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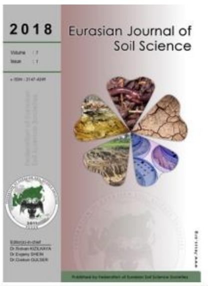

Soil-landscape relationship as indicated by pedogenesis data on selected soils from Southwestern, Iran

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Abstract

Soils of semiarid regions of Dehdasht and Choram in Southwestern Iran have formed on alluvium derived from mixed calcareous-gypsiferous materials from Lower Miocene to Upper Pliocene. In order to characterize and classify the soils and to determine the soil-landscape relationship in the area, nine pedons located on different physiographic positions including plateau, river alluvial plain, piedmont plain, alluvial plain and alluvial fan have been described, sampled and analyzed. Physicochemical analyses, clay mineralogy and micromorphological studies were performed. The results showed that topography and parent material were two important soil forming factors affecting soil formation in the area. The soils were dominated by carbonate, gypsum, and clay illuviation and accumulation. More developed soils were found on the stable plateau and piedmont plain. Clay illuviation and argillic horizon development in soils of the more stable alluvial plain were assumed to be relict features from presumably more humid climates. Palygorskite, illite, chlorite, smectite, kaolinite, and quartz clay minerals were identified in almost all physiographic surfaces, but more palygorskite and less smectite were found in the soils with gypsiferous parent materials. Observations by SEM revealed the occurrence of neoformed palygorskite as thread-like faces and coating of gypsum crystals and marly matrix. Coating and infilling of gypsum and calcite crystals in voids and channels were common pedofeatures observed in the soils studied. Two different distribution patterns of Fe-Mn oxides were identified in aquic and non-aquic soils.

Keywords: Clay mineralogy, gypsum, soil landscape, soil micromorphology.

Introduction

There have been many attempts to correlate soil properties with various factors, such as parent material and topography (McBratney et al., 2000). Soil geomorphology is an assessment of the genetic relationships between soils and landforms (Gerrard, 1992). Birkeland (1999) defined soil geomorphology as the study of soils and their use in evaluating landform evolution, age and stability, surface processes and paleoclimates.

The differences in soil properties with landscape position are usually attributed to differences in runoff, erosion, and deposition processes, which affect soil genesis and vegetation development (Dahlgren et al., 1997; Lark, 1999). Moazallahi and Farpoor (2011) found the landscape as a significant soil forming factor causing different physicochemical and clay mineralogical properties in soils of southern Iran. Khresat and Qudah (2006) found that carbonate, clay elluviation–illuviation, and salt accumulation are the dominant pedogenic processes in the arid soils of northeastern Jordan.

Sanjari et al. (2011) investigated paleosols with argillic horizons on stable pediment surfaces in Jiroft area, central Iran. They found that secondary gypsum and calcite were accumulated in mantled pediments, but

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moving down the slope toward lowlands, salts-more soluble than gypsum-have been accumulated. Nooraie (2010) in the study performed in Loot Desert, reported a close relationship between geomorphic position and soil genesis and evolution. He pointed out that undeveloped Entisols were formed on young unstable pediment surfaces. On the other hand, salic, gypsic, petrosalic, and petrogypsic horizons were formed on developed soils of playa landform.

Study of clay minerals and their alteration provides important information on the pedogenic history of soils as well as soil genesis and evolution (Wilson, 1999). Clay mineralogy in soil studies helps in better conception of soil genesis and development (Moore and Reynolds, 1997). Soil clay minerals have two main sources: (1) neoformation and transformation by pedogenic processes, and (2) inheritance from parent rocks, or addition by eolian or fluvial processes to soil surface (Schaetzl and Anderson, 2005).

Palygorskite, smectite, chlorite, illite, kaolinite, and vermiculite have been reported as dominant clay minerals in arid and semi-arid areas of Iran (Salehi et al., 2002; Khormali and Abtahi, 2003; Owliaie et al., 2006; Nadimi and Farpoor, 2013; Sarmast et al., 2016; Sarmast et al., 2017). Neoformation of palygorskite as a result of calcite and gypsum precipitation seems to be a major pathway for the occurrence of this mineral in the studied soils of southwestern Iran. Moreover, large amounts of smectite seem to be inherited from the Miocene marl formations (Owliaie et al., 2006). A close relationship between geomorphic positions and palygorskite morphology and its origin was reported by Farpoor et al. (2002) in Rafsanjan area in the south-central part of Iran.

High amounts of gypsum are frequently found in soils of arid and semi-arid environments. Many macro and micro forms of soil gypsum have been reported in the literature. Owliaie et al. (2006) reported prismatic, lenticular, platy, tabular, pseudo-hexagonal, and hexagonal as well as interlocked plates of gypsum in relation to stage of soil development of the studied soils of southwestern part of Iran. They found a clear relationship between the size of pore space in soil matrix and dimensions of lenticular crystals.

Hashemi et al. (2011) reported that soil moisture, texture, and landscape position play an important role in the formation of pedogenic gypsum. They stated that well-crystallized gypsum was observed in soils with the lighter texture. The shape, size, and position of gypsum crystals, within the soil matrix, were used to determine their source (Buck and Van Hoesen, 2002; Carter and Inskeep, 1988).

Calcite is one of the best studied, but also one of the most flexible pedogenic minerals. It shows a wide variety of shapes and habits, and occurs as well in arid and semiarid soils with restrained drainage (Stoops and Delvigne, 1990). The occurrence of calcitic pedofeatures in calcareous soils of southern and southwestern Iran has often been reported in the literature (Khormali et al, 2006; Owliaie et al., 2006; Owliaie, 2012). According to Wright (1987), the type of pedogenic calcium carbonate is controlled mainly by the parent material, climate, and vegetation.

Iron and manganese oxides as well as hydroxide minerals are very active constituents in soils because they are sensitive to environmental changes and they move frequently along soil cracks or holes and deposit in peds (McKenzie 1989; Dixon and Skinner, 1992). In soils, the reduction and oxidation of iron and manganese, as a result of seasonal changes in soil moisture, contributes to the formation of cutans, forming coatings and concretions (Zhang and Karathanasis, 1997; Liu et al., 2002). Owliaie (2014) reported two different distribution patterns of Fe-Mn oxides in aquic and non-aquic soils due to more mobility of these oxides in aquic conditions.

The Dehdasht and Choram Plains in the center of Kohgilouye Province have relatively large diversity in terms of topography, soil types, and geological formations that have made this an appropriate area to study the relationship between these factors. Limited data are available for the pedogenesis of this area; therefore, the aims of the present research were to study 1) the physicochemical and morphological soil properties, and micromorphology of the soils related to physiographic positions, 2) the soil genesis and classification using both Soil Taxonomy and World Reference Base (WRB) Systems, and 3) the mineralogy of clay fraction in the studied soils.

Material and Methods

Study area

Dehdasht and Choram Plains are located in the central part of Kohgilouye Province, Southwestern Iran (Figure 1). Mean elevation of Dehdasht and Choram Plains are 790 and 735 m above sea level (a.s.l.), respectively. Two seasonal rivers which pass through the plain, have distinctive effects on transportation and sedimentation of materials (Figure 2).

Figure 1. Location of Kohgilouye Province, southwestern Iran and the study area

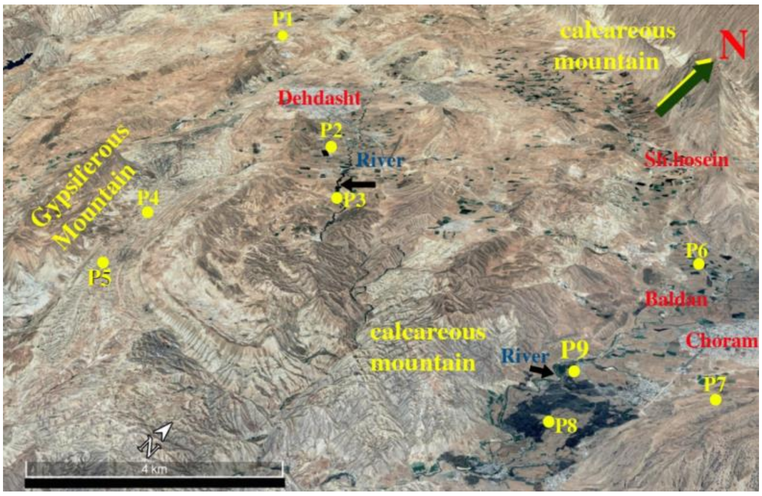

Figure 2. Map of the study area indicating topographic positions and representative pedons.

This region is part of the Zagros orogenic zone, which extends throughout the province. As indicated in Figure 3, four main geological units are recognized in the area. The Bakhtiari Formation, exposed in the east and southeast Mountains, consist of sandstone, limestone, conglomerate and gray marl (Upper Pliocene). The Gachsaran Formation (Lower Miocene) is composed of thick bedded alternating layers of anhydrite and marls (exposed in the east and south of the region) (Figures 2, 3). The Mishan Formation (Lower to Middle Miocene) consists of gray marls with ferruginous materials at its base (exposed parallel to Gachsaran Formation). The Aghajari Formation (Upper Miocene to Pliocene) consists of red sandstone, pebbly sandstone and silty marls with gypsum interlayer (exposed in central and northeast of the region. Overlying the Aghajari Formation are Quaternary alluvium and recent deposits (Geological Survey of Iran, 1995).

The soil moisture regime of the study area is ustic, and the temperature regime is hyperthermic (Banaei 1998). Climatic data indicates a mean annual rainfall of 478 mm, and a mean annual temperature of 21.5 °C (for a 25-year recording period at Dehdasht weather station).

Soil transect and field characterization

Different landforms in the area were identified using Google Earth and topographical maps, together with detailed field work. Piedmont plain, alluvial fan, alluvial plain, river alluvial plain, and plateau were dominant physiographic units recognized in the area studied (Figure 2).

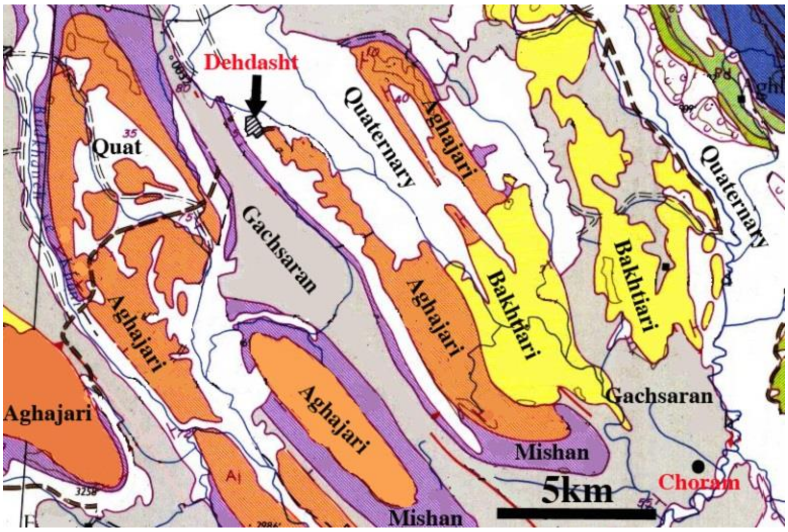

Figure 3. Regional geological map of the study area

Nine representative pedons on different physiographic units were sampled and studied, (Figure 2). Pedon 1 on plateau, pedons 2, 4, 6 and 8 on the piedmont plain, pedons 3 and 9 on the river alluvial plain, and pedons 5 and 7 on the alluvial fan were studied. Soil pedons were classified according to Taxonomy (Soil Survey Staff, 2014) and WRB (FAO, 2015) systems.

Air-dried soil samples were sieved through a 2 mm sieve and routine soil physical and chemical properties were investigated. Organic carbon was measured by wet oxidation with chromic acid and back titration with ferrous ammonium (Jackson, 1975). Calcium carbonate equivalent (CCE) was measured by acid neutralization and gypsum was determined by precipitation with acetone (Salinity Laboratory Staff, 1954). Cation exchange capacity (CEC) was determined using sodium acetate (NaOAc) at a pH of 8.2 (Chapman, 1965). Soil pH was measured with a glass electrode in a saturated paste and electrical conductivity (EC) was determined in the saturation extract (Salinity Laboratory Staff, 1954). Soil texture was determined using the pipette method (Day, 1965).

Fifteen soil samples were selected for clay mineralogical analysis. Calcium carbonate, organic matter, and iron oxides were removed and clay fraction was separated (Jackson, 1975; Kittric and Hope, 1963). Four slides including Mg saturated, Mg saturated and treated by ethylene glycol, K saturated, and K saturated and heated to 550 °C were analyzed using a Philips D500 diffractometer, using Ni-filtered Cukα radiation (40 kV, 30 mA). Four major geological strata were sampled for mineralogical studies. The semi-quantitative contents of the clay minerals were estimated according to Johns et al. (1954). Semi-quantitative assessments make the identification of individual components in polymineralic samples much more valuable. Small soil clods were mounted on aluminum stubs and coated with gold for scanning electron microscopy (SEM) observation using a Cambridge SEM.

Thin sections were prepared using the methods described by Murphy (1986). Undisturbed soil samples were impregnated under vacuum with an acetone-diluted polyester resin (60/40 ratio). Oriented sections were cut with a diamond saw and cemented onto glass microscope slides. They were ground and polished to a thickness of about 20-30 µm. Micromorphological descriptions were made according to Stoops (2003) using a Zeiss petrographic microscope.

Results and Discussion

Physicochemical properties

Table 1 shows the physicochemical properties of the studied pedons. All the soils are calcareous or gypsiferous throughout the profile. Calcium carbonate equivalent (CCE) varied between 38.1 and 86.3%. An increasing trend of calcium carbonate with depth was recorded in most of the pedons studied. Electrical conductivity of saturation extracts (ECe) was between 0.2 and 2.3 dSm^{-1}. More EC contents were measured in gypsic horizons. The soils exhibited a narrow range of pH (7.4 to 8.2) within their solums. Clay content was measured to be between 20 and 55% and gypsum content to be between trace amounts and 8.6 %. The organic carbon content is generally low to moderate, varied between 0.12 and 4.84%. The most content of OC was measured in mollic epipedon of pedon 8. The low organic matter content of the studied soils contributed to land degradation. CEC varied between 6.3 to 36.8 cmol$_{(+)}$kg^{-1}. More CEC was measured in the soils of physiographic surfaces of piedmont plains and plateau with more clay content.

The studied soils were classified as Entisols, Inceptisols, Alfisols, and Mollisols with calcic, gypsic, cambic, and argillic horizons and ochric and mollic epipedons based on Soil Taxonomy (Soil Survey Staff, 2014) and Calsisols, Cambisols, Regosols, Gypsisols, Luvisols, and Kastanozems based on WRB (FAO, 2015).

Table 1. Physicochemical properties of representative pedons

Horizon	Depth (cm)	EC (dS/m)	pH	CCE (%)	Gypsum (%)	OC (%)	Sand (%)	Silt (%)	Clay (%)	CEC cmolkg^{-1}
Pedon 1 (Plateau)										
Ap	0-25	0.8	7.7	41.5	ng	1.25	33.0	42.0	25.0	15.1
Btk1	25-70	0.6	7.8	45.1	ng	0.62	25.0	42.0	34.0	17.0
Btk2	70-110	0.5	8.0	43.7	0.7	0.42	38.0	22.0	40.0	14.9
C	110-140	0.4	8.2	48.8	0.8	0.12	32.0	38.0	30.0	11.8
USDA: Calcic Haplustalfs					WRB: Calcic Luvisols (Ochric)					
Pedon 2 (Piedmont plain)										
Ap	0-25	0.7	7.6	44.0	ng	1.48	17.0	43.0	39.0	18.6
Btk	25-50	0.8	7.7	51.1	0.5	0.70	15.0	30.0	55.0	19.8
Bk1	50-85	1.8	8.0	56.1	1.0	0.62	11.0	38.0	51.0	16.1
Bk2	85-115	2.0	7.7	58.4	1.4	0.32	23.0	35.0	42.0	13.5
USDA: Calcic Haplustalfs					WRB: Calcic Luvisols (Ochric)					
Pedon 3 (River alluvial plain)										
Ap	0-30	0.5	7.9	45.0	0.7	0.95	29.0	30.0	31.0	14.8
C1	30-75	0.3	7.8	86.3	0.9	0.72	38.0	27.0	35.0	10.8
C2	75-125	0.7	8.1	83.0	1.0	0.52	27.0	40.0	33.0	10.2
USDA: Typic Ustorthents					WRB: Calcaric Regosols (Loamic, Ochric)					
Pedon 4 (Piedmont plain)										
Ap	0-20	0.7	7.9	49.8	0.9	0.81	42.0	32.0	26.0	9.2
Bw	20-60	1.4	7.8	60.2	3.9	0.51	44.0	26.0	30.0	9.5
Bky1	60-95	1.9	7.5	57.3	5.7	0.37	41.0	31.0	28.0	6.8
Bky2	95-125	2.3	7.5	58.2	8.6	0.25	46.0	28.0	26.0	6.4
USDA: Gypsic Calciustepts					WRB: Calcic Gypsisols (Loamic, Ochric)					
Pedon 5 (Alluvial fan)										
Ap	0-20	1.2	7.6	55.2	2.2	0.81	45.0	35.0	21.0	8.8
Bky	20-55	1.7	7.8	59.9	6.4	0.35	46.0	29.0	25.0	6.9
C	55-100	1.5	7.4	66.7	3.7	0.20	43.0	34.0	23.0	6.3
USDA: Gypsic Calciustepts					WRB: Calcic Gypsisols (Loamic, Ochric)					
Pedon 6 (Piedmont plain)										
Ap	0-30	0.6	7.5	52.5	1.7	0.92	17.0	46.0	37.0	21.5
Bk1	30-60	0.4	7.7	56.0	0.5	0.42	21.0	36.0	43.0	19.0
Bk2	60-90	0.2	7.8	53.5	0.2	0.33	22.0	42.0	36.0	14.9
Ck	90-125	0.3	7.9	62.8	0.1	0.12	28.0	42.0	30.0	12.4
USDA: Typic Calciustepts					WRB: Haplic Calcisols (Loamic, Ochric)					
Pedon 7 (Alluvial fan)										
Ap	0-30	0.5	7.9	70.0	0.5	1.32	36.0	27.0	37.0	16.5
Bw1	30-75	0.3	8.1	73.3	0.4	0.65	42.0	20.0	38.0	12.2
Bw2	75-120	0.3	8.4	78.2	0.7	0.42	49.0	23.0	28.0	8.4
USDA: Fluventic Haplustepts					WRB: Fluvic Calcaric Cambisols (Loamic, Ochric)					
Pedon 8 (Piedmont plain)										
Apg	0-25	0.4	7.4	38.1	0.4	4.84	34.0	33.0	33.0	36.8
Bkg	25-80	0.3	7.8	58.3	0.6	2.02	36.0	26.0	38.0	21.4
C	80-130	0.3	8.0	67.7	0.5	0.49	31.0	33.0	36.0	12.2
USDA: Typic Calciaquolls					WRB: Calcic Gleyic Kastanozems (Loamic)					
Pedon 9 (River alluvial plain)										
Ap	0-25	0.9	7.4	64.1	0.4	1.40	41.0	30.0	29.0	12.5
C1	25-75	0.5	7.9	68.4	0.5	0.79	33.0	33.0	34.0	11.0
C2	75-130	0.3	8.1	72.8	0.5	0.56	29.0	35.0	36.0	11.7
USDA: Typic Ustifluvents					WRB: Calcaric Fluvisols (Loamic, Ochric)					

EC electrical conductivity, OC organic carbon, CCE calcium carbonate equivalent, CF coarse fragments (more than 2 mm), ng negligible

The soils formed adjacent to Gachsaran Formation (pedons 4 and 5), in the west of the study area, have a mixture of gypsiferous and calcareous parent materials. The formation of secondary gypsum and calcite is the dominant pedogenic process in these soils. The depth of calcic and gypsic horizons in these soils was highly related to the amount of precipitation and physiographic position. These pedons were classified as Gypsic Calciustepts. Pedon 8 in Choram region (piedmont plain) is a paddy soil with a locally aquic soil moisture regime and a mollic epipedon at surface and a calcic horizon at subsurface. This pedon was classified as Typic Calciquolls (Table 1).

Undeveloped Entisols (pedons 3 and 9) were formed on young unstable river alluvial plain with seasonal sedimentation by Dehdasht and Choram Rivers, respectively. These pedons were classified as Typic Ustorthents and Typic Ustifluvents, respectively. The northern sector of the region shows stable physiographic units of plateau and piedmont plain. The most evolved soil pedons were described in this sector (Calcic Haplustalfs).

Clay content increased with depth in most of the pedons, indicating illuviation of clay. The presence of argillic horizons in the more stable positions of plateau and piedmont plain (Pedons 1 and 2) in a semi-arid region, indicated a more humid paleoclimate in the history of the area. Micromorphological observations support these findings (Figure 6e). No argillic horizon was found in the other unstable positions. It seems that the stability of the geomorphic surface has been an important factor affecting the formation/preservation of argillic horizon through time. Besides, the formation of argillic horizons in arid soils of Central Iran was attributed to a more humid paleoclimate reported by Nadimi and Farpoor (2013).

The size, shape, and position of gypsum crystals, within the soil matrix, have been used to determine their origin (Buck and Van Hoesen, 2002). It has been suggested that diversity of crystal morphology results from changing micro-environmental conditions in soils through time (Amit and Yaalon, 1996). SEM observations of the present study showed that pedogenic gypsum crystals can occur individually or in clusters (nodules and plugs) within the soil groundmass and pores (Figures 5e and 5f). Amit and Yaalon (1996) identified four different crystal forms of gypsum included lenticular, prismatic, alabastrine microcrystalline, and fibrous crystals in relation to stage of soil development.

Clay minerals

Rocks

Chlorite, illite, smectite, palygorskite, quartz, and interstratified minerals are the major clay minerals within the rock samples studied (Table 2). Smectite was dominant in the younger sediments (Bakhtiari and Aghajari formations), in comparison with the older sediments (Mishan and Gachsaran formations) in which palygorskite was most abundant. The inverse correlation between smectite and palygorskite supports the hypothesis of the conversion of these two minerals to each other. Only small amounts of palygorskite were observed in the youngest formation. The association of smectite and palygorskite in the Oligo–Miocene limestone and marl is consistent with the results of the others (Pletsch et al., 1996; Khormali and Abtahi, 2003). Moderate to large quantities of illite and chlorite were found in all formations. Khademi and Mermut (1998) found palygorskite and sepiolite and appreciable amounts of mica and smectite in the clay fraction of the Oligo–Miocene limestone of central Iran. All formations contained small quantities of interstratified minerals, but only the youngest contained measurable amounts of quartz.

Table 2. Relative abundance of different clay minerals in the clay fraction of the carbonate-free residues of the rock samples studied[a]

Rock	Age	Ch.	Il.	Sm.	Pa.	Qr.	Is.
R1	Lower Miocene	++	+++	+	+++	+	+
R2	Lower to Middle Miocene	+++	++	++	++	+.	+
R3	Upper Miocene to Pliocene	++	++	+++	+	+	+
R4	Upper Pliocene	++	++	+++	+	++	+

+: Relative abundance of minerals, tr=trace. [a]Ch, chlorite; Il, illite; Sm, smectite; Pa, palygorskite; Qr, quartz; Ve, vermiculite; Is, Interstratified minerals. R1=Gachsaran, R2=Mishan, R3=Aghajari, R4=Bakhtiari.

Soils

Palygorskite, chlorite, illite, smectite, vermiculite, kaolinite, quartz and interstratified minerals are the major clay minerals within the soils (Table 3). The presence of moderate to high contents of illite and chlorite in the soils can be related to inheritance from parent rocks. Larger contents of these minerals in parent rocks or sediments support this hypothesis. High leaching together with low pH and removal of interlayer hydroxides were reported as the ideal conditions for chlorite formation in soils (Branhisel and Berstesch, 1992). That is why the arid moisture regime of the present research is not favorable for the pedogenic formation of chlorite. Thus, chlorite in soils of the study area is inherited (Owliaie et al., 2006).

However, there is some indication that mica may form pedogenically in arid soils as well, but only in special conditions, mainly through K fixation of pre-existing smectite (Mahjoory, 1975; Sanguesa et al., 2000). Simple transformation of illite to smectite may play a major role in decreasing illite content at soil surface (i.e. pedons 1, 2, 6 and 8). Climatic condition in the study area can provide a leaching environment for the release of K^+ from illite. Moreover, the soil environment, high in Mg and Si mobility, may create favorable condition for the formation of smectite through transformation at the soil surface (Owliaie et al., 2006).

Table 3. Relative abundance of clay minerals [a] (<2 µm)

Pedon/horizon	Ch.	Il.	Sm.	Pa.	Ka.	Ve.	Qr.	Is.
1/Ap	++	+	+++	+	+	+	tr.	tr.
1/Btk2	+++	++	++	++	tr.	+	+	+
2/Ap	++	+	+++	++	+	tr.	tr.	+
2/Btk	++	+++	+	++	tr.	tr.	+	+
2/Bk2	++	+++	+	++	+	tr.	++	+
4/Ap	++	+	++	++	+	tr.	+	tr.
4/Bky1	++	+	+	++++	+	tr.	+	tr.
5/Ap	+	++	++	++	+	+	+	tr.
5/Bky	++	++	+	++++	+	tr.	+	+
6/Ap	++	+	+++	+	tr.	+	tr.	tr.
6/Bk2	+++	++	+	++	tr.	tr.	+	+
8/Apg	+	+	++++	+	tr.	tr.	+	+
8/Bkg	++	++	+++	tr.	+	+	tr.	tr.
9/Ap	+	+	+++	tr.	+	+	+	tr.
9/C2	++	++	+	++	+	tr.	+	tr.

+: Relative abundance of minerals, tr= trace.

[a] Ch, chlorite; Il, illite; Sm, smectite; Pa, palygorskite; Ka, kaolinite; Qr, quartz; Ve, vermiculite; Is, Interstratified minerals.

Maximum content of smectite is noticed in pedon 8 with aquic soil moisture regime (Table 3 and Figure 4d). The presence of large amounts of this mineral in poorly soils is reported by Abtahi and Khormali (2001) and Aoudjit et al. (1995). They discussed there are three main sources of smectite in soils: (1) neoformation from soil solution, (2) detrital origin or inheritance, (3) transformation of other clay minerals. Low-lying topography, poor drainage and base-rich parent material, favorable chemical conditions characterized by high pH, high silica activity and an abundance of basic cations are the factors strongly influenced the origin and distribution of smectite in soils.

Some part of the smectite is inherited from highly smectite marl formations, but the distinction between inherited and newly-formed clay minerals is difficult to discern. Some part of the smectite is inherited from highly smectite marl formations, although some may be the product of palygorskite weathering and transformation of illite particularly at the surface horizons.

A broad smectite peak (Figures 4a and 4b) after ethylene glycol treatment of some horizons (i.e. Btk2 horizon of pedon 4 and Ap horizon of pedon 2) appeared indicating the presence of high charge and/or low crystalline smectite in the soil, which suggests the inheritance origin of this mineral in the studied soils. In contrast, a sharp smectite peak in aquic soil (pedon 8), suggests a pedogenic origin of this mineral (Figure 4d). Smectites with lower layer charge are present in the soils having a longer effective time of pedogenesis, suggesting alteration of the high-charge smectites with time (Gillot et al., 2001). Rezapour et al. (2012) and Rezapour (2014) reported low crystalline smectite in the cultivated soils of northwestern of Iran, suggested a neoformed clay mineral.

Trace to very low contents of vermiculite is observed in surface horizons of the soils studied. The occurrence and stability of vermiculite in calcareous and silica-rich soils have not been well-documented (Boettinger and Southard, 1995). According to Wilson (1999) with regard to the transformation of clay minerals, a general example would be: illite →vermicullite →smectite.

At about pH > 6 (as in case of the studied soils), Al is not soluble. In contrast, Si is highly soluble especially in the common pH of around 8 (as in calcareous soils of southern Iran). Therefore, high Mg present in calcareous materials can substitute Al in the lattice and form smectite. However, vermiculite is not stable and there is no evidence showing the existence of this mineral in the studied soils. Alteration of mica is the main pathway for the occurrence of pedogenic vermiculite in the soils (Churchman and Lowe, 2012).

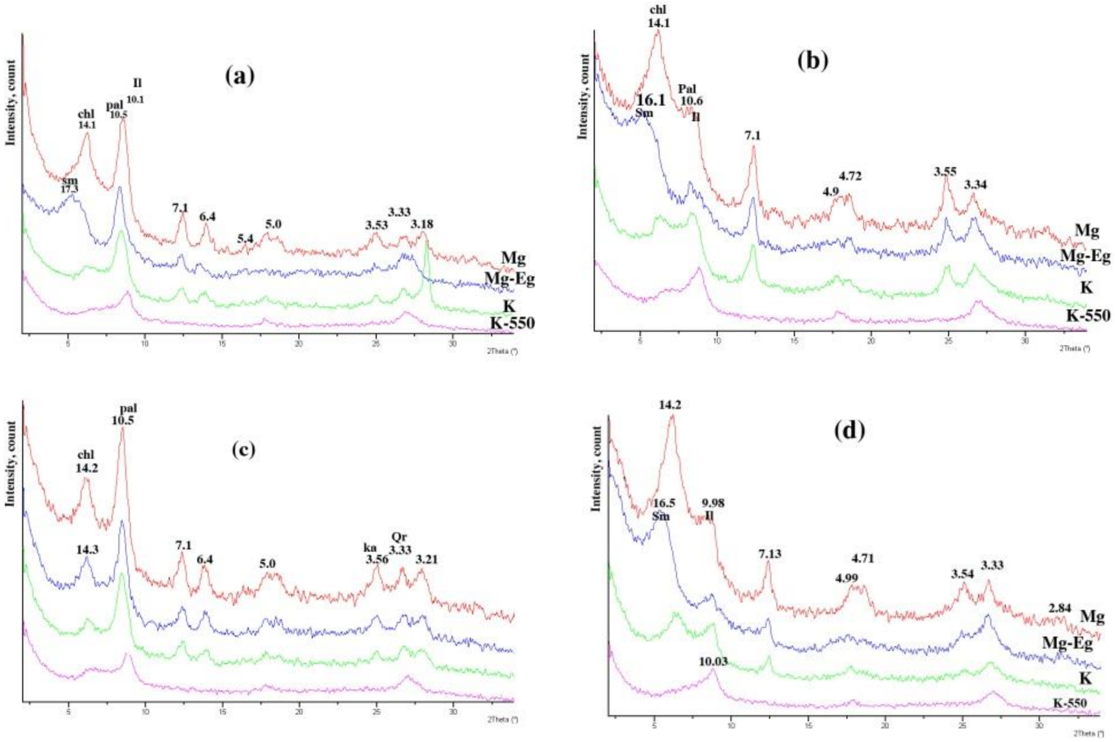

Figure 4. X-Ray diffractograms of the clay fraction, a) Btk2 horizon of pedon 1, b) Ap horizon of pedon 2, c) Bky1 horizon of pedon 4, d) Apg horizon of pedon 8, Sm: Smectite, I: Illite, Pa: Palygorskite, Ch: Chlorite, Ka: Kaolinite. Mg=Mg saturated; Mg-Eg=Mg saturated with Ethylene glycol; K=K saturated; K-550=K saturated and heated to 550 °C.

The results of the current research indicate that inheritance origin due to a moderate to large amount of smectite in parent rocks especially in younger formations and transformation from palygorskite are the main pathways for the occurrence of smectite in the soils studied (except for the pedon 8 with aquic condition). Illite is a main precursor mineral for the formation of smectite in soils, particularly at the surface horizons. Palygorskite is another possible precursor mineral for smectite formation in similar environments. The results indicate that there is a reverse correlation between smectite and palygorskite in the studied pedons. The maximum of palygorskite is observed in deeper horizons. It can indicate that palygorskite, weathers and transforms to smectite at soil surface. Similar results are reported in literature (Abtahi, 1980; Khademi and Mermut, 1998; Owliaie et al., 2006).

Increase of Mg/Ca ratio after gypsum crystallization in Tertiary followed by Miocene orogenic activities in arid lands of Iran was reported in the literature (Khademi and Mermut, 1998; Owliaie et al., 2006; Moazallahi and Farpoor, 2009). Farpoor et al. (2002) have reported a close relationship between geomorphic positions and palygorskite morphology and origin in the soils of Rafsanjan area in the south central part of Iran. A close relationship between palygorskite morphology and depth of soil was observed on different landforms in the soils of southwestern Iran (Owliaie et al., 2006).

Traces to minor contents of quartz and interstratified minerals are observed in clay fraction of the studied soils (Table 3). More contents of these minerals are found in clay fraction of the deeper horizon with lower weathering suggesting a lithogenic origin for these minerals.

According to the results (Tables 2 and 3), the relative amount of palygorskite in soils is much more than the parent rock samples (especially in gypsiferous soils). It may suggest that the pedogenic origin for palygorskite formation is more important than lithogenic. It has been stated that palygorskite in soils of arid and semi-arid environment has two main origins: (1) inheritance from parent materials and (2) pedogenic formation (Badraoui et al., 1992; Monger and Daugherty, 1991). Pedogenic palygorskite has been proposed to form by alteration of precursor minerals such as smectite or by precipitation from solution (Singer, 1984). Neoformation of palygorskite seems to need large activities of Si and Mg with a pH of about 8 (Singer, 1989). Figure 5d shows SEM micrographs of palygorskite fibers on gypsum crystals (Bky1 horizon of pedon 4).

A high amount of palygorskite was observed in gypsiferous pedons (pedons 4 and 5) compared with calcareous pedons (Table 3). Owliaie et al. (2006) concluded that calcareous and gypsiferous soils can provide buffered alkaline media with essential anions and cations for pedogenic formation of palygorskite but properties of the gypsiferous soils may result in a more favorable medium for this purpose.

Presence of first (7.1 Å) and second (3.57 Å) order peaks of kaolinite prove the formation of this clay mineral in the soils studied (Dixon and Weed, 1989). Warm and humid climate with good drainage was reported for kaolinite formation (Nadimi and Farpoor, 2013; Khormali and Abtahi, 2003). Since such an environment could not be found in the area at present, kaolinite should have been inherited in the studied soils. Besides, the role of kaolinite-bearing eolian deposits in the arid environment of the present research should not be neglected as a probable source of this mineral.

Abbaslou et al. (2013) in a study in arid regions of Hormozgan Province, southern Iran, concluded that the soil mineralogy did not vary systematically with depth but showed spatial variations, and the relative influence of mineral distribution in topsoils was mainly affected by parent rocks and the geomorphological setting.

Micromorphology

Table 4 shows a brief description of some micromorphological properties of thin sections from selected soils. The overall microstructure of the studied soils ranged between weakly and well separated subangular blocky. The c/f 10μm related distribution is porphyric and ranged from 2/8 in the Bkg horizon of pedon 8 to 6/4 in the Bky2 horizon of pedon 4. Reddish brown groundmass dominated in the soils with gypsiferous parent material (particularly pedons 4 and 5), whereas yellowish brown to bright brown groundmass prevailed in the soils with calcareous parent materials. Since soils are highly calcareous or gypsiferous, the b-fabric is mostly crystallitic (Figures 6a, 6b, 6c, 6g and 6i), except in the soils with argillic horizons (pedons 1 and 2), where it can be speckled b-fabric when calcite depletion occurs (Table 4, Figure 6e). Within the studied soils coating and infilling of gypsum (as lenticular and psedo-hexagonal forms) and calcite crystals in voids and channels (Figure 5a) as well as Fe and Mn oxide nodules were common.

Few large lithogenic calcite nodules are impregnated by Fe oxides (Figure 6d). Calcite has been shown to be an efficient absorber of some impurities such as Mn^{2+}, Fe^{2+}, organic matter, etc (Van Beynen et al., 2001). Few Fe/Mn oxides were observed as dense nodules in the matrix of non-aquic soils, due to less degree of weathering of primary minerals (Figures 6b and 6d). In Bkg horizon of pedon 8 with an aquic condition, Fe/Mn oxides were observed as distributed hypocoating around voids and channels (Figure 6f). In a micromorphological study in southwestern Iran, Owliaie (2014) reported two different distribution patterns of Fe/Mn oxides in aquic and non-aquic soils due to more mobility of these oxides in aquic conditions. In aquic soils, these oxides were observed as hypocoating or quasicoating mostly with concentric internal fabric.

In the Btk horizon of pedon 1 located on a stable surface (plateau), some channels in thin sections, were covered with illuvial-clay coatings (Figure 6e)., however no clay coating was observed in the Btk horizon of pedon 2. More stability of pedon 1 compared to pedon 2 might be a reason for preserving clay skins. The absence of clay coating in thin sections of argillic horizons of highly calcareous soils of arid and semiarid regions is either tied to high shrink–swell potential, caused by the considerable amount of expandable clays (Nettleton et al., 1969; Nettleton and Peterson, 1983) or to the disruption force of growing crystals, such as gypsum or calcite (Khademi and Mermut, 2003) or to engulfment with carbonates (Mahmoodi, 1979). Soil horizons with high extensibility, were mostly missing clay coatings on the faces of peds because of high shrink–swell activity of the groundmass (Griffin and Buol, 1988). As mentioned above, smectite is the major clay mineral of the studied soils, particularly in more stable landforms.

SEM and thin section observations exhibited needle shaped (acicular) calcite as loose infilling in voids and channels of the Bk1 horizon of pedon 6 and Btk horizon of pedon 2 (Figure 5c and 6c). The length and width range of these needles were 20 to 80 μm and 1 to 2 μm, respectively. The origin of needle-shaped calcite has been discussed for a long time and is usually interpreted in two ways: in relation to organic material (roots, root hairs, bacteria, algae, and fungi) and as physicochemical phenomena (Wright, 1984).

Verrecchia and Verrecchia (1994) in a review on the morphology and genesis of needle-shaped calcite showed four types and several subtypes that from which three types are the result of biological methods whereas one is the result of physico-chemical crystallizations related to evaporation and desiccation. Preservation of needle-fiber calcite in soils indicates that the pedogenesis was weak (lack of leaching) and/or the climate of the environment was arid to semiarid (Wright, 1984). However, Strong et al. (1992) reported the occurrence of this form of calcite in cool and wet climate with abundant carbonate and high degree of biological activity.

Specific morphologies of calcite accumulation related to vegetation have been described in calcareous soils. In these soils, roots are responsible for the concentration of sparitic calcite crystals, also called cytomorphic calcite in the root channel (Jaillard et al., 1991). Cytomorphic calcites were observed in the Bk1 horizon of pedons 5 (Figure 5b). According to Monger (2002), biotic processes include CO_2 input into the soil via respiration, Ca^{2+} extraction by roots, and direct precipitation by organisms. The results of a micromorphological study in the soils of Kohgilouye Province, southwestern Iran, showed that cytomorphic calcite pedofeature, was more common in the near-surface horizons of the regions with higher rainfall and denser vegetation (Owliaie, 2012).

Table 4. Thin section description of the pedons studied.

Pedon/ horizon	Microstructure	c/f ratio (10 µm)	Micromass, b-fabric, color	Pedofeatures
1/Btk1	Moderate to well- developed subangular blocky, partly channel structure, porosity (~15%)	4/6	Crystallitic, speckled b-fabric, reddish brown	Dense and loose calcite coating and infilling in voids and channels, few to common clay coatings, dark reddish to black Fe/Mn oxides in matrix and Fe impregnation in calcite nodules.
2/Btk	Moderately developed subangular blocky with interpedal channels, porosity (~20%)	3/7	Crystallitic, speckled b-fabric, reddish brown	Coating of calcite in channels and voids, small calcite nodules, dark reddish to black Fe/Mn oxides in matrix.
2/Bk1	Weak developed subangular blocky, partly channel structure, porosity (~10%)	5/5	Crystallitic, b-fabric, ellowish brown	Loose and dense calcite infilling in voids and channels, coating of calcite along channels, few micritic calcite nodules, few Fe-Mn oxide in ground mass
4/Bw	Moderately developed subangular blocky, porosity (~50%)	4/6	Crystallitic b-fabric, light yellowish brown	Few micritic calcite nodules, few Fe-Mn oxide in ground mass
4/Bky2	Weak developed subangular blocky, porosity (~30%)	6/4	Crystallitic b-fabric, light yellowish brown	Coating of calcite in channels, few medium to large lenticular gypsum crystals in voids, channels and matrix.
5/Bky	Weak developed subangular blocky porosity (~20%) with some planes	3/7	Crystallitic b-fabric, light brown	Infilling of calcite in channels and voids, few fine to medium gypsum crystals in voids and matrix
6/Bk1	Moderately developed subangular blocky with interpedal channels, porosity (~20%)	3/7	Crystallitic b-fabric, yellowish brown	Dense calcite infilling in voids and channels, few needle-like calcite crystals, few Fe-Mn oxide in ground mass
7/Bw1	Weak to moderately developed subangular blocky with some planes, porosity (~20%)	4/6	Crystallitic b-fabric, yellowish brown	Few micritic calcite nodules, few Fe-Mn oxide in ground mass and calcite nodules.
8/Apg	Weak developed subangular, porosity (~25%)	4/6	Crystallitic b-fabric, yellowish red	Very few calcite nodule, oxidized plant residues, Fe-Mn oxide in ground mass
8/Bkg	Weak developed subangular, porosity (~25%)	2/8	Crystallitic b-fabric, reddish brown	Few calcite nodule, calcite infilling in voids and channels oxidized, plant residues, hypocoating of Fe oxide in voids
9/Ap	Weak developed subangular, porosity (~20%)	3/7	Crystallitic b-fabric, yellowish brown	Very few calcite nodule, oxidized plant residues, spheroidal faunal excrements in voids and channels

Faunal excrements were observed in thin section of Ap horizon of pedon 8. These pedofeatures were as organic spheroids (less than 25µm in diameter), and as a vermiform structure with oriented fabric (50 to 150 µm in length), within voids and channels, suggesting high biological activity in this soil (Figure 6j). In addition, plant residues (organs and tissues) in different stages of decomposition, were observed in the thin sections of some surface soils (Figures 6h and 6j). Lenticular, sub-lenticular and pseudo-hexagonal gypsum crystals, are dominant pedofeatures observed in the thin sections of the Bky1 and Bky2 horizons of pedon 4 (Figure 6g) and Bky horizon of pedon 5 (Figures 6i). Gypsum interlocked plates were found mostly in deeper horizons with a larger content of gypsum. SEM observations showed gypsum crystals as individual prismatic crystals (80 to 100 µm in length and 20 µm in width) distributed in soil matrix (Figure 5e), and subhedral crystals (20 to 30 µm) located in large voids (Figure 5f). The lenticular crystals vary in length between 100 and 250 µm and in diameter between 50 and 100 µm. Larger crystals were found in the soils with larger voids. Jafarzadeh and Burnham (1992) believed that lenticular gypsum crystals may form in any environmental condition. However, Amit and Yaalon (1996) have reported ionic impurity and unlimited pore space as the necessary conditions for the formation of lenticular gypsum.

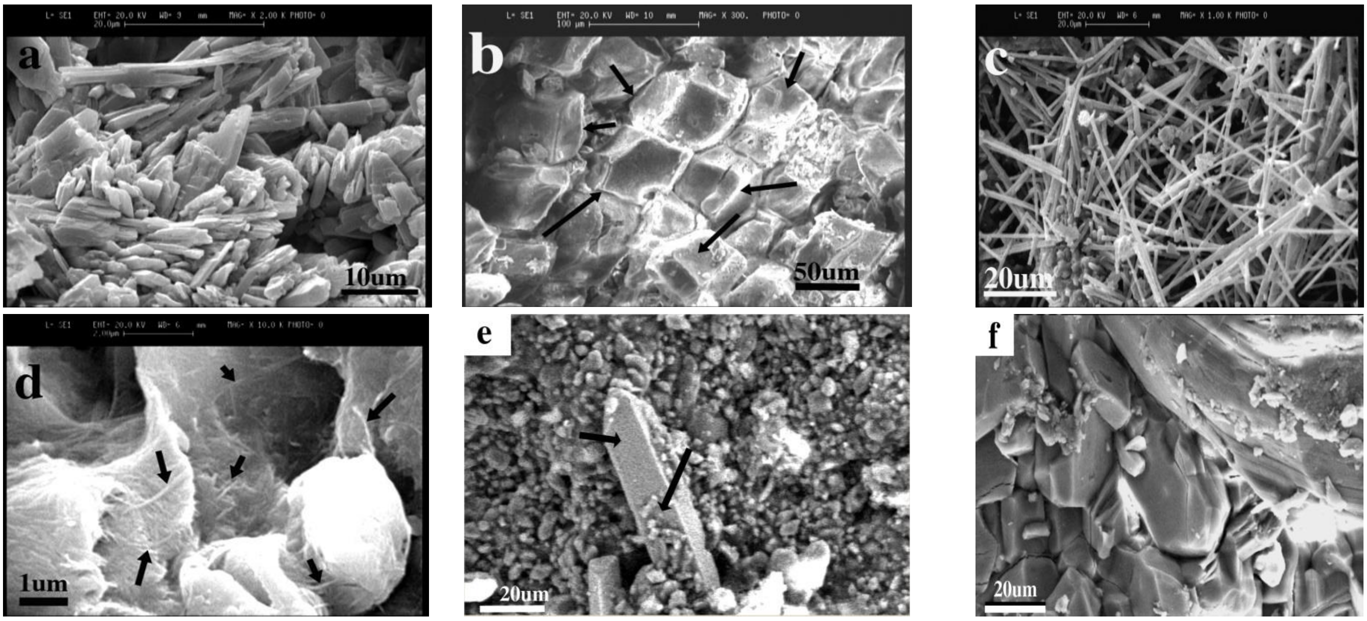

Figure 5. SEM micrographs of (a) euhedral calcite crystal of Bk2 horizon of pedon 6, (b) cytomorphic calcite crystals, Bk1 horizon of pedon 2 (c) needle-like calcite crystals of Btk horizon of pedon 2, (d) palygorskite fibers on gypsum crystal, Bky1 horizon of pedon 4, (e) individual prismatic gypsum crystal, Bky1 horizon of pedon 4, (f) integration of subhedral gypsum crystals, Bky horizon of pedon 5.

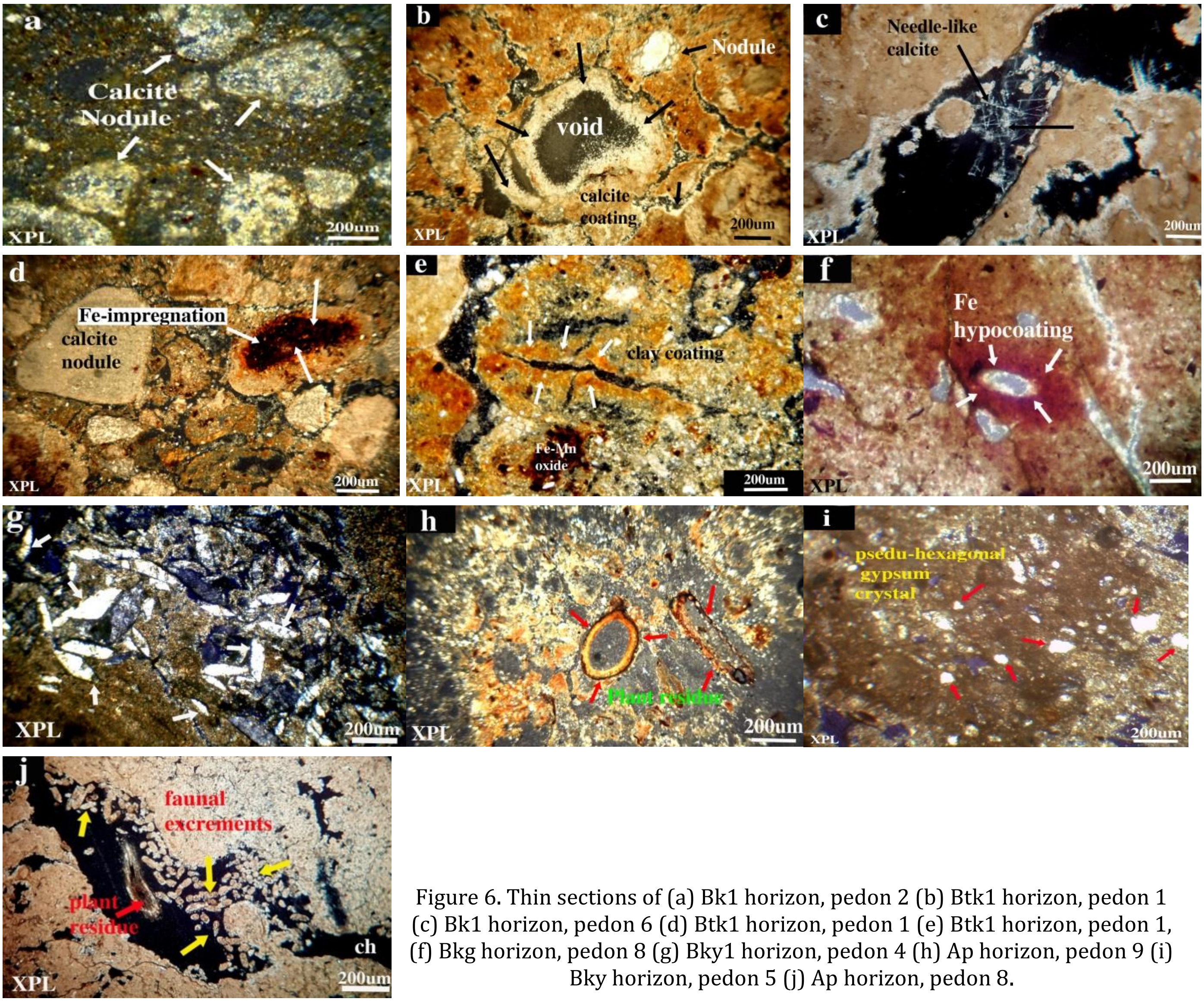

Figure 6. Thin sections of (a) Bk1 horizon, pedon 2 (b) Btk1 horizon, pedon 1 (c) Bk1 horizon, pedon 6 (d) Btk1 horizon, pedon 1 (e) Btk1 horizon, pedon 1, (f) Bkg horizon, pedon 8 (g) Bky1 horizon, pedon 4 (h) Ap horizon, pedon 9 (i) Bky horizon, pedon 5 (j) Ap horizon, pedon 8.

Conclusion

The results of the present study showed that soil formation on different physiographic surfaces and geological strata and its physicochemical, mineralogical, and micromorphological characteristics are closely influenced by landscape position and parent material. More developed soils were found on the stable plateau and piedmont plain; however, the soils formed on the unstable river alluvial plain and alluvial fan showed a minimum of development. Spatial distribution of calcareous and gypsiferous geological strata was responsible for the occurrence of calcic and gypsic horizons in the studied pedons. Mountain runoff water is the main source for the soil gypsum. The depth of calcic and gypsic horizons in the soils was highly related to the amount of precipitation and landscape position. The presence of argillic horizons in the more stable positions of plateau and piedmont plain soils in a semi-arid region indicated a more humid paleoclimate in the history of the area. Smectite, illite, chlorite, palygorskite, kaolinite and quartz clay minerals were identified in almost all landscape surfaces, but more palygorskite and less smectite were found in the soils with gypsiferous parent materials. A large amount of smectite is inherited from the marl formations, although some may be the product of transformation of illite and also palygorskite weathering, particularly at the surface horizons. In the soil with aquic soil moisture regime, neoformation of smectite seems to be the main pathway for the occurrence of this clay mineral. Coating and infilling of gypsum and calcite crystals in voids and channels as well as Fe and Mn oxide nodules and hypocoating (in aquic soil) were common pedofeatures observed in the soils studied. Faunal excrements were observed in the thin section of surface horizons with more biological activity. Co-occurrence of illuvial clay features and pedogenic carbonates were observed in pedons located on the stable physiographic surface suggesting the occurrence of polygenetic soils.

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