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Micromorphology of Pedogenic Carbonate Features in Soils of Kohgilouye, Southwestern Iran

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ABSTRACT

The micromorphology of pedogenic carbonate features in calcareous soils of arid and semiarid regions of Kohgilouye Province, Southwestern Iran, has been studied to determine their genesis and distribution in different climatic regions. Eight representative pedons (from a total number of 24 pedons) were studied in aridic-ustic (minimum rainfall), ustic and xeric (maximum rainfall) soil moisture regimes. Micromorphological studies indicated that the frequency of secondary calcite as pedogenic nodules, coating or infilling in voids or channels increase from aridic-ustic to xeric soil moisture regimes. The presence of pedogenic calcite coating superimposed on clay coatings in pedons of more humid regions probably suggests a complex history of carbonate leaching, deposition of secondary calcite and clay illuviation. Pendants of calcite were observed in soils with coarser texture in aridic-ustic region as a common pedofeature. Pedogenic nodules in more developed soils of xeric regions were harder containing denser and more contiguous micritic calcite. Degree of impregnation of calcite nodules with Fe/Mn oxides as well as calcite depletion pedofeatures increase in areas with higher rainfall. Needle shaped calcite and cytomorphic calcite were observed in the near surface horizons of the regions with higher rainfall and denser vegetation growth of ustic and xeric soil moisture regimes.

Keywords: Arid zone, Calcite, Micromorphology, Soil, Southwestern Iran.

INTRODUCTION

Arid and semi-arid soils cover over a third of the world landmasses and are becoming increasingly more important worldwide because of increased human populations and consumption of natural resources (Buol *et al.,* 1997). Calcite is one of the best studied, but also one of the most variable pedogenic minerals. It shows a wide variety of shapes and habits, and occurs as well in arid and semiarid soils as in temperate and tropical soils with restrained drainage (Stoops and Delvigne, 1990).

Secondary or pedogenic carbonates are those that are formed through the processes responsible for the soil development. They are found in relatively dry soils and develop under natural good drainage and vegetation comprising grass and shrubs mixture. The differences among estimates are a result, at least in part, of the difficulty of differentiating between primary carbonates (lithogenic carbonates) and carbonates of secondary origin or pedogenic carbonates. 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).

According to Wright (1987) the type of pedogenic calcium carbonate is controlled mainly by the parent material, climate, and vegetation. The formation of pedogenic carbonates involves complex processes of dissolution, translocation and precipitation. Four models have commonly been used to describe pedogenic carbonate formation namely, the *per decensum, per ascensum, in situ,* and biogenic models (Monger, 2002). In most micromorphological descriptions, a distinction is made only between

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microcrystalline (sometimes called micritic), crystalline (sparitic) and acicular calcite (Stoops and Delvigne, 1990). Lithogenic carbonate dissolves under ambient moisture and a relatively high soil CO_2 partial pressure and the dissolved Ca^{2+}, Mg^{2+} and CO_3^{2-} ions move downward with the percolating soil water. As the moisture content decreases, calcite precipitates (Wang and Anderson, 1998). Development of various pedogenic features, such as channels, cutans, pedotubules and secondary carbonates in soils of arid regions is due to major processes of dissolution, leaching and recrystallization (Chen, 1997).

Pedogenic carbonate has been studied with respect to its importance for plant nutrition, carbon sequestration, landscape age, paleoclimatology, paleoecology, and as a phenomenon *per se* (Monger, 2002). Micromorphological analysis of carbonate nodules and nodular fabrics in different soil materials shows that their development is a function of several factors: nature of the host matrix (texture, porosity), carbonate and non-carbonate clay distribution, bulk density and the interactions among them (Wiede and Yaalon, 1982).

Distinction between pedogenic and lithogenic carbonate is of great importance, e.g., in soil classification, and has been discussed several times in the literature (Monger and Gallegos, 2000; Nordt et al., 2000).

No previous studies have been performed on the genesis and micromorphology of the well developed and diverse calcitic pedofeatures in soils of Kohgilouye Province. The main objective of this study is therefore to investigate the genesis of different calcitic features in the calcareous soils of the different climatic regions of southwestern Iran, using micromorphological studies.

Background of the Studied Area

Kohgilouye Province with a land area of about 1.6 million ha, is located in southwestern Iran. The elevation of the province varies from 300 m above the sea level (a.s.l.) in the southwest to 4,400 m a.s.l. in the northeast. The mean annual precipitation ranges from about 350 mm in southwestern parts to about 1,000 mm in southeastern regions of the Province. General data and a location map of the regions studied are presented in Table 1 and Figure 1. The soil parent material is moderately to highly calcareous, although parent material of southwestern sectors is dominated by a combination of calcareous and gypsiferous materials (pedon 8). Based on previous soil surveys, eight representative pedons (from a total number of 24 pedons) with calcic horizons were selected for this investigation in different climatic regions of the Province. Soils were described and classified according to the Soil Survey Manual (Soil Survey Staff, 1993) and Keys to Soil Taxonomy (Soil Survey Staff, 2010), respectively.

MATERIALS AND METHODS

Chemical and Physical Analyses

Particle-size distribution was determined using sodium hexametaphosphate for the determination of sand, silt and clay fractions by the pipette method (Day, 1965). Alkaline-earth carbonate was measured by acid neutralization (Salinity Laboratory Staff, 1954). Organic carbon was measured by wet oxidation with chromic acid and back titration with ferrous ammonium sulphate (Nelson, 1982). Determination of the soil pH was in a saturation paste and electrical conductivity (EC) in a saturation extract (Salinity Laboratory Staff, 1954).

Micromorphological Analyses

Thin sections with an area about 30 cm^2 were prepared using standard techniques (Murphy, 1986). Air-dried oriented clods were impregnated under vacuum with an acetone diluted polyester resin (50/50 ratio),

Table 1. Some general data of the pedons studied.

Pedon	Region	Latitude and longitude	Soil classification	Mean annual rainfall (mm)	Mean annual temperature (°C)	Mean annual transpiration (mm)	Soil moisture and temperature regime
1	Mansurkhani	30°42′07″N 51°40′36″E	Chromic Calcixerert	950	11.3	1810	Xeric-Mesic
2	Najafabad	30°37′00″N 51°35′25″E	Calcic Haploxeralf	860	14.5	1905	Xeric- Mesic
3	Abgarm	30°42′17″N 51°28′27″E	Calcic Argixeroll	860	12.1	1850	Xeric-Mesic
4	Dashtak	30°49′39″N 51°27′36″E	Calcic Rhodxeralf	750	12.1	1810	Xeric-Mesic
5	Khami	30°21′12″N 50°53′56″E	Calcic Haplustalf	500	21.0	2700	Ustic-Hyperthermic
6	Dalan	30°22′04″N 50°29′24″E	Calcic Haplustept	500	21.0	2800	Ustic-Hyperthermic
7	Khanahmad	30°18′09″N 50°57′16″E	Typic Calciustept	390	21.4	2934	Aridic,ustic-Hyperthermic
8	Abrigon	30°23′10″N 50°34′34″E	Gypsic Calciustept	370	23.0	3392	Aridic,ustic-Hyperthermic

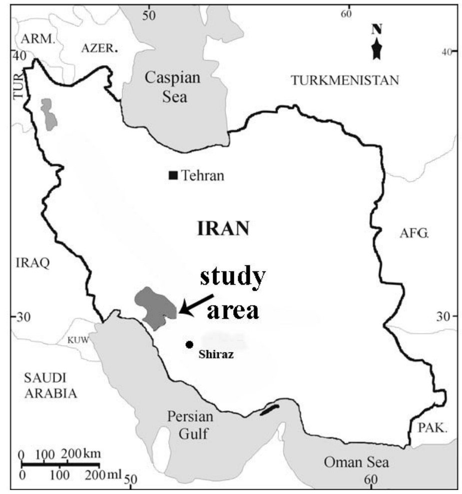

Figure 1. Location map of the study area.

and cured for a minimum of one week. Oriented sections were cut with a diamond saw and cemented onto glass microscope slides. The slides were ground and polished to a thickness of 30 μm and described following the guidelines of Stoops (2003).

SEM Studies

Undisturbed dried samples were mounted on aluminum stubs using double-sided tape and carbon paste, then coated with gold and examined using a Cambridge scanning electron microscope (SEM). Intact soil samples were also observed using a Dino-Lite digital microscope at 60-230X magnification with 1.3M pixel resolution.

RESULTS AND DISCUSSION

General Results

Soil Texture of the studied soils varied from silty loam in pedon 8 to clay in pedons 1, 2 and 4 (Table 2). All soils were calcareous throughout the profile and in most pedons calcium carbonate increased with depth (Table 2). Pedogenic gypsum in pedon 8 occurred as medium to large needle shaped crystals as well as mycelium. The

Table 2. Some physico-chemical and morphological properties of the pedons studied.

Horizon	Lower depth (cm)	Sand	Silt (%)	Clay	pH	OC [a] (%)	CCE [b]	EC [c] dSm^{-1}	Color (moist)
Pedon 1 - Chromic Calcixerert									
Ap	20	14	42	44	7.8	0.5	11	0.51	10YR4/3
Btss	65	18	29	53	8.0	0.6	18	0.42	10YR4/3
Bk	125	22	27	51	8.0	0.7	23	0.48	10YR4.5/3
Pedon 2 - Calcic Haploxeralf									
Ap	25	18	38	44	7.5	0.5	29	0.30	7.5YR4/4
Btk1	75	22	26	52	7.4	0.4	38	0.23	7.5YR4/4
Btk2	115	20	30	50	7.5	0.4	46	0.27	7.5YR4/4
Btk3	150	28	25	47	7.7	0.2	49	0.38	7.5YR5/4
Pedon 3 - Calcic Argixeroll									
Ap	25	25	36	39	7.5	1.5	20	0.57	10YR3/1
Bt	50	19	32	49	7.7	0.7	24	0.31	7.5YR4/4
Btk	100	40	26	34	7.8	0.2	55	0.24	10YR4/4
Pedon 4 - Calcic Rhodxeralf									
Ap	25	18	38	44	7.5	0.5	29	0.60	5R4/3
Btk1	75	22	26	52	7.4	0.4	38	0.28	10R3/5
Btk2	115	20	30	50	7.5	0.4	46	0.24	10R3/6
Btk3	150	28	25	47	7.7	0.2	49	0.21	10R3/6
Pedon 5 - Calcic Haplustalf									
Ap	20	30	44	26	7.5	1.4	30	0.53	7.5YR4/4
Btk1	45	25	36	39	7.6	0.7	32	0.47	10YR4/4
Btk2	100	23	42	35	7.6	0.3	35	0.75	10YR4/4
Ck	150	44	36	20	7.5	0.2	79	0.91	7.5YR8/1
Pedon 6 - Calcic Haplustept									
Ap	30	26	46	28	7.4	1.6	42	0.73	10YR4/4
Bw	55	20	46	34	7.5	1.1	37	0.74	7.5YR4/4
Bk1	95	22	44	34	7.7	0.2	47	0.31	7.5YR4/4
Bk2	150	22	48	30	7.7	0.1	48	0.30	7.5YR4/4
Pedon 7 - Typic Calciustept									
Ap	20	24	52	24	7.4	1.1	55	0.78	10YR4/4
Bk1	65	26	45	29	7.5	0.3	58	0.54	10YR4/4
Bk2	90	24	49	27	7.9	0.3	60	0.31	10YR4/

overall microstructure of the studied soils ranged between weakly and well separated subangular blocky (Table 3). The $c/f_{10\mu m}$ related distribution (the ratio between the part occupied by the coarse and fine material, respectively) is porphyric and ranged from 2/8 in the Btss horizon of pedon 1 to 8/2 in the Byk horizon of pedon 8 (Table 3). The content of skeleton grains (i.e., coarse material) was higher in the soils of more arid regions. The majority of the pedons of the xeric regions had a high content of fine material, accounting for 40-70%. Dark reddish to reddish brown groundmass dominated in the soils of xeric regions (particularly pedons 2 and 4), whilst

Table 3. Thin section description of the pedons studied.

Pedon/ Horizon	Microstructure	*c/f* ratio 10 µm	Micromass, color, b-fabric	Pedofeatures
1/Btss	Well developed subangular blocky with well accommodated channels, porosity (~20%)	2/8	Crystallitic (95%) and granostriated (5%) b-fabric, dark reddish brown	Yellowish clay coating around channels, few dark reddish Fe oxide nodules
1/Bk	Moderately developed subangular blocky with moderate channels	4/6	Crystallitic b-fabric, reddish brown	Few to common micritic calcite nodules, dark reddish to black Fe/Mn oxides
2/Btk1	Moderately developed subangular blocky, porosity (~40%), channels and planes	4/6	Crystallitic (80%) and speckled (20%) b-fabric, reddish brown	Calcite depletion pedofeatures, dark reddish to black Fe/Mn oxides, common micritic and sparitic calcite nodules, needle shaped calcite (100-200µm), very few clay coating around calcite nodules
2/Btk2	As above, porosity (~30%)	5/5	As above	As above with more lithogenic calcite nodules and without needle shaped calcite
2/Btk3	As above	6/4	As above	As above
3/Bt	Moderately developed subangular blocky, porosity (~30%)	3/7	Crystallitic (50%) and speckled (50%) b-fabric, reddish brown	Calcite depletion pedofeatures, few micritic calcite nodules, few clay coating
3/Btk	Weak to moderately developed subangular blocky, porosity (~20%), with some planes	4/6	Crystallitic (80%) and speckled (20%) b-fabric, brown	Dense and loose calcite infilling in voids and channels, few clay coatings, dark reddish to black Fe/Mn oxides in matrix and calcite nodules.
4/Btk1	Well developed subangular blocky, porosity (~20%)	3/7	Crystallitic (20%), speckled (75%) and granostriated (5%) b-fabric, dark reddish brown	Calcite depletion pedofeatures with reddish soil matrix , few micritic calcite nodules, few clay coating
4/Btk2	Well developed subangular blocky, porosity (~35%)	4/6	As above, reddish brown	Micritic calcite infilling in weathered nodules, crystallitic (50%) b-fabric
4/Btk3	Moderately developed subangular blocky, porosity (~40%)	4/6	As above, reddish brown	As above with common lithogenic calcite nodules.
5/Btk1	Weakly to moderately developed subangular blocky, porosity (~40%), interpedal channels	5/5	Crystallitic (mostly) and partly speckled (very few) b-fabric, brown	Many cytomorphic calcites as infilling in voids, common micritic calcite nodules, very few clay coatings, few reddish Fe oxide nodules.
5/Btk2	As above, porosity (~25%),	4/6	As above	As above with coarser calcite nodules
6/Bk1	Weakly developed subangular blocky, porosity (~50%),	3/7	Crystallitic b-fabric, yellowish brown	Very few reddish Fe oxide nodules, coarse typic micritic calcite nodules and coating and infilling in channels and voids.
6/Bk2	As, porosity (~30%),	5/5	As above	As above with more typic and lithogenic calcite nodules.
7/Bk1	Moderately developed subangular blocky, porosity (~50%)	3/7	Crystallitic b-fabric, brown	Coarse typic micritic nodules, small calcite crystals in channels
7/Bk2	Weak to moderately developed subangular blocky, porosity (~30%),	5/5	Crystallitic b-fabric, yellowish brown	Very coarse lithogenic calcite nodules (2-4 mm), calcite coating around coarser fragments
8/Bk	Moderately developed subangular blocky, partly channel structure, porosity (~40%)	5/5	Crystallitic b-fabric, yellowish brown	Laminar pendents underneath calcite nodules, small calcite crystals in voids and channels
8/Byk	As above, some chambers, porosity (~50%)	8/2	Crystallitic b-fabric, yellowish brown	Fine typic micritic calcite nodules, few fine to medium gypsum crystals in voids and matrix

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yellowish brown to bright brown groundmass prevailed in the soils of aridic-ustic regions (Table 3). Also the soil groundmass differentiated remarkably in pedon 8 resulting from different parent materials (red and grey marls). Since soils are highly calcareous, the b-fabric is mostly calcitic crystallitic, except in some soils with argillic horizons, where it can be speckled when calcite depletion occurs as well as granostriated b-fabric (Table 3). Within the soils of more humid regions, spots, coating, hypocoating, diffusive rings and concentrations of ferromanganese formations were common. Some phsico-chemical and morphological properties as well as thin section description of the pedons studied are presented in Tables 2 and 3.

Aridic-ustic Regions (Pedons 7 and 8)

The ratio of mean annual rainfall to mean annual evaporation can be used as an index for the evaluation of soil leaching. This index in aridic-ustic, ustic and xeric regions of the study area were 0.12, 0.18 and 0.47, respectively. In more arid regions, dissolved carbonates move upward during periods of drying and precipitate in the solum and hence, this factor has an important role in redistribution of calcite and other soluble minerals along the soil profile. According to Machette (1985), calcite accumulation in arid soils has been attributed to upward capillary and laterally flowing calcareous ground water, *in situ* weathering of calcium-containing minerals, and calcareous dustfall.

In dry soils, calcite mainly occurs as microcrystalline interflorescences (impregnations) which tend to become purer and coarser through recrystallization, casually combined with epigenetic replacement of the silicate minerals (Stoops and Delvigne, 1990).

In these pedons pedogenic carbonates were closer to the surface as a result of the lower precipitation and lower average depth of the wetting front. Micromorphological observations of thin sections confirmed that the calcite features are as medium to coarse typic lithogenic nodules (200-6,000 μm in size) with sharp boundary as well as calcite pendants beneath small gravels or previously formed calcite nodules (Figures 2-a, 2-b and Table 3). The microstructure of the Bk horizons is weak to moderately developed, subangular blocky and high porosity with interpedal. These soils exhibited coarser texture with larger voids hence, secondary carbonate precipitates in interpedal and/or interpedal voids as large sparry crystals. Sparry calcite has been attributed to both precipitation from supersaturated solutions and micrite recrystallization. Large voids are the main sites for calcite precipitation, as

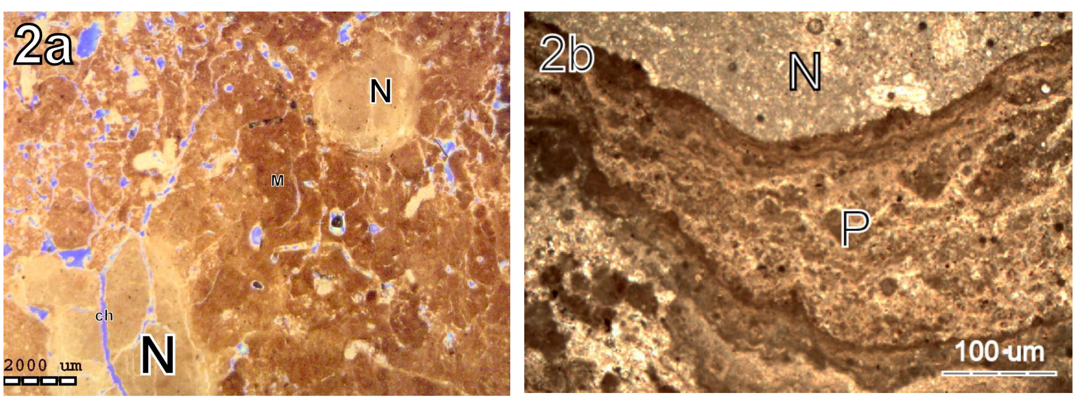

Figure 2. (a) Large lithogenic typic calcite nodules (N) in soil matrix, Bk2 horizon of pedon 7, with crystallitic b-fabric (crossed polarisers), (b) Laminar pendant of calcite (P) formed beneath a calcite nodule (N) in pedon 8 (Bk horizon) (crossed polarisers)

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they dry more rapidly than smaller ones and are usually in more direct contact with lower atmospheric concentration of CO_2 (Chadwick *et al.*, 1987). None to very few Fe/Mn oxides were observed in soil matrix due to less degree of weathering of primary minerals. Coarse skeleton grains (50-200 µm in diameter) were dominated consisting mainly of quartz, lithogenic calcite and other primary minerals.

The Bk2 horizon of pedon 7 and the Bk horizon of pedon 8 exhibited laminar carbonate pendants underneath the limestone fragments or calcite nodules. According to Khormali *et al.* (2006) and Wang and Anderson (1998) lithogenic carbonate pebbles show larger crystals with apparent rhombohedral cleavage. Most studies have shown that the calcitic pendants display a complex layering which could result from sequential aggradations (Chadwick *et al.*, 1989; Courty *et al.*, 1994). The darker appearance of the micritic bands in calcite pendants could be caused by a higher Si content (Blank and Fosberg, 1990) or clay and/or organic matter (Treadwell-Steitz and McFadden, 2000). Changes in crystal morphology have been recognized as the major factor causing lamination, although the common occurrence of dark rims would suggest organic enrichment (Blank and Fosberg, 1990).

No clay coating was observed in the thin sections of the aridic-ustic soils. The high carbonate content throughout the soils must inhibit present clay translocation because it causes flocculation. According to Mack (1992), carbonates are retained in soil profiles only where the annual precipitation is < 600 mm. In western parts of Kohgilouye Province, annual precipitation is less than this and seems insufficient to leach carbonates so that clay can subsequently be dispersed and translocated.

Few pedogenic calcite crystals as micrite and microspar oriented around pores and channels as well as fine calcite nodules (up to 40 µm) with diffused boundary were observed in the Bk1 horizon of pedon 7 and the Bk horizon of pedon 8, suggesting slow accumulation of calcium carbonate, limiting the formation of coarser nodules. Ducloux *et al.* (1984) studying pendants on a pebble, observed the following sequence of habits: amorphous carbonate > monocrystalline needles > polycrystalline needles and rods > compound needles and scalenohedral crystallites > rhombohedral crystals. According to Stoops and Delvigne (1990) in arid soils, calcite mainly occurs as microcrystalline (impregnations) which tend to become purer and coarser through recrystallization, combined with epigenetic replacement of the silicate minerals.

Ustic Regions (Pedons 7 and 8)

In these pedons, secondary calcium carbonate occurred as infilling of pores with sparitic cytomorphic calcite (Figures 3-a and 5-a), few fine typic calcite nodules as well as

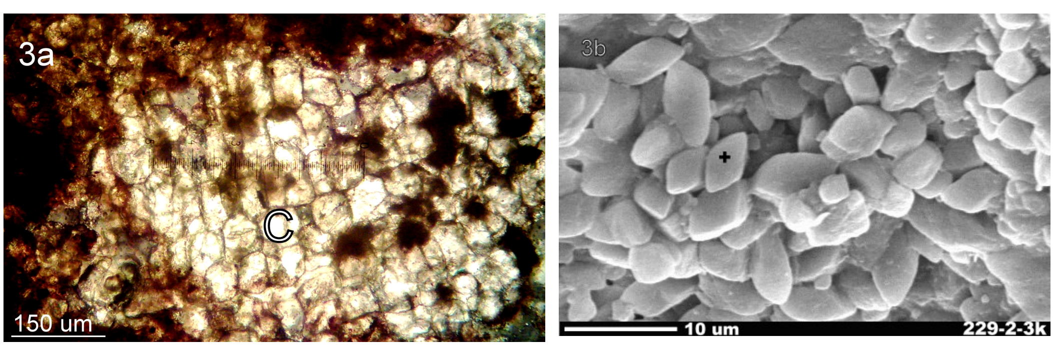

Figure 3. (a) Cytomorphic calcite crystals (C) in root channel in pedon 5 (Btk1 horizon) (crossed polarisers), (b) SEM image of rhombohedral calcite in micritic nodule of pedon 6 (Bk1).

micritic calcite coating along channels. Pedogenic nodules were mostly soft and small in size and contained loose micrite crystals, suggesting lower development of pedogenic calcite, compared with more humid regions. The Btk horizons exhibited very few yellowish clay coatings along small channels. The b-fabric is mostly calcitic crystallitic and partly speckled in the Btk horizons of the pedon 5. Illuvial clay features (with weak optical-orientation compared to the pedons of xeric regions) and pedogenic carbonates were observed in this pedon. This suggests that the soils are polygenetic and that clay illuviation preceded carbonate accumulation. Polygenetic soils occur when climate changes are great enough to produce new soil properties without obliterating existing properties (Chadwick *et al.*, 1995). Therefore, these illuvial features may not be the products of the current climate, but probably formed in a more humid climate.

Few to common reddish to brownish Fe/Mn oxides are seen in soil matrix. Few large lithogenic calcite nodules are impregnated by Fe oxides. SEM analyses showed micrite to microspar euhedral calcite crystals of about 4-7 μm in pedogenic nodules of the Bk1 horizon of the pedon 6 (Figure 3-b) as well as sparitic calcite (20-80 μm) with sharp border in the Btk2 horizon of pedon 5. A steady source of ions and slow precipitation produce spars with euhedral habits. In contrast, rapid precipitation, such as is the case of semi-arid environments, favors micrite (Chadwick *et al.*, 1989). According to Watts (1980) very quick crystallization gives rise to microcrystalline (micritic) calcite. Most probably the Mg content of both the calcite and the soil solution will also play a role in the crystallization.

Cytomorphic and needle shaped calcite are the dominant features in the ustic regions of southern Iran, rather than calcite nodules, pointing to different processes of accumulation, rather steered by biological factors than pure physico-chemical ones (Khormali *et al.*, 2006). Needle shaped calcite (acicular) were not observed in the pedons studied in this region.

The occurrence of cytomorphic calcite in the pedons studied suggests the specific environmental conditions for its formation (Herrero et al., 1992). A relatively high rainfall and favorable temperature results in denser vegetation and a high biological activity. An extensive study on calcified root cells was carried out by Jaillard (1987), who described the biomineralization of roots mainly in strongly calcareous soils. Calcium carbonate in the soil matrix is dissolved by a $H^+/HCO3^-$ exchange and excretion of organic acids. The available Ca^{2+} is taken by the root, absorbed by the cells and mechanisms of vacuolian crystals explains 95% of the mass of the calcified cells, whereas the outer part of the cell mineralizes during plasmolysis.

The occurrence of polyconcave calcite crystals (fine sand size) with a fan like extinction pattern in root residues or root channels, surrounded by a decalcified hypocoating was described in detail by Herrero (1987) and Jaillard (1987). The oligoblastic grains are systematically filling in the lumen of the plant cells. As a result of pedoturbation these cytomorphic grains can become incorporated in the groundmass where they can accumulate and constitute up to 25% of the soil material.

Xeric Regions (Pedons 1, 2, 3 and 4)

In the field studies of this climatic region, pedogenic calcite was observed as mycelium threads (Figure 5-b), soft masses (powdery pockets) and nodules (mostly pedogenic). Clay illuviation is one of the most important pedogenic processes for the pedons studied in this region. In contrast, pedogenic carbonate accumulation primarily occurs in soils with ustic and aridic-ustic moisture regimes. Clay skins or films on ped surface or on the walls of the voids imply the translocation and subsequent accumulation of clay. Most of these pedons exhibited both clay illuviation and calcium carbonate accumulation. Theoretically, the pedogenic processes for clay illuviation and calcium carbonate accumulation should be contradictory to each other, since large quantities of Ca^{2+} tend to cause clay flocculation and reduce illuviation. However, these pedogenic features may be observed in the same soil at approximately the same depth. The presence of both features implies a complex history of carbonate leaching, deposition of secondary calcite and clay illuviation (Gunal and Ransom, 2006). This hypothesis is supported by the fact that some channel clay coatings (pedons 1 and 3) are covered by calcite deposits.

The b-fabric in Btss and Btk1 horizons of pedons 1 and 4 were mostly crystallitic, speckeled and granostriated. The granostriated b-fabric indicates much stress orientation of clay minerals due to shrink-swell activity in these pedons.

The more favorable climatic conditions and more biological activity as a result of denser vegetation have accelerated the process of dissolution-precipitation and recrystallization of pedogenic calcite. Higher rainfall in this region has removed more calcium carbonate from the surface to deeper horizons. Presence of large numbers of calcite nodules in deeper horizons in comparison with surface horizons confirms this hypothesis (Figure 4a). Reddish to reddish brown groundmass (expressed by speckled b-fabric), dominated in the surface horizons of this region (pedons 2 and 4) resulted from more depletion of calcium carbonate. The calcite depletion pedofeatures can be interpreted either as nonrecalcified zones or as the result of a more recent decalcification process.

More detailed observations regarding the position of the decalcified zones indicated that these zones take place frequently next to the channels and voids as well as external parts of microstructures (Figures 4-a and 4-b). Most calcite nodules are impregnated by Fe oxides (in the cases of dendritic Mn-oxides) as a result of higher degree of weathering, releasing Fe/Mn from primary minerals (Figure 4-b). Calcite has been shown to be an efficient absorber of some impurities such as organic mater, Mn^{2+}, Fe^{2+}, etc (Van Beynen *et al.*, 2001). Rounded (anhedral) sparitic calcite crystals (20-100 µm) were also observed in weathered nodules (Figure 5-d).

Comparing with more arid regions, pedogenic nodules in this area were harder, containing denser and more contiguous micritic calcite, suggesting more development of pedogenic nodules.

Micromorphological observations exhibited needle shaped (acicular) calcite as loose infilling in voids of the Btk1 horizon of pedon 2 (Figures 4-c and 5-e). SEM analyses of the Btk1 horizon of pedon 2 showed acicular calcite crystals with a width of 2 µm and length of 20-50 µm distributed in soil matrix. In most cases, fibers are joined at high angles by a cement of anhedral material (Figure 4-d). These needles are mainly of the MA type of Verrecchia and Verrecchia (1994). The MA type needles are long and smooth, composed of variable numbers of individual fibers, most commonly two. They have a mean length of 15- 20 µm and are less than 1 µm wide.

Calcified filaments or rod-shaped calcite were observed commonly in SEM images, probably as a result of calcite deposition on root hairs or mycelium threads (Figures 4-e and 4-f).

The origin of needle-fiber calcite has been discussed for many years and is usually interpreted in two ways: by purely physicochemical phenomena or in relation with organic material (roots, root hairs, bacteria, algae and fungi). A review on the morphology and genesis of needle-shaped calcite made by Verrecchia and Verrecchia (1994) showed four types and several subtypes from which three types are the result of biological processes whereas one is the result of physico-chemical crystallizations related to evaporation and desiccation.

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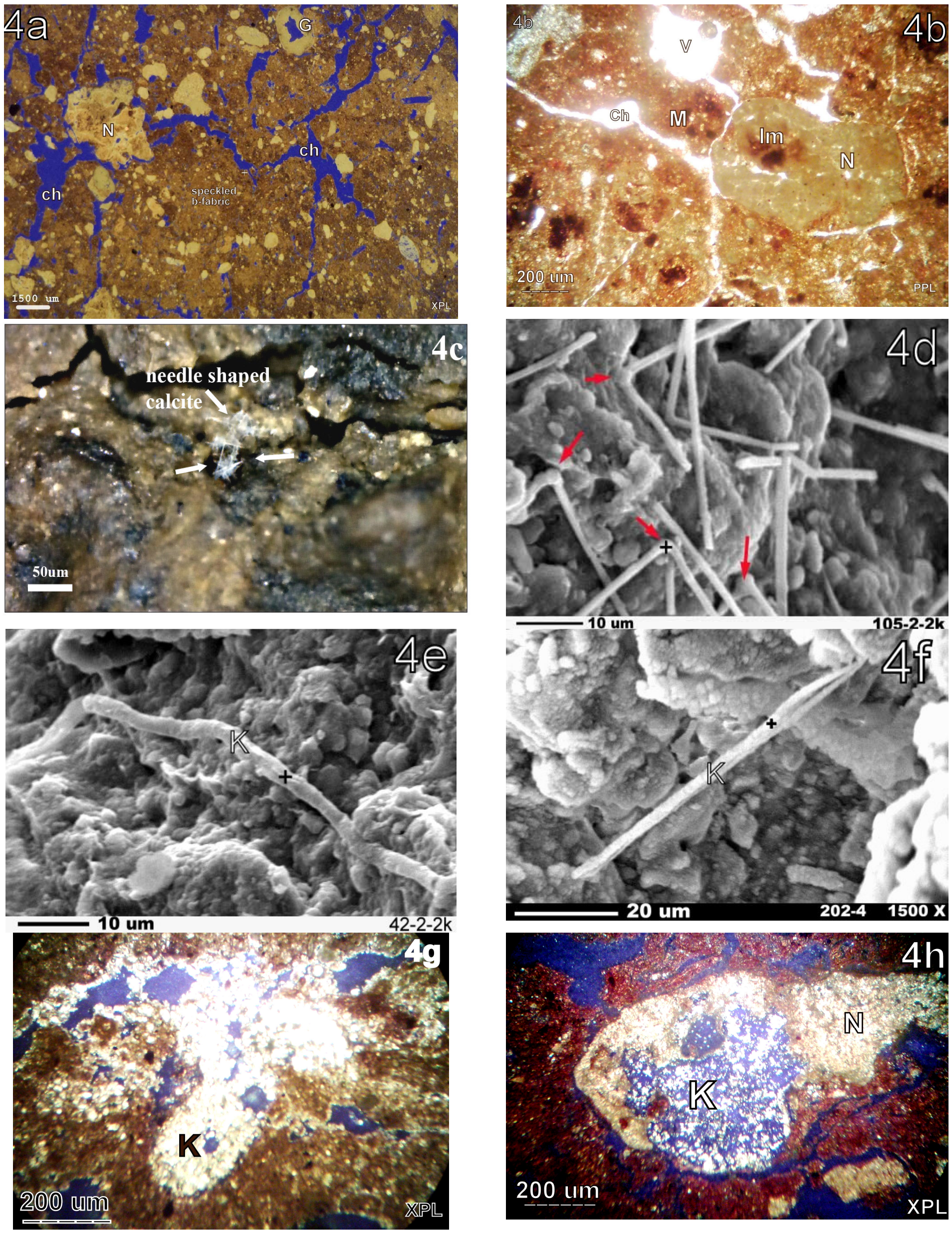

Figure 4. (a) Pedogenic and liothogenic calcite nodules, crystallitic and speckled b-fabric of pedon 2, Btk2 horizon (crossed polarisers); (b) Dark reddish Fe/Mn oxide nodules in groundmass and impregnation (Im) in calcite nodules of pedon 4, Btk horizon (plain light); (c) Bundles of needle shaped calcite, formed on ped surface (50 -100 µm), of pedon 2, Btk1horizon, (digital microscope); (d) SEM image of needle shaped calcite in the Btk1 horizon of pedon 2; (e) and (f) SEM images of calcified filaments (K) of pedon 1, Bk horizon; (g) Dense infilling of micritic calcite crystals (K) in voids and channels of pedon 3, Bt horizon (crossed polarisers), (h) Micritic calcite infilling in a weathered nodule of pedon 4, Btk2 horizon (crossed polarisers)

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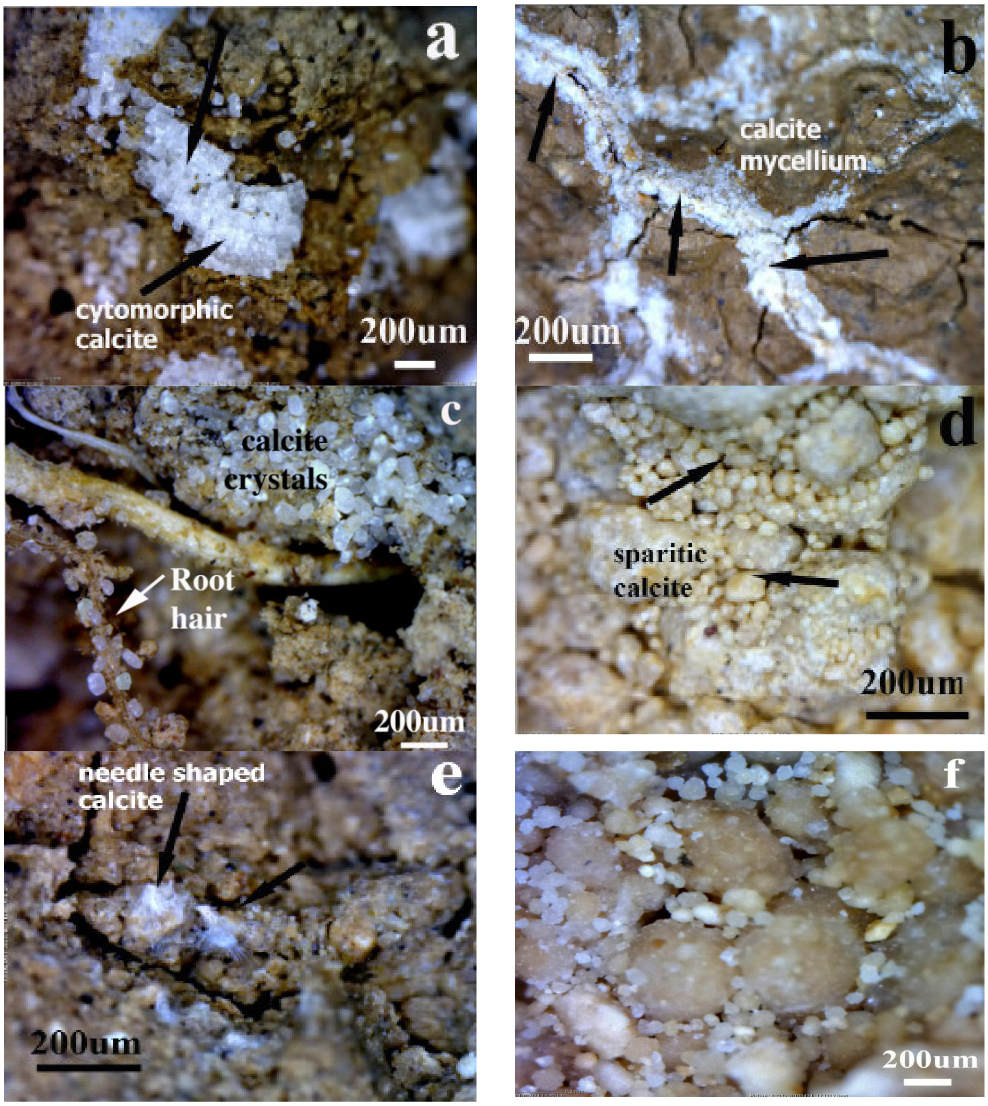

Figure 5. (a) Cytomorphic calcite crystals in Btk1 horizon of pedon 5; (b) Calcite mycelium threads along channels in the Btk1 horizon of pedon 2; (c) Accumulation of sparitic calcite crystals on root hairs, in the Btk1 horizon of pedon 2; (d) Rounded (anhedral) sparitic calcite crystals (20-100 µm) in a weathered nodule in the Btk2 horizon of pedon 2; (e) Bundles of needle shaped calcite crystals with low degree of crystallization, formed in void and ped surface (50-200 µm in length), in the Btk1 horizon of pedon 2, (f) Recrystallization of small calcite crystals (mostly 10-50 µm) in a calcite nodule in the Btk2 horizon of pedon 1.

Wright (1984) emphasized the relation between micro-organisms and needle shaped calcite. In several soils of the Pampa a deposition of equant calcite crystallites around mycelium threads were observed.

In well drained steppe soils acicular calcite filling in the biopores seems to be the most abundant form, even as in some semi-arid soils (Stoops and Delvigne, 1990). According to Wright (1984) 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. However, Strong *et al.* (1992) demonstrated its occurrence under cool and wet climate in a well-drained gravel deposit with abundant carbonate clasts and high degree of biological activity. In this study, needle-like calcite was formed in areas with relatively higher rainfall (xeric and ustic soil moisture regimes) and denser vegetative growth in the near surface horizons, confirming their biological origin (Figures 4-c, 5-c and 5-e).

In the relatively moist zones of the soils of the tropics, calcite forms relatively large, coarse grain aggregates (Stoops and Delvigne, 1990).

According to Monger (2002), biotic processes include CO_2 input into soil via respiration, Ca^2+ extraction by roots, and direct precipitation by organisms. These depend on and contribute to abiotic processes, which include chemical weathering of Ca-silicates, dissolution of pre-existing $CaCO_3$, and precipitation of carbonate resulting from temperature and moisture changes in soil.

A considerable amount of calcite occurs also as coatings along channels as well as dense almost complete infilling of channels, voids and vugs in the pedons 1 and 3 (Figure 4-g). In a number of samples lithogenic calcite nodules exhibited weathered pits with geodic internal fabrics. In soils with vertic properties (pedons 1 and 4) due to pedoturbation processes, the nodules formed are subjected to recrystallization, resulting in a micritic pattern (Figures 4-h and 5-f). Accoring to Bathurst (1971) evidence for recrystallization includes (i) an irregular distribution of crystal size, (ii) abrupt contact between spar and micrite, and (iii) wavy intercrystalline boundaries. Chadwick *et al.* (1987) indicated that calcite has a preference for self-nucleation, and calcite plugs large voids by preferential precipitation on previously deposited calcite crystals. However, Wieder and Yaalon (1974) observed that in some Israeli soils, dispersed clay minerals served as nucleation points for the formation of micritic calcite.

CONCLUSIONS

The overall results indicated that the soil moisture regime (available water-holding capacity) plays a critical role not only in determining the mass of carbonate that can be dissolved and redistributed in the soil, but also determines the pattern of carbonate redistribution with depth, as well as size, shape and modes of calcite crystals over the duration of soil development. Occurrence of pedogenic calcite, in the form of nodules or microcrystals as coatings along channels or infilling (dense or loose) in voids increase in areas with higher rainfall. This is a more favorable condition of dissolution (weathering) and precipitation of calcite. Micromorphological observations of thin sections of soils with xeric and ustic soil moisture regimes exhibited calcite depletion pedofeatures with speckeled and granostriated (in Btk horizons) b-fabrics. In addition to speckeled b-fabric (in decalcified zones), other less developed soils showed calcitic crystallitic b-fabric since they are highly calcareous or gypsiferous. Pedogenic nodules in more developed soils of xeric regions were harder containing denser and more contiguous micritic calcite. The degree of calcite impregnation with Fe/Mn oxides increases in areas with higher rainfall as a result of releasing Fe/Mn from primary minerals as well as drying and wetting cycles. The presence of pedogenic calcite coating superimposed on clay coatings suggests that decalcification of carbonates followed clay illuviation. Pendants of calcite are observed as a dominant calcitic pedofeature in the pedons of more arid areas underneath coarser materials such as calcite nodules and small gravels. Cytomorphic and needle-like calcite were almost observed in areas with relatively higher rainfall and denser vegetative growth in the near surface horizons, confirming their biological origin. The micromorphological characteristics of the soils studied were suggested based on the previous descriptions for identifying diagnostic horizons (especially calcic and argillic horizons) and as diagnostic features for differentiating theses soils. Further

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investigation of pedogenic carbonate features in the soils studied and other calcareous soils of southern Iran is required.

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میکرومورفولوژی پدیده‌های پدوژنیک کربنات در خاک‌های استان کهگیلویه و بویراحمد، جنوب غرب ایران

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چکیده

میکرومورفولوژی پدیده‌های کلسیتی در خاک‌های آهکی استان کهگیلویه و بویراحمد، در جنوب غرب ایران به منظور تعیین منشا و توزیع این پدیده‌ها در مناطق مختلف اقلیمی مورد مطالعه قرار گرفت. هشت نیمرخ شاهد خاک (از مجموع ۲۴ نیمرخ) در رژیم های رطوبتی اریدیک-یوستیک (حداقل بارندگی)، یوستیک و زریک (حداکثر بارندگی) مطالعه گردیدند. مطالعات میکرومورفولوژیکی نشان داد که آهک ثانویه در اشکال سخت دانه پدوژنیکی، پوشش یا پر شدن در حفرات یا کانال ها (مجاری) از رژیم رطوبتی اریدیک-یوستیک به سمت زریک افزایش می‌یابد. حضور پوشش کلسیت پدوژنیک در مجاورت پوشش رس در نیمرخ‌های با رژیم رطوبتی زریک (در مواردی یوستیک) احتمالاً بیانگر پیشینه ترکیبی این خاک با توالی آبشویی کربنات، رسوب کربنات و آبشویی رس می‌باشد. پندانت‌های (آویزه‌های) آهکی در خاک های با بافت درشت‌تر در منطقه اریدیک-یوستیک به عنوان یک پدیده غالب مشاهده گردیدند. نودول‌های پدوژنیک خاک‌های تکامل یافته‌تر مناطق زریک، سخت‌تر و حاوی کلسیت میکریتی متراکم و پیوسته‌تر بودند. میزان تلقیح سخت دانه‌های آهکی توسط اکسیدهای آهن و منگنز، همچنین تخلیه آهک از ماتریکس خاک با افزایش میزان بارندگی رابطه مستقیم نشان داده است. اشکال سوزنی شکل و سیتومورفیک آهک در افق‌های سطحی مناطق با بارندگی بیشتر و تراکم بیشتر پوشش گیاهی با رژیم های رطوبتی زریک و یوستیک مشاهده گردیدند.

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