Micromorphological characteristic of salt affected soils

1. Optical Properties

Salt affected soils from each location have different micromorphological properties. The full micromorphological descriptions of salt affected soils are given in Appendix B. Figures 49-53 show the micromorphological features of surface soils whereas micromorphological features of subsoils are given in Figures 54-58. Micromorphological characteristics will be described separately for representative locations and for surface soils and subsoils.

1.1 Micromorphological Features of Surface Soils

Micromorphological examination of soils in the study found differences in size of materials between each location and between surface soils and subsoils. Consequently the microstructure of these soils differs. Surface soils mostly have more coarse sized materials than subsoils except for the depositional layers that are present in some pedons. The microstructure of coarse textured salt affected soils is compact grain, bridged grain and intergrain channel structure for location 1 (Figure 49). For location 3 common microstructure is vughy, compact grain and single grain (Figure 51) whereas compact grain and pellicular grain structure are common for location 5 (Figure 53). These microstructures are normally found in sandy soils. Fine texture salt affected soil shows common channel structure and moderate subangular blocky structure at location 2 (Figure 50) whereas weak to strong developed angular and subangular blocky structures are common at location 4 (Figure 52). Pores are mainly simple packing voids, vughs and channels for locations 1, 2, 3 and 5 and planar voids for location 4.

Quartz and runiquartz grains are common as skeleton materials and are present in different sizes and amounts reflecting the diversity of parent materials. Quartz grains at location 3 are smaller in sizes than that at the other locations. The coarse/fine ratio with a lower size limit at 10 μm is the same for locations 1, 3 and 5 (coarse faction is more than 60%). Locations 2 and 4 have a fine fraction greater than 60 percent. Quartz grain shapes are subangular to subrounded with various sizes. Zircon crystals occur at all locations. The fine fraction consists of variously colored clay to fine silt materials with a dotted appearance. Organic pigments are common in surface soils materials. The clay and silt materials mixed with organic pigment are present only in Pedons 3 and 11 at location 1 and location 3 (Figures 49c and 51a) which is probably due to this area has received organic matter as a soil amendment.

Impure halite occurs in voids as a common crystalline pedofeature for locations 1, 2, 4 and 5 (Figure 49, 50, 52 and 53), and the amount of halite varies considerately within a pedon. The impure halite is distinct in pedons that have a salt crust or salt patch. The crystalline halite is not present at location 3 which has relatively low EC values and no evidence of salt observed in the field. Calcite is present only in Pedon 1 (Figure 49a). Amorphous pedofeatures consisting of manganiferrous impregnative s-matrix are present at location 1 (Figure 49d) and manganiferrous impregnative nodules are present at locations 2 and 3 (Figures 50a, e and 51b-e). A texture pedofeatures consisting of clay mixed with manganiferrous mottle is present in location 2 (Figure 50d) and loose continuous excrement infilling is present in location 4 (Figure 52).

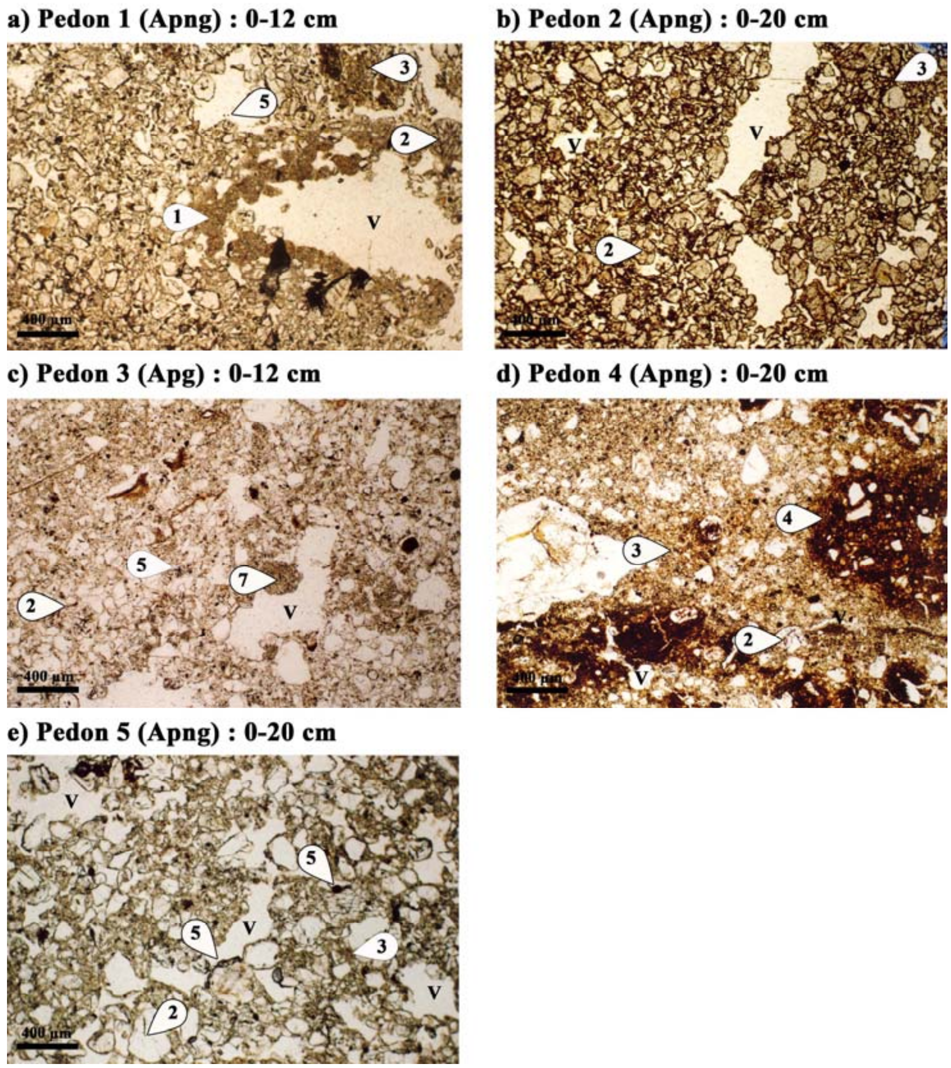

Figure 49 Micromorphological features of the surface soils for salt affected soils at location 1.

1 carbonate materials

2 quartz/ runi-quartz grains

3 clay bridged or surrounded quartz grains/ variously colored clay to fine silt materials

4 manganiferrous impregnative s-matrix

5 impure halite in voids/ coated on wall of voids

7 clay and silt materials mixed with organic pigment

V void

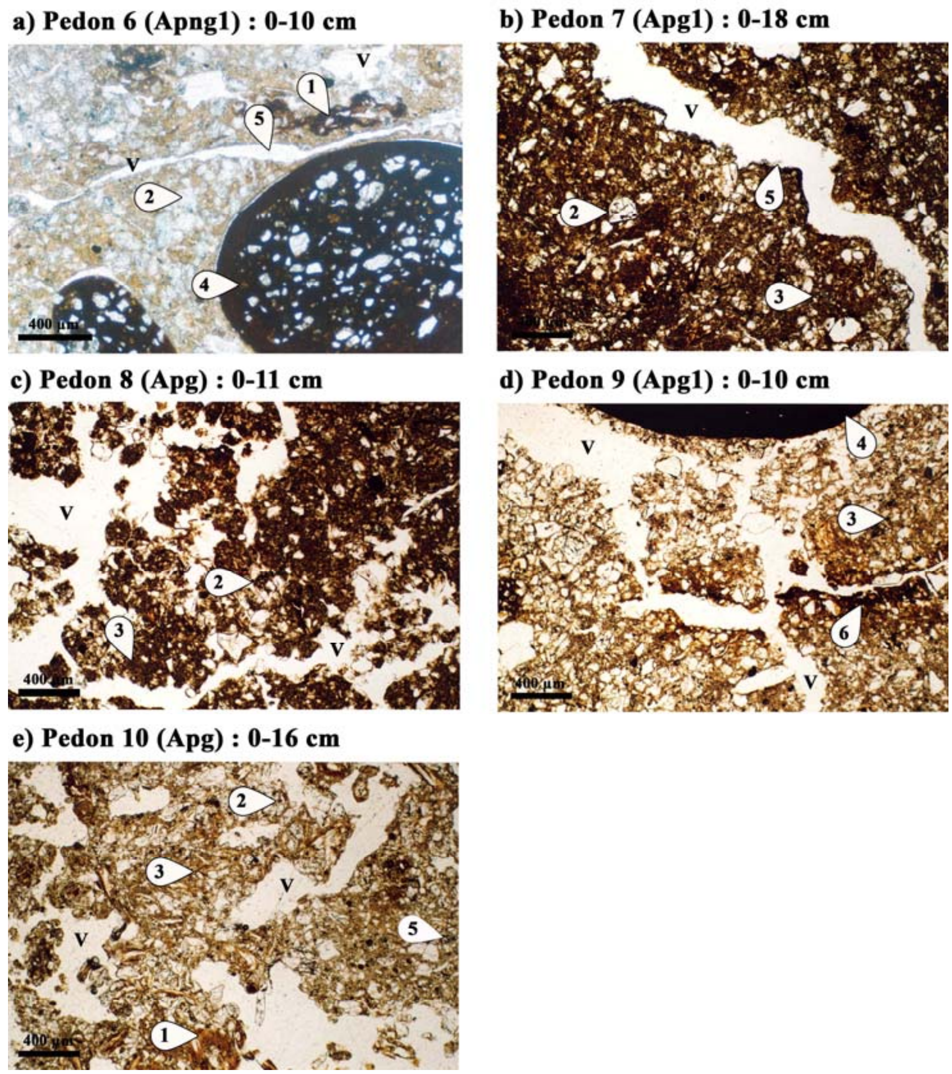

Figure 50 Micromorphological features of the surface soils of salt affected soils at location 2.

1 plant tissue residue; 2 quartz/ runi-quartz grains

3 variously colored clay to fine silt materials

4 manganiferrous impregnative s-nodules

5 impure halite in voids/ coated on wall of voids

6 clay mixed with manganiferrous mottle

V void

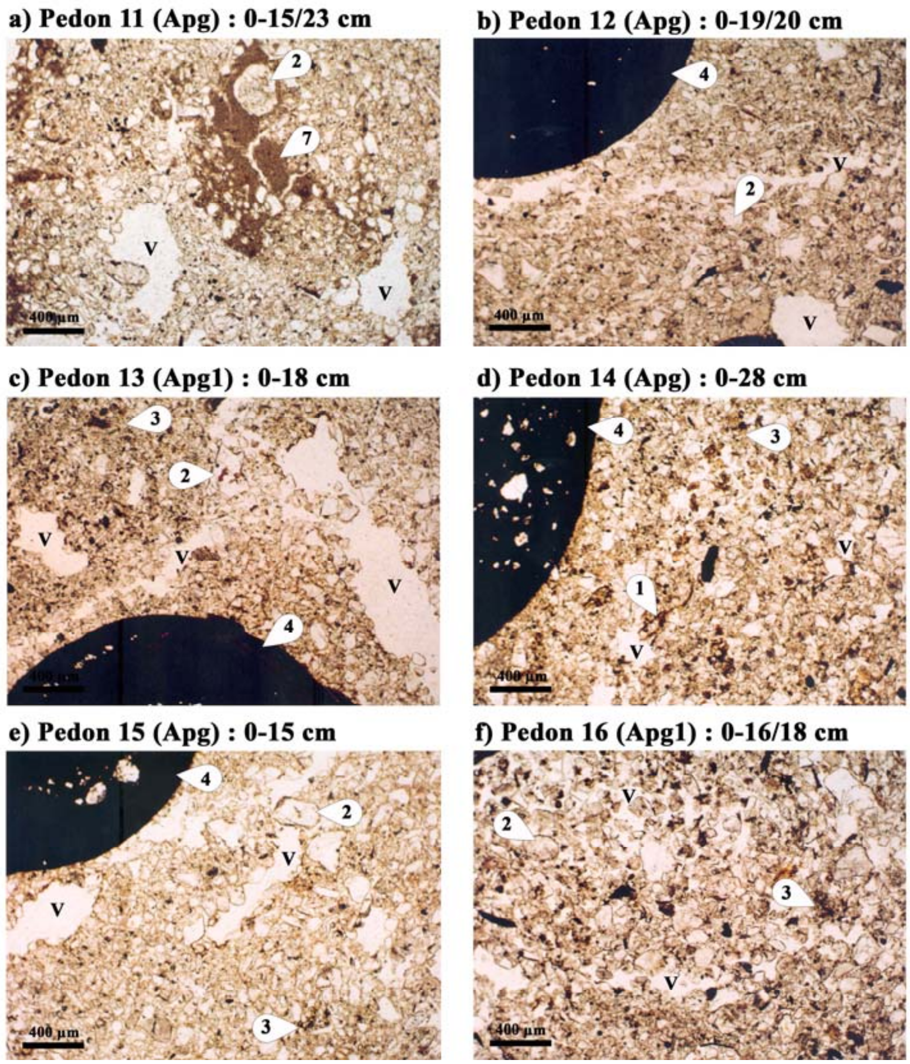

Figure 51 Micromorphological features of the surface soils of salt affected soils at location 3.

1 organic pigment/ highly decomposed plant tissue residue

2 quartz/ runi-quartz grains

3 variously colored clay to fine silt materials

4 ferruginous or manganiferrous impregnative nodules

7 clay and silt materials mixed with organic pigment

V void

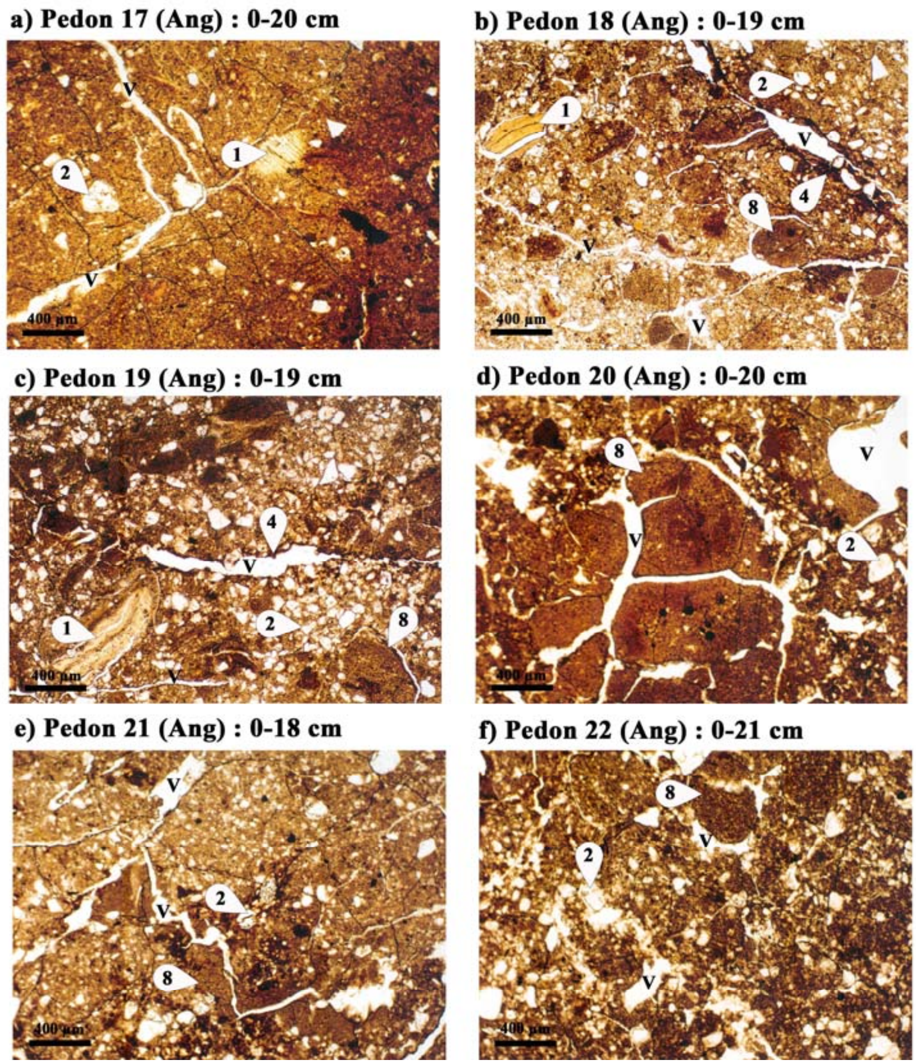

Figure 52 Micromorphological features of the surface soils of salt affected soils at location 4.

1 plant tissue residue;

2 quartz/ runi-quartz grains

4 clay hypo-coating

8 loose continuous excremental infilling (clay and fine silt materials)

V void

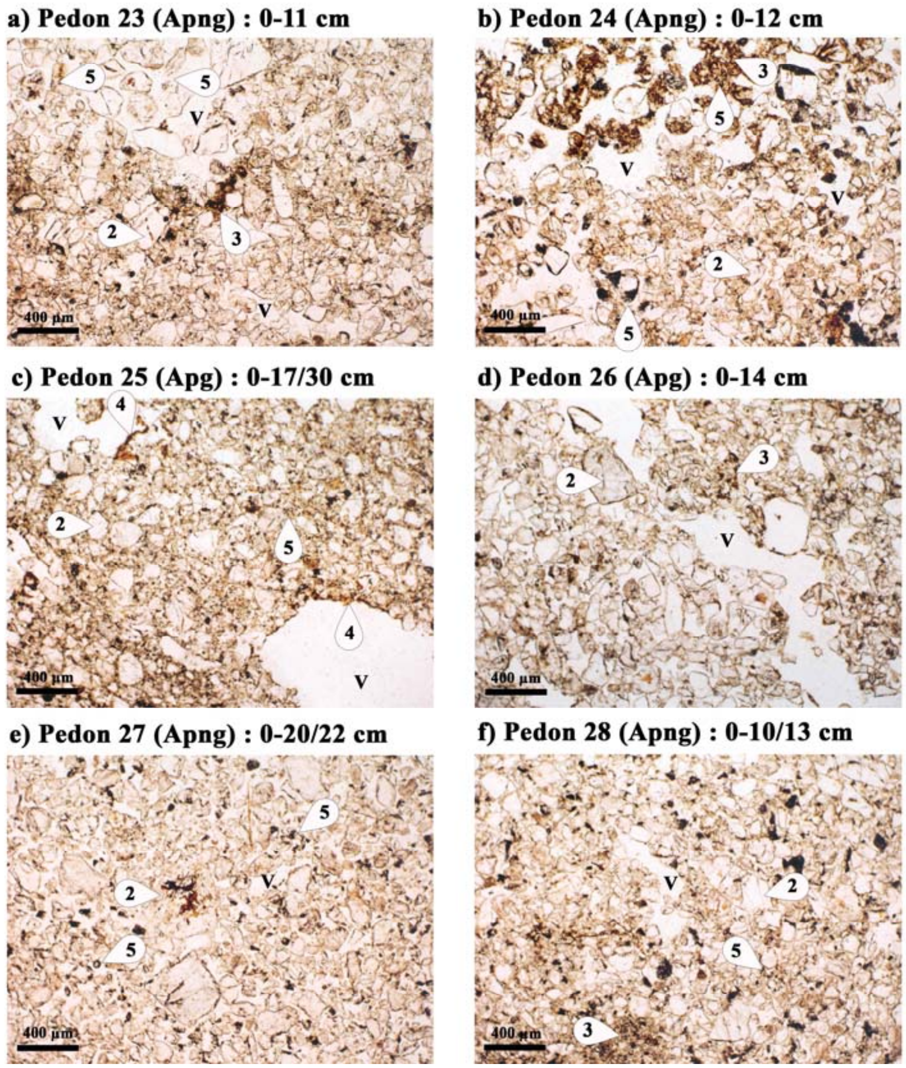

Figure 53 Micromorphological features of the surface soils of salt affected soils at location 5.

2 quartz/ runi-quartz grains

3 variously colored clay to fine silt materials

4 clay coated on void

5 impure halite in voids/ coated on wall of voids

V void

1.2 Micromorphological Features of Subsoils

The micromorphological features of subsoil horizons are shown in Figures 54-58. The bridged grain structure is a common microstructure for location 1. Location 2 soils contain channels and has a subangular blocky structure, soils at location 3 have a channel structure, and weak to strong developed angular and subangular blocky structures are common in location 4 whereas compact grain structure and bridged grain structure are common in location 5. The minerals in the coarse fraction are the same as in the surface soils, but the amount decreases in the subsoils particularly for location 3, reflecting the less sandy textured. The fine fraction of the soils has various colors with the clay to fine silt size materials having a dotted and speckled appearance.

Impure halite in voids is a common crystalline pedofeature for locations 1, 2, 4 and 5 (Figures 54, 55, 57 and 58). In addition, the prismatic gypsum cluster is present as crystalline pedofeatures in location 2 (Figure 55). The amorphous pedofeatures are manganiferrous impregnated nodules and impregnative s-matrix which are present at all locations (Figures 54-58). The manganiferrous impregnated nodules (Figures 55, 57 and 58) are present at locations 2, 4 and 5 whereas manganiferrous impregnated s-matrix is present at all locations (Figures 54-58). A common textural pedofeature consists of clay or clay mixed with iron oxide which coats and infills voids (Figures 54-58). All subsoils have clay coatings on the walls of voids and on quartz and bridged grains. This is the characteristic of an argillic horizon where illuvial clay has been introduced. Sand grain shapes vary from subangular to subrounded indicating a mixture of long and short distance water transported materials which is consistent with the diverse provenance of these soils. Runi-quartz grains may also be an indicator of water transported materials (Buol, *et al.,* 2003). Concretions and nodules of iron-manganese oxides occur in the soils. The former may indicate the occurrence of wetting and drying cycles with associated oxidation-reduction (James and Bartlett, 2000) whereas concretions indicate transporte materials and nodules are formed *in situ* (Stolt, *et al*., 1994).

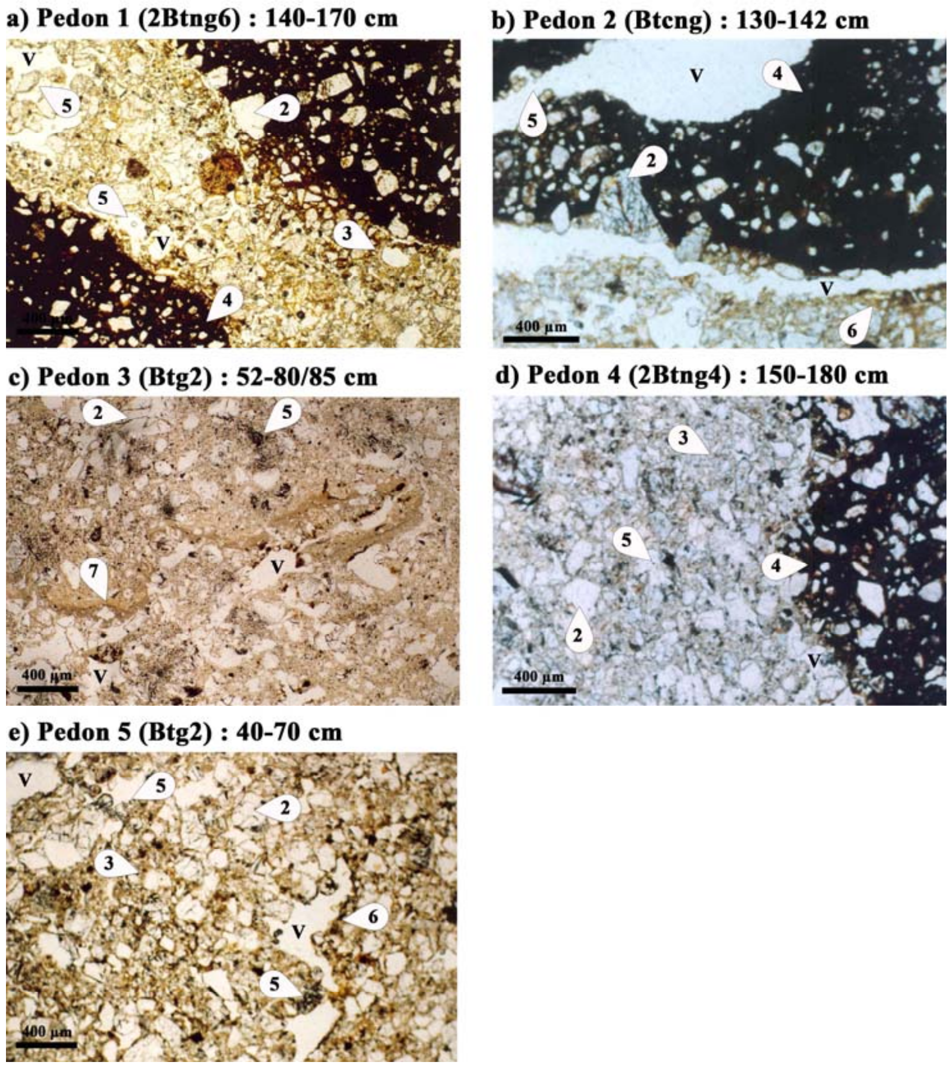

Figure 54 Micromorphological features of subsoils for salt affected soils at location 1.

2 quartz/ runi-quartz grains

3 clay bridged or surrounded quartz grains/ variously colored clay to fine silt materials

4 manganiferrous impregnative s-matrix

5 impure halite in voids/ coated on wall of voids

6 clay hypo-coating

7 clay infilling

V void

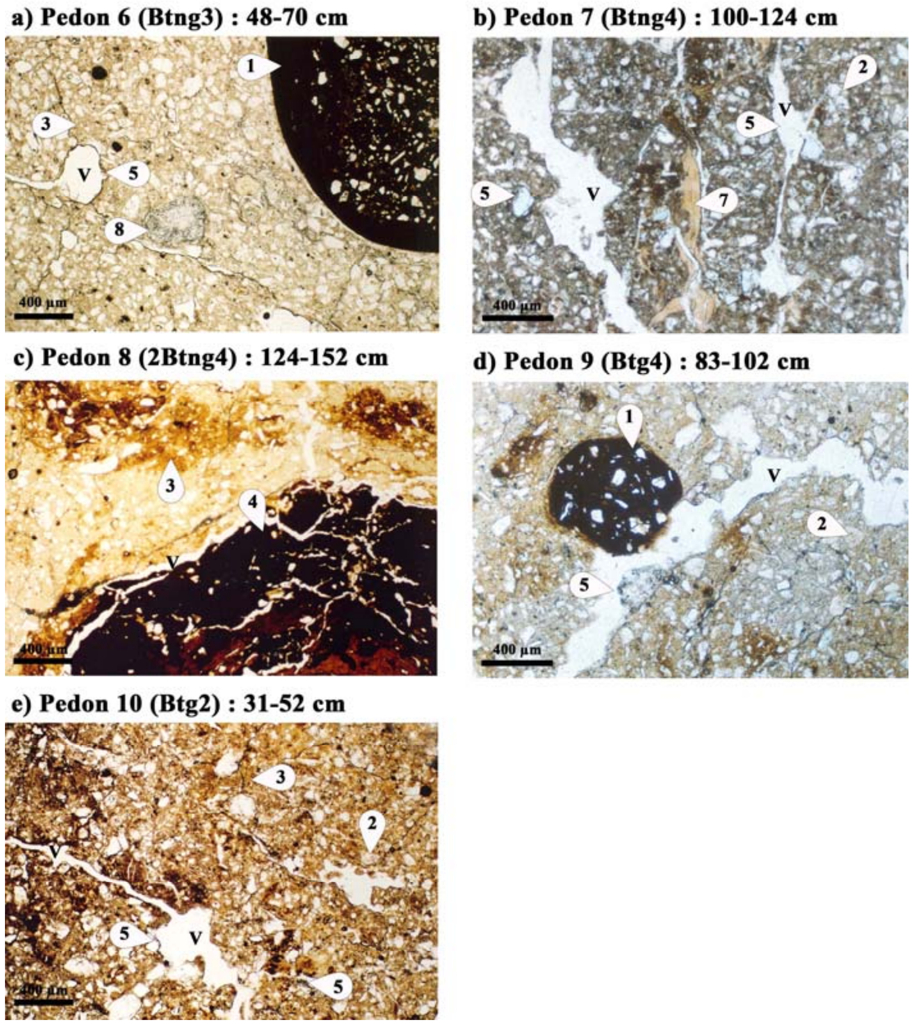

Figure 55 Micromorphological features of subsoils for salt affected soils at location 2.

1 manganiferrous impregnative nodules

2 quartz/ runi-quartz grains

3 variously colored clay to fine silt materials matrix

4 manganiferrous impregnative s-matrix

5 impure halite in voids/ coated on wall of voids

7 clay infilling

8 gypsum

V void

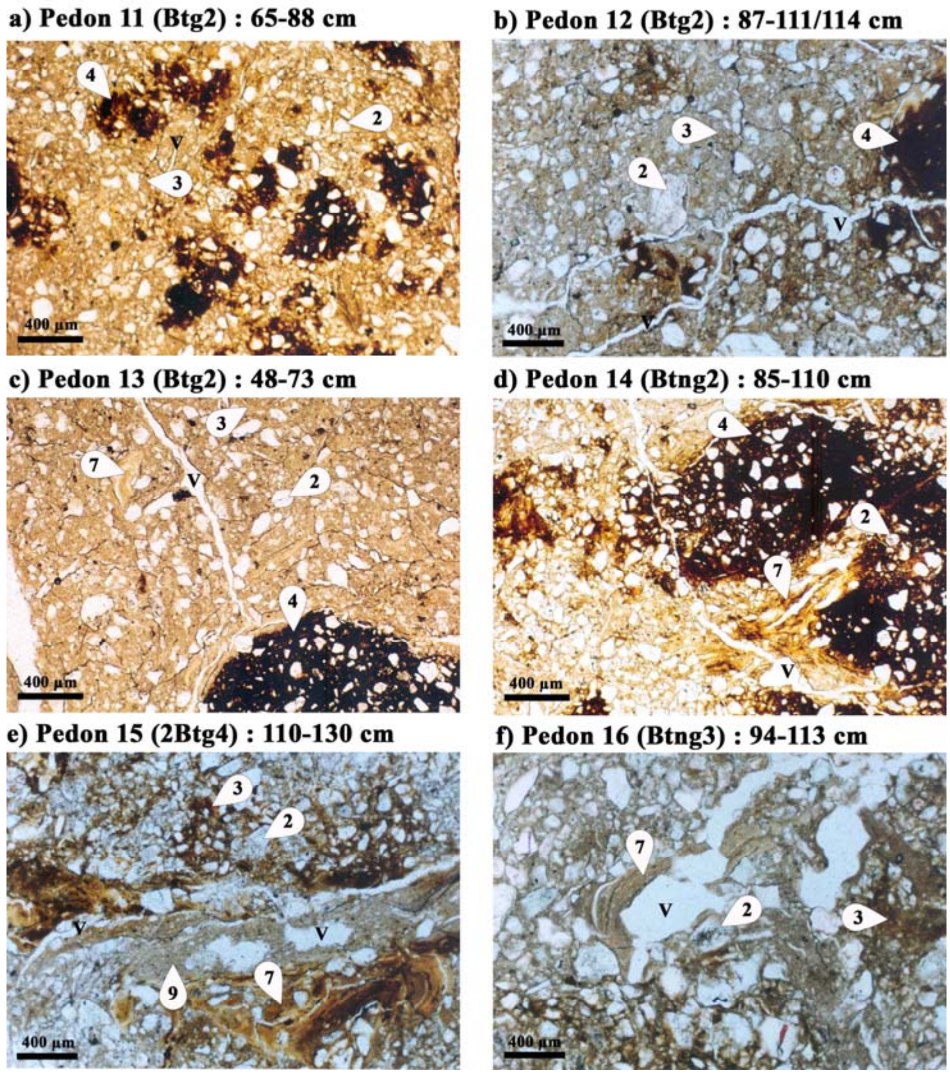

Figure 56 Micromorphological features of subsoils for salt affected soils at location 3.

2 quartz/ runi-quartz grains

3 variously colored clay to fine silt materials matrix

4 manganiferrous impregnative s-matrix

7 clay infilling; 9 silt infilling

V void

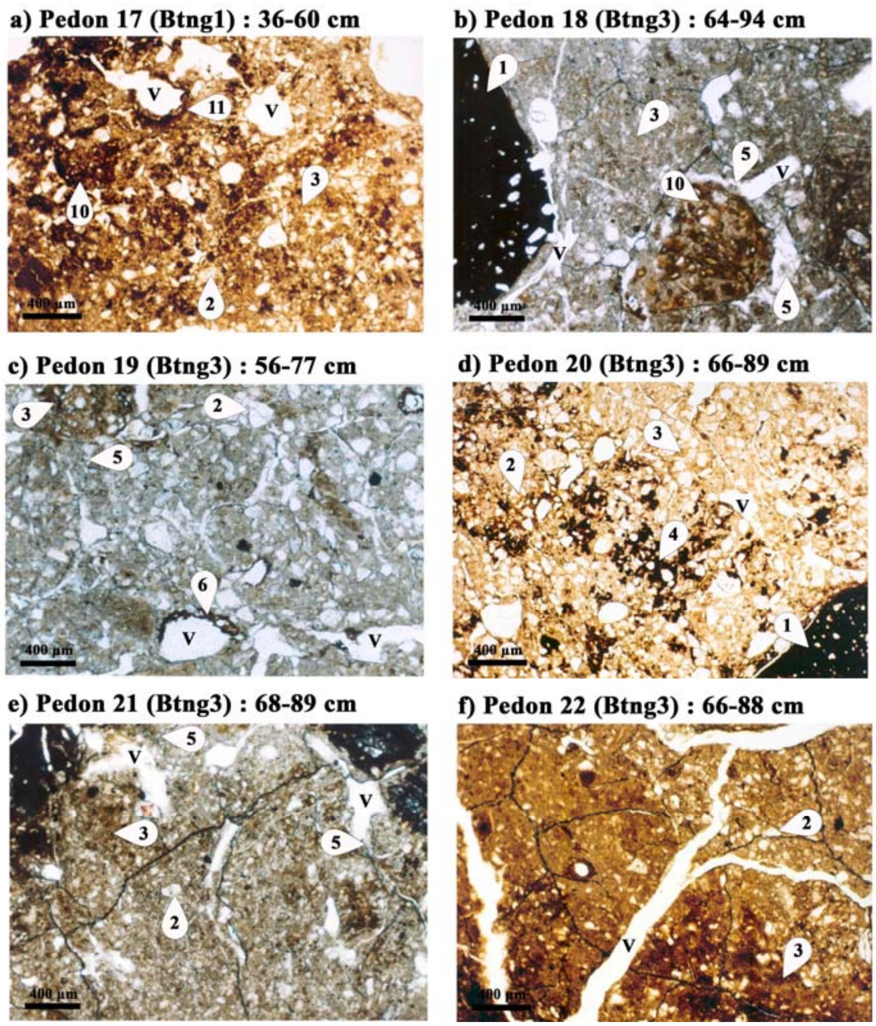

Figure 57 Micromorphological features of subsoils for salt affected soils at location 4.

1 manganiferrous impregnative nodules

2 quartz/ runi-quartz grains

3 variously colored clay to fine silt materials matrix

4 manganiferrous impregnative s-matrix

5 impure halite in voids/ coated on wall of voids

6 clay hypo-coating

10 loose continuous excremental infilling (clay and fine silt size)

11 clay quasi-coating on void

V void

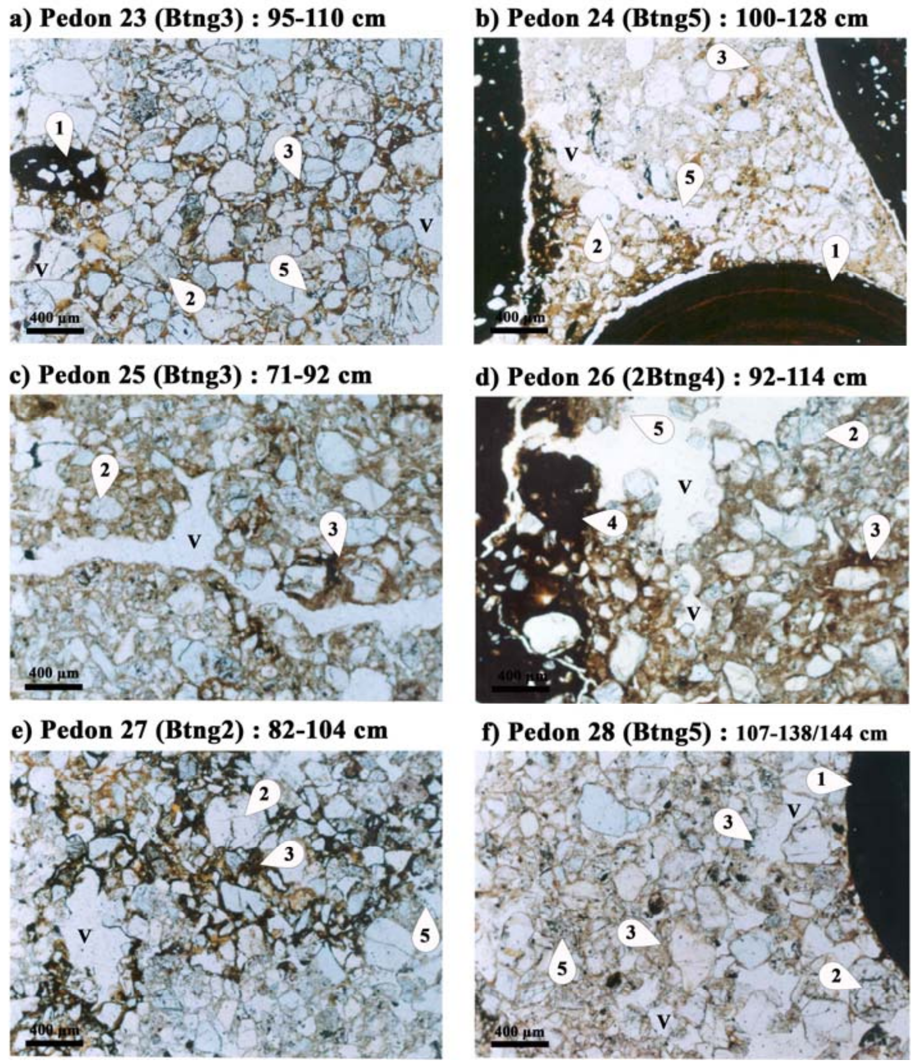

Figure 58 Micromorphological features of subsoils for salt affected soils at location 5.

1 manganiferrous impregnative nodules;

2 quartz/ runi-quartz grains

3 variously colored clay to fine silt materials matrix;

4 manganiferrous impregnative s-matrix;

5 impure halite in voids/ mixed with clay and silt materials

V void

Micromorphological characteristics of these soils indicate the influence of salt, especially in locations 1, 2, 4 and 5. Figure 59 show the accumulation of salt (halite and gypsum) in these soils under high magnification. The accumulation of salt present at different horizons and depth is related to the conditions that control vertical salt movement in soils profile. The micromorphological features of an associated substratum horizon are give in Figure 60. This horizon has a high salt content especially the weathered substratum rock. Under weathering salt (calcite and halite) will be leached from the rock matrix as in Figure 60. The substratum rock contain high amounts of salt and is associated with the saline rocks appearing on the geologic map of this area (Figure 1). The depth of substratum rock is one factor controlling the occurence and distribution of salt affected soil.

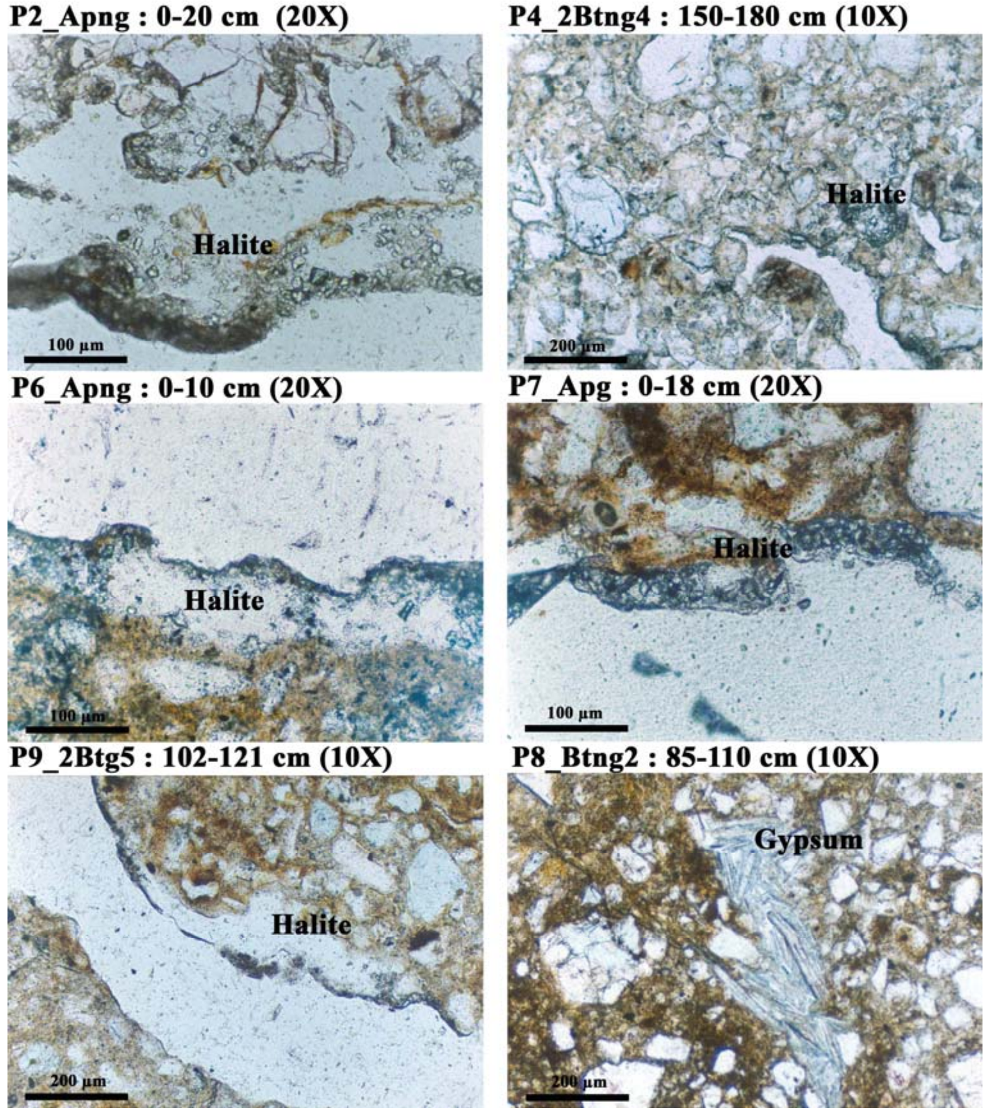

Figure 59 Micromorphological features of salt (halite and gypsum) accumulation in salt affected soils.

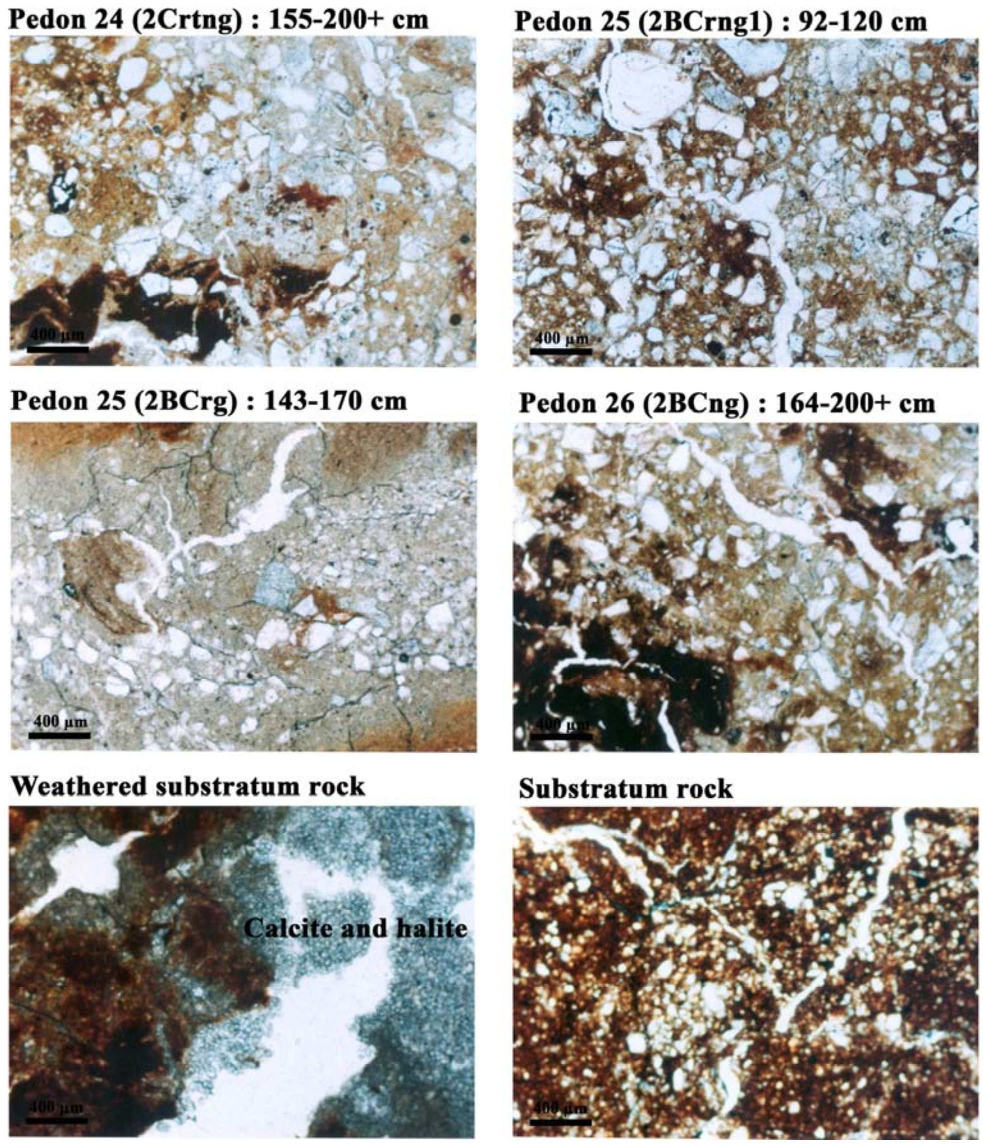

Figure 60 Micromorphological features in substratum of salt affected soils at location 5.

2. Spatial Distribution of Elements in Soil Materials

The SEM images (Figures 61, 62 and 65-67) and element maps show that the major element in the soils is Si with much of it present as quartz and a lesser amount present in clay together with Al. Fe is a relatively minor element being present partly in local concentrations as mottles, concretions or nodules. Ca is a minor element in most of the Apng horizon of Pedon 1 but is locally concentrated in areas of calcite as were described for the optical micrographs. The element maps of Na and Cl clearly show the widespread distribution of halite in Pedons 1 (Figure 61), 6 (Figure 62), 22 (Figure 66) and 23 (Figure 67). The Na map of some horizons at location 3 shows Na accumulations but Cl is not present. The EC values are low whereas ESP and exchangeable Na are high (Appendix C, Table C2). The amount of Al increases in B horizons and is present as the fine fraction including clay coating, clay infilling and clay matrix. The S map shows the presence of accumulation only in the fine textured salt affected soils (locations 2 and 4). The high S zones in the S map were identified as $BaSO_4$ under SEM_EDS analysis (Figure 63b). $BaSO_4$ has accumulated as a group of crystals at location 2.

Figure 63a is a SEM micrograph of a feature in the thin section of the Apng horizon of pedon 1 showing halite and calcite crystals. The EDS spectra indicate that the crystals are halite, calcium chloride and calcite. Sulfur mapping clearly indicates areas of prismatic gypsum but some sulfur is contained in crystals of barite ($BaSO_4$) (Figure 63b). Sylvite (KCl) is also common within voids. Calcium as calcite is a common salt accumulation mineral in these soils and is present in various forms including concretion ball with quartz (Figure 64a) and acuumulations in the substratum and weathered substratum rock (Figure 64b, c).

The normalized element composition of the soil matrix of representative materials is depicted in a triangle graphs for SiO_2: Al_2O_3: Fe_2O_3 in Figures 61, 62 and 65-68. The data point for the matrix of soil from location 1 are mostly displaced from the 'kaolin line' (Figures 61 and 68a) towards the SiO_2 apex, indicating that a relatively Si-rich clay mineral is present in the matrix. XRD analysis indicates the presence (15-40 %) of the relatively (to kaolin) Si-rich clay minerals illite and smectite in the soils which may have crystallized within the soil (Table 5). For soil samples P1_2Btng6 the analyses of the highly iron rich matrix conform to the kaolin line and it is interpreted that this material was introduced into the profile as a transported ferruginous concretion. The high iron matrix and the Fe mapping are consistent with the presence of manganiferrous impregnative s-matrix or nodules that were observed in the field (Appendix A) and under optical analysis of thin section samples (Appendix B and Figures 49 and 54).

The data points for the matrix of soils from location 2 are mostly located off the kaolin line (Figures 62 and 68b) towards the SiO_2 apex due to the presence of Si-rich clay. XRD analysis indicates a moderate percentage of smectite and interstratified 1.0 nm and 1.4 nm minerals in soils but the amount of these minerals in clay fraction is mostly less than 20 % (Table 5) indicating that fine quartz or amorphous silica be present. The displacement of data points near the Fe_2O_3 apex from the average matrix line to coincide with the kaolin line in P6_Apng samples (Figure 68b) may represent inherited oxide impregnated iron rich kaolinitic nodules. For other soils (eg. P8_2Btng4) the position of analytical points on the average matrix Al_2O_3/SiO_2 line indicates that induration of the matrix by iron oxide has formed nodules *in situ*. The high iron matrix and the Fe mapping are consistent with the presence of manganiferrous impregnative s-matrix or nodules that were observed in the field (Appendix A) and under optical analysis of thin section samples (Appendix B and Figures 50 and 55).

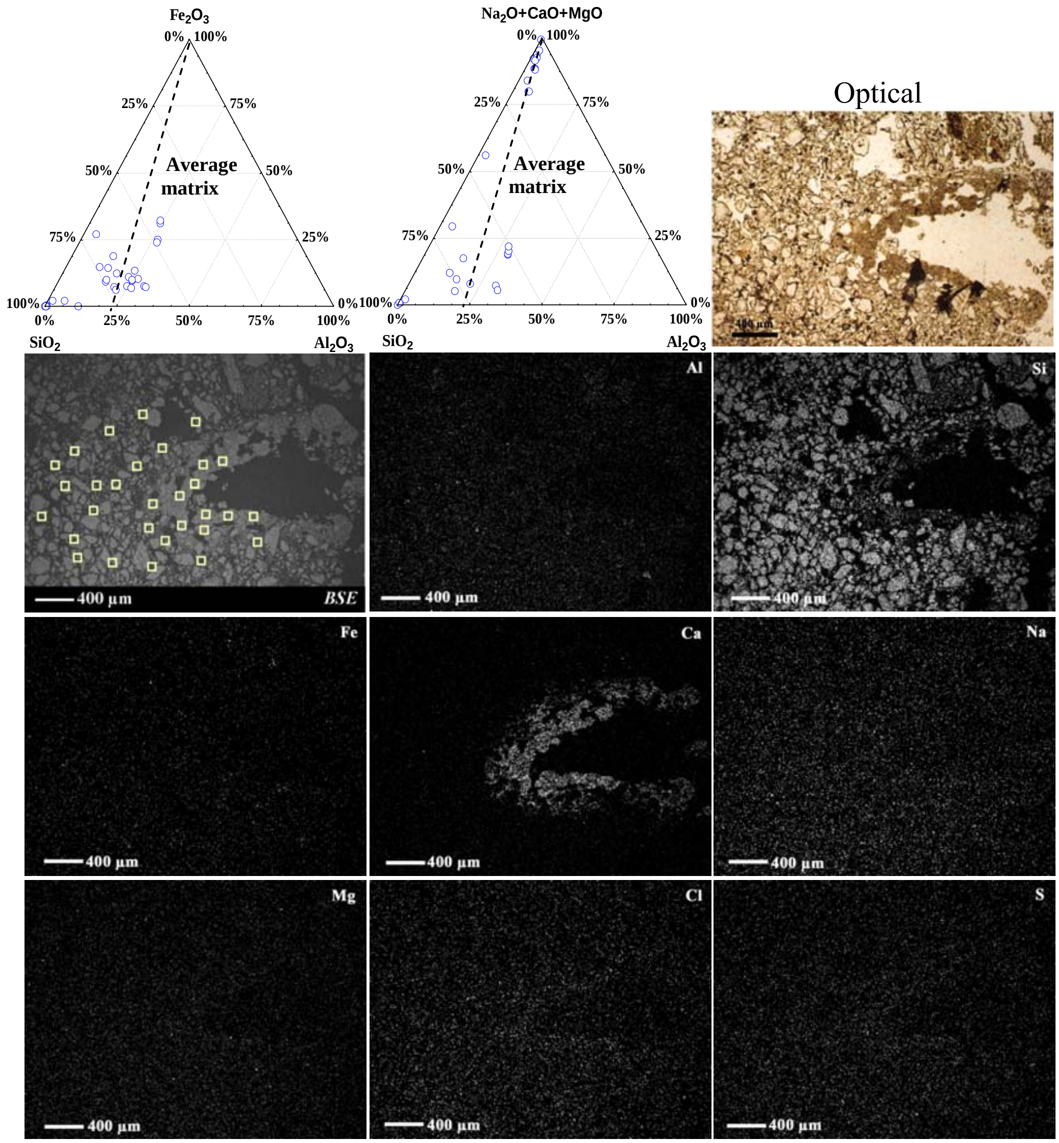

Figure 61 Normalized composition triangular graphs for soil matrix (SiO_2: Al_2O_3: Fe_2O_3, SiO_2: Al_2O_3: Na_2O+ CaO+ MgO), Optical image, Backscattered electron micrograph and EDS element (Al, Si, Fe, Ca, Na, Mg, Cl, S) maps for the Apng horizon of Pedon 1, location 1.

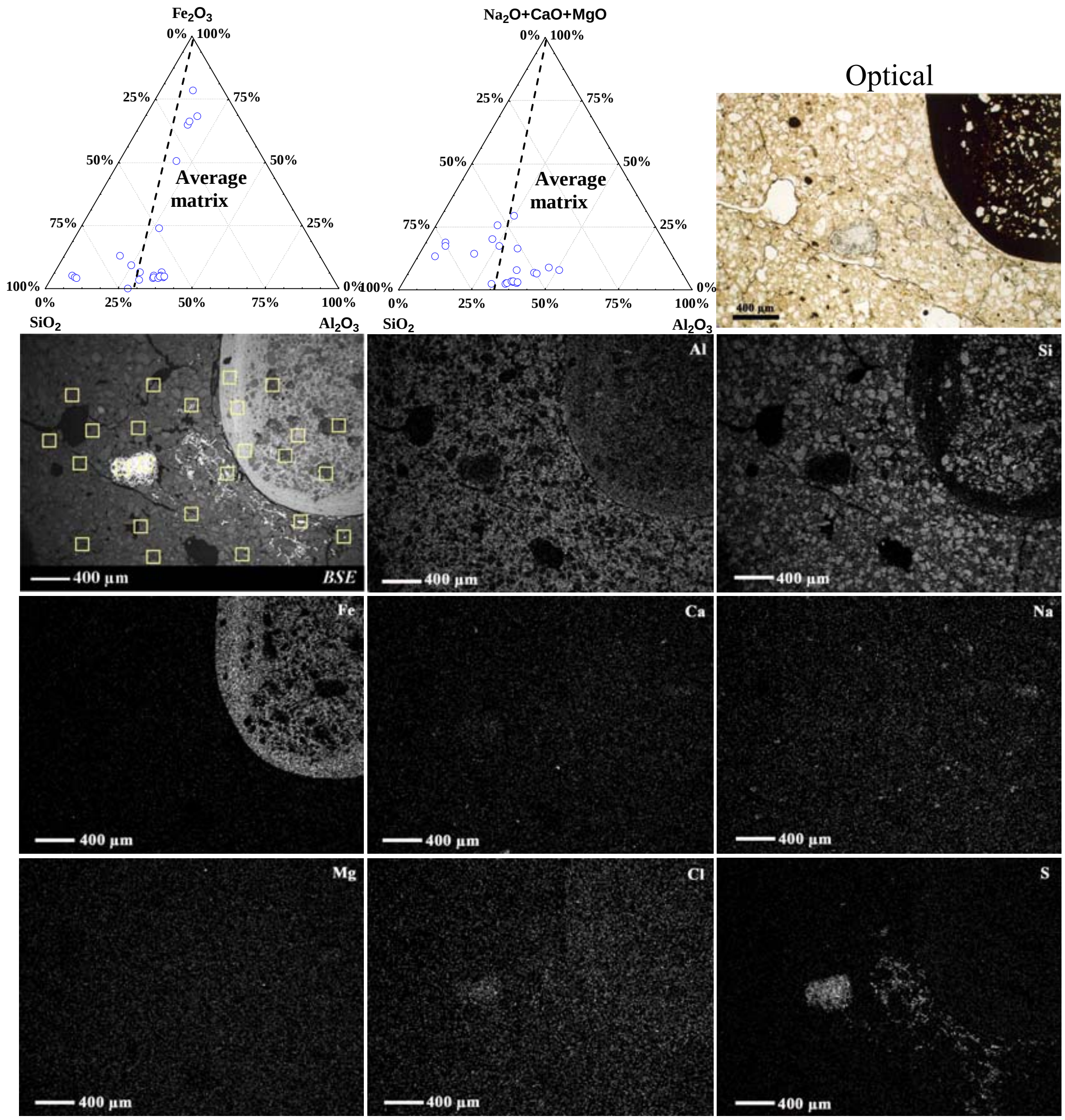

Figure 62 Normalized composition triangular graphs (SiO_2: Al_2O_3: Fe_2O_3, SiO_2: Al_2O_3: Na_2O+ CaO+ MgO), Optical image, Backscattered electron micrograph and EDS element (Al, Si, Fe, Ca, Na, Mg, Cl, S) maps for the Btng3 horizon of soil in Pedon 6, location 2.

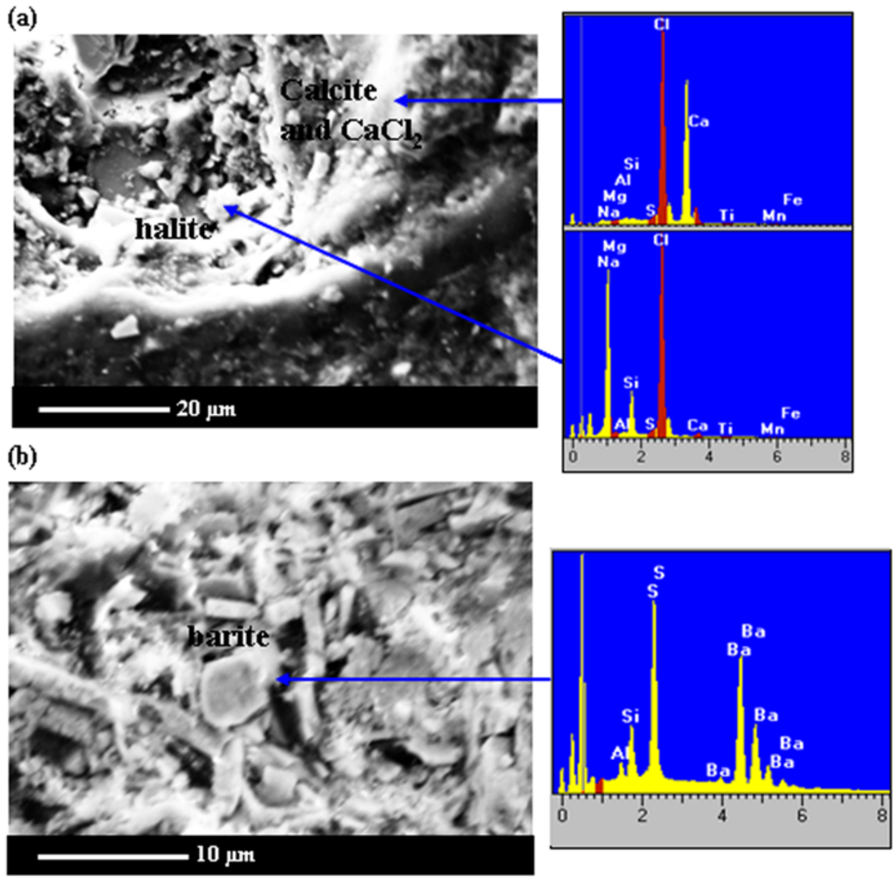

Figure 63 Secondary electron image of a thin section and EDS spectra showing (a) halite, calcium chloride and calcite accumulations in the Apng horizon of Pedon 1, location 1: (b) barite accumulation in Btng3 horizon of Pedon 6, location 2.

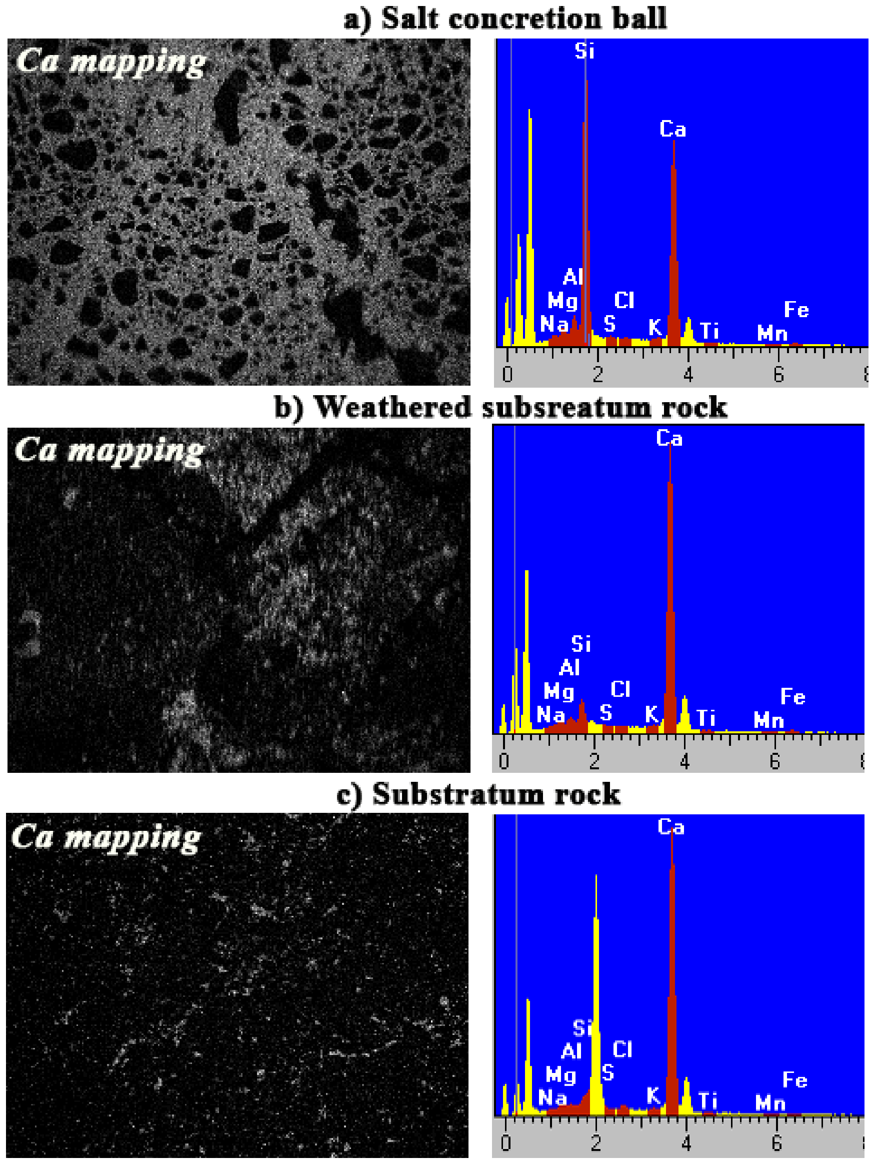

Figure 64 Ca mapping and EDS spectra showing of calcium accumulations as $CaCO_3$; a) in salt concretion ball (lower part in pedon 1 at location 1), b) in weathered substratum and c) in subsratum rock (lower part at location 5).

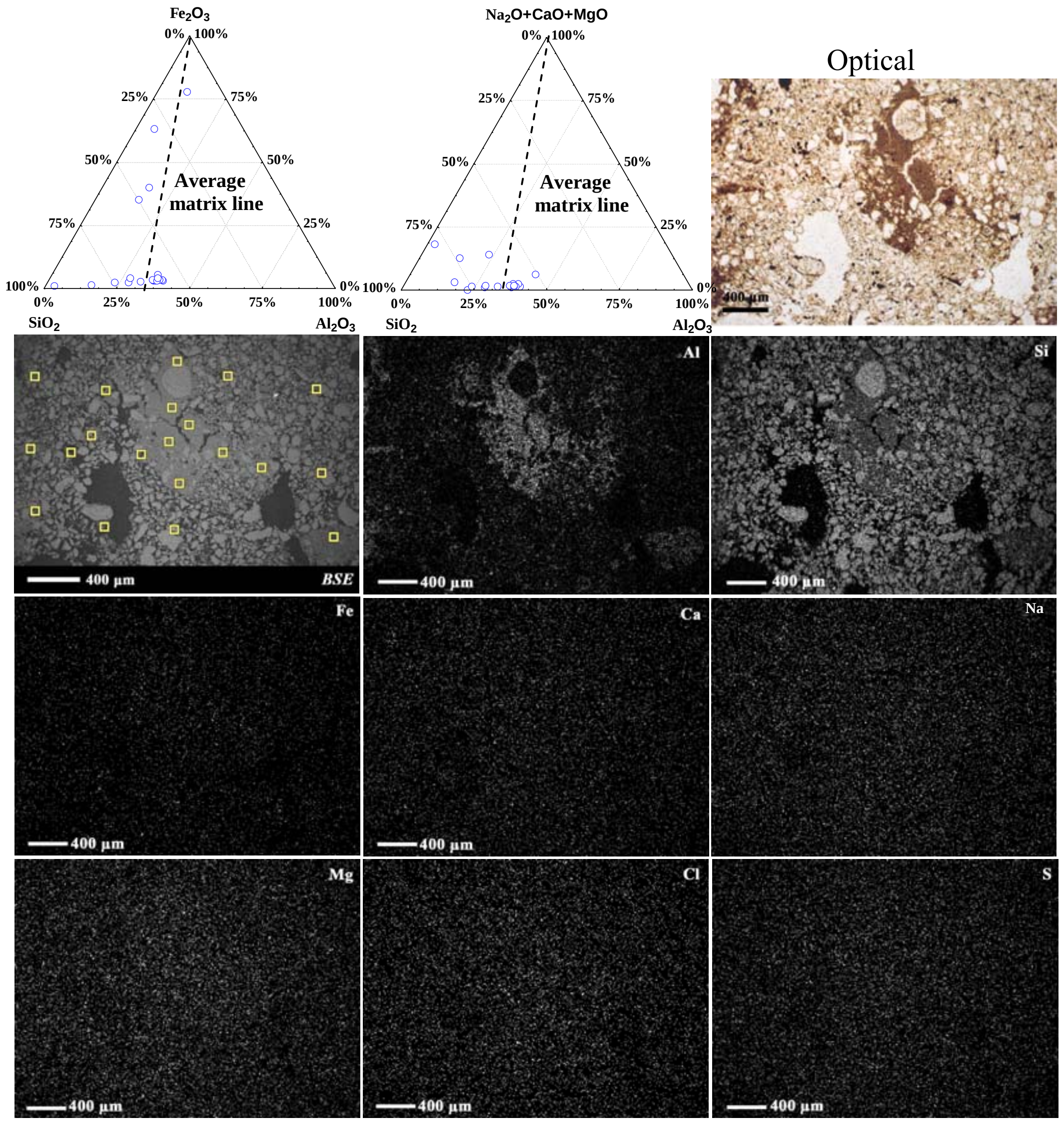

Figure 65 Normalized composition triangular graphs (SiO_2: Al_2O_3: Fe_2O_3, SiO_2: Al_2O_3: Na_2O+ CaO+ MgO), Optical image, Backscattered electron micrograph and EDS element (Al, Si, Fe, Ca, Na, Mg, Cl, S) maps for the Apng horizon of soil in Pedon 11, location 3.

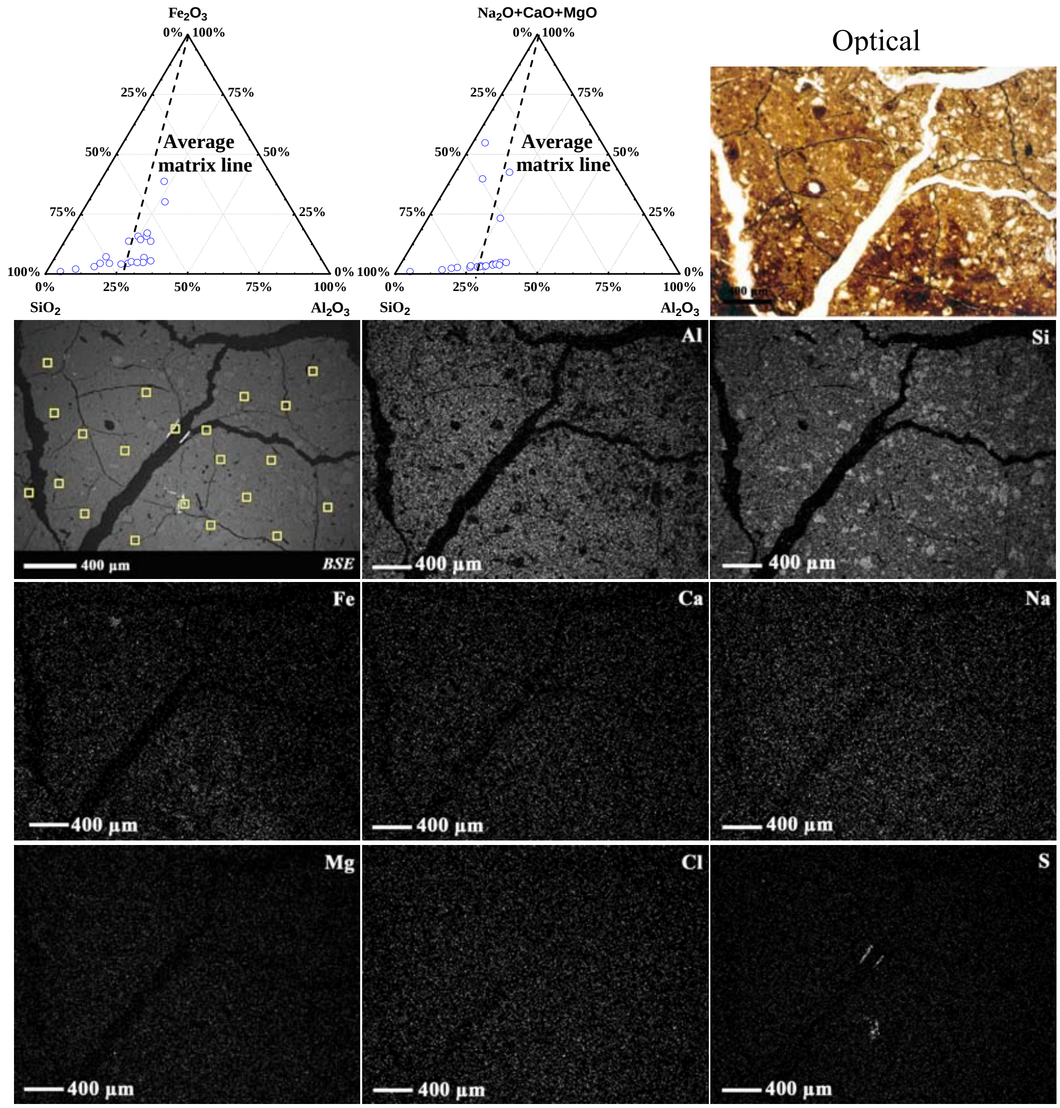

Figure 66 Normalized composition triangular graphs (SiO_2: Al_2O_3: Fe_2O_3, SiO_2: Al_2O_3: Na_2O+ CaO+ MgO), Optical image, Backscattered electron micrograph and EDS element (Al, Si, Fe, Ca, Na, Mg, Cl, S) maps for the Btng2 horizon of soil in Pedon 22, location 4.

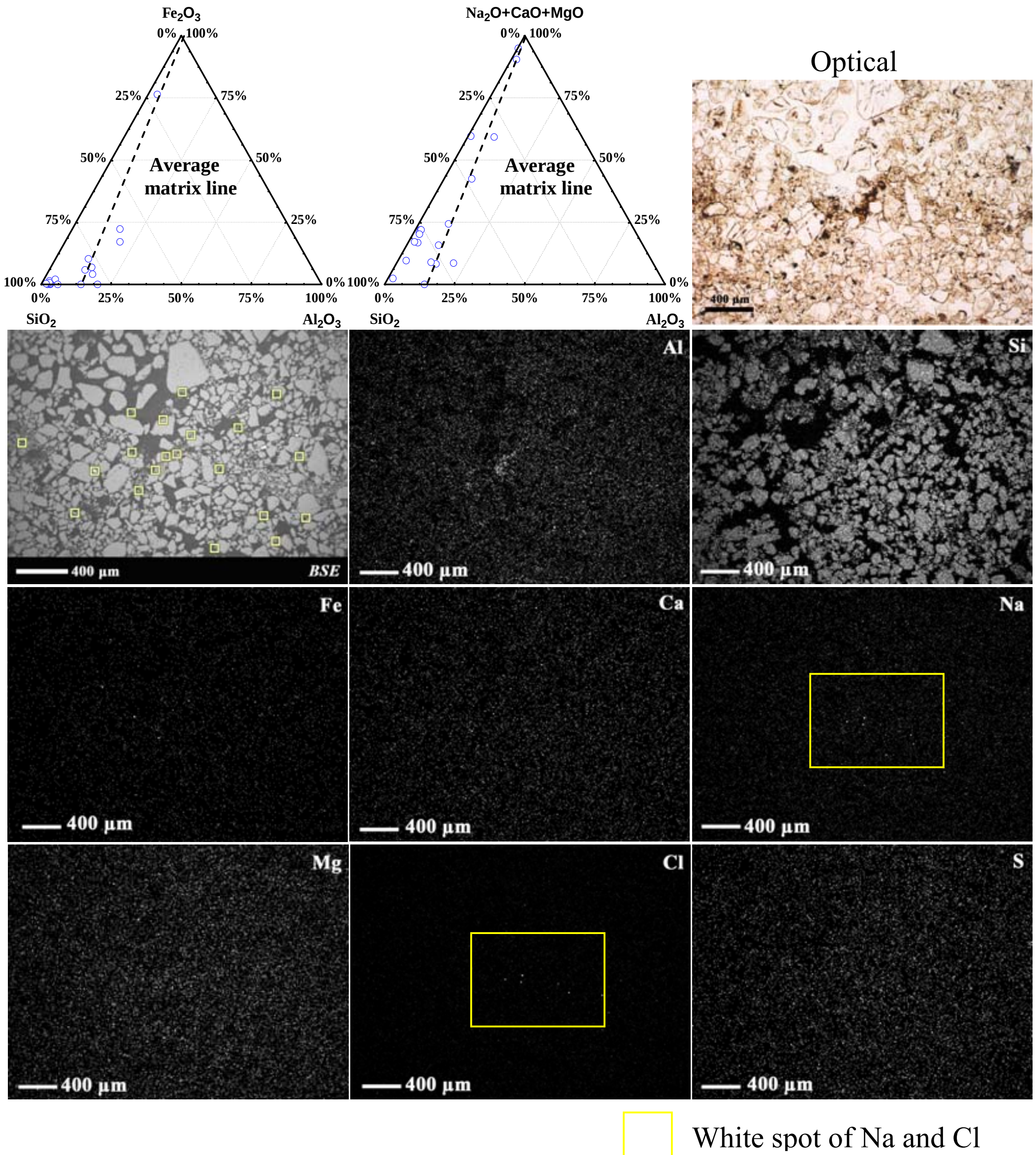

Figure 67 Normalized composition triangular graphs (SiO_2: Al_2O_3: Fe_2O_3, SiO_2: Al_2O_3: Na_2O+ CaO+ MgO), Optical image, Backscattered electron micrograph and EDS element (Al, Si, Fe, Ca, Na, Mg, Cl, S) maps for the Apng horizon of soil in Pedon 23, location 5.

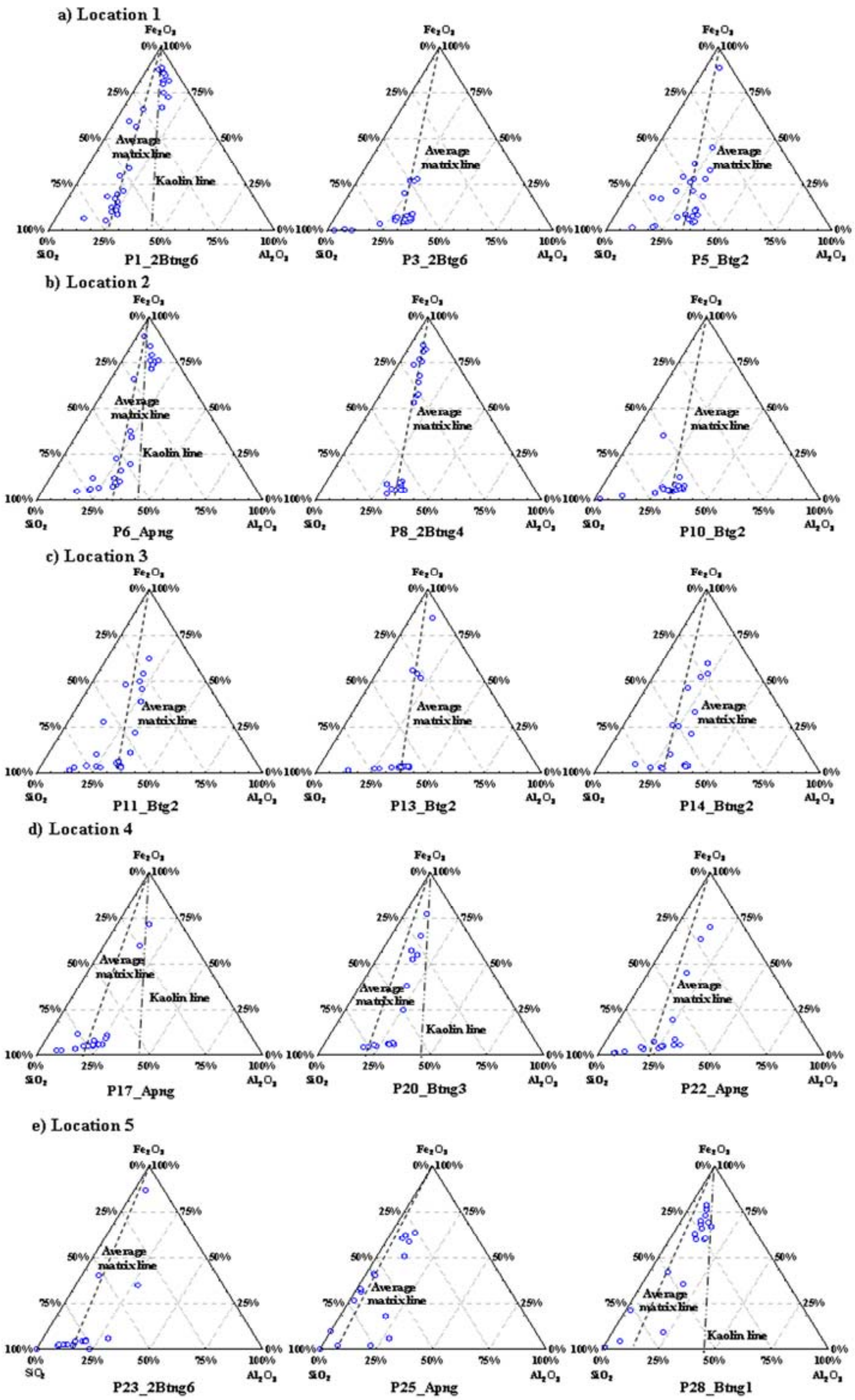

Figure 68 Normalized (SiO_2, Al_2O_3, Fe_2O) composition triangular graphs of soil matrix from each location, the average matrix line corresponds to the average SiO_2:Al_2O ratio for the lower Fe_2O_3 concentration analyzed point.

The normalized element composition of the matrix of pedon 11 (Apng horizon) shows data points that are also located away from the kaolin line (Figure 65) on the average matrix line indicating a relatively Si-rich clay mineral is present in the matrix. However XRD analysis does not indicate high presenceage of a Si-rich clay mineral (illite, smectite, interstratified 1.0 nm and 1.4 nm minerals) at this location (Table 5), so the small quartz crystals or amorphous SiO_2 may be present within the matrix. The displacement of some data points on the kaolin line towards Fe_2O_3 apex may be due partly to Fe substituting for Al in kaolin as commonly occurs in tropical soils (Hart *et al.,* 2002). For the subsoil horizon at location 3 the XRD analysis indicates the dominance of kaolin but some data points for the soil matrix are displaced from the kaolin line (Figure 68c) towards a higher percentage of Si. This may indicate the presence of very fine-grained quartz in the matrix, which is consistent with the particle size analyses of the soil that indicate that much (up to 45%) silt is present. The high iron matrix and the Fe mapping of surface and subsoils horizons are consistent with the present of manganiferrous impregnative s-matrix or nodules that was observal in the field (Appendix A) and under optical analysis of thin section samples (Appendix B and Figures 51 and 56).

The data points for the matrix of soils from location 4 are mostly located off the kaolin line (Figures 66 and 68d) towards the SiO_2 apex indicate the presence of a Si-rich clay mineral. XRD result indicate a moderate percentage amount of 2:1 clay mineral in the soil (Table 5) as it is present as one of dominant minerals in clay fraction (mixed of kaolin, smectite and quartz) (Table 5). For the other horizon at location 4 (Figure 68d) the XRD analysis indicates mixed clay minerals dominanted by kaolin, smectite and quartz. The data points for the soil matrix are displaced from the kaolin line (Figure 68d) towards a higher percentage of Si. This may indicate the presence of very fine-grained quartz in the matrix that relate to the higher percent quartz in clay fraction of this location. The displacement of data points on the kaolin line towards Fe_2O_3 apex (Figure 68d) is consistent with Fe mapping (Figure 66), although field morphology and micromorphology indicated that vary small amounts of manganiferrous impregnative s-matrix or nodules were present at this location (Appendix B and Figures 52 and 57).

The data points for the matrix of soil from location 5 are mostly displaced from the 'kaolin line' (Figures 67 and 68e) towards the SiO_2 apex, indicating that the matrix mostly is quartz that is consistent with the high amount of sand in this soil (Appendix C, Table C1 and Figure 11e). The high SiO_2 in this location is coincident with the total SiO_2 analyzed by total analysis (XRF) (Appendix C, Table C10) and mineralogy of the soil is dominanted by guartz (Table 5). For soil samples P28_Btng1 analyses of the highly iron rich matrix conform to the kaolin line and it is interpreted as this material having been introduced into the profile as a transported ferruginous concretion. The high iron matrix and the Fe mapping of surface and subsoil horizons are consistent with the presence of manganiferrous impregnative s-matrix or nodules that were observed in the field (Appendix A) and under optical analysis of thin section samples (Appendix B and Figures 53 and 58).

The normalized element composition of the matrix in the triangle graph between SiO_2: Al_2O_3: Na_2O+CaO+MgO (Figures 59, 60 and 63-65) indicates that the combined salts of Na, Ca and Mg have mostly indurated the soil matrix as most points fall on the matrix line. The combined salts of Na, Ca and Mg indurating the soil matrix is clearly observed for the Apng horizon of pedon 23 at location 5 (Figure 67) and is consistent with optical observations of halite accumulated in this soil (Figure 58).

3. <u>Synthesis</u>

Soil microstructures are different due to the differences in their texture. The compact grain and bridged grain structures are common in sandy-textured soils whereas channel and subangular blocky structures are common in the clayey textured soils. Quartz and runi-quartz grains are common as skeleton materials, but are present in different sizes and amounts.

Optical micromorphology and SEM/EDS analysis results clearly show the accumulation of salt in some profiles. Halite occurs in voids in soils at locations 1, 2, 4 and 5 and is abundant in Pedons 1, 2, 6 and 23 where salt crusts exist. Calcium as calcite was present in one profile (P1_Apng) in location 1 in a salt concretion ball that found in the lower part of pedon 1 (≈ 200 cm depth) in which common salt accumulation minerals in the BC and C horizon of location 5 and present in substratum and weathered substratum rock. Gypsum ($CaSO_4.2H_2O$), barite ($BaSO_4$) and sylvite (KCl) are present in some of the soils. The preservation of kaolin matrix in indurated nodules with more siliceous clay minerals (smectite, illite) in surrounding matrix may simply reflect the diverse provenance of these soil materials. The smectite and illite may have been derived from the local rocks or have crystallized within the profile which has experienced resilication due to the import and abundance of dissolved silica. Combined salts of Na, Ca and Mg have indurated the soil matrix of some horizons.

Micromorphologically, the clearest evidence of salt effect in these soils are the impure halite and the halite coatings in voids. Other indicative evidences are the manganiferrous impregnative nodules induced by the relatively high pH of the soils (Stiles *et al.,* 2001; Buol *et al.,* 2003) as the combined effect of halite and calcite. The high salt effect also induces the conditions found in the SEM/EDS analysis. These micromorphological analysis results on salt effect and the data on minerals in clay fraction along with the lowland condition where soils have extended period of water stagnancy and low leaching under tropical savanna climate the accumulation of silica can induce the crystallization of some smectite from kaolinite in the soils. The condition is interpreted as an evidence of resilication that started with salinization of the soils creating a high pH condition for silica dissolution (Jenny, 1980; Buol *et al.,* 2003). The low leaching environment promotes the accumulation of dissolved silica leading to the addition of silica into the kaolinite forming smectite structure (Tan, 1982). The forming of illite cannot be clearly explained but the presence of sylvite in the soils also suggest the possibility. Nevertheless, this resilication process, as indicated by the analytical data is generally limited and occurring only in the highly salt affected soils with very poorly drained situation. Wherever leaching is effective the crystallization of smectite from kaolinite is not possible.

Classification

1. Soil classification

Based on Soil Taxonomy (Soil Survey Staff, 2006), all soils have clay accumulations in the subsoil justifying an argillic horizon and they have base saturation of more than 35%, so they are Alfisols. They have developed under aquic condition, so their suborder is Aqualf. Most soils have sodium accumulations in the subsoils that can be justified as a natric horizon, so their great group is Natraqualf. Pedons 9 and 13 do not either have natric horizon or other salt affected properties in subsoils, so they are Endoaqualfs. All of the soils in locations 1, 2, 3 and 5 are in Typic subgroup. The soil in location 4 showed cracks within 125 cm that are 5 mm or more wide and slickensides in a layer thicker more 15 cm and mixed mineralogy, so they belong to the Vertic subgroup. Details of family name include particle-size classes, mineralogy classes, cation-exchange activity classes and soil temperature classes of the these soils are shown as follows;

Location 1: Coarse textured salt affected soils (Phera Yun, Khon Kaen)

Pedon 1 : Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic

Pedon 2 : Typic Natraqualf; coarse-loamy, mixed, semiactive isohyperthemic

Pedon 3 : Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic

Pedon 4 : Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic

Pedon 5 : Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic

Location 2: Fine textured salt affected soils (Phimai, Nakhon Ratchasima)

Pedon 6 : TypicNatraqualf; fine, kaolinitic, isohyperthemic

Pedon 7 : Typic Natraqualf; very fine, kaolinitic, isohyperthemic

Pedon 8 : Typic Natraqualf; fine, kaolinitic, isohyperthemic

Pedon 9 : Typic Endoaqualf; fine, kaolinitic, isohyperthemic

Pedon 10 : Typic Natraqualf; fine, kaolinitic, isohyperthemic

Location 3: medium textured salt affected soils (Suwanaphume, Roi Et)

Pedon 11 : Typic Natraqualf; fine, kaolinitic, isohyperthemic

Pedon 12 : Typic Natraqualf; fine, kaolinitic, isohyperthemic

Pedon 13 : Typic Endoaqualf; fine, kaolinitic, isohyperthemic

Pedon 14 : Typic Natraqualf; fine-loamy, mixed, active, isohyperthemic

Pedon 15 : Typic Natraqualf; fine, kaolinitic, isohyperthemic

Pedon 16 : Typic Natraqualf; fine-loamy, mixed, semiactive, isohyperthemic

Location 4: Fine textured salt affected soils (Ban Phai, Khon Kaen)

Pedon 17 : Vertic Natraqualfs; fine-loamy, mixed, semiactive, isohyperthemic

Pedon 18 : Vertic Natraqualfs; fine-loamy, mixed, semiactive, isohyperthemic

Pedon 19 : Vertic Natraqualfs; fine-loamy, mixed, semiactive, isohyperthemic

Pedon 20 : Vertic Natraqualfs; fine-loamy, mixed, semiactive, isohyperthemic

Pedon 21 : Vertic Natraqualfs; fine-loamy, mixed, semiactive, isohyperthemic

Pedon 22 : Vertic Natraqualfs; fine-loamy, mixed, semiactive, isohyperthemic

Location 5: Coarse textured salt affected soils (Bau Yai, Nakhon Ratchasima)

Pedon 23 : Typic Natraqualf; sandy, silicious, subactive, isohyperthemic

Pedon 24 : Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic

Pedon 25 : Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic

Pedon 26 : Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic

Pedon 27 : Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic

Pedon 28 : Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic

2. <u>Salt Affected Soils Classification</u>

The salt affected soils classification based on the values of EC, SAR or ESP (U.S. Salinity Laboratory Staff, 1954; Brady and Weil, 2002) allows the soils to be classified into four groups (Table 7): Pedons 1-8, 10, and 17-28 are saline sodic soils, pedon 9 is saline soil, pedons 11-12 and 14-16 are sodic soils and pedon 13 is a normal soil. It should be noted that the soils in location 4 (pedons 17-22) have very low pH values indicating acid conditions, so the soils at this location are proposed to be called acid saline sodic soils.

Table 7 Classification of salt affected soils based on index salt effect parameters in this study.

Pedon/ location		Salt affected soil group
Location 1		
	Pedons 1-5	Saline sodic soils
Location 2		
	Pedons 6-8	Saline sodic soils
	Pedon 9	Saline soils
	Pedon 10	Saline sodic soils
Location 3		
	Pedons 11-12	Sodic soils
	Pedon 13	Normal soil
	Pedon 14-16	Sodic soils
Location 4		
	Pedon 17-22	Saline sodic soils (acid saline sodic soils)
Location 5		
	Pedons 23-28	Saline sodic soils

CONCLUSION

Result of this study of variability of natural soil systems as affected by salinity lavels in Thailand reveal several interesting points relating to influence of salt and soil texture. Salt affected soils have various parent materials and are developed under various physiographic conditions. The landforms are flat to gently undulating, having 1-2 % slope. The surface salt crust or salt patch or bare soil present in the most highly salt affected soils, often with some halophytic plants. These characteristics are environmental indicators of salt affected soils that can be observed in the field. All of salt affected soils are deep. The salt affected soils show relatively high to high degrees of development with the presence of an argillic horizon in all pedons and a sodium accumulation horizon (natric horizon) in some frofiles. The natric (n) horizon is coincident with the SAR and/or ESP values. Depositional layers and weathered rock are present in some profiles. Soil matrix color is variable and clayey soils have darker colors. Soil texture varies from loamy sand to clay indicating that salt affected soils can occur for any type of soil texture. The moderate subangular blocky and angular blocky structures are common, however some horizons have massive, granular, prismatic and columnar structures. Prismatic and columnar structures are present only at location 3 where soils have high pH, low EC and high extractable bases especially sodium.

Generally, salt affected soils have poor physical properties including high bulk density and low hydraulic conductivity. Medium to very high bulk density and very slow to moderate rapid hydraulic conductivity are present in these salt affected soils. The bulk density value of salt affected soil shows a positive relationship with exchangeable sodium in some locations indicating that salt may have induced the variation in their physical properties. When salt affected the soil the bulk density can be high to very high and the hydraulic conductivity can be slow to very slow in almost any soil texture group. It can be conclude that salt can induce the soil to have poor physical properties but there is not a simple relationship because soils are complex natural systems.

Salt affected soils vary greatly in chemical properties and relationships of chemical properties are diverse. Salt affected soils have the range of reaction from extremely acid to strongly alkaline. The low pH (acid condition) indicates that some salt affected soils in Thailand develop under acid conditions. These soils have very low to medium organic matter. The surface soils has high organic matter and the values decrease with depth. The OM concentration clearly correlates with total nitrogen. Large variations of available phosphorus and available potassium occur ranging from very low to very high. Their very high values in some of the lower horizon in location 5 are due to the influence of parent rock containing high phosphorus and potassium. Available potassium that varies with location and depth probably attributed their low physiographic positions on landscape and poor leaching conditions. The high available potassium at locations 4 and 5 is coincident with the presence of a high potassium interlayer clay mineral (illite). Salt affected soils have high exchangeable bases. Ca and Na are major exchangeable bases in these soils whereas Mg and K are minor. Some lower horizons at location 5 (BC and C horizons) have very high exchangeable bases influenced by parent materials that contain high amounts of bases particulaly Ca as revealed by total analysis (XRF) and the presence of calcite in the whole soils. The extractable acidity of salt affected soils is very low to very high whereas CEC is very low to very high. The very large variation of CEC reflects soil texture and also the types of clay mineral. Most of these soils have BS of more than 35 percent and often about 100 percent. The very high BS of salt affected soils is influenced by the high concentrations of soluble salt in the soil.

The EC value has a very large variation between locations and also in each pedon in the location. Most of salt affected soils (locations 1, 2, 4 and 5) have EC values of more than 4 dS m^{-1}in some part of the soil profile. The variation with depth of EC reflects soil texture which controls soluble salt movement in soil profiles. The affect of parent rock (containing rock salt) and the high bulk density affect saline water movement. Location 3 has very low EC value, less than 4 dS m^{-1} (0.2-3.6 dS m^{-1}) and tends to increase with depth. The low EC and the increasing of EC with depth may be due to the soils experience of salt leaching (desalinization). SAR values of salt affected soils are variable. Pedons 1, 2, 23 and 25 have high SAR of more than 13 whareas other pedons have the SAR values less than 13. Most of these soils have ESP values of more than 15 percent in some parts of soil profiles are classified as natric (n) horizons. Salt affected soils have higher amounts of soluble salt than do normal soils. Sodium (Na) is the major soluble salt in these soils with some soluble calcium (Ca) whereas soluble magnesium (Mg) and potassium (K) are minor.

Total chemical compositions of the whole soil in salt affected soils are consistent with their mineralogical compositions. Total silica and alumina content have a large range. SiO_2 in these soils is high for every type of texture indicating that all major minerals contain SiO_2. Al_2O_3 content tends to increase with depth together with the amount of clay minerals. The amount of total Fe_2O_3 in salt affected soils also have a large range. The high concentration of Fe_2O_3 in some of these soils is related to the acuumulation of iron oxide concretions, nodules and red mottles. The TiO_2 content in salt affected soils is low. CaO is present as a major constituent whereas K_2O, MgO and Na_2O are mostly minor. Very high CaO, K_2O and MgO concentrations in some C and BC horizons coincide with high values of exchangeable Ca and Mg which are related to parent rocks that contain high amounts of Ca, Mg and K. In very hightly salt affected soils the Na_2O concentration is coincident with the high soluble Na particularly in the surface horizon. The distributions of Mn in these soils are very variable and tend to be associated with the nodules, concretions and mottles. The concentration of S in these soils is highly variable. High S is present in fine texture soils, particularly in location 4 as it is related to the acid condition. The concentrations of Cl in these soils are higher than in normal Thai soils. The amount of Cl varies between locations and pedons. Very high Cl concentrations in surface soils indicate the presence of a salt crust or salt patch and are associated with high EC, Na, ESP and SAR.

The geochemistry of the salt affected soils reveals that their chemical composition is highly diverse at each location due to the large variations in texture arising from the presence of depositional layers. High EC values and Cl concentrations exist in many samples due to the influence of salt bearing country rocks. The soils have a wide range of chemical properties, with five main elemental affinity groups being recognized. Minerals in salt affected soils consist predominantly of quartz and clay minerals kaolin, smectite, illite and vermiculite occurring in various proportions. Halite occurred in the surface horizon due to the high salt accumulation. Halite and calcite occurred in BC and C horizons are consistent with the geologic condition that contains rock salt deposits. The clay fraction consists predominantly of kaolin and smectite and trace of illite and interstratified minerals. The mineralogy of the silt fraction is dominated by quartz with trace of feldspar in some pedons. The smectite of these soils is mostly beidellite. Montmorillonite is present with beidellite in some samples. Montmorillonite tends to be associated acid conditions. Kaolin morphology includes annhedral, subhedral and euhedral faces of platy crystals. Low EC values are associated with a higher percentage of euhedral faces. The median size of crystal tends to be smaller than those of kaolin crystals in other Thai soils and is also smaller than platy kaolin particles in other soils from tropical and Mediterranean climates. There is no relationship between the number of euhedral face and kaolin crystal size. There are no relationships of kaolin properties (mean size by TEM, CSD001 and number of euhedral face) with measuring parameter of salinity (EC, SAR, ESP and pH).

Soil microstructures vary due to differences in texture. Compact grain and bridged grain structures are common in sandy-textured salt affected soils whereas channel and subangular blocky structures are common in clayey salt affected soils. Quartz and runi-quartz grains are common as skeleton materials, but are present in different sizes and amounts. Optical micromorphology and SEM/EDS analysis clearly show the accumulation of salt in some profiles. Halite occurs in voids in soils at locations 1, 2, 4 and 5 where salt crusts or salt patch exist. Calcium as calcite is present in salt concretion balls and salt accumulation minerals in substratum and weathered substratum rock. Gypsum ($CaSO_4.2H_2O$), barite ($BaSO_4$) and sylvite (KCl) are present in some of the salt affected soils. The preservation of kaolin matrix in indurated nodules with more siliceous clay minerals (smectite, illite) in surrounding matrix may simply reflect the diverse provenance of these soil materials. The smectite and illite may have crystallized within the profile which may have experienced resilication due to the import and abundance of dissolved silica and other ions. Salts of Na, Ca and Mg have indurated the soil matrix in some horizons.

All salt affected soils can classified as Alfisols that have clay accumulations in the subsoil justifying an argillic horizon and they have base saturation of more than 35 percent. They have developed under aquic condition, so their suborder is Aqualf. Most soils have sodium accumulations in the subsoils justified as natric horizon, so their great groups is Natraqualfs. Based on the values of EC, SAR or ESP the soils can be classified into four groups: Saline sodic soils (pedons 1-8, 10, and 17-28), saline soil (pedon 9) is, sodic soils (pedons 11-12 and 14-16) and pedon 13 is a normal soil. To be noted that the soil in pedons 17-22 have very low pH value indicating acid condition, so the soils in this location are proposed to be in a group called acid saline sodic soils.

LITERATURES CITED

Abder-Ruhman, M. 1980. **Mineralogical Characteristics of Soils from East Central Alberta**. M.S. Thesis, Univ. of Alberta, Edmonton.

Abrol, I.P., J.S.P. Yadav and F.I. Massound. 1988. **Salt Affected Soil and Their Management**. Rome, FAO.

Abu-Sharar, T.M., E.T. Bingham and J.O. Rhodes. 1987. Reduction in hydraulic conductivity in relation to clay dispersion and disaggregation. **Soil Sci. Soc. Am. J.** 51: 342-346.

Agbu, P.A., R.L. Jones and N. Ahmad. 1990. Mineralogy and weathering of a Trinidad Ultisol developed in porcellanite. **Soil Sci.** 149: 272-278.

Al-Janabi, K.Z. and D.I. Lewis. 1982. Salt affected soil in the Platte River Valley of Central Nebraska: properties and classification. **Soil Sci. Soc. Am. J.** 46: 1037-1042.

Alloway, B.J. 1995. The origins of heavy metals in soils, pp. 29–39. *In*: B.J. Alloway, ed. **Heavy Metals in Soils.** Chapman & Hall, London.

Arshad, M.A. and S. Pawluk. 1966. Characteristics of some solonetzic soil in the glacial Lake Edomonton basin of Alberta. **J. Soil Sci.** 17: 36-47.

Arunin, S. 1992. Strategies for utilizing salt affected lands in Thailand, pp 26-37. *In* **International Symposium on Strategies for Utilizing Salt Affected Lands**. Department of Land Development, Ministry of Agriculture and Cooperatives, Bangkok.

Beery, M. and L.P. Wilding. 1971. The relationship between soil pH and base-saturation percentage for surface and subsoil horizons of selected Mollisols, Alfisols, and Ultisols in Ohio. **The Ohio Journal of Science** 71: 43-55.

Bettany, J.R. 2002. **Soil Salinity.** Available Source http:// www.ndsp.gov.au/ salinity/ Salinity-information/basin-sheets/B1.html, May 1, 2003.

Ben N., Y. Takahisa and H. Akio. Smectite diagenesis in neogene marine sandstone and mudstone of the Niigata basin, Japan. **Clays Clay Miner.** 48: 26-42.

Blake, G.R. and K.H. Hartge. 1986. Bulk density, pp. 363-382. *In* A. Klute, ed. **Methods of Soil Analysis. Part I. Physical and Mineralogical Methods.** Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

Borchardt, G. 1989. Smectite, pp. 675-727. *In* J.B. Dixon and S.B. Weed, eds. **Minerals in Soil Environments.** SSSA Book Series No. 1. SSSA, Madison, Wisconsin, USA.

Brady, N.C. and R.R. Weil. 2002. **The Nature and Properties of Soils**. 13th ed. Prentice-Hall, Inc., New Jersey, USA.

Brady, P.V., and J.V. Walther. 1989. **Silicated Dissolution Rates as a Function of pH and Temperature.** Geological Society of America (GSA). Boulder, CO, Evanston, Illinois, USA.

Bray, R.H. and L.T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. **Soil Sci.** 59: 39-45.

Brewer, R. 1964. **Fabric and Mineral Analysis of Soils.** John Wiley and Sons, Inc., New York.

Brindley, G.W. and G. Brown. 1980. X-ray diffraction procedures for clay mineral identification, pp. 305-359. *In* G.W. Brindley and G. Brown, eds. **Crystal Structures of Clay Minerals and Their X-ray Identification**. Mineralogical Society Monograph. No. 5. Spottiswoode Ballantyne Ltd., London.

Bullock, P.N., F.A. Jongerius, G. Stoops, T. Tursina and U. Babel. 1985. **Handbook for Soil Thin Section Description**. Waine Research Publ., England.

Buol, S.W., R.J. Southard, R.C. Graham, and P.A. McDaniel. 2003. **Soil Genesis and Classification.** 5th ed. Iowa State Press, USA.

Caballero, R., A. Bustos and R. Roman. 2001. Soil salinity under traditional and improved irrigation schedules in Central Spain. **Soil Sci. Soc. Am. J.** 65: 1210-1218.

Ceuppens, J., M.C.S. Wapereis and K.M. Miezan. 1997. Soil salinization precesses in rice irrigation schemes in the Senegal River Delta. **Soil Sci. Soc. Am. J.** 61: 1122-1130.

Chadwick, O.A. and R.C. Graham. 2000. Pedogenic processes, pp. 41-72. *In* M.E. Sumner, ed. **Handbook of Soil Science**, CRC Press LLC.

Chapman, H.D. 1965. Cation exchange capacity, pp. 891-901. *In* C.A. Black, ed. **Methods of Soil Analysis. Part II. Chemical and Microbiological Properties.** Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

Charusiri, P., S. Imsamut, Z. Zhuang, T. Ampaiwan and X. Xu. 2006. Paleomagnatism of the earliest Cretaceous to early late Cretaceous sandstones, Khorat Group, Northeast Thailand: implications for tectonic plate movement of the Indochina block. **Gondwana Res.** 9: 310-325.

Chhabra, R. 1996. **Soil Salinity and Water Quality**. A.A. Balkema Publishers, Old Post Road, Brookfield, USA.

Commonwealth of Australia. 2001. The nature of salt affected soils. **Salinity Information Package**. Available Source http:// www.ndsp.gov.au/salinity/ Salinity-information/basin-sheets/B1.html, June 8, 2003.

Department of Land Development. 1990. **Distribution of salt affected soils in the northeast region 1: 100,000 map**. Bangkok, Thailand.

Department of Mineral Resources. 1985. **Geologic Map of Thailand**. **1: 250,000.** Bangkok, Thailand.

Dheeradilok, P., T. Wongwanich, W. Tansathien and P. Chaodumrong. 1992. An introduction to geology of Thailand, pp. 737-752. In C. Piancharoen, ed. **National Resource of Thailand: Potential for Future Development 17-24 November, 1992**. Department of Mineral Resource, Bangkok, Thailand.

Dodd, J.D. and R.T. Coupland. 1966. Vegetation of saline areas in Saskatchewan. **Ecology** 47: 958-968.

Dixon, J.B. and D.G. Schulze. 2002. **Soil Mineralogy with Environmental Applications**. Soil Science Society of America Publisher, Madison, Wisconsin, USA.

Dudas, M.J. and S. Pawluk. 1982. Reevaluation of occurrence of interstratified clays and other phyllosilicates in southern Alberta soils. **Can. J. Soil Sci.** 62: 61-69.

Evans, C.D., T.D. Davies, Jr. P.J. Wigington, M. Tranter and W.A. Kretser. 1996. Use of factor analysis to investigate processes controlling the chemical composition of four streams in Adirondack Mountain, New York. **J. Hydrol.** 185: 297-316.

Fanning, D.S. and M.C.B. Fanning. 1989. **Soil Morphology, Genesis, and Classification**. John Wiley & Sons, Inc., New York.

FAO. 2000. Salt affected soil. **FAO AGL 2000.** Available Source: http://www.fao.org/ag/AGL/agll/prosoil/salt.htm, May 14, 2002.

Fitzpatrick, R., P. Rengasamy, R. Merry and J. Cox. 2001. Is dryland soil salinisation reversible. *In* **National Dryland Salinity Program**. Australia.

Frenkel, H., C. Amrhein and J.J. Jurinak. 1983. The effect of exchangeable cations on soil mineral weathering. **Soil Sci. Soc. Am. J.** 47: 649-653.

Ghassemi, F., A.J. Jakeman and H.A. Nix. 1995. **Salinization of Land and Water Resources: Human Cases, Extent, Management and Case Studies**. Center for Resource and Environmental Studies, Australian National University, Canberra, Australia.

Glopper, R.J. de. 1971. **Preliminary Report on Tidal Land Reclamation in Thailand**. Land Development Department, Bangkok, Thailand.

Gee, G.W. and J.W Bauder. 1986. Particle-size analysis, pp. 961-1010. *In*: A. Klute, ed. **Methods of Soil Analysis**. **Part I. Physical and Mineralogical Methods.** Amer. Soc. Agron. Inc., Madison, Wisconsin, USA

Greene-Kelley, R. 1953. The identification of montmorillonoids in clays. **J. Soil Sci.** 4: 233-237.

Haluschak, P. 2000. Pedologist. **Monitoba Agriculture and Food, Soil and Crop Branch**. Available Source http: // news.Farmca.com/maviune zoon/soil salinity.html, October 18, 2002.

Harris, S.A. 1960. Saline soils in the Kirkuk Plain, Northern Iraq. **J. Soil Sci.** 11(1): 114-130.

Hart, R.D., R.J. Gilkes, S. Siradz and B. Singh. 2002. The nature of soil kaolins from Indonesia and Western Australia. **Clays Clay Miner.** 50(2): 198-207.

Hattori, T. and Y. Takaya. 1989. **Salinity in Thailand**. Report of ADRC short term expert (22) JICA.

Haworth, H.F., N. Pongpan and C. Piancharoen. 1966. **Groundwater Resources Development of Northeast Thailand**. Groundwater Bull. No.2. Dept. of Mineral Resources. Thailand.

Heck, R.J. and A.R. Mermut. 1992. Genesis of Natriborolls (Solonetzic) in a closed Lake Basin in Saskatchewan, Canada. **Soil Sci. Soc. Am. J.** 56: 842-848.

Henri, D. 1999. Geology 3710. **Introduction to Soil Science**. Available Source http://www.valdosta edu/~grissino, March 22, 2002.

Hoontrakul, D. 1988. **An Assessment on Problem and Potential of Salt Affected Soils in Mae Klong Basin**. M.S. Thesis, Kasesart University, Bangkok. (in Thai with English Abstract).

Intvan, S. 1992. Research institute for soil science and agricultural chemistry of the Hungarian Academy of Sciences, Budapest (Hungary). *In* **International Symposium on Strategies for Utilizing Salt Affected Lands**. Department of Land Development, Ministry of Agriculture and Cooperatives, Bangkok.

Isbell R.F., R. Reeve and J.T. Hutton. 1983. Salt and sodicity: in soils, pp. 107-111. *In* **An Australian Viewpoint, Division of Soils.** CSIRO, Australia.

Ivanava, Ye. N. and A.F. Bol'Shakov. 1972. Academician K.K. Gedroyts' theory of solonchaks, solonetzes and solods and its subsequent elabaration. **Sov. Soil Sci.** 4: 156-171.

Jackson, K.L. 1965. **Soil Chemical Analysis: Advanced Course**. Department of Soils, University of Wisconsin.

James, B.R. and R.J. Bertlett. 2000. Redox Phenomena, pp B169-B194. *In*: M.E. Sumner, ed. **Handbook of Soil Science.** CRC Press LLC.

Karathanasis, A.D. and B.F. Hajek. 1996. X-ray Fluorescence Spectrometry, pp 161-224. *In*: D.L. Sparks, A.L. Page, P.A. Helmke and R.H. Loeppert, eds. **Methods of Soil Analysis. Part III. Chemical Method.** Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

Karimpour, R. 2002. Effected of salinity and sodicity on soil physical properties (structure & hydraulic conductivity) in Damphan Playa. *In* **Proceedings 17th World Congress of Soil Science**, Symposium No. 33. Bangkok, Thailand.

Keller, L.P., G.J. McCarthy and J.L. Richardson. 1986. Mineralogy and stability of soil evaporites in North Dakota. **Soil Sci. Soc. Am. J.** 50: 1069-1071.

Kheoruenromne, I. 1999. **Soil Survey Laboratory Manual**. Department of Soil Science, Faculty of Agriculture, Kasetsart University, Bangkok. (in Thai)

Kishk, F. and M.N. Hassan. 1972. Chemical and mineralogical composition of the clay fraction of some salt affected soils in Egypt, p. 33. *In* **Int. Symp. Salt Affected Soils, Cairo.** Natl. INF. Document Center, Cairo.

Klages, M.G. and A.R. Southard. 1968. Weathering of montmorillonite during formation of a solodic soil and associated soils. **Soil Sci.** 106: 363-368.

Klute, A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: laboratory methods, pp. 687-734. *In* A. Kulte, ed. **Methods of Soil Analysis. Part I. Physical and Mineralogical Methods.** Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

Kodama, H. 1979. Clay minerals in Canadian soils: their origin, distribution and alteration. **Can. J. Soil Sci**. 59: 37-85.

Kohut, C.K. and M.J. Dudas. 1994. Characteristics of clay minerals in saline alkaline soils in Alberta, Canada. **Soil Sci. Soc. Am. J.** 58: 1260-1269.

Kooistra, M.J. 1983. Light microscope and submicroscope observations of salt in marine alluvium (India). **Geoderma** 30: 149-160.

Kotb, Tarek H.S., T. Watanabe, Y. Ogino and K.K. Tanji. 2000. Soil salinization in the Nile Delta and related policy issues in Egypt. **Agr. Water Manage.** 43: 239-261.

Kumru, M. N. and M. Bakaç. 2003. R-mode factor analysis applied to distribution of elements in soils from Aydin basin, Turkey. **J. Geochem. Explor.** 77: 81-91.

Lindsay, W. L. 1979. **Chemical Equilibria in Soils.** John Wiley&Sons, Inc., New York, USA.

Lynch, J. 1999. Additional provisional elemental values for LKSD-1, LKSD-2, LKSD-3, LKSD-4, STSD-1, STSD-2, STSD-3 and STSD-4. Geostandards Newsletter. **Geostand. Geoanal.** 23: 251-260.

Mali, V.S., N.A. Zende and U.K. Verma. 2002. Correlation between soil physical-chemical properties and available micronutrients in salt affected soils. *In* **The 17th World Congress of Soil Science**, Symposium No. 33. Bangkok, Thailand.

Mann, L.C. and M.M. Boehm. 1983. Soil genesis in a Natrargig-Haplargid complex in Northern Montana. **Soil Sci. Soc. Am. J.** 47: 1186-1192.

Master Plan Organisation (MOP). 1986. National water plan, pp. 1-25. *In* **MPO Report**. Vol. I, Ministry of Irrigation,Water Development and Flood Control, Dhaka 1000, Bangladesh.

Mickey, S. and B.J. Kristiansen. 2001. **Soil conditions and transplast status in Burger Draw**. Available Source: http://www.powderriverbasin.org, May 4, 2003.

Millot, G. 1979. **Geology of Clays; Weathering, Sedimentology, Geochemistry**. Springer-Verlag, Heidelberg.

Mondal, K.M., S.I. Bhuiyan, D.T. Franco. 2001. Soil salinity reduction and prediction of salt dynamics in the coastal ricelands of Bangladesh. **Agr. Water Mange.** 47: 9-23.

National Soil Survey Center. 1996. **Soil Survey Laboratory Methods Manual**. United States Department of Agriculture, Natl. Soil Surv. Cent., Soil Surv. Lab., Soil Survey Investigation No. 42, Version 3.

Nelson, D.W. and L.E. Sommers. 1996. Total carbon, and organic matter, pp. 961-1010. *In*: D.L. Sparks, A.L. Page, P.A. Helmke and R.H. Loeppert, eds. **Methods of Soil Analysis. Part III. Chemical Method.** Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

NSW SOE. 2000. Land Backgrounder 3. **NSW SOE**. Available Source http://www.epa. nsw.gov.au/soe/soe2000/bi/bl-3.htm, May 1, 2003.

Oster, J.D. and J. Shainberg. 1979. Exchangeable cation hydrolysis on soil weathering as affected by exchangeable sodium. **Soil Sci. Soc. Am. J.** 43: 70-75.

Panichapong, S. 1981. Distribution, characteristics and utilization of problem soil in Thailand, pp. 131-146. *In* **International Symposium on Distribution Characteristics and Utilization of Problem Soil**. Tsukuba, Japan.

Pawluk, S. 1982. Salinization an solonetz formation. *In* **Proceedings Alberta Soil Science Workshop** 19th, Edmonton, Alaerta. Agric Soil Feed Testing Lab, Edmonton, AB.

Piancharoen, C. 1973. **Hydrological Map of Northeast Thailand** (scale 1: 500,000). Groundwater Development Dept. of Mineral Resources, Thailand.

Post, W.M., J. Pastor, P.J. Zinke, and A.G. Stangenberger. 1985. Global pattern of soil nitrogen storage. **Nature** 317: 613-616.

Promdecha, P. 2001. **Mineralogy and Chemistry of Salt Affected Soils in Sakhon Nakhon basin, Northeast Thailand**. M.S. Thesis, Kasesart University, Bangkok (in Thai with English Abstract).

Radogna, V.M. and G. Padovano. 1992. Secondary salinization in agricultural soils of south Italy. *In* **Proceedings of the International Symposium on Strategies for Utilizing Salt Affected Lands**. Department of Land Development, Ministry of Agriculture and Cooperatives, Bangkok.

Redmann, R.E. 1972. Plant communities and soils of an Eastern North Dakota prairie. **Bull. Terrey Bot. Club** 99: 65-76.

Rengasamy, P. and M.E. Sumner. 1998. Processes involved in sodic behaviour, pp. 35-50. *In* M.E. Sumner and R. Naidu, eds. **Sodic Soil: Distribution, Properties, Management and Environmental Consequences**. Oxford University Press.

Rhoades, J.D. 1982. Soluble Salts, pp. 167-179. *In* C.A. Black, ed. **Methods of Soil Analysis. Part II. Chemical and Microbiological Properties.** Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

Rojanapremsuk, S. 1990. **Characteristics of Salt Affected Soils, Problem and Remedial Measures for the Utilization of Salt Affected Land in Nam Phong Irrigation Project Stage 2**. M.S. Thesis, Kasesart University, Bangkok (in Thai with English Abstract).

Salama, R.B., T.J. Hatton and W.R. Dawes. 1999a. Predicting land use impacts on regional scale groundwater recharge and discharge. **J. Env. Qual**. 28: 446-460.

Salama, R.B., C.I. Otto and R.W. Fitzpatrick. 1999b. Contributions of groundwater conditions to soil and water salinization. **Hydrogeol. J**. 7: 46-64.

Samani, A. 1992. Determine the sensivity scales of soils to saline and sodic water in Garizate region at Yazd province. *In* **Proceeding of Seminar on the Problems of Iranian Desert and Kavir**, Yazd, Iran, Vol. 1.

Sawhney, B.L. 1989. Interstatification in layer silicates, pp.789-828. *In* J.B. Dixon, and S. B. Weed, eds. **Minerals in Soil Environments**. SSSA Book Series No. 1. SSSA, Madison, Wisconsin.

Seelig , B.D., J.L. Richardson and W.T. Barker. 1990. Characteristics and taxonomy of sodic soils as a function of landform position. **Soil Sci. Soc. Am. J.** 54: 1690-1697.

Seelig, B.D. 2000. Salinity and Sodicity in North Dakota Soil. **NdSU Extension Service**. Available Source http://www.ext. nodak.edu/extpubs/plantsci/ soilfert/eb57-1. Htm, May 1, 2003.

Shainbery, I. and M.J. Singer. 1985. Effect of electorolyte concentration on the hydraulic properties of depositional crust. **Soil Sci. Soc. Am. J**. 49: 1260-1263.

Sinanuwong, S. and Y. Takaya. 1974. Saline soil in Northeast Thailand, pp 105-120. *In* **S.E. Asian Studies**. Kyoto Univ, Japan.

Singer, M.J. and D.N. Munns. 1996. **Soil: An Introduction**. 3rd ed. Prentice-Hall Publishing Co., New Jersey.

Singh, B. and R.J. Gilkes. 1991. Concentration of iron oxides from soil clays by 5M NaOH treatment: the complete removal of sodalite and kaolin. **Clay miner.** 26: 463-472.

Singh, B. and R.J. Gilkes. 1992. Properties of soil kaolins from south-western Australia. **J. Soil Sci.** 43: 645-667.

Skaris, R.L., J.L. Richardson, G.J. McEarthy and A. Maianu. 1987. Evaporite mineralogy and groundwater chemistry associated with saline soil in Eastern North Dakota. **Soil Sci. Soc. Am. J.** 51: 1372-1377.

Soil Survey Division Staff. 1993. **Soil Survey Manual**. United States Department of Agricluture, Washington, D.C.

Soil Survey Staff. 2006. **Key to Soil Taxonomy.** 10th ed. USDA-NRCS. Washington, DC.

Soltanpour, P.N., G.W. Johnson, S.M. Workman, J.B. Jr. Jone and R.O. Miller. 1996. Inductive coupled plasma emission spectrometry and inductively coupled plasma-mass spectrometry, pp. 91-139. *In* D.L. Sparks, A.L. Page, P.A. Helmke and R.H. Loeppert, eds. **Methods of Soil Analysis. Part III. Chemical Method.** Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

Songsawadi, K. 1994. **Properties and Salinity Level of Roi Et Saline Variant in Changwat Nakhon Ratchasima**. M.S. Thesis, Kasesart University, Bangkok (in Thai with English Abstract).

SOS Environment, Inc. 2001. Sodic Soil Remediation. **SOS Environment**. Available Source http://sosenvironmental.com/DeSalt1. htm, March 14, 2002.

Stolt, M.H., C.M. Ogg and J.C. Baker. 1994. Strongly contrasting redoximorphic patterns in Virginia valley and ridge Paleosols. **Soil Sci. Soc. Am. J.** 58: 477-184.

Stoops, G. 1970. Scanning electron microscope applied to the micromorphological study of laterite. **Pedologie** 20: 268-280.

Suddhiprakarn, A. and I. Kheoruenromne. 1998. Mineralogy and micromorphology of salt affected soils in Central Plain, Thailand. **Thai J. Agri. Sci.** 31(1): 3-20.

Sys, C.I. 1980. **Tropical Soil-II**. State University of Ghent. Gent, Belgium.

Takai, Y., T. Nagano, M. Kimura, J. Sugi and S. Vacharotayan. 1987. **Coastal and Inland Salt Affected Soil in Thailand: Their Characteristic and Improvement**. Nodai Research Institute, Tokyo University of Agriculture.

Thanachit, S. 2006. **Mineralogical Trends Along some Soil Catenae in Thailand.** Ph.D. Thesis, Kasetsart University, Bangkok, Thailand.

Thomas, G.W. 1987a. Exchangeable cations, pp. 159-161. *In* C.A. Black, ed. **Methods of Soil Analysis. Part II. Chemical and Microbiological Properties.** Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

______. 1987b. Exchangeable acidity, pp. 161-163. *In* C.A. Black, ed. **Methods of Soil Analysis. Part II. Chemical and Microbiological Properties.** Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

Timpson, M.E., J.L. Richardson, L.P. Keller and G.J. McEarthy. 1986. Evaporite mineralogy associated with saline seeps in Southwestern North Dakota. **Soil Sci. Soc. Am. J.** 50: 490-493.

Topark-Ngarm, B., N. Midori and G. Itsuo. 1992. Salt affected soils in Northeast Thailand: Annual changes of surface soil reaction and their differences with vegetation and mulching, pp. 269-289. *In* **Proceedings of the International Symposium on Strategies for Utilizing Salt Affected Lands**. Department of Land Development, Ministry of Agriculture and Cooperatives, Bangkok.

Trakoonyingcharoen, P., I. Kheoruenromne, A. Suddhiprakarn and R.J. Gilkes. 2006. Properties of kaolins in red Oxisoil and red Ultisols in Thailand. **Appl. Clay Sci.** 32: 25-39.

Ungar, I.A. 1967. Vegetation-soil relationships on saline soils in Northern Kansas. **Am. Midl. Nat**. 78: 98-120.

______. 1970. Species-soil relationships on sulfate dominated soils of South Dakota. **Am. Midl. Nat.** 83: 343-357.

______. 1974. Inland halophytes of the United States. *In* R.J. Reimold and W.H. Queen, eds. **Ecology of Halophytes.** Academic Press, New York.

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. *In* L.A. Richards, ed. **Diagnosis and Improvement of Saline and Alkali Soils**. U.S. Department of Agriculture Handbook No. 60.

Uysal, I.T., S.D. Golding, and M. Glikson. 2000. Petrographic and isotope constraints on the origin of authigenic carbonate minerals and the associate fluid evolution in Late Permian coal measures, Bowen Basin (Queensland), Australia. **Sediment Geol.** 136: 189-206.

Várallyay, G. 1968. Salt accumulation processes in the Hungarian Danube valley, pp. 36-45. *In* J. Gerrard, ed. **Alluvial Soils**. Van Nostrand Reinhold Company Inc., New York, USA.

Vichiansinpa, J. 1992. **An Analysis on Properties and Potential of Salt Affected Soils in Khorat Basin.** Ph.D. Thesis, Kasesart University, Bangkok (in Thai with English Abstract).

Victoria C., L.M., L.M.W., Hover, R.P., Donald, and A.M. Martini. 1999. Mg-smectite authigenesis in a marine evaporative environment, Salina Ometepec, Baja California. **Clays Clay Miner.** 47: 252-268.

Vijarnsorn, P. 1972. **Characteristic and Genesis of Granites Derived Soil in Peninsular Thailand.** M.S. Thesis. Illinois University.

Walkley, A. and C.A. Black. 1934. An examination of degtjareff method for determining soil organic matter and a proposed modification of the chroma acid titration method. **Soil Sci.** 37: 29-35.

Wentz, D. and H. Vanderpluym. 1998. **Trends in Dryland Salinity**. Available Source http://www.agric.gov.ab.ca/sustain, August 28, 2002.

White, E.M. 1964. Morphological-chemical relationships of some thin-A horizon solodized soils derived from moderately fine material on a well drained slope. **Soil Sci.** 98: 256-263.

White, G.N. and W.R. Dixon. 1995. Scanning electron microscopy of minerals in soils. **TSEMJ.** 26: 1.

Whittig, L.D. 1965. X-ray diffraction technique for minerals identification and mineralogical composition, pp. 671-698. *In* C.A. Black, ed. **Methods of Soil Analysis. Part I. Physical and Mineralogical Methods.** Agronomy, No. 9. Amer. Soc. Agron. Inc., Madison, Wisconsin, USA.

Williams, B.G. and W.S. Semple. 2001. Implications of the chemical composition of saline seepage scalds, pp. 1-6. *In* C. Grose, L. Bond and T. Pinkard, eds. **Wanted Sustainable Futures for Saline Lands**, Seventh National PURSL Conference, Launceston,Tasmania.

Williamson, D.R., A.J. Peck, V. Turner and S. Arunnin. 1989. Groundwater hydrology and salinity in a valley in Northeast Thailand. **Groundwater Contamination IAHS Publ.** 185: 147-154.

Yuvaniyama, A. 1994. North saline soil (in Thai), pp. 76-77. *In* S. Arunin, ed. **The Saline Soils of Thailand**. Soil Salinity Section Research. Soil and Water Conservation and Management Div., Land Development Dept., Bangkok, Thailand.

Yuvaniyama, A., S. Arunin and Y. Takai. 1996. Management of saline soil in the Northeast of Thailand. **Thai J. Agric. Sci**. 29:1-10.

Zonn, S.V. 1986. Saline (Holomorphic) soils, pp. 365-379. *In* **Tropical and Subtropical Soil Science**. Mir Publishers, Moscow.