Soil-Forming Factors and Processes

6

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Abstract

Soil-forming processes and the formation of diagnostic horizons in different regions of Iran are mainly influenced by the overall semiarid and arid climate and high calcareous conditions of the soils. Calcium carbonate redistribution, gypsum accumulation, soil salinization, and alkalization are therefore the major processes in these climatic and soil conditions. Clay migration is also a possible process occurring in these highly calcareous conditions either through the decalcification of the upper sola and the subsequent clay migration as a commonly accepted model or by the effect of previous high exchangeable Na in soils. Clay-accumulated horizons of the extreme arid regions could be regarded, as paleo-features. Calcitic features are mainly associated with the soil water availability and the vegetation. These features vary from pendants in the skeletal soils, nodules, cemented petrocalcic, and mycelium mainly in the arid zones. In areas with higher vegetative growth and favorable precipitation and temperature, needle-shaped calcite and cytomorphic type, which are associated with the biological activity, are also observed. Formation of gypsum accumulation horizons is the result of dissolution of gypsum and formation of gypsic and hypergypsic horizons. Two sources are mainly responsible for the soils high in gypsum which are geologic formations outcropped in some areas and saline lakes high in sulfate. Salt-affected soils are widespread in Iran. The evolutionary sequence suggested for these soils is as follows: salinization and alkalization; desalinization; solonetzation; and dealkalization. Vertic features, organic matter accumulation, gleization, etc., are among other processes happening in different climate zones.

Keywords

Soil formation • Arid and Semi-arid region • Carbonates • Salinization • Gypsum

6.1 Introduction

Climate, topography, parent material, organism, and time as soil-forming factors determine the dominant soil-forming processes and consequently the type of soils in a region. Considering the fact that climate of Iran is dominantly of arid and semiarid type, and the parent material is mainly containing high calcium carbonate, the major soil-forming processes are closely related to different climatic zones of Iran.

Arid zones: Areas with arid zones include mainly the central and eastern arid zones, coastal Persian Gulf, Oman Sea, and eastern Caspian Sea regions. Due to the extreme aridity, soluble salt and gypsum accumulation are dominant in the soils of these regions. Salt-affected soils are distributed throughout arid to semiarid regions of Iran (see Chap. 7). They occupy about 15% of the country's surface area, which is almost equal to the total arable lands. These soils are formed in nearly level to level surfaces including depressions under the

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influence of a fluctuating ground water table (Mahjoori 1975). The origin of salts in many regions is related to the parent materials that formed from saline and gypsiferous marl deposits and carried by water and redeposited. Among the countries in arid and semiarid regions, Iran seems to have the largest area of gypsiferous soils in the world (see Chap. 7), covering about 27 to 28 mha (Mahmoodi 1994; Roozitalab 1994). Saline soils comprise around 16 to 23 mha of arable lands in Iran (Siadat et al. 1997).

The major clay minerals in these arid saline conditions are palygorskite, smectite, chlorite, illite, and kaolinite (see Chap. 10). Chlorite and illite (micaceous minerals) are commonly believed to be inherited largely from parent rocks (Wilson 1999; Mahjoory 1975). Environmental conditions are suggested to lead to smectite formation in Aridisols. Smectite in arid soils has been noted in Iran (Abtahi 1977). Neoformation of smectite was reported by Gharaee and Mahjoory (1984) and by Givi and Abtahi (1985) under saline and alkaline conditions with high concentrations of Si, Mg, and Al in southern Iran. Very few occurrences of vermiculite have been reported in soils of arid and semiarid regions (Abtahi 1977, 1985; Khademi and Mermut 1998; Khormali and Abtahi 2001).

Most of the gypsum-enriched soils in Esfahan and neighboring Provinces occur on alluvial fans, dissected floodplains (old dissected alluvium), and piedmonts (Toomanian et al. 2001). The physical environment might play a great role in the formation of different gypsic pedofeatures. The form of gypsum crystallization changes intricately in space and is often ephemeral in time, making it difficult to draw firm conclusions linking crystal shape to particular environments or soil types (Jafarzadeh and Burnham 1992). Stable isotope geochemistry of gypsum deposits in central and south central regions provided useful information on the major source of gypsum, which is believed to be of evaporate associated with lower Cretaceous marine sulfate, which shows how far the shallow water bodies of post-Tethyan era extended in central and southern Iran (Khademi and Mermut 1998).

Coastal plains of Persian Gulf and Oman Sea also show aridic soil moisture regime (SMR) and mostly of hyperthermic temperature regime (see Chap. 7). Aridisols and Entisols are dominant, and their properties are closely associated with the parent material (Abbaslou et al. 2013).

The south-eastern Caspian Sea region is characterized by a pronounced precipitation gradient of about 800 mm year^{-1} over about 80 km distance from north (arid) to south (humid). In the lowlands, salt-affected soils are dominant. The main factor responsible for the formation of large area affected by salinity and sodicity is the low-lying topography and arid climate. The soils are mainly classified as Aquisalids with simultaneous salinization and solonetzation processes. Gleization and formation of iron/manganese oxides are also visible in the soil profile.

Semiarid zones: Mediterranean type climate or xeric soil moisture regime (SMR) comprises the semiarid regions of Zagros and Alborz Mountains and valleys and major south and south-eastern parts of the Caspian Sea lowlands. These areas are characterized by cold and rainy winters and hot dry summers. The Zagros topographic features extend from northwest of Iran to the southeast. The entire area shows mountains and intermountain valley regions. The calcareous parent rocks are dominant bedrocks, and therefore, calcium carbonate dissolution/precipitation plays a major role in the formation of the soils and the processes dominant in soils. Formation of secondary calcium carbonate, decalcification and following clay illuviation, and accumulation of gypsum are the major processes in these regions (see Chap. 7). Combined intermountain valley topography and the alternate dry and moist soils help develop pedoturbation features and the vertic properties. The Vertisols are typical for the western Iran, and the present studies have confirmed that the formation of these soils is closely related to the accumulation of clay and the occurrence of smectite (Heidari et al. 2005a).

Major parts of Khuzestan Plain and southern parts of Zagros Mountain Ranges are comprised of very hot semiarid climate (ustic SMR).The soils of Khuzestan Province, a primary crop production area in southwestern Iran, are extremely carbonated (see Chap. 7), with more than 40 percent carbonate content in most parts. The carbonatic nature of the parent material, in addition to the low precipitation of the region, has enhanced accumulation of secondary lime minerals in the soil mineralogy control section so that the carbonatic or mixed (calcareous) mineralogy classes are common in the region. Soils are mainly classified as orders of the Entisols and Inceptisols. The young (recently formed) Entisols of the region belong to Fluvents of the Holocene age. Redoximorphic features (brown mottling in a pale green soil matrix) in Fluvaquents represent hydric conditions (seasonally saturated) in young, flood plain soils.

In the Caspian Sea regions, the extensive loess deposits in the area reach a thickness of about 70 m in the loess plateau of Golestan Province. Organic matter accumulation and the formation of mollic epipedon are the dominant processes occur in the steppe (rainfall of 400–600 mm). Calcification and formation of calcic horizons are typical for loess-derived soils. In the north-facing slopes of the Alborz mountain ranges with the forest vegetation and higher rainfall, deeper leaching of calcite and formation of the argillic horizon are dominant. Soils are mainly Alfisols (see Chap. 7). The loess deposits of the study area contain several paleosols showing different degrees of weathering probably related of paleo-climatic conditions and duration of soil development (see Chap. 8). As based on pedostratigraphy and luminescence dating, the paleosols have been correlated with interglacial and interstadial phases of the Middle to Upper Quaternary (Frechen et al. 2009).

South and southwestern Caspian Sea areas are composed of lowlands and floodplains in the north adjacent to the Caspian Sea and piedmonts, hills, and mountains. The precipitation increases from east (Gorgan 600 mm) to west (Anzali 1500 mm). Aquic conditions in soils of lowlands and floodplains are often associated with redoximorphic features. The main soil types are Haplaquepts (Gleysols, WRB 2014), and the soils are showing either episaturation or endosaturation. Aquic moisture regime is associated here with the seawater intrusion resulting in the formation of saline and alkaline soils. The soils are mainly Aquisalids. In the mountainous and hilly areas, the Entisols and Alfisols are dominant. Gleization, salinization, and clay illuviation are the major processes in these regions.

Humid and sub-humid zones: Highlands of Alborz Mountain Ranges in the north-facing slopes are comprised of udic soil moisture regime up to about 1500 m asl. Role of climate is far important than the other soil-forming factors leading to intensive leaching of carbonates and in parts soil acidity. Emadi et al. (2012) studied the soils of Mazandaran Province along an east-west transect in xeric, ustic, and udic regions. Soils of the ustic and udic soil moisture regime were classified as Calcic Haplustalfs and Mollic Halpudalfs (Soil Survey Staff 2014) or Calcic Luvisol and Haplic Luvisol (WRB 2014), respectively, indicating the conditions were favorable for the downward decalcification and the subsequent clay illuviation and formation of moderately to strongly developed argillic horizons. Gleization is another main feature occurring in soils of udic regions mainly due to paddy rice cultivation.

6.2 Soil-Forming Processes

Soil genesis deals with the factors and processes of soil formation. The formation of soil is the result of the interaction of five soil-forming factors: parent material, climate, organisms, topographic position or slope, and time. As mentioned earlier, soil-forming processes are mainly directed by the dominant arid and semiarid climate and highly calcareous conditions. The dominant soil-forming processes are as follows: (1) translocation of silicate clays, (2) calcium carbonate redistribution, (3) gypsum accumulation, (4) salinization, (5) hydromorphism, (6) accumulation and humification of organic matter, and (7) swelling and shrinkage. The net effect of these processes is the development of soil horizons, that is, the genesis of soil.

6.2.1 Translocation of Silicate Clays

Mechanical migration of clay particles down the pores and their subsequent illuviation in the deeper horizons is the commonly accepted major process in the formation of Bt or argillic horizons. Considering the soil-forming factors, majority of the soils in Iran are highly calcareous formed mainly from limestone parent rocks (see Chap. 10). This includes aridic, xeric, and ustic SMR regions of almost all ecological zones (see Chap. 8). In humid regions of northern Iran, the leaching is more intense. Argillic horizons are of different development stages.

In order to quantitatively compare the different Bt horizons, a Micromorphological Index of Soil Evolution in Highly Calcareous Arid to Semiarid Conditions (MISECA) was developed (Khormali et al. 2003). Some main micromorphological features such as clay coating, decalcified zones, Fe/Mn oxides, microstructure, etc., are considered as factors of soil development in MISECA index. Table 6.1 shows classes of degree of soil development according to MISECA. (Khormali et al. 2003). According to the calculated MISECA values, the argillic horizons of the soils in the studied Fars Province differ in their degree of development. Soil-forming factors in this province are very variable, and therefore, the findings could be generalized to other parts of Iran since they are mainly derived from limestone.

Occurrence of clay-enriched horizons or Bt (argillic) has been studied in semiarid and arid regions of Iran (Khademi and Mermut 2003; Khormali et al. 2003). Khormali et al. (2003) studied the ten representative pedons with argillic horizons in Fars Province along with different climates and precipitations gradient of 200 mm to 600 mm. All the studied soils were formed in highly calcareous parent material. Based on the genesis and degree of development three types of argillic horizons could be distinguished:

- argillic horizons formed on older landscape units, showing few to highly developed calcite depletion pedofeatures in the groundmass (MISECA = 9–19) (semiarid to regions, precipitation of 400–600 mm)
- argillic horizons with little or no calcite depletion pedofeatures in soils that previously had a high Na content (MISECA = 7 and 9) (semiarid regions, precipitation of about 350 mm)
- argillic horizons with little or no calcite depletion pedofeatures formed in the past wetter conditions (MISECA = 7). (Arid regions, present precipitation of 200–300 mm).

6.2.1.1 Clay Illuviation in Highly Calcareous Conditions

Evidences show that these soils have experienced the decalcification of the upper horizons and subsequent clay migration from topsoil and accumulation in the subsoil. Micromorphology can be a good evidence by the fact that the upper layers and Bt horizons show striated and speckled b-fabric, confirming the decalcification of the

Table 6.1 Classes of degree of soil development according to the MISECA values, based on field and laboratory analyses

MISECA	Degree of soil development
0–8	Weakly developed
9–16	Moderately developed
17–24	Well developed

topsoil while in the Btk horizons combination of the calcitic crystallitic and speckled b-fabric are visible, indicating the simultaneous recalcification and partial dissolution of carbonates. In the Bk horizons, large accumulation of the carbonate as pedogenic features and presence of the matrix carbonate have resulted in the dominance of calcitic crystallitic b-fabric(Figs. 6.1 and 6.2).

In the Btk horizon, coatings of secondary carbonate along channels and other voids have been subsequently covered by coatings of strongly oriented reddish yellow clay, indicating that decalcification of the upper layers (Ap and Bt) and downward movement of the carbonates occurred prior to the formation of clay coatings. The presence of some calcite coatings overlying clay coatings suggests a later recarbonation followed by movement of carbonate (Fig. 6.2).

Most micromorphological studies of argillic horizons in arid, semiarid, and Mediterranean regions have shown few to no clay coatings present. This could be related to the strong shrink/swell properties of soils with large clay contents and periodic moist and dry phases (Kemp and Zarate 2000).

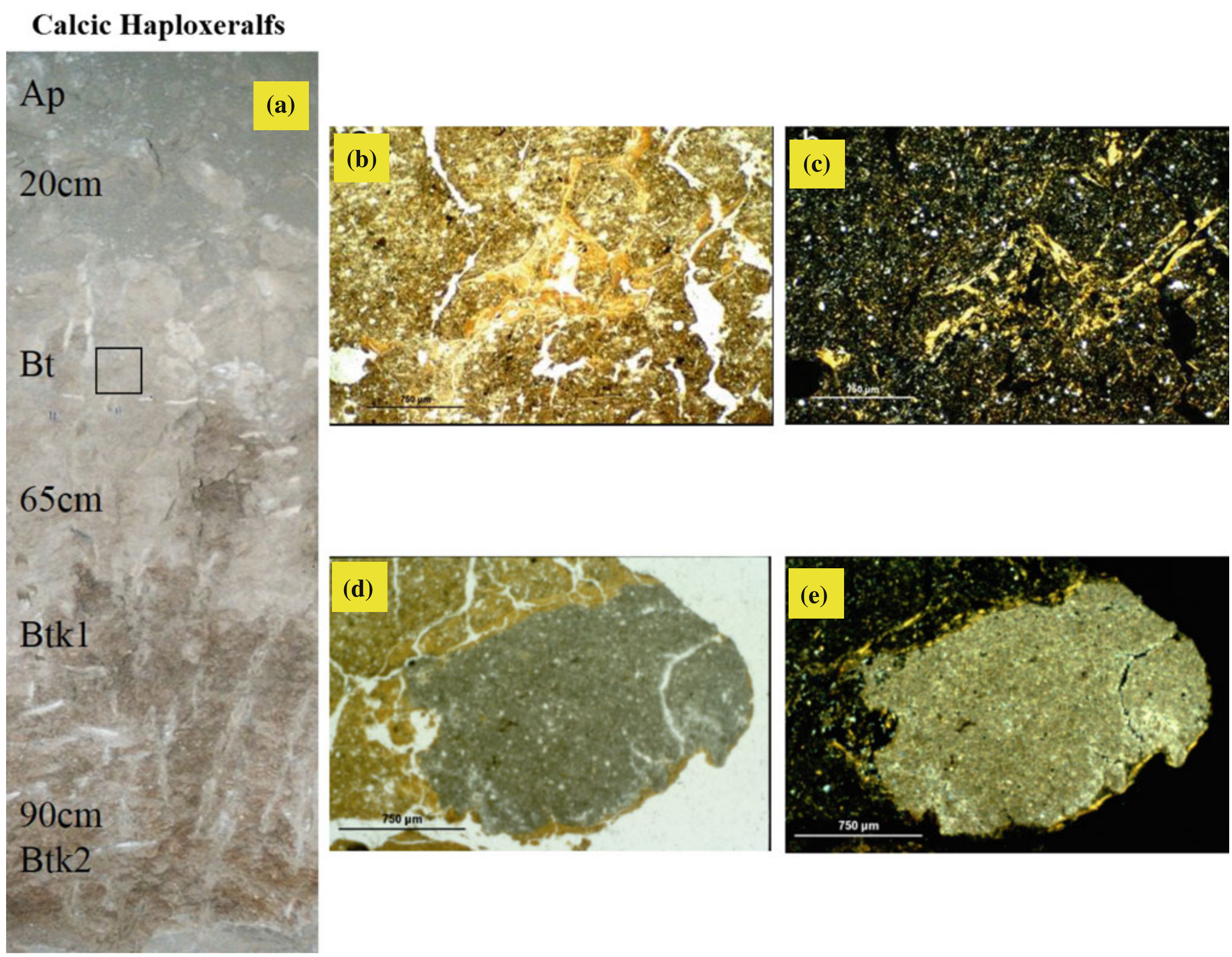


Fig. 6.1 **a** A Calcic Haploxeralfs in Fars Province; (**b** and **c**): Plain polarized light (PPL) and Crossed-polarized light (XPL) images showing speckled b-fabric and clay coatings in Bt horizon; (**d** and **e**): PPL and XPL of a typic calcite nodule coated by illuvial clay in the Btk horizon (Khormali 2003)

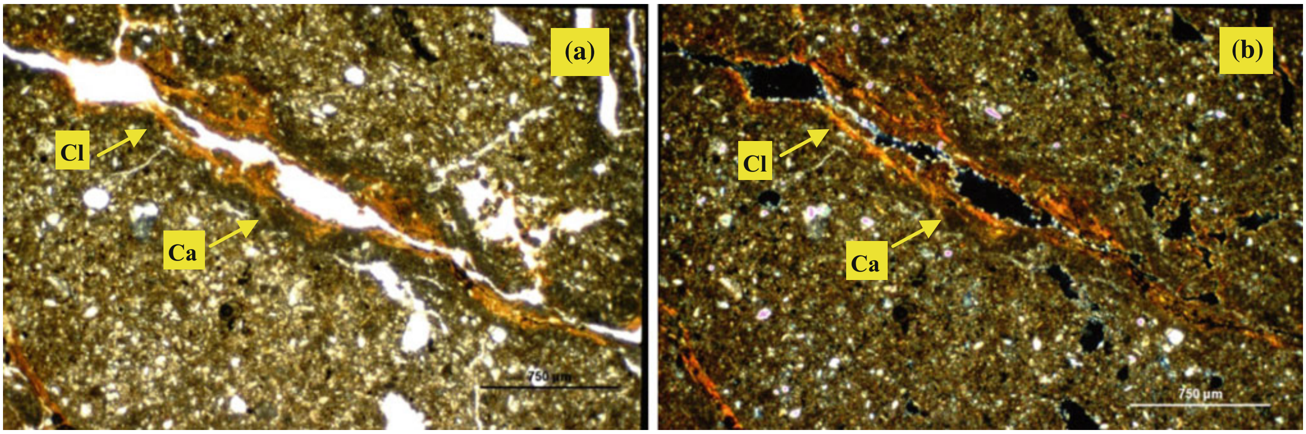


Fig. 6.2 Clay coatings (Cl) invaded by calcite (Ca) as a result of recalcification (Calcic Haploxeralfs, Btk2). **a** PPL and **b** XPL (Khormali 2003)

In contrast to the high calcareous soils of major parts of Iran, argillic horizons of the northern Iran and specifically those of loess origin are less calcified. Clay coatings are best expressed in soils formed in humid regions showing the speckled b-fabric. From the semiarid zones to the humid regions, the thickness of the clay coating and the area covered by clay coatings increased. Thicker oriented clay coatings (50–300 µm) were associated with relatively higher clay content and higher relative abundance of the vermiculite. The dominance of vermiculite and illite in humid region soils (as opposed to smectite) limited the shrink/swell potential and thus helped reduce the disruption of clay coatings (Khormali et al. 2012). The type of the clay minerals present also affected the thickness and orientation of clay skins. Gunal and Ransom (2006) reported similar results in different soils of the precipitation gradient of 540–715 mm. They showed thicker clay coatings were related to the more humid regions.

Smectite constitutes the major portion of the clay minerals in well-drained Alfisols, somewhat poorly drained Mollisols, and Calcixerepts with high precipitation. It is detected in trace amounts in the soils of more arid areas. Therefore, it can be concluded that in well-drained soils, with increasing soil-available moisture, smectite increases. Increase in soil available moisture, and consequently a relatively leaching environment for the release of K^+ from micaceous minerals and mainly illite, in the calcareous environment with high Mg^{++} and high Si mobility, might provide favorable conditions for the formation of smectite through transformation (Khormali and Abtahi 2003).

The different degrees of development of the argillic horizons are greatly dependent upon the earlier degree of decalcification, and this in turn reflects the effects of soil-forming factors, especially the climate.

6.2.1.2 Clay Illuviation in Previous High Na Condition

According to Abtahi (1977), formation of argillic horizons in arid saline and alkaline environments of Lakes Shiraz and Neyriz is possibly related to the effect of past high sodium content of the lakes. These soils have undergone the following processes:

Salinization–Alkalization—Desalinization—Solonetzation—Steppification

Lakes Neyriz and Shiraz (Lake Maharlu), two of the interior Zagros mountain lakes with saline and alkaline water, are probably remnants of the post-Tethyan sea in Fars Province (Fig. 6.3). Lake Shiraz (Maharloo) contains 5200 ppm of Na and 5320 ppm of Cl (Krinsley 1970). After their maximum development about 20,000 BP, the lakes started drying up because of increasing temperature and evaporation, producing salt-affected soils. According to Abtahi (1977), the formation of argillic horizons in soils near these lakes could be related to clay dispersion resulting from the high sodium content of this saline and alkaline environment.

In such an environment, clay can migrate to lower horizons even in the presence of abundant calcium carbonate. Very few calcite depletion pedofeatures are seen as small areas with speckled b-fabric in the thin sections of Btn horizons and only fragments of clay coatings occur (Fig. 6.4). The lower limpidity of these clay coatings, which is commonly observed in natric horizons, indicates that they contain coarser clay than the coatings in other pedons. The MISECA score is 7 and 9 for these Btn horizons, suggesting weak to moderate development (Khormali et al. 2003).

6.2.1.3 Paleo-Bt Horizons in Arid Regions

According to Khormali et al. (2003), argillic horizons were also identified in the present arid climate. In Ghatrouyeh

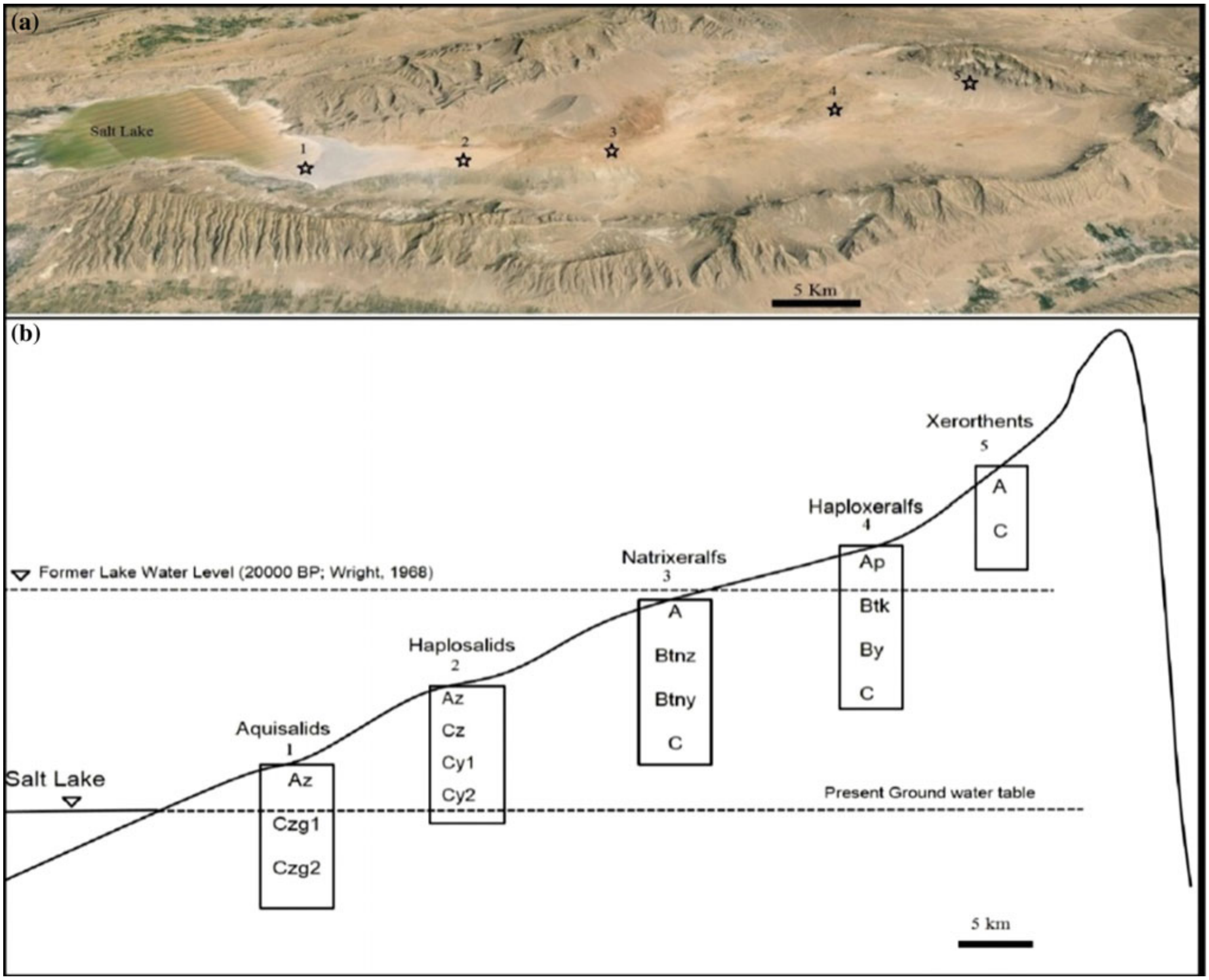


Fig. 6.3 Soil formation along a catena in Sarvestan plain of Fars Province. The sequence of the soils is representing the former saline lake retreatment (Khormali 2003)

plain of Neiriz, Fars Province, a moderately high degree of decalcification is indicated by the presence of many calcite depletion pedofeatures, but the present rainfall is about 200 mm, suggesting that in the past the climate must have been less arid (Fig. 6.5).

Preservation of the argillic horizon within these soils could have been favored by the presence of coarse limestone and other rock fragments, which would act as a stable skeleton allowing preservation of clay coatings under shrink-swell conditions. Argillic horizons seem to form much easier in a coarser than in finer textured soils. MISECA for these Bt horizons is about 7, indicating a lower degree of development than other pedons. The pebble surfaces serve as sites for silicate clay and carbonate accumulations (Gile and Grossman 1968). Several factors may contribute to the stability of pebble surfaces. In contrast to the surfaces of peds of fine earth that move inward and outward as the ped expands and contracts, the surface of pebbles remains stationary unless the pebble is displaced. Volume change of the soil on wetting should be reduced due to less fine earth per unit volume. Furthermore, the fine earth in each interstice between pebbles tends to act as a discrete unit.

Khademi and Mermut (2003) investigated the formation of argillic horizons in central Iran, Isfahan region with aridic moisture regime. They found argillic horizon as the most distinct subsurface horizon of the soils developed on colluvial fans. Evidence of illuviation is provided by the increase in the clay content and the fine to total clay ratio in the subsoil compared to the overlying horizon(s) and by the well-developed, but considerably disrupted, clay coatings observed in thin sections. Since swelling and shrinkage do not seem to be effective, the disruption of clay coatings was likely due to the gypsum and carbonate crystallization process.

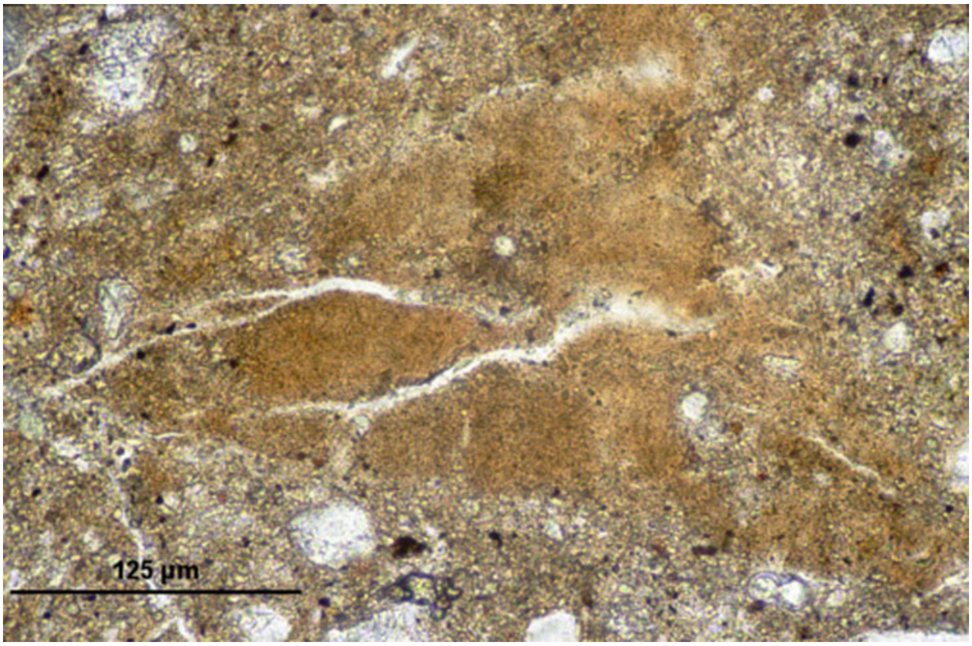


Fig. 6.4 PPL image of the Btn horizon showing speckled clay coatings typical for natric horizons (Khormali 2003)

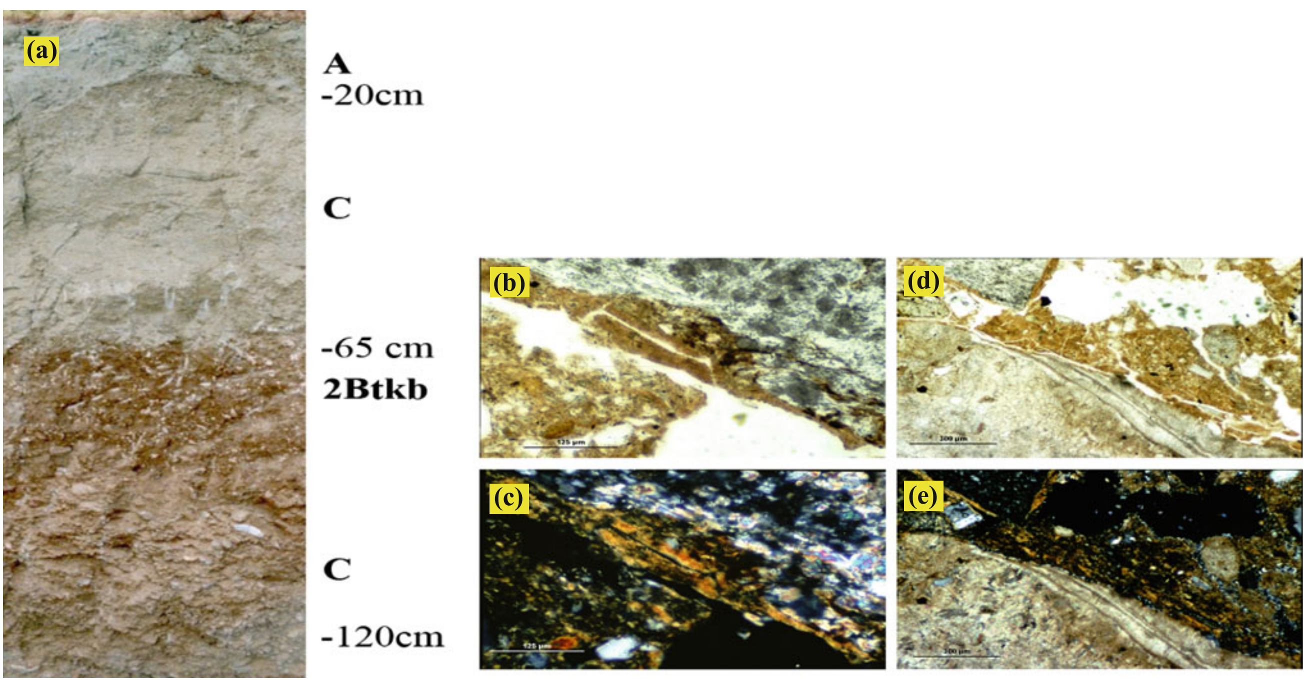


Fig. 6.5 **a** A Typic Torriorthents underlying a buried argillic horizon in the arid region of Fars Province. PPL and XPL micromorphology images show the preservation of clay coatings under (**b** and **c**) and surrounding limestone fragments (**d** and **e**) (Khormali 2003)

The coexistence of argillic, calcic, and gypsic horizons in colluvial soils is a peculiar combination, suggesting a multistage pedogenesis in this landscape. Paleo-argillic horizons were likely developed under a moister environment than today. Sufficient rainfall contributed to the removal of carbonates from the topsoil and the subsequent eluviation of clay to form the argillic horizon. Addition of more carbonates from a colluvial source or as aerosols and the gypsum deposition occurred continuously with time, and these processes slowed down considerably since the area became arid.

Based on geological and biological evidence, Moatamed (1988) has suggested a more humid climate for Iran in the early to middle Holocene. Mahmudi (1987) believes that, during the period of glaciation, central and southern parts of Iran were experiencing a climate with more rainfall than today, whereas in interglaciation periods, the climatic conditions were rather the same as today. The stable isotope geochemistry of the gypsum hydration water from the soils showed the preservation of isotopically lighter water which is an indication of an environment with more precipitation (Khademi et al. 1997). The paleo-argillic horizon was likely formed during a period of more moisture. During the transition from the moister climate to today's arid conditions, gypsum accumulation likely occurred with an isotopic signature of the paleo-environment. The present moisture regime is not sufficiently moist to move clays down in the profile.

6.2.2 Calcium Carbonate Redistribution

Soil carbonate is an important soil component because it serves as an indicator of landscape stability and paleoclimate, it affects nutrient availability, and it has implications for carbon sequestration (Gile et al. 1966; Cerling 1984; Monger et al. 2011). Without invoking biomineralization processes, many authors have traditionally, and successfully, modeled the precipitation and dissolution of calcium carbonate in soil using the classical equation below:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

6.2.2.1 Calcitic Features in Arid Regions

The soils in arid and semiarid regions of Iran are mainly calcareous. The presence and the mode of formation of secondary carbonates were established by the carbon and oxygen stable isotopes (Khademi and Mermut 1999). The large amount of carbonates in the surface horizons is due to addition of carbonatic debris to the surface horizon by colluviation and aeolian processes. Below the A horizon, secondary carbonates occur as soft masses and nodules. In Btky horizons, coexistence of secondary carbonates and gypsum either as pendants below the pebbles or as crystals filling the soil pores are the major macromorphological features observed within the very gravelly soil matrix.

Several lines of evidence suggest that carbonate accumulation in the Btky horizons occurred both before and after clay accumulation. These include the presence of clay skins on secondary carbonate crystals observed in micromorphological studies, the presence of both calcic and argillic horizon at depths >1 m, and the higher amount of primary calcium carbonate in the topsoil and secondary carbonates in the subsoil as proven by the stable isotope approach (Khademi and Mermut 1999). The dissolution of carbonate from the topsoil and its precipitation in the lower horizons created favorable conditions for the removal of the clay particles from the topsoil and flocculation of these particles in the zone, where carbonate accumulated. The lower content of nodules in the more arid areas can be explained by a lower precipitation slowing down the process of dissolution—recrystallization and therefore limiting the formation of nodules.

Depending upon soil texture and degree of soil development, a different development of the carbonate pendents is observed. It can only be a thin, single layer of micritic calcite underneath the gravel in the less developed soils or show an alternation of darker micrite and lighter sparite bands in the more developed and somewhat heavier textured soils (Fig. 6.6). The dark-brown bands may be clay and/or organic matter (Treadwell-Steitz and McFadden 2000).

According to Blank and Fosberg (1990), layered carbonate coatings around pebbles represent a stratigraphic sequence and are generally older than the late Pleistocene.

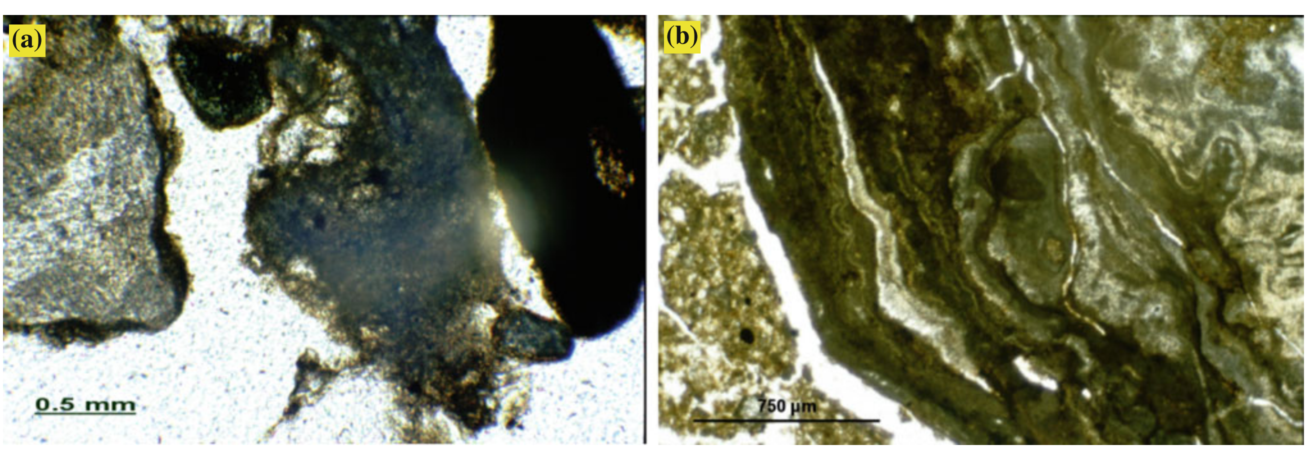


Fig. 6.6 **a** PPL images of the calcite coatings in a. less developed Torriorthents with only thin coating and **b** higher developed Haplocalcids showing many alternating bands of calcite accumulations (Khormali 2003)

Therefore, the presence of calcite pendants in these pardons can be considered as an indication of their formation during less arid climate of the past.

6.2.2.2 Calcitic features in semiarid regions

In contrast to the arid regions, the more favorable climatic conditions and denser vegetative growth in the semiarid regions could accelerate the process of dissolution–precipitation and recrystallization of calcite. The higher degree of dissolution of carbonates from the surface horizons and their precipitation in the deeper horizons are confirmed by the relatively high difference in the total $CaCO_3$ in the surface compared to the deeper horizons (Khormali et al. 2006), and the presence of only a few to common nodules in the near surface horizons compared to the large number of nodules in the deeper sola.

The calcite depletion pedofeatures, expressed partly by a speckled b-fabric, especially in the more developed Haploxeralfs are also an indication of higher dissolution and depletion of calcite in upper horizons (Khormali et al. 2003). The impregnation of some calcite nodules by Fe-oxide is the result of a higher degree of weathering, liberating iron from primary minerals. The presence of weathered limestone fragments in such soils confirms the higher degree of weathering (Fig. 6.7).

Owliaei (2012) studied the calcitic features of south-western Iran and found that 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 pedonsof 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.

Cytomorphic and needle-shaped calcite are the dominant features in the semiarid regions, rather than calcite nodules, pointing to different processes of accumulation, rather steered by biological factors than pure physico-chemical ones (Fig. 6.8). The occurrence of cytomorphic calcite in the studied pedons suggests the specific environmental conditions for its formation (Herrero et al. 1992): a relative high rainfall and favorable temperature resulting in denser vegetation as indicated by the formation of a mollic epipedon and a high biological activity. Needle-shaped calcite of fungal origin was found are also found beside cytomorphic calcite, in the near surface horizons with higher biologic activity (Khormali et al. 2006, 2014).

6.2.3 Gypsum Accumulation

Formation of secondary gypsum or gypsic horizon is mainly related to the process of recrystallization from previous soil gypsum and precipitation from evaporates in the presence of shallow ground water table. Two sources were responsible for the soils high in gypsum which are geologic formations, outcropped in some areas, and saline lakes high in sulfate. Morphology of gypsum was different related to the environment in which they have been formed. Pendants of gypsum were typical in the plateau soils with high stoniness (Fig. 6.9). Larger elongated crystals of gypsum were formed under the influence of saline ground water table, and small crystalline gypsum is characteristic for well-drained soils high in gypsum content in their C horizon. Gypsiferrous soils mainly occur in areas with P/ET° (ratio of precipitation to evapotranspiration) of less than 0.2, which corresponds, to more aridic climate with high evapotranspiration (Khormali 2003).

Hashemi et al. (2011) suggested that the amount of gypsum accumulation in their study area depends on soil

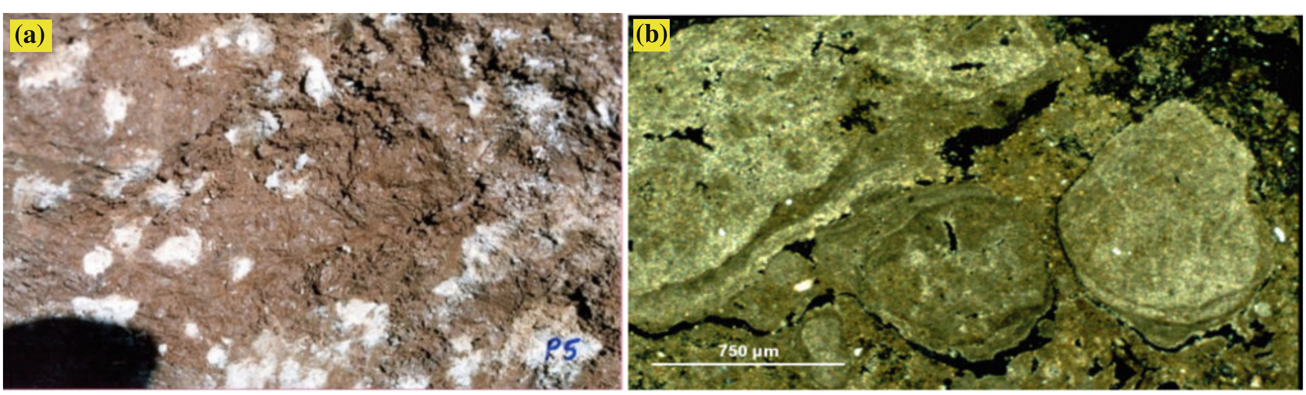


Fig. 6.7 **a** A Btk horizon of a Calcic Haploxeralf in northwestern Fars Province showing soft masses of calcite and **b** XPL images of calcite nodules in the Bk horizon of the same pedon (Khormali 2003)

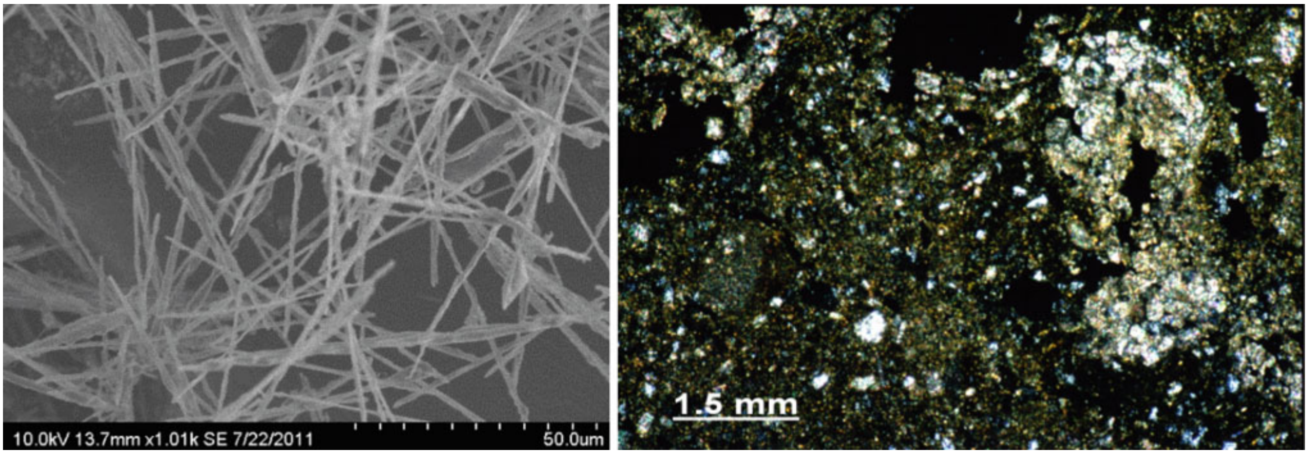


Fig. 6.8 SEM image of needle-shaped calcite (left) and XPL image of cytomorphic calcite (right) (Khormali 2003)

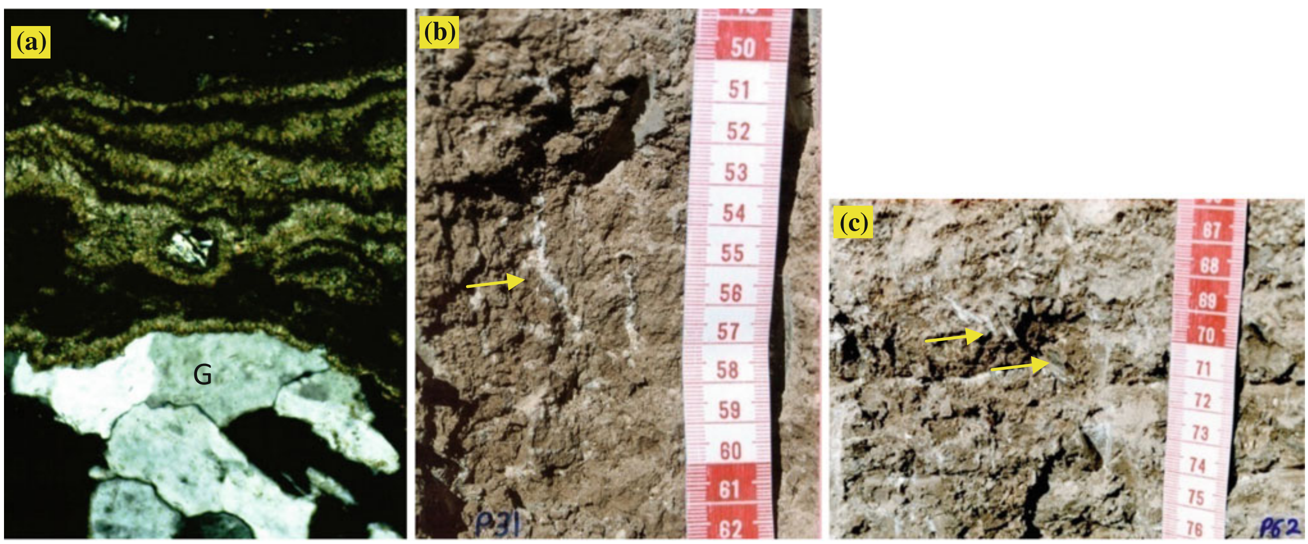


Fig. 6.9 **a** XPL image of gypsum pendant (G) underlying the calcite pendant in a Calcic Argigypsids (**b** and **c**) Gypsum as mycelium and crystals in GypsicAquisalidsin Fars Province (Khormali, 2003)

moisture regimes rather than soil temperature regimes. They also concluded that micromorphology of gypsum crystals vary at different moisture regimes. Interlocked plates, acicular, fibrous,prismatic and blade forms in arid zones, and lenticular gypsum in semiarid zones are dominant; however, in the subsoil, clusters of lenticular, rod like, and tabular shapes are observed. Under hot and dry conditions, due to more evaporation and capillary rise, vertically arranged columnar, cubic, and needle shapes of gypsum were dominant. Toomanian et al. (2001) studied gypsum-enriched soils of central Iran and showed that the distribution, arrangement, and orientation patterns of the secondary gypsum crystals were largely depended to the physical environment. Soil fabric and microstructure, coarse to fine-related distribution pattern and voids play a considerable role in the formation of different gypsic pedofeatures.

With regard to the role of gypsum in the neoformation of clay minerals, Owliaei (2012) found close relationship between palygorskite morphology and depth of soil on gypsiferous landforms with minimum of erosion. Gypsiferous soils showed more pedogenic palygorskite compared to calcareous soils of southwestern Iran Karimi et al. (2009) provided further evidence which supports that the gypsiferous marls of hilly lands of eastern Iran contain palygorskite and the presence of this mineral was used as a proxy for origin of loess in that area. Palygorskite is considered to be inherited in plateau soils of the arid regions, whereas its occurrence in saline and alkaline soils and soils high in gypsum is mainly of authigenic origin.

Farpoor (2012) studied the soil–geomorphology relationship in the Sirjan area of southern-central Iran and mentioned that pediments with the most gypsum and palygorskite accumulation have been the peripheries of such closed water bodies of the past times. The lack of palygorskite in mantled pediments could be a clue to support the argument that pediments of the area have been located at positions that are too high to be affected by ancient water bodies. Khademi et al. (1997) and Toomanian et al. (2001) studied the genesis of gypsiferous soils on alluvial fans and fan remnants, where the gypsum source was from upper watersheds. In the study area, gypsum originates mainly from the weathering of Cretaceous limestone and Jurassic shale of the surrounding sediments. Their isotopic work on geochemistry of gypsiferous Aridisols from central Iran confirms that the most common rocks of Cretaceous and Oligo–Miocene age contain an appreciable amount of sulfate with a $\delta^{34}S$ value ranging from 11.45 to 13.96 and the sulfate in the Lower Cretaceous sediments controls the geochemistry of the younger geologic formations and consequently the sulfate in soils. From their point of view, the source of sulfates is from seawater that entered these sediments during tertiary and is a potential source for gypsum.

Considering the morphology and physical characteristics of soils and based on other observations, four genetic stages of gypsic horizons development were proposed (Toomanian et al. 2001):

- *Stage one*: Formation of gypsic lenticular crystals in voids through runoff from geologic sediments carrying gypsum in solution to the soils of the coarse textured upper fans.
- *Stage two:* Continued crystallization of gypsum crystals and formation of xenotopic or hyp-idiotopic morphology.
- *Stage three:* Formation of thin pendants and gypsic horizons with chitonic and enaulic distribution patterns.
- *Stage four:* Formation of hyper gypsic horizons.

In addition to very big-sized gypsum pendants (as large as 10 cm), gypsum occurs as microscopic forms in the gypsic horizons studied. Microscopic gypsum crystals appear as random lenticular and granular crystals, along channels and planar voids with no apparent orientation to the associated surface. Gypsum also occurs as relatively larger interlocking plates.

The sequence of horizons along with their chemical and micromorphological properties reveals that gypsum was accumulated in the deep colluvial soils through the downward water movement (per descendum mode). The formation of gypsum pendants under gravels further supports this hypothesis. Whereas gypsic and salic surface horizons in the alluvial plain are the result of an upward movement of salt-loaded brine (per ascendum mode), lagoonal conditions best describe the deposition of extremely high amount of gypsum throughout the pedons on the plateaus, as supported by the stable isotope geochemistry (Khademi et al. 1997) and clay mineralogy (Khademi and Mermut 1998).

Moghiseh and Heidari (2012) studied the co-occurrence of gypsum and halite and their morphological expressions in Bam region, Iran. Micromorphological observations demonstrate that the dominant cementing agent in the soils is halite rather than gypsum. However, due to the inexistence of petrosalic diagnostic horizon in Keys to Soil Taxonomy, these soils are to be classified as Petrogypsic Haplosalids at subgroup level in Soil Taxonomy. In WRB Taxonomy, they are classified as Petrosalic Solonchaks. Co-occurrence of gypsum and halite in the same horizon, their specific layering and vertical distribution patterns in the studied pedons might be considered as indicators for polygenetic soils in this area.

6.2.4 Salinization

The evolution of salt-affected soils has been studied by several authors (Abtahi 1977). However, the theory developed by Kovda (1973) seems to be the most logical for the calcareous soils of Iran. He has recognized four stages in the formation of soils affected by salinity, they are (i) salinization and alkalinization, (ii) desalinization, (iii) solonetzation, and (iv) dealkalinization.

In an attempt to trace the sequence of soil formation under saline conditions and clay translocation in highly calcareous soils of southern Iran, some laboratory experiments were carried out by Abtahi (1977). Based on his observations, an evolutionary sequence of soil formation under saline condition in the semiarid calcareous material is suggested. This sequence is salinization and alkalization; desalinization; solonetzation; and dealkalization (Fig. 6.10).

The evolution of soil color is important in this sequence. The transition from desalinization to solonetzation is associated with a marked change of pH. Salts in soil cause the clay to be flocculated so that water-dispersable clay content is lower in the saline soils. Dispersability of the clay probably is affected by the same factors as swelling of clay. The type of clay, the exchangeable cation on the clay, the free salts present in the soil, the concentration and composition of the electrolyte, and the presence of other materials in association with clay such as iron oxides, aluminum oxides, and organic matter are the main factors with regard to the clay dispersion. The exchangeable Na appears to be the major cause of clay dispersion and migration after most of the salt has leached. As soon as the excess salt has been leached from the saline-sodic soil, the Na could cause dispersion and migration of the clay.

Through time, Ca dissolved from the calcite in soils and parent rocks could replace the Na out of the exchange sites

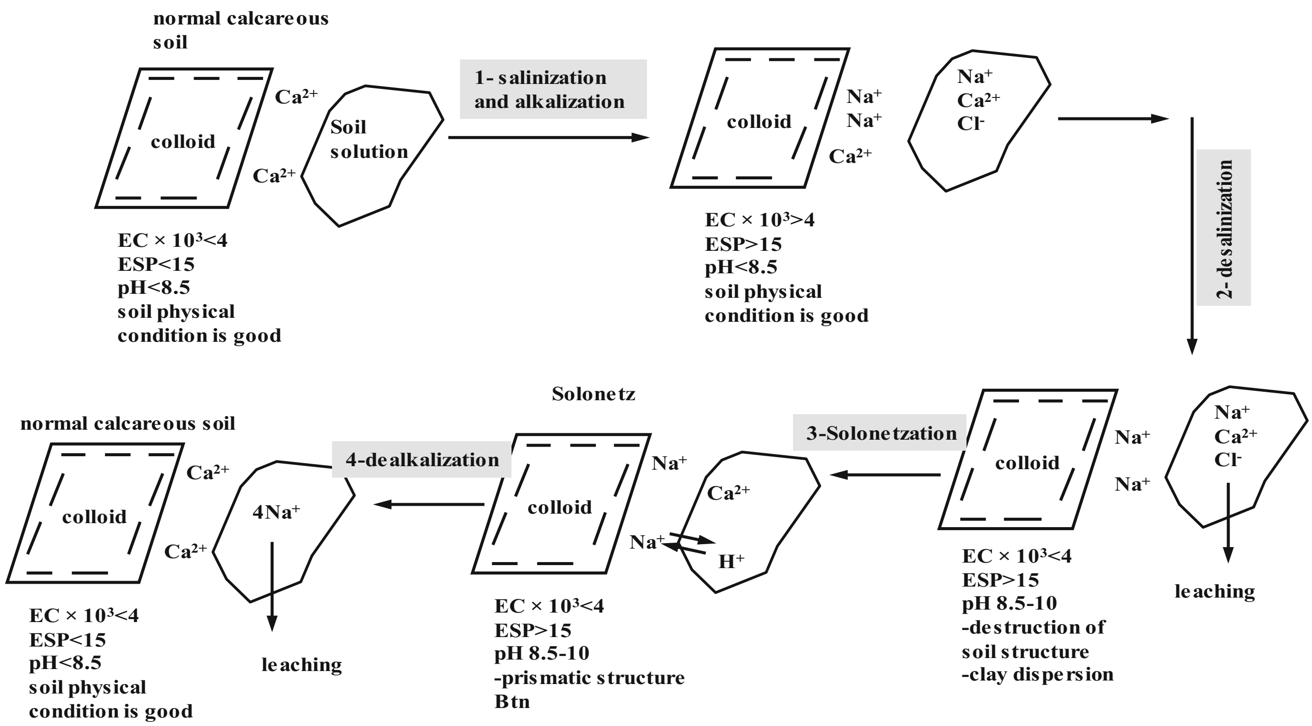


Fig. 6.10 Stages of development of saline-sodic soils under calcareous parent material

and this is the dealkalization stage where the soil physical and chemical conditions become favorable and the normal calcareous soils form.

6.2.5 Aquic Conditions in Paddy Soils

Paddy soils are a kind of artificial hydromorphism or hydragric Anthrosols; soils with prominent characteristics result from human activities, virtually any soil material modified through cultivation or by addition of materials (Fig. 6.11) (Wilding and Ahrens 2005).

Growing rice in soils on alluvial plains is very popular in northern Iran. Surface water irrigation and shallow ground water influence the soil morphology of these soils simultaneously. Hassannezhad et al. (2008) investigated the impact of anthraquic conditions on morphology, the different forms of redoximorphic features and distributions and the processes responsible for the formation or transformation of hydromorphic soils.

The most important processes have been influenced by redox condition, addition and removal of chemical components and soil particles, and changes in physical, chemical and microbiological properties through irrigation or drainage, or both. In other words, gleization and eluviations, mottle forming (oxidized illuviation and segregation of iron and manganese and separation of manganese from iron), degradation, cutan forming, redistribution of exchangeable

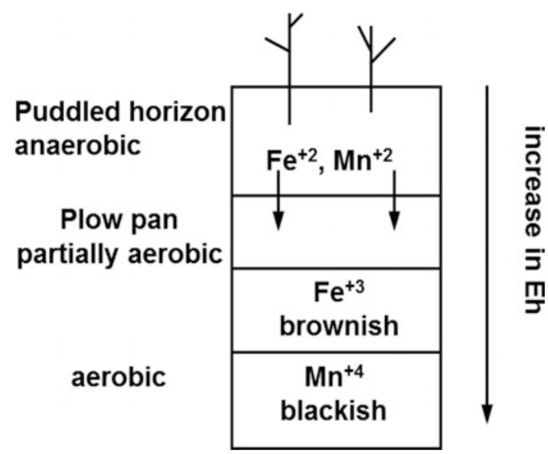


Fig. 6.11 Soil processes in a puddled pedon

bases, accumulation (or decomposition), and alteration of organic matter and other processes lead to the profile differentiation of rice soils.

Results of the study done by Hassannezhad et al. (2008) indicated that the effect of irrigation water on pedogenesis with respect to saturation, reduction, and redoximorphic features was greater than that of the shallow ground water. This study demonstrated that moisture regimes in soils with anthraquic saturation can be characterized in the same way as in soils with either episaturation or endosaturation. On alluvial plains, the soil conditions range from continuously reducing controlled by high groundwater to alternating reduction and oxidation because of artificial submergence and groundwater fluctuations. Artificially induced leaching losses, previously prevented by a high groundwater table, are partly compensated during paddy cultivation by the rejuvenation process of alluvial deposition. Soil samples, which no longer receive river-sediment, are more strongly developed.

Micromorphology provides a means to identify the presence of hydromorphic features that may otherwise be missed in the field if only the naked eye is used. The observation of hydromorphic features in thin sections suggests that careful observations in the field, using a hand lens, may increase the likelihood of identification of horizons in problem soils with aquic conditions. Fe nodules may be one of the easiest diagnostic features to find because they have sharp boundaries. However, these small features appear very similar to Fe-coated coarse fragments, and, in addition, nodules with sharp boundaries are often interpreted as relict features.

6.2.6 Organic Matter Accumulation

Accumulation of organic matter in soils and the formation of mollicepipedon is typical steppe regions with loess parent material. Mollisols are the dominant zonal soils in Golestan Province mainly formed in southern Gorgan River plains where there is a typical steppe climate with the annual precipitation of about 400–650 mm. The parent material contains high amounts of silt particles mainly derived from the loess deposits in the region. The province was formerly called white gold area due to vast cotton fields growing mainly on Mollisols or organic matter rich soils. The total area of Mollisols formed on Gorgan River plain reaches about 100,000 hectares, which reaches to more than 150,000 ha considering those of the hilly regions. Figure 6.12 shows the unique precipitation gradient (>800 mm – <200 mm) along a north-south transect extending from Alborz mountain ranges in south to the border with Turkmenistan in north. Along this transect Mollisols with different degrees of development have formed. Hapludolls/Hapludalfs (Phaeozems/Luvisols) are dominant in the forest–grassland transition zone (600–700 mm) grading to Calcixerolls (Chernozems) in the typic xeric regions (500–600 mm) and finally to Calcixerolls/Haploxerollsin (Kastanozems) the drier parts of the steppe (300–500 mm).

Figure 6.13 shows micromorphological features of a PachicArgixerolls in the Agh-Emam region northeast of the town of Azadshar on the north-facing slope of a loess covered hill rising about 270 m above the plain of Gorgan River. The profile is a typical example of Mollisols in Golestan Province. The parent material is brown, comparatively clayey loess. Soil moisture regime is xeric, and the temperature regime is thermic. The whole hill slope has been formerly under a mixture of pasture and forest. The mean slope of the study site is about 15–20%, and there is no evidence of soil erosion, runoff, and sedimentation in this area. Mollic epipedon is about 80 cm (Pachic subgroup) overlying the argillic horizon of about 30 cm over deep calcic horizon (up to 90 cm thick) overlying the loess parent material.

Very high biologic activity in the mollice pipedon is confirmed by the micromorphological studies showing the dominant excremental pedofeatures along with the well-separated granular/crumb microstructure. Root and organic residues are also dominant. In the Bt horizon, deep decalcification and subsequent clay accumulation have resulted in the development of speckled b-fabric with clay coatings along voids. Calcitic pedofeatures are observed deep in the Bk horizons mainly as nodules, needles, and coatings.

In the dry xeric regions of Golestan Province where the soil is covered by short grass vegetation especially on the north-facing slopes, thin mollic epipedons have formed. The underlying horizons are either cambic or weak calcic horizons. These soils are classified as Typic Calcixerolls or Kastanozems. These soils grade to Chernozems (or Phaeozems) in the southern typic xeric regions and to Inceptisols (Cambisols) or Aridisols (Calcisols) in its northern margin where the humidity is lower and the soil moisture regime is aridic (Fig. 6.14). In contrast to the Mollisols of the more

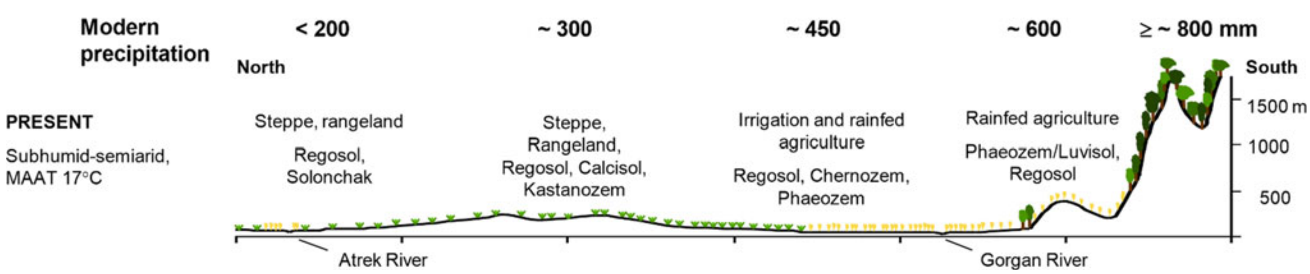


Fig. 6.12 A north-south transect extending from Alborz mountain ranges in south to the border with Turkmenistan in north showing precipitation gradient, vegetation, land use and soils (Kehl and Khormali 2014)

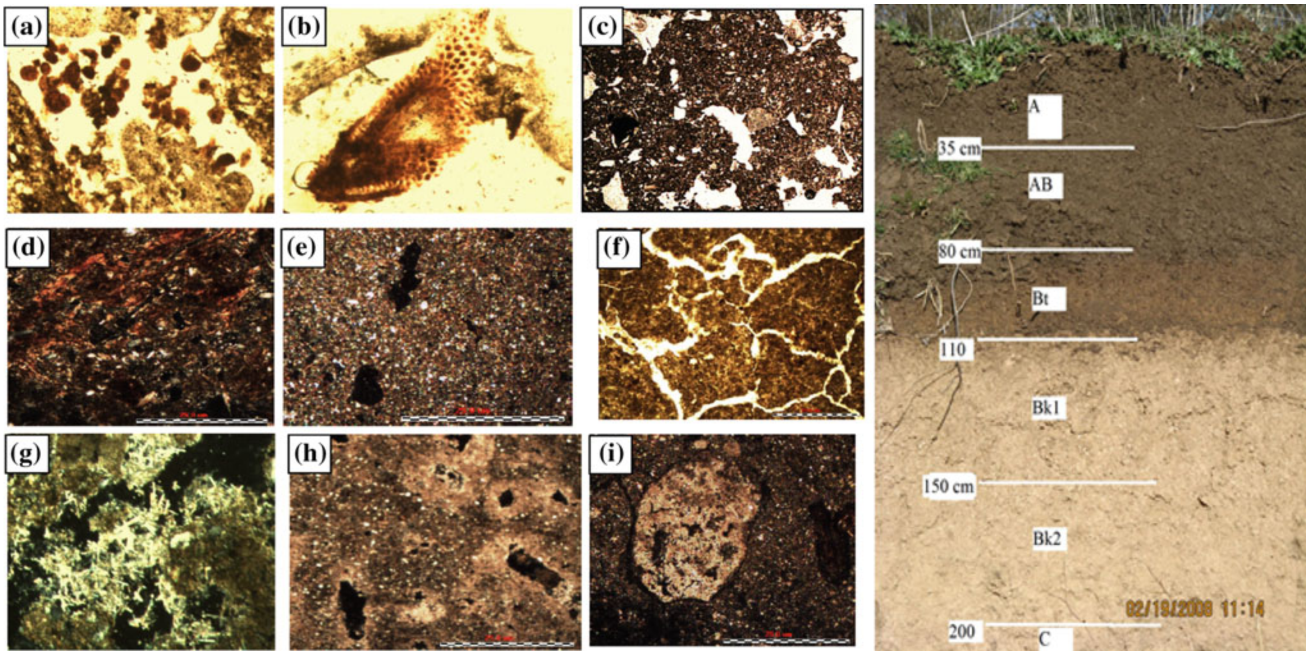


Fig. 6.13 Photograph and micromorphological features of a Pachic Argixeroll in Golestan Province; **a**, **b**, **c**: PPL image showing excremental pedofeatures, root residues, and granular/crumb microstructure in mollic epipedon, respectively; **d**, **e**, **f**: clay coatings, speckled b-fabric and well-separated angular blocky microstructure in the Bt horizon, respectively; **g**, **h**, **i**: needle-shaped, coating, and nodule of calcite in the Bk horizon, respectively under XPL

humid regions, there is no sign of decalcification or clay illuviation in this drier part of the steppe.

Khormali and Kehl (2011) studied the clay mineralogical evolution along a north-south transect in northern Iran with the precipitation gradient of >800 mm in south to <200 mm in north with the border with Turkmenistan. In the aridic regions of northern parts, the dominant clay minerals are illite and chlorite mainly of inherited from loess parent materials. In the typic xeric regions where there is higher soil available moisture (P/ET_ > 0.4), smectite content increases especially in the Bt horizons and is believed to be mainly of transformed origin. Increasing soil available moisture, and consequently a relative leaching environment for the release of K from micaceous mineral sand mainly illite, in the calcareous environment with high Mg^{+2} and high Si^{+4} mobility may provide favorable conditions for the formation of smectite through transformation.

In the more humid areas, vermiculite appears and constitutes the major portion of the clay fraction. Vermiculite is present in small amounts in the loess material, and the occurrence of vermiculite in the forest land is due to higher leaching conditions and the removal of K mainly from mica. In high chemical weathering conditions, hydroxy-interlayer vermiculite can also be formed.

Although Golestan Province is well known for its Mollisols, these soils are also found in other regions where the conditions are suitable. A Mollisol catena in highly calcareous parent material under semiarid 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, the longest time of saturation, and greatest organic carbon content and have 50 cm thick mollic epipedons. Subsurface horizons have characteristics of cambic horizon. No calcic horizon has 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 the discharge from a shallow water table. Evapotranspiration was mainly reponsible for precipitation of seconday carbonates.

The soils formed on the higher landscape positions with very deep water tables 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, because of organic matter addition and transformation, and translocation of $CaCO_3$.

Fig. 6.14 A Kastanozem (Typic Calcixerolls) showing a Mollic Epipedon (Location 37° 35′ 49.7″ N, 55° 25′ 36.3″E)

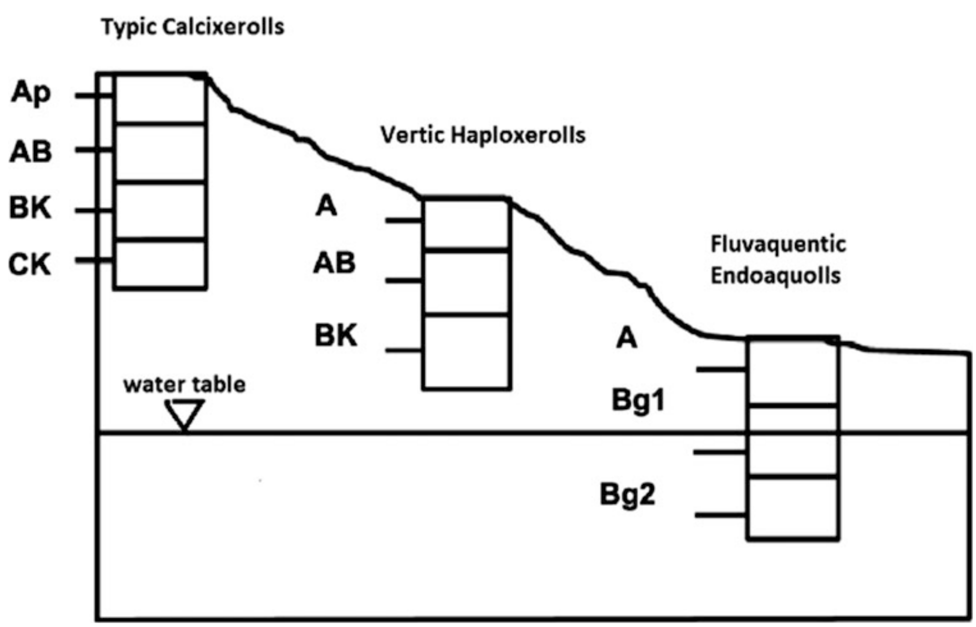


Fig. 6.15 A Mollisols catena in Kurdestan, western Iran (Nabiollahy et al. 2006)

A Mollisols catena was studied in semiarid region of western Iran as illustrated by Fig. 6.15 (Khormali and Nabiollahi 2009; Nabiollahi et al. 2006). Soils formed on the upper section of the alluvial valley bottom i.e., Typic Calcixerolls with the deepest water table, had lower OC and thinner mollic epipedon comparing to other soils. The soils were not saturated and showed no evidence of redoximorphic featuers. Presence of secondary carbonate and calcic horizons were mainly related to the dissolution of the carbonate in the upper soil horizons and its downward leaching and precipitation in the lower horizons. Speckled and striated b-fabric of the near surface soil horizons are the

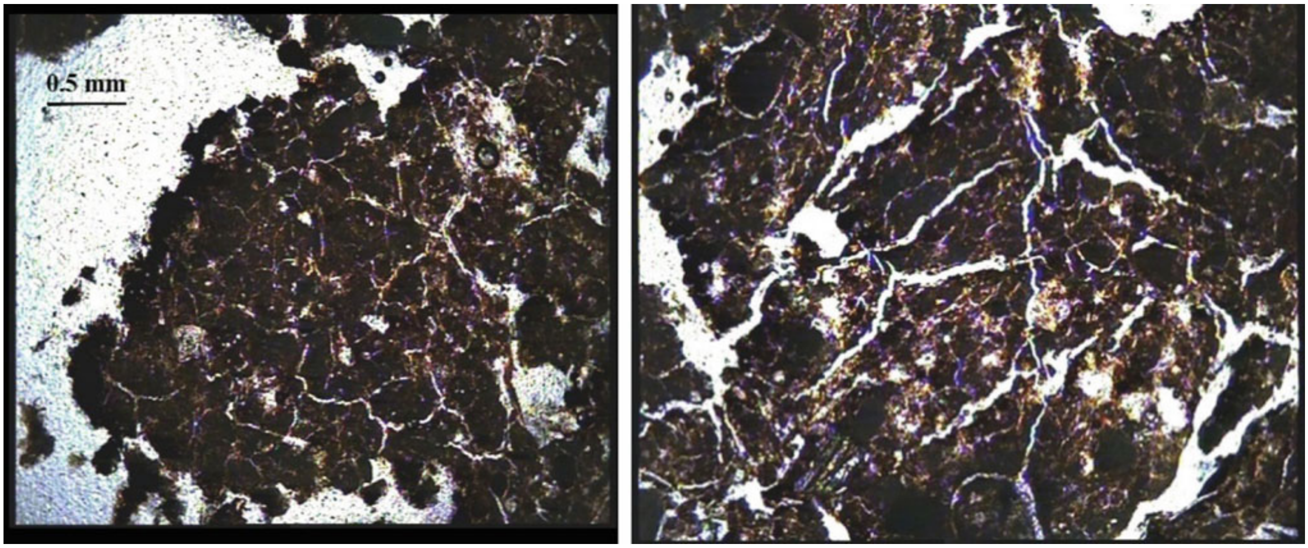


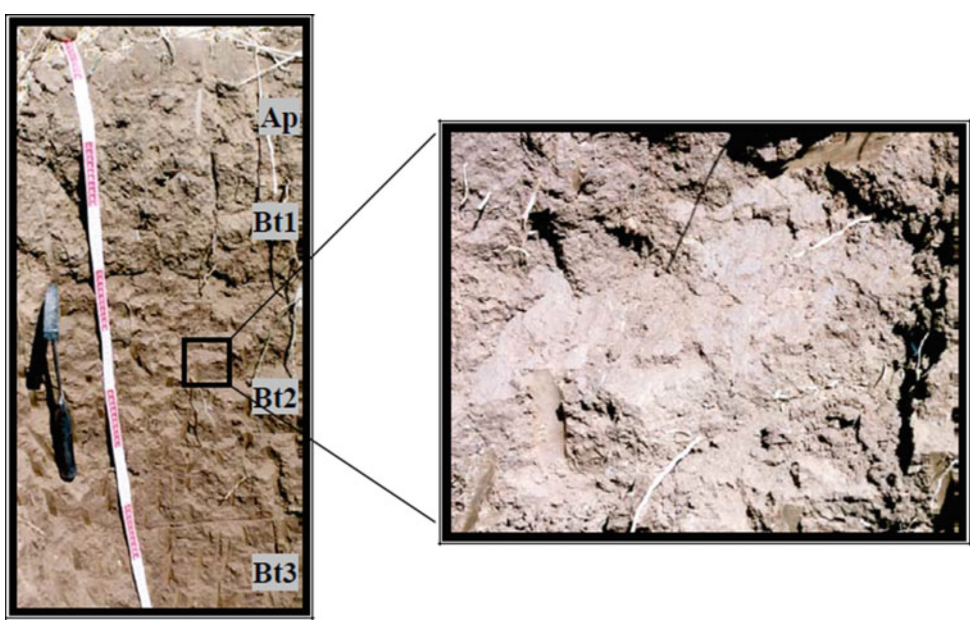
Fig. 6.16 PPL images of the mollic epipedon in Typic Calcixerolls (left) and vertic Haploxerolls (right) showing granular and angular blocky microstructure separated by planar voids, respectively (Khormali and Nabiallahi 2009)

evidences of carbonate depletion from surface layers. Soils of the mid-valley section i.e., Vertic Haploxerolls, with water table depth (1–2 m) have periodic saturation (Fig. 6.16). Thickness of the mollic epipedons and OC were lower than the soils of the lower valley bottom. Soils of the lower valley bottom or low lands classified as Fluvaquentic Endoaquolls had thick dark mollic epipedons and the highest OC comparing to other soils. In the well-drained soils, illite was dominant. In contrast, in poorly drained soils of the lower valley bottom, smectite was the dominant clay mineral. Abtahi and Khormali (2001) found smectite as a major clay mineral in poorly drained Calciaquolls of southern Iran.

6.2.7 Vertic Features

Vertisols in Iran were developed in regions with different climatic conditions and bedrock compositions. Khormali (2003) reported the formation of slickensides in Vertisols and Vertic Haploxeralfs in Fars Province containing high smectite (Fig. 6.17). Heidari et al. (2005b) carried out a mineralogical and micromorphological study to characterize Vertisols from separate regions, revealing an aberrant soil composition for one study area, where the clay fraction is not dominated by smectite. Vertisols are mainly characterized by the occurrence of planar voids, a porphyricc/f (coarse/fine)

Fig. 6.17 High shrink-swell properties resulted in the formation of slickensides in a Vertic Haploxeralfs in Fars Province (Khormali 2003)



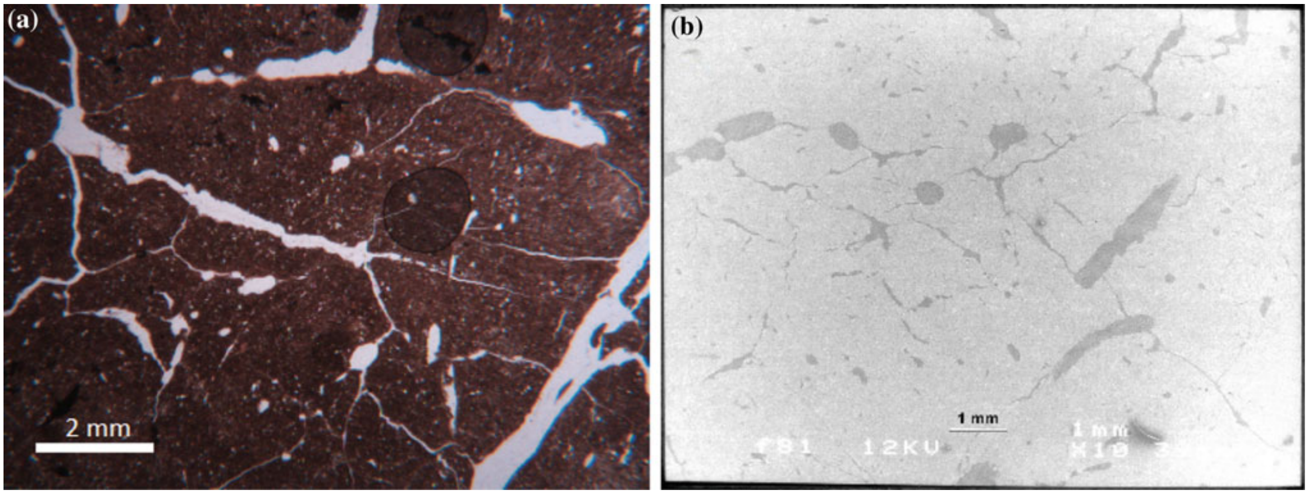


Fig. 6.18 Planar voids associated with moderately separated angular blocky microstructure as wedge-shaped peds in a Haploxerert (**a**. PPL, and **b**. Backscattered SEM, Khormali, 2003)

related distribution pattern and striated b-fabrics, as far as this type of b-fabric is not masked by microcrystalline calcite (Fig. 6.18). Common pedofeatures are various types of carbonate and Fe/Mn hydroxide accumulations.

The composition of the clay fraction of the studied Vertisols shows that development of vertic properties is not always determined by the presence of smectite, but that it can also be related to high fine clay content. The presence of high amounts of fine clay, which is not necessarily smectitic, can be sufficient to cause vertic behavior (Heidari et al. 2005b).

6.3 Conclusion

Major parts of Iran are of arid and semiarid climate, and there is a high amount of calcium carbonate in soils. Climatic zones therefore seems best describe the formation and distribution of soils, and the major soil-forming processes are those associated with soil carbonate redistribution and soluble salts. Local conditions determine which process is dominant. In arid regions therefore, calcitic features, salinization, and gypsification are dominant. In the semiarid zones, clay illuviation, organic matter accumulation, and vertic processes are observed. In the subhumid and humid regions, the illuviation of clay is more intense and gleization is the other major process. To better understand how the soil-forming processes act, the geomorphic background and paleo-environmental reconstruction seems also of great importance.

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