Iran Agricultural Research 21:39-60 (2002)

GENESIS AND DISTRIBUTION OF PALYGORSKITE AND ASSOCIATED CLAY MINERALS IN RAFSANJAN SOILS ON DIFFERENT GEOMORPHIC SURFACES

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(Received: February 27, 2001)

ABSTRACT

Palygorskite is a mineral of great importance in arid and semiarid soils and sediments. This fibrous clay mineral has been reported in Iranian Aridisols. The main objective of this study was to determine the presence and the origin of palygorskite in Rafsanjan soils in central Iran and to study the relationship between this clay mineral and geomorphic surfaces. Soils occurring on two perpendicular transects were studied. The first transect is located in Nough area, 30 km north of Rafsanjan, and the second one extends to Ali-Abad village 20 km south of Rafsanjan valley. Palygorskite, illite, chlorite, smectite, and quartz were observed in all soils using XRD, TEM, and EDX analyses. In the first transect, palygorskite crystals decreased in number and size from east (rock pediment) to the west (mantled pediments and playas). A trace amount of smectite was found in rock pediment position; in contrast, there was more smectite in other soil profiles. Due to more precipitation in the area of second transect, $CaCO_3$ illuviation has been occurring. Besides, palygorskite has easily been weathered and transformed to smectite. On the other hand, highly

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smectitic Marl formations resulted in greater amount of this mineral in the second transect as compared to the first one.

Key words: Palygorskite, Geomorphology, Weathering, Central Iran.

تحقیقات کشاورزی ایران

(۱۳۸۱) ۶۰- ۲۱: ۳۹

نحوه تشکیل و توزیع پالیگورسکایت و کانی های رسی همراه در خاک های سطوح مختلف ژئومرفولوژی درحوالی رفسنجان

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چکیده

درمیان کانی های موجود درخاک ها و رسوب های نواحی خشک ونیمه خشک، کانی پالیگورسکایت به دلیل فراوانی بالا ازاهمیت ویژه ای برخوردار است . این اهمیت درمورد اریدیسول های ایران نیز درست است. پژوهش کنونی برای مطالعه کانی شناسی رسی خاک های منطقه رفسنجان در مرکز ایران وتعیین ارتباط بین کانی های رسی وسطوح ژئومورفولوژی انجام شد. برای این کار، دو ترانسکت عمود برهم مطالعه شدند. ترانسکت اول، واقع درمنطقه نوق، ۳۰ کیلومتری شمال رفسنجان قرار دارد. ترانسکت دوم از روستای علی آباد واقع در ۲۰ کیلومتری جنوب رفسنجان آغاز شده وتا دشت رفسنجان ادامه دارد. کانی های رسی

پالیگورسکایت، ایلایت ، کوارتز، کلرایت و اسمکتایت درکلیه خاک ها به وسیلهٔ دیفرکتوگرام های حاصل ازدستگاه پراش پرتو ایکس، تجزیه عنصری میکروسکوپ الکترونی روبشی و عبوری شناسائی شد. درترانسکت اول، ازسمت شرق (پدیمنت سنگی) به غرب (پدیمنت پوشیده وپلایا) ازمیزان فراوانی ونیز اندازه بلورهای پالیگورسکایت کاسته شد. میزان کانی اسمکتایت درموقعیت ژئومورفولوژیکی پدیمنت سنگی بسیاراندک بوده ولی درسایر پروفیل ها به وفور دیده می شود. درترانسکت دوم، به دلیل رطوبت بیشتر، شستشوی آهک رخ داده و نیز هوادیدگی وتغییر شکل پالیگورسکایت به اسمکتایت به راحتی انجام شده است . از سوی دیگر، وجود سازندهای مارنی غنی از اسمکتایت باعث گردیده که میزان این کانی درترانسکت دوم نسبت به ترانسکت اول فراوان ترباشد.

INTRODUCTION

Elprince *et al.* (8), Monger and Daugherty (23), Pletsch *et al.* (26), and Stahr *et al.* (33) reported palygorskite as an important clay mineral in arid and semiarid soils and sediments. Palygorskite has been reported from Iranian soils by Mahjoory (22), Abtahi (1, 2), Gharaee and Mahjoory (10) and Givi and Abtahi (11) in southern Iran. Haghnia (14) reported palygorskite from the north eastern soils of Iran and Toomanian (34) and Khademi and Mermut (18, 19) observed this mineral in soils of Isfahan in central Iran. Soil mineralogists have discussed different origins for this silicate clay in soils and sediments of arid regions. Lee *et al.* (21), Shadfan and Mashhadi (28), and Badraoui *et al.* (3) believed in inherited source for palygorskite. In contrast, Eswaran and Barzanji (9), Singer and Nourrish (30), Elprince *et al.* (8), Singer (29), Monger and Daugherty (23), and Botha and Hughes (5) claimed the authigenic formation of palygorskite in the soils they studied.

Palygorskite was first reported in Iran by Henderson and Robertson (16) and Burnett *et al.* (7), but they did not discuss the source of palygorskite in their studies. Nevertheless, Mahjoory (22), Abtahi (2), Gharaee and Mahjoory (10), and Givi and Abtahi (11) have shown evidences for the authigenic formation of palygorskite in southern Iran. Haghnia (14) reported a neoformation source for palygorskite in Mashhad. Both inherited and pedogenic sources of palygorskite were mentioned by Toomanian (34) in Isfahan Aridisols. The occurrence and genesis of palygorskite in Isfahan were also studied by Khademi and Mermut (18) who explained two sources of palygorskite in central Iran:

> " ... (i) Inheritance from parent material; and (ii) pedogenic formation. Inherited palygorskite is either passed on from the parent rock to the soil or added to the soil by palygorskite-rich aeolian dusts or alluvial materials (detrital origin). Pedogenic palygorskite can be the result of either *in situ* transformation of another mineral or authigenic formation from solution."

There were three ideal conditions for palygorskite formation in soils, and sediments of central Iran as discussed by Khademi and Mermut (18):

i) Increase in Mg/Ca ratio due to gypsum crystallization in the shallow water bodies.

ii) Increasing environmental pH due to warm climate.

iii) Increased soluble Si due to enriched hydrothermal solutions.

Geological formations of Rafsanjan area are completely different from those of central and southern Iran because igneous and methamorphic formations have led to special complexity in the area. The present study was performed to:

i) Investigate the clay mineralogy of Rafsanjan soils with special attention to the genesis and distribution of palygorskite.

ii) Study mineral types and crystal morphology relationships with different geomorphic surfaces.

MATERIALS AND METHODS

Field Studies

The study area extends from Ali-Abad 20 km south to Nough 30 km north of Rafsanjan (Fig. 1). Two perpendicular transects were selected to study the variation of soils, clay minerals, and geomorphic surfaces. The first east-west transect is located between Davaran mountains (E), which separate the Nough area from Zarand valley and Badbakhtkooh mountains (W), which separate Koshkooyeh-Anar valley from Nough. Seven pedons were studied and described in this transect using Soil Conservation Service (31) guideline(Fig. 2). The second north-south transect (Ali-Abad) starts from 20 km south of Rafsanjan and extends to Rafsanjan valley (Fig. 3). Six pedons were investigated in this transect. It is to be noted that a vast area of sand dunes and sand arcs is located between these two transects which is out of the scope of the present research. The mean annual precipitation varies from about 100 mm in Rafsanjan to about 60 mm in Nough area.

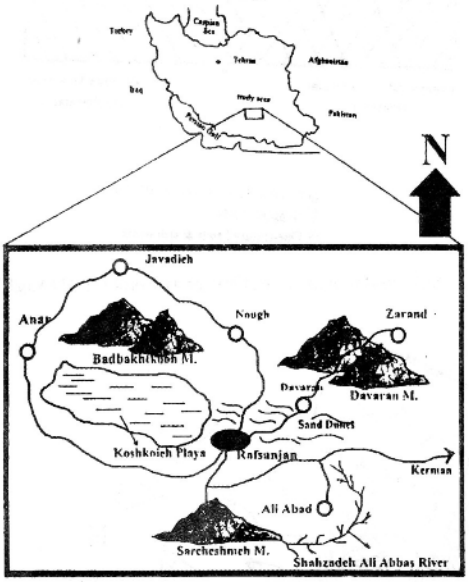


Fig. 1. Location of the study area in central Iran.

This area is part of the central Iran geologic zone as a NW-SE depression. Badbakhtkooh block includes upper Cretaceous flysch and Eocene volcanoes. In contrast, Davaran Mountains consist of middle Comberian to Jurasic dolomite, sandstone, calcareous shales and siltstone, and lower Cretaceous conglomerate (24). Calcareous and gypsiferous Neogene formations are found in south and north east of Rafsanjan. Fine and coarse grain gypsiferous Pliocene conglomerate formations are found south of the study area (Ali-Abad transect). In addition, Marl exposure is observed beneath the Pliocene conglomerates.

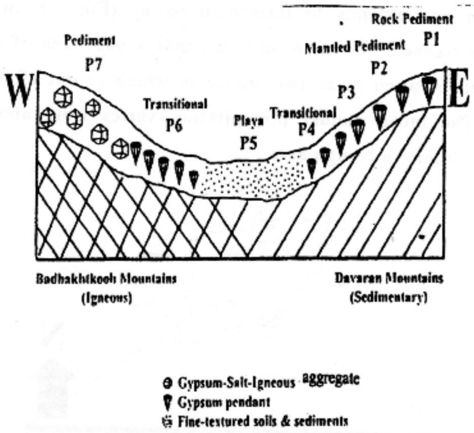


Fig. 2. Schematic cross section of transect 1 (Nough).

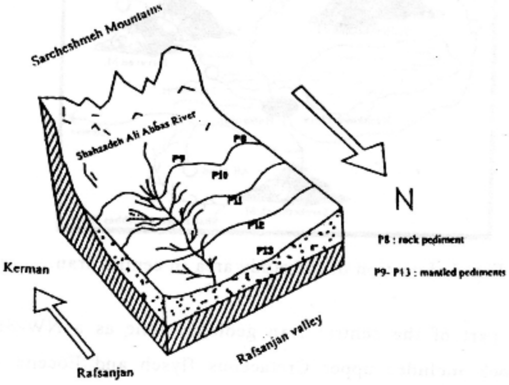


Fig. 3. Schematic figure of transect 2 (Ali-Abad).

Laboratory Studies

Air-dried soil samples were crushed and passed through a 2-mm sieve. For mineralogical study, selected samples were first repeatedly washed to remove gypsum and soluble salts. Carbonates and Fe-oxides were then removed by 1 M sodium acetate buffer solution (pH 5) and dithionate citrate bicarbonate (DCB), respectively (17). The clay fraction of the samples was separated by centrifuge as described by Jackson (17). Fourty mg of clay was weighed and saturated with Mg and K, separately. Vortex and ultrasound were used to make the suspensions homogenous. Homogenous saturated suspensions were transferred on uniform slides to ensure similar thickness for semi-quantitative analysis. Five treatments were done on each sample: Mg-saturated, Mg-saturated and ethylene glycole, K-saturated, K-saturated and heated at 350 °C, and K-saturated and heated at 550 °C. Slides were analyzed using a Shimadzu X-Ray diffractometer with Cu Kα radiation operated at 40 kV and 40 mA.

Several clay samples and selected calcite and gypsum crystals were mounted on Al stubs and coated with gold for energy dispersive X-ray spectrometry (EDX) 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 TECNAI, F20, Philips transmission electron microscope at an accelerating voltage of 60 kV.

Particle size distribution analysis was performed by the pipette method. Calcium carbonate equivalent content was determined by back titration and semiquantitative determination of gypsum was carried out using oven-dry method (25).

RESULTS AND DISCUSSIONS

Since different results were obtained from the first and the second transects, results and discussions for each transect will be presented in details separately (Fig. 1).

Transect 1

Different landforms were identified on the first transect (Fig. 2). Pediment with rock outcrops (rock pediment), on the east side next to Davaran mountains, geologically consists of calcareous-gypsiferous Neogene formations with gypsum fragments on the surface and fully developed gypsum pendants within the soil (pedon 1). Soils occurring on this landform have low electrical conductivity (less than 9.2 dS m^{-1}) and high gypsum content (up to 78.6 %) (Table 1). They are classified as Typic Haplogypsids (32). Table 2 shows morphology and classification of the soils studied. Down to the west, mantled pediment surface which is covered by alluvium, includes the second and third representative pedons with gypsum pendants of smaller size. Because of similar physico-chemical properties and taxonomic classification of these two soils with the first pedon, their properties are not included in Tables 1 and 2. The fourth soil profile, classified as Typic Petrogypsids, is covered by aeolian sand particles at the surface and is a transition between pediment and playa surfaces. The lowest part of this transect (pedon 5) is the place where fine and saline playa sediments have been deposited. Puffy ground is observed at the surface of this landform due to salt crystallization. High EC values (306.2 dS m^{-1}) show the magnitude of salt accumulation in this soil which has the criteria of Typic Haplosalids. Finally, pedon 7 which is located on the pediment surface lies on Eocene volcano (Petrogypsic Haplosalids). As Table 1 shows, EC values for pedons 6 and 7 are much higher than those for soils on east slopes (pedons 1, 2, 3, and 4).

Palygorskite, illite, smectite, chlorite, and quartz were found in all soils studied, but the presence of kaolinite was not proven (Figs. 4 and 5). Iron rich chlorite minerals give relatively weak first and third order reflections and strong second and fourth order reflections (6, 13). In such a condition, the presence of 7.2 A° peak is not enough to differentiate kaolinite from chlorite. Since the 2.38 A° peak was absent, there seems to be no kaolinite in soil samples and the 7.2 A° peak is probably due to iron rich chlorite. Besides, no hexagonal crystal of kaolinite was found using TEM studies.

Table 1. Physical and chemical properties of selected pedons.

	Depth	pH	EC	C.C.E†.	Gypsum	Particle Size Distribution		
						Sand	Silt	Clay
Horizon	cm	Paste	dS m^{-1}	%			%	
Pedon 1 (Typic Haplogypsids)								
A	0-150	7.1	2.4	47.0	7.9	57	20	23
By1	15-450	7.3	2.4	9.5	78.6	60	20	20
By2	45-800	7.5	2.6	30.8	43.8	61	16	23
By3	80-105	7.5	6.6	35.2	28.6	65	19	16
C	> 105	7.5	9.2	54.0	11.6	68	14	18
Pedon 4 (Typic Petrogypsids)								
A	0-150	7.7	2.7	19.0	13.9	43	25	32
Bym	15-350	7.8	3.3	9.0	74.2	45	24	31
2By1	35-600	7.8	3.5	21.5	36.1	44	26	30
2By2	60-750	7.9	3.8	17.2	52.7	50	24	26
3Bym	75-900	7.9	3.9	24.5	33.1	45	30	25
4By3	90-150	7.9	4.4	28.8	7.6	38	34	28
Pedon 5 (Typic Haplosalids)								
A	0-200	7.1	306.2	51.0	11.3	17	38	45
Bz1	20-500	7.6	126.1	49.5	12.6	17	37	46
Bz2	50-700	7.8	52.5	43.5	13.2	15	40	45
Bz3	70-100	8.1	4.3	51.5	10.3	15	41	44
C	>100	8.3	8.8	72.0	7.1	40	33	27
Pedon 6 (Gypsic Haplosalids)								
A1	0-500	7.6	162.1	40.5	4.2	26	35	39
Az	5-150	7.8	170.3	38.0	7.2	29	37	34
Bzm	15-300	7.2	486.2	42.0	9.4	30	30	40
Byz	30-500	8.0	99.7	31.5	31.8	22	40	38
Btz1	50-950	8.1	93.3	30.0	13.5	19	33	48
Btz2	95-135	8.2	78.2	25.0	8.8	21	30	49
Pedon 7 (Petrogypsic Haplosalids)								
Az	0-500	7.4	48.8	23.5	17.4	30	40	30
Byzm	5-250	7.0	182.1	15.0	41.1	40	35	25
Pedon 8 (Typic Haplogypsids)								
A	0-600	7.6	3.4	22.0	8.9	56	18	26
By1	6-400	7.6	2.0	19.5	21.1	68	11	21
By2	40-650	7.6	2.4	37.5	17.9	70	12	18
By3	65-900	7.6	2.4	89.0	11.8	62	18	20
By4	90-115	7.7	2.6	36.0	6.2	74	12	14
C	115-160	7.7	3.6	16.5	9.9	70	11	19
Pedon 12 (Typic Calcigypsids)								
A	0-100	8.0	2.1	18.5	7.8	53	20	27
Bk	10-350	8.0	1.5	18.0	11.8	57	18	25
By1	35-550	7.8	2.6	14.5	31.8	61	11	28
By2	55-750	8.0	4.6	12.5	21.7	63	17	20
By3	75-100	8.1	7.1	14	13.4	63	14	23
C	100-160	8.3	13.3	15.5	5.8	69	13	18

† C.C.E.: Calcium Carbonate Equivalent.

Table 2. Morphology and classification of selected pedons.

Horizon	Depth cm	Color (moist)	Structure†	Consistence (moist)	Boundary	Remacks
Pedon 1, Rock pediment (Typic Haplogypsids)+						
A	0-150	7.5YR 4/4	m2gr	lo	as	
By1	15-450	10YR 6/3	See remarks	fr	ds	Pure columnar gypsum clods
By2	45-800	7.5YR 4/4	m2sbk	fr	ds	
By3	80-105	7.5YR 5/4	m2sbk	efi	ds	
C	> 105	.5YR 5/4	m	lo		
Pedon 4, Transition of Pediment and playa (Typic Petrogypsids)$^{+}$						
A	0-150	5YR 4/3	sg	lo	as	
Bym	15-350	5YR 4/6	m	fi	as	
2By1	35-600	7.5YR 4/4	m1abk	fr	gs	
2By2	60-750	7.5YR 5/4	m1abk	fr	as	
3Bym	75-900	7.5YR 4/4	m	efi	as	
4By3	90-150	7.5YR 4/4	m1abk	fr		
Pedon 5, Playa (Gypsic Haplosalids)$^{+}$						
A	0-200	7.5YR 6/3	m1abk	fi	as	Puffy ground on the surface
Bz1	20-500	7.5YR 6/3	m	efi	ds	
Bz2	50-700	7.5YR 5/4	m	fi	ds	
Bz3	70-100	10YR 5/4	m	efi	as	
C	>100	2.5YR 8/2	m	efi		
Pedon 6, Transition of Pediment and playa (Gypsic Haplosalids)$^{+}$						
A1	0-500	7.5YR 4/4	m2p1	fr	as	A wind deposited horizon
Az	5-150	7.5YR 4/6	m2abk	fr	as	
Bzm	15-300	7.5YR 3/3	m	fr	as	
Byz	30-500	7.5YR 4/4	mlsbk	fi	as	
Btz1	50-950	7.5YR 4.5/4	m2abk	fr	as	
Btz	95-135	7.5YR 5/4	m2abk	fr	as	
Pedon 7, Rock Pediment on Eocene Volcanic (Petrogypsic Haplosalids)$^{+}$						
Az	0-500	5YR 4/3	sg	fr	ci	
Byzm	5-250	7.5YR 5/1	m	fi	ci	
R	>250					
Pedon 8, Rock Pediment (Typic Haplogypsids)$^{++}$						
A	0-600	7.5YR 5/3	sg	lo	as	
By1	6-400	7.5YR 4/1	mlsbk	fr	gs	
By2	40-650	5YR 3/1	mlsbk	fr	cs	
By3	65-900	7.5 YR 3/2	sg	lo	as	
By4	90-115	5YR 3/2	sg	lo	as	
C	115-160	5YR 3/2	sg	lo		
Pedon 12, Mantled Pediment (Typic Calcigypsids)$^{++}$						
A	0-10	5YR3/3	mlgr	fr	as	
Bk	10-35	7.5 YR 5/3	m2sbk	vfr	as	
By1	35-55	10YR3/3	M2sbk	vfr	gs	
By2	55-75	10YR3/2	sg	vfr	gs	
By3	75-100	5YR 2.5/1	sg	fi	as	
C	100-160	5YR 3/1	sg	lo		

† Symbols used according to abbreviation given in Schoeneberger *et al.* (31).

+ and ++ refer to 1st and 2nd transects, respectively.

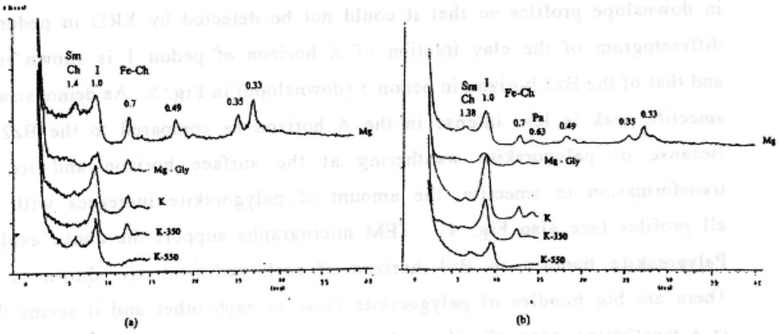


Fig. 4. X-Ray diffractograms of the clay fraction of pedon 1 (rock pediment). (a) A horizon, (b) C horizon. Mg=Mg-saturated, air dried; Mg-Gly=Mg saturated, Ethylene glycol; K=K-saturated, air dried; K-350=K-saturated, heated to 350°C; K-550=K-saturated, heated to 550°C

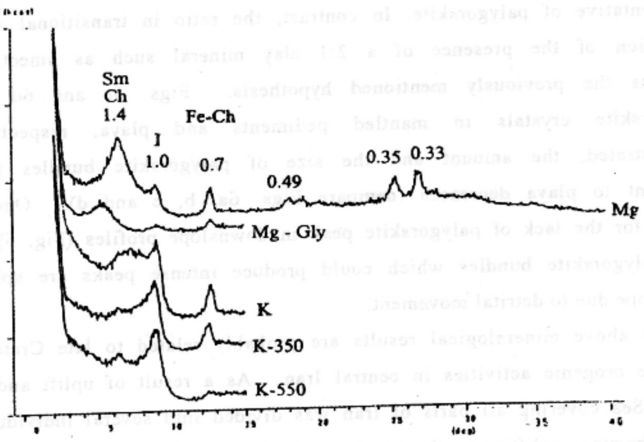


Fig. 5. X-Ray diffractograms of the clay fraction in Bz2 horizon, profile 5 (playa).

There was less smectite present in all horizons of profile 1 than any other positions in the first transect. In contrast, palygorskite peak intensity decreases in downslope profiles so that it could not be detected by XRD in pedon 5. The diffractogram of the clay fraction of A horizon of pedon 1 is shown in Fig. 4a and that of the Bz2 horizon in pedon 5 (downslope) in Fig. 5. As demonstrated, smectite peak is less intense in the A horizon as compared to the Bz2 horizon. Because of palygorskite weathering at the surface horizon and its probable transformation to smectite, the amount of palygorskite increases with depth in all profiles (see also Fig. 4). TEM micrographs support the above explanations. Palygorskite bundles in By1 horizon of rock pediment are shown in Fig. 6a. There are big bundles of palygorskite close to each other and it seems that there is a weathering zone of palygorskite to another clay mineral (probably smectite) in this horizon. With increasing depth, relative proportion of palygorskite increases (Fig. 6b), but bundles are split and many of them seem to have been transformed to smectite. Fig. 7a shows the elemental analysis of pure palygorskite bundles in the A horizon while Fig. 7b shows the elemental analyses of the transitional zone. As demonstrated, the Mg/Al ratio in Fig 7a is representative of palygorskite. In contrast, the ratio in transitional zone is an indication of the presence of a 2:1 clay mineral such as smectite, which supports the previously mentioned hypothesis. Figs. 6c and 6d show the palygorskite crystals in mantled pediments and playa, respectively. As demonstrated, the amount and the size of palygorskite bundles from rock pediment to playa decreases (compare Figs. 6a, b, c and d). One possible reason for the lack of palygorskite peak in downslope profiles (Fig. 5) could be that palygorskite bundles which could produce intense peaks are split toward downslope due to detrital movement.

The above mineralogical results are probably related to late Cretaceous to Miocene orogenic activities in central Iran. As a result of uplift and folding, Tethys Sea covering all parts of Iran was divided into several individual lakes. With frequent upliftings, the number of these small water bodies increased. Gavkhooni, Sirjan, Abarkooh, Koshkooyeh, and Nough playas are examples of such lakes (20). The alteration of Badbakhtkooh block due to carbonate rich hydrothermal solutions in late Tertiary and subsequent weathering has led to release of elements essential for the evaporite mineral formations in Nough area (24). Because of a warm and arid climate of Tertiary, evaporation of closed lakes has caused crystallization of evaporite minerals especially gypsum at the lake peripheries. These areas are the rock pediment geomorphic surfaces of the present time. As a result of gypsum crystallization, Mg/Ca ratio increased in the host water which could, in turn, encourage palygorskite

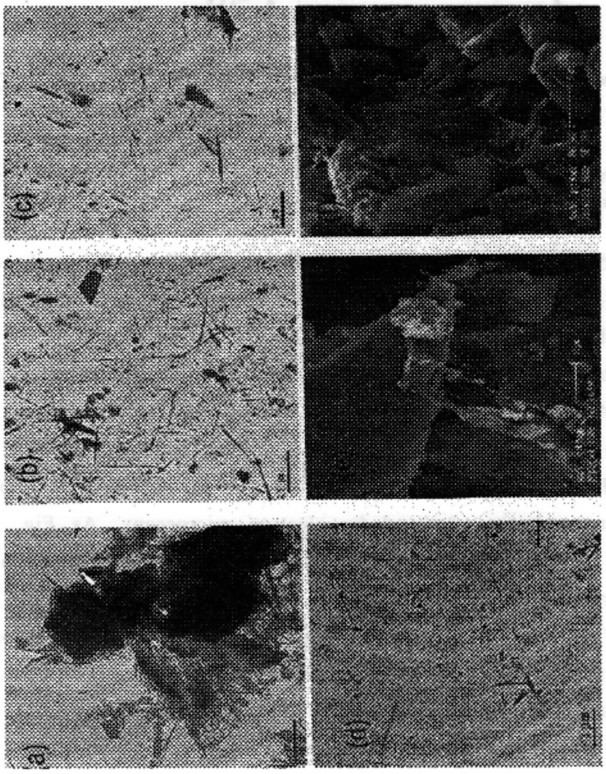


Fig. 6. Electron micrographs showing the distribution of palygorskite on different geomorphic positions. (a) and (b) TEM micrographs of By1 and By3 horizons from rock pediment, (c) and (d) TEM micrographs of By1 and Bz2 horizons from mantled pediment and playa, respectively (e) and (f) SEM micrographs showing palygorskite around gypsum and calcite crystals (By2 and Bk horizons of mantled pediment), respectively.

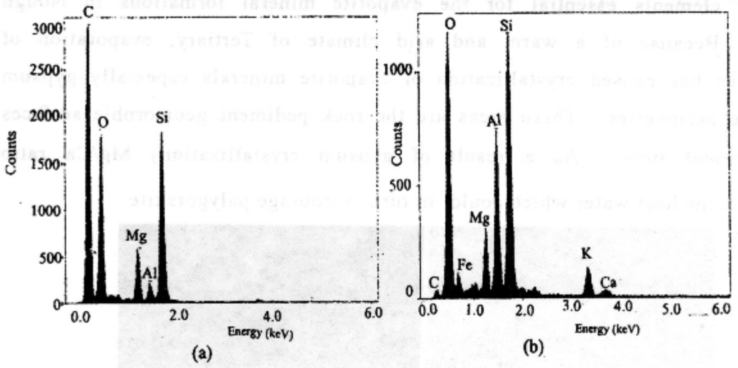


Fig. 7. Elemental analysis (TEM/EDX.EMI) of (a): pure palygorskite and (b): transitional zone.

formation (15). An increase in pH due to gypsum formation at the expense of carbonate dissolution also occurred (18). Silica rich hydrothermal solutions together with an increase in pH and Mg/Ca ratio have provided necessary conditions for palygorskite formation in the rock pediment surfaces (authigenic formation). After palygorskite formation, Mg/Ca ratio has decreased leading to the presence of less smectite in this geomorphic position. Toward downslope positions palygorskite quantity decreases so that its detection is impossible by XRD and can only be observed by electron microscopy. As Fig. 6e shows, palygorskite crystals are observed around gypsum crystals in gypsic horizons on pediment surfaces (profiles 2, 3, and 4). Such an association could be due to repetition of dissolution and crystalization of gypsum and its accompaniment with palygorskite crystals all through the slope (detrital origin) (18). Another plausible reason is palygorskite engulfing around gypsum crystals (pedogenic formation) as also observed by Eswaran and Barzangi (9).

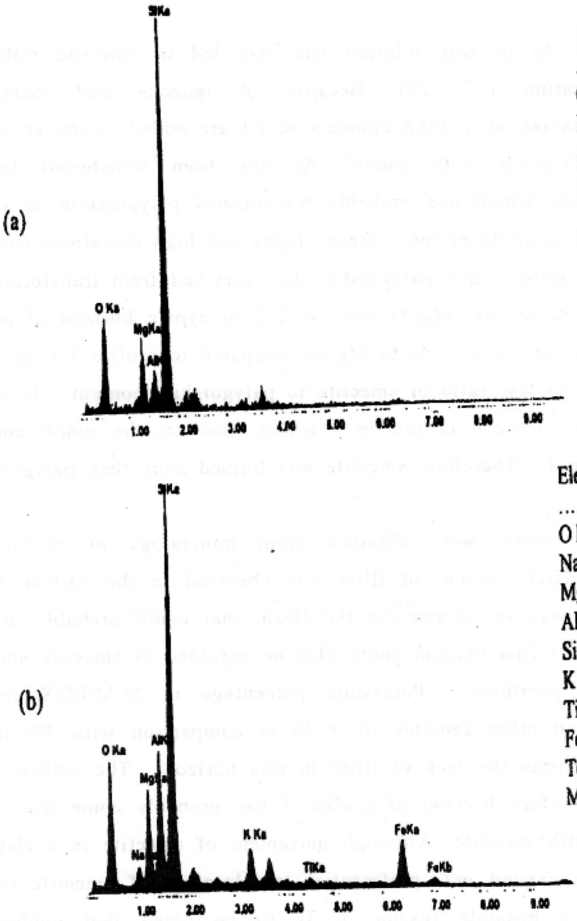
Smectite was observed in all profiles except in the rock pediment surface (profile 1). Some possible explanations for the above results are as follows:

(i) Palygorskite has been transformed to smectite because of more humidity in downslope positions (3, 12, 27).

(ii) Mg/Ca ratio has decreased due to continuing evaporation of the closed basin in Nough area. Since evaporation causes lowering of the lake water, smectite has formed at lower geomorphic surfaces instead of palygorskite. Khademi and Mermut (18) arrived at similar conclusion in the Isfahan region. Besides, high ground water at some periods of the year and poor drainage in pedons 5 and 6 might have promoted the formation of smectite from soil solution in downslope (4)

(iii) High soluble Al in soil solution has also led to smectite rather than palygorskite formation (27, 29). Because of igneous and metamorphic formations in Rafsanjan area, high amounts of Al are added to the environment by weathering. Together with runoff, Al has been transferred to lower geomorphic positions which has probably transformed palygorskite to smectite. However, profile 1 is an exception. Steep slopes and high elevations have much lower water penetration, thus palygorskite has survived from transformation to smectite. As Fig. 8a shows, Mg/Al ratio is 2:2 in gypsic horizon of profile 1 which represents lower ratio of Al to Mg as compared to profile 5 (Fig. 8b). It consequently leads to less ratio of smectite to palygorskite content. In contrast, Mg/Al ratio in Bz2 horizon of profile 5 which receieves the runoff consisting high Al is equal to 1. Therefore, smectite was formed more than palygorskite in this position.

Interesting results were obtained from mineralogy of profile 7 on Eocene volcanics. High amount of illite was observed in the surface horizon, but smectite peak was so intense for the Byzm that could probably mask the illite peak (Fig. 9). This horizon could also be regarded as smectite source for lower geomorphic positions. Potassium percentage in SEM/EDX in Byzm horizon is less than other samples (0.38 % in comparison with 1% in other samples). This confirms the lack of illite in this horizon. The authors believe that illite in the surface horizon of profile 7 has probably come from aeolian sources together with smectite. Although movement of smectite in a Haplosalid soil is not simply carried out, preferential translocation of smectite to lower horizons can be a possible reason. It is to be noted that evidences of discontinuity were not observed in the field. It should also be mentioned that the occurrence of hard aggregates consisting of gypsum, salt, and weathered fragments of Eocene volcanic rocks in Byzm horizon is another reason for the wind action, since salt accumulation in this soil could neither have come from weathering of volcanic rocks, nor from high water table.



Element	Atomic %
O k	64.786
Mg k	6.686
Al k	3.058
Si k	25.469
Total	100.000
Mg/Al	2.2

Element	Atomic %
O k	60.993
Na k	2.634
Mg k	7.303
Al k	7.331
Si k	17.525
K k	1.384
Ti k	0.220
Fe k	2.609
Total	100.000
Mg/Al	0.99

Fig. 8. Elemental analysis (SEM/EDX) of the clay fraction in (a): Byzm horizon of profile 1. (b): Bz2 horizon of profile 5.

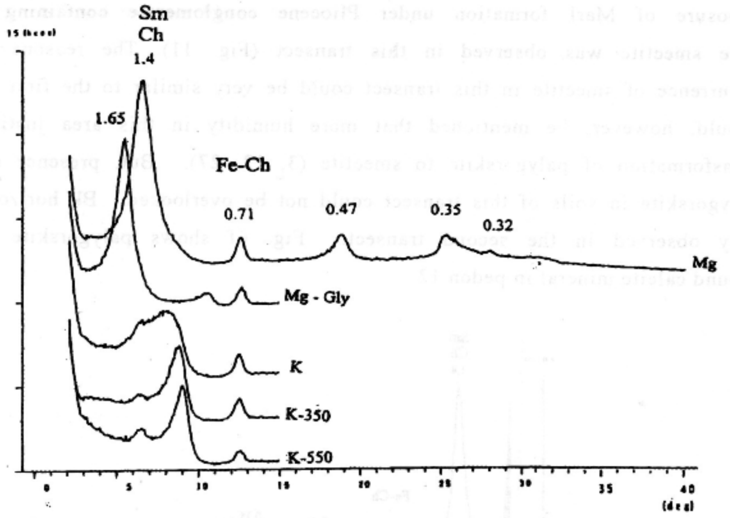


Fig. 9. X-Ray diffractograms of the clay fraction in Byzm horizon, profile 7.

Transect 2

As Fig. 3 shows, the second transect starts from 20 km south of Rafsanjan and extends to Rafsanjan valley. This transect is located at the end of Bardsir-Baghin-Rafsanjan basin. Mean annual precipitation in this area is more than the Nough region (100 mm as compared to 60 mm). In addition, this transect receives some runoff water from Sarcheshmeh mountains. Thus, Bk horizons are usually observed in soils on this transect. This area starts from profile 8 in southern part on gypsiferous Pliocene conglomerates (Table 1) and extends to profile 13 on Rafsanjan valley floor to the north (Fluvents). Shahzadeh Ali-Abbas river and surface runoff from Sarcheshmeh mountains have dissected the area, creating a rolling topography on Pliocene conglomerate formations. Overall, the relief of the area decreases toward the center of Rafsanjan valley to the north.

Palygorskite, smectite, chlorite, and quartz were identified in the second transect. Formation of minerals in this transect seems to be very similar to the first transect, but smectite peaks are usually more intense (Fig. 10). This may be due to the fact that smectite is inherited from Marl formations (3). An exposure of Marl formation under Pliocene conglomerate containing almost pure smectite was observed in this transect (Fig. 11). The reasons for the occurrence of smectite in this transect could be very similar to the first one. It should, however, be mentioned that more humidity in this area justifies the transformation of palygorskite to smectite (3, 12, 27). But, presence of some palygorskite in soils of this transect could not be overlooked. Bk horizons were only observed in the second transect. Fig. 6f shows palygorskite crystals around calcite mineral in pedon 12.

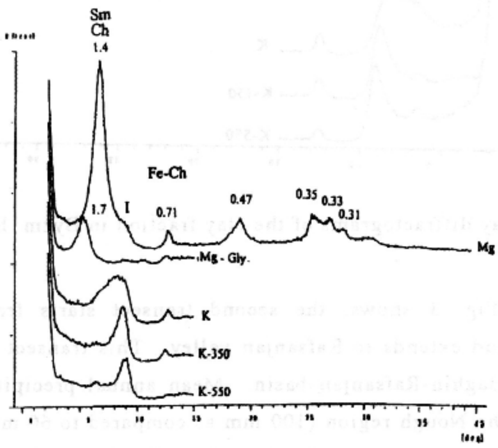


Fig. 10. X-Ray diffractograms of the clay fraction in By2 horizon, profile 10.

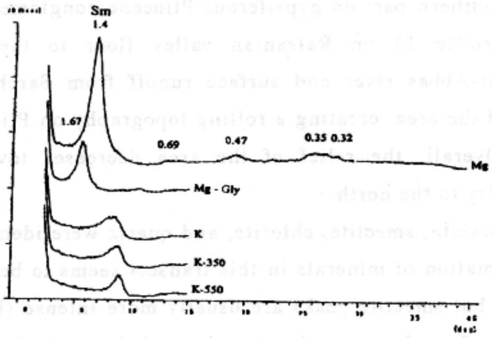


Fig. 11. X-Ray diffractograms of the clay fraction in Marl formation.

CONCLUSIONS

Palygorskite, smectite, chlorite, illite, and quartz are dominant clay minerals in Rafsanjan soils. An increase in Mg/Ca ratio at the time of gypsum formation, high pH, and high soluble Si has made palygorskite formation possible at the peripheries of interior lakes during Neogene. Since that time, palygorskite bundles have been preserved due to aridity, and detrital movement has taken these crystals to lower geomorphic positions. In lower positions, however, palygorskite has transformed to smectite as a result of less aridity and more water supplied by runoff.

Close relationship between palygorskite morphology and geomorphic positions were observed. Upper geomorphic surfaces (rock pediments) included crystals greater in size and number. Conversely, the crystals were so small and few in lower positions that could only be observed by electron microscopy.

Palygorskite of both pedogenic (in upper surfaces) and inherited (in mantled pediments and playas) origins are present in the soils studied. This fibrous clay mineral has been transformed to smectite especially in mantled pediments and playas which receive more water from runoff. More smectite was observed in the second transect (Ali-Abad) than the first one (Nough), which may have originated from either transformation of palygorskite to smectite or inheritance from marly formations in the area.

ACKNOWLEDGEMENTS

We would like to express our thanks to the College of Agriculture, Isfahan University of Technology for the financial support of this study. We also thank Prof. H. Roy Krouse, University of Calgary, Canada for his invaluable help and partial financial support of SEM and TEM analyses performed in this study.

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