powdery gypsum, saline taste (many)
	3Byzm	abrupt wavy	20-30	Massive	7.5YR6/2	Gravely sand	Cemented by gypsum saline taste
	4Byz1	clear wavy	30-40	Single grain+ Massive	10YR5/3	Gravely sandy loam	Powdery gypsum (common)
	4Byz2	clear wavy	40-58	Single grain+ Massive	10YR4/3	Silt loam	Gypsum pendants 0.5 – 2 cm length (many)
	5Cz1	clear wavy	58-97	Massive	10YR4/2	Gravely clay loam	Powdery gypsum (common)
	5Cz2	clear wavy	97-110	Massive	10YR4/3	Loam	Powdery gypsum (few)
	5Cz3		110-130	Massive	10YR5/3	Loam	Powdery gypsum (few)
4	A	abrupt wavy	0-3	Granular+ Massive	10YR6/5	Silt loam	Desert pavement, patches of gypsum crust
	2Byz	abrupt wavy	3-14	Single grain+ Massive	7.5YR6/2	Gravely clay loam	Massive and powdery gypsum (many)
	3Byzm	abrupt wavy	14-27	Massive	7.5YR4/3	Gravely sand	Saline taste
	4Byz1	clear wavy	27-54	Single grain+ Massive	7.5YR5/3	Gravely loam	Powdery gypsum, saline taste (common)

Pedon No.	Horizon	boundary	Depth (cm)	Soil Structure	Colour (moist)	Field Texture	Remarks
4	4Byz2	clear wavy	54-80	Single grain	10YR4/2	Very gravely silt loam	Gypsum pendants 0.5 – 3 cm length (many)
	5Cz1		80-120	Massive	10YR5/4	Loam	Powdery gypsum (few)
5	A	abrupt wavy	0-3	Granular+ Massive	10YR4/3	Loamy sand	Desert pavement, patches of gypsum crust
	2Byz	abrupt wavy	3-20	Single grain	7.5YR6/2	Gravely sandy loam	Massive and powdery gypsum (many)
	3Byzm	abrupt wavy	20-35	Massive	7.5YR6/3	Gravely sandy loam	Massive and powdery gypsum (many), saline taste
	4Byz1	clear wavy	35-50	Single grain	10YR5/2	Gravely sand	Powdery gypsum (common)
	5Byz2	clear wavy	50-67	Single grain	10YR5/2	Gravely silt loam	Gypsum pendants 0.5 – 3 cm length (many)
	5Byz3		37-85	Single grain	10YR5/3	Gravely sandy loam	Powdery gypsum (common)
6	A	abrupt wavy	0-5	Granular+ Massive	10YR4/2	Silt loam	Desert pavement, patches of gypsum crust
	2Byz	abrupt wavy	5-22	Single grain	10YR6/2	Sandy loam	Powdery gypsum (many) saline taste
	3Byzm	abrupt wavy	22-38	Massive	7.5YR4/2	Gravely sandy loam	Powdery gypsum (many) saline taste
	4Byz1	abrupt wavy	38-56	Single grain	10YR4/2	Gravely sandy loam	Powdery gypsum (common)
	5Byz2	clear wavy	56-70	Single grain	10YR4/2	Gravely sandy loam	Gypsum pendants 0.5 cm length (many)
	5Bz1	clear wavy	70-90	Single grain	10YR4/3	Gravely loamy sand	Powdery gypsum (few) saline taste
	6Bz2	clear wavy	90-110	Single grain	10YR4/2	Gravely sandy loam	Powdery gypsum (few) saline taste
7	A	abrupt wavy	0-5	Granular+ Massive	Not described		Desert pavement, patches of gypsum crust
	2Byz	abrupt wavy	5-17	Single grain		Gravely clay loam	

Pedon No.	Horizon	boundary	Depth (cm)	Soil Structure	Colour (moist)	Field Texture	Remarks
7	3Byzm	abrupt wavy	17-35	Massive	Not described	Gravely sandy loam	Powdery gypsum (many) saline taste
	4Byz1	clear wavy	35-50	Single grain		Gravely sandy loam	Powdery gypsum (few) saline taste
	4Byz2	clear wavy	50-80	Single grain		Gravely loam	Powdery gypsum (few) saline taste
	5yz1	clear wavy	80-110	Single grain		Gravely clay loam	Powdery gypsum (few) saline taste
8	A	Not described	0-4	Not described			
	2Byz		4-15				
	3Byzm		15-32				
	4Byz1		32-56				
	4Byz2		56-85				
	5Cz1		85-110				

The soil surface is covered for about 75-80 % by desert pavement; consisting of more or less sub-rounded to rounded, gravel sized fragments (2-7 cm in diameter) of igneous and sandstone composition. White powdery gypsum crusts cover the remaining surface, forming patches of a few cm, up to about 30 cm in diameter (Figure 2A.a). A thin discontinuous surface horizon (A horizon), abruptly overlays a loose and fine single grained horizon with the maximum content of gypsum (2Byz horizon) (Table 1, Figure 2B). At a depth of about 15 cm, a very hard cemented horizon (3Byzm), more than 20 cm thick, starts that cannot be dug by spade and only hardly broken by hammer (Figure 2A.b). Dry fragments (> 10 cm diameter) slake when submerged for 24 h in water. Dry soil consistence decreases within the 4Byz1 horizon, due to a remarkable decrease in gypsum (Table 2). The gypsum content increases again and rather long 0.5-3 cm gypsum pendants appear beneath the gravels within the 5Byz2 horizon (Figure 2A.c). This horizon gradually merges into a massive and clayey horizon with very few gypsum crystals, which extends down to about 120-130 cm depth. Beneath this a very hard, massive sedimentarylayer withvery fine texture occurs.

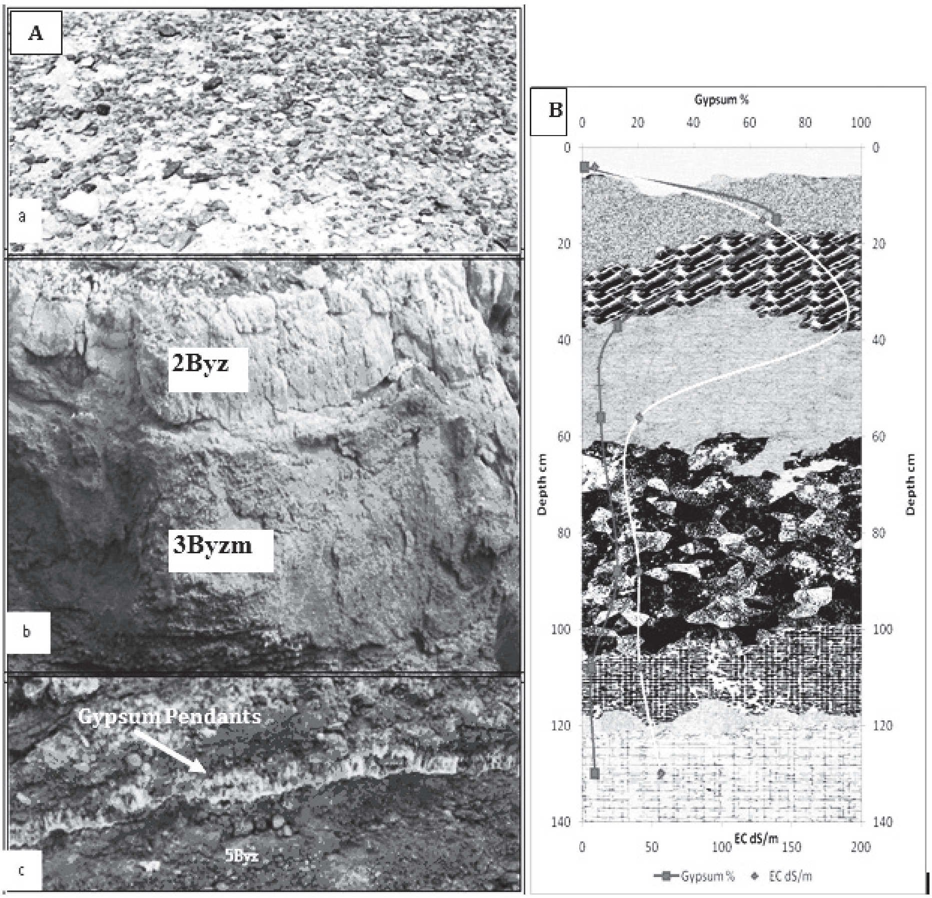

Figure 2. A) Field aspect of a typical profile (Pedon 2) in the Bam region; a) soil surface (vertical view): white powdery gypsum crusts overlain by dark coloured desert pavement; b) 2Byz horizon with maximum gypsum content (>60%) and 3Byzm horizon cemented by gypsum and halite; c) 5Byz horizon showing gypsum pendants forming a continuous feature by linking. B) Schematic representation of a hypothetical profile of the Bam region, and variations of gypsum and halite content.

3.2 Physico-chemical properties

Table 2 shows the results of physico-chemical analysis for eight representative pedons and their classification. Organic matter content is very low (< 0.1 %), pH varies between 7.0 and 8.6, and electrical conductivity varies between 25 to 187 dS m^{-1} indicating strong to very strong saline soils.

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

Horizon	Depth (cm)	*EC (dS m^{-1})	**pHse	¤RF (>2mm)	Gypsum %	¥CCE %	OC %	Water Extractable ions (meq L^{-1})					
								Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-
Pedon 1 Petrogypsic Haplosalids													
A	0-3	47.5	8.4	-	1.1	9.32	0.12	485.9	4.2	2.8	1.5	504.4	22.2
2Byz	3-20	155.1	8.1	10	34.5	4.2	0.10	1642.6	2.6	1.5	2.8	1710.2	17.4
3Byzm	20-40	178.1	8.4	20	11.7	2.6	0.08	1894.9	5.6	1.5	3.1	1854.0	11.6
4Byz1	40-60	132.7	8.1	10	2.4	3.0	0.04	1364.4	1.2	1.0	3.6	1362.7	10.2
4Byz2	60-80	180.1	8.2	30	23.2	1.6	0.09	1901.2	2.1	1.6	0.6	1846.3	8.4
5Byz3	80-120	101.3	8.5	20	6.4	1.8	0.09	1105.2	2.9	1.5	0.8	1011.0	12.3
Pedon 2 Petrogypsic Haplosalids													
A	0-4	90.2	8.19	-	0.8	9.68	0.09	764.4	4.2	3.7	3.2	850.1	20.3
2Byz	4-15	129.2	8.01	10	69.5	3.00	0.02	1300.2	3.9	1.1	5.4	1350.0	15.6
3Byzm	15-37	187.7	7.92	20	12.7	1.06	0.00	1860.8	5.7	1.4	1.5	2100.0	8.6
4Byz1	37-56	40.8	8.77	20	6.6	1.94	0.02	421.4	1.2	2.6	2.0	380.4	29.4
5Byz2	56-88	40.6	8.65	40	12.6	1.91	0.02	320.6	1.1	1.5	2.3	346.7	31.6
6Cz1	88-108	41.3	8.41	10	3.3	9.39	0.07	360.8	1.1	2.8	2.5	325.1	22.6
6Cz2	108-130	56.4	8.53	-	4.5	16.25	0.08	760.4	1.4	3.0	1.7	680.3	23.4
Pedon 3 Petrogypsic Haplosalids													
A	0-5	25.22	8.36	-	0.8	6.57	0.08	320.0	1.72	2.5	3.8	460.3	33.3
2Byz	5-20	150.2	7.97	10	62.5	7.56	0.06	1659.5	1.6	5.1	1.1	1400.5	16.42
3Byzm	20-30	184.4	7.80	15	24.0	2.26	0.00	1800.7	6.61	2.0	0.7	1900.61	17.95
4Byz1	30-40	79.93	8.26	10	8.6	8.55	0.06	743.3	3.9	4.1	1.3	741.14	20.75
4Byz2	40-58	50.85	8.46	30	15.6	9.89	0.05	607.2	1.36	2.8	4.2	652.65	22.74
5Cz1	58-97	75.73	8.21	5	2.7	17.7	0.09	694.4	1.6	1.5	4.1	450.45	26.63
5Cz2	97-110	29.10	8.52	-	4.0	14.7	0.12	380.1	0.59	0.4	2.1	265.85	29.45
5Cz3	110-130	85.02	8.15	-	7.5	14.4	0.10	887.3	1.3	2.5	2.3	766.48	20.46
Pedon 4 Petrogypsic Haplosalids													
A	0-3	50.2	7.6	-	1.8	7.9	0.08	564.1	2.1	3.5	2.9	500.3	26.3
2Byz	3-14	169.8	7.04	10	27.6	6.4	0.06	1123.2	8.4	3.4	2.9	1200.2	15.6
3Byzm	14-27	187.0	7.12	20	15.7	3.2	0.00	2100.9	4.1	3.5	0.5	2235.2	18.2
4Byz1	27-54	37.2	7.37	10	4.7	8.5	0.04	454.4	0.78	1.4	0.4	385.3	24.4
4Byz2	54-80	31.7	7.35	10	11.7	11.8	0.06	476.4	0.72	2.1	0.9	425.6	22.1
5Cz1	80-120	72.2	7.16	-	4.2	13.8	0.09	764.4	1.6	1.6	1.3	692.3	26.6

Horizon	Depth (cm)	*EC (dS m-1)	**pHse	¤RF (>2mm)	Gypsum %	¥CCE %	OC %	Water Extractable ions (meq L-1)					
								Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-
Pedon 5 Petrogypsic Haplosalids													
A	0-3	26.01	7.55	0	1.2	6.5	0.16	309.1	1.71	2.4	3.0	254.6	43.3
2Byz	3-20	168.7	7.58	10	47.8	2.04	0.09	1650.4	5.11	2.6	1.2	1542.6	26.6
3Byzm	20-35	188.1	7.66	20	24.0	0.84	0.03	1975.6	6.91	1.3	2.5	1854.5	12.4
4Byz1	35-50	30.18	7.74	40	13.3	1.07	0.08	360.8	4.78	2.0	1.1	325.6	21.4
5Byz2	50-67	29.39	7.40	20	10.4	3.5	0.12	310.6	0.90	1.1	1.0	310.6	26.0
5Byz3	37-85	51.54	7.8	20	15.2	9.8	0.11	643.4	4.78	3.0	1.5	631.2	14.6
Pedon 6 Petrogypsic Haplosalids													
A	0-5	16.67	7.99	0	1.0	7.7	0.11	150.2	1.2	1.8	0.4	136.6	32.2
2Byz	5-22	147.5	8.2	5	29.6	2.4	0.06	1462.2	1.2	2.4	2.4	1290.7	35.4
3Byzm	22-38	188.4	7.35	20	11.5	1.2	0.00	1962.2	2.9	1.6	1.4	1987.9	11.4
4Byz1	38-56	80.89	7.93	10	7.0	3.5	0.00	841.3	1.4	2.0	0.4	867.4	26.6
5Byz2	56-70	71.5	8.09	30	5.4	2.6	0.08	743.7	1.7	1.3	1.0	756.9	40.1
5Bz1	70-90	34.75	8.23	40	4.0	4.59	0.08	364.6	0.8	1.5	1.3	367.4	35.3
6Bz2	90-110	23.2	7.98	30	4.6	3.3	0.09	246.2	0.5	2.0	0.5	262.3	28.1
Pedon 7 Petrogypsic Haplosalids													
A	0-5	40.6	8.20	0	0.9	8.2	0.11	390.6	4.2	3.7	3.2	385.6	20.0
2Byz	5-17	120.3	8.01	10	35.6	2.1	0.09	1300.3	3.9	1.1	5.4	1274.6	29.0
3Byzm	17-35	176.5	7.92	20	23.9	0.85	0.03	1875.5	5.7	1.4	1.5	734.3	8.0
4Byz1	35-50	65.3	8.3	30	10.5	1.8	0.07	710.3	1.2	2.6	2.0	731.2	15.0
4Byz2	50-80	70.6	8.15	20	12.5	4.5	0.13	679.3	1.1	1.5	2.3	681.6	31.0
5yz1	80-110	82.6	8.41	0	15.3	10.5	0.11	794.5	1.1	2.8	2.5	784.6	30.2
Pedon 8 Petrogypsic Haplosalids													
A	0-4	38.5	8.19	-	1.2	10.6	0.09	418.4	4.2	3.7	3.2	423.6	20.1
2Byz	4-15	134.6	8.01	10	65.9	2.31	0.09	1558.4	3.9	1.1	5.4	1310.1	15.3
3Byzm	15-32	168.1	7.97	20	30.5	0.96	0.00	1785.8	5.7	1.4	1.5	1780.1	8.8
4Byz1	32-56	65.3	8.77	20	6.5	1.06	0.02	585.9	1.2	2.6	2.0	643.7	29.6
4Byz2	56-85	45.3	8.65	40	13.2	4.5	0.02	410.6	1.1	1.5	2.3	385.6	31.4
5Cz1	85-110	72.2	7.16	-	4.2	13.8	0.09	764.4	1.6	1.6	1.3	692.3	26.6

* Electric Conductivity (EC), **pH of saturated extract, ¤Rock Fragment %, ¥Calcuim Carbonate Equivalent.

The higher EC values were found in the upper parts of the soil profiles (2Byz and 3Byzm horizons). The higher contents of gypsum (27 to 69 %) were determined in the uppermost B-horizons (2Byz). Calcium carbonate equivalent (CCE) ranged from 1 to 16%, with an irregular vertical distribution pattern.

3.3 Micromorphology

Although the studied 2Byz horizons (three thin sections) show significant local differences, they have some characteristic properties in common. The microstructure, without considering soluble minerals (gypsum and halite) ranges from open spaced enaulic to granular. The coarse components consist of fine gravel and coarse to medium sand sized, rounded grains of quartz, volcanic rock and limestone fragments. The fine material in the aggregates is light greyish brown and speckled with a stipple speckled or calcitic crystallitic b-fabric. The interaggregate/intermineral spaces are filled either with fine grained (< 75 µm) xenotopic gypsum (missing crystalline form) (Figure 3), or with fibrous bassanite or hemihydrate ($CaSO_4$ ($0.5H_2O$)) alteromorph after coarse (about 2 mm) xenotopic gypsum (Figure 4), or dominated by xenotopic halite. In the latter case, halite forms also coatings of parallel oriented, slightly elongated crystals on the larger constituents. Also in the two first mentioned fabrics, considerable amounts of halite occur interstitially.

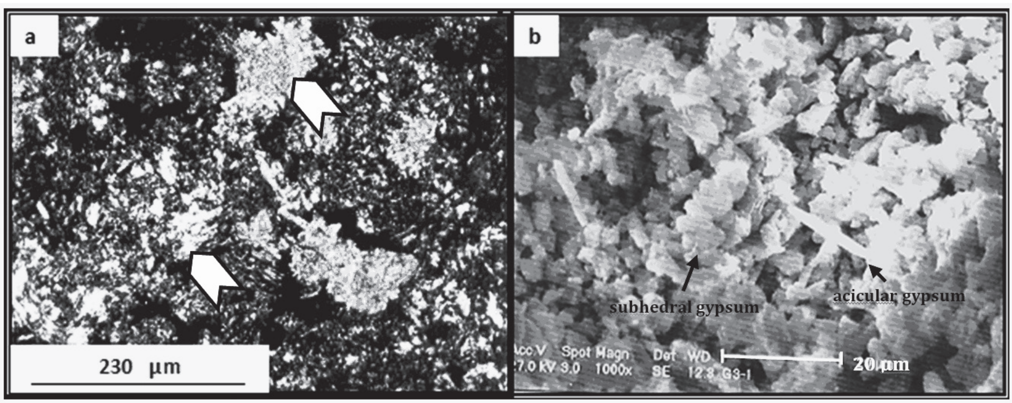

Figure 3. a) Fine grained xenotopic gypsum in transmitted light (XPL), b) subhedral and acicular gypsum crystals (SEM). 2Byz horizon of Pedon 4.

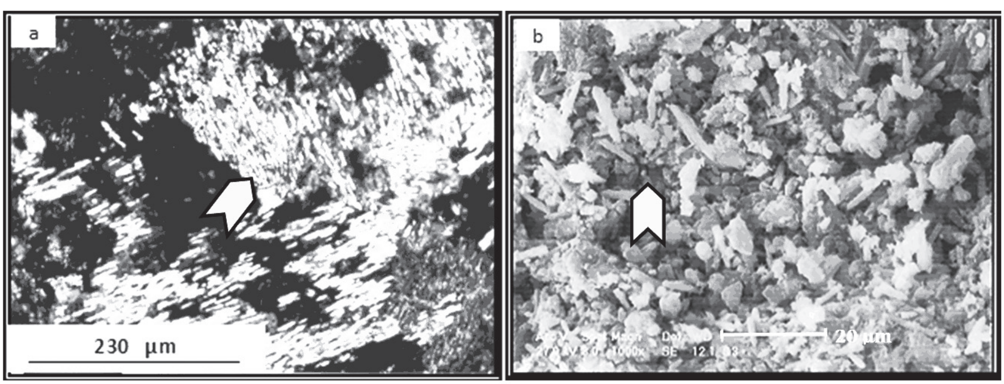

Figure 4. Fibrous bassanite, alteromorph after xenotopic gypsum a) in transmitted light (XPL), b) SEM of fine bassanite resulting from gypsum dehydration. 2Byz horizon of Pedon 2.

The 3Byzm horizon has, without considering soluble minerals, a granular to enaulic basic microstructure with abundant rounded rock fragments. Gypsum occurs as xenotopic coatings around the coarse materials, and the remaining space being filled by xenotopic halite (Figures 5 – 7).

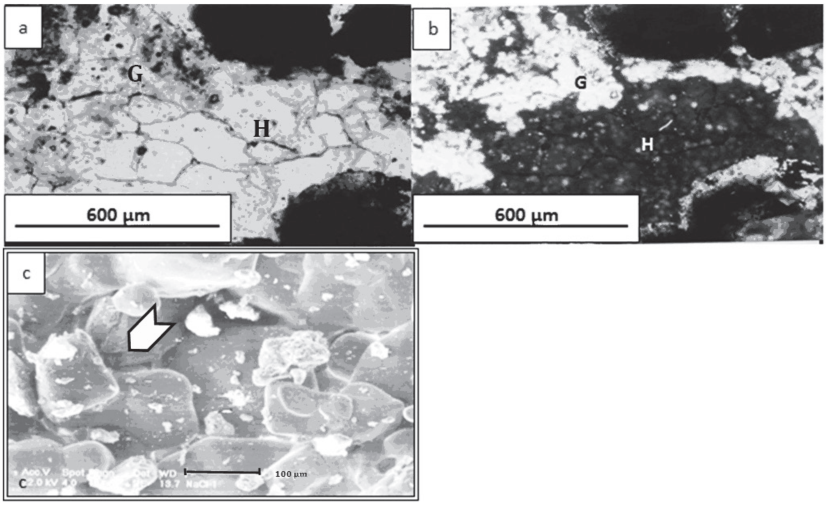

Figure 5. Anhedral gypsum (G) coating and halite (H) infilling. a) PPL and b) XPL, c) cubic halite crystals (SEM). 3Byzm horizon of Pedon 1.

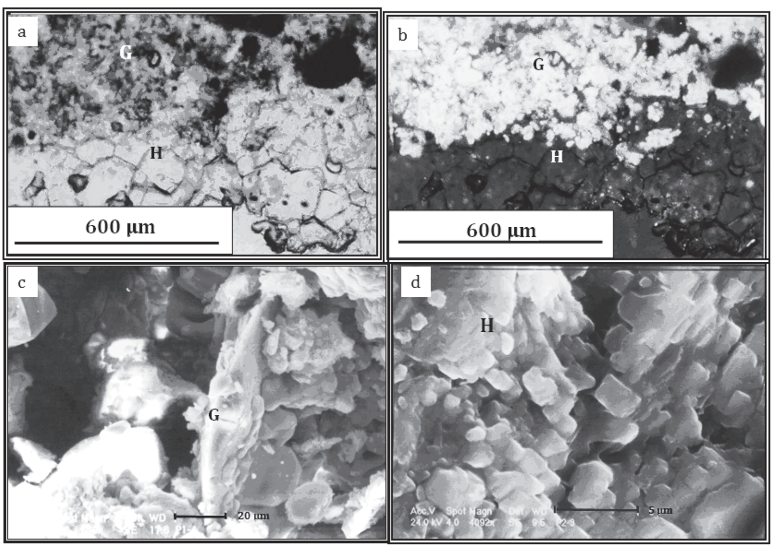

Figure 6. Gypsum (G) and halite (H) crystals in petrogypsic/salic horizon as coatings and infillings a) PPL, b) XPL, c) lenticular gypsum (SEM). d) halite (SEM). 3Byzm horizon of Pedon 2.

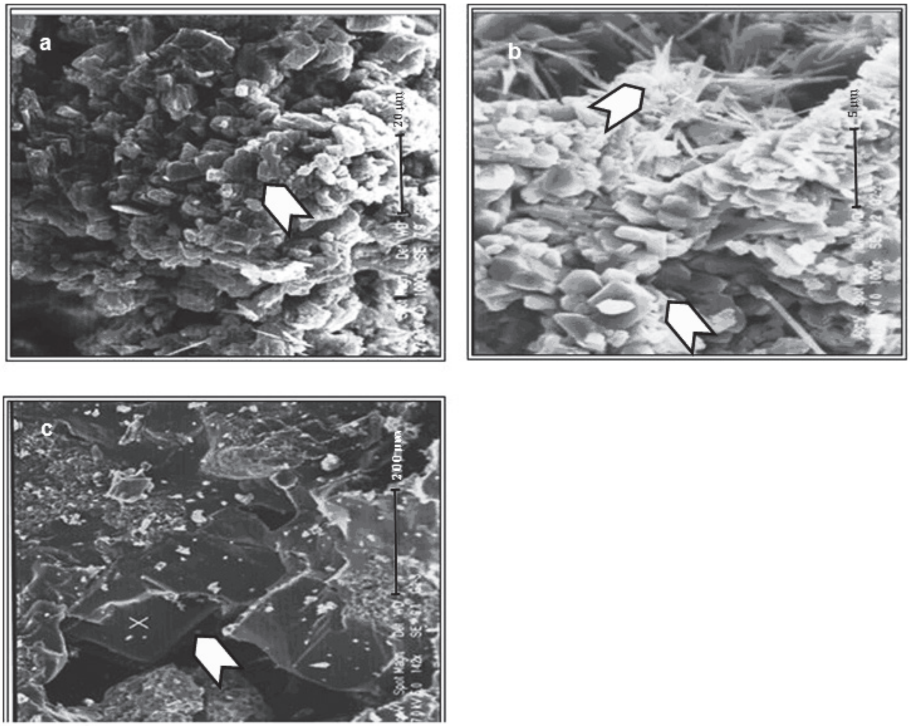

Figure 7. SEM of different parts of petrogypsic/salic horizon. a) granular and sub-lenticular gypsum crystals; b) radial gypsum crystals (rosette), at the upper boundary of the horizon; (c) halite crystals and gypsum at the lower boundary of 3Byzm horizon, Pedon 6.

In the underlying horizons, no halite is observed in thin sections. At a depth of about 80-88 cm (5Byz) the amount of gypsum increases considerably, occurring as pendants of lath shaped crystals oriented perpendicularly to the lower side of the gravels (Figures 2c and 8). In some cases pendants of neighbouring gravels tend to melt together, forming “link pendants”. In some cases this may give the impression of a gypsum vein.

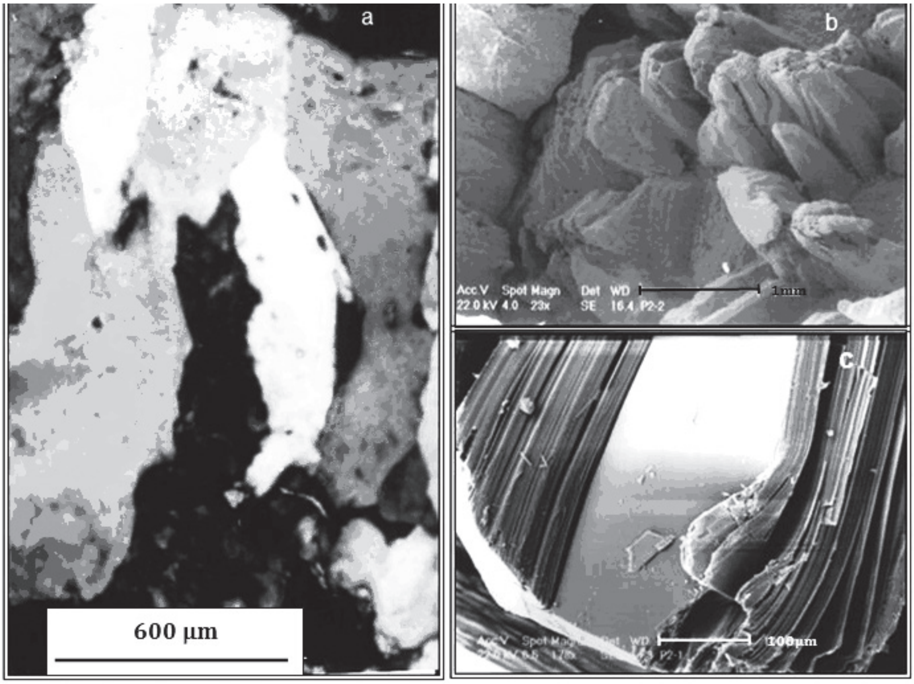

Figure 8. Palisade fabric in gypsum pendants. a) transmitted light (XPL) (the higher interference colours are caused by uneven thickness of the thin section); b and c) SEM images. Note the clear cleavage planes of the gypsum. 4Byz horizon of Pedon 2.

4. Discussion

The distinct and unique characteristic properties of these soils are the bimodal vertical distribution of gypsum, and the close combination of gypsum and halite. The first and highest concentration of gypsum occurs in the 2Byz horizon near the surface. Deeper, the gypsum concentration gradually decreases till a second, much smaller, maximum in most 5Byz horizons. The halite maxima are always situated below the gypsum concentrations, pointing to an accumulation per descendum, as halite is more soluble than gypsum.

The coarse xenotopic gypsum fabric (Figure 3), that can only form in deeper layers (Poch *et al.*, 2010), of most 2Byz horizons, and the very thin (3 – 5 cm) A horizons (Figure 2) point to a truncation of a much thicker A horizon. This severe wind erosion is confirmed by the presence of a desert pavement. The occurrence, in some pedons, of bassanite, alteromorph after gypsum (Figure 4) is caused by partial dehydration due to local high surface temperatures (the highest air temperature recorded is 47 °C, but surface temperatures are much higher, and might even been higher in the past), also point to surface conditions. The underlying 3Byzm horizon is strongly cemented by halite in combination with gypsum.

The bimodal distribution of gypsum and halite with depth most probably points to a polygenic origin of the profiles. In a first pedogenesis, corresponding to a less arid phase, gypsum and halite must have been leached to form the present day 3Byz accumulation horizons by descending solutions.

Dissolution rate of gypsum in the presence of halite rises (Jafarzadeh, 2002) due to formation of more soluble Na_2SO_4, by consumption of sulphate and sodium ions which moves more easily within such a gravelly environment.

As the gypsum occurs mainly as coatings on the sand grains, and interstitial voids are filled by halite, it is clear that the latter material crystallised later, probably when the climate became more arid. From the observations it is not clear whether the overlying material (present 2Byz horizon and topsoil) were already present, and completely leached of gypsum and halite, or were partly deposited later. Anyway, the relatively high content of particles larger than 2 mm excludes an aeolian origin, but does not exclude an accumulation of wind born salts (gypsum, halite) from geologic origin during the more arid period. During a next less arid period genesis of a new salic and gypsic horizon took place, the present 2Byz.

Micromorphological evidences (coarse xenotopic gypsum) shows that this horizon was formed in depth. In a later, more arid phase, part of the A horizon must have been removed by aeolian activity, as proven by the desert pavement. In some pedons the fine grained gypsum in the 2Byz points to a formation or recrystallisation near the surface after truncation.

Based on geological and biological evidences, the climate change in Iran is documented (Mahmoudi, 1987; Krinsley, 1970; Khademi, *et al*. 1997, Khademi and Mermut, 2003; Farpoor, *et al*. 2004). Most of them believe that during glacial stages climatic conditions were drier and colder than today. Compared to today, an increased rainfall is supposed during the Pleistocene or Lower Holocene wet phases (Kehl, 2009). For our study area, no similar information is available, and further dating studies are needed.

4.1 Implications for soil classification

Based on physico-chemical, macro- and micromorphological properties of the studied pedons salic and gypsic horizons (Soil Survey Staff, 2010) with their upper boundary within and below 100 cm from the soil surface were identified. In addition there is a horizon at about 15-37 cm depth in all studied pedons, which has the partial requirements of the petrogypsic horizon (Soil Survey Staff, 2010) and petrosalic horizon (IUSS, 2006). This horizon appears cemented and indurated in the field, but the cementing agent is mainly halite, rather than gypsum.

The diagnostic saliferous/gypsiferous horizon, omnipresent (present everywhere) in these soils displays again the ambiguity of the requirements for a petrogypsic horizon in Soil Taxonomy (Soil Survey Staff, 1999), as already commented by Herrero (2004). In his review, he has shown some ambiguities in field gypseous horizons characterization; like detection of secondary gypsum or the degree of cementation and the definition of "strongly enough cemented with gypsum that the dry fragments do not slake in water". If the other known cementing agents, like carbonates or silica were present in large amounts in these types of hard pans, the cemented horizon would probably be characterised as petrocalcic or duripan horizon respectively, which are well defined in Soil Taxonomy (Soil Survey Staff, 1999). In the case that the main cementing agent is composed of salts more soluble than gypsum, a petrosalic horizon as defined in WRB classification system of (IUSS, 2006) should be more logic.

Although the amount of soluble salts as cementing agent in these horizons is comparable to that of gypsum, and the fact that this huge concentration of salt never can be dissolved in present dry climate (<

100 mm precipitation), it has to be considered as a petrogypsic horizon in Soil Survey Staff (1999) as a petrosalic horizon is inexistent in this classification.
Therefore, we have considered it as a petrogypsic/salic horizon in our classification procedure. Finally, the type and depth of the recognized diagnostic horizon together with the aridic soil moisture regime (Banaei, 1998) have lead us to classify these soils as fine loamy, gypsic, hyperthermic, Petrogypsic Haplosalids (Soil Survey Staff, 2010) and Petrosalic Solonchaks (IUSS, 2006). Although, classifying these soils as Petrogypsic Haplosalids by Soil Survey Staff (2010), gives more importance to salic horizon compared to gypsic horizon, but discards the role of halite as cementing agent in petric horizon. Also classifying as Petrosalic Solonchaks (IUSS, 2006) puts more emphasis on salic horizon and its petrifying characteristics but does not consider the role of gypsum at subunit level. These can be considered as need to revision in both classification systems. Regarding the diagnostic saliferous-gypsiferous horizon in these soils, this study illustrates that it is necessary to include micromorphological characteristics of the petrogypsic horizon in its definition in Soil Taxonomy (i.e. like argillic horizon) as it is also recommended by Herrero (2004). The distribution pattern of gypsum in petrogypsic horizon with low gypsum content should be indicated, as the cementing agent is not dominantly gypsum.

5. Conclusions

The sequence of horizons, along with the physicochemical, macro- and micromorphological properties of the soils on alluvial fans in the Bam Region (Iran), reveals that these gypsum and halite accumulations have different modes of formation. The bottom located gypsic and salic horizons are developed through downward movement of water (per-descendum mode) during a first, less arid pedogenic cycle, whereas, gypsum and salts on the upper petrogypsic/salic horizon are related to a second, less arid pedogenic period. It is not clear whether the latter horizons formed in an existing, leached material, or in a new sediment cover. The distribution pattern of gypsum and salts suggested that the gypsum pendants at the bottom of the profile have been formed during the first pedogenic period. The coarse texture of the xenotopic gypsum in the upper horizon suggests their formation in depth, followed by truncation, probably by deflation, of the original profile during the present more arid climate.

It is suggested that the micromorphological properties of this type of petrogypsic horizon in which not only gypsum, but halite is the main cementing agent, should be included in the classification requirements.

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