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# GENESIS AND MORPHOLOGICAL CHARACTERISTICS OF MOLLISOLS FORMED IN A CATENA UNDER WATER TABLE INFLUENCE IN SOUTHERN IRAN

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## ABSTRACT

A Mollisol catena in highly calcareous parent material under semi-arid conditions of southern Iran was studied to determine the effects of water table depth and its fluctuations on the organic carbon content of mollic epipedons, genesis of subsurface horizons, and mineralogical variations in these horizons. The soils formed on depressions (microlows), have the shallowest water table (about 1m in July and 25 cm in January), the longest time of saturation, greatest organic carbon content, and have 50 cm thick mollic epipedons. Grayish brown matrices (10YR 5/2) and yellowish brown (10YR 5/6) mottles are also apparent in B horizons. Subsurface horizons have characteristics of cambic horizon. No calcic horizon have formed in these soils, mainly due to the lack of wetting and drying cycles due to the permanent saturation. The soils with a water table depth of deeper than 1 m, have cyclic saturated conditions. Organic matter content and thickness of mollic epipedons of these soils are less than that of the soils on microlows. They show developed calcic horizons. Secondary carbonates present in B horizons of these soils are related mainly to discharge from a shallow water table, which have precipitated as secondary carbonates in the sola due to evapotranspiration and precipitation from upper horizons. The soils formed on the higher landscape positions with very deep water tables (deeper than 2m in winters) show lower amounts of organic carbon and very thin mollic epipedon. They are not saturated and do not show redoximorphic features. Only a cambic horizon has formed in these soils, as a result of organic matter addition and transformation, and translocation of $CaCO_3$. Mineralogical study of the B horizons of these three studied soils, showed that there is a little difference in type of clay minerals between different members of the hydrosequence, but the relative amount of clay minerals are different due to weathering conditions, which are affected by internal drainage. The major mineral in the well drained soils (Barab series) is palygorskite, while in poorly drained soils (Pole Bahadoran series), smectite is dominant. In very poorly drained soils of the depressions (Dehnow series), almost permanent saturation has inhibited weathering processes of minerals. In these soils chlorite and illite are the dominant minerals. A new category for Soil Taxonomy, Fluvaquentic Calciaquolls, is proposed to accommodate Calciaquolls which have fluventic origin (Pole Bahadoran soil series).

*Key Words*: Profile development; Soil catena; Calcareous soils; Mollisols; Groundwater; Calcic horizon; Landscape; Palygorskite; Smectite.

## INTRODUCTION

The effect of internal drainage and water table depth on soil morphology, genesis and weathering of clay minerals have been studied by many researchers. Khan and Fenton (1) showed that the presence of secondary carbonates in the soil of a Mollisol catena, is mainly related to groundwater discharge from a shallow water table. This shallow water table contributed to higher concentrations of soluble calcium bicarbonate which precipitate as secondary carbonates in the sola in lower landscape positions due to evapotranspiration and desiccation. Similar results were reported by Knuteson et al. (2) in the study of Calciaquolls. They concluded that dissolved carbonates were moved upward during periods of drying and freezing and precipitated in the solum of a Bearden soil (Fine-silty, frigid, Aeric Calciaquolls) in North Dakota.

Soil color, mottling, organic matter, and reduction-oxidation patterns are the other soil features commonly affected by seasonal fluctuations of ground water table. Numerous workers (3,4,5,6,7,8,9,10,11,12,13) have investigated morphological features, organic matter accumulation and other soil properties in relation to water tables. They attributed the presence of gray mottles to fluctuating water tables. Zobeck and Ritchie (14) observed in well drained and moderately well drained soils, low chroma mottles at depths slightly below the highest water table levels, while in poorly drained soils, low chroma mottles were observed above the highest water table level. The significance of soil mottling can be derived from an analysis of morphological features formed by a process of reduction and oxidation of iron and manganese compounds. Reduction and associated mobilization of Fe and Mn compounds in the soil are caused by anaerobic metabolic microbial action which can occur in non-aerated saturated soil (11).

The relative abundance and distribution of clay minerals also have a close relationship with internal drainage. Hargaritt and Liversey (15), reported more smectite in poorly drained than in associated, better drained soils. However, Naidu et al. (16), found that chlorite dominates the clay fraction of some imperfectly drained soils. In general, soils at upper slope members with very deep water table are chloritic and illitic, while those of lower slopes with poor drainage condition are mainly montmorillonitic.

Occurrence of palygorskite has been reported as a clay component of soils in dry regions. According to Abtahi (17,18), the presence of palygorskite in soils of Iran could be due to pedogenetic processes. He thought that smectite might be the precursor mineral of palygorskite in Iran.

Objectives of this investigation were: to study of the effect of water table depth on: (i) mollic epipedon characteristics, (ii) genesis of the subsurface horizons, mainly formation of calcic horizon, and (iii) mineralogy of subsurface horizons.

## MATERIALS AND METHODS

The Mollisol catena are composed of the following soils: Barab series (Fine-loamy, carbonatic, hyperthermic, Torrifluventic Haplustolls), Pole Bahadoran series (Fine-loamy, carbonatic, hyperthermic, Typic Calciaquolls), and Dehnow series (Fine, carbonatic, hyperthermic, Fluvaquentic Endoaquolls). Their natural drainage varies from well drained to very poorly drained soils.

The study area is located on the Darab plain of southern Iran (Figs.1 and 2), and is used for both agricultural and non-agricultural purposes. Seasonal fluctuations of water table play an important role in the genesis of these soils as well as their present and potential use. In the microlow area (Dehnow soil) groundwater fluctuates between 25cm in January and 1m in July, while in microhigh soils (Pole Bahadoran) the groundwater is deeper than one meter.

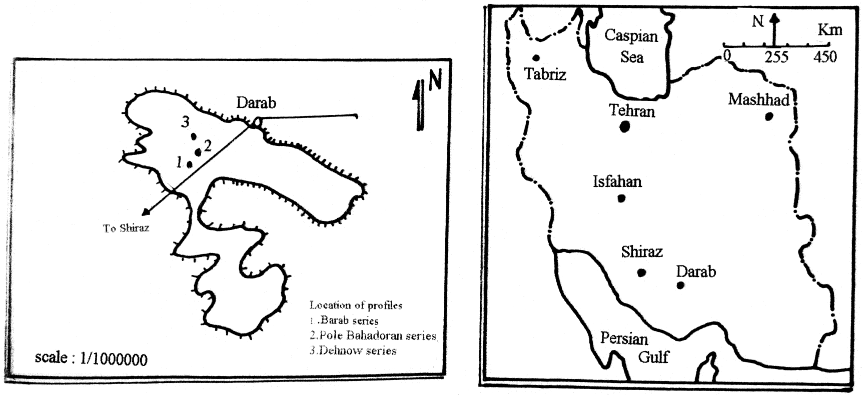

*Figure 1.* Location map of the studied area.

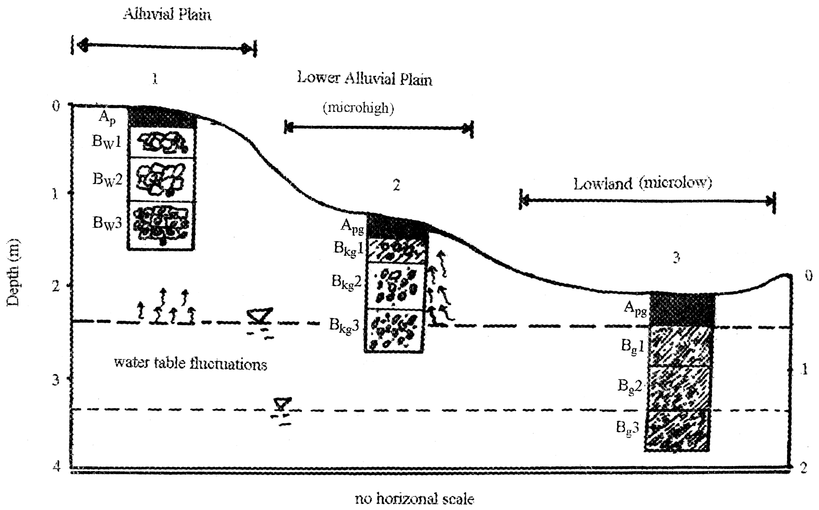

*Figure 2.* Cross section of the studied catena. 1. Barab series, Torrifluventic Haplustolls; 2. Pole Bahadoran series, Typic Calciaquolls; 3. Dehnow series, Fluvaquentic Endoaquolls.

The climate is moderate warm desertic with an average annual rainfall of 257 mm. The soil moisture regime of the area is ustic according to the "Soil Moisture and Temperature Regime Map of Iran" (19). The parent material of the soils is mostly alluvium and is highly calcareous being derived from the surrounding limestone mountains.

Selection of the pedon sites was based on previous studies (20). The selected sites were from different physiographic positions with different soils of the studied catena. Soils were described and classified according to The Soil Survey Manual (21) and Keys to Soil Taxonomy (22), respectively. Soil samples of different horizons were taken for laboratory analysis.

## Physico-Chemical Methods

Particle-size distribution was determined after the dissolution of $CaCO_3$ with 2 *N* HCl, and decomposition of organic matter with 30% $H_2O_2$. After repeated washing for removal of salts, the soils were dispersed using sodium hexametaphosphate, and the sand, silt and clay fraction were separated by sedimentation and determined by the pipette method (23). Alkaline-earth carbonate (lime), was measured by acid neutralization (24).

Organic carbon was measured by wet oxidation with chromic acid and back titrated with ferrous ammonium sulfate (25). Gypsum ($CaSO_4 \cdot 2H_2O$) was determined by precipitation with acetone (24). Soil pH was measured using a saturation paste procedure, and also in groundwater by a Schott pH-meter, model CG 824 (24). Electrical conductivity (total soluble salts) was determined in the saturation paste extract (24). Cation exchange capacity (CEC) was determined using sodium acetate (NaOAc) at pH 8.2 for soil and clay fraction of the soils (26).

## Mineralogical Analysis

The removal of chemical cementing agents and separation of the clay fractions were done according to the methods of Kittrick and Hope (27) and Jackson (28), but with some modifications. The carbonates were initially removed using 1 *N* sodium acetate buffered at pH 4.2. The addition of 1 *N* sodium acetate was continued until no effervescence was observed with 1 *N* HCl (28).

The neutralization was performed in a water bath at 75–80°. The organic matter was then oxidized by treating the carbonate-free soils with 30% $H_2O_2$, and digestion in a water bath. This treatment also dissolved $MnO_2$ (28). Free iron oxides were removed from samples by the citrate dithionate method of Mehra and Jackson (29).

The iron-free samples were centrifuged at 750 rpm for 5.4 minute and the clay separates were removed and studied by X-ray diffraction using Ni filtered CuK $\propto$ radiation (40 kV and 40 mA), a range factor of 400 cps and a time constant of 1 s. X-ray diffractograms were obtained from Mg-saturated soil clays both before and after glycerol solvation. Potassium-saturated samples were also studied by X-ray diffraction after drying at room temperature and after heating at 550°C for 2 hours. Electron micrographs of citrate-dithionite treated clays were obtained with a Philips SM 300 electron microscope following the techniques of Bates (30).

## RESULTS AND DISCUSSION

### Morphology and Evolution of Mollic Epipedon

Organic matter content is the most important feature of a mollic epipedon. As shown in Tables 1 and 2, organic carbon content of different members of the hydrosequence is different mainly due to the effect of ground water table. Well drained soils of upper slopes (i.e., Barab series) are in an oxidized state and have the lowest content of organic carbon in comparison with those of the lower slopes. As the water table approaches to the soil surface, anaerobic conditions favorable to organic matter accumulation becomes more pronounced (Pole Bahadoran soils, Table 2). The shallow water table in the Dehnow soil (about 1m in July and 25 cm in January) has resulted in greater amounts of organic carbon throughout the whole profile. Also the thickness of the mollic epipedon, as affected by the water table, increases from the upland soils (Barab series) toward the lowland soils (Dehnow series) (Table 1).

The ground water table also affects the soil structure development through organic carbon accumulation. As shown in Table 1, the mollic epipedon of the microlow soils (Dehnow) shows a very strong granular structure which reflects the effect of the large amount of organic carbon resulting from the shallow ground water table. As the organic carbon content decreases, the structure of the soil particles weakens (Pole-Bahadoran). The weakest structure is in the Barab soils, which have the lowest organic carbon content (Table 1).

Soil color and redoximorphic features are also properties which are a result of the effect of ground water table. The mollic epipedon of the microlow soils show very dark gray colors (10 YR 5/1) and also common medium distinct yellowish brown (10 YR 5/6) mottles in the subsurface horizons (21). Evidence of gleying is shown in all horizons (Table 1). Toward microhigh (i.e., Pole Bahadoran soils) in which the water table depth is about 1.5 m (in July), the chroma increases, and a very dark grayish brown color is shown. Evidence of gleying and mottling are also present. However soils on the upper slopes (i.e., Barab) show no redoximorphic features, due to very deep water table and the chroma of the subsurface horizons are higher than those for lower topographic positions.

### Genesis of Subsurface Horizons

Formation of the subsurface horizons was studied in this catena. The Barab series which is formed in the higher landscape positions with a very deep water table was classified as Torrifluventic Haplustolls. These soils have a mollic epipedon and show evidence of a fluventic origin. Very few secondary calcium carbonates were observed in the subsurface horizons of the Barab soils and only a cambic horizon has formed. The observations presented by Pennock and Vereeken (31) allow the discussion of several pedological processes of which two of them were responsible for the formation of cambic horizon in these soils; addition of organic matter, and transformation and translocation of $CaCO_3$. The most probable cause for structure formation is the organic matter accumulation (Table 1).

Calcium carbonates occur as nodules and soft powdery pockets in subsurface horizons, which indicate their translocation during rainy seasons and reprecipitation during hot dry summers (17,18). These secondary calcium carbonates occur in amounts too small to meet the requirements of a calcic horizon. At lower elevations over lower alluvial plain (microhigh), with water table depth of about 1.5m, soils contain calcic horizons. These soils are classified as Typic Calciaquolls (Pole Bahadoran series) (Tables 1 and 2 ). According to Knuteson (32), conditions which favor the formation of these soils are (i) the capillary fringe from a water table approaching the root zone, (ii) evapotranspiration exceeds precipitation during the summer months, and (iii) bicarbonate and sulfate anions dominate the composition of shallow ground water and both anions promote preservation of calcium by calcite and gypsum formation.

Local surface relief (micro-relief) is also an important soil forming factor in this physiographic unit (32). Similar results were reported by Khan and Fenton (1). They relate the secondary carbonates present in the soils studied to discharge from a shallow water table. This shallow water table contributed to higher concentrations of soluble calcium bicarbonate that precipitated as secondary carbonates in the sola on lower landscape positions due to evapotransportation and desiccation.

Therefore, the main reasons for the presence of a well developed calcic horizon in Pole Bahadoran series are the occurrence of a shallow water table along with its high evapotranspiration, and the translocation of carbonates from upper horizons in rainy seasons and precipitation during hot dry summers. Since the climate of the studied area is hot desertic (annual rainfall of 257 mm), this latter effect may not be dominant in the study area. Table 2 shows the accumulation of calcium carbonates in Bkg1 horizon.

A fluventic origin of these soils is indicated by an organic carbon content of more than 0.2% at a depth of 125 cm; an irregular decrease of organic carbon with depth; and the presence of many snail shells through the profile. Presently, these soils are classified as Typic Calciaquolls. However, to accommodate these kinds of Calciaquolls which are fluventic in origin, a new subgroup of Fluvaquentic Calciaquolls is suggested for inclusion in the Soil Taxonomy (Table 2).

Soils formed in microlows (Dehnow series) with a water table approaching the soil surface (25 cm in January and 1m in July), have very strong blocky struc-

***Table 1.*** Morphology and Classification of the Soils Studied

| Horizon | Depth cm | Colour (Moist) | Structure* | Consistence* (Moist) | Boundary* | Other Components† |
|---|---|---|---|---|---|---|
| *Alluvial plain, Barab series (Torrifluventic Haplustolls)* | | | | | | |
| $A_p$ | 0–20 | 10YR 3/2 | f1abk±m1gr | fi | gs | Few to common fine roots |
| $B_w1$ | 20–501 | 10YR 4/2 | c1abk | fi | cs | Few fine roots |
| $B_w2$ | 50–85 | 10YR 4/4 | c2abk | fi | gs | - |
| $B_w3$ | 85–140 | 10YR 4/4 | c1abk | fi | - | - |
| *Lower alluvial plain (microhigh) Pole-Bahadoran series (Typic Calciaquolls)* | | | | | | |
| $A_{pg}$ | 0–23 | 10YR 3/2 | f1abk±m2gr | fr | cs | Few to common fine roots |
| $B_{kg}1$ | 23–65 | 10YR 5/2 | c1abk | fi | cs | Common fine irregular lime powdery pockets, few to common fine roots, common snail shells |
| $B_{kg}2$ | 65–100 | 10YR 4/2 | m1abk | fi | gs | Many fine irregular lime powdery pockets and concretions, common snail shells |
| $B_{kg}3$ | 100–140 | 10YR 4/2 | m1abk | fi | - | Few fine lime powdery pockets, few fine faint dark grayish brown (2.5YR 4/2) mottles, common snail shells |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | *Lowland (microlow) Dehnow series (Fluvaquentic Endoaquolls)* | | | | |
| $A_{pg}$ | 0–25 | 10YR 3/1 | m3gr | fi | gs | Many fine roots |
| $B_g1$ | 25–50 | 10YR 3/2 | m2abk±(gr) | fi | cs | Few fine faint mottles, many fine roots |
| $B_g2$ | 50–90 | 2.5YR 4/2 | m2abk | vfi | cs | Few fine faint mottles, few snail shells, common fine roots |
| $B_g3$ | 90–140 | 10YR 6/1 | m2abk | vfi | - | Common medium distinct yellowish brown (10YR 5/6) mottles, few fine lime powdery pockets, few fine roots |

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* Symbols used according to abbreviation given in Soils Survey Manual, USDA Handbook No.18, P.139–140, 195.

† All soils are calcareous throughout.

± Indicates primary structure that parts to secondary structure when ruptured.

***Table 2.*** Selected Physico-Chemical Properties of Three Pedons Studied

| | | Particle Size Distribution | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Depth | Sand | Silt | Clay | Textural | pH | *OC | #CCE | &SP | Gypsum | φCEC | □EC |
| Horizon | cm | | % | | Class | Paste | | | % | | cmol kg$^{-1}$ | dSm$^{-1}$ |
| | | | | | *Barab series* | | | | | | | |
| $A_p$ | 0–20 | 26.2 | 43.8 | 30.0 | cl | 7.7 | 2.6 | 37.1 | 54.0 | 0.2 | 19.0 | 0.7 |
| $B_w1$ | 20–50 | 34.2 | 31.6 | 34.2 | cl | 7.8 | 0.1 | 41.5 | 53.1 | 0.2 | 18.3 | 0.3 |
| $B_w2$ | 50–85 | 31.6 | 38.2 | 32.0 | cl | 7.8 | 0.5 | 48.2 | 48.3 | 0.1 | 15.7 | 0.3 |
| $B_w3$ | 85–140 | 29.2 | 40.0 | 30.8 | cl | 8.0 | 0.4 | 39.1 | 39.1 | 0.1 | 16.0 | 0.4 |
| | | | | | *Pole Bahadoran series* | | | | | | | |
| $A_{pg}$ | 0–23 | 24.6 | 45.7 | 29.7 | cl | 7.5 | 2.8 | 45.6 | 63.5 | 0.3 | 19.8 | 2.3 |
| $B_{kg}1$ | 23–65 | 36.6 | 37.7 | 25.7 | l | 7.8 | 1.0 | 58.1 | 57.5 | 0.2 | 14.7 | 2.4 |
| $B_{kg}2$ | 65–100 | 34.6 | 41.7 | 23.7 | l | 8.1 | 1.2 | 68.7 | 63.5 | 0.2 | 13.9 | 3.1 |
| $B_{kg}3$ | 100–140 | 30.6 | 42.7 | 26.7 | l | 7.8 | 0.9 | 62.5 | 59.8 | 0.2 | 15.0 | 3.2 |
| | | | | | *Dehnow series* | | | | | | | |
| $A_{pg}$ | 0–25 | 23.0 | 35.5 | 41.5 | c | 8.1 | 4.9 | 38.8 | 60.8 | 0.2 | 30.4 | 3.4 |
| $B_g1$ | 25–50 | 15.2 | 32.0 | 52.8 | c | 8.2 | 1.8 | 39.2 | 52.7 | 0.1 | 29.0 | 1.4 |
| $B_g2$ | 50–90 | 23.2 | 34.0 | 42.8 | c | 1.2 | 1.2 | 41.3 | 50.1 | 0.3 | 23.0 | 1.1 |
| $B_g3$ | 90–140 | 31.2 | 37.0 | 31.8 | cl | 0.8 | 0.8 | 41.5 | 41.5 | 0.2 | 16.8 | 0.7 |

tr=trace, *OC=Organic Carbon, #CCE=Calcium Carbonate Equivalent, &SP=Saturation Percentage, φCEC=Cation Exchange Capacity, □EC=Electrical Conductivity.

ture, mainly due to high amounts of organic carbon, and meet the requirements for a cambic horizon. Calcic horizons are not been seen in this pedon mainly due to the lack of wetting and drying cycles. The nearly permanent saturated conditions in the lower horizons has prevented the carbonates from precipitating as secondary forms (i.e., powdery pockets and concretions).

## Mineralogy of Studied Soils

X-ray diffraction analysis of the less than 2 μm fraction from each subsurface horizon of studied soils (Fig. 3, Table 3) indicates that the minerals were similar in type, but differ in concentration. According to Dadgari (33), this difference could be attributed to the change in drainage conditions which has resulted from variations in the topography and ground water table depth.

The X-ray diffractograms show the presence of illite, smectite, chlorite, palygorskite, and quartz, with traces of vermiculite (Fig.3, Table 3). As shown in Table 3, smectite is the dominant clay mineral in the clay fraction of the Pole Bahadoran series. This higher concentration of smectite is reflected in the relative high CEC value of the clay fractions (Table 3). The poorly drained characteristics of these soils have provided weathering conditions favorable for the formation of

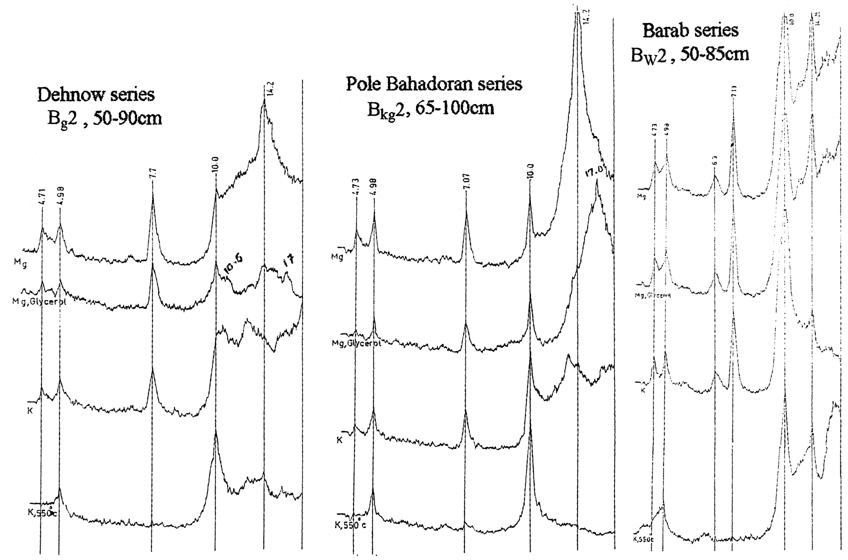

*Figure 3.* X-ray diffractograms of clay of the subsoil of Barab series, Pole Bahadoran series, and Dehnow series

***Table 3.*** CEC and Mineralogy of Clays and Soil Free Iron Oxides

| Pedon | Horizon | Depth cm | Clay[#] Mineralogy | CEC* of Clay cmol $kg^{-1}$ | Free $Fe_2O_3$ % |
|---|---|---|---|---|---|
| Barab | $B_w2$ | 50–85 | Pa Ch I Sm | 47 | 0.5 |
| Pole Bahadoran | $B_{kg}2$ | 65–100 | Sm Ch I Pa | 75 | 1.0 |
| Dehnow | $B_g2$ | 50–90 | Ch I Sm Pa | 57 | 1.2 |

[#] Pa=Palygorskite, Ch=Chlorite, Sm=Smectite, I=Illite (note that minerals are reported as increasing trend from right to left).

*CEC=Cation Exchange Capacity (of clay fraction,i.e. <0.002 mm).

smectites from transformation of chlorite and illite or its neoformation from soil solution. The higher content of $Fe_2O_3$ in this profile indicates the more weathered condition of this soil, and an adequate supply of Mg and Fe coupled with the poor drainage conditions to provide favorable conditions for smectite formation.

In the Barab soil with a very deep water table palygorskite forms the dominant mineral of the clay fraction. Conditions which favor the formation of this mineral are; an arid climate; a non leaching environment and calcareous soil parent material. According to Abtahi (34), Millot (35), Millot et al. (36), and Singer and Norrish (37), palygorskite formation is favored by high pH, $H_4SiO_4$, $Ca^{++}$, and $Mg^{++}$ and low Al activities. Alkaline-earth elements needed for this neoformation may be derived from the weathering of limestone and dolomitic limestone parent materials. Silicon (Si) is fairly ubiquitous in primary and secondary minerals and will also be present as dissolved $Si(OH)_4$ in the groundwater. According to Wiersma (38) part of the necessary $SiO_2$ originates from finely distributed silica present in the limestone. This mineral has been detected in southern Iran (17,18). Abtahi (18) found that with increasing calcium carbonate, palygorskite content increases in the soil. He also indicated that the limestone of southern Iran, contains only minor amounts of palygorskite. Abtahi (17,18) also stated that the same parent rocks contain equal amounts of illite, chlorite, and quartz. Therefore, it may be concluded that as a result of time and semi-arid pedogenesis in the study area, palygorskite increases as smectite, chlorite and vermiculite decreases (Table 3).

The presence of palygorskite in the studied soils have been confirmed by the electron micrographs of Fe free clay samples (Fig. 4). Only very small amounts of this mineral have been detected in the Pole Bahadoran and Dehnow soils as discussed earlier.

Finally, in the Dehnow soil, chlorite and illite form the dominant clay minerals in the soil samples which is in disagreement with the above discussed idea that smectite is dominant in soils with poorly drained conditions. Almost permanent saturated conditions of these soils, and the absence of enough leaching for

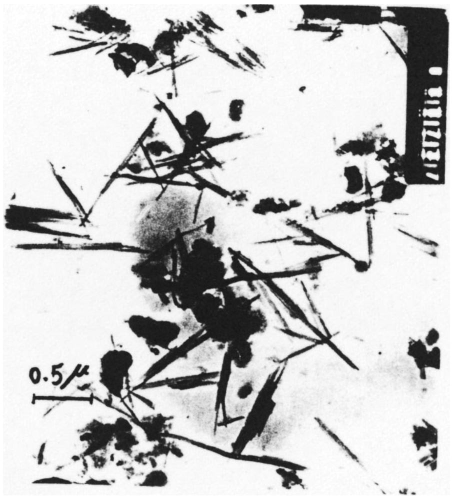

***Figure 4.*** Electron micrographs of clay from the subsurface horizon of Dehnow series (Lowlands).

removal of some cations (e.g., $K^+$) from the soil solution, which is a prerequisite for transformation of chlorite and illite into smectite, have inhibited the weathering process and transformation of these minerals into smectite.

## CONCLUSIONS

Marked differences in the morphological and mineralogical properties, and genesis of subsurface horizons were associated with variation in landscape and depth of groundwater.

In microlow (lowlands) areas, groundwater fluctuates between 25 cm to 1 m depth, while in microhigh (lower alluvial plain) and upper alluvial plain areas, it is deeper than 1 m and 2 m, respectively.

Soil color, mottling and reduction-oxidation patterns are soil features commonly affected by seasonally high ground water table. Gray matrices and yellowish brown mottles have formed in the lowlands area with shallow groundwater, while soils formed in the higher landscape positions with very deep water table do not show redoximorphic features.

As the water table comes closer to the soil surface, organic matter accumulation and thickness of the mollic epipedon of the studied catena increased. Soils with a cambic subsurface horizon and very thick mollic epipedon (Fluvaquentic Endoaquolls) have formed on the lowland area with shallow groundwater. Soils with calcic horizon and mollic epipedon (Typic Calciaquolls) have formed on the lower alluvial plain with deeper groundwater while soils without any diagnostic subsurface horizon, except a thin mollic epipedon (Torrifluventic Haplustolls), have formed on the upper alluvial plain with very deep groundwater.

The major mineral in the well drained soils of the studied catena is palygorskite, while in the poorly drained soils smectite is dominant. In very poorly drained soils of the depressions, almost permanent saturation inhibited weathering processes of minerals. In these soils chlorite and illite are the dominant minerals.

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