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Soil Genesis and Clay Mineralogy along the Xeric-Aridic Climotoposequence in South Central Iran

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ABSTRACT

Topography and climate are two important soil forming factors affecting genesis and clay mineralogy of soils. Calcareous and gypsiferous soils are widely spread in arid and semiarid parts of Iran and palygorskite is a dominant clay mineral in these soils. The objectives of the study were to: (1) determine soil genesis and classification along the climotoposequence and (2) investigate clay mineralogy and mode of mineral formation in soils along the sequence. The study area is a transect located in the southwest of Kerman Province covering 1,200 km^2 beginning from Kerman Plain (1,840 m above sea level) with aridic moisture regime and extending to Lalehzar elevation (3207 m above sea level) with xeric moisture regime. Soil parent material changed from recent Quaternary alluvium in north of the transect (Kerman Plain) to the materials originated from weathering of igneous granodiorites of Lalehzar Mountains in the south. Illite, high charge smectite, palygorskite, chlorite and kaolinite clay minerals were found in almost all the soils studied. Smectite-vermiculite interstratified minerals were found only in Histosols (pedon 8 at lowland geomorphic position close to Lalehzar Mountain), which are attributed to higher soil moisture in this geomorphic surface. Palygorskite bundles were associated with both calcite and gypsum crystals and they were both pedogenic and inherited from the parent material. Due to higher soil moisture at the end of the transect (Lalehzar elevation), palygorskite was not observed. A close relation was found between soil properties, topography, and climate in the studied sequence.

Keywords: Central Iran, Climotoposequence, Mixed interstratified minerals, Palygorskite.

INTRODUCTION

Climate and topography are two important soil forming factors affecting genesis, characteristics, and classification of soils. However, studies on soil climotoposequences require specific conditions to minimize the effect of soil forming factors other than climate and topography (Jenny, 1980). Weathering, evapotranspiration, water percolation, geomorphic position and amount of precipitation are among other properties that change along climotoposequences (Egli *et al*., 2003; Rustad *et al*., 2001). On the other hand, as the mineralogy of the clay fraction is related to the pedogenic processes in the soil, clay minerals are used as indicators of pedogenesis (Bonifacio *et al*., 2009). Interaction of source area lithology with climate affects distribution and evolution of clay minerals assemblages (Saez *et al*., 2003). Considering the weathering rates as a function of climate, Egli *et al*. (2003) found that the differences in the clay mineralogy linked well with the weathering intensity.

Gypsiferous (Gypsids) and calcareous (Calcids) soils are the two most widespread suborders (about 12 and 7.6%, respectively) formed in central parts of Iran (Roozitalab, 1994). Besides, calcic horizon in Inceptisols of western parts of Iran has also been reported (Salehi *et al*., 2002).

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Palygorskite is a dominant clay mineral in gypsiferous and calcareous Aridisols. Both soils can provide buffered alkaline media with necessary anions and cations for palygorskite crystallization; however, characteristics of the solution chemistry of the gypsiferous soils may result more favorable medium (Gamil *et al*., 2008). A Si and Mg-rich environment with high pH but impoverished in Al and Fe is favorable for the formation of palygorskite and sepiolite (Singer, 1989; Shadfan *et al*., 1985).

Mg/Ca ratio increased during gypsum formation, so palygorskite was formed in close association with gypsum crystals. Shallow water bodies and high temperature increased the pH (due to photosynthesis) and, consequently, enhanced Si solubility (Khademi and Mermut, 1998). These conditions seem to have taken place in central Iran during the Tertiary (Farpoor *et al*., 2002; Khademi and Mermut, 1998). Supporting the above-mentioned hypothesis, Khademi and Mermut (1998), Farpoor *et al*. (2002), Farpoor and Krouse (2008) and Karimi *et al*. (2009) found palygorskite as a dominant clay mineral in gypsiferous Aridisols of Isfahan, Rafsanjan, Loot, and Mashad areas of Iran, respectively.

Under semiarid conditions, palygorskite has been formed from smectite in some calcareous soils of southern Iran (Abtahi, 1980). Salehi *et al*. (2002) have also reported that petrocalcic horizons of Zagros region with a xeric moisture regime contain more palygorskite than other horizons. Despite the presence of palygorskite in cambic horizon, it has been better preserved when surrounded by calcite crystals.

On the other hand, the presence of palygorskite in sediments could be attributed to the reaction of montmorilonite with Mg-rich pore water. After the precipitation of calcite, the ratio of Mg ions increases in Mg-rich pore water. Authigenic palygorskite may have been precipitated from solution supersaturated within the calcretized horizons. The silica and alumina required for the authigenesis of palygorskite are most probably derived from the dissolution of clays and quartz during the calcretization process, while Mg was derived from Mg-rich pore water (Khalaf, 2007; Bouza *et al*., 2007; Watts, 1980).

Three hypotheses have been proposed to explain the presence of palygorskite and sepiolite in pedogenic and sedimentary environments: (1) inheritance from parent materials (Heine and Völkel, 2010; Farpoor *et al*., 2002; Khademi and Mermut, 1998), (2) detrital origin either by aeolian additions or by transport of alluvial materials (Ugolini *et al*. 2008; Khademi and Mermut, 1998), and (3) autigenesis in soils of arid regions (Hassouba and Shaw, 1980). According to the last hypothesis, palygorskite could be formed in flood plains and alluvial fan soils of Sado Basin, Portugal, affected by fluctuations of the water table (Pimentel, 2002). Both inherited and pedogenic sources of palygorskite were reported in soils of central Iran (Farpoor *et al*., 2002; Khademi and Mermut, 1998) and Namibia (Heine and Völkel, 2010).

Solid state transformation and dissolution/crystallization are the two mechanisms responsible for the formation of different mixed-layer clays (Srodon, 1999). Hydromorphic conditions and increase of soil moisture are ideal conditions for mixed layer mineral formation (Raucsik *et al*., 2002; Perederij, 2001). Besides, random interstratified minerals were reported in humid soils of northern Iran by Torabi *et al*. (2001) and Ramazanpour and Bakhshipour (2003).

The objectives of the present study were:

a). To study soil genesis and classification along the climotoposequence of south central Iran.

b). To investigate clay minerals and their mode of formation along the gradient.

MATERIALS AND METHODS

Field Studies

The studied climotoposequence is a north-east to south-west transect (Figure 1) that covers an area of about 1,200 km^2. The mean annual precipitation of the area varies between 151 and 227 mm and the air temperature between 15.7^oC in Kerman

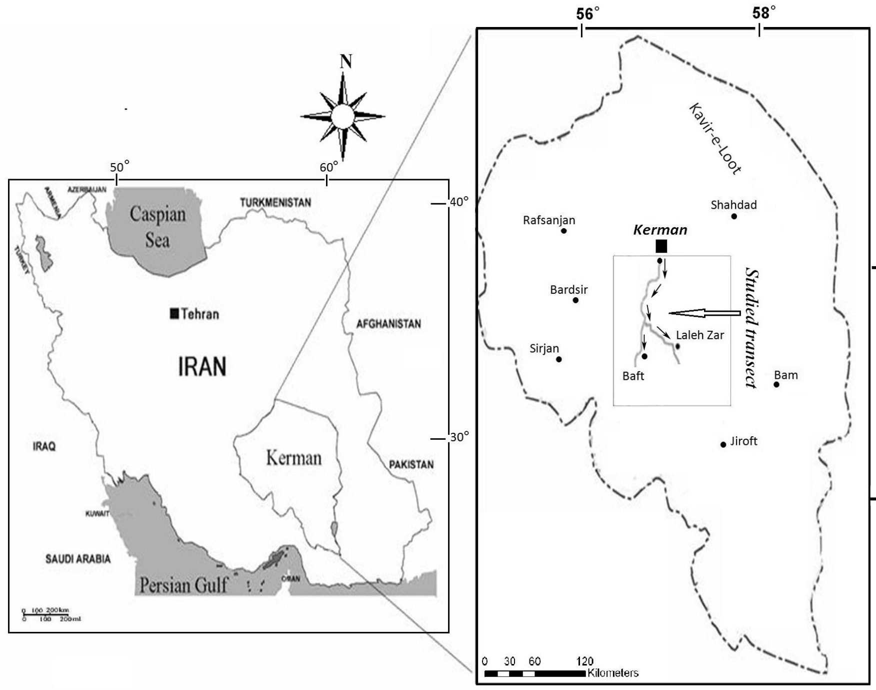

Figure 1. Location of the study area.

Plain (in the north of the transect, 1,840 m above sea level) and 9.7°C in Lalehzar (in the south of the transect, 3,207 m above sea level), respectively (Meteorological Organization of Iran, 2009). Soil moisture and temperature regimes in Kerman Plain are aridic and mesic that change to xeric and mesic in the south of the transect i.e. Lalehzar elevations (Banaie, 1998). Different geomorphic surfaces including Kerman Plain, rock pediment, piedmont plain, and lowlands of Lalehzar Mountains were studied (Figure 2). From the geological point of view, Kerman Plain was formed on recent Quaternary alluvium. The fine textured alluvium of Quaternary is the parent material of soils formed in this geomorphic position. On the other hand, Rock pediments are located on Neogene formations. Parent material in this surface consists of shallow alluvium with remnants of weathered sandstone, siltstone, and gypsiferous marls. Piedmont plains are also alluvium dominated by coarse gravels of Quaternary. Lalehzar Mountains are granodiorites of Post-Miocene age that highly affect organic surface material in this position (Geological Survey of Iran, 1995).

Eight representative pedons on different geomorphic positions (Figure 2) were described and all soil horizons were sampled according to Soil Taxonomy (Soil Survey Staff, 2010). Two pedons (1 and 2) were studied on Kerman Plain and rock pediment surfaces, respectively. Due to the large area covered by piedmont plain, 4 representative pedons (3, 4, 5, and 6) on this geomorphic surface were studied to show the variation in soil characteristics. Two pedons (7 and 8) were also sampled at lowland position of Lalehzar Mountains due to difference in soil properties.

Laboratory Studies

Air-dried soil samples were crushed and passed through a 2-mm sieve. Routine physicochemical analysis was performed on the samples. Calcium carbonate equivalent content was determined by back titration and gypsum content was investigated by acetone method (Nelson, 1982). Particle size

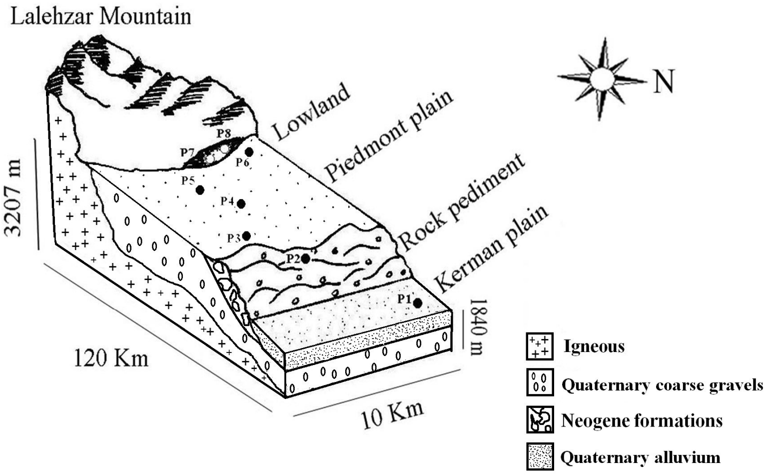

Figure 2. The studied transect showing different geomorphic surfaces of the area.

distribution was analyzed by pipette method (Gee and Bauder, 1986). Organic carbon was measured by the Nelson and Sommers (1982) method.

For mineralogical studies, selected samples were first repeatedly washed to remove gypsum and soluble salts. Carbonate and Fe-oxides were then removed by 1 M sodium acetate buffer solution (pH 5) and dithionate citrate bicarbonate (DCB) respectively (Jackson, 1975). The clay fraction of the samples was separated by centrifuge (Kittric and Hope, 1963). Clay suspensions were saturated with Mg and K, separately. Five treatments were done on each sample: Mg-saturated, Mg-saturated and ethylene glycole, K-saturated, K-saturated and heated at 350^{o}C, and K-saturated and heated at 550^{o}C. Slides were analyzed using a Bruker D8 Advance X-ray diffractometer with Cu Kα radiation operated at 40 kV and 40 mA. Semi-quantitative estimation of clay minerals performed using methods described by Jones *et al*. (1954) and Karimzadeh *et al*. (2004).

Several soil samples and selected calcite and gypsum crystals were mounted on Al stubs and coated with gold for energy dispersive X-ray spectrometry (EDS) and SEM observations using XL 30 ESEM Philips microscope.

To perform transmission electron microscope (TEM) studies, diluted suspensions of selected clay samples were transferred to Cu grids coated with Formwar and studied by a Hitachi H-7650 transmission electron microscope at an accelerating voltage of 80 kV.

RESULTS AND DISCUSSION

Morphology and Physicochemical Properties

The first representative pedon is located in Kerman Plain (Figure 2), which is the lowest (about 1,840 m asl) and the most arid part of the climotoposequence studied. Recent Quaternary alluvium is the main parent material for the soils of this geomorphic position. There are two Bk horizons in this pedon and due to the arid moisture regime in this landform, the Bt horizon is not formed. This soil is classified as Typic Haplocalcids (Table 1). Moving up the transect, on rock pediment geomorphic surface (Figure 2), Gypsic Haplosalids with the EC as high as 63.3 dS/m were observed. From geological point of view, this pedon is located on gypsiferous Neogene formations (Geological Survey of Iran, 1995). High coarse gravel

Table 1. Physical and chemical properties of some selected pedons.

Horizon	Depth (cm)	pH	EC (ds m^{-1})	OM (%)	$CaCO_3$ (%)	Gypsum (%)	Sand (%)	Silt (%)	Clay (%)	SAR
Pedon 1 (Kerman Plain), Typic Haplocalcids (Lat. 30° 05' 20.5″, Long. 57°01'44.4″)										
A	0-30	8.2	1.01	0.36	18.37	-	74	6	20	0.96
Bk1	30-51	8.2	0.75	0.43	15.37	-	68	10	22	1.50
Bk2	51-85	8.2	0.56	0.29	15.75	-	80	6	14	2.20
C1	85-110	8.5	0.37	0.33	14.37	-	94	2	4	1.70
C2	110-140	8.5	0.63	0.29	13.25	-	90	6	4	24.32
Pedon 2 (Rock pediment), Gypsic Haplosalids (Lat. 30° 01' 04″, Long. 56° 59'23″)										
A	0-10	7.5	11.30	0.09	26.25	50	46	32	22	3.61
Byz1	10-50	7.4	49.1	0.40	23.25	74	82	12	6	13.84
Byz2	50-80	7.4	63.3	0.57	19.62	76.5	88	6	6	15.60
Byz3	80-110	7.5	50.4	0.43	22.37	78	88	6	6	16.60
Byz4	110-140	7.6	49.9	0.50	21.00	79.5	88	6	6	21.52
Pedon 3 (Piedmont plain), Typic Natrigypsids (Lat. 29° 54' 10.4″, Long. 56° 58'17.9″)										
A	0-20	8	1.44	0.36	17.75	-	83	10	7	0.76
Bw	20-50	8.7	3.15	0.02	17.50	-	79	8	13	5.80
Btnk	50-90	8.1	9.16	0.29	25.00	-	53	20	27	32.30
By	90-140	8	17.47	0.22	20.50	65	59	20	21	31.54
C1	140-160	8	19.62	0.33	21.75	14.5	55	22	23	36.94
C2	160-200	8	19.05	0.12	21.50	-	73	12	15	29.58
Pedon 4 (Piedmont plain), Typic Natrigypsids (Lat. 29° 51' 59.2″, Long. 56° 52'33.1″)										
A	0-20	7.9	10.55	0.60	24.5	-	45	14	41	27.84
Bw1	20-40	8.4	1.37	0.36	23.1	-	51	10	39	3.90
Bw2	40-65	7.9	4.45	0.57	19.5	49.5	51	20	29	6.52
Byn	65-95	8.0	10.31	0.33	21.0	57.3	43	26	31	25.00
Btny	95-140	8.3	24.4	0.33	21.6	58.5	37	25	38	42.86
Pedon 5 (Piedmont plain), Calcic Haplosalids (Lat. 29° 49' 17.8″, Long. 56° 47'30.8″)										
A	0-5	7.5	9.95	1.00	26.25	7.0	16	55	29	7.17
Bk	5-30	7.4	15.07	0.40	24.12	16.8	37	38	25	7.49
Bz	30-60	7.5	35.8	0.50	18.25	24.7	75	0	25	23.91
Btn1	60-90	7.6	26.5	0.33	15.00	24.7	35	34	31	28.89
Btn2	90-120	7.6	26.9	0.47	14.75	24.7	35	18	47	26.38
Pedon 6 (Piedmont plain), Petrocalcic Calcixerepts (Lat. 29° 45' 43.8″, Long. 56° 46'51″)										
Az	0-30	7.3	86.30	0.57	20.75	11.40	62	16	22	-
Bk1	30-70	7.9	13.95	0.50	22.75	13.70	72	12	16	17.18
Bk2	70-100	8.0	6.75	0.57	23.75	15.40	72	14	14	10.39
Bkm	100-132	7.9	6.76	0.47	32.50	15.25	56	28	16	4.37
Pedon 7 (Lowland), Fluvaquentic Epiaquolls (Lat. 29° 28' 2.9″, Long. 56° 50'52.6″)										
Ag	0-30	6.4	1.48	22.20	10.00	-	34	22	44	-
Bwg1	30-60	6.7	0.82	11.20	8.87	-	46	22	32	-
Bwg2	60-90	7.0	0.58	5.86	8.25	-	66	18	16	-
Cg1	90-120	6.9	0.72	5.82	10.62	-	60	22	18	-
Cg2	120-150	7.0	0.50	7.60	8.50	-	56	22	22	-
Pedon 8 (Lowland), Typic Haplohemists (Lat. 29° 27' 15.8″, Long. 56° 37'13.6″)										
Oe1	0-30	7.3	1.46	46.00	14.62	-	36	50	14	-
Oe2	30-60	7.1	1.67	26.90	10.87	-	28	42	30	-
Bwg1	60-90	7.4	0.56	19.40	11.87	-	5	52	43	-
Bwg2	90-120	7.4	0.56	9.96	7.87	-	32	35	33	-
Cg	120-150	7.0	0.47	10.20	9.75	-	28	46	26	-

content (10-80%) made gypsum pendants to be formed in this position. Saline and non saline gypsiferous Neogene formations with the same properties were found by Farpoor *et al*. (2002) and Farpoor and Krouse (2008) in Rafsanjan and Loot areas, as well. Rock pediments seem to be the source of gypsum for soils of the area.

Three more pedons on piedmont plain were also studied (pedons 3-5). Coarse textured alluviums of Quaternary are the dominant parent material on this geomorphic position. Comparing with pedons 1 and 2 (Kerman Plain and rock pediment), more moisture has affected these soils. Sodium adsorption ratio in pedon 3 is high (SAR= 36) and, together with moisture present in the soil, caused the formation of Btnk horizon (Table 1). This soil is classified as Typic Natrigypsids. A saline polygonal structure (EC= 10.6 dS m^{-1}) on the surface of soil in Pedon 4 was observed. Pedon 5 on piedmont plain had a sodicity with black spots of dispersed organic matter on the surface. The Bk, Bz, and Btn horizons were formed in this pedon (Calcic Haplosalids). The argillic/natric horizons are not considered in the classification of Haplosalids. On the other hand, these horizons, especially in the case of natric horizon, could be limiting near the surface. That is why it is suggested that Natric Calcisalids subgroup is added to Soil Taxonomy (Soil Survey Staff, 2010).

Pedon 6 is also located in piedmont plain, but, in the zone of xeric moisture regime. This soil has a salic horizon in the surface (Az) and a well developed petrocalcic horizon at a depth of 100 cm (Table 1). No evidence of ground water was found and it seems that salts added to the surface from surrounding formations could not have leached from the soil profile and this was due to the presence of petrocalcic horizon. Water evaporation throughout the summer enhanced the capillary movement and formed the Az horizon at the surface. According to Soil Taxonomy (Soil Survey Staff, 2010), this soil is classified as Petrocalcic Calcixerepts. Pedon 7 (Typic Epiaquolls) is close to Lalehzar Mountains (3,207m asl) with a xeric moisture regime and is saturated with water for about 6 months during normal years. Mollic epipedon is formed in this position with about 22% organic matter (Table 1). Pedon 8 is an organic soil with about 46% organic matter (Table 1) with intermediate decomposition (Typic Haplohemists). Melted snows together with rainfall in lowlands of Lalehzar Mountains do not provide conditions for organic matter decomposition. Pedons 7 and 8 are located in lowland position of Lalehzar Mountains and are developed from the parent material highly affected by igneous rocks of Lalehzar Mountains. Results of the study clearly showed that moving up the transect, parent material, topography, and climate changed. That is why soil properties, as well as soil classifications also changed along the transect.

Clay Mineralogy

Illite, high charge smectite, palygorskite, chlorite, and kaolinite silicate clay minerals were found in almost all the soils studied. Figure 3 (a, b) shows the clay mineralogy of the Bk1 and C1 horizons of pedon 1. As mentioned above, three ideal conditions for palygorskite formation in soils and sediments of central Iran were reported by Khademi and Mermut (1998) and Farpoor *et al*. (2002). Increase of Mg/Ca ratio in shallow water bodies after gypsum crystallization, increase of environmental pH due to warm climate of Tertiary, and increase of soluble Si due to enriched hydrothermal solutions were suggested by the above researchers in Isfahan and Rafsanjan areas for the formation of palygorskite. Kerman area has also experienced the same climate (Farpoor and Krouse, 2008) and probably the same trend of palygorskite formation.

Both inherited and pedogenic sources of palygorskite were reported in Iran (Khormali and Abtahi, 2003; Farpoor *et al*., 2002;

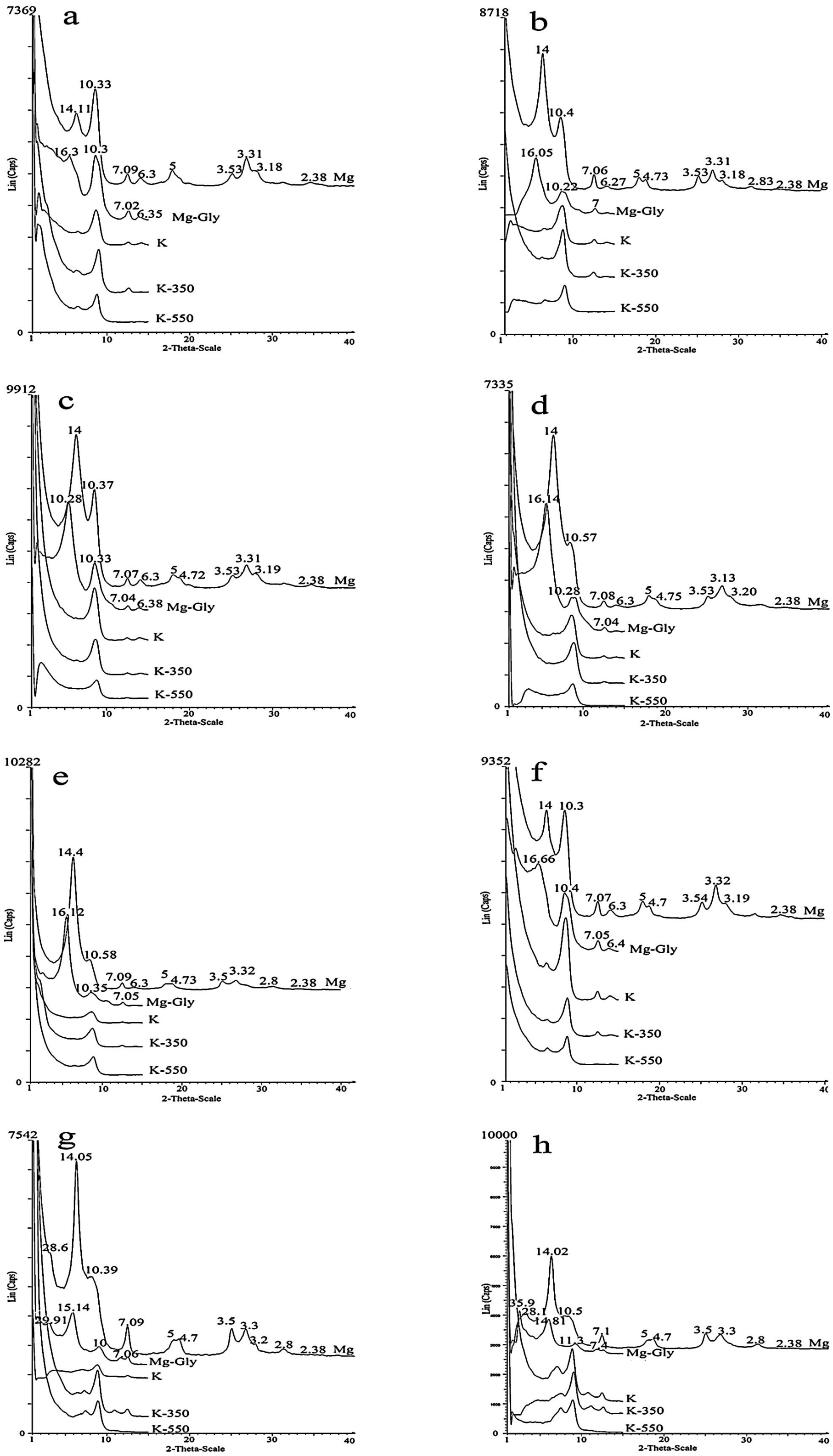

Figure 3. X-ray diffractograms of the clay fraction of: (a, b) Bk1 and C1 horizons of pedon 1 ; (c, d) Btnk and C1 horizons of pedon 3; (e) Byn horizon of pedon 4; (f) Bk1 horizon of pedon 6, (g, h) Oe2 and Cg horizons of pedon 8, respectively.

Khademi and Mermut, 1998). As calcite spars in this pedon are covered by palygorskite (Figure 4-a), pedogenic source of this mineral cannot be neglected. On the other hand, palygorskite bundles were observed in both the Bk1 and C1 horizons through XRD (Figure 3) and TEM (Figures 5-a and 5-b) studies. That is why the inheritance of palygorskite from parent material is also plausible.

Palygorskite content in pedon 1 decreased with depth, but smectite increased in the

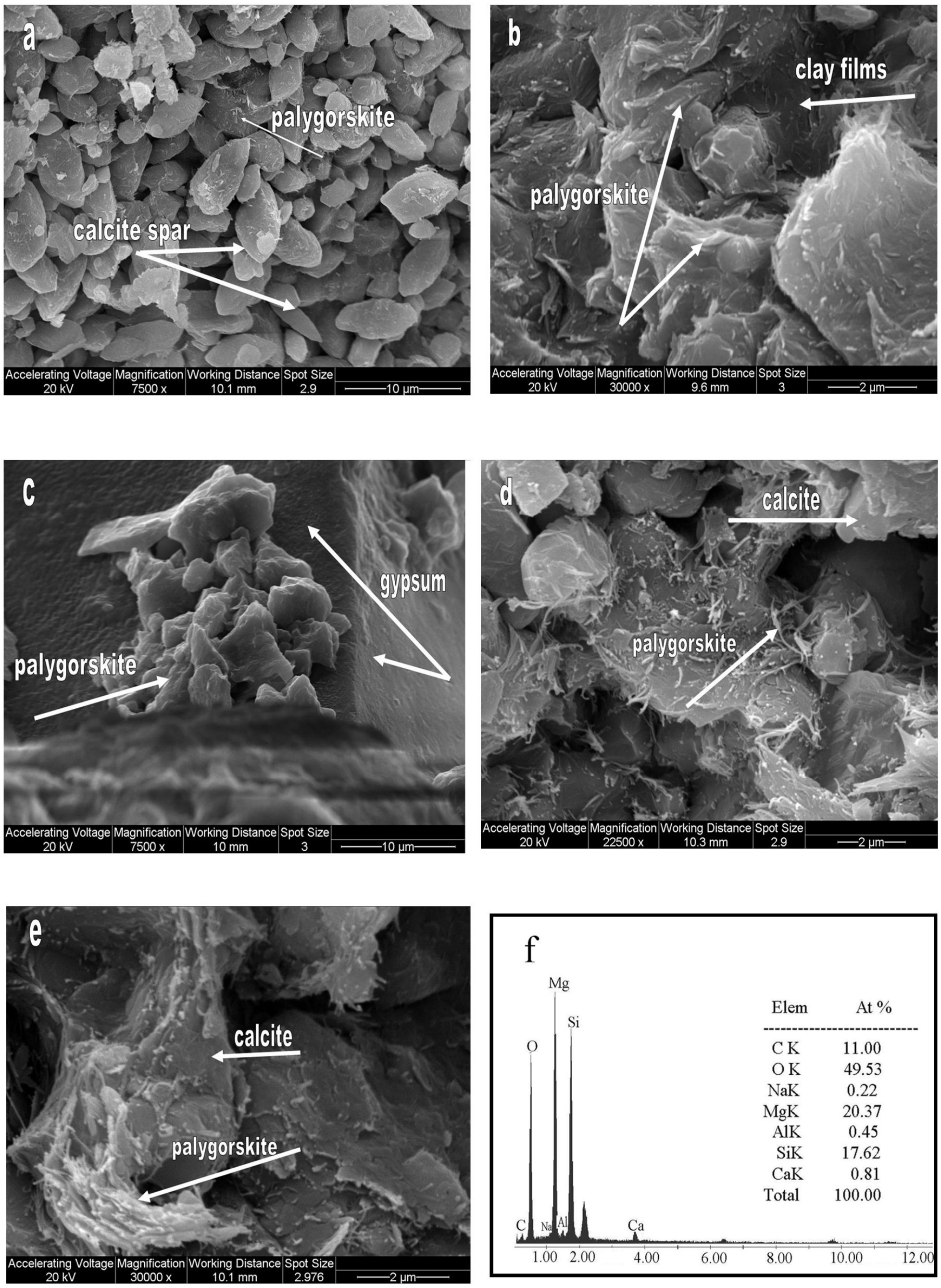

Figure 4. SEM micrographs showing palygorskite crystals around calcite and gypsum: (a) Bk (pedon1); (b) Btnk (pedon 3); (c) Byn (pedon 4); (d, e) Bk2 and Bkm (pedon 6), (f) Elemental analysis (SEM/EDS) of the clay fraction in Btnk horizon of pedon 3.

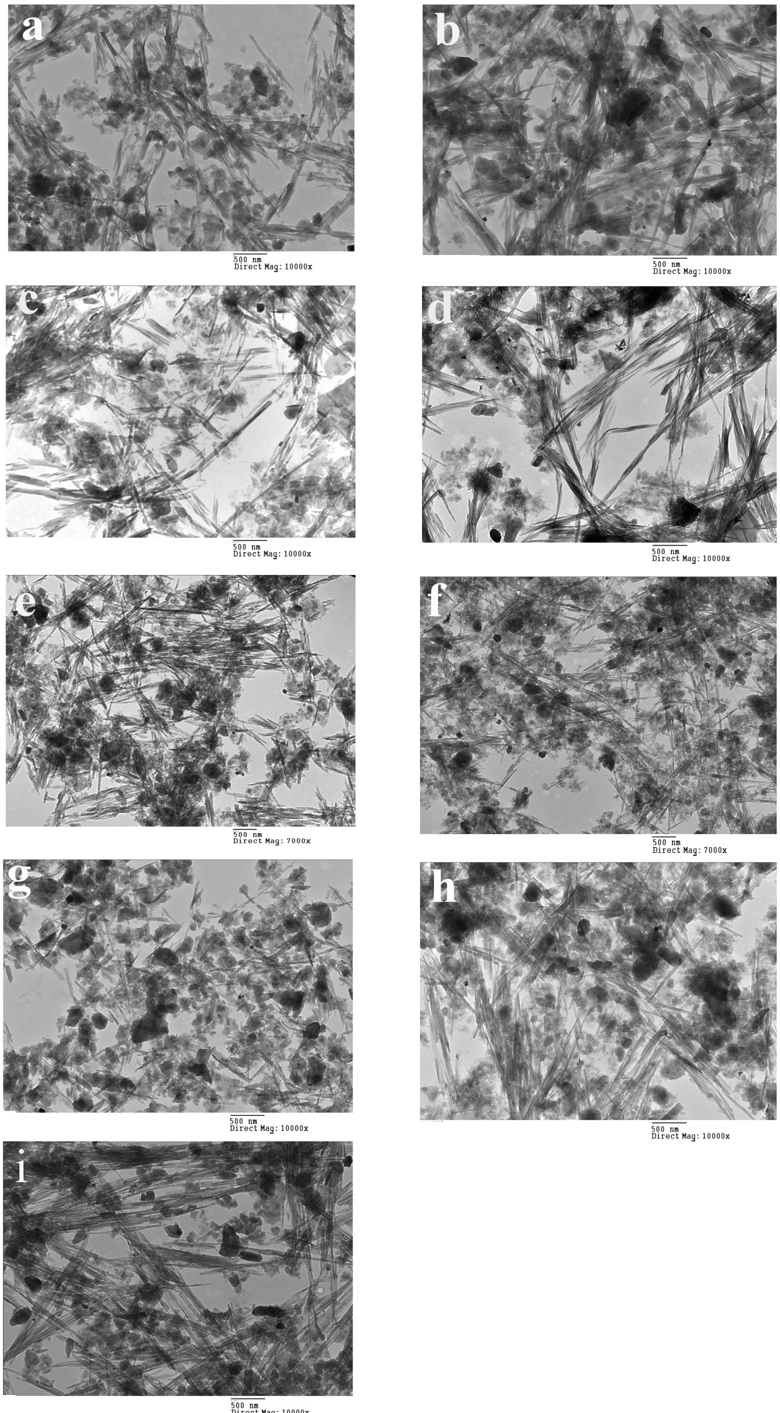

Figure 5. TEM micrographs showing the distribution of palygorskite crystals in different pedons: (a, b) Bk1 and C1 horizons of pedon 1; (c, d) Byz1 and Byz4 horizons of pedon 2; (e, f) Btnk and C1 horizons of pedon 3; (g, h) Bk and Btn2 horizons of pedon 5, (i) Bk1 horizon of pedon 6.

same trend (Table 2). Increase of smectite by depth could be attributed to inheritance of this mineral from parent material rich in smectite (Figure 3-b). On the other hand, percolating water in this geomorphic position might have affected transformation of palygorskite to smectite with increasing depth (Karimzadeh *et al.*, 2004), which intern could be a plausible reason for decreasing of palygorskite in C1 horizon of this pedon.

Table 2. Semi-quantitative analysis of clay minerals in the clay fraction of soils under study.

Pedon	Horizon	Sm [a]	Ill [b]	Pl [c]	Ch [d]	K [e]	In [f]
1	Bk1	XX	XXX	XXX	X	X	-
1	C1	XXXX	XXX	XX	X X	X	-
2	Bk1	XXXXX	XX	XX	X	X	-
2	C1	XXXXXX	X	X	tr[g]	X	-
4	Byn	XXXXXX	X	X	tr	X	-
6	Bk1	XXX	XX	XXX	XX	X	-
8	Oe2	XXXX	XX	-	XX	XX	X
8	Cg	XXXX	XX	-	XX	XX	X

[a] Smectite; [b] Illite; [c] Palygorskite; [d] Chlorite; [e] Kaolinite; [f] Interstratified, [g] Trace amount. X: 5-10%; XX: 10-20%; XXX: 20-35%; XXXX: 35-50%; XXXXX: 50-70%, XXXXXX: > 70 %.

Illite, chlorite and kaolinite clay minerals have a relatively similar abundance in different depths of geomorphic positions that is why inheritance from parent material is the only possible source of these minerals (Karimzadeh *et al*., 2004). On the other hand, an environment with higher temperature and more humidity and leaching is needed for pedogenic formation of kaolonite and chlorite (Barnhisel and Bretsch, 1989), but such environmental conditions were not present in the area under study, except pedon 8, which will be discussed in the following sections.

Pedon 2 on rock pediment had several Byz horizons (Table 1) and palygorskite bundles were found in TEM observations (Figures 5-c and 5-d). Smectite in pedon 2 is much more abundant than illite and palygorskite comparing to pedon 1 (Table 2). Inheritance of smectite from parent material seems to be the major origin of this mineral as the C1 horizon is rich in smectite. Besides, transformation of illite and palygorskite to smectite could be another source of smectite in this pedon. It is to be noted that Neogene formations are reported as the source of palygorskite for lower geomorphic positions in Isfahan (Khademi and Mermut, 1998), Rafsanjan (Farpoor *et al*., 2001), and Kerman (Farpoor and Krouse, 2008) areas, central Iran. Consequently, lower palygorskite content of pedon 2 on Neogene formations compared with pedon 1 could be a support for palygorskite to smectite transformation (Abbaslou and Abtahi, 2007; Karimzadeh *et al*., 2004).

In pedon 3, Smectite, illite, kaolinite, and palygorskite were found in the Btnk and C1 horizons (Figures 3-c and 3-d). Both sources of pedogenic and inherited palygorskite are probable since the parent material (C1) has large amounts of this fibrous clay mineral. On the other hand, calcite crystals of the Btnk horizon were coated by palygorskite (Figure 4-b) that could be an evidence of pedogenic palygorskite formation. However, no palygorskite fibers were observed on gypsum crystals in the by horizon. Palygorskite coating on gypsum crystals were reported by Eswaran and Barzanji (1974) and Khademi and Mermut (1998). However, palygorskite fibers seem to be better preserved when surrounded by calcite (Khademi and Mermut, 1998; Verrecchia and Lee Coustumer, 1996).

Figure 4-b shows a clay coating in the Btnk horizon of pedon 3. Looking at the chemical composition of this clay coating by EDS (Figure 4-f) a magnesium silicate with the Mg/Al ratio of 0.8 was found. This also supports clay illuviation in this horizon in addition to particle size analysis (Table 1) for argillic/natric horizon formation (Abtahi and Khormali, 2001). This soil is classified as Typic Natrigypsids. Palygorskite bundles were also found in TEM observations of the Btnk and C1 horizons (Figures 5-e and 5-f).

The same clay minerals were found in pedon 4 (Figure 3-e). Besides, palygorskite coatings around gypsum crystals were observed under the SEM (Figure 4-c) and TEM. Palygorskite was also found in the Bk and Btn2 horizons of pedon 5 (Figures 5-g and 5-h). The estimated amount and size of fibers increased with depth and the crystals in the Btn2 were bundle-like.

Smectite, illite, kaolinite, chlorite, and palygorskite clay minerals were found in the Bk1 horizon of pedon 6 in X-ray diagrams (Figure 3-f). Both the Bk2 and Bkm horizons showed palygorskite in SEM studies (Figures 4-d and 4-e), but the crystals in the Bkm horizon were as bundles compared with small and splinted crystals in the Bk2 horizon. Although the soil moisture regime in this position is xeric, palygorskite fibers around calcite crystals are preserved. Khademi and Mermut (1998) also reported the preservation of palygorskite around calcite crystals in Isfahan area, central Iran. Presence of palygorskite in xeric soil moisture regime of Zagros area, Iran, was also reported by Salehi *et al*. (2002) and Khormali and Abtahi (2003). Palygorskite fibers in the Bk1 horizon of this soil were also observed by TEM studies (Figure 5-i).

Smectite content in this soil decreased and palygorskite increased compared with pedon 4. As also mentioned in the morphology and physicochemical section, due to the presence of a petrocalcic limiting layer in the depth of 100 cm of this soil, water percolation in this pedon was hindered and a saline soil was therefore formed. The presence of shallow saline water in the soil profile during time may have caused transformation of smectite to palygorskite due to stability field of these minerals (Abbaslou and Abtahi, 2007; Givi and Abtahi, 1985).

Chlorite, illite, kaolinite, smectite, and some regular interstratified clay minerals were found in Oe2 and Cg horizons of pedon 8 (Figures 3-g and 3-h). Low-lying topography, poor drainage, and high pH and silica activity are important factors highly affecting neoformation of smectite in soils (Abbaslou and Abtahi, 2007; Karimzadeh *et al*., 2004; Aoudjit *et al*., 1995; Abtahi, 1977). Lowland position of pedon 8, together with melted snow and relatively high precipitation provide the favorable condition for smectite neoformation from solution in Oe2 and Cg horizons of pedon 8. On the other hand, due to high soil water content in this geomorphic position, the ideal conditions for palygorskite formation were not present in the pedon. Besides, if palygorskite could have been formed in a different situation of the past climate, transformation of palygorskite to smectite (another plausible reason for smectite formation) has occurred due to high water content of the soil at present (Owliaie *et al*., 2006; Paquet and Millot, 1972). As a result, palygorskite was not found in this landform (Figures 3-g and 3-h, Table 2). It is to be noted that this soil was formed at lowlands of igneous Lalehzar Mountains and no palygorskite in parent material was observed (Figure 3-g).

More kaolinite was found in this pedon (Table 2) compared with soils of lower geomorphic positions, which could be attributed to more available water in lowland position. Humidity could also cause more weathering needed for regular interstratified smectite-vermiculite formation in pedon 8. The expansion of 28 A° peak in ethylene glycole treatment shows that smectite and/or vermiculite should be included in the regular interstratified clay mineral. However, this peak disappeared in K treatment especially when heated to 550^{o}C. Therefore, chlorite could not be included. Besides, the 10 A° peak increased in K treatment and heating that supports smectite and/or vermiculite inclusion in the mixed mineral (Barnhisel and Bretsch, 1989). If mica was also included, the Mg saturated treatment peak could only reach up to 24 A°. Based on the presence of 28 A° peak and the above discussion, smectite-vermiculite could be the only regular interstratified clay mineral formed in pedon 8. However, the low expansion (from 28.6 A° to 29.9 A°) in the Oe2 horizon shows that a high charge smectite is included (Torabi Golsefidi *et al*., 2001; Borchardt, 1992).

CONCLUSIONS

Results of the study clearly showed a close relationship between soil properties and parent material, topography, and climate. Smectite, illite, kaolinite and chlorite clay minerals were found in almost all soils studied. Palygorskite mineral was found in soils of the arid part as a dominant clay mineral, but due to increasing soil moisture in the upper part of the transect, palygorskite was not formed and/or transformed to smectite. Both pedogenic and inherited sources of palygorskite were observed. Regular smectite-vermiculite mixed clay minerals were only found in the Histosols at the end of the transect. Moving from north of the transect (Kerman Plain with aridic soil moisture regime on recent Quaternary alluvium) to the south (Lalehzar lowlands with xeric moisture regime on parent materials with an igneous origin), Aridisols, Inceptisols, Mollisols, and Histosols were developed, respectively, along the transect.

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نحوه تشکیل و کانی شناسی رسی خاکهای واقع بر ردیف پستی بلندی اقلیمی زریک-اریدیک در جنوب ایران مرکزی

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چکیده

پستی بلندی و اقلیم دو عامل مهم تشکیل دهنده خاک هستند که بر روی نحوه تشکیل و کانی شناسی رسی خاکها تاثیر می گذارند. خاکهای گچی و آهکی در بخشهای خشک و نیمه خشک ایران گستره وسیعی داشته و پالیگورسکیت کانی رسی غالب در این خاکها به شمار می رود. اهداف تحقیق عبارت بودند از: (۱) تعیین نحوه تشکیل و طبقه بندی خاک در طول ردیف پستی بلندی اقلیمی و (۲) کانی شناسی رسی و تعیین نحوه تشکیل کانیها در طول ردیف. منطقه مورد مطالعه عبارت است از یک برش طولی واقع در جنوب غرب کرمان که ۱۲۰۰ کیلومتر مربع را در بر گرفته و از دشت کرمان (با ارتفاع ۱۸۰۰ متر از سطح دریا) با رژیم رطوبتی اریدیک شروع شده و تا ارتفاعات لاله زار (با ارتفاع ۳۲۰۷ متر از سطح دریا) با رژیم رطوبتی زریک امتداد یافته است. ماده مادری خاک از رسوبات اخیر کواترنری در شمال برش طولی (دشت کرمان) تا گرانودیوریتهای آذرین هوادیده مربوط به کوه های لاله زار در جنوب تغییر نمود. کانی های رسی ایلیت، اسمکتیت با بار لایه ای زیاد، پالیگورسکیت، کلریت، و کائولینیت تقریبا در کلیه خاکهای مورد مطالعه یافت شد. برخی آلومینوسیلیکاتهای منظم بین لایه ای، تنها در هیستوسولها (پروفیل ۸ در موقعیت ژئومرفولوژیکی پست در مجاورت کوه لاله زار) مشاهده گردید که به رطوبت فراوان تر در خاک این سطح ژئومرفولوژیکی نسبت داده شد. دسته های پالیگورسکیت با بلورهای گچ و آهک همراه بوده و دارای هر دو منشاء خاکساز و به ارث رسیده از مواد مادری می باشد. تغییر شکل پالیگورسکیت به اسمکتیت به دلیل رطوبت بیشتر در خاکهای انتهای برش طولی (ارتفاعات لاله زار) مشاهده گردید. ارتباط نزدیکی بین خصوصیات خاک با پستی بلندی، اقلیم، و مواد مادری یافت شد.