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Micromorphology and classification of Argids and associated gypsiferous Aridisols from central Iran

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Abstract

Gypsiferous Aridisols occupy the largest area within the Iranian Aridisols. Information on the genesis and classification of these soils is rather limited. Objectives of this research were to study the micromorphology of the gypsic, argillic, and calcic horizons, to understand the mode of formation of gypsic horizon in three different landscapes, and to test the criteria of the most recently revised Soil Taxonomy and FAO classification system in selected gypsiferous Aridisols occurring in central Iran. A total of 15 representative pedons occurring on three different landscapes (colluvial fans, plateaus, and alluvial plain) were studied. Evidence of illuviation in the colluvial soils is provided by the increase in the clay content and the fine to total clay ratio in the subsoil and by the well-developed, but considerably disrupted, clay coatings observed in thin sections. In addition to pendants, gypsum occurs as microscopic-sized particles, such as single and radiating fibrous shaped particles, random lenticular and granular crystals, along channels and planar voids with no apparent orientation to the associated surface. Gypsum also occurs as relatively larger interlocking plates. The horizon sequence, together with their chemical and micromorphological properties, reveals that gypsum accumulated in different landscapes has different modes of formation. The coexistence of argillic, calcic, and gypsic horizons in colluvial soils is a peculiar combination, suggesting a multistage pedogenesis in this landscape. Paleo-argillic horizons were likely developed under a moister environment than today. This study has also shown that the most recently revised version of the American Soil Taxonomy and FAO soil classification can reasonably well classify these soils. However, there is still a need to modify the criteria of both classification systems at the lower levels, particularly for the classification of the soils that are polygenetic.

Keywords: Gypsiferous soils; Micromorphology; Argillic; Calcic; Gypsic; Aridisols

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1. Introduction

Aridisols occupy more than 18% of the earth's land surface and are the most common soils in the world (Brady, 1990). These and associated desert soils are important natural resources; however, lack of moisture does not allow them to be properly utilized for crop production (Nettleton and Peterson, 1983). Aridisol is the dominant soil order in the Middle East. While 65% of Iran has an aridic soil moisture regime, gypsiferous Aridisols (Gypsids) occupy the largest area among the other Iranian Aridisols (Roozitalab, 1994). Information on the genesis and classification of Aridisols in Iran is rather limited.

Common to many soils in arid regions is the presence of argillic horizon (Nettleton et al., 1969). Identification of argillic horizons in these soils is fundamental to soil classification (Soil Survey Staff, 1999), interpretation of dominant soil-forming processes (Southard and Southard, 1985), and more importantly, understanding the paleoenvironmental conditions under which this horizon was developed (Nettleton and Peterson, 1983; Southard and Southard, 1985; Johnson, 1990). Of pivotal importance to the identification of argillic horizons is the evidence of clay illuviation, either as clay films on ped surfaces or as oriented clay in thin section (Soil Survey Staff, 1999). Micromorphological studies are, therefore, needed for better understanding the genesis of Aridisols.

Pedogenesis of argillic horizons in Aridisols with or without a calcic horizon has been investigated (Gile and Grossman, 1968; Smeck et al., 1968; Nettleton et al., 1969, 1975, 1989, 1990; Southard and Southard, 1985; Shenggeng, 1990; Ducloux et al., 1995). Aridisols with a combination of argillic, calcic, and gypsic horizons, however, have received little attention. Such soils were reported by Muckel (1990) from New Mexico with the emphasis on their classification and no information on their micromorphology and genesis.

The classification of Arid soils has been revised in two internationally accepted systems including the American Soil Taxonomy and the FAO classification. Despite the fact that the new revisions are expected to improve the classification of gypsiferous and other Arid soils (Boyadgiev and Verheye, 1996), it has not been sufficiently tested in the field. On the other hand, understanding the gypsification processes will enable soil scientists to make suggestions for the classification of gypsiferous soils (Porta and Herrero, 1990) which is needed to predict their behavior under both natural and artificial conditions (Herrero and Porta, 2000).

The objectives of this work were to: (1) establish the presence of argillic horizons within the gypsic and calcic horizons by micromorphological studies, (2) understand the mechanism how these horizons coexist, and (3) test the new criteria of the revised Soil Taxonomy (Soil Survey Staff, 1999) for the classification of selected gypsiferous Aridisols occurring in central Iran.

2. Materials and methods

2.1. Study area

Soils located near the city of Isfahan, about 400 km south of Tehran in central Iran were studied (Fig. 1). The study area is 100 km long in a west to east direction, and about 70 km

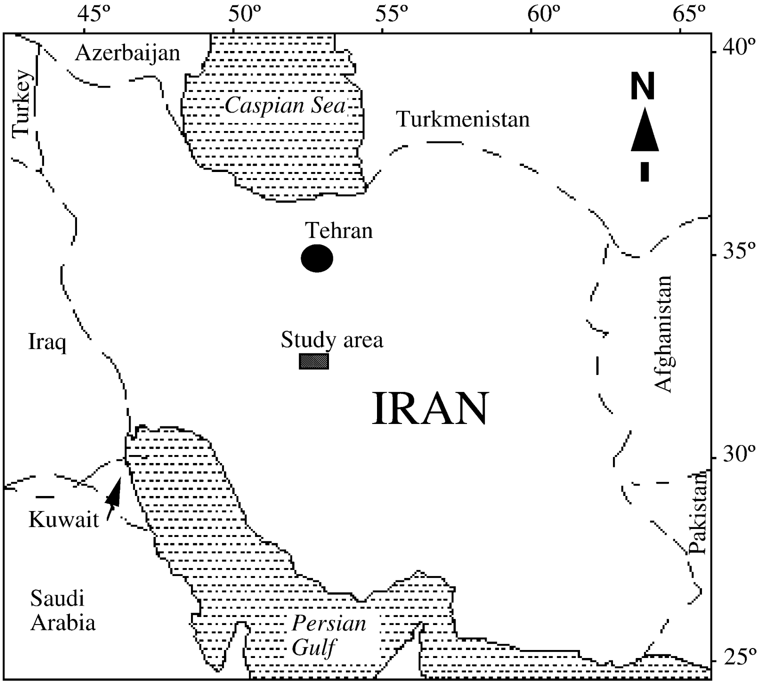

Fig. 1. The study area in central Iran.

wide in a north to south direction (Fig. 2). It is characterized by a dry climate with hot temperatures. The mean annual atmospheric temperature is 14.7 °C and the mean summer and winter temperatures are 25.8 and 5.8 °C, respectively. The soils have aridic moisture and thermic temperature regimes.

Physiographically, the study area consists of an alluvial plain around the Zayandehrud River, plateaus, and gravelly colluvial fans surrounded by mountains, mostly of sedimentary origin (Fig. 3). Colluvial fans are gravelly deposits, accumulated at the base of steep mountains or hill slopes. Plateaus are undulating landscapes that show strong signs of wind erosion and are located between colluvial fans and the alluvial plain. They also are gravelly and extremely gypsiferous (>50% gypsum in gypsic horizons). The alluvial plain is a flat, nongravelly, fine-textured, and young landscape forming a rather narrow band on both sides of the river. In this landscape, gypsiferous soils can be found only where the saline ground water is near the soil surface. Cretaceous and Jurassic rocks, consisting mainly of limestone and shale are exposed in a large part of the area studied.

Both disturbed and undisturbed soil samples were taken from 15 representative pedons on three different landscapes. Diagnostic horizons were identified using the criteria of Soil Survey Staff (1999). The pedons were classified according to Soil Taxonomy (Soil Survey Staff, 1999), and also based on the criteria suggested by FAO/ISRIC/ISSS (1998).

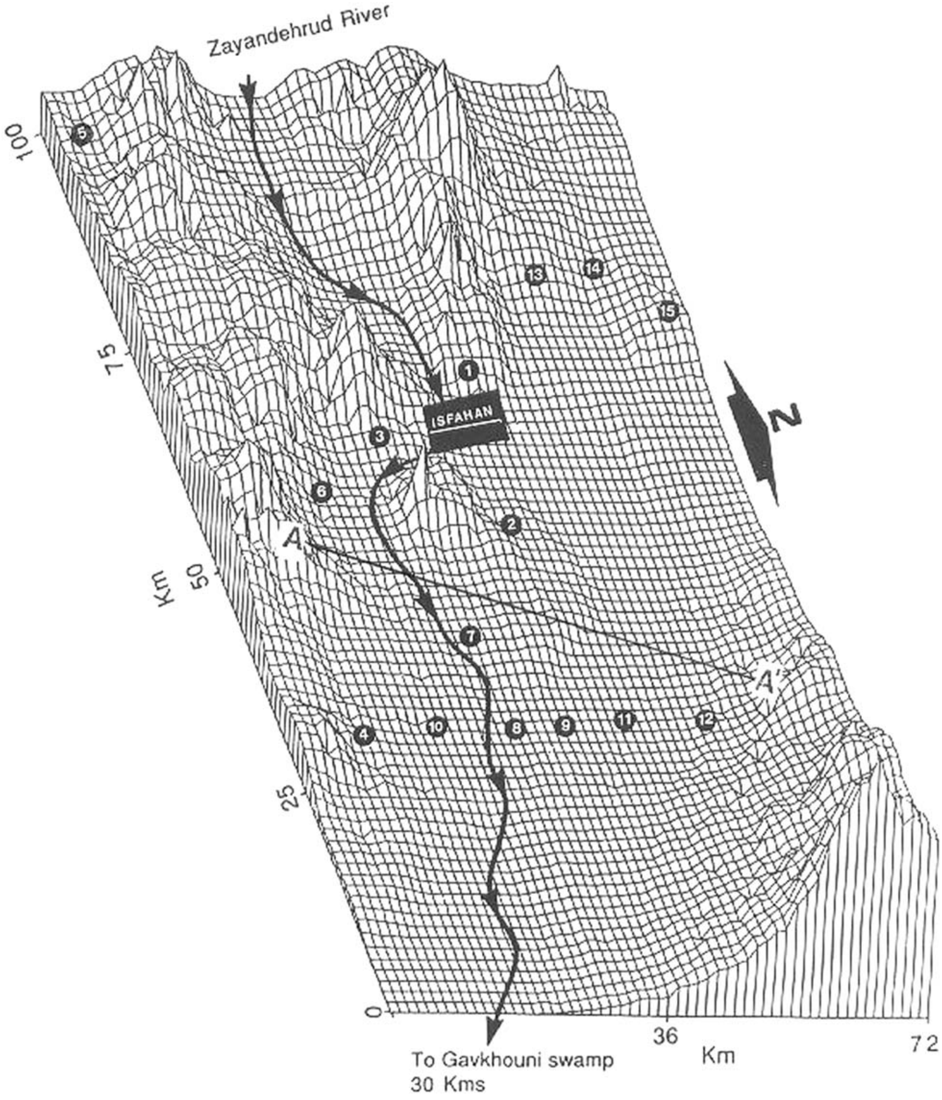

Fig. 2. Block diagram of the study area and the locations of the pedons studied. Cross section of A_A′ is shown in Fig. 3.

2.2. Laboratory studies

2.2.1. Physicochemical analyses

The soil samples, collected from the different horizons of the profiles, were air-dried at room temperature. The dry samples were ground to pass through a 2-mm sieve. Saturation pastes of the soils were prepared, the pH of the paste measured and extracts

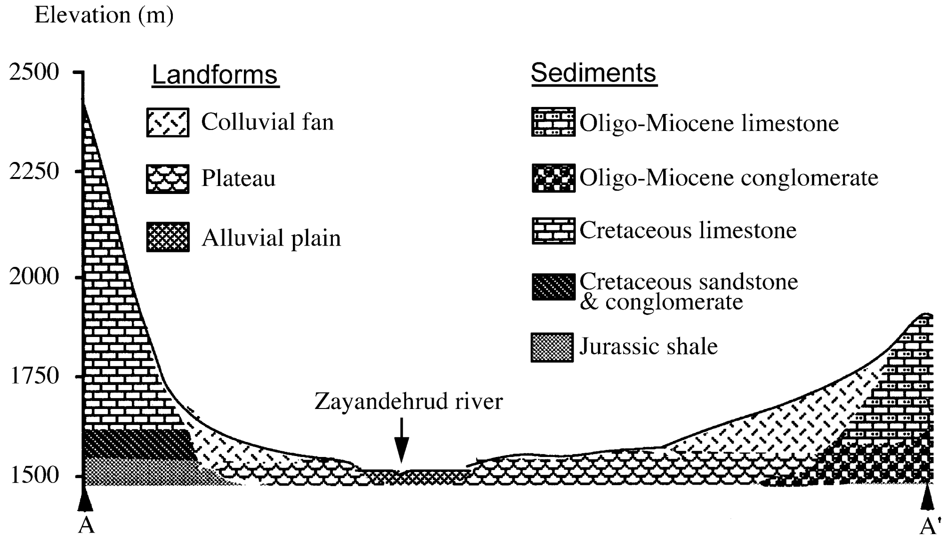

Fig. 3. Cross section showing the sedimentary petrology and different landforms of the study area. A_A′ is about 60 km.

were obtained by vacuum suction. The EC values of the saturation extracts were determined using a pipette type of conductivity cell. Total carbon content of the soil samples was measured by carbonator at 1100 °C. The amount of inorganic carbon was determined by acid digestion and the two-endpoint titration method (Tiessen et al., 1983). Organic carbon was then calculated by subtraction. Gypsum content of the soils was determined using the method of Berigari and Al-Any (1994). Mechanical analysis of bulk soils was carried out by pipette method (Gee and Bauder, 1986). To obtain gypsum-free clay fractions, soil samples were first heated to 105 °C overnight, transferred to dialysis bags and washed with distilled water for about 3 weeks (Rivers et al., 1982). Gypsum-free samples were then treated with sodium acetate (pH = 5), 30% H_2O_2, and dithionate citrate bicarbonate (DCB) solution (Jackson, 1979). Different-sized fractions were separated by centrifuge and the fine clay to total clay ratios (FC/TC) were calculated.

2.2.2. Thin section preparation

Undisturbed soil samples were impregnated with a mixture of 2000 ml of Canus-C32 resin (Canus Plastics, Ottawa, Ontario), 1 ml of catalyst (Mek peroxide 50%), and 0.5 ml of accelerator (cobalt naphthenate). Acetone (1250 ml) was added to this mixture to decrease the viscosity. The blocks of hardened soils were mounted on 75 × 100 mm frosted microscope slides, cut to about 500 μm thickness by diamond-edged saw, then polished to about 25 μm thickness initially by a Logitech LP30 Lapping and Polishing Machine, followed by hand polishing. Thin sections were studied under the petrographic microscope (Mermut, 1992) and described according to Bullock et al. (1985).

2.2.3. SEM observations

Soil aggregates were studied by scanning electron microscope (SEM). The samples were mounted on Al stubs using a double-faced tape, then coated with gold and examined using a Philips 505 SEM.

3. Results and discussions

3.1. General soil properties

Table 1 presents the key morphological features of the soils. Some physical and chemical properties of representative pedons from different landscapes are listed in Table 2.

Based on the EC of the saturation extracts, colluvial soils and soils on plateaus are slightly to moderately saline, alluvial soils show a very wide range in salinity. The depth to the groundwater table is closely associated with the depth to an impermeable layer, soil management practices, and the position of the soil in the landscape. Extremely high salinity of the soils with shallow groundwater is due to the capillary movement of water, which is loaded with soluble salts to the surface where the water evaporates and the salt concentrates. The presence of gypsum in the

Table 1
Macromorphological description of representative pedons from three landscapes*

Horizon	Depth (cm)	Color (moist)	Gravel (%)	Structure	Consistence	Boundary	Special features
Pedon 6 (colluvial fan)							
A	0–33	10YR 5/4	45	massive	wss, dso	as	
Btk1	33–84	5YR 4/4	45	1 m abk	wvs, dsh	gs	common $CaCO_3$ as soft masses and nodules
Btk2	84–145	5YR 5/6	50	2 m-c abk	wvs, dh	as	common $CaCO_3$ as soft masses and nodules
Btky	145–190	5YR 4/6	55	1 m-c abk	wvs, dvh		common $CaCO_3$ as soft masses; gypsum pendants
Pedon 10 (plateau)							
A	0–8	10YR 4/4	25	massive	dso	as	
By1	8–19	10YR 8/3	20	massive	dsh	cs	abundant gypsum pendants
By2	19–95	5Y 8/1	50	massive	dh	cs	abundant gypsum pendants
By3	95–150	5Y 8/1	65	massive	dh		abundant gypsum pendants
Pedon 8 (alluvial plain)							
Azy	0–10	10YR 4/3	–	1 vf gr	wss, dso	as	common gypsum crystals
Bzy	10–35	10YR 5/3	–	2 f sbk	wss, dsh	cs	few gypsum crystals
Bz	35–70	10YR 6/3	–	2 f sbk	wss, dh	gs	
Bw1	70–110	10YR 5/3	–	2 f sbk	wss, dh	gs	
Bw2	110–160	10YR 5/4	–	3 f sbk	wvs, dh		

* Abbreviations according to USDA-SCS (1979).

Table 2
Some physicochemical properties of selected pedons from three landscapes

Horizon	Depth (cm)	pH[a]	EC (dS m^{-1})	Sand	Silt	Clay	FC/TC[b]	Gypsum	OC[c]	$CaCO_3$ equiv.
					%				g kg^{-1}	
Colluvial fans (pedon 6)										
A	0–33	7.77	4.14	62	18	20	0.31	0	11.7	564
Btk1	33–84	7.65	7.18	43	17	40	0.54	0	2.6	478
Btk2	84–145	7.61	6.65	45	19	36	0.66	0	3.0	542
Btky	145–190	7.60	7.80	52	16	32	0.53	82	2.2	501
Plateau (pedon 10)										
A	0–8	7.50	2.66	38	45	17	0.10	49	4.3	303
By1	8–19	7.55	2.33	nd*	nd	nd	nd	869	1.9	66
By2	19–95	7.75	2.57	nd	nd	nd	nd	730	0.6	100
By3	95–150	7.54	3.14	nd	nd	nd	nd	396	0.5	216
Alluvial plain with deep groundwater (pedon 7)										
Ap	0–27	7.44	5.60	32	37	31	0.46	30	8.8	365
Bw1	27–75	7.46	5.20	13	50	37	0.46	27	7.0	348
Bw2	75–160	7.55	6.18	11	40	49	0.59	26	9.1	328
Bw3	160–200	7.39	18.1	8	51	41	0.62	42	4.0	321
Alluvial plain with shallow groundwater (pedon 8)										
Azy	0–10	7.14	248	23	42	35	0.35	86	6.4	175
Bzy	10–35	7.67	159	29	49	22	0.43	42	5.3	325
Bz	35–70	7.79	104	15	62	23	0.46	22	3.6	354
Bw1	70–110	7.97	50.9	59	27	14	0.45	10	3.8	293
Bw2	110–160	8.14	28.1	2	54	44	0.43	19	2.7	356

[a] pH in saturated paste.
[b] FC/TC = fine clay to total clay ratio (carbonate free).
[c] OC = organic carbon.
* nd = not determined.

surface horizons and decrease in EC and gypsum content with depth also support this view. Similar conditions were reported by Timpson et al. (1986) for soils in North Dakota.

In the colluvial soils, there is a distinct increase in both the clay content and the fine clay to total clay ratio with depth and one to two units of hue difference in color between the surface horizon (A) and the B horizons (Tables 1 and 2). The A horizon is yellowish brown, with an abrupt change to reddish brown in the Btk horizon. These are indications of clay illuviation.

The subsurface soil horizons of colluvial fans and the surface horizons of some alluvial soils are rich in gypsum, whereas soils on the plateaus are entirely and extremely gypsiferous (Table 2). As also described by Herrero et al. (1992), soils on plateaus can be considered hypergypsic. Chen (1997) refers to such soils as pedogenic gypcrete. Alluvial soils are almost gravel-free, in contrast to soils on colluvial fans and plateaus that contain a very high amount of coarse fragments (Table 1).

3.2. Micromorphology and genesis of diagnostic horizons

3.2.1. Argillic horizon

Thin section studies under the light microscope and the examination of peds under a scanning electron microscope (SEM) indicate that the higher clay content and the fine clay to total clay ratio in the subsoil in colluvial fans are due to clay illuviation. As seen in Fig. 4a and b, the well-oriented, moderately thick single grain clay coatings have developed around the sand-sized parent rock fragments. Clay illuviation also occurs as embedded grain and ped clay coatings as observed both in thin sections (Fig. 4c and d) and under the SEM (Fig. 4e).

While some clay coatings on natural surfaces (pores, grains, peds) are preserved in the soils studied, the majority of them, however, are disrupted (Fig. 4c) and are similar to those described by Mermut and Jongerius (1980). The clay coating disruption, deformation, and occasional absence have been attributed to many factors in arid regions. Buol and Yesilsoy (1964) in the study of Mohave sandy loam profile concluded that lack of oriented clay in the soil indicates that clay skins, if formed, had been destroyed by natural turbations or the content of halloysite had prevented good orientation. Gile and Grossman (1968) noted that illuviation clay coatings on ped surfaces were lacking in the Argids of southern New Mexico, although oriented clay coatings were present on sand grains and pebbles. They believe that carbonate crystallization is a major factor contributing to the disruption of illuviation clay coatings.

Carbonate may also mask the evidence of illuviation (Nettleton et al., 1989). Nettleton et al. (1969) and Mermut and Jongerius (1980) suggest that the disruption of clay coatings is mainly related to shrink–swell potentials. Clay coatings are absent in horizons having a shrink–swell potential of more than 4%. Evidence that clay illuviation had indeed taken place in soils with no visible clay coatings was based on their presence in the coarse-textured soils in the same area (Nettleton et al., 1969).

Nettleton et al. (1969) report that, in some clayey argillic horizons, clay coatings probably have been destroyed by a combination of root and animal activities, crystallization of calcium carbonate, and shrink–swell pressure brought on by wetting and drying. Reynders (1972) believed that micro-churning and swelling and shrinking have obliterated the evidence of clay illuviation in the B horizons in some Aridisols in Morocco. When illuviation occurs sufficiently deep to escape present-day wetting and drying and physical turbations, clay coatings may be preserved (Allen, 1985). For example, coatings in very deep argillic horizons in buried soils were shown to be well preserved and consist of strongly oriented channel clay coatings (Allen and Goss, 1973).

Based on soil mineralogy studies (Khademi and Mermut, 1998), clay fractions of the soils are dominated by palygorskite and almost no expandable clays are present in these soils. Therefore, swelling and contraction upon wetting and drying do not seem to have contributed to clay skin distortion. Instead, the disruption of clay skins in the gypsiferous soils studied can be mostly ascribed to the gypsum crystallization and secondary carbonate formation. It appears that the gypsum crystallization (Fig. 5b and c) as well as the formation of some other minerals such as celectite (Fig. 5a) under dry climate creates a high pressure that could distort the clay coatings and mix them

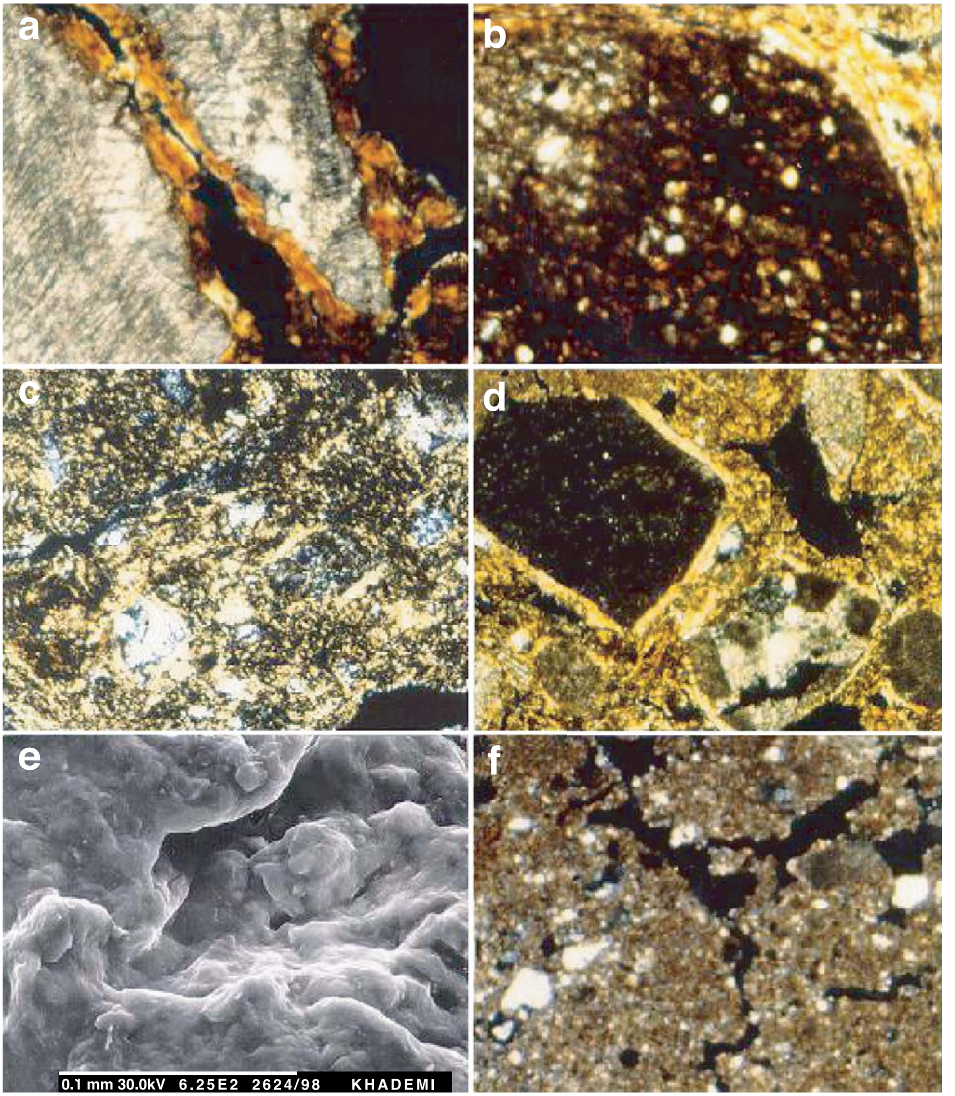

Fig. 4. Micrographs showing the clay illuviation in the colluvial soils. (a) Distinct free grain clay coatings in Btk1 horizon of pedon 6, XPL; (b) oriented clay around a sand-sized particle in 2Btk horizon of pedon 3, XPL; (c) remnants of detached and intermixed clay coatings embedded with soil matrix in Btk2 horizon of pedon 6, XPL; (d) embedded grain clay coatings in the 2Btky horizon of pedon 4, XPL; (e) SEM micrographs of illuviated clay in Btky horizon of pedon 6; (f) crystallitic b-fabric of the cambic horizon (Bw1) of pedon 7, XPL. Frame length of micrographs a and b is 0.75 mm and of c, d, and f 2 mm.

with the soil matrix (Fig. 4c). Formation of secondary carbonate could also help the displacement process and mask the clay coatings (Gile and Grossman, 1968; Nettleton et al., 1989).

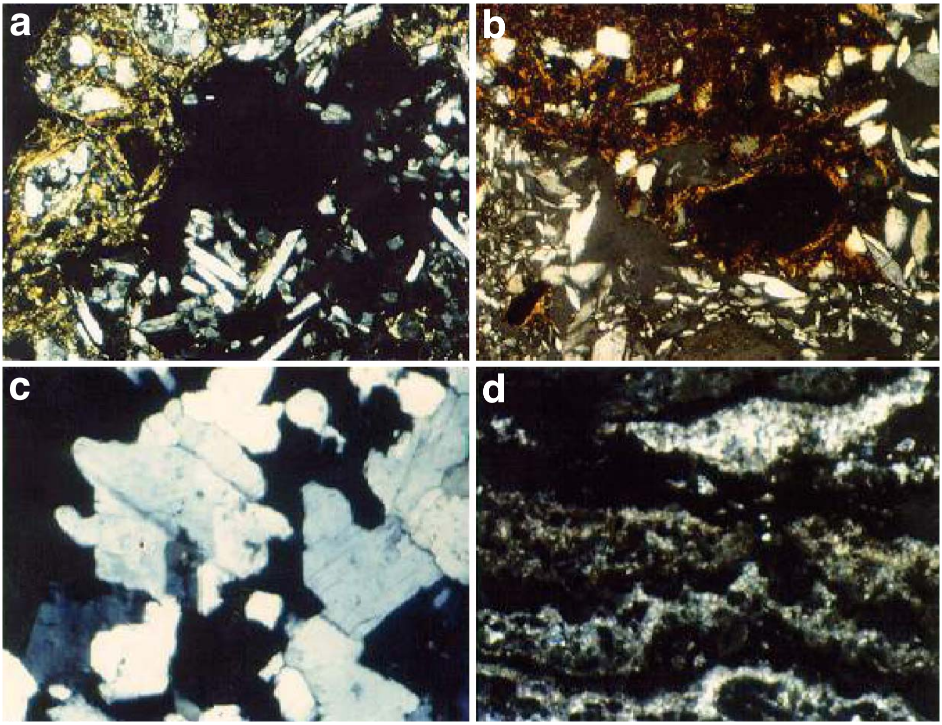

Fig. 5. (a) Prismatic celectite crystals formed in soil pores in 2Bty horizon of pedon 3, XPL; (b) lenticular gypsum crystals in the Btky2 horizon of pedon 2, XPL; (c) relatively large interlocking gypsum crystals in the Btky horizon of pedon 6, XPL; (c), (d) laminar banding of pedogenic calcite in the Btky horizon of pedon 2, XPL. Frame length of all micrographs is 2 mm.

The pebble surfaces serve as sites for silicate clay and carbonate accumulations (Gile and Grossman, 1968). Several factors may contribute to the stability of pebble surfaces. In contrast to the surfaces of peds of fine earth that move inward and outward as the ped expands and contracts, the surface of pebbles remain stationary unless the pebble is displaced. Volume change of the soil on wetting should be reduced due to less fine earth per unit volume. Furthermore, the fine earth in each interstice between pebbles tends to act as a discrete unit.

Very small volume of fine earth available for roots and soil fauna and the fact that pebble surfaces are preferred sites for carbonate accumulation make the clay coatings in gravelly argillic horizons particularly vulnerable to disruption. Preservation of the clay coatings and their remnants in the soils studied with harsh disrupting forces shows that a profound clay illuviation has occurred.

Clay increase in argillic horizons in Aridisols has been attributed to different factors. Nettleton et al. (1975) and Smith and Buol (1968) believe that the clay increase in the argillic horizon is partly due to the illuviation of fine clay and partly as a result of clay formation in situ. Ducloux et al. (1995) reported that the Argids of Mapimi Reserve resulted principally from clay neogenesis under current climatic conditions. Reconstruction of gains and losses of clay in horizons by Smeck et al. (1968) showed that carbonate dilution was partly contributing to the clay increase in Bt horizons. In the soils studied with distinct clay coatings the increases in clay content in the B horizon were mostly due to physical illuviation process.

3.2.2. Gypsic and calcic horizons

In addition to very-big-sized gypsum pendants (as large as 10 cm), gypsum occurs as microscopic forms in the gypsic horizons studied. Microscopic gypsum crystals appear as random lenticular and granular crystals (Fig. 5b), along channels, and planar voids with no apparent orientation to the associated surface. Gypsum also occurs as relatively larger interlocking plates (Fig. 5c).

The sequence of horizons along with their chemical and micromorphological properties reveals that gypsum was accumulated in the deep colluvial soils through the downward water movement (per descendum mode). The formation of gypsum pendants under gravels (Table 1) further supports this hypothesis. Whereas, gypsic and salic surface horizons in the alluvial plain are the result of an upward movement of salt-loaded brine (per ascendum mode), lagoonal conditions best describe the deposition of extremely high amount of gypsum throughout the pedons on the plateaus, as supported by the stable isotope geochemistry (Khademi et al., 1997) and clay mineralogy (Khademi and Mermut, 1998).

The soils in all three landscapes studied are calcareous, however, pedogenic carbonates are found only in the B horizons of colluvial soils. The presence and the mode of formation of secondary carbonates were established by the carbon and oxygen stable isotopes (Khademi and Mermut, 1999). The zone of pedogenic carbonates does not contain more carbonate than the overlying horizon (A) which is counterintuitive. The large amount of carbonates in the surface horizons is due to addition of carbonatic debris to the surface horizon by colluviation and aeolian processes. Below the A horizon, secondary carbonates occur as soft masses and nodules. In Btky horizons, coexistence of secondary carbonates and gypsum either as pendants below the pebbles or as crystals filling the soil pores are the major macromorphological features observed within the very gravelly soil matrix.

The accumulation of pedogenic calcite is a common feature in the colluvial soils studied (Khademi and Mermut, 1999). Although carbonates tend to inhibit the movement of clay in suspension (Gile and Hawley, 1972), the majority of Aridisols with argillic horizon, including the colluvial soils of this study, are calcareous. Rostad et al. (1976) believe that the degree of development of the argillic horizon is dependent in part on the carbonate content of the parent material. They reported that the soils derived from a high-carbonate parent material would have a more pronounced argillic horizon due to the concentrating effect of carbonate weathering and the addition of clay residue from the carbonates than soils derived from materials low in carbonates. Johnson (1990) believes that the coexistence of calcic and argillic horizons is due to deposition of calcium carbonates on the surface of existing Argids. Indeed, Argids appear to have formed on the old Pleistocene surfaces (Nettleton et al., 1975; Johnson, 1990).

Several lines of evidence suggest that carbonate accumulation in the Btky horizons occurred both before and after clay accumulation. These include the presence of clay skins on secondary carbonate crystals observed in micromorphological studies, the presence of both calcic and argillic horizon at depths >1 m, and the higher amount of primary calcium carbonate in the topsoil and secondary carbonates in the subsoil as proven by the stable isotope approach (Khademi and Mermut, 1999). The dissolution of carbonate from the topsoil and its precipitation in the lower horizons created favorable conditions for the removal of the clay particles from the topsoil and flocculation of these particles in the zone where carbonate accumulated.

The structure of these soils is highly controlled by pebbles (>2 mm in diameter) that occupy an appreciable volume of the soil. Pebbles and coarse sand particles consist of either limestone or shale. Fine earth occupies the spaces between pebbles. Carbonate pendants under coarse fragments are commonly thick enough to be identified visually. More indurated pedogenic carbonates appear as laminae in thin sections (Fig. 5d), suggesting their periodic precipitation. As the diameter of the particle increases, the thickness of the pendant in soil tends to increase. Gile and Grossman (1968) attributed this to the increase of the contributing volume which supplies water loaded with carbonate.

Weakly oriented mixtures of carbonates, silicate clays, and appreciable amount of quartz grains are observed in the calcareous subsoils of the alluvial plain (Fig. 4f). These soils occur on the young alluvial deposits of the Zayandehrud River and are much less developed compared to colluvial soils.

3.2.3. Argillic horizons as indicators of paleoenvironment

Despite the fact that the argillic horizon is a distinct character of the soils occurring in colluvial fans, its formation under today's arid conditions is unlikely. Many pedologists believe that the argillic horizons in Aridisols were formed in a climate moister than today's environment (e.g. Gile and Grossman, 1968; Nettleton et al., 1990; Nettleton and Peterson, 1983; Johnson, 1990; Eghbal and Southard, 1993). Nettleton et al. (1975) conclude that the present climate does not seem to be adequate to produce argillic horizons in soils of desert areas of the southwestern United States and state that the older Argids are probably the products of a moister Pleistocene climate. Southard and Southard (1985) found that in Aridisols of northern Utah, argillic horizons formed in about 9000 years, under the influence of at least two pluvial periods of much higher rainfall than today.

Based on geological and biological evidence, Moatamed (1988) has suggested a more humid climate for Iran in the early to middle Holocene. Mahmudi (1987) believes that, during the period of glaciation, central and southern parts of Iran were experiencing a climate with more rainfall than today, whereas in interglaciation periods the climatic conditions were rather the same as today. Bobek (1963), while indicating clearly that in Iran we are still far from a satisfactory knowledge about climatic changes, questions the presence of any pluvial periods in any way comparable with those of near-Eastern countries. However, he agrees on the existence of a more humid type of climate in Iran in the Pliocene. Krinsley (1970) pointed out that the Pleistocene climatic patterns of Iran were similar to those of the present. Stable isotope composition of the gypsum hydration water from the soils showed the preservation of isotopically lighter water which is an indication of an environment with more precipitation (Khademi et al., 1997). The paleo-argillic horizon was likely formed during a period of more moisture. During the transition from the moister climate to today's arid conditions, gypsum accumulation likely occurred with an isotopic signature of the paleoenvironment. The present moisture regime is not sufficiently moist to move clays down in the profile.

3.3. Classification of soils

Diagnostic horizons with their upper boundary within and below 100 cm are listed in Table 3. The summary of the classification of soils in different systems is given in Table 4. It is clear that the criteria of Soil Taxonomy (Soil Survey Staff, 1999) reasonably well classify the soils. The proposed suborder, Gypsids, resulted in a good classification of selected New Mexican soils from the stand point of soil use and management (Muckel, 1990). Soils with calcic, gypsic, and argillic horizons (pedons 1, 2, 3, 4, and 6) are placed in either "Typic Gypsiargids", if the gypsic horizon is deeper than 150 cm, or "Calcic Argigypsids", if the upper boundary of gypsic horizon is within 100 cm. In pedons 1 and 6, where the upper boundaries of calcic and argillic horizons occur within the top 100 cm, and there is a gypsic horizon between 100 to 150 cm depth, this combination is not accommodated by Soil Taxonomy. A new subgroup "Calcic Gypsiargids" is, therefore, suggested for the classification of these soils. This subgroup is defined as "Gypsiargids that have a calcic horizon that has its upper boundary within 150 cm of the soil surface".

Table 3
Subsurface diagnostic horizons in the soils studied

Pedon no.	Upper boundary within 1 m	Upper boundary below 1 m
Colluvial fans		
1	argillic, calcic	calcic, gypsic
2	argillic, calcic, gypsic	argillic, calcic, gypsic
3	argillic, calcic, gypsic	gypsic
4	argillic, calcic, gypsic	gypsic
6	argillic, calcic	gypsic
12	argillic, calcic	–
Plateaus		
5	gypsic	gypsic
9	gypsic, petrogypsic	gypsic
10	gypsic	gypsic
11	gypsic	gypsic
13	gypsic	gypsic
14	gypsic	gypsic
15	gypsic	gypsic
Alluvial plain		
7	cambic	cambic
8	salic, gypsic, cambic	cambic

Table 4
Comparative classification of the soils studied

Pedon no.	Subgroups (Soil Survey Staff, 1999)	Soil units (FAO/ISRIC/ISSS, 1998)
Colluvial Fans		
1	Typic Gypsiargids (Calcic Gypsiargids)*	Luvic Calcisols (Luvigypsic Calcisols)*
2	Calcic Argigypsids	Calcic Gypsisols (Calciluvic Gypsisols)*
3	Calcic Argigypsids	Calcic Gypsisols (Calciluvic Gypsisols)*
4	Calcic Argigypsids	Calcic Gypsisols (Calciluvic Gypsisols)*
6	Typic Gypsiargids (Calcic Gypsiargids)*	Luvic Calcisols (Luvigypsic Calcisols)*
12	Typic Calciargids	Luvic Calcisols
Plateaus		
5	Typic Haplogypsids	Haplic Gypsisols
9	Typic Petrogypsids	Petric Gypsisols
10	Leptic Haplogypsids	Hypergypsic Gypsisols
11	Leptic Haplogypsids	Hypergypsic Gypsisols
13	Leptic Haplogypsids	Hypergypsic Gypsisols
14	Leptic Haplogypsids	Hypergypsic Gypsisols
15	Leptic Haplogypsids	Hypergypsic Gypsisols
Alluvial plain		
7	Typic Haplocambids	Calcaric Cambisols
8	Gypsic Haplosalids	Sodic Solonchaks

*New proposal.

According to Soil Survey Staff (1999), extremely gypsiferous soils in plateaus with gypsic horizon as the only diagnostic subsurface horizon are classified as "Typic Haplogypsids". Likewise, alluvial soils with cambic and salic horizons are grouped as "Typic Haplocambids" and "Typic Haplosalids", respectively. More emphasis placed on soluble salts (salic horizon) and gypsum accumulation is an important consideration for the use and management of Aridisols (Florea and Al-Joumaa, 1998).

While the FAO soil classification system (FAO/ISRIC/ISSS, 1998) separates the soils on plateaus and alluvial plains reasonably well, it cannot properly classify the soils with several diagnostic subsurface horizons, namely, colluvial soils. In pedons where calcic, argillic (argic B), and gypsic horizons coexist, the presence of all three horizons is not properly recognized at soil unit level. A soil unit "Luvigypsic Calcisols" is proposed for those pedons having an argillic and a calcic horizon in the upper 100 cm and a gypsic layer below these diagnostic layers (pedons 1 and 6). Similarly, a soil unit "Calciluvic Gypsisols" is suggested for pedons having the three mentioned diagnostic horizons whose upper boundaries occur in the top 100 cm (pedons 2, 3, and 4). Although less important, the FAO system also does not recognize the gypsic horizon when the soil is loaded with both gypsum and more soluble salts (pedon 8).

4. Conclusions

The sequence of horizons along with their chemical and micromorphological properties reveal that gypsum accumulated in different landscapes has different modes of formation. While the gypsic horizon in the deep colluvial soils was developed through the downward water movement (per descendum mode), surface gypsic and salic horizons in the alluvial plain are considered to be the result of an upward movement of salt-loaded brine (per ascendum mode). The deposition of extremely high amounts of gypsum throughout the pedons on plateaus seems to have originally occurred under shallow lagoonal conditions as supported by the stable isotope geochemistry and the clay mineralogy studies.

An argillic horizon is the most distinct subsurface horizon of the soils developed on colluvial fans. Evidence of illuviation is provided by the increase in the clay content and the fine to total clay ratio in the subsoil compared to the overlying horizon(s) and by the well-developed, but considerably disrupted, clay coatings observed in thin sections. Since swelling and shrinkage do not seem to be effective, the disruption of clay coatings was likely due to the gypsum and carbonate crystallization process.

The coexistence of argillic, calcic, and gypsic horizons in colluvial soils is a peculiar combination, suggesting a multistage pedogenesis in this landscape. Paleo-argillic horizons were likely developed under a moister environment than today. Sufficient rainfall contributed to the removal of carbonates from the topsoil and the subsequent eluviation of clay to form the argillic horizon. Addition of more carbonates from a colluvial source or as aerosols and the gypsum deposition occurred continuously with time and these processes slowed down considerably since the area became arid.

This study has shown that the criteria of the most recently revised version of the American Soil Taxonomy (Soil Survey Staff, 1999) have greatly improved the classification of the Aridisols studied. More emphasis placed on the more soluble constituents such as gypsum and other more soluble salts in the salic and gypsic horizons appeared to be more pertinent for the classification of extremely gypsiferous soils. However, there is still a need to modify the criteria of this system at the lower levels (i.e. subgroups), particularly for the classification of the soils that have undergone polypedogenesis. The FAO classification system (FAO/ISRIC/ISSS, 1998) encounters almost the same difficulties and needs to be amended accordingly.

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