Physical Properties of Salt Affected Soils

1. Particle Size Distribution

The full analytical data for particle size distribution of salt affected soils are given in the Appendix C, Table C1. A texture triangle for the soils is shown in Figure 10. Soils mostly have quite different textures at each of the five locations. The texture groups are consistent with field texture determination. Soils at locations 1 and 5 are relatively mixed textured (loamy sand to sandy clay), at locations 2 and 4 soils are fine textured (clay to sandy clay) with the coarser textured horizons being due to depositional grading of sediments, whereas soils at location 3 have a coarse textured topsoil (loamy sand and sandy loam) and fine textured subsoil (sandy clay).

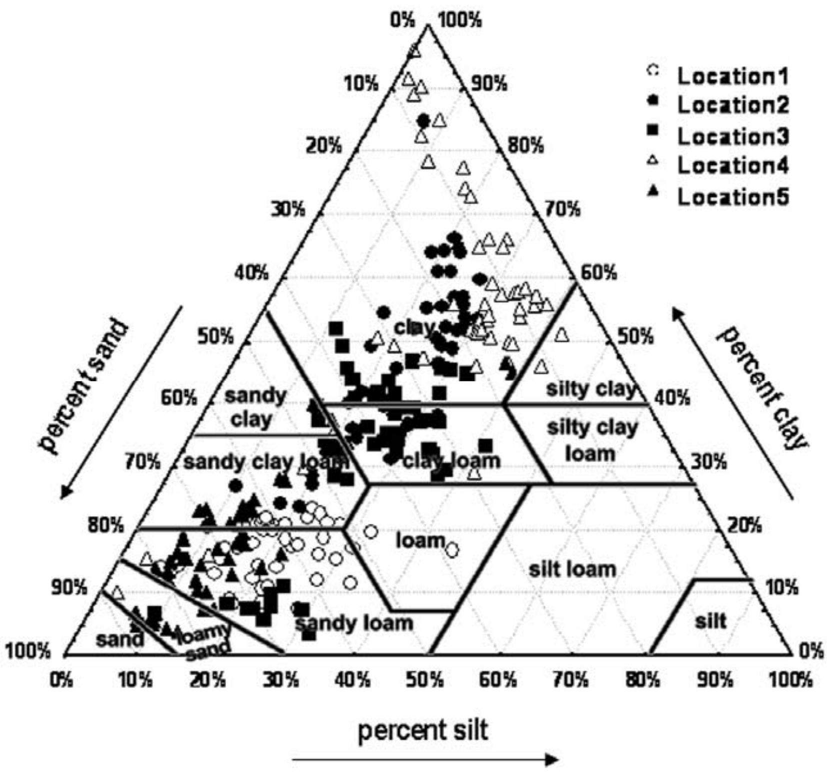


Figure 10 Ternary graph of sand, silt and clay concentrations for the salt affected soils in this study.

At some locations, individual soil profiles have very different textures relative to other profiles at that location (eg. locations 4, 5). These outlier profiles are probably indicative of very different parent materials.

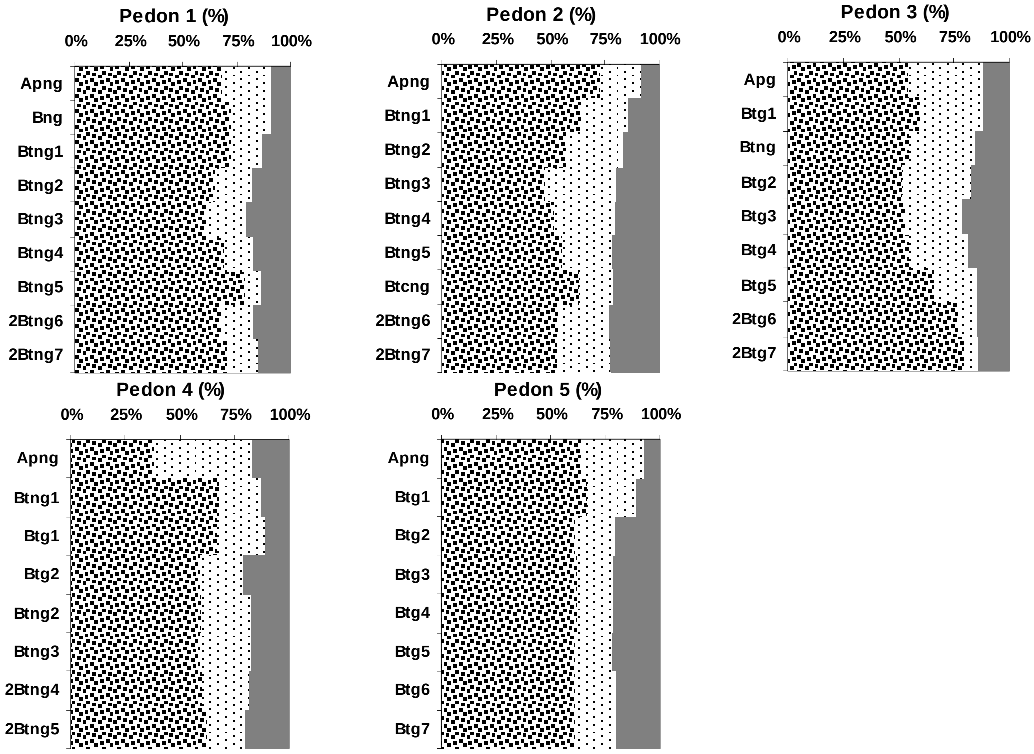
The distribution of sand silt and clay in each profile is shown in Figure 11a-e. Some profiles show erratic variations in clay percentage with depth that probably corresponds to depositional layers. Some profiles show systematically increasing clay percentage with depth that may be due to pedogenesis (eluvation) and illuviation but may also reflect the presence of depositional layers and a progressive coarseing of deposits (Dheeradilok *et al*., 1992).

The soils at locations 1 and 5 contain high amounts of sand particles (range from 381-875 g kg^{-1}) (Figure 11a and e) and have low clay contents (<400 g kg^{-1}) in all horizons except the BC and C horizon at location 5 (Figure 11e). Location 5 exhibits more variation in particle size distribution with depth than at location 1. The variation is associated with the depositional layers and a substratum layer that can be observed in the field.

The soils at locations 2 and 4 contain low to medium amounts of sand particles (Figure 11b, d) and have medium to high clay contents in all horizons except for subhorizons that are depositional layers consisting of alluvium over *in situ* residuum derived from clastic sedimentary rocks (location 2) and alluvium (location 4) (Table 1). Location 4 has the highest clay content (Figure 11b and d) reflecting the physiographic condition which is a depression on an erosional plain and the parent material is alluvium (Table 1).

The particle size distribution is very different between topsoils and subsoils for location 3 (Figure 11c). The topsoil (A) horizon contain high amounts of sand particles whereas subsoil horizons contains high amounts of clay and silt particles. The different distribution of particles size with depth at this location is consistent with the parent material at this location which is wash over residuum derived from clastic sedimentary rocks (Dheeradilok *et al*., 1992).

(a) Location 1



(b) Location 2

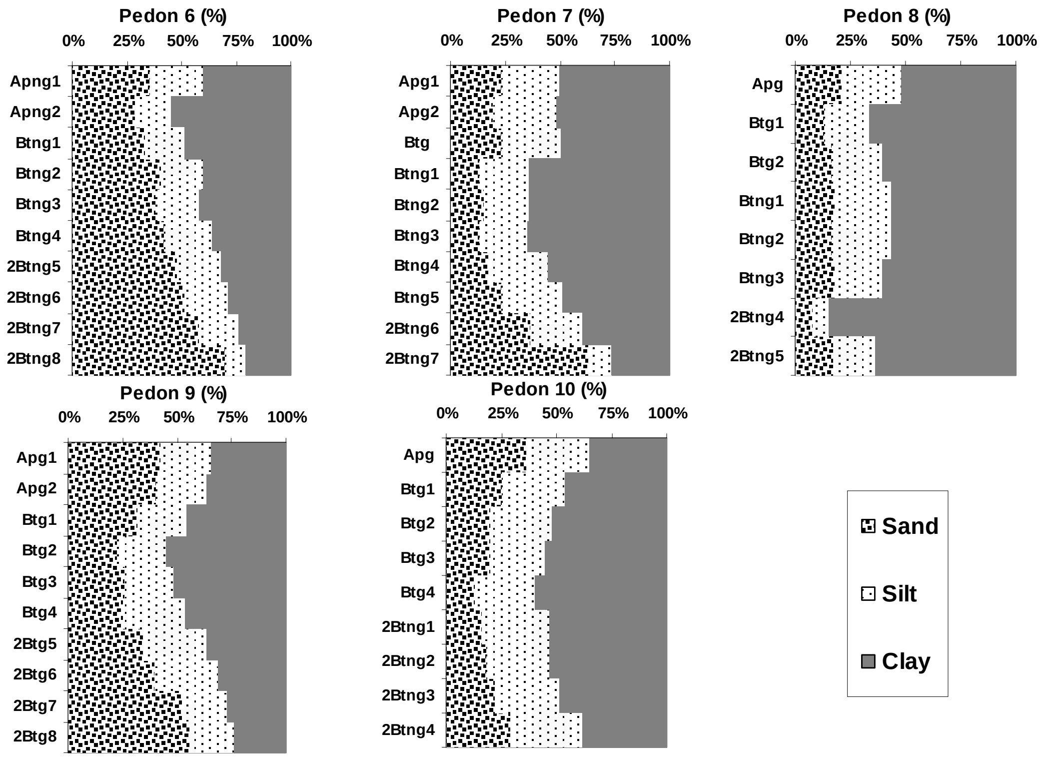
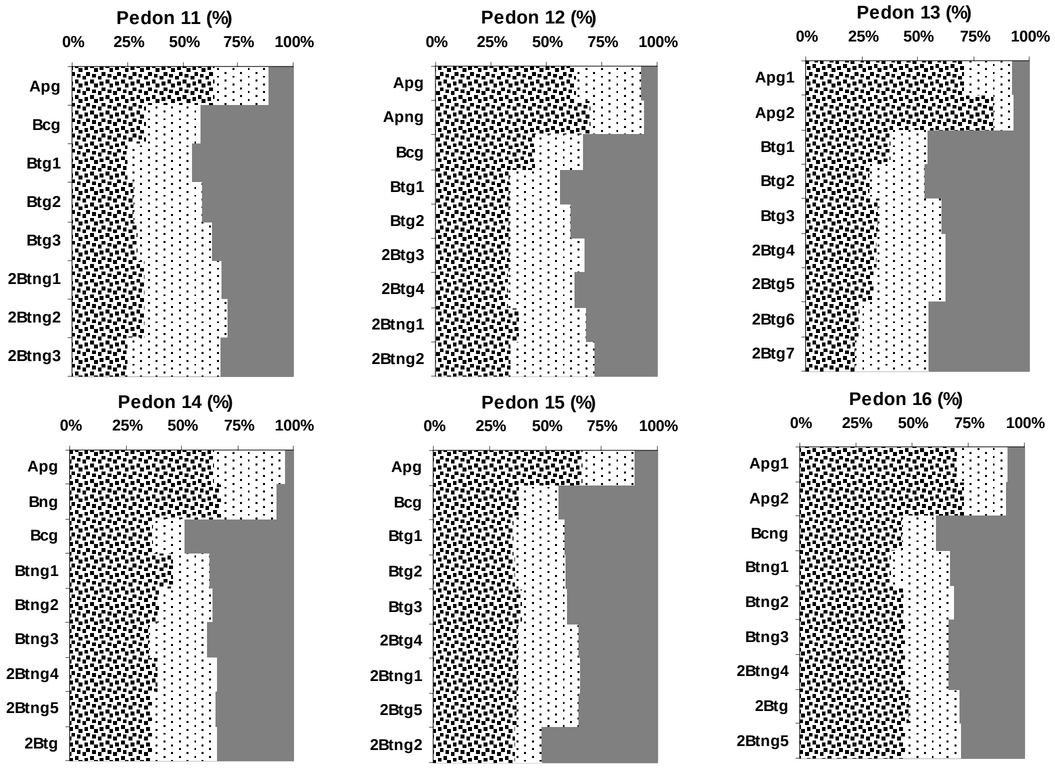
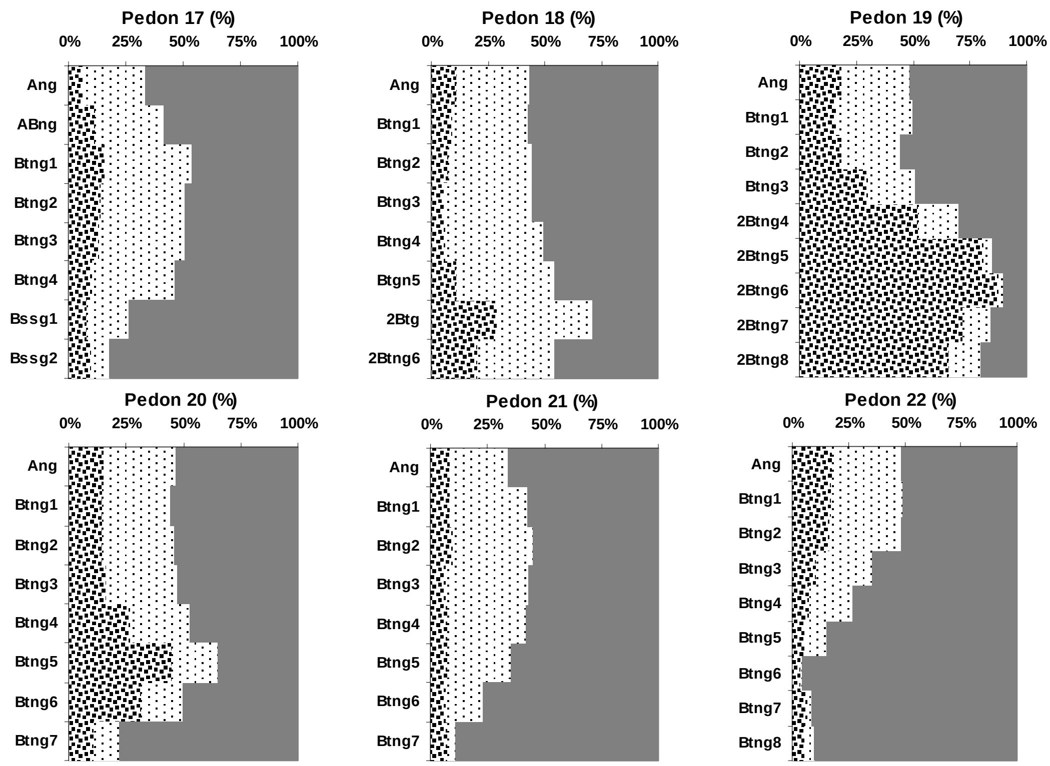


Figure 11 Profile distributions of sand silt and clay of salt affected soils from each location in this study.

(c) Location 3



(d) Location 4



<u>Figure 11</u> (Continued)

(e) Location 5

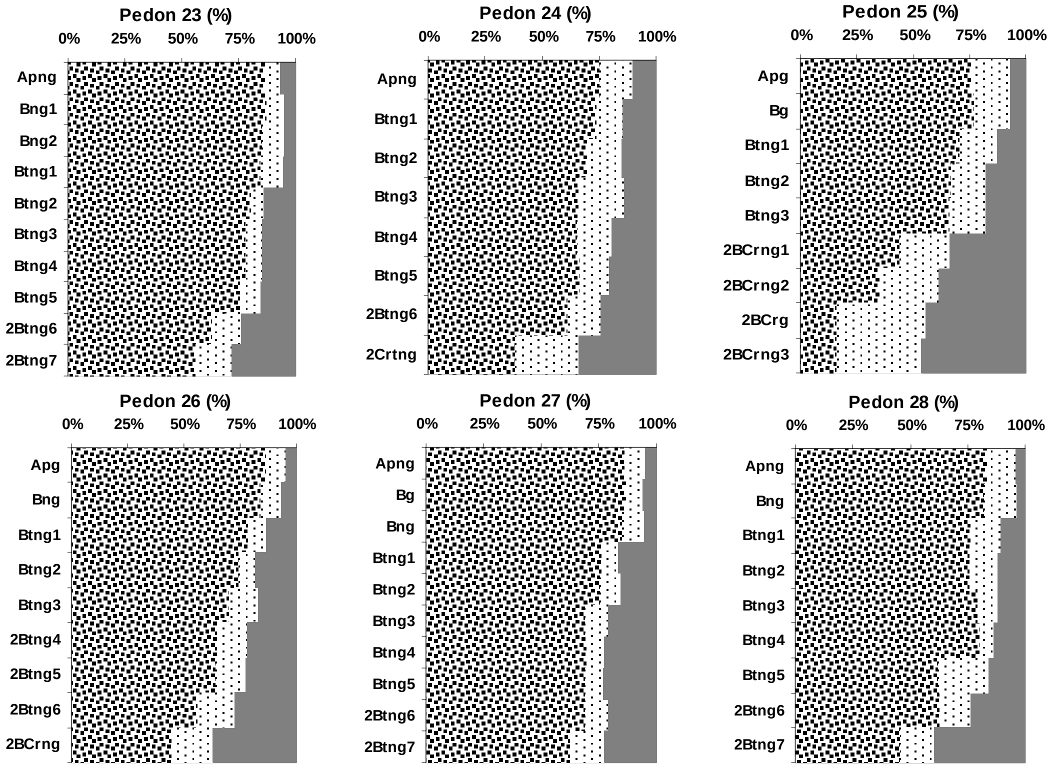


Figure 11 (Continued)

2. Bulk density (BD)

The bulk density values of salt affected soils are medium to very high, ranging from 1.39-2.43 Mg m^{-3}, (Appendix C, Table C1). The depth functions of bulk density values for salt affected in Northeast Thailand are shown in Figure 12a-e, and Figure 12f shows the median and standard deviation values for all salt affected soils. Most of these salt affected soils have high bulk density values of more than 1.6 Mg m^{-3} (Figure 12a-e) and the median value is about 1.74-1.93 Mg m^{-3} with the standard deviation between 0.06-0.16 with the increasing trend with depth (Figure 12f).

In general the bulk density value of soils has a positive relationship with the amounts of fine fractions (clay and silt). Normally, fine textured soils have higher bulk density values than coarse textured soils, but this trend is not evident for these salt affected soils. The bulk density value of salt affected soils shows a positive relationship with exchangeable sodium except for location 4 (Figure 13). There is a quite clear relationship between bulk density and exchangeable sodium for locations 3 and 5 with R^2=0.543 and 0.556 respectively (Figure 13c and d). The bulk density does not show a significant relationship with other soil properties used to classify salt affected soils (EC, SAR and ESP). In addition, most of the salt affected soils in this study have a closer and positive relationship between bulk density and exchangeable sodium than for bulk density versus clay concentration.

The bulk density of soils can be high for any type of soils depending how the flocculation and dispersion of clay in soil is affected by the concentration of salt. Dispersion occurs for low concentrations of salt whereas flocculation occurs for high concentration of salt (Takai *et al*., 1987; Arunin, 1992). Dispersion and flocculation may occur in salt affected soils as a cycle during the year as the amount of water in the soil changes. The small sized particles (clay and silt size) are dispersed in soils at low salt concentrations and flocculated in voids at high salt concentrations. This process causes high bulk density value in soils encountered in this research (Takai *et al*., 1987; Arunin, 1992). So, all of salt affected soils (fine, medium or coarse textured soils) have relatively high bulk density values somewhere in the soil profile (Figure 12).

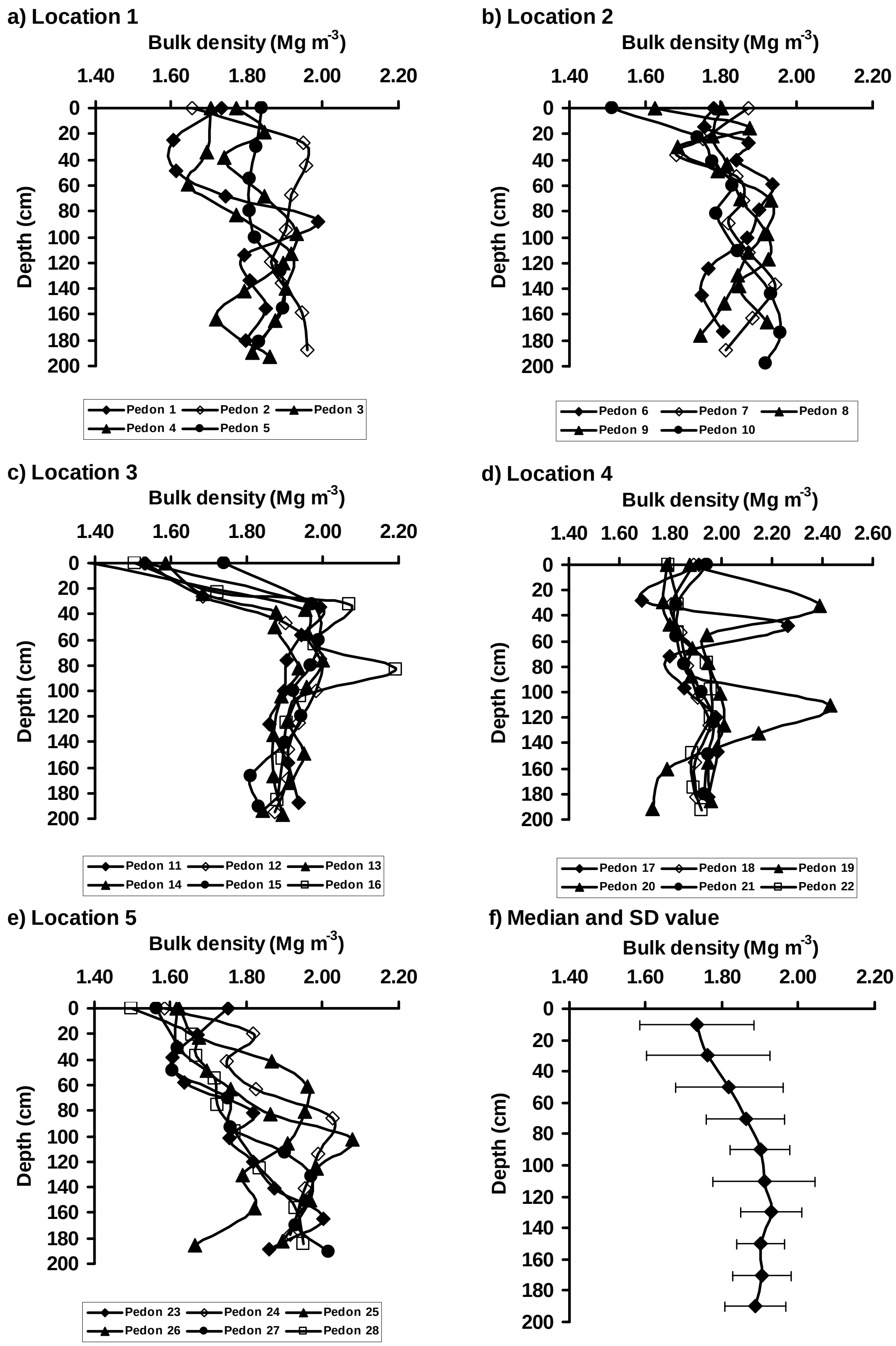
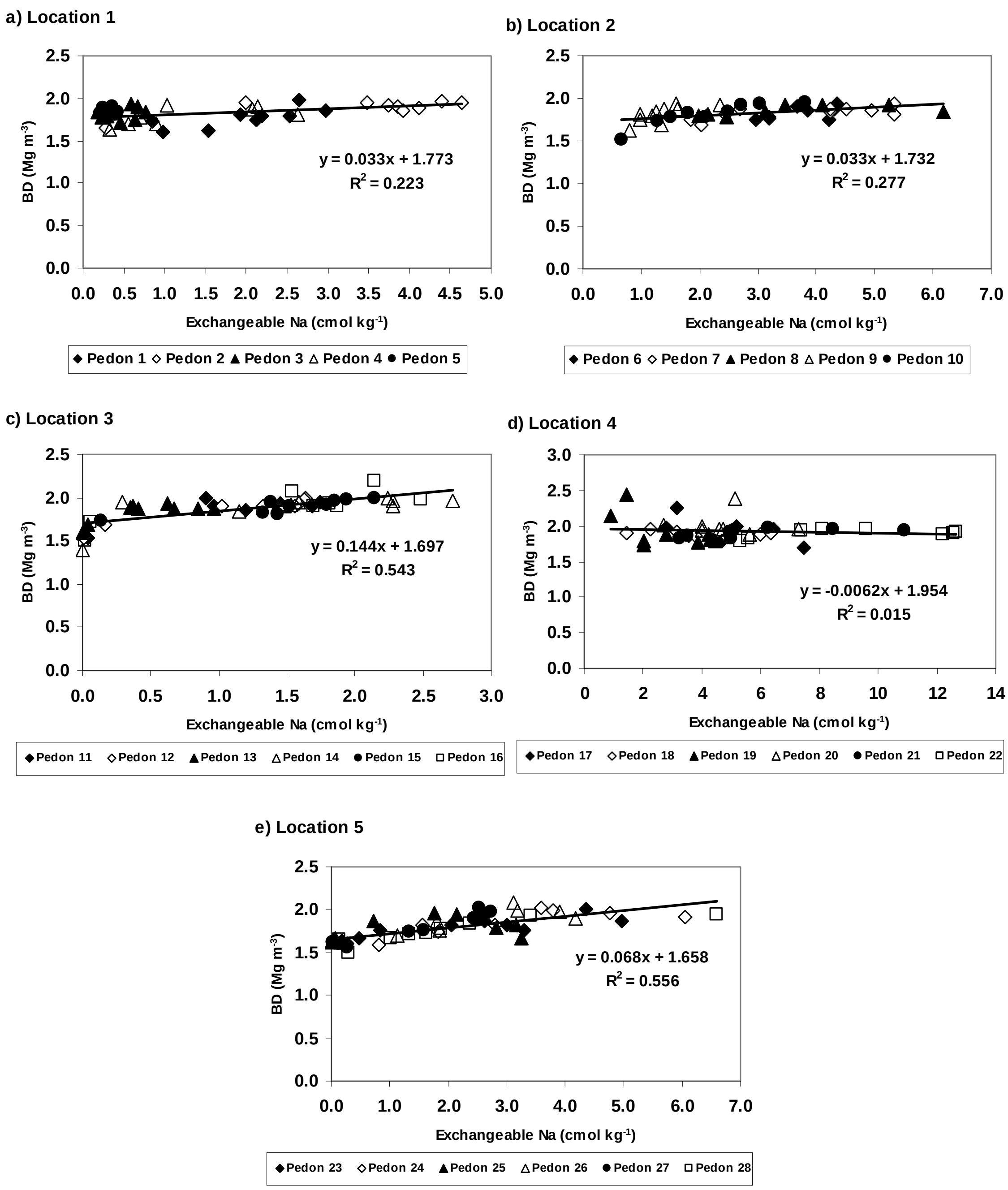


Figure 12 Depth functions showing bulk density values for salt affected soils in this study: a) samples from location 1, b) samples from location 2, c) samples from location 3, d) samples from location 4, e) samples from location 5 and e) the median and standard deviation value for all samples.



<u>Figure 13</u> Bivarate graphs showing relationships between bulk density and exchangeable Na for salt affected soils; a) location 1, b) location 2, c) location 3, d) location 4 and e) location 5.

3. Hydraulic Conductivity (Ksat)

Hydraulic conductivity value (Ksat) values of topsoil and subsurface soil horizons for salt affected soils are given in the Appendix C, Table C1. There are very large variations between locations which have classified ratings as very slow to moderate rapid, with Ksat ranging from 0.00097-6.86 cm hr^{-1}. Figure 14 shows the hydraulic conductivity value and classified rating for salt affected soils in each pedon from each location.

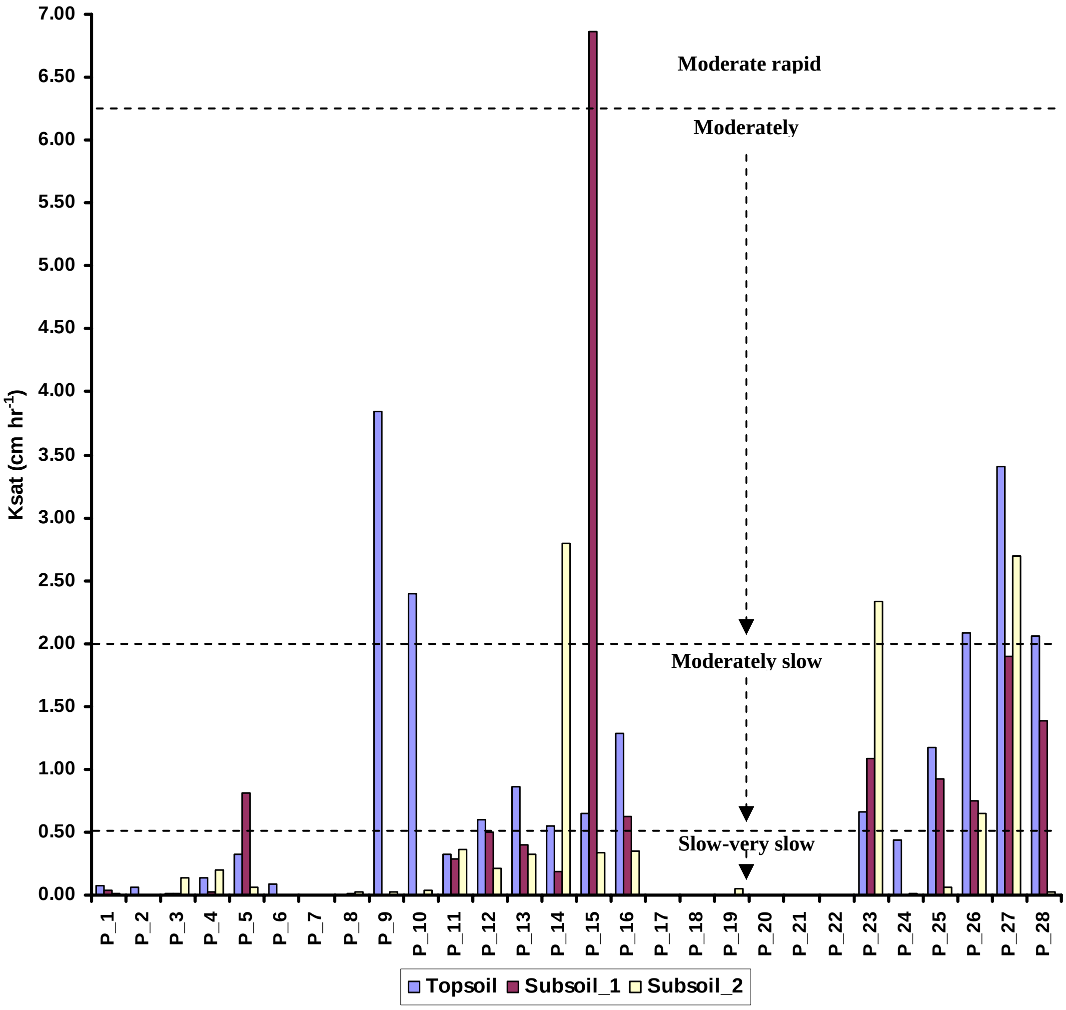


Figure 14 Graph showing the hydraulic conductivity and classified ratings for salt affected soils in this study.

Most of salt affected soils have hydraulic conductivity rating as very slow to moderately slow (Figure 14). Very slow to slow hydraulic conductivity values apply to locations 1, 2 and 4 whereas the slow to moderately rapid classes apply to locations 3 and 5 (Figure 14). The low value of hydraulic conductivity is related to the small particle size (clay and silt) distribution in the soil. Clayey textured soils normally have lower hydraulic conductivity that sandy textured soils, but for salt affected soil this difference is not clear. The low hydraulic conductivity value occurs for all soil textures such as at location 1 where the soil has a sandy texture and locations 2 and 4 soils that have a clayey texture (Figure 14).

The variation of hydraulic conductivity value between samples may be affected by salt, but there is not a significant relationship between hydraulic conductivity values and any other soil properties. Only for soils at location 5 does the hydraulic conductivity value have a negative relationship with bulk density, exchangeable Na and clay concentration (Figure 15). However, this is not a clear relationship and the R^2 is guite low. It may be concluded that when salt affects the soils the hydraulic conductivity value can be slow to very slow for any soil texture group but the relationship between hydraulic conductivity and salinity is complex.

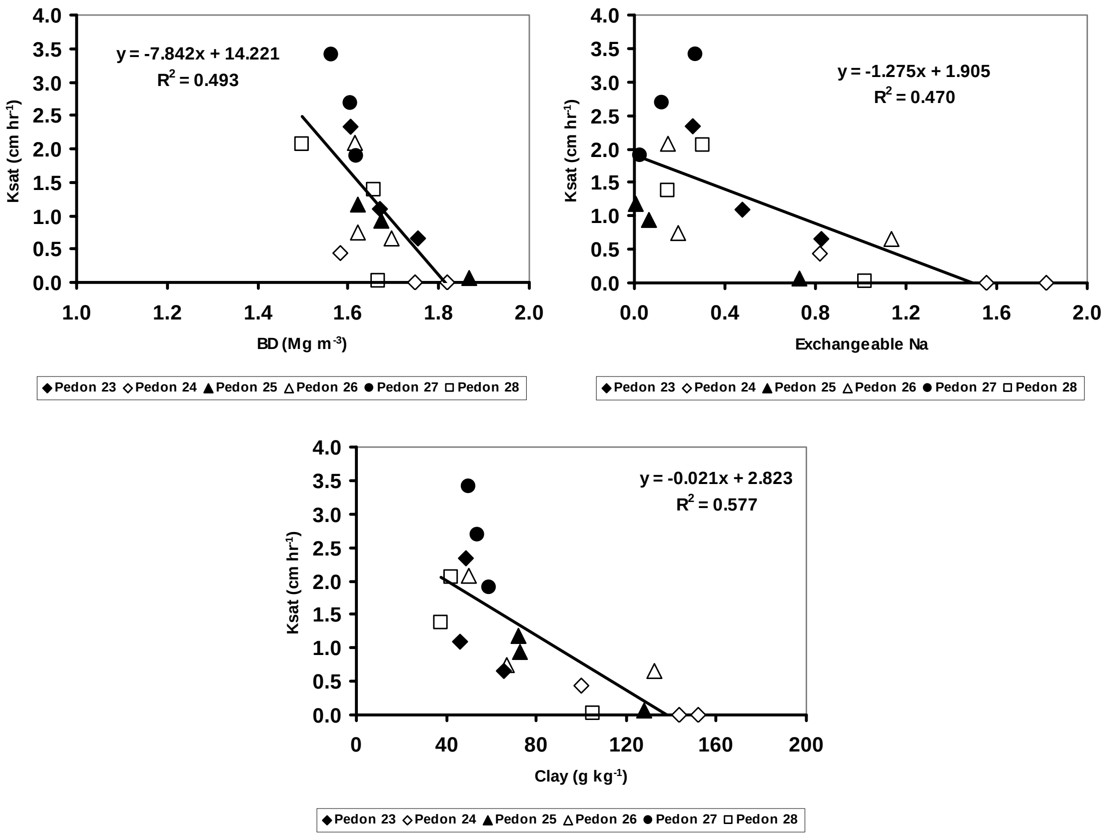


Figure 15 The bivarate graphs showing the relationships between hydraulic conductivity (Ksat) and bulk density, exchangeable Na and clay concentration for salt affected soils at location 5.

4. Synthesis

Salt affected soils in Northeast Thailand have various textures. The texture groups are consistent with field texture determination. Soils at locations 1 and 5 are relatively coarse textured (loamy sand to sandy clay), at locations 2 and 4 soils are fine textured (clay to sandy clay), whereas soils at location 3 have a coarse textured topsoil (loamy sand and sandy loam) and fine textured subsoil (sandy clay). Generally, salt affected soils have poor physical properties include high bulk density and low hydraulic conductivity. The bulk density value of soils normally has a positive relationship with the concentration of the fine fractions clay and silt in soils.

Fine textured soils have higher bulk density value than coarse textured soils, but this trend is not clear for these salt affected soils. The bulk density of salt affected soils is medium to very high. It shows a positive relationship with exchangeable sodium except for location 4. There is a clear relationship between bulk density and exchangeable sodium for locations 3 and 5. This is in line with the presence of a natric horizon attributed the translocation of clay into the subsoil under the influence of the sodium ion (sodicity). The natric horizon is a dense accumulation horizon with blocky, prismatic or columnar structure (Ivanava and Bol'Shakov, 1972; Soil Survey Staff, 2006). Their hydraulic conductivity is very variable with ratings from very slow to moderate rapid. The variation in hydraulic conductivity may be affected by salt, but there is no systematic relationship. When salt affects the soils their hydraulic conductivity can be slow to very slow for any soil texture group. Salt can induce the soil have poor physical properties (high bulk density and low hydraulic conductivity) but this effect is not consistent.

Chemical Properties of Salt Affected Soils

The full analytical data for chemical properties of salt affected soils are given in the Appendix C, Table C2.

1. General Chemical Properties

1.1 Soil Reaction (pH)

The trends of pH values with depth for salt affected soils at locations 1 to location 5 are given in Figures 16a and b, to Figures 20a and b respectively.

pH (H_2O1:1) of salt affected soils ranges from 4.1-8.8 (extremely acid to strongly alkaline) (Appendix C, Table C2). Soils from each location present a wide variation of soil pH. For location 1 pH ranges from 4.1-8-8 (extremely acid to strongly alkaline), location 2 from 4.9-7.2 (very strongly acid to neutral), location 3 from 4.7-8.0 (very strongly acid to moderately alkaline), location 4 from 4.1-6.4 (extremely acid to slightly acid) and location 5 from 4.7-8.8 (very strongly acid to strongly alkaline). Low pH values are present in clayey salt affected soils (locations 2 and 4) particularly at location 4. pH value tends to increase with depth for soils at locations 2 and 5 whereas at locations 1, 3 and 4 the pH values vary irregularly with depth (Figures 16a-20a).

pH value measured in KCl are consistently lower than those measured in water (Appendix C, Table C2 and Figures 16b-20b), thus delta pH values of these soils is negative (Beery and Wilding, 1971; Soil Survey Staff, 2006).

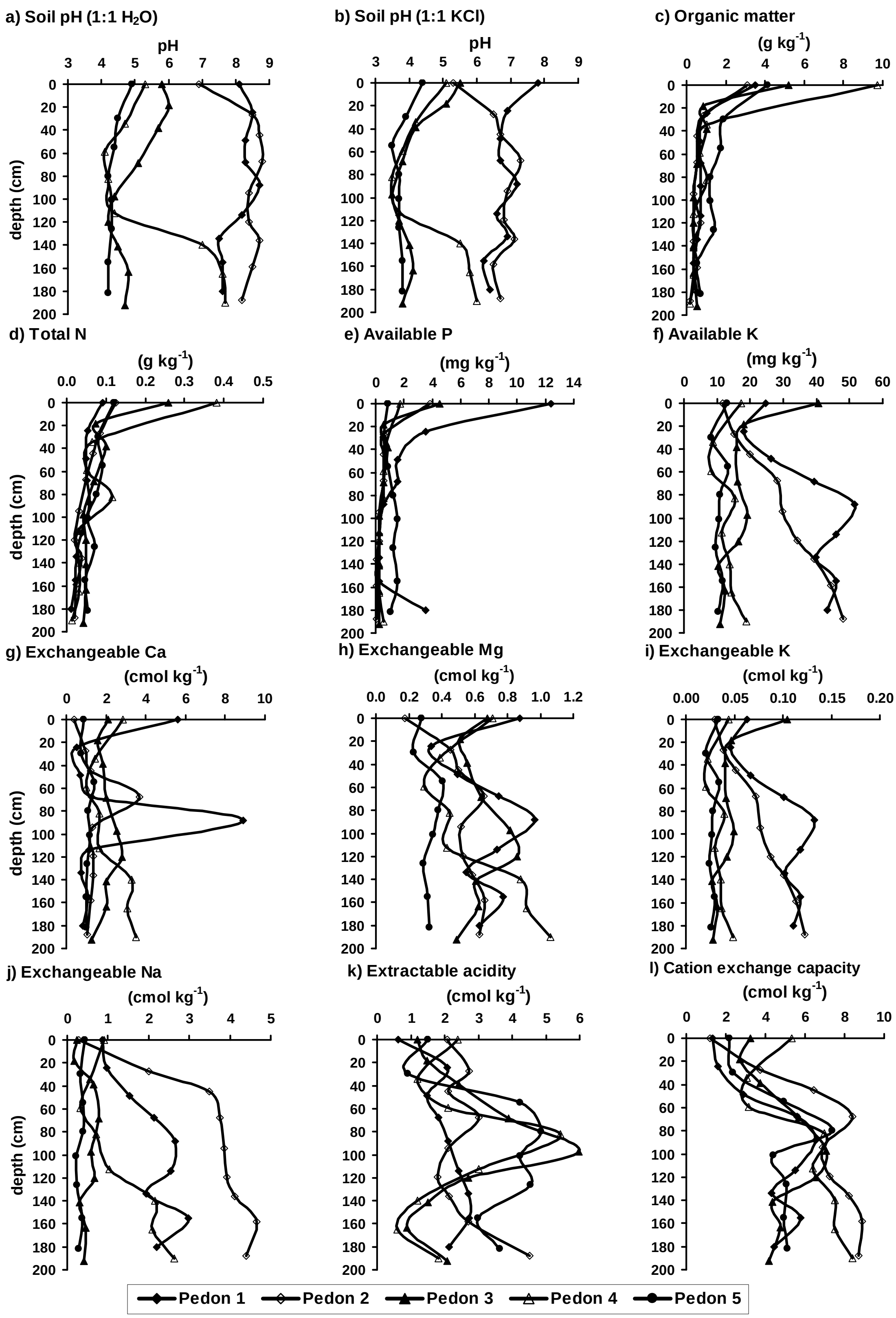


Figure 16 Depth functions of some chemical properties for salt affected soils at location 1.

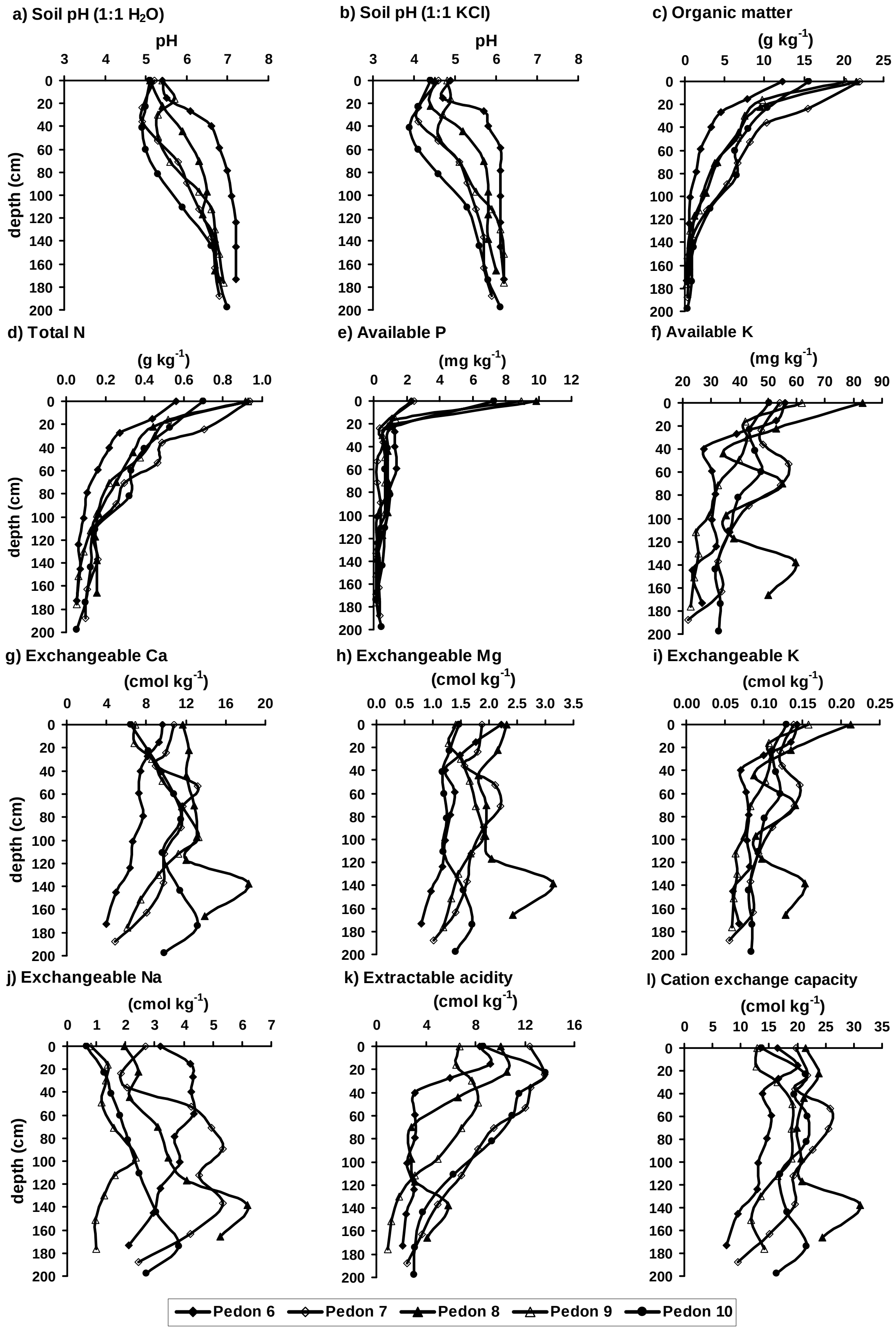


Figure 17 Depth functions of some chemical properties for salt affected soils at location 2.

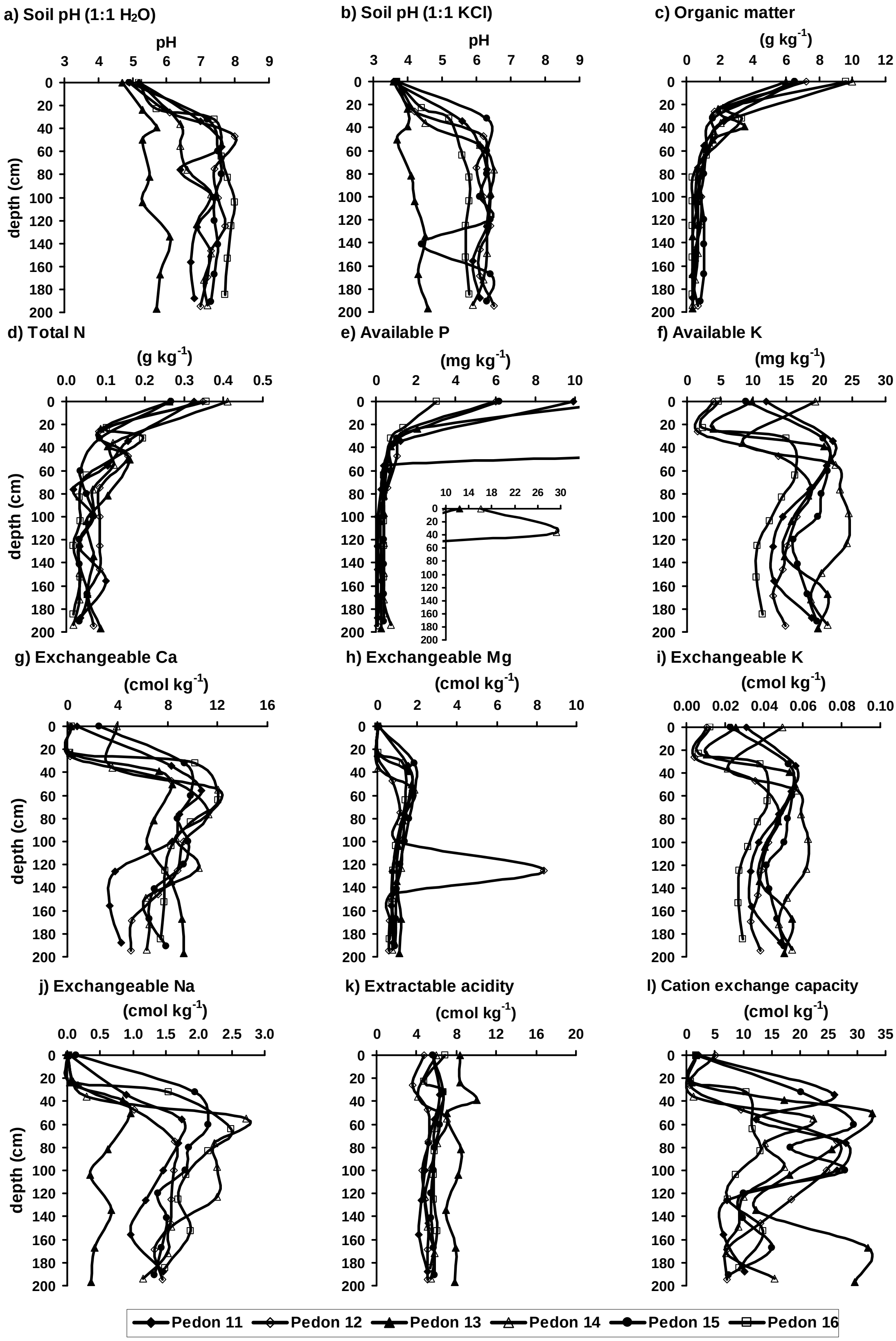


Figure 18 Depth functions of some chemical properties for salt affected soils at location 3.

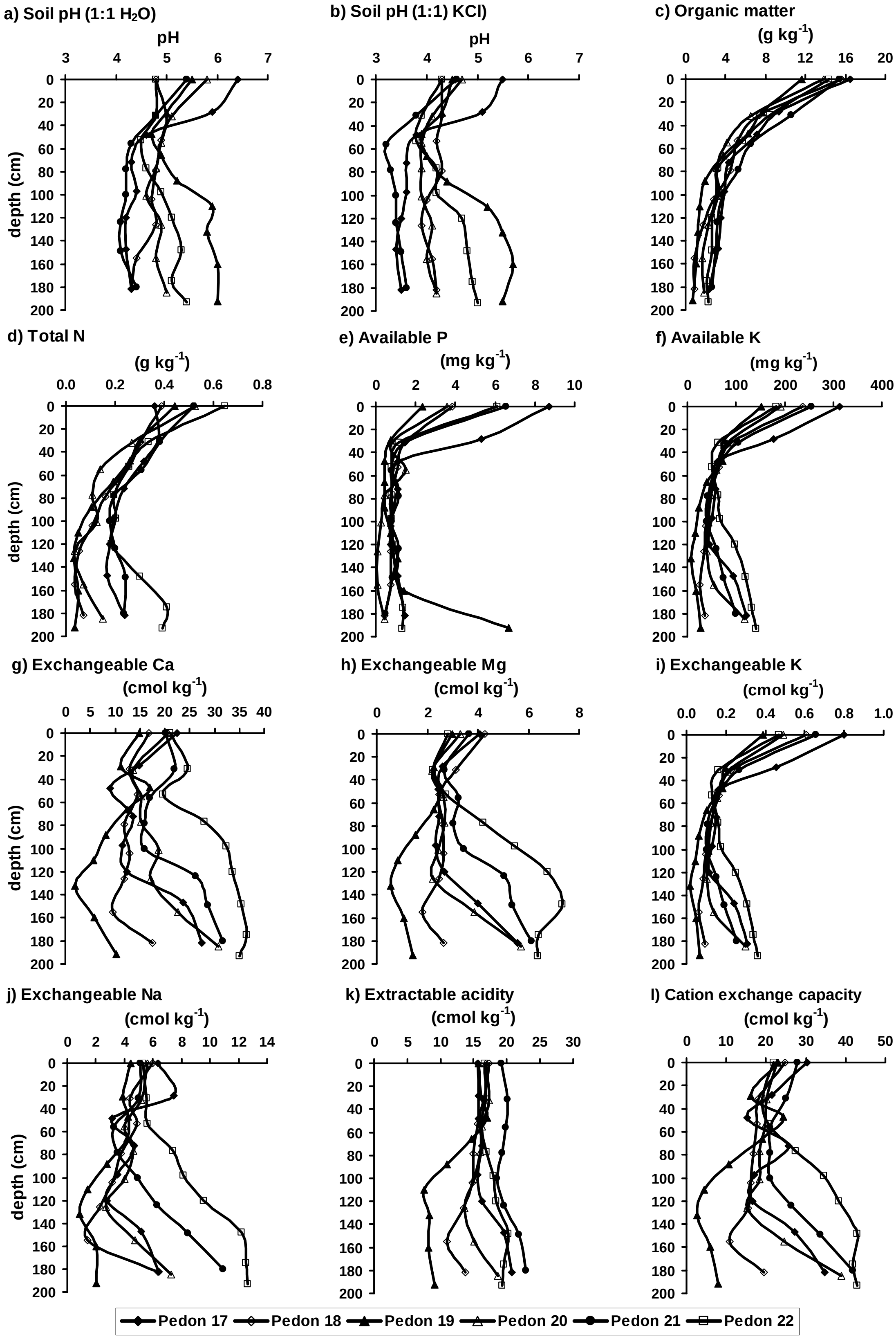


Figure 19 Depth functions of some chemical properties for salt affected soils at location 4.

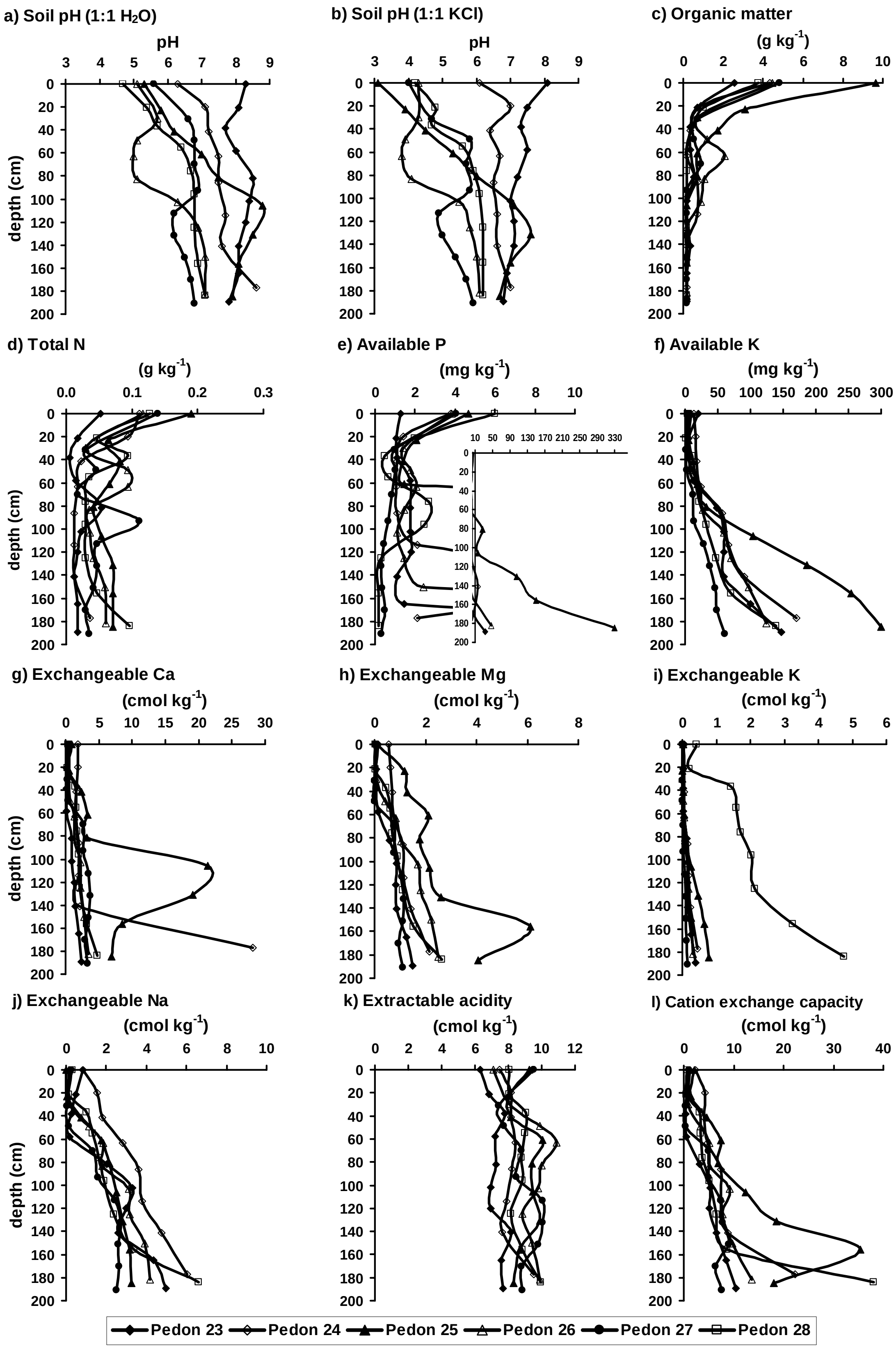


Figure 20 Depth functions of some chemical properties for salt affected soils at location 5.

1.2 Organic Matter (OM)

The trends of organic matter with depth in salt affected soils are shown in Figures 16c-20c. Coarse and medium textured salt affected soils (locations 1, 3 and 5) have lower amounts of organic matter than fine textured salt affected soils (locations 2 and 4), ranging from very low to medium (0.17-9.97 g kg^{-1}) and very low (0.17-3.51 g kg^{-1}) for surface horizons whereas organic matter in subsurface horizon ranges from 2.58-9.75 g kg^{-1}, very low to low. Organic matter of fine textured salt affected soils is very low to medium (2.66-22.01 g kg^{-1}) and is very low to medium (2.66-15.54 g kg^{-1}) in surface horizon whereas organic matter in subsurface horizon ranges from 11.67-22.01 g kg^{-1}, moderately low to medium. All of profiles show a decrease in organic matter with depth which it is a typical of tropical soils (Agbu *et al*., 1990; Buol *et al*., 2003).

The statistical relationships of organic matter with orther chemical properties for all of samples are give in Appendix C, Table C4 whereas the relationships of organic matter with other chemical properties for each location are given in Appendix C, Tables C5-C9. Organic matter abundance in these soils from all locations is clearly correlated (the correlation value $\geq$ 0.70) with total nitrogen (Appendix C, Tables C4-C9, Figures 16c-20c and 16d-20d), but there is no clear correlation with the other chemical properties. For location 2 organic matter is clearly correlated (the correlation value $\geq$ 0.70) with available phosphorus, available and exchangeable potassium, extractable acidity and %BS by sum (Appendix C, Table C6) and is clearly correlated with available, exchangeable and soluble potassium for location 4 (Appendix C, Table C8).

1.3 Total Nitrogen

The depth trends of total nitrogen in these soils are shown in Figures 16d-20d. The ratings of total nitrogen in these soils are very low to medium (0.01-0.94 g kg^{-1}). The clayey textured soils have higher total nitrogen ratings from very low to medium (0.03-0.94 g kg^{-1}) than the mixed textured soils, with very low total nitrogen

(0.01-0.41 g kg^{-1}). All of profiles show a decrease in total nitrogen with depth. The total nitrogen distributions in salt affected soils from all locations clearly correlate (the correlation value ≥ 0.70) with organic matter (Appendix C, Tables C4-C9). The correlations of total nitrogen with the other chemical properties for all locations and separated in each location are comparable with that of organic matter (Appendix C, Tables C4-9).

1.4 Available Phosphorus

Trends of available phosphorus with depth in these soils are shown in Figures 16e-20e. Available phosphorus in these soils has a large range being from very low to very high (0.06-330.50 mg kg^{-1}). Available phosphorus of most surface horizons is very low, ranging from 0.88-9.89 mg kg^{-1} (very low to moderately low) except for pedons 1, 13 and 14 have medium to moderately high available phosphorus (12.37-16.09 mg kg^{-1}). Available phosphorus of most subsurface horizons is very low, ranging from 0.06-6.67 mg kg^{-1} (very low to moderately low) except for the lower horizons in location 5 and the Bng horizon in pedon 14 that have moderately high to very high available phosphorus (15.59-330.50 mg kg^{-1}). Very high available phosphorus is due to the influence of parent rock containing high amounts of phosphorus. This result is in line with the data from the total analysis (XRF) (Appendix C, Table C10) of these samples that show the presence of high value of phosphorus. The high available phosphorus in the Bng horizon of pedon 14 is probably due to the effect of fertilizer management as is the case for the surface horizon. The high available phosphorus in an A horizon may be due to intensive application of fertilizer under rice cultivation but for pedon 1 it may be possibly due to the effects of salt. The surface soil of pedon 1 is used for rice production but the area is so highly affected by salt that rice cannot grow, so phosphorus is not removed from the soil by plants. Vijarnsorn (1972) reported the higher content of available phosphorus may occur from the decomposition of plant residues and there is stronger retention of this phosphorus against leaching in the surface soil. The relationships of available phosphorus with the other soil properties are given in Appendix C, Tables C4-C9.

1.5 Available Potassium

Available potassium in these soils shows a large variation, from very low to very high, ranging 1.47-312.45 mg kg^{-1}. Trends of available potassium with depth are shown in Figures 16f-20f. The available potassium varies with depth and values are also very different between each location. The soils at location 3 have the lowest available potassium ratings of very low (1.58-24.44 mg kg^{-1}), very low to low (8.15-51.52 mg kg^{-1}) at location 1, very low to medium (21.93-83.07 mg kg^{-1}) at location 2 and very low to very high at locations 4 and 5 with ranges from 7.82-312.45 mg kg^{-1} and 1.47-299.76 mg kg^{-1} respectively. The variation with depth of available potassium probably indicates that it has not been leached due to these soils being in the lower part of physiographic position (Table 2). The high available potassium in locations 4 and 5 is in line with the presence of high potassium inter layer (illite) (Table 5). Finally the salinity developing in these soils will introduce some K as KCl and other salts are generally the component of the total salinity in soils.

The relationships of available potassium with other chemical properties are given in Appendix C, Tables C4-C9 and it is not highly correlated with any chemical properties when considering salts from all locations. Howevery, the available potassium is highly correlated (the correlation value $\geq$ 0.70) with some chemical properties in the mixed and medium textured soils including significant correlation with exchangeable sodium for location 1, significant correlation with exchangeable calcium, Sum bases, CEC (by sum) and % BS (by sum) for location 3 and significant correlations with exchangeable magnesium, Sum bases and CEC for location 5 (Appendix C, Tables C5, C7 and C9).

1.6 Exchangeable Bases

The full data for exchangeable bases (Ca, Mg, K and Na) are given in Appendix C, Table C2. Ca and Na are the major exchangeable bases in these soils and ranges from 0.11-36.43 cmol kg^{-1} and 0.002-12.66 cmol kg^{-1} respectively. Mg and K have low values ranging from 0.01-8.37 cmol kg^{-1} and 0.004-0.80 cmol kg^{-1}

respectively. The exchangeable bases are higher for clayey salt affected soils whereas sandy salt affected soils have the lower values except for the lower horizons for location 5 (pedons 24 and 25) that are BC and C horizons. These result show the influence of parent materials that contain high levels of bases particulally Ca (Appendix C, Table C2 and Figure 20g-j), which is consistent with the total analyses (XRF) (Appendix C, Table C10) and the presence of calcite in the whole soils (Table 5). Soils at location 4 have the highest exchangeable Ca and Na concentrations which are consistent with their low positions on the landscape (Table 1 and Figure 4). Sodium is the major exchangeable cation for most of these soils, so these soils are mostly sodic.

The trends of exchangeable bases with depth are shown in Figures 16-20g-j and the correlations of exchangeable bases with other chemical properties are given in Appendix C, Tables C4-C9.

1.7 Extractable Acidity (EA)

The extractable acidity of the salt affected soils is very low to very high, ranging from 0.61-22.83 cmol kg^{-1}. Mostly extractable acidity of these soils is very low to moderately high except for soils in location 4 that have moderately high to very high extractable acidity, ranging from 7.48-22.83 cmol kg^{-1} (Appendix C, Table C2). Trends of extractable acidity with depth are shown in Figures 16k-20k. The extractable acidity has a high significant correlation (the correlation value $\geq$ 0.70) with CEC (by sum) for all locations (Appendix C, Table C4). The bivarate graph shows the close relationship (R^2=0.75) but the data points are not randomly distributed about the regiession line (Figure 21a). There are various linear relationships or no relationship when data for each traverse are plotted separately. Only soils from locations 2 and 4 have highly significant relationships (Appendix C, Tables C6 and C8) with the bivarate graph showing good relationship between EA and CEC (by sum) with R^2=0.53 and 0.72 (Figure 21b, e). Extractable acidity does not show close relationships with other chemical properties (Appendix C, Tables C4-C9).

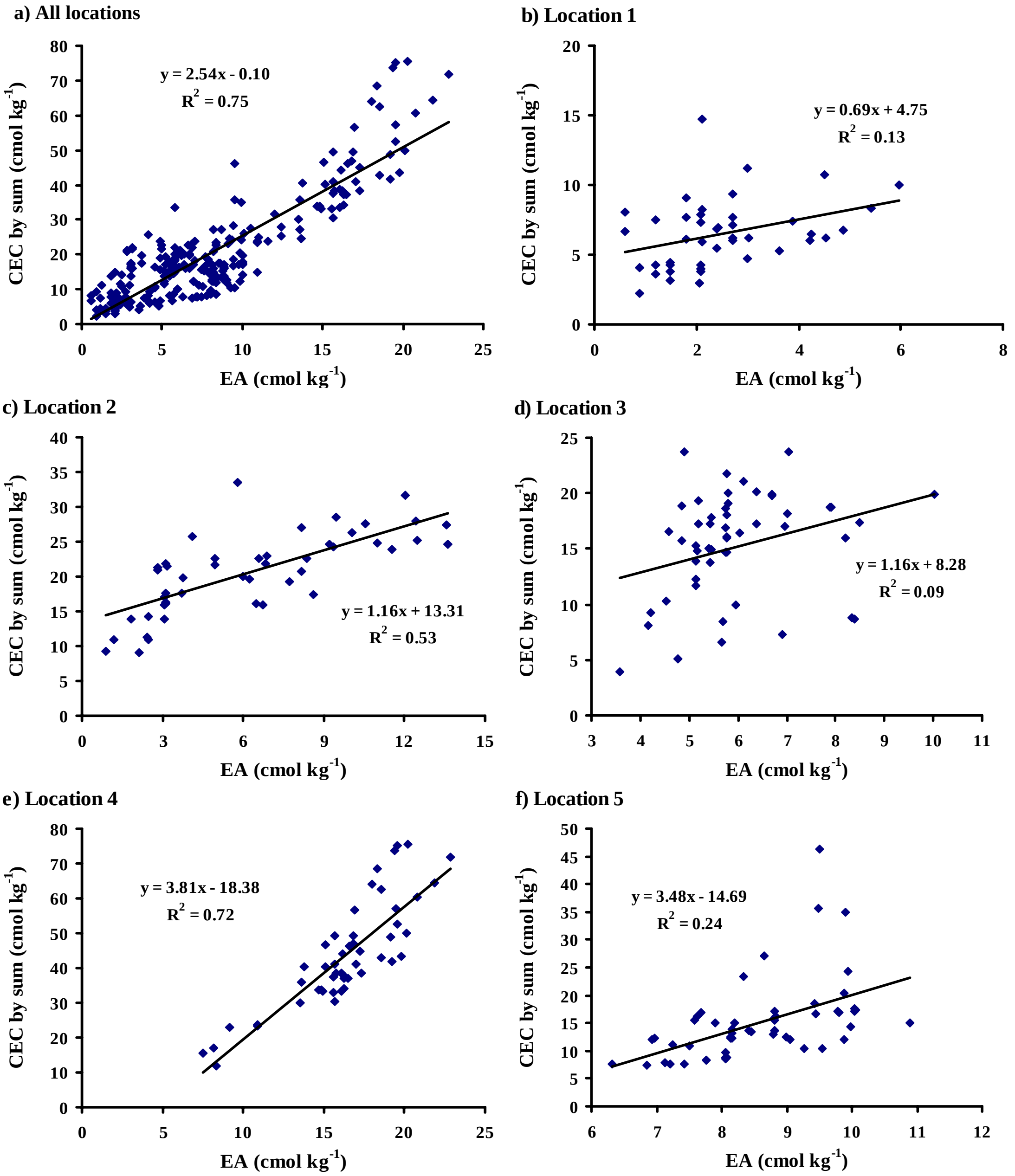


Figure 21 Bivarate relationships between EA and CEC by sum of cations for salt affected soils; a) samples from all locations, b) Location 1, c) Location 2, d) Location 3, e) Location 4 and d) Location 5.

1.8 Cation Exchange Capacity (CEC)

Salt affected soils have very low to very high CEC values, ranging from0.30-42.98 cmol(+) kg^{-1}. The CEC of the soils can be used to separate the soils into two groups. Group 1 has medium low to low CEC (CEC ≤ 10 cmol kg^{-1}) and consists of sandy soils (locations 1 and 5) whereas for locations 2, 3 and 4 the CEC is medium to high (CEC >10-30 cmol kg^{-1}) as the soil contains more clay (Table 3). The variation of CEC value reflects soil texture and also type of clay mineral. The distribution of cation exchange capacity in the salt affected soils is shown in Figures 16l-20l. CEC of most coarse and medium textured soils increases with depth and is related to clay concentration whereas, the fine textured soils normally have high CEC thoughout soil profile with the variations similarly reflecting changes in clay concentration. The CEC of these soils does not show high significant relationships (the correlation value ≥ 0.70) with any chemical properties (Appendix C, Tables C4-C9).

Figure 22 shows the relationships of CEC and CEC_clay with clay concentration. The clay concentration is clearly related to CEC (R^2=0.84) (Figure 22a). The CEC_clay is not related to clay concentration (Figure 22b) indicating that these soils have different amount and type of clay minerals (Table 5).

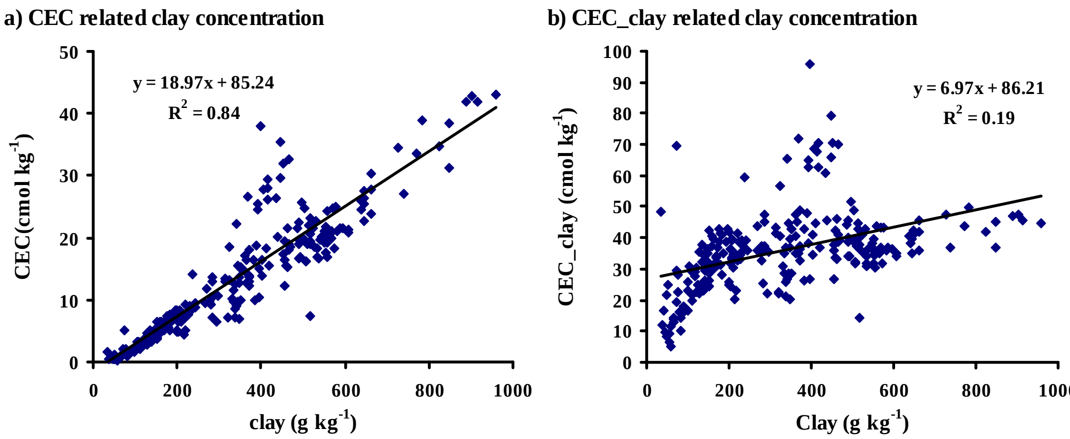


Figure 22 a) Bivarate graph showing the relationships between CEC and clay concentration, the low relationship between CEC_clay and clay distribution.

1.9 Base Saturation Percentage by Sum (%BS)

The percentage base saturation (%BS) of these soils ranges from low to high (7.40-2195). Most of these soils have high %BS of more than 35 percent. The low %BS present in some surface horizons of location 3 that have very high sand concentration and low EC. The %BS of of salt affected soils correlates with electrical conductivity (EC) (the correlation value ≥ 0.70) (Appendix C, Table C4). Under high EC value %BS of the soils will be very high due to high soluble salt in the soil system (Appendix C, Tables C2 and C3). This correlation does not show the high significant relationships when considered in each location. It has high significant relationships (the correlation value ≥ 0.70) in locations 1 and 5 that are sandy soils. (Appendix C, Tables C5 and C9). The bivarate graph showing the relationship of %BS with EC value for soil from all locations are given in Figure 23a whereas Figure 23 b-f shows the relationship of %BS with EC value for soil from each location. It has high relationship in locations 1 and 5 that are sandy soils (Figure 23b and f). Low to medium relationships in locations 2 and 4 (Figure 23c and e) whereas location 3 that has EC value lower than 4 dS m^{-1} shows no trend of relationship (very low R^2) (Figure 23f). Very high %BS of these soils is influenced by high soluble salt in the soil system.

The correlations of %BS with other chemical properties are given in Appendix C, Tables C4-C9.

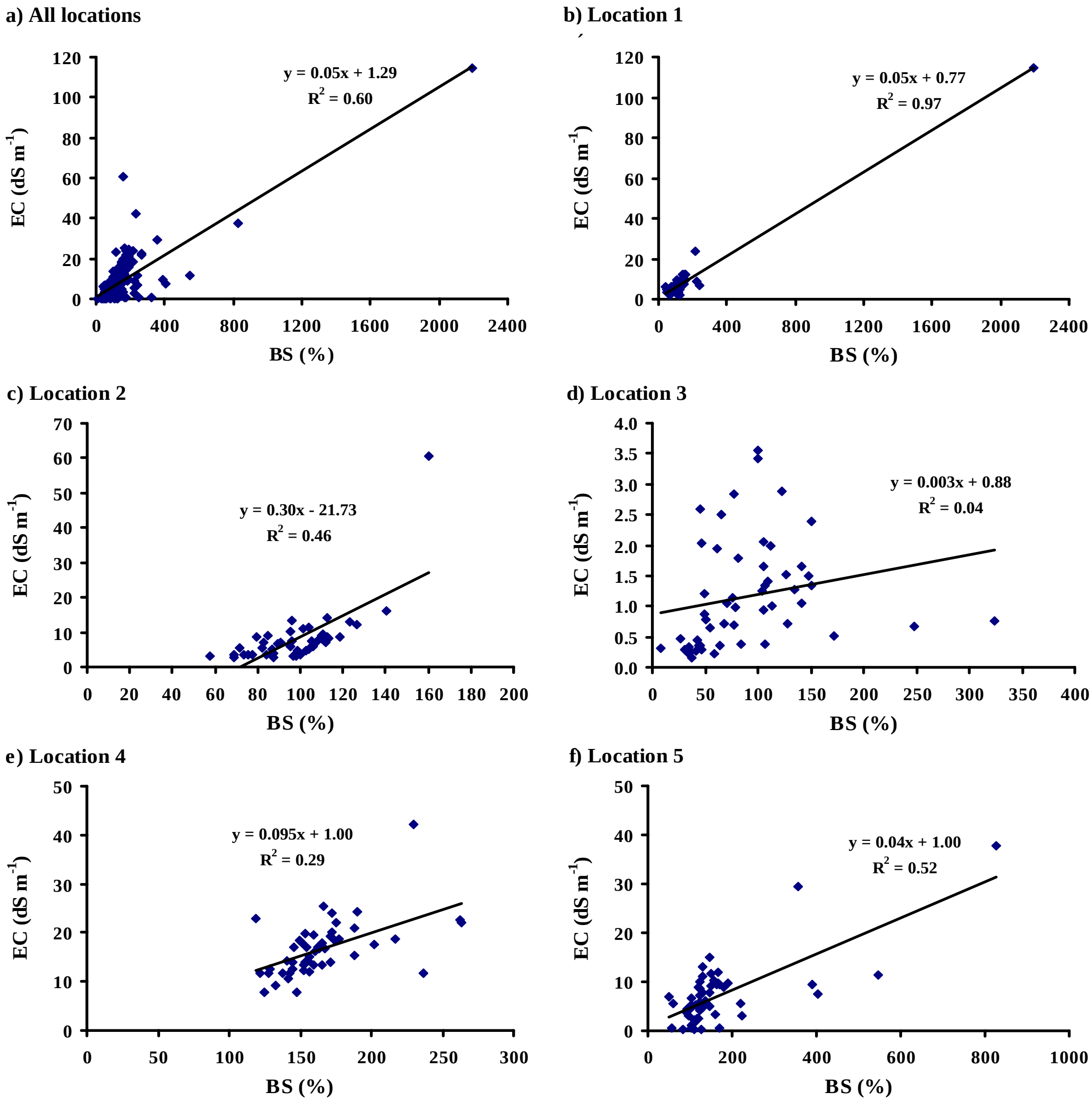


Figure 23 Bivarate graph showing the relationships between %BS and EC value of salt affected soils; a) samples from all locations, b) Location 1, c) Location 2, d) Location 3, e) Location 4 and d) Location 5.

2. <u>The Chemical Criteria for Classifying Salt Affected Soils</u>

The chemical criteria used to classify salt affected soils include electrical conductivity (EC) and sodium adsorption ratio (SAR) and/or exchangeable sodium percentage (ESP). The full data set of EC, SAR and ESP of these soils are given in Appendix C, Table C2.

2.1 Electrical Conductivity (EC)

The trend with depth of EC values of salt affected soils from each location is shown in Figure 24a-e. The EC values of these soils range from 0.2-114.3 dS m^{-1} and there is a very large variation between locations and also in each pedon at a location (Appendix C, Table C2 and Figure 24a-e). The EC values for many soil samples are more than 4 dS m^{-1} (median =5.8, SD =10.2) indicating that many of these soils are salt affected basing on the classification of Brady and Weil (2002).

Most of the salt affected soils at location 1 have high EC values of more than 4 dS m^{-1}, ranging from 2.0-114.3 dS m^{-1}. Generally, the highest EC value is in surface soils which is consistent with the presence of a salt crusts. The high EC value in surface soil is caused by the upward movement of saline groundwater under high evaporation. The variation with depth of EC value in this location reflects the soil texture as in sandy textured soil the soluble salt is easily moved though the soils profile. In addition, some of the lower horizons have high EC value is probably due to the effect of parent rock (rock salt) and the high bulk density retards the movement of the saline water. The EC tends to decrease or remain constant with depth as shown in Figure 24a.

Soils in location 2 have high EC values of more than 4 dS m^{-1}, ranging from 2.8-60.5 dS m^{-1}. Surface soils generally have the highest EC values particularly in Pedon 6 that has a salt patch at the surface. Pedon 6 has high EC and more variation with depth than other pedons at this location (Figure 24b). The high EC in the lower horizon may be due to the depositional layer. This horizon has a coarser texture than dose the upper horizon, so it is interpreted that there is salt movement up to the surface soil.

Soils at location 3 have EC values less than 4 dS m^{-1} (0.2-3.6 dS m^{-1}). The EC values at this location increases with depth (Figure 24c). The low EC and the increasing EC with depth may be due to these soils being at a stage of salt leaching (desalinization). Soils at this location have relatively little salt but EC is higher than 2 dS m^{-1} in some horizons, and will affect plant growth (Brady and Weil, 2002).

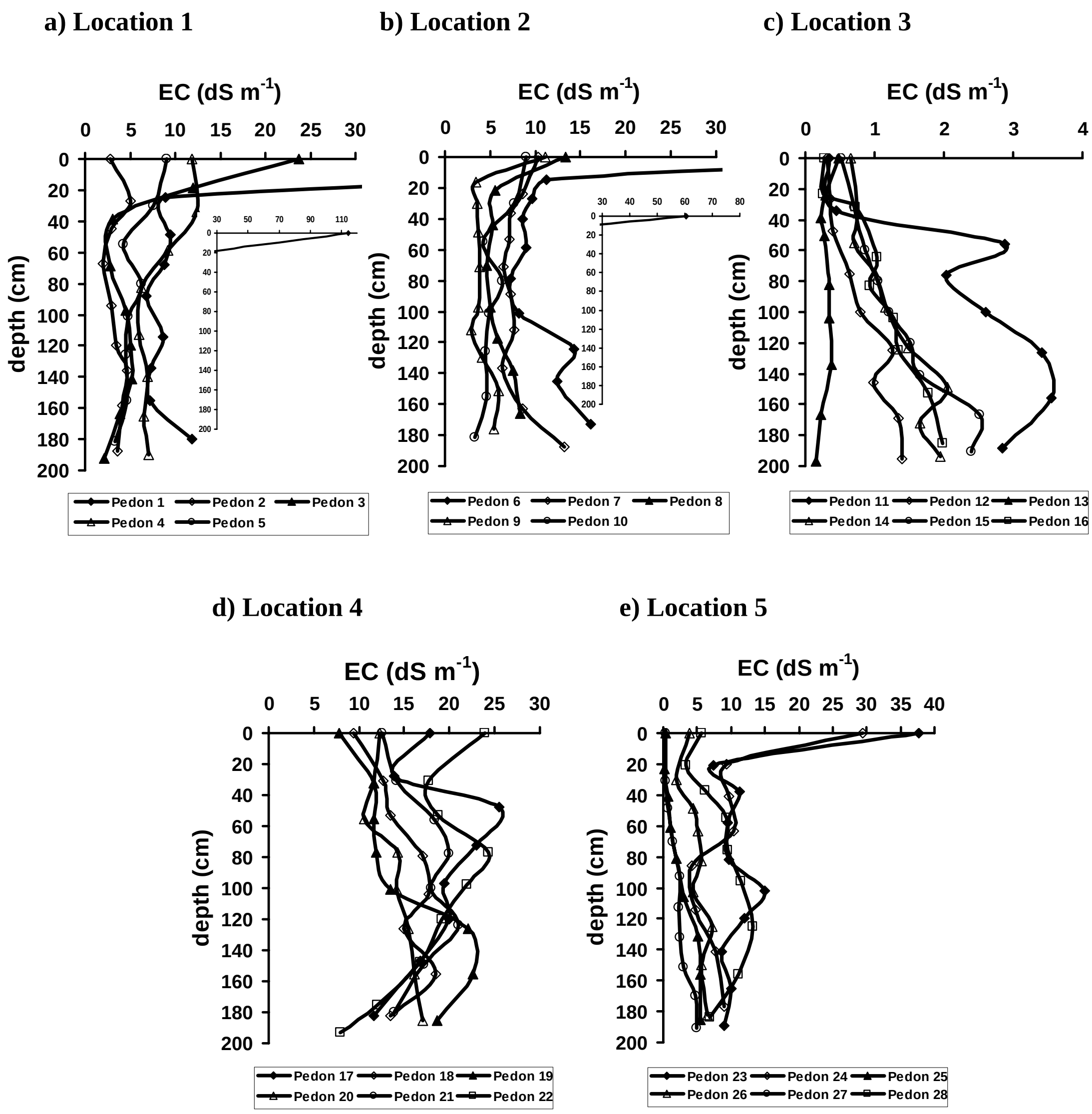


Figure 24 Depth functions of EC for salt affected soils in this study.

All of soils at location 4 have high EC values of more than 4 dS m^{-1} (7.8-42.1 dS m^{-1}) and quite uniform with depth (Figure 24d).

The trend of EC value with depth for soils at location 5 is shown in Figure 24e. The EC values of soils at location 5 vary between pedons. Pedons 23 and 24 have very high EC values thoughout the soil profile, ranging from 4.2-37.7 dS m^{-1}, most horizons in pedon 28 have high EC values, ranging from 3.3-13.2 dS m^{-1} whereas pedons 25 , 26, 27 have high EC values only in some horizons, ranging from 0.3-7.1 dS m^{-1}. The low EC values in the upper part of pedon 24 and 25 are the effect of the high bulk density horizon break (Figure 24e and and Figure 12e).

The relationships of EC values and chemical properties of salt affected soils are given in Appendix C, Tables C4-C9. The EC values for all salt affected soils show highly significant correlations (the correlation value $\geq$ 0.70) with %BS and soluble sodium (Appendix C, Table C4), but the bivarate graph shows a poor distribution of data points despite the high relationships (R^2=0.60 and 0.59) (Figures 23a and 25a). The relationships of EC with the other chemical properties are different for each location. The EC values are correlated with soluble sodium in 3 locations including locations 1, 2 and location 5 (Appendix C, Tables C5, C6 and C9). Moreover, the EC value is related to soluble magnesium for location 1, soluble magnesium and calcium for location 2 and sodium adsorption ratio (SAR) for location 5 (Appendix C, Tables C5, C6 and C9). Figure 25b-h shows the significant relationships of EC with some chemical properties. These results indicate that despite highly significant relationships of EC with other soils properties (soluble Na, Mg, Ca and SAR) the data points are not randomly distributed about the regression lines showing that several factors contribute to EC values.

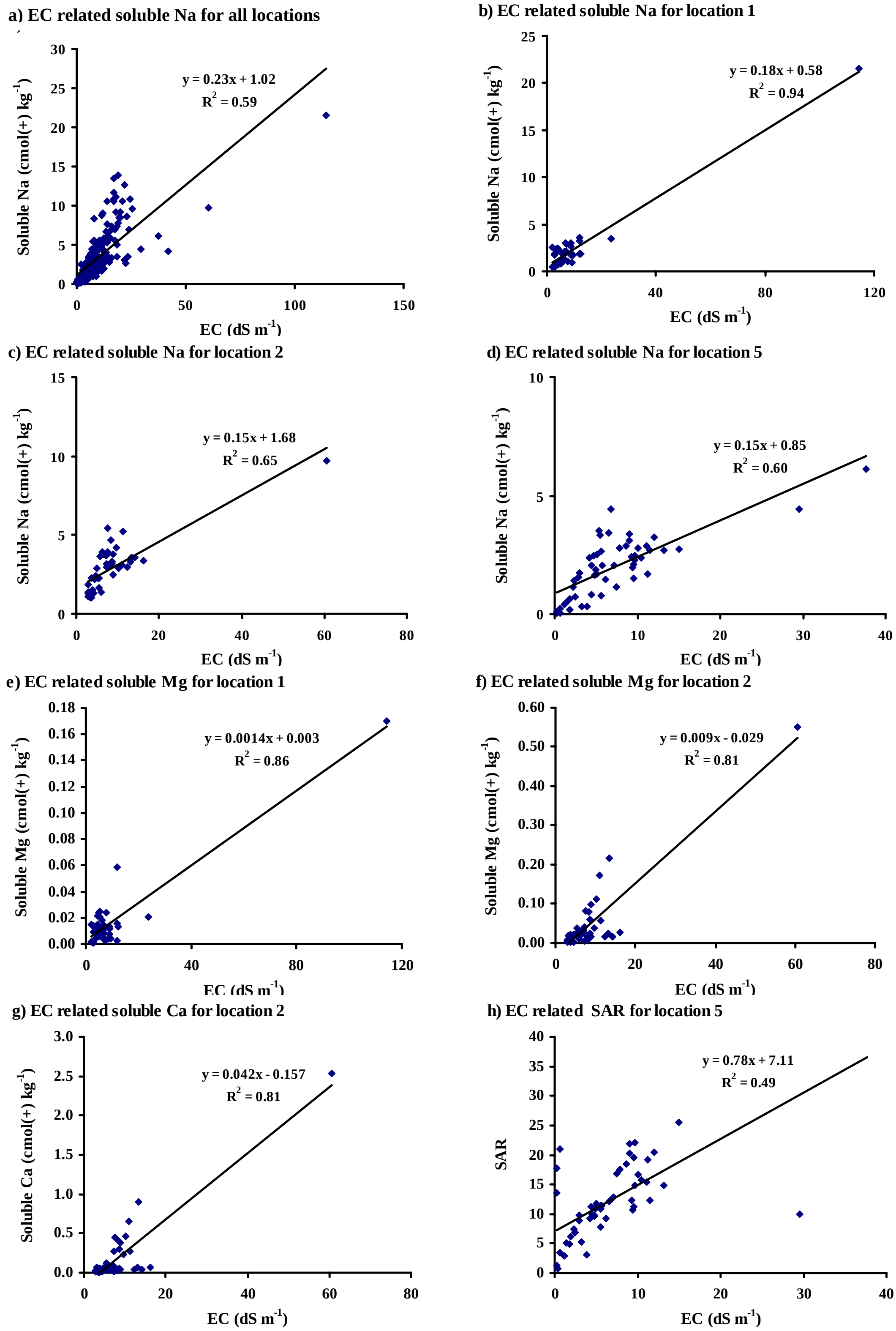


Figure 25 The significant correlations of EC value with some chemical properties.

2.2 Sodium Adsorption Ratio (SAR)

SAR values of salt affected soils differ between locations and also differ within locations and within soil profiles (Figure 26a-e). All data of SAR value in these soils are given in Appendix C, Table C2. The range of SAR values in these soils is 0.8-77.3. Pedons 1, 2, 23 and 25 have high SAR of more than 13 whareas the other pedons have the SAR values less than 13.

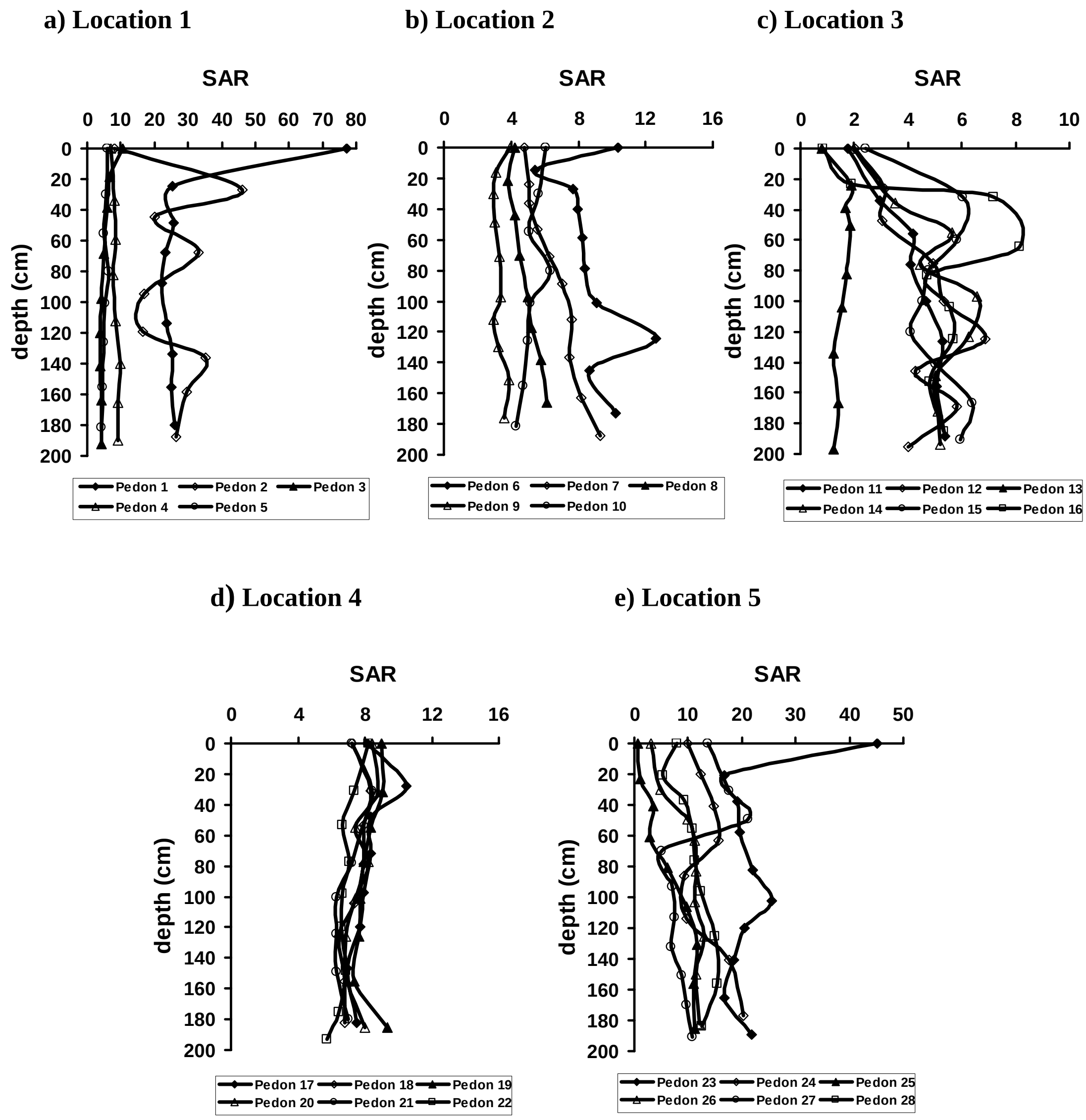


Figure 26 Depth functions of SAR values for salt affected soils in this study.

The correlations matrix for chemical properties of salt affected soils from all locations is given in Appendix C, Table C4 and for soils from each location the data are given in Appendix C, Tables C5-C9. The SAR values show highly significant correlation (the correlation value ≥ 0.70) with exchangeable sodium percentage (ESP) for all locations combined (Appendix C, Table C4). The SAR values do not show the high correlation with ESP for each location, but do show a high correlation with ESP for locations 1 and 2 (Appendix C, Tables C5 and C6). The correlation matrix among chemical properties from each location indicates that SAR values have highly significant relationships with ESP, %BS and pH for soils from location 1 (Appendix C, Table C5), with ESP, %BS and exchangeable sodium for soils from location 2 (Appendix C, Table C6), with exchange sodium and pH for soils from location 3 (Appendix C, Table C7) and EC for soils from location 5 (Appendix C, Table C9). The bivarate graphs showing the relationships of SAR and EC value is in Figure 25h whereas the bivarate graphs for the high significant relationships of SAR with other chemical properties are not shown. However, the plots of SAR with some related properties do not show clear systematic relationships despite the high R^2 or the data point are not randomly distributed about the regression line.

2.3 Exchangeable Sodium Percentage (ESP)

The full data for ESP values for these soils are given in Appendix C, Table C2. The ranges of ESP values in these soils is 0.1-105.4 percent. ESP values of salt affected soils differ between locations and also within locations and soil profiles (Figure 27a-e). Most of these soils have ESP values of more than 15 percent in some part of soil profile and are thus classified as a natric (n) horizon. The high ESP value does not occur for Pedons 9 and 13. The correlations of ESP values with chemical properties of these soils are given in Appendix C, Table C4. ESP does not show a high significant correlation (the correlation value ≥ 0.70) with any chemical properties. However, the ESP has high significant relationship with SAR and %BS for soils at location 2 (Appendix C, Table C6).

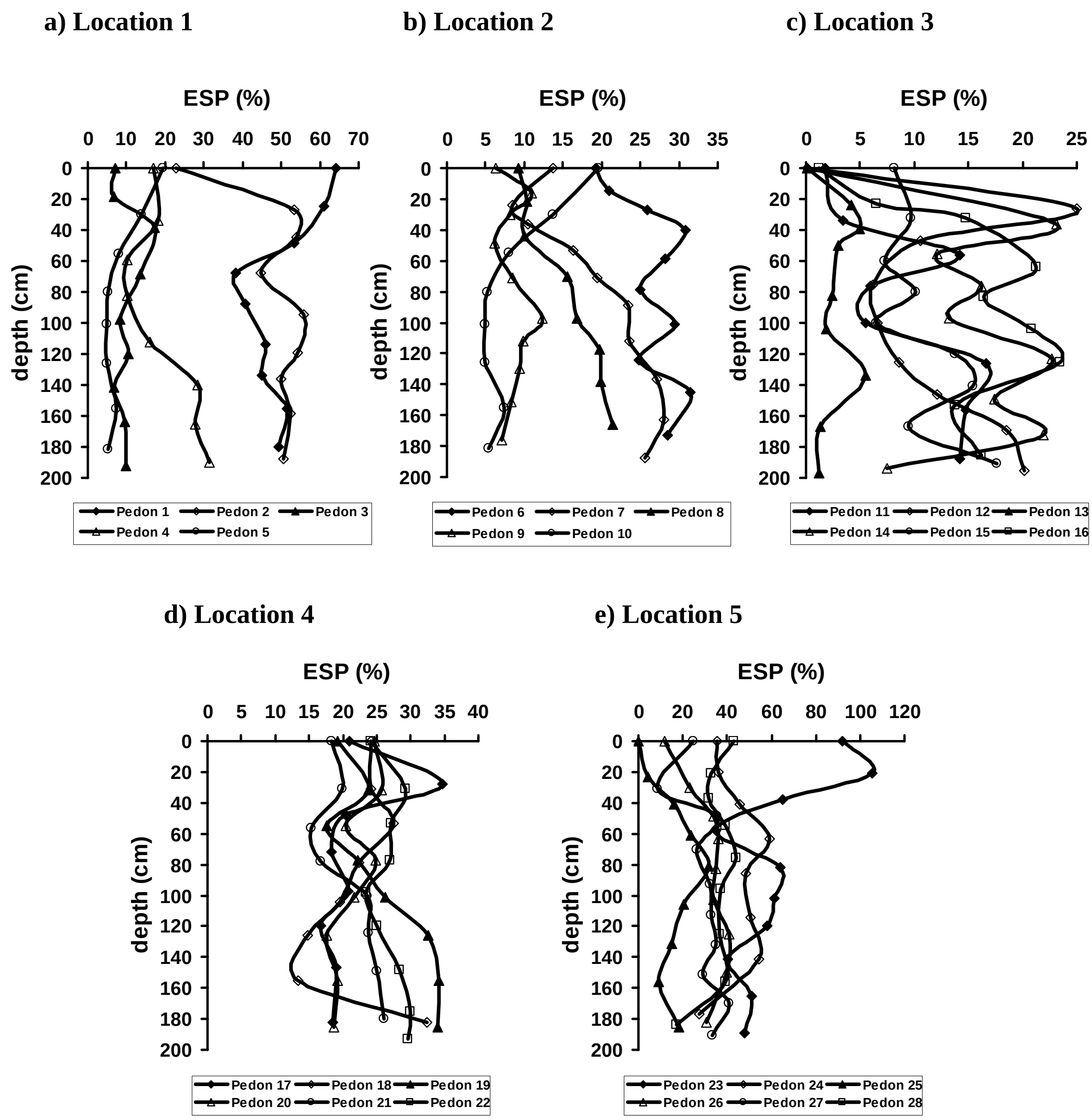


Figure 27 Depth functions of ESP values for salt affected soils in this study.

2.4 Soluble Salts (cations)

The soluble salt (cation) concentrations in these soils are given in Appendix C, Table C3. Sodium (Na) is the major soluble salt in these soils, ranges from 0.03-21.54 cmol(+) kg^{-1} with minor amounts of soluble calcium (Ca), ranging from 0.0-2.54 cmol(+) kg^{-1} whereas soluble magnesium (Mg) and potassium (K) are minor ranging from 0.0-0.77 and 0.001-0.43 cmol(+) kg^{-1} respectively.

The correlations of soluble cation concentration with chemical properties of these soils are given in Appendix C, Table C4. There are highly significant correlations (the correlation value ≥ 0.70) of soluble Ca with soluble Mg, soluble Mg with exchangeable calcium and CEC (by sum), and soluble Na with exchangeable Na, CEC (by sum), EC, soluble Ca and soluble Mg. The soluble salts at each location show relationships with chemical properties. The relationships of soluble cations with chemical properties of soils for each location are given in Appendix C, Tables C5-C9.

3. Total Chemical Analysis

Chemical compositions of the whole soil for these salt affected soils by XRF are shown in Appendix C, Table C10. This analyses are consistent with their mineralogical analyses (Table 5)

3.1 SiO_2 and Al_2O_3

Total Silica and Alumina content have a large range. SiO_2 ranges from 543.6 to 996.4 g kg^{-1}, Al_2O_3 ranges from not detectable to 252.1 g kg^{-1}. SiO_2 in these soils is abundant for any texture class as it is a major component of the major sand, silt and clay minerals. This result is thus consistent with the mineral properties (Table 5) and the element mapping (Figures 59, 60 and 63-65) that indicate the presence of Si-rich clay minerals. Another potential cause of high SiO_2 may be the resilication that occurs in these soils. Al_2O_3 concentration tends to increase with depth consistent with the increasing abundance of clay minerals (Table 5).

3.2 Fe_2O_3 and TiO_2

Concentration of total Fe_2O_3 in salt affected soils ranges from 1.43-69.48 g kg^{-1}. The clayey soils (locations 2 and 4) have higher Fe_2O_3 values than do the sandy soils (locations 1 and 2) whereas for location 3 the sandy texture in topsoil and clayey texture of subsoils results in a very large variation of Fe_2O_3 concentration in the soil profile. The high concentration of Fe_2O_3 in some of these soils relates to the acuumulation of iron oxide concretions and nodules and also the presence of red mottles (Appendix A).

The concentrations of TiO_2 in the salt affected soils are low, ranging from 1.0-15.01 g kg^{-1}. TiO_2 concentration is lowest in the sandy textured soils (locations 1 and 5). The different concentration of TiO_2 at each location reflects the influence of parent material. The TiO_2 in some samples is sufficiently high and present as the light spot under scanning electron microscope (SEM) analysis of thin section samples.

3.3 CaO, K_2O, MgO and Na_2O

Concentrations of CaO, K_2O, MgO and Na_2O range from very low to very high. A very large range of CaO is present in these soils (0-114.59 g kg^{-1}). Most of the soils have the CaO value ranging from 0-12.73 g kg^{-1}. The very high CaO concentration is present in only the C and BC horizons at location 5. This result is due to the presence of calcite in these horizons (Table 5), which is a consequence of the influence of parent material that contains much Ca.

The concentration of K_2O range from 0-63.48 g kg^{-1} and MgO ranges from 0.33-60.69 g kg^{-1}. The high concentrations of K_2O and MgO in the C and BC horizon in location 5 are related to parent material. The concentration of Na_2O ranges from 0.4-21.43 g kg^{-1}. The Na_2O concentrations are similar to the soluble Na (Appendix C, Table C3). The concentrations of CaO, K_2O and MgO are not coincident with the soluble Ca, K and Mg are hard to dissolve than Na.

Soils in location 4 tend to have high concentrations of CaO, K_2O, MgO and Na_2O reflecting the physiographic condition that they are on the depression on a erosional plain that have little leaching.

3.4 Manganese (Mn)

The distribution of Mn in these soils is very varable ranging from 22 to 4536 mg kg^{-1}. The very high Mn in Btng 1 of pedon 28 is due to the presence of Mg-oxide nodules and concretions and Mn-oxide impregnative S-matrix seen in thin section samples and the field (Appendices A and B). The concentration of Mn in these soils generally tends to be associated with nodules, concretions and mottles.

3.5 Sulphur (S)

The distribution of S in salt affected soils is highly variable. S in these soils ranges from not detectable to 3610 mg kg^{-1}. The coarse texture and medium textured soils have very low S concentration whereas the fine textured soils have high S, particularly in location 4. The soils in location 4 have high S ranging from 65-2145 mg kg^{-1} which may be related to the pH condition of this location that are acid condition. However, despite acid conditions and high S these soils also have high exchangeable, soluble and total bases (Appendix C, Tables C2, C3 and C10).

3.6 Chlorine (Cl)

Amount of Cl in salt affected soils also shows a large range. Cl ranges from not detectable to 21180 mg kg^{-1}. The concentrations of Cl in these soils are higher than is normal for Thai soils (Table 4). Cl concentrations tend to be associated with the concentration of Na (Appendix C, Table C10) indicating that sodium chloride (NaCl) is the major salt in these soils. The surface soils that have a salt crust or salt patch have very high Cl concentrations and also high EC, Na, ESP and SAR. Cl concentrations at location 3 are the lowest and are associated with low EC values and the field morphology indicats that there is no salt crust or salt patch at the surface. The variation with depth of Cl tends to follow EC values. The result of Cl concentration by XRF analysis is consistent with the element mapping of Cl by SEM/EDS analysis (Figures 59, 60 and 63-65).

4. Synthesis

Salt affected soils have diverse chemical properties. Salt affected soils from each location present a large variation of soil pH. The pH ranges from extremely acid to strongly alkaline. The low pH (acid condition) indicates that salt affected soils in Thailand can develop under acid condition. These soils have very low to medium organic matter concentrations. The surface horizon has high concentrations of organic matter and the value tends to decrese with depth. The OM value clearly correlates with total nitrogen. The total nitrogen concentration in these soils ranges from very low to medium. Available phosphorus ranges from very low to very high. Very high available phosphorus in some of the lower horizons at location 5 reflects the influence of parent rock containing high phosphorus (Charusiri *et al*., 2006). Available phosphorus is associated with EC for location 1. Large variations of available potassium are present in these soils, ranging from very low to very high. The available potassium varies with location and depth probably due to these soils being in lower physiographic positions that have low leaching conditions. The high available potassium at locations 4 and 5 is coincident with the presence of high interlayer potassium (illite). Available potassium shows highly significant positive correlation with exchangeable sodium for location 1, significant correlation with exchangeable calcium, Sum bases, CEC (by sum) and % BS (by sum) for location 3 and significant correlation with exchangeable magnesium, Sum bases and CEC for location 5.

Salt affected soils have high exchangeable bases. Ca and Na are major exchangeable bases in these soils whereas Mg and K are minor. The exchangeable bases are high in clayey salt affected soils whereas sandy salt affected soils have lower values. Some lower horizons at location 5 (BC and C horizons) have very high exchangeable bases influenced by parent materials that contain high bases particulraly Ca which coincides with total analysis (XRF) results and the presence of calcite in the whole soils. The extractable acidity of salt affected soils is very low to very high except for location 4 that soils have moderately high to very high extractable acidity. The extractable acidity is highly significantly correlated with CEC (by sum), but there is not a clear relationship due to the data points not being uniformly distributed about the regression line. Soils at locations 2 and 4 have several high significant relationships and the bivarate graphs show quite good relationships between EA and CEC (by sum). CEC of salt affected soils is very low to very high and the very large variation of CEC values reflects soil texture and also the types of clay mineral. The CEC of these soils does not show a highly significant correlation with any chemical properties. CEC is clearly related to the distribution of clay indicating that the high CEC reflect high clay abundance in the soil. The CEC_clay is not related to the distribution of clay indicating that these soils having different amount and type of clay mineral. Most of these soils have BS of more than 35 percent. The low %BS present in some surface horizons of location 3 that have very high amount of sand and low EC. The %BS of salt affected soils is correlated with electrical conductivity (EC) for all locations but does not show a highly significant relationship for each location. A high significant relationship (high R^2) of %BS and EC value only exists for soils at locations 1 and 5. Very high %BS of salt affected soils is probably inaccurate as it is influenced by high soluble salts in the soil system.

The EC values show a very large variation between locations and also between pedons at each location. Most 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 value reflects soil texture control of soluble salt movement in soil profiles. The coarse textured soils show a high variation of EC values within a location and with depth. In addition, some lower horizons have high EC values due to the effect of parent rock (rock salt) and the high bulk density causing restricting movement of saline water. The low EC value in the upper part of Pedons 24 and 25 is the effect of the high density horizon. Location 3 has low EC values, less than 4 dS m^{-1} (0.2-3.6 dS m^{-1}) and a trend for EC to increase with depth. The low EC and the increase of EC with depth may be due to these soils undergoing salt leaching (desalinization). The EC value for all salt affected soils shows highly significant relationships with %BS and soluble sodium, but data point are not randomly distributed about the regression line. Soils from each location show the different relationships of EC with the chemical properties. The EC value is correlated with soluble sodium for locations 1, 2 and location 5, the EC value is correlated with soluble magnesium for location 1, soluble magnesium and calcium for location 2 and SAR for location 5. The high EC values tend to be associated with soils having high soluble Na, Mg, Ca and SAR values.

The SAR values of salt affected soils vary between locations and also within locations and soil profiles. Pedons 1, 2, 23 and 25 have high SAR values of more than 13 whereas the other pedons have SAR value less than 13. The SAR value shows highly significant relationships with ESP for all locations whereas the SAR value does not show a high correlation with ESP for each location. The SAR values show a high correlation with ESP for locations 1 and 2, have highly significant relationships with ESP, %BS and pH for location 1, is correlated with ESP, %BS and exchangeable sodium for soils at location 2, correlated with exchange sodium and pH for soils at location 3 and correlated with EC for soils at location 5. The bivarate plots of SAR with some related properties do not show clear relationships. The ESP values of salt affected soils differ between locations and also vary within locations and soil profiles. Most of these soils have ESP values of more than 15 percent in some part of soil profile and so are classified as the natric (n) horizon. The high ESP value is not present in Pedons 9 and 13. The ESP does not show a highly significant relationship with any chemical property. However, the ESP value is significantly correlated with SAR and %BS for soils at location 2.

The salt affected soils have higher contents of soluble salt than normal soils (Arunin, 1992). Sodium (Na) is the major soluble cation in these soils with relative minor amounts of soluble calcium (Ca) and little magnesium (Mg) and potassium (K). There is a highly significant correlation of soluble Ca with soluble Mg, soluble Mg with exchangeable calcium and CEC (by sum), and soluble Na with exchangeable Na, CEC (by sum), EC, soluble Ca and soluble Mg. For each location soluble salt shows different relationships with chemical properties.

The total chemical compositions of whole salt affected soils determined by XRF are consistent with their mineralogical analyses. Total silica and alumina concentrations have large ranges. SiO_2 in these soils is high for every type of texture as SiO_2 is a constituent of both quartz and clay minerals. High SiO_2 may also be a consequence of resilication occurring in these soils. Al_2O_3 content tends to increase with depth consistent with the increasing percentage of clay minerals. Concentrations of total Fe_2O_3 in salt affected soils have a large range. The clayey soils have high Fe_2O_3 concentrations than sandy soils. The high concentration of Fe_2O_3 in some samples of these soils is associated with the accuumulation of iron oxide concretions, nodules and red mottles. Concentrations of total TiO_2 in salt affected soils are low.

CaO is present as a major alkali whereas K_2O, MgO and Na_2O are relatively minor. Very high CaO, K_2O and MgO concentrations occur in the C and BC horizon of sandy salt affected soil at location 5 and are coincident with the high exchangeable Ca and Mg which are related to parent rocks that contain high CaO, MgO and K_2O. The high Na_2O value is coincident with high soluble Na that occurs in the surface horizon of the highly salt affected soil profiles and is associated with high EC values. The concentrations of CaO, K_2O and MgO are not coincident with the concentration of soluble Ca, K and Mg indicating that these elements are mostly not present in soluble salts. Soils at location 4 tend to have high concentrations of CaO, K_2O, MgO and Na_2O reflecting the physiographic position that is in a depression on an erosional plain with low leaching. The distribution of Mn in these soils is very variable and Mn tends to be associated with nodules, concretions and mottles. Sulphur (S) in these soils show a large variation. High S is present in fine textured soils, particularly at location 4 and is related to the acid conditions at this location. The concentrations of Cl in these soils are higher than in normal Thai soils. The amount of Cl deffer between locations and pedons. Very high Cl concentration in surface soils is associated with the presence of a salt crust or salt patch and also high values of EC, Na, ESP and SAR. Chloride (Cl) concentrations at location 3 are lowest and are associated with low EC values and a field morphology that indicates the absence of a salt crust or salt patch on the surface. The variation with depth of Cl tends to be associated with EC value. The Cl concentrations tend to be associated with concentrations of Na indicating that sodium chloride (NaCl) is the major salt in these soils.

Geochemistry of Salt Affected Soils

1. Geochemical Data of Salt Affected Soils

The full analytical data for each location comprise large documents which are given in Appendix C, Table C11. Table 4 gives the median and SD values of element concentrations for each location to provide an indication of the values observed in this research. All median values for each location are associated with large values of SD indicating that the chemical composition of soils is highly diverse at each location.

Silicon is the major component of these soils (median, SD = 371, 49 g kg^{-1}). Aluminum and Fe are important constituents of soils at all locations. High Cl concentrations exist in many samples (median, SD =1.27, 3.66 g kg^{-1}) attributed the influence of salinity. Soils at location 3 have lower concentrations of Cl than for other locations, but values are still higher than for normal soils (Table 4) (Lindsay, 1979).

Median concerntrations of Al, Si, Mg, K, Ca, Li, P, V, Cr, Co, Ni, Cu, Zn, Ga, As, Rb, Sr, Mo, Cs, Pb and U in salt affected soils were similar to the average values for Thai soils, whereas the median concentration of Mn in salt affected soils was above the average value for some Thai soils (Thanachit, 2006). The median contents of Fe and Ti are smaller than average values for Thai soils (Thanachit, 2006) (Table 4). In comparison to worldwide soils the median concentrations of Si, S and Cl in salt affected soils are above normal values reflecting the salt affected nature of these soils. Median contents of Al, Fe, Na, Mg, K, Li, Be, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, As, Mo, Cd, I, and Pb in salt affected soils are similar to those of worldwide soils. Sodium concentrations in these salt affected (high NaCl) Thai soils are similar to those of worldwide soils because many soils elsewhere contain Na in feldspars. Median contents of Ca, N, P, Ti, Br, Rb, Sr and Ag are smaller than for worldwide soils (Lindsay, 1979) (Table 4). The high Si concentrations in these soils could be in an amorphous form of silica derived from periodic high pH induced quartz dissolution (Brady and Walther, 1989).

2. Distribution of Elements and Properties in Salt Affected Soils

Result of factor analysis of standardized chemical analyses are given in Figures 28a and b. Two factors explain only 52.7% of the variation in the data when the complete data set is analyzed. This poor explanation of the data and the absence of a limited numbers of close associations of elements or samples is attributed to diversity of parent materials, the impact of salinity and various operating pedogenic processes.

In the factor diagram five groups of attributes are recognized (Figure. 28a). Group 1 consist of clay and elements that are commonly associated with clay minerals and oxides (Al, Ga, Cs, Sr, Fe, U, Pb, Rb, V, Be and Zn). Group 2 consists of sand, Mo, Si which is mostly in quartz and Cr which is mostly in sand within the resistant spinels chromiferous magnetite and chromite (Alloway, 1995). Group 3 consists of pH in water and pH in KCl, group 4 consists of S, OC and N most likely reflecting biological inputs and group 5 represents total salinity (EC), Na and associated halides (Cl, Br, I). The soil samples are widely distributed in the corresponding factor diagram Figure 28b although there is some grouping of samples for each location. Several samples from location 5 are major outliers because these horizons have high concentration of Ca and Mg in authigenic calcite (Uysal *et al.*, 2000) (Table 5).

Table 4 Median (±SD) values for element concentrations for salt affected soils in this study.

Properties	All locations n=248		Location 1 n=43		Location 2 n=47		Location 3 n=53		Location 4 n=50		Location 5 n=55		[A]Thai soils		[B]Worldwide Normal soils	
	Median	SD	Median	SD	Median	SD	Median	SD	Median	SD	Median	SD	Mean	SD	Range	Average
Major element ($g\ kg^{-1}$)																
Si	371	49	422	14	327	27	367	39	355	40	418	57	220-463	0.8-39	230-350	320
Al	61	33	25	10	90	19	71	31	68	24	25	22	3-157	0.6-24	10-300	71
Fe	14	11	8.7	2.4	27	7.5	14	9.1	26	9.5	8.1	9.7	100-176	0.5-30	7-550	38
Na	3.40	2.40	2.80	2.35	4.20	2.24	2.10	1.17	6.05	1.42	3.30	7.82	-	-	0.75-7.5	6.3
Mg	2.50	4.30	1.60	0.70	3.40	0.68	1.50	0.77	4.25	2.12	2.70	8.36	0-8.5	0-3.9	0.6-6	5
K	2.50	5.50	1.10	0.91	4.30	1.33	1.60	0.78	5.05	3.82	1.80	10.13	0.4-17.3	0-9.4	0.4-30	8.3
Ca	1.60	6.05	0.40	0.35	3.60	0.79	1.50	0.82	3.50	2.16	0.50	26	0.1-8.3	0-4.2	7-500	13.7
S	15.0	214	2.0	5.8	90.0	102	2.0	15.4	408	297	10.0	47.1	-	-	0.03-10	0.7
N	0.09	0.16	0.05	0.06	0.22	0.24	0.07	0.09	0.20	0.14	0.04	0.04	-	-	0.2-4	1.4
OC	1.80	6.89	1.19	2.94	5.64	10.07	1.51	3.96	5.96	7.25	0.59	2.87	-	-	-	-
Cl	1.27	3.66	1.19	2.18	2.37	1.55	0.26	0.25	6.42	4.87	1.21	0.78	-	-	0.02-0.9	0.1
Minor element ($mg\ kg^{-1}$)																
Li	19.1	10.9	20.0	10.3	26.4	8.9	14.4	6.9	28.7	9.8	11.4	9.3	0.7-29	0.4-17	5-200	20
Be	0.93	0.62	0.59	0.70	1.46	0.49	0.84	0.40	1.33	0.50	0.42	0.45	-	-	0.1-40	6
P	34.1	55.0	58.8	22.8	40.2	39.8	15.4	14.5	40.5	30.0	18.3	99.9	30-544	12-335	200-5000	600
Ti	145	61	127	25	163	40	186	63	174	49	100	82	900-24000	0.1-2.6	1000-10000	4000
V	41.1	22.4	34.6	7.6	67.6	19.0	37.5	16.7	59.4	19.6	23.0	19.2	10-311	3.3-80	20-500	100
Cr	293	189	511	122	224	73	248	131	168	108	505	163	5-354	1-160	1-1000	100
Mn	182	436	281	401	223	202	79	467	152	135	276	665	8.4-26	2-11	20-3000	600
Co	6.85	5.51	5.66	6.27	9.42	3.71	6.15	8.34	7.23	3.41	5.52	3.43	0.2-80	0.1-25	1-40	8
Ni	21.76	6.52	29.95	9.82	25.20	3.06	18.55	4.22	16.95	2.80	23.27	3.43	20-147	4-32	5-500	40
Cu	6.86	4.03	6.92	5.16	10.36	3.19	5.70	1.54	9.47	4.23	4.96	1.57	1.4-76	0.4-16.8	2-100	30
Zn	13.15	10.19	8.67	4.42	24.68	6.04	8.77	4.84	20.86	9.74	7.81	9.85	12-101	2-41	10-300	50
Ga	9.29	5.83	4.32	1.94	16.65	4.01	8.64	4.23	12.27	4.23	5.13	4.62	1.3-36	0.2-8	5-70	14
As	1.34	0.98	1.33	0.54	1.54	0.78	0.81	0.49	1.37	0.51	1.89	1.41	0.5-6	0.2-12.8	1-50	5
Br	0.48	1.20	1.09	1.04	0.97	1.55	1.11	1.27	0.09	0.94	0.00	0.74	-	-	1-10	5
Rb	15.12	17.22	9.01	4.95	30.05	8.95	8.77	4.52	39.68	18.88	10.69	14.06	3-54	0.5-6	50-500	10
Sr	11.74	13.32	3.70	1.91	18.19	4.61	11.00	5.12	29.50	16.53	5.73	5.15	2-80	1.1-29	50-1000	200
Mo	2.22	3.24	6.68	1.86	0.00	0.17	0.37	1.65	1.76	1.43	5.90	2.20	0.3-2	0.2-2.8	0.2-5	2
Ag	0.00	0.23	0.32	0.38	0.00	0.01	nd.		0.00	0.01	0.00	0.001	-	-	0.01-5	0.05
Cd	0.01	0.02	0.04	0.02	0.00	0.01	0.00	0.01	0.01	0.01	0.02	0.02	-	-	0.01-0.7	0.06
I	0.30	0.80	0.03	0.97	0.69	1.15	0.27	0.60	0.58	0.57	0.12	0.19	-	-	0.1-40	5
Cs	2.66	2.00	1.74	0.51	5.01	1.47	2.57	1.35	5.33	1.68	1.56	1.30	0.3-4.4	0-2.3	0.3-25	6
Pb	7.54	5.20	5.62	3.25	11.91	4.34	4.80	3.54	12.18	4.50	3.81	3.99	8.8-23.7	0.5-17.8	2-200	10
U	0.48	0.68	0.23	0.08	1.56	0.64	0.48	0.21	1.50	0.52	0.25	0.19	0.2-1.6	0-1.3	-	-

[A] Mean and SD of total concentration of element in soil of Northeast, Thailand (Thanachit, 2006)

[B] Range and Average of total concentration of element in soil for normal worldwide soil (Lindsay, 1979)

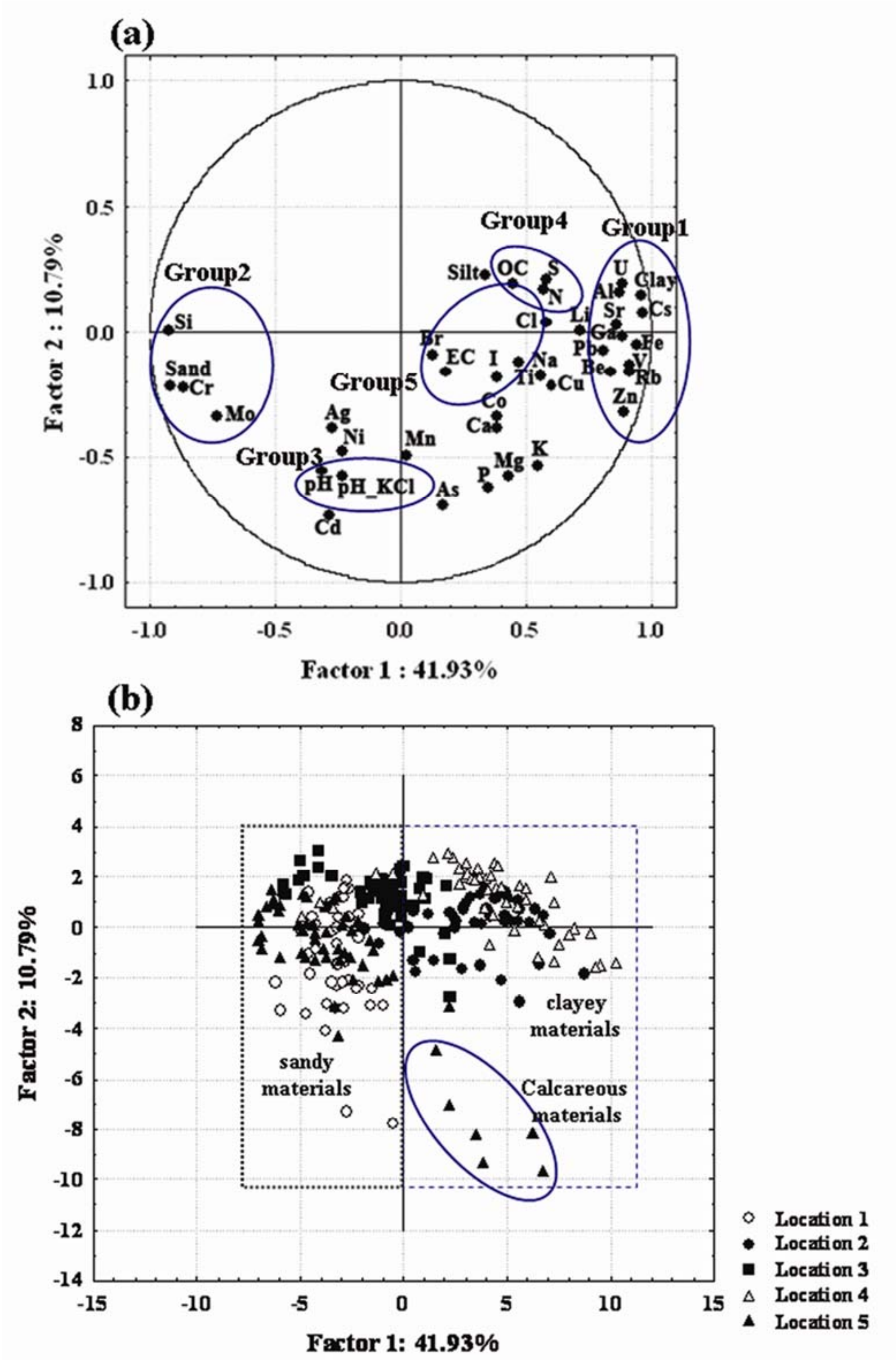


Figure 28 Factor analysis for sand, silt, clay, pH, EC and element concentrations in salt affected soils. (a) Distribution of attributes, (b) Distribution of soil samples.

3. Comparative Distribution of Elements and Properties between Salt Affected Samples and Non-Salt Affected Samples

To geochemically compare salt affected samples and non-salt affected samples data of the whole set of samples (248 samples) are separate into two groups. The high EC and /or ESP samples (EC>4 dS m^{-1} and ESP>15%) comprised 192 samples, whereas the other 56 samples are low in EC and ESP. Result of factor analysis of standardized data for the high EC and/or ESP samples show that two factors explain only 55.18 % of the variation in the data (Figure 29a and b). Five groups of attributes are recognized in the attribute factor diagram for the high EC and/or ESP samples (Figure 29a). Groups 1, 2 and 3 remain the same with that of the overall data set analyzed (Figure 28a). Groups 4 and 5 changed. Group 4 consists of S, OC, N and Cl and group 5 represents total salinity (EC), Br and I. The soil samples are widely distributed in the corresponding factor diagram (Figure 29b) in the same fashion as in the overall data set analyzed (248 samples). There is some grouping attributed texture and the major outliers samples because these horizons have high concentrations of Ca in authigenic calcite.

Result of factor analysis of standardized data for the low EC and ESP samples show that two factors explain 62.25 % of the variation in the data (Figure 30a and b). These low EC and ESP samples consist of five groups of attributes in the attribute factor diagram (Figure 30a). Group 1 is very similar to that of the overall data set (248 samples) but including Li. Groups 2, 3 and 4 are the same with those of the overall all data set (248 samples). Groups 5 changed to consist of total salinity (EC), Cl and I. The distribution of soil samples are separated into 3 groups in the corresponding attribute factor diagram of soil texture (Figure 30b). This higher percentages that could be explained by the two factors of the low EC and low ESP samples indicate well the difference between the salt affected soils and the adjacent non-salt affected soils in the whole set of samples. The low percentages that could be explained by the two factors for the whole set of samples (Figure 28a and b) indicate that the geochemical diversity existed in these soils at least partially attributed the effect of salt in natural soil system.

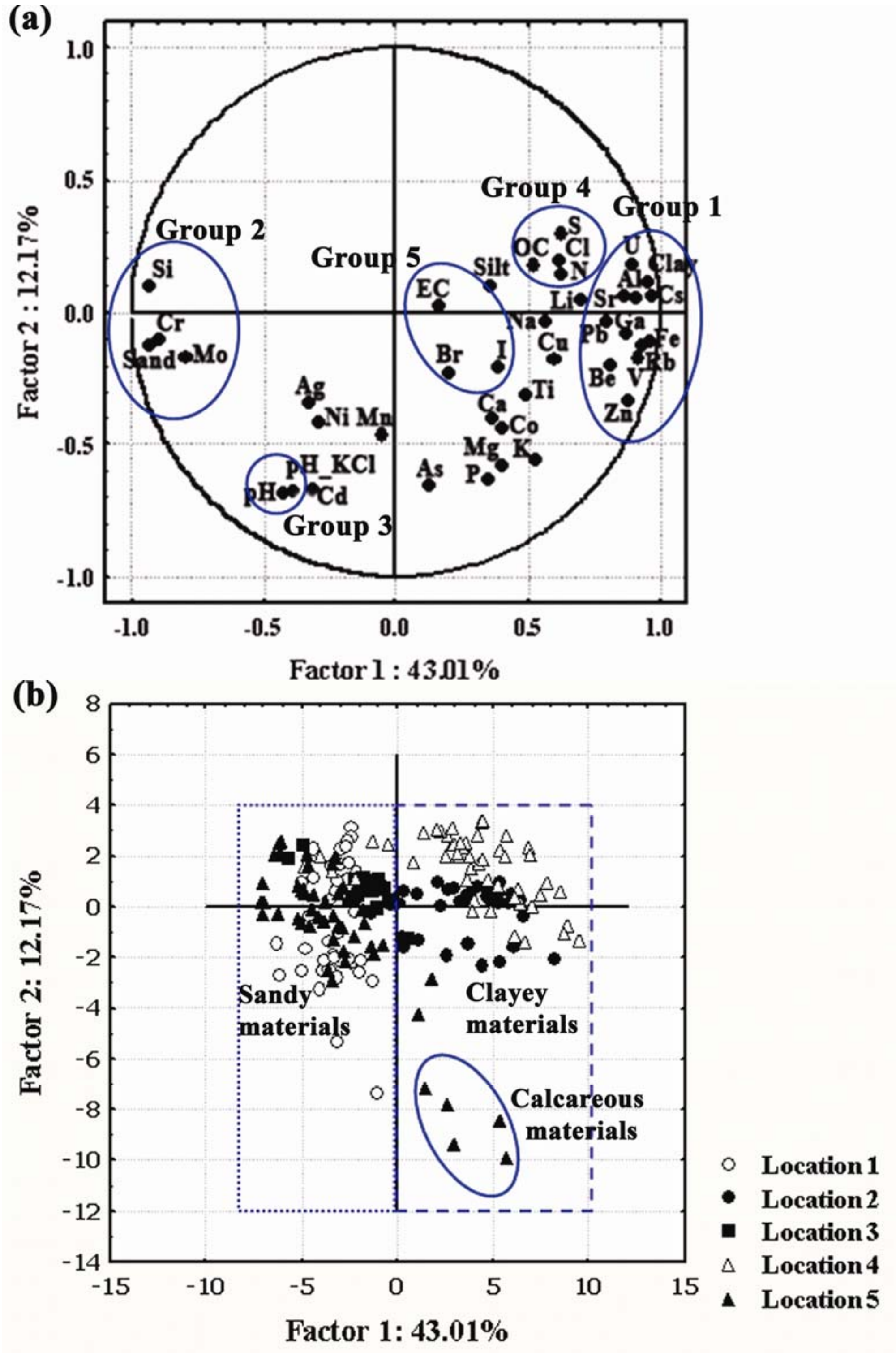


Figure 29 Factor analysis for sand, silt, clay, pH, EC and element concentrations for high EC and/or ESP samples (192 samples) in salt affected soils. (a) Distribution of attributes, (b) Distribution of soil samples.

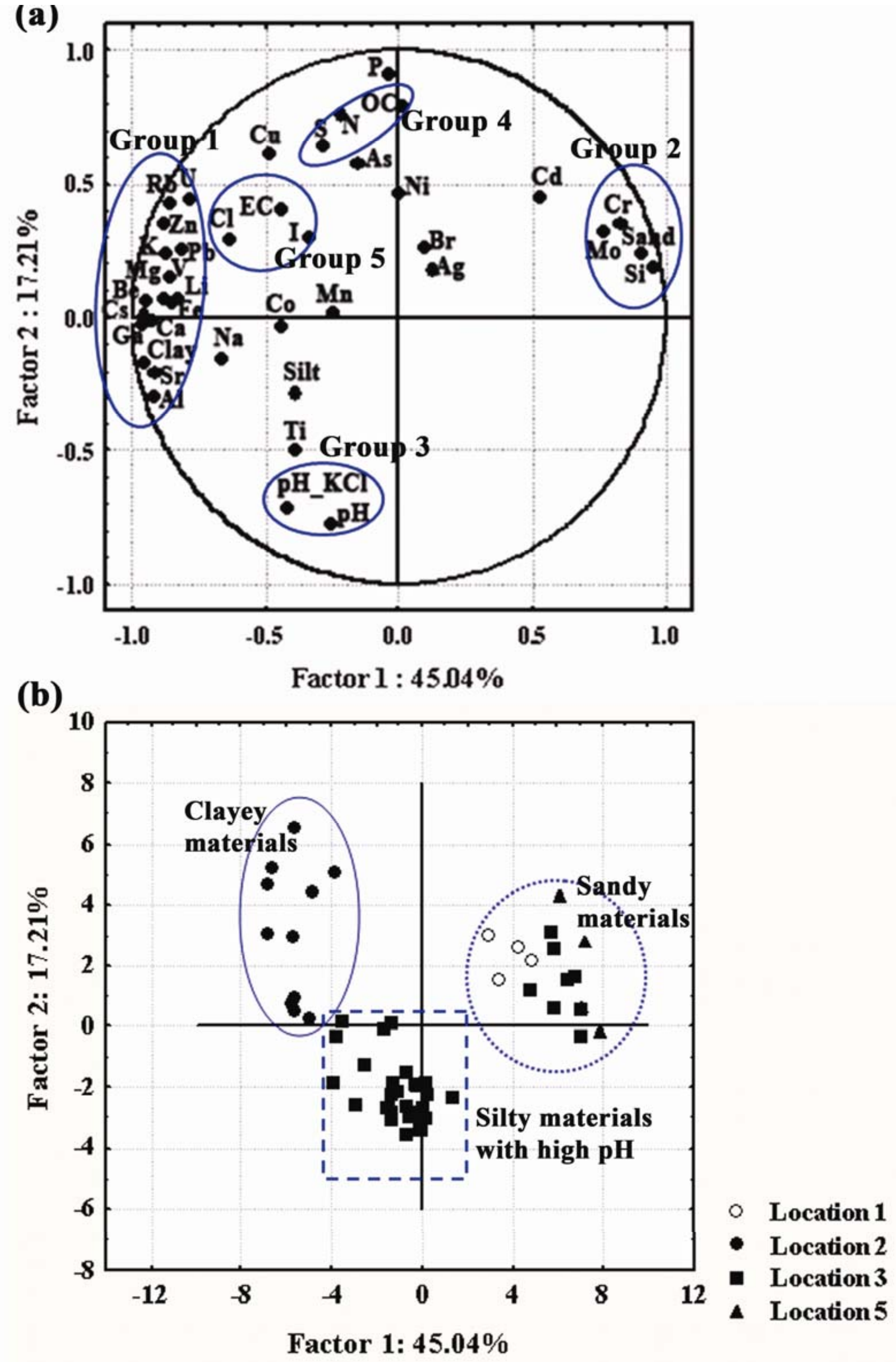


Figure 30 Factor analysis for sand, silt, clay, pH, EC and element concentrations for low EC and ESP samples (56 samples) in salt affected soils. (a) Distribution of attributes, (b) Distribution of soil samples.

4. <u>Relationships of Elements in Soils</u>

The full data for the correlation matrix for the chemical composition of salt affected soils are given in Appendix C, Table C12. Figure 31 shows bivariate plots for pairs of data indicated by Figure 28a as being highly correlated. Chromium, Mo and sand are closely related (Figures 31a, e) with most Cr being likely present as resistant spinels in the sand fraction. The Cr-sand relationship is actually a curve indicating that some sandy materials are relatively deficient in Cr, possibly attribute differences in provenance (Alloway, 1995). Similarly, although Al and clay are strongly correlated (Figure 31c) there are systematic deviations from a single straight line indicating that the clay fraction contains clay minerals with various Al concentration as was in fact observed by XRD (kaolin, smectite, vermiculite, illite) (Table 5). Iron is also closely related to clay content (Figure 31d) and in this case there is no systematic deviation from a single straight line attribute difference in mineralogy or provenance, much of the Fe is present as free secondary iron oxides. It should be noted that these associations between elements related to the composition of the parent sediments and not to the impact of salinity. The commonly observed close relationship between N and OC applies to these soils with the N:C ratio of 0.020 being lower than the values for most soils which range from 0.03-0.1 (Post *et al.*, 1985).

For other elements where apparently close relationships are identified in Figure 28a these are actually quite complex associations. For example, the concentration of Mo is closely related to sand percentage for some samples, but for other samples there is no association (Figure 31e). Some expected relationships reflecting the salt effect could not be observed by this analysis, for example Br might be expected to correlate with salinity but although these attributes are adjacent in the factor diagram and are grouped with Cl and I, there is no systematic relationship of Br with EC (Figure 31f).

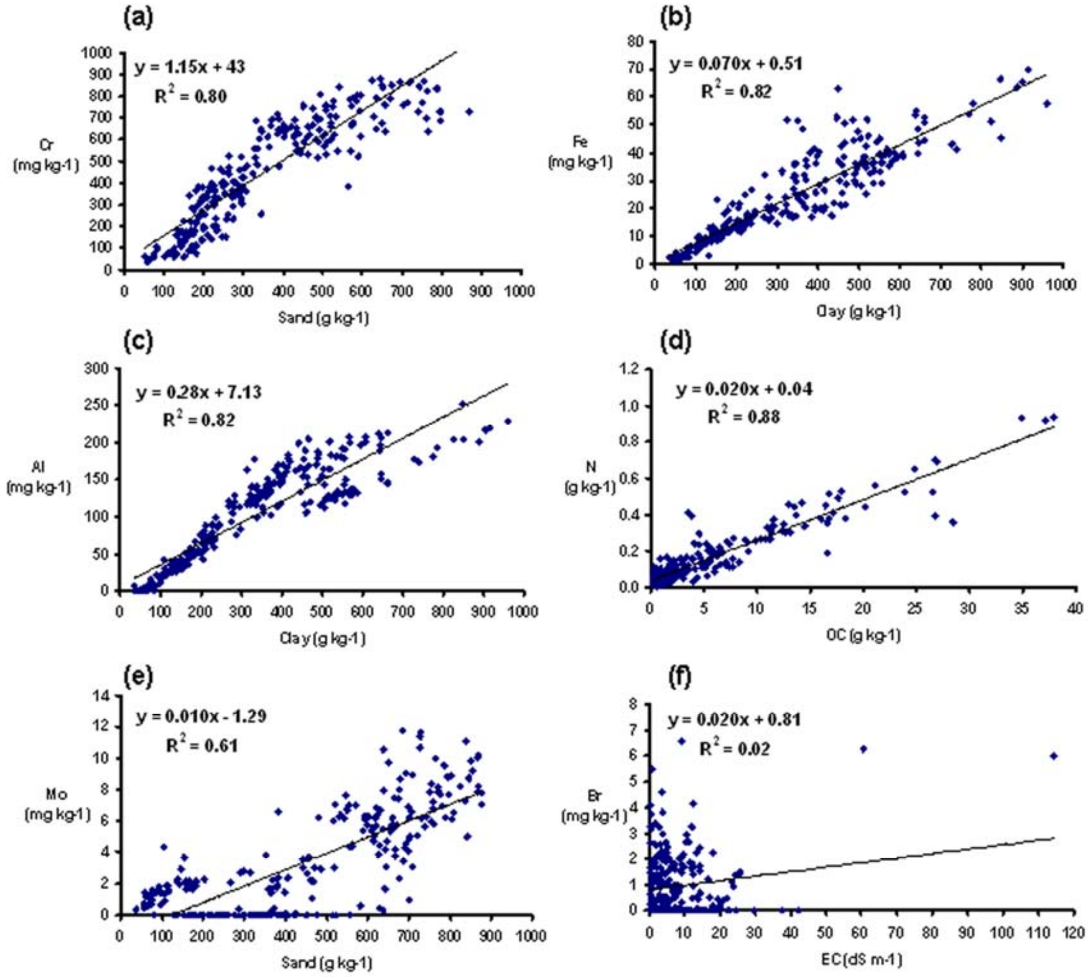


Figure 31 Bivarate relationships between concentrations of (a) sand and chromium: (b) organic carbon and nitrogen: (c) clay and aluminum: (d) clay and iron: (e) sand and molybdenum: (f) EC and bromine for salt affected soils in this study.

5. Depth and Salinity Variations in Element Composition and Soil Properties

Depth functions of mean factor scores based on element concentrations and other properties of the soils provide an indication of the homogeneity of soil parent materials within profiles (Figure 32). For this calculation of factor scores we have omitted OC, N, EC, Na, Ca, K, Mg, Cl, I and Br as these attributes incorporate post depositional impacts of organic material and salinity on the profiles.

Values of factor 1 mainly reflect soil texture, being negative for more sandy samples, therefore depth function plots of this factor are similar to those for percentage sand (Figure 10). Factor 2 is not strongly associated with any single soil property (Figure 28a), combining effects of clay content and Mn concentration.

Attribute the strong influence of texture on chemical composition the depth functions of mean factor 1 and 2 scores (Figure 32) are quite similar to the depth functions for particle size classes (Figure 10.). For some profiles both sets of depth functions show clear evidence of depositional layering and the contribution of pedogenesis (illuviation) to other profiles is indicated.

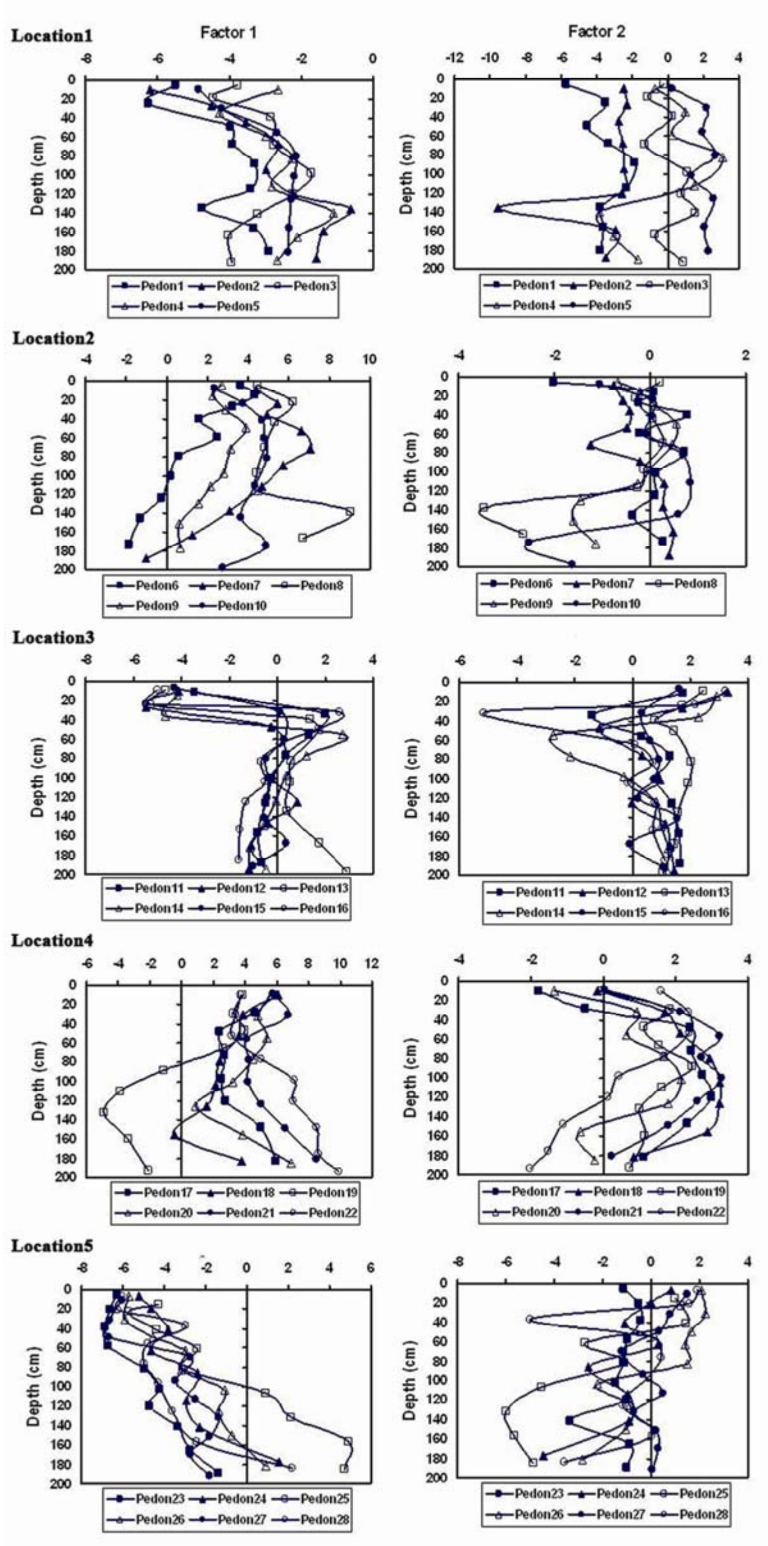


Figure 32 Depth functions of factor 1 and 2 scores based on pH, element concentration and textural soil properties at each location for salt affected soils in this study.

4. Synthesis

The chemical composition of soils is highly diverse at each location attribute the large variations in texture arising from the presence of depositional layers. Silicon is the major component whereas Al and Fe are mostly relatively minor constituents of the soils. High EC values and Cl concentrations exist in many samples attribute the influence of salt bearing country rocks. Factor analysis allows the properties and chemical composition of studied soils to be compared both within and between profiles. The soils have wide range of properties, with five main elemental affinity groups being recognized. Group 1 is a broader group consisting of clay and elements that are commonly associated with clay minerals and oxides (Al, Ga, Cs, Sr, Fe, U, Pb, Rb, V, Be and Zn). Group 2 consists of sand, Si, Mo and Cr. Group 3 consists of pH in water and pH in KCl, Group 4 consists of S, OC and N reflecting biological activity and Group 5 represents the effects of salinity comprising EC, Na, Cl, Br and I.

The higher percentages that could be explained by the two factors of the low EC and low ESP samples indicate well the difference between the salt affected soils and the adjacent non-salt affected soils in the whole set of samples. They also indicate that the geochemical diversity existing in these soils at least partially attribute the effect of salt in the natural soil system.

Mineralogical Properties of Salt Affected Soils

1. Minerals in Soils

The selected random powder XRD patterns of salt minerals present in soil shown in Figure 33 and the semiquantitative mineralogy in soil is given in Table 5. The quartz and clay mineral distributions within soils profiles that are indicated in Table 5 reflect the diverse textures and trends in particle size with depth (Figure 11) with sandy materials being quartz rich. The soils consist predominantly of quartz with the clay minerals kaolin, smectite, illite and vermiculite occurring in various proportions. Small amount of calcite, halite, feldspar and iron oxides (Goethite, Hematite and Lepidocrocite) are found in some samples. Halite exists in the surface horizon of Pedons 1, 23 and 24 (Table 5, Figure 33a) attribute the high salt accumulation (the surface contains a salt crust). Halite and calcite occurred in BC and C horizons at location 5 (Table 5 and Figure 33b) is consistent with the geology of this area which contains rock salt deposits (Department of Mineral Resources, 1985). In these horizons (BC and C) there are also peaks of minerals at about 0.52 nm. This is probably the peak of akaganeite minerals (Table 5 and Figure 33b).

Figure 34 shows the relationship between percentage total clay minerals determined by XRD and percentage clay determined by particle size analysis. The close linear relationship (R^2=0.95) of near unit slope (slope=1.06) shows that the XRD method provides an excellent measure of clay concentration that appears to be insensitive to differences in crystallinity of the clay minerals. It should be noted that the points in this graph actually follow a shallow curve and thus show a systematic deviation from the 1:1 line. The XRD method appears to overestimate the percentage clay for values of about 50% clay, which may reflect the presence of clay minerals in silt and sand size fractions.

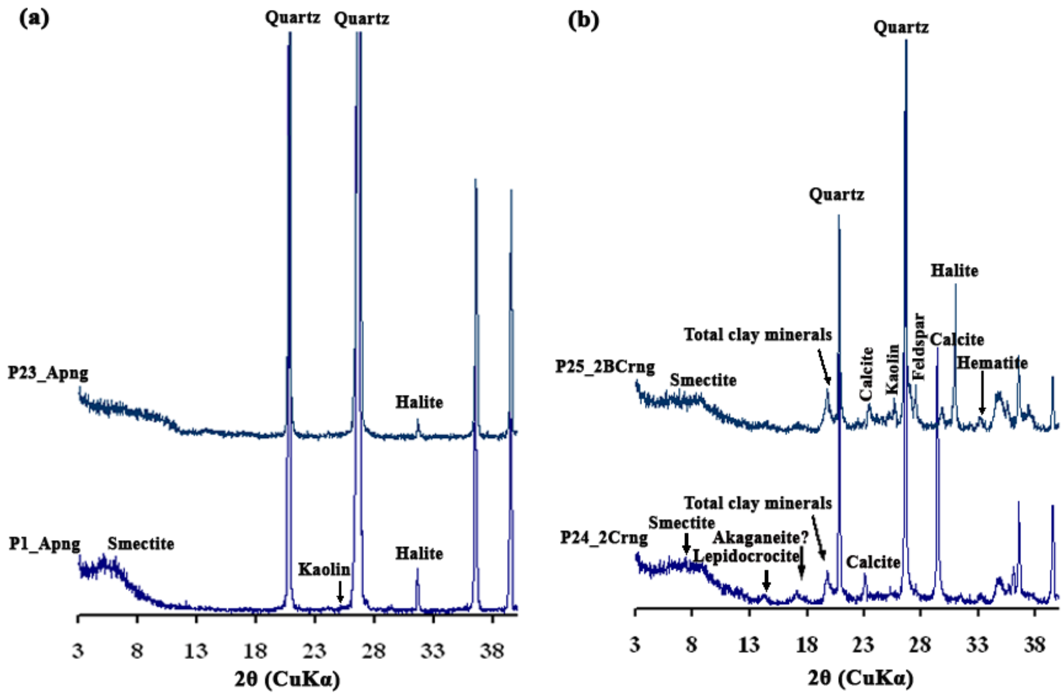


Figure 33 Typical random powder XRD patterns of salty soils showing major diffraction lines of some salt minerals; (a) halite in the surface horizon of coarse textured soils, (b) calcite and halite in the lower subsoil horizons that are in contact with saline parent rock.

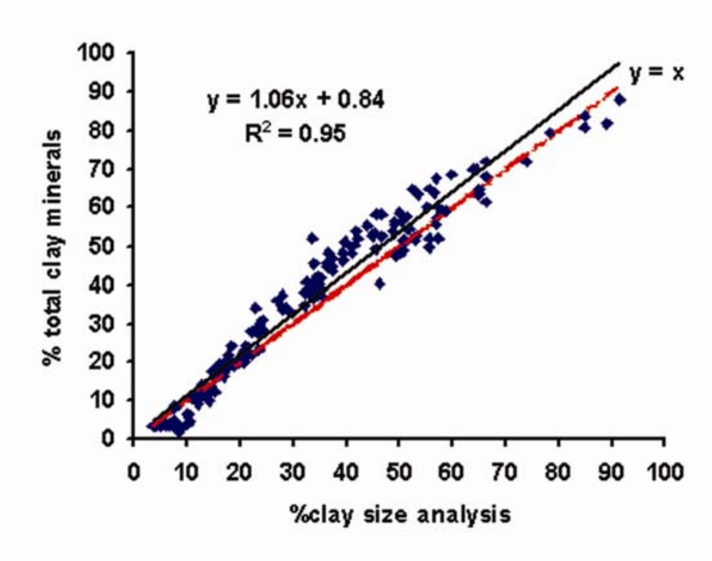


Figure 34 The relationship between percentage total clay minerals determined by random powder x- ray diffraction and percentage clay determined by the pipette method for samples of salt affected soils (n=155) in this study.

The amounts of quartz, kaolin and combined other clay minerals differ greatly between and within locations (Figure 35), this graph dose not include accessory minerals (calcite, feldspar, etc.). The soil samples from locations 2, 4 and 5 exhibit large variations in mineralogy attribute the presence of discrete sediment layers, whereas for location 3 most variation of the clay minerals reflects the difference in texture between topsoil and subsoil, for location 1 the mineralogical composition of soils is quite uniform.

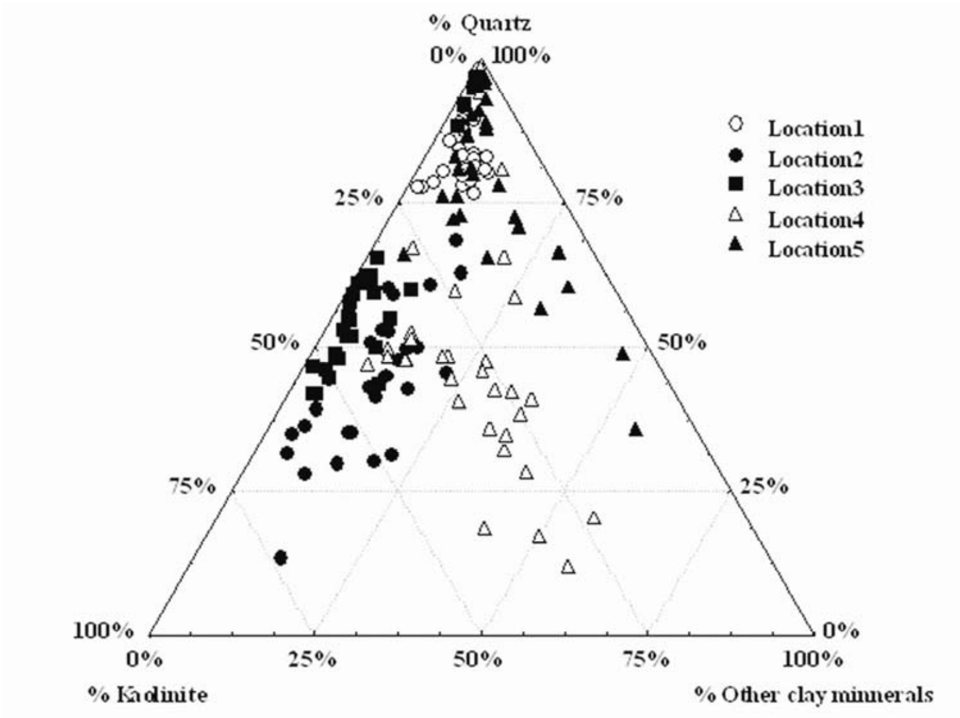


Figure 35 Composition triangle for the abundance of quartz, kaolin and total other clay minerals in samples of salt affected soils (n=155) in this study.

2. Minerals in Clay and Silt Fraction

The semiquantitative mineralogy in clay and silt fraction is given in Table 5. The soil consists predominantly of kaolin and smectite and trace of illite and interstratified minerals. Some of the soils have abundant quartz in the clay fraction (Table 5).

Table 5 Semi-quantitative mineralogical analysis of salt affected soils in this study.

Horizon	**Depth**	**[A] Mineral in soil (%)**				**[B]clay fraction**						**[C]silt fraction**	
	cm	Q	Kao	Other	Other minerals	Kao	Smec	Int	Ill	Chlo	Q	Q	Fel
Location 1 : Sandy textured salt affected soils *(Roi Et, saline variant)*													
Pedon 1 Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic													
Apng	0-12	96.3	1.5	1.2	Ha (1)	xx	x	nd	nd	nd	xxx	xxxx	nd
Bng	12-37	97.1	1.8	1.1	nd	xxx	nd	xx	nd	nd	xx	xxxx	nd
Btng2	60-76	85.8	11.6	2.6	nd	xxxx	x	nd	nd	nd	x	xxxx	nd
Btng4	100-128	83.7	9.1	7.2	nd	xxx	xx	nd	tr	nd	x	xxxx	nd
2Btng6	140-170	82.8	7.8	9.4	nd	xx	xx	nd	x	nd	x	xxxx	nd
Pedon 2 Typic Natraqualf; coarse-loamy, mixed, semiactive isohyperthemic													
Apng	0-20	98.1	1.3	0.6	nd	xx	x	nd	nd	nd	xxx	xxxx	nd
Btng1	20-34	87.3	8.9	3.8	nd	xxxx	xx	nd	nd	nd	x	xxxx	nd
Btng3	55-80	80.0	8.9	11.1	nd	xx	xxx	nd	tr	nd	x	xxxx	nd
Btng5	109-130	78.0	13.7	8.3	nd	xxx	xx	nd	tr	nd	xx	xxxx	nd
Btcng	130-142	79.0	12.1	8.8	nd	xxx	xx	nd	x	nd	xx	xxxx	nd
2Btng6	142-175	76.6	12.9	10.5	nd	xxx	xx	nd	x	nd	xx	xxxx	nd
Pedon 3 Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic													
Apg	0-12	89.2	6.5	4.3	nd	xx	x	nd	x	nd	xxx	xxxx	tr
Btng	25-48/52	84.4	11.0	4.7	nd	xxxx	x	nd	x	nd	x	xxxx	nd
Btg2	52-80/85	83.2	11.0	5.8	nd	xxx	xx	nd	tr	nd	xx	xxxx	nd
Btg4	110-130	80.9	11.6	7.5	nd	xxx	xx	nd	x	nd	x	xxxx	nd
2Btg6	153-180	82.6	9.7	7.7	nd	xxx	xx	nd	x	nd	x	xxxx	nd
Pedon 4 Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic													
Apng	0-20	80.6	15.5	3.8	nd	xxx	x	nd	nd	nd	xx	xxxx	nd
Btg1	48-70	89.4	8.1	2.6	nd	xxx	x	nd	tr	nd	xx	xxxx	nd
Btng2	95-130	79.6	12.8	7.6	nd	xxx	xx	nd	tr	nd	x	xxxx	nd
Btng3	130-148/150	81.0	10.0	8.5	Ha (0.5)	xxx	xxx	nd	tr	nd	x	xxxx	nd
2Btng4	150-180	80.7	9.1	10.2	nd	xxx	xxx	nd	tr	nd	x	xxxx	nd

Table 5 (Continued)

Horizon	Depth	[A] Mineral in soil (%)				[B] clay fraction						[C] silt fraction	
	cm	Q	Kao	Other	Other minerals	Kao	Smec	Int	Ill	Chlo	Q	Q	Fel
Pedon 5 Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic													
Apng	0-20	91.8	6.5	1.7	nd	xxx	x	nd	nd	nd	xx	xxxx	nd
Btg1	20-40	88.7	9.0	2.3	nd	xxx	x	nd	nd	nd	xx	xxxx	nd
Btg2	40-70	77.7	19.8	2.4	nd	xxxx	x	nd	nd	nd	x	xxxx	nd
Btg4	90-112	77.7	20.6	1.7	nd	xxxx	x	nd	nd	nd	x	xxxx	nd
Btg6	14-170	78.5	17.9	3.6	nd	xxxx	nd	x	nd	nd	x	xxxx	nd
Location 2 : Clayey textured salt affected soils *(Phimai series)*													
Pedon 6 Typic Natraqualf; fine, kaolinitic, isohyperthemic													
Apng1	0-10	49.6	36.5	13.9	nd	xxxx	xx	nd	tr	nd	x	xxxx	nd
Btng1	20-33	44.1	50.7	5.2	nd	xxxx	x	nd	tr	nd	tr	xxxx	nd
Btng3	48-70	47.7	38.5	13.8	nd	xxxx	nd	xx	tr	xx	tr	xxxx	nd
Btng4	70-88	51.3	37.1	8.6	Fel (2), Goe (1)	xxxx	x	nd	tr	nd	x	xxxx	nd
2Btng5	88-114	59.0	27.0	11.6	Fel (1.5), Goe (0.9)	xxxx	xx	nd	tr	nd	tr	xxxx	tr
2Btng7	135-156	67.2	19.4	11.8	Fel (1), Goe (0.6)	xxx	xx	nd	x	nd	x	xxxx	tr
Pedon 7 Typic Natraqualf; very fine, kaolinitic, isohyperthemic													
Apg1	0-18	42.4	44.5	11.8	Goe (1.3)	xxxx	x	nd	tr	nd	x	xxxx	tr
Btg	30-42	41.3	45.1	13.6	nd	xxxx	x	nd	tr	nd	x	xxxx	nd
Btng1	42-53/64	30.0	51.1	18.9	nd	xxxx	nd	xx	tr	nd	x	xxxx	nd
Btng2	64-79	29.7	56.8	13.5	nd	xxxx	x	nd	tr	nd	x	xxxx	nd
Btng4	100-124	35.0	51.8	13.2	nd	xxxx	x	nd	tr	nd	x	xxxx	nd
2Btng6	151-176	51.7	36.8	9.5	Fel (2)	xxxx	x	nd	tr	nd	x	xxxx	nd
Pedon 8 Typic Natraqualf; fine, kaolinitic, isohyperthemic													
Apg	0-11	34.9	52.5	12.6	nd	xxxx	x	nd	tr	nd	x	xxxx	nd
Btg1	11-32	27.9	62.5	9.6	nd	xxxx	x	nd	tr	nd	x	xxxx	nd
Btng1	56-65/85	34.0	59.9	4.0	Fel (2)	xxxx	x	nd	nd	nd	tr	xxxx	nd
Btng2	85-110	31.4	62.6	5.3	Fel (0.7)	xxxx	x	nd	nd	nd	tr	xxxx	nd
2Btng4	124-152	12.9	71.1	13.0	Goe (3)	xxxx	x	nd	tr	nd	tr	xxxx	nd

Table 5 (Continued)

Horizon	Depth	[A] Mineral in soil (%)				[B] clay fraction						[C] silt fraction	
	cm	Q	Kao	Other	Other minerals	Kao	Smec	Int	Ill	Chlo	Q	Q	Fel
Pedon 9 Typic Endoaqualf; fine, kaolinitic, isohyperthemic													
Apg1	0-10	59.8	33.4	5.8	Fel (1)	xxxx	x	nd	tr	nd	x	xxxx	tr
Btg1	22-38	50.8	40.9	8.3	nd	xxxx	x	nd	tr	nd	x	xxxx	tr
Btg2	38-60	38.7	54.5	5.8	Fel (1)	xxxx	x	nd	tr	nd	tr	xxxx	tr
Btg4	83-102	42.6	39.9	13.0	Fel (3), Goe (1.5)	xxxx	xx	nd	tr	nd	tr	xxxx	tr
2Btg5	102-121	48.4	33.6	15.0	Fel (2.5), Goe (1.1)	xxxx	xx	nd	tr	nd	x	xxxx	tr
2Btg7	140-162	60.8	21.1	15.1	Fel (2), Goe (1)	xxx	xx	nd	tr	nd	x	xxxx	tr
Pedon 10 Typic Natraqualf; fine, kaolinitic, isohyperthemic													
Apg	0-16	57.8	32.9	7.3	Fel (2)	xxxx	x	nd	tr	nd	x	xxxx	nd
Btg2	31-52	45.5	32.3	22.2	nd	xxx	nd	xx	tr	nd	x	xxxx	nd
Btg4	69-95	31.1	47.7	21.2	nd	xxxx	nd	xx	tr	nd	x	xxxx	nd
2Btng2	95-128	36.3	58.4	5.3	nd	xxxx	x	nd	nd	nd	x	xxxx	nd
2Btng4	161-187	40.1	37.3	16.6	Fel (5), Goe (1)	xxxx	xx	nd	tr	nd	x	xxxx	nd
Location 3 : Sandy over clayey textures salt affected soils *(Kula Ronghai series)*													
Pedon 11 Typic Natraqualf; fine, kaolinitic, isohyperthemic													
Apg	0-15/23	88.4	9.4	2.2	nd	xxxx	nd	x	nd	nd	x	xxxx	nd
Bcg	23-46	46.0	50.1	3.9	nd	xxxx	x	nd	nd	nd	tr	xxxx	nd
Btg2	65-88	49.7	41.1	9.2	nd	xxxx	nd	x	nd	nd	tr	xxxx	nd
2Btng1	113-140	62.2	35.8	2.0	nd	xxxx	tr	nd	nd	nd	x	xxxx	nd
2Btng3	172-205+	61.9	36.0	2.1	nd	xxxx	tr	nd	tr	nd	x	xxxx	nd
Pedon 12 Typic Natraqualf; fine, kaolinitic, isohyperthemic													
Apg	0-19/20	92.1	6.5	1.5	nd	xxxx	nd	x	nd	nd	xx	xxxx	nd
Bcg	42-54/63	59.8	30.6	9.6	nd	xxxx	nd	xx	nd	nd	tr	xxxx	nd
Btg2	87-111/114	51.7	43.6	4.7	nd	xxxx	x	nd	nd	nd	tr	xxxx	nd
2Btg3	114-137	59.2	36.5	4.3	nd	xxxx	x	nd	nd	nd	x	xxxx	nd
2Btng1	155-183	65.4	32.7	1.8	nd	xxxx	x	nd	nd	nd	x	xxxx	nd

Table 5 (Continued)

Horizon	**Depth**	[A] **Mineral in soil (%)**				[B] **clay fraction**						[C] **silt fraction**	
	cm	Q	Kao	Other	Other minerals	Kao	Smec	Int	Ill	Chlo	Q	Q	Fel
Pedon 13 Typic Endoaqualf; fine, kaolinitic, isohyperthemic													
Apg1	0-18	91.7	6.5	1.9	nd	xxx	nd	x	nd	nd	xx	xxxx	nd
Btg1	30-48	41.8	54.3	3.9	nd	xxxx	x	nd	nd	nd	tr	xxxx	nd
Btg2	48-73	41.7	53.6	4.7	nd	xxxx	x	nd	nd	nd	tr	xxxx	nd
2Btg4	91-118	55.1	42.2	2.6	nd	xxxx	x	nd	nd	nd	x	xxxx	nd
2Btg6	150-185	46.3	52.1	1.6	nd	xxxx	tr	nd	nd	nd	x	xxxx	nd
Pedon 14 Typic Natraqualf; fine-loamy, mixed, active, isohyperthemic													
Apg	0-28	96.6	2.5	0.9	nd	xxx	nd	x	nd	nd	xx	xxxx	nd
Bng	28-44	95.1	3.6	1.3	nd	xxx	nd	xx	nd	nd	xx	xxxx	nd
Bcg	44-66	43.4	43.7	12.9	nd	xxxx	nd	xx	nd	nd	nd	xxxx	nd
Btng1	66-85	53.1	43.8	3.1	nd	xxxx	x	nd	nd	nd	nd	xxxx	nd
Btng2	85-110	55.0	36.1	8.8	nd	xxxx	nd	x	nd	nd	tr	xxxx	nd
2Btng4	137-161	58.9	39.6	1.6	nd	xxxx	tr	nd	nd	nd	x	xxxx	nd
2Btg	183-206+	57.6	40.8	1.6	nd	xxxx	tr	nd	nd	nd	x	xxxx	nd
Pedon 15 Typic Natraqualf; fine, kaolinitic, isohyperthemic													
Apg	0-15	96.4	2.7	0.9	nd	xxxx	nd	xx	nd	nd	x	xxxx	nd
Bcg	15-50	44.5	50.3	5.1	nd	xxxx	x	nd	nd	nd	nd	xxxx	nd
Btg2	70-90	51.8	44.2	4.0	nd	xxxx	x	nd	nd	nd	tr	xxxx	nd
2Btg4	110-130	61.5	35.7	2.9	nd	xxxx	x	nd	nd	nd	x	xxxx	nd
2Btg5	153-182	62.5	35.2	2.2	nd	xxxx	x	nd	nd	nd	x	xxxx	nd
Pedon 16 Typic Natraqualf; fine-loamy, mixed, semiactive, isohyperthemic													
Apg1	0-16/18	96.9	2.2	1.0	nd	xxx	nd	x	nd	nd	xx	xxxx	nd
Bcng	28-47/57	48.7	47.4	3.9	nd	xxxx	x	nd	nd	nd	nd	xxxx	nd
Btng1	57-72	48.1	47.3	4.6	nd	xxxx	x	nd	nd	nd	tr	xxxx	nd
Btng3	94-113	54.6	42.3	3.1	nd	xxxx	x	nd	nd	nd	tr	xxxx	nd
2Btng4	113-138	60.9	37.7	1.4	nd	xxxx	tr	nd	nd	nd	x	xxxx	nd
2Btng5	169-202+	62.6	36.0	1.4	nd	xxxx	tr	nd	nd	nd	x	xxxx	nd

Table 5 (Continued)

Horizon	Depth	[A] Mineral in soil (%)				[B] clay fraction						[C] silt fraction	
	cm	Q	Kao	Other	Other minerals	Kao	Smec	Int	Ill	Chlo	Q	Q	Fel
Location 4 : Clayey textured salt affected soils *(Udon series)*													
Pedon 17 Vertic Natraqualf; fine-loamy, mixed, semiactive, isohyperthemic													
Ang	0-20	31.8	30.4	37.8	nd	xx	xx	nd	x	nd	xx	xxxx	nd
ABng	20-36	40.7	21.9	37.4	nd	xx	xx	nd	x	nd	xx	xxxx	nd
Btng1	36-60	59.5	24.0	16.5	nd	xxx	xx	nd	tr	nd	xx	xxxx	nd
Btng3	85-110	52.4	34.1	13.5	nd	xxx	x	nd	tr	nd	xxx	xxxx	nd
Bssg1	130-165	27.9	29.2	42.9	nd	xx	xx	nd	x	nd	xx	xxxx	nd
Pedon 18 Vertic Natraqualf; fine-loamy, mixed, semiactive, isohyperthemic													
Ang	0-19	41.7	24.1	33.2	Fel (1)	xx	xx	nd	x	nd	xx	xxxx	nd
Btng1	19-43	47.8	37.2	15.0	nd	xxx	x	nd	tr	nd	xx	xxxx	nd
Btng3	64-94	49.0	38.8	11.1	Fel (1)	xxx	x	nd	tr	nd	xx	xxxx	nd
Btng4	94-113	51.1	34.9	14.0	nd	xxx	x	nd	tr	nd	xx	xxxx	nd
2Btng6	140-169	64.7	13.7	20.6	Fel (1)	xx	xxx	nd	tr	nd	xx	xxxx	nd
Pedon 19 Vertic Natraqualf; fine-loamy, mixed, semiactive, isohyperthemic													
Ang	0-19	42.2	26.8	31.0	nd	xx	xx	nd	x	nd	xx	xxxx	nd
Btng1	19-38	48.4	30.7	20.9	nd	xxx	xx	nd	x	nd	xx	xxxx	nd
Btng3	56-77	46.6	43.6	9.9	nd	xxxx	x	nd	tr	nd	x	xxxx	nd
2Btng4	77-100	67.3	26.5	6.2	nd	xxxx	x	nd	tr	nd	x	xxxx	nd
2Btng6	119-146	94.0	3.0	3.0	nd	xx	xx	nd	tr	nd	xx	xxxx	nd
2Btng7	146-175	80.7	6.4	12.9	nd	xx	xxx	nd	tr	nd	xx	xxxx	nd
Pedon 20 Vertic Natraqualf; fine-loamy, mixed, semiactive, isohyperthemic													
Ang	0-20	47.3	25.5	27.2	nd	xx	xx	nd	x	nd	xx	xxxx	nd
Btng1	20-44	47.7	37.3	15.0	nd	xxx	x	nd	tr	nd	xx	xxxx	nd
Btng3	66-89	48.3	39.6	12.0	nd	xxx	x	nd	tr	nd	xx	xxxx	nd
Btng5	113-139	58.5	15.5	26.0	nd	xx	xxx	nd	tr	nd	xx	xxxx	nd
Btng7	171-200+	20.3	23.0	56.7	nd	xx	xxx	nd	x	nd	xx	xxxx	nd

Table 5 (Continued)

Horizon	**Depth**	[A] **Mineral in soil (%)**				[B] **clay fraction**						[C] **silt fraction**	
	cm	Q	Kao	Other	Other minerals	Kao	Smec	Int	Ill	Chlo	Q	Q	Fel
Pedon 21 Vertic Natraqualf; fine-loamy, mixed, semiactive, isohyperthemic													
Ang	0-18	38.2	24.9	36.8	nd	xx	xx	nd	x	nd	xx	xxxx	nd
Btng1	18-45	40.4	33.1	26.5	nd	xx	xx	nd	x	nd	xx	xxxx	nd
Btng3	68-89	44.2	32.4	23.4	nd	xxx	x	nd	x	nd	xx	xxxx	nd
Btng4	89-112	34.0	28.8	36.2	Fel (1)	xx	xx	nd	x	nd	xx	xxxx	nd
Btng7	161-200+	16.9	32.4	49.8	Fel (1)	xx	xx	nd	x	nd	xx	xxxx	nd
Pedon 22 Vertic Natraqualf; fine-loamy, mixed, semiactive, isohyperthemic													
Ang	0-21	45.6	26.9	27.4	nd	xx	xx	nd	x	nd	xxx	xxxx	nd
Btng1	21-41	47.8	31.4	20.0	Fel (0.8)	xxx	xx	nd	tr	nd	xx	xxxx	nd
Btng3	66-88	35.3	30.5	33.2	Fel (1)	xx	xx	nd	x	nd	xx	xxxx	nd
Btng5	108-132	18.0	40.1	40.9	Fel (1)	xx	xx	nd	x	nd	x	xxxx	nd
Btng7	165-184	11.7	31.1	57.2	nd	xx	xxx	nd	x	nd	x	xxxx	nd
Location 5 : Sandy textured salt affected soils *(Roi Et, saline variant 2)*													
Pedon 23 Typic Natraqualf; sandy, silicious, subactive, isohyperthemic													
Apng	0-11	95.7	1.6	1.8	Ha (1)	x	x	nd	tr	nd	xxxx	xxxx	nd
Bng2	30-47	96.5	1.2	2.3	nd	x	nd	x	tr	nd	xxxx	xxxx	nd
Btng1	47-69	95.5	1.8	2.7	nd	x	x	nd	tr	nd	xxxx	xxxx	nd
Btng3	95-110	90.3	6.2	3.5	nd	xxx	xx	nd	tr	nd	x	xxxx	nd
Btng5	130-153	87.7	5.2	7.1	nd	xx	xx	nd	x	nd	xx	xxxx	nd
2Btng6	153-178	70.6	9.0	20.4	nd	x	x	nd	xx	nd	xx	xxxx	nd
2Btng7	178-200+	66.3	5.1	28.6	nd	x	x	nd	xxx	nd	xxx	xxxx	nd
Pedon 24 Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic													
Apng	0-12	92.2	2.9	4.3	Ha (0.5)	xx	nd	xxx	x	nd	xx	xxxx	nd
Btng1	12-30	86.3	8.8	4.9	nd	xxx	xx	nd	tr	nd	x	xxxx	nd
Btng3	53-73	87.9	5.1	7.0	nd	xx	xxx	nd	tr	nd	x	xxxx	nd
Btng5	100-128	80.0	11.2	8.9	nd	xx	x	nd	x	nd	xx	xxxx	nd
2Btng6	128-155	72.2	8.6	19.2	nd	xx	x	nd	xx	nd	xx	xxxx	nd
2Crtng	155-200+	36.7	3.5	35.8	Ha (1), Ca (20), Fel (1), He (2), Le, Ak?	x	x	nd	xxx	nd	xx	xxxx	nd

Table 5 (Continued)

Horizon	Depth	[A] Mineral in soil (%)				[B] clay fraction						[C] silt fraction	
	cm	Q	Kao	Other	Other minerals	Kao	Smec	Int	Ill	Chlo	Q	Q	Fel
Pedon 25	Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic												
Apg	0-17/30	95.7	1.9	2.4	nd	xx	xx	nd	tr	nd	xx	xxxx	nd
Bg	17-30	95.5	2.4	2.0	nd	xx	xx	nd	tr	nd	xx	xxxx	nd
Btng1	30-52	88.8	4.8	6.4	nd	xx	xx	nd	tr	nd	xx	xxxx	nd
Btng3	71-92	78.1	8.4	13.6	nd	xx	xx	nd	tr	nd	xx	xxxx	nd
2BCrng1	92-120	55.3	6.0	30.3	Ha (0.7), Ca (5.5), Fel (1.4), He (0.8), Le.	x	nd	x	xxx	nd	xx	xxxx	nd
2BCrg	143-170	29.0	7.0	43.2	Ha (3), Ca (11), Fel (3.8), He (3), Le, Ak?	x	nd	x	xxx	nd	xxx	xxxx	tr
Pedon 26	Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic												
Apg	0-14	96.8	1.1	2.1	nd	x	nd	x	tr	nd	xxxx	xxxx	nd
Bng	14-31/46	96.3	1.9	1.8	nd	x	nd	x	tr	nd	xxxx	xxxx	nd
Btng2	53-73	76.0	15.5	8.4	nd	xxx	nd	xx	tr	nd	x	xxxx	nd
2Btng4	92-114	71.9	18.1	10.1	nd	xxx	x	nd	x	nd	xx	xxxx	nd
2Btng6	137-164	65.2	16.2	18.6	nd	xx	x	nd	x	tr	xxx	xxxx	nd
2BCrng	164-200+	56.5	12.8	30.7	nd	xx	nd	x	x	x	xx	xxxx	nd
Pedon 27	Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic												
Apng	0-20/22	95.7	2.9	1.3	nd	xxx	x	nd	tr	nd	xx	xxxx	nd
Bg	22-40	96.6	1.7	1.7	nd	x	nd	x	tr	nd	xxxx	xxxx	nd
Btng1	58-82	80.8	12.7	6.5	nd	xxxx	nd	xx	tr	nd	x	xxxx	nd
Btng2	82-104	83.0	12.4	4.7	nd	xxx	x	nd	x	nd	x	xxxx	nd
Btng4	122-143	65.8	28.4	5.7	nd	xxxx	x	nd	x	nd	x	xxxx	nd
2Btng6	160-180	76.0	17.9	6.1	nd	xxxx	x	nd	x	nd	x	xxxx	nd
Pedon 28	Typic Natraqualf; coarse-loamy, mixed, semiactive, isohyperthemic												
Apng	0-10/13	96.8	1.9	1.3	nd	xx	nd	x	tr	nd	xxx	xxxx	nd
Bng	13-30	96.7	1.3	2.0	nd	x	nd	nd	tr	nd	xxxx	xxxx	nd
Btng1	30-44	95.2	3.0	1.7	nd	xxx	xx	nd	tr	nd	x	xxxx	nd
Btng3	66-86	91.0	4.7	4.3	nd	xxx	xx	nd	x	nd	x	xxxx	nd
Btng5	107-138/144	81.1	10.9	8.0	nd	xxx	xx	nd	x	nd	x	xxxx	nd
2Btng6	144-168	72.5	16.9	10.7	nd	xxx	x	nd	x	nd	xx	xxxx	nd

[A] Minerals in whole soil by random powder, reported in percent; Q=quartz; Kao=kaolin; Other=other clay minerals (not kaolin); Ha=halite; Cal=calcite; Fel=feldspar;Goe=goethite; and He= hematite

[B,C] Minerals in clay and silt fraction, tr= < 5%; x=5-20%; xx=20-40%; xxx=40-60%; xxxx=>60%; and nd= not detected Kao=kaolin; Smec= smectite; Int= interstratified 10 Å and 14 Å minerals; Ill= illite; Chlo= chlolite; and Q=quartz

The dominant mineral at location 1 is quartz with kaolin and smectite being minor minerals, and trace amounts of illite occurring in some horizons. The term kaolin indicates combined kaolinites of various structural order status and 0.7 nm halloysite if present (Brindley and Brown, 1980). Other mineral present in these soils is a small amount of halite in the Apng horizon of pedon1 (highly affected by salt, high EC) and in the lower B horizon in pedon 4 (slightly affected by salt) (Table 5).

Kaolin is a major clay mineral with quartz at location 2. The other clay minerals are smectite with a trace of illite. Accessory minerals include goethite and feldspar in some horizons (Table 5).

The mineral composition of soils at location 3 shows that surface horizons are dominated by quartz because of their sandy texture whereas the subsoil horizons are dominated by kaolin and quartz with a trace of smectite. Significant amount of other minerals are not present in these soils (Table 5).

The dominant minerals for location 4 are smectite, kaolin and quartz. Traces of illite and feldspar occur for some horizons (Table 5). The amounts of smectite, kaolin and quartz are very diverse within individual soil profiles. In the A horizons and the lower B horizons (2B horizon) quartz is dominant, whereas in the upper B horizon smectite and kaolin are dominant possibly attribute a combination of depositional layering, pedogenic process (e.g. authigenesis of smectite) and smectite being a component of the altered rocks present in the subsoil (Victoria *et al*., 1999; Ben *et al*., 2000) (Table 5).

For location 5, quartz is the dominant mineral with minor kaolin, smectite and illite. Calcite occurs in the C and BC horizons and small amounts of halite are present in the Apng horizon of Pedons 23 and 24 (highly affected by salt) and in C and BC horizon of Pedons 24 and 25. In addition, the C and BC horizons also contain feldspar, hematite and goethite (Table 5). In these pedons C and BC horizons have developed from local salt bearing rocks and thus have a different mineral composition from near surface horizons which are composed of more recent sediment (Department of Mineral Resources, 1982). In particular the C and BC horizons contain much ofsmectite indicating that this mineral occurs in the weathered rocks.

High amounts of smectite are present in the clay fraction of some of the soils except for those at location 3 that have very high amounts of kaolin (Table 5). This result may indicate that the salinity effect increases solubility of silica that induces resilication. So, some of the kaolin mineral can alter to 2:1 clay minerals under high salt affected conditions. The interstratified 10 Å and 14 Å minerals found in some horizons of locations 1, 2, 3 and 5 are not present in soils at location 4 that have low pH values (Table 5 and Appendix C, Table C2). Also, where the soils have the interstratified minerals smectite is not present (Table 5). Therefore, it is a possibility that the interstratified mineral is a part in the alteration process of a 1:1 to 2:1 clay minerals, but the process is incomplete. Moreover, the low pH condition may also affect this process. Chlorite is also present in only the 2BCrng horizon of Pedon 26 (Table 5) which is consistent with the geology of this area which contains rock salt deposits. The mineralogy of the silt fraction is dominated by quartz with traces of feldspar in some pedons (Table 5).

The diversity of mineral compositions among locations is primarily related to soil texture which in turn reflects the diverse parent materials and different extents of soil development. Soils at locations 2 and 4 have the same texture and similar parent materials but the types of clay mineral are different which may be due to authigenesis of smectite and illite (Millot, 1970). Location 2 is on a higher part of floodplain where leaching is less retarded as compared to location 4 in the depression where salts accumulate, so authigenic smectite may have crystallized from the higher concentration of silica in soil solution at this location (Borchardt, 1989, Dixon and Schulze, 2002).

As smectite reflections for some soils are very broad and the d-spacings are not the same as for perfect smectite which may be attributed interstratification of other clay minerals with smectite (Sawhney, 1989), another hypothesis could be that the smectites in these soils were forming from the resilicating 1:1 clay minerals.

3. Distinction of Smectite Group

Smectite group minerals are minor minerals and in some horizon the amount of smectite is higher than 30 percent (Table 5). The Green-Kelly test allows the identification of smectite species in high smectite samples. Figure 36 shows XRD patterns that enable the distinction between beidelite and montmorillonite by the Green-Kelly test. The 001 spacing of about 1.0 nm indicates a montmorillonite, and a spacing of 1.70-1.78 nm a beidellite (Brindley and Brown, 1980). Figure 37 shows the XRD patterns of Mg-saturated and glycerol solvated and Li-saturated, heated at 250 ºC and glycerol solvated.

The peak at 1.0 nm can either be illite or montmorillonite peak. The different of peak area from both treatments indicate the amount of montmorillonite. The kaolin peak at 0.72 nm was used as standard intensity between both treatments to determine the percentage of beidellite and montmorillonite. The percentage of beidelite and montmorillonite are shown in Table 6. Most of samples have beidelite dominant. Montmorillonite are also present with beidellite in some samples and some are not detected (Table 6). The three samples (P6_Btng3, P10_Btg2 and P22_Btng7) have montmorillonite dominant (Table 6).

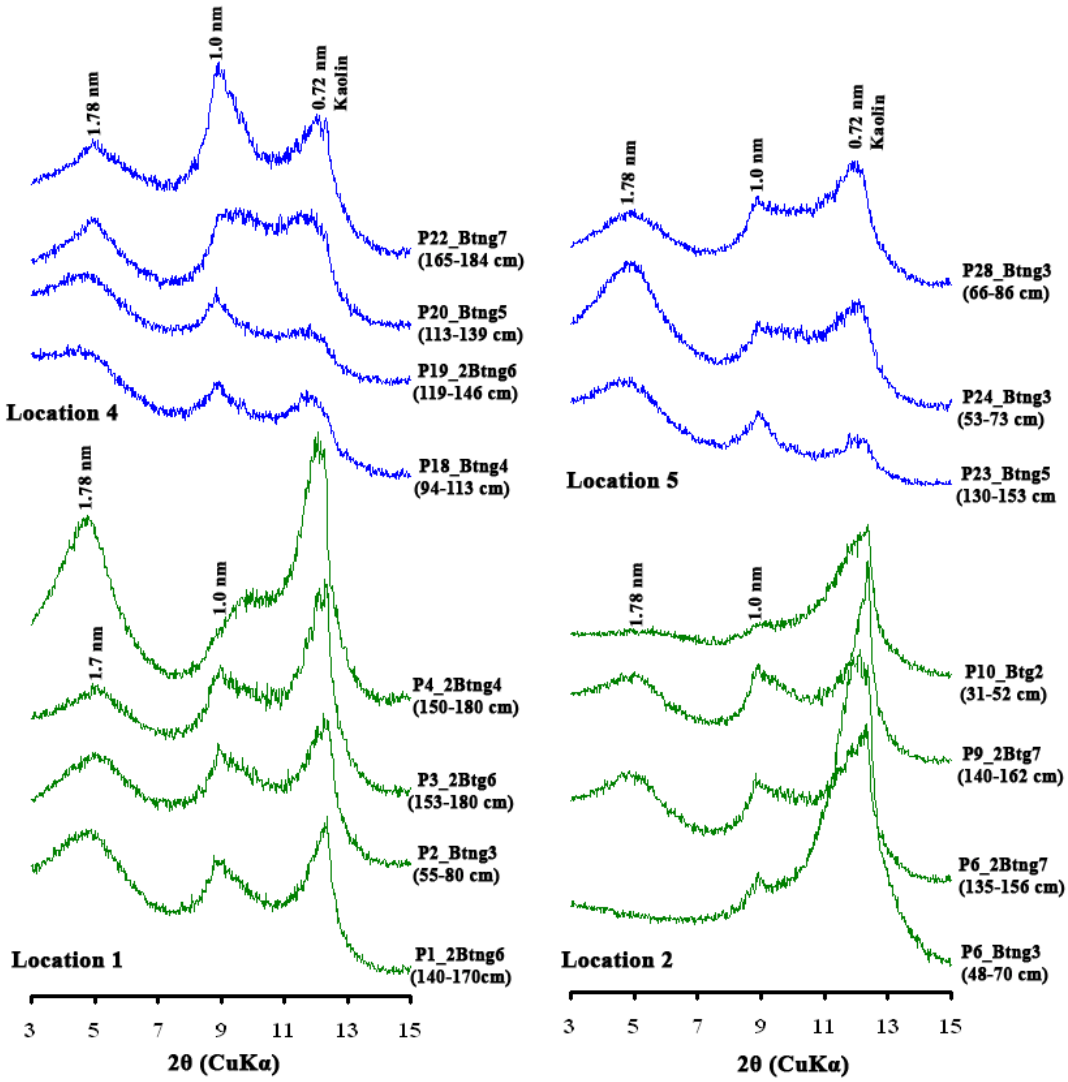


Figure 36 XRD patterns of oriented clay of salt affected soils showing the distinction between beidellite and montmorillonite provided by the Green-Kelly test. Samples were Li-saturated, heated at 250 ºC and glycerol solvated which results in the following basal spacings ~1.8 nm (beidellite) and 1.0 nm (montmorillonite). The 0.72 nm refection is due to kaolin.

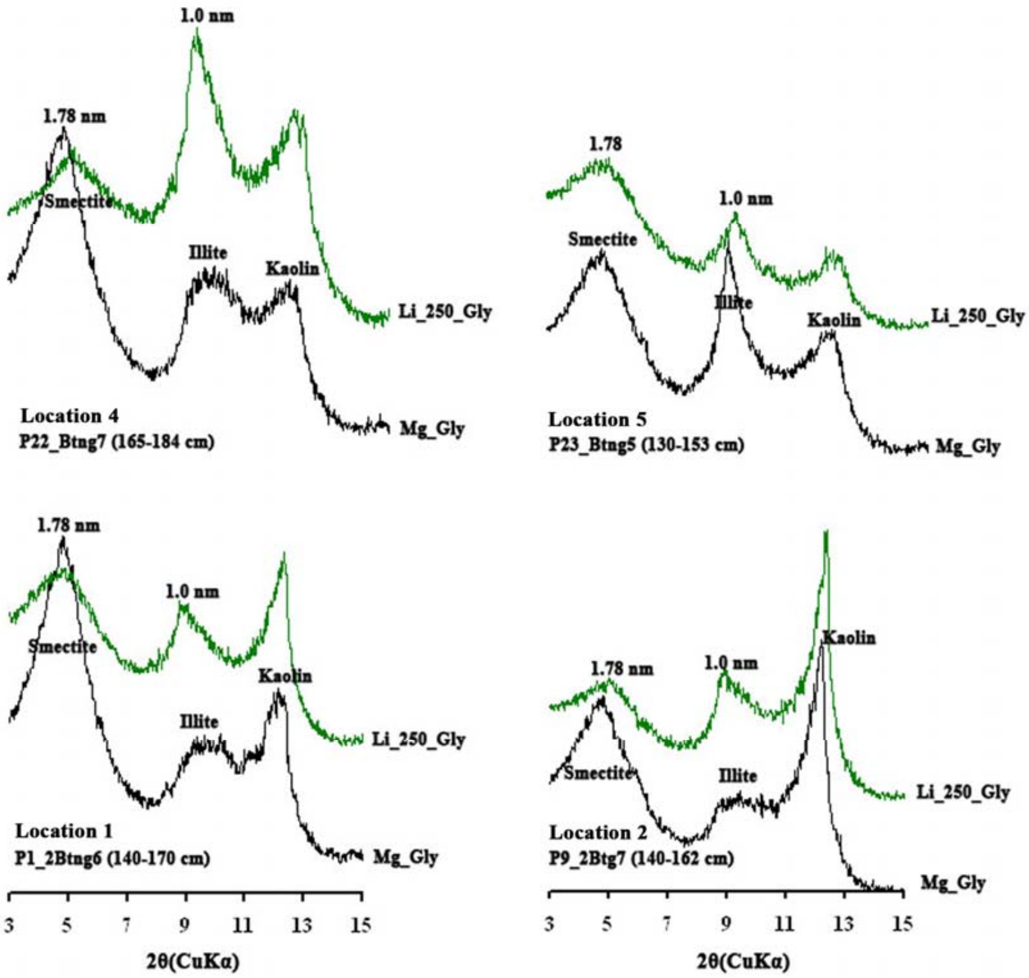


Figure 37 XRD patterns of the oriented clay fraction of salt affected soils showing the distinction between beidellite and montmorillonite provided by the Green-Kelly test: the Li_250_Gly is Li-saturated, heated at 250 ºC and glycerol solvated, the Mg_Gly is Mg-saturated and glycerol solvated which results in the following basal spacings ~1.8 nm (beidellite), 1.0 nm (montmorillonite and illite) and the 0.72 nm refection is kaolin.

Table 6 The relative percentages of minerals of the smectite group (beidellite and montmorillonite) in the clay of salt affected soils provided by the Green-Kelly test and based on a comparison of the intensitis of 001 reffections.

Soil samples	% Smectite	
	Beidellite	Montmorillonite
P1_Bng	100	nd
P1_2Btng6	82	18
P2_Btng3	85	15
P3_2Btng6	64	36
P4_2Btg4	88	12
P5_Btg6	100	nd
P6_Btng3	15	85
P6_2Btng7	81	19
P9_2Btg7	59	41
P10_Btg2	30	70
P11_Bcg	100	nd
P12_Bcg	100	nd
P18_Btng4	100	nd
P19_2Btng6	66	44
P20_Btng5	100	nd
P22_Btng7	39	61
P23_Btng5	80	20
P24_Apng	100	nd
P24_Btng	100	nd
P25_Bg	100	nd
P27_Btng1	100	nd
P28_Btng3	100	nd

4. **Properties of Kaolin**

The electron micrographs of kaolin are shown in Figures 38-42. Quite similar dominant morphologies for different samples include anhedral, subhedral and euhedral face of platy crystals. Tubular crystals are not present.

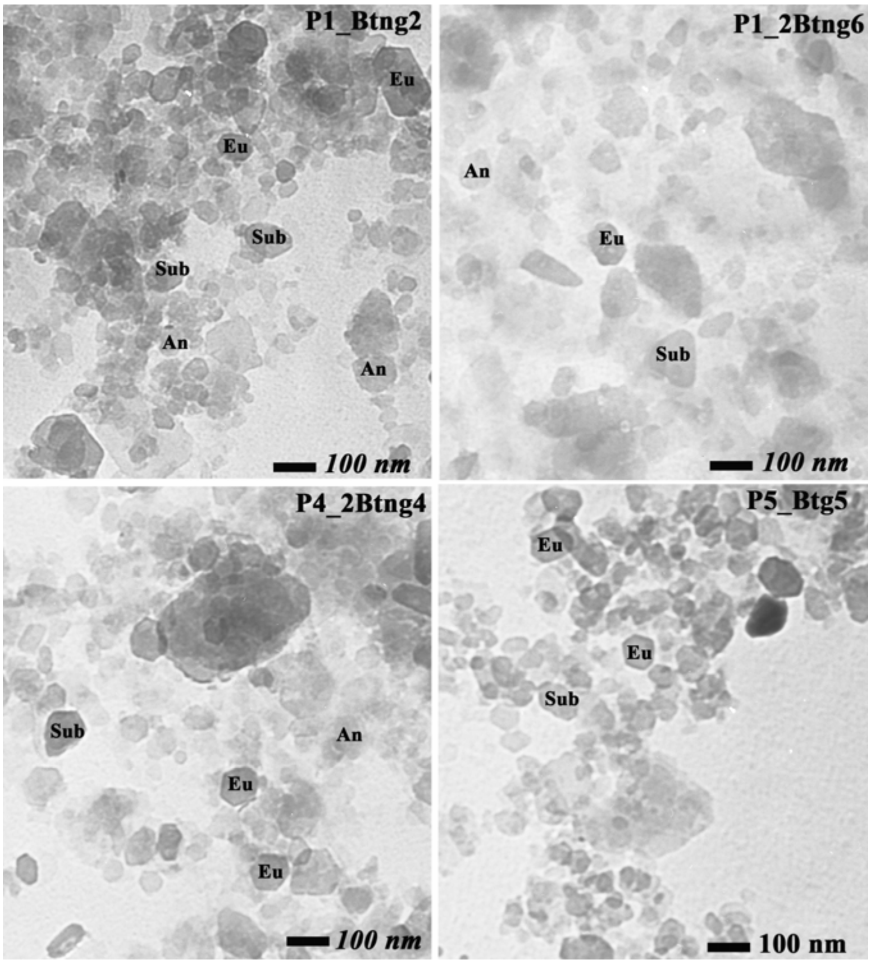


Figure 38 Transmission electron microscope (TEM) micrographs of kaolin from salt affected soils at location 1 showing the wide ranges of crystal morphology and sizes. Various morphologies are indicated in the Figure: Eu=euhedral crystal, Sub=subhedral crystal and An=anhedral crystal.

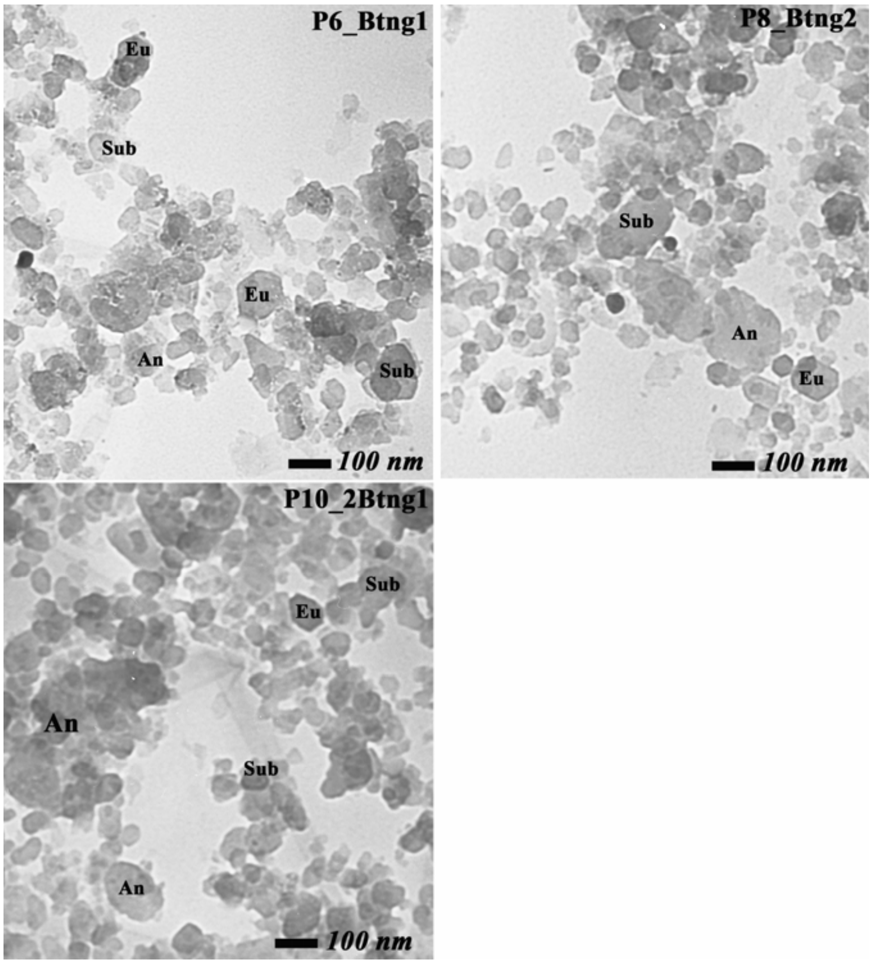


Figure 39 Transmission electron microscope (TEM) micrographs of kaolin from salt affected soils at location 2 showing the wide ranges of crystal morphology and sizes. Various morphologies are indicated in the Figure: Eu=euhedral crystal, Sub=subhedral crystal and An=anhedral crystal.

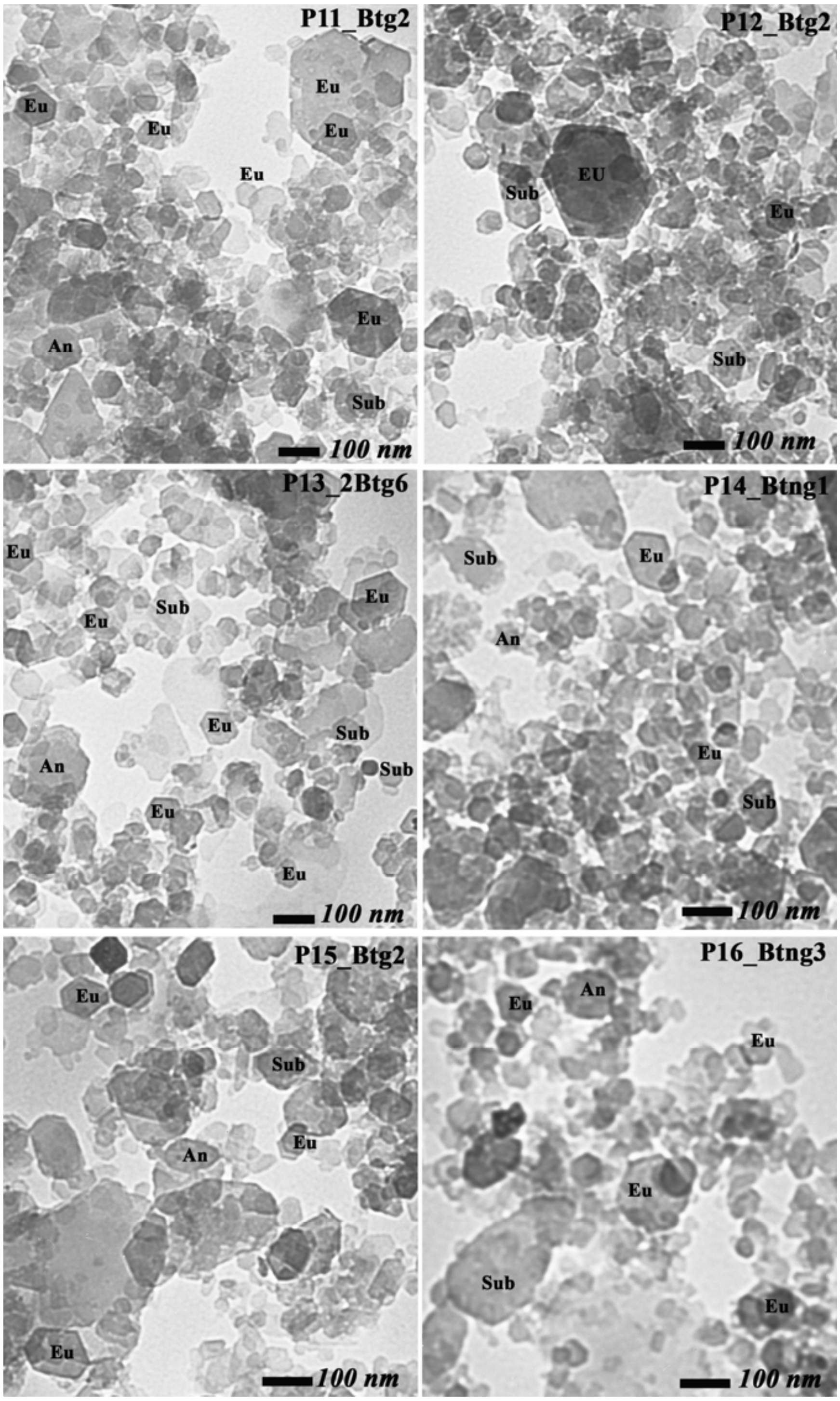


Figure 40 Transmission electron microscope (TEM) micrographs of kaolin from salt affected soils at location 3 showing the wide ranges of crystal morphology and sizes. Various morphologies are indicated in the Figure: Eu=euhedral crystal, Sub=subhedral crystal and An=anhedral crystal.

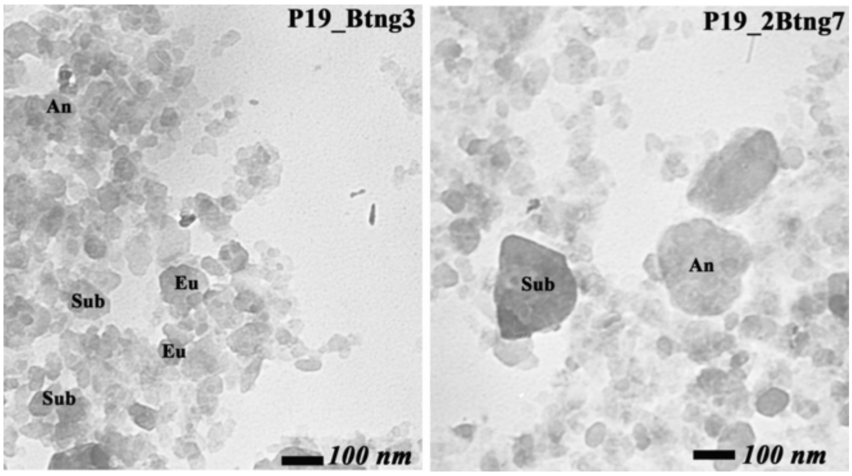


Figure 41 Transmission electron microscope (TEM) micrographs of kaolin from salt affected soils at location 4 showing the wide ranges of crystal morphology and sizes. Various morphologies are indicated in the Figure: Eu=euhedral crystal, Sub=subhedral crystal and An=anhedral crystal.

Figure 43 is a triangle graph showing the percentage abundance of three morphologies of kaolin. Kaolin from location 3 that has low EC has a higher percent of euhedral faces. The median size of crystal ranges from 46-69 nm with the standard deviation rangeing from 13.0-31.2 and the crystal size distribution is not normally distributed (Figure 44). Small kaolin crystals are present in all of the samples; they are smaller than those Thai kaolin crystals reported by Trakoonyingcharoen *et al.* (2006). The crystal sizes of kaolin are also smaller than platy kaolin particles in soils from tropical and Mediterranean climates observed by Singh and Gilkes (1992) and Hart *et al*. (2002) ranging from 50-200 nm.

Figure 45a showing a quite strong relationship between mean size of kaolin crystal size and the standard deviation (R^2=0.69) indicats that standard deviation increases with crystal size. The coefficient of variance changes slightly with crystal size showing that all kaolins have similar shaped crystal size distributions (Figure 45b). Figure 46 shows that there is no relationship between the number of euhedral face and kaolin size for any sample. The coherently scattering domain (CSD) size derived from the width at half height (WHH) of XRD reflections using the Scherrer equation indicates that the CSD size of soil kaolin crystals ranges from 3.5-8.5 nm for

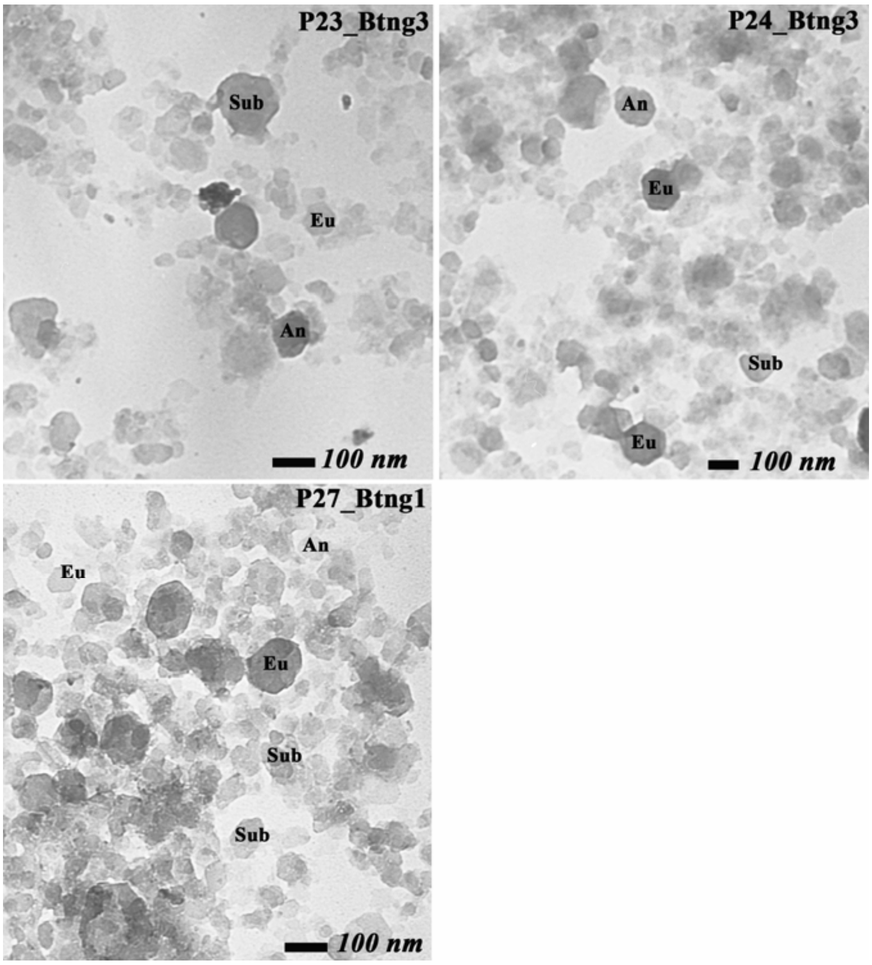


Figure 42 Transmission electron microscope (TEM) micrographs of kaolin from salt affected soils at location 5 showing the wide ranges of crystal morphology and sizes. Various morphologies are indicated in the Figure: Eu=euhedral crystal, Sub=subhedral crystal and An=anhedral crystal.

001. A comparison of crystal sizes derived from TEM and XRD line broadening (Figure 47) indicates that particle size determined by TEM is larger than values derived by XRD by a factor of about 8.7 and that the two estimates of crystal size are weakly significantly correlated (R^2=0.22). A major cause of this difference is that XRD measurement are of size in the c-axis direction which is much smaller that the width of the platy crystals (a, b directions) measured by electron microscopy (Hart *et al.,* 2002). The ratio of these two measurements gives an indication of shape (e.g. width/ thickness=8.7).

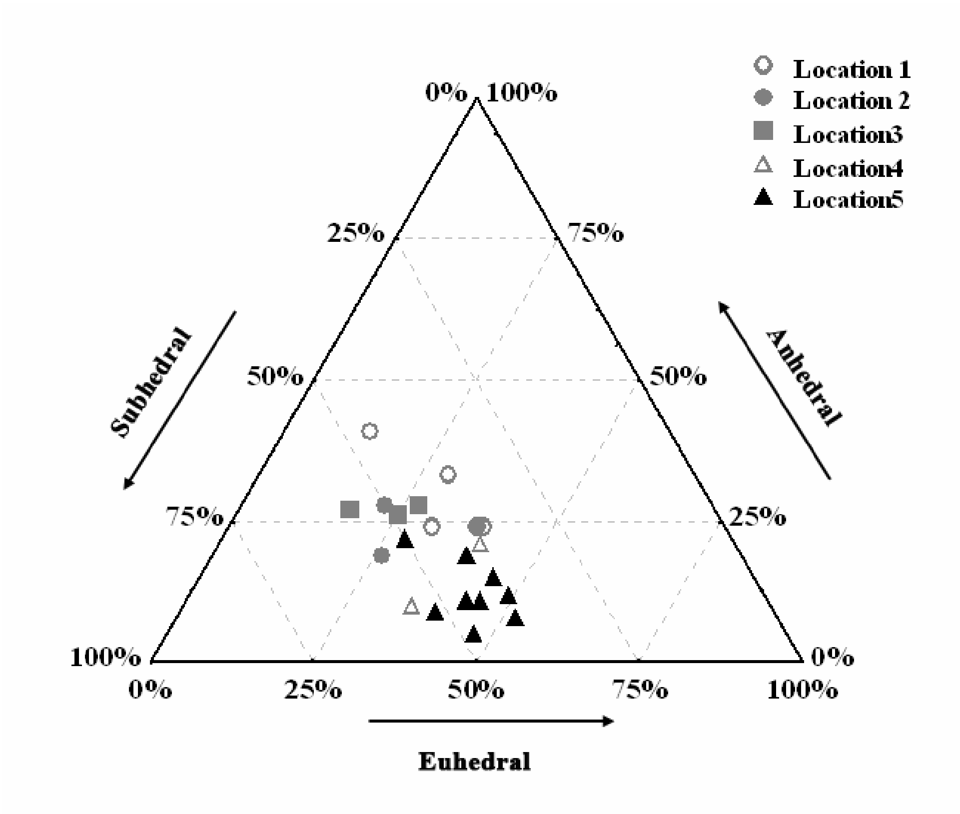


Figure 43 Triangle graph representing the shapes of kaolin crystrals (0 plane faces=Anhedral, 1-3 faces=Subhedral, 4-6 faces=Euhedral) for selected kaolin samples dominant of the clay fraction of salt affected soils in this study.

The properties of kaolin (mean size by TEM, CSD001 and number of euhedral face) do not show clear relationships with soil properties (EC, SAR, ESP and pH) (Figure 48). There is a weak inverse relationship between the mean size of kaolin crystals by TEM and EC value (R^2=0.22) whereas there are no significant relationships with SAR, ESP and pH (Figure 48a). The inverse relationship of CSD001 with EC value is quite significant (R^2=0.52) and there are weak inverse relationships with SAR and ESP values (R^2=0.14 and 0.31 respectively) (Figure 48b). No significant relationships exist between the number of euhedral face and EC, SAR, ESP and pH (Figure 48c) but the data seem to show a slight inverse relationship of the number of euhedral faces with SAR and ESP values, with R^2=0.18 and 0.22 respectively (Figure 48c).

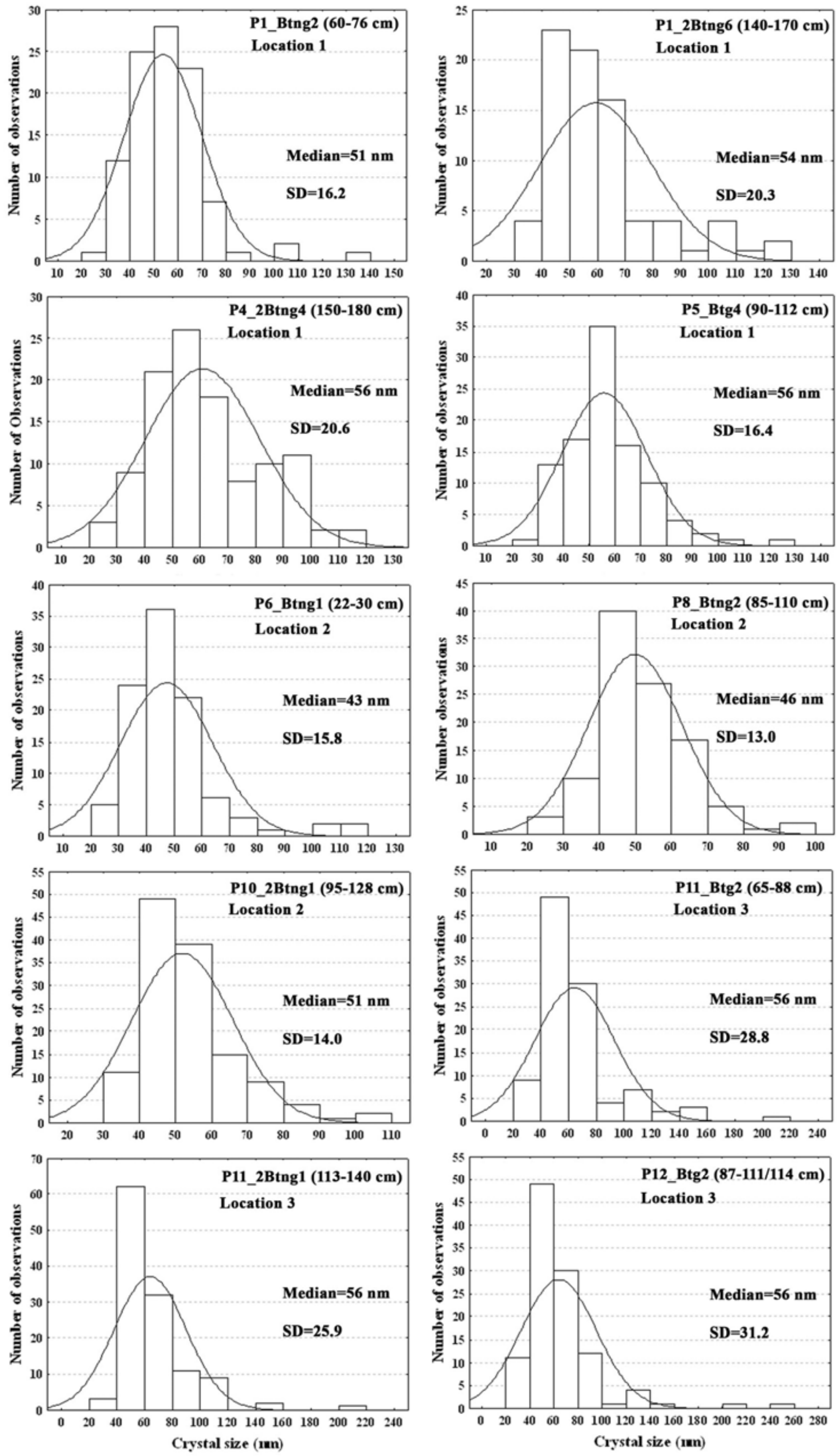


Figure 44 Histograms showing the size distribution of kaolin crystals in salt affected soils in this study.

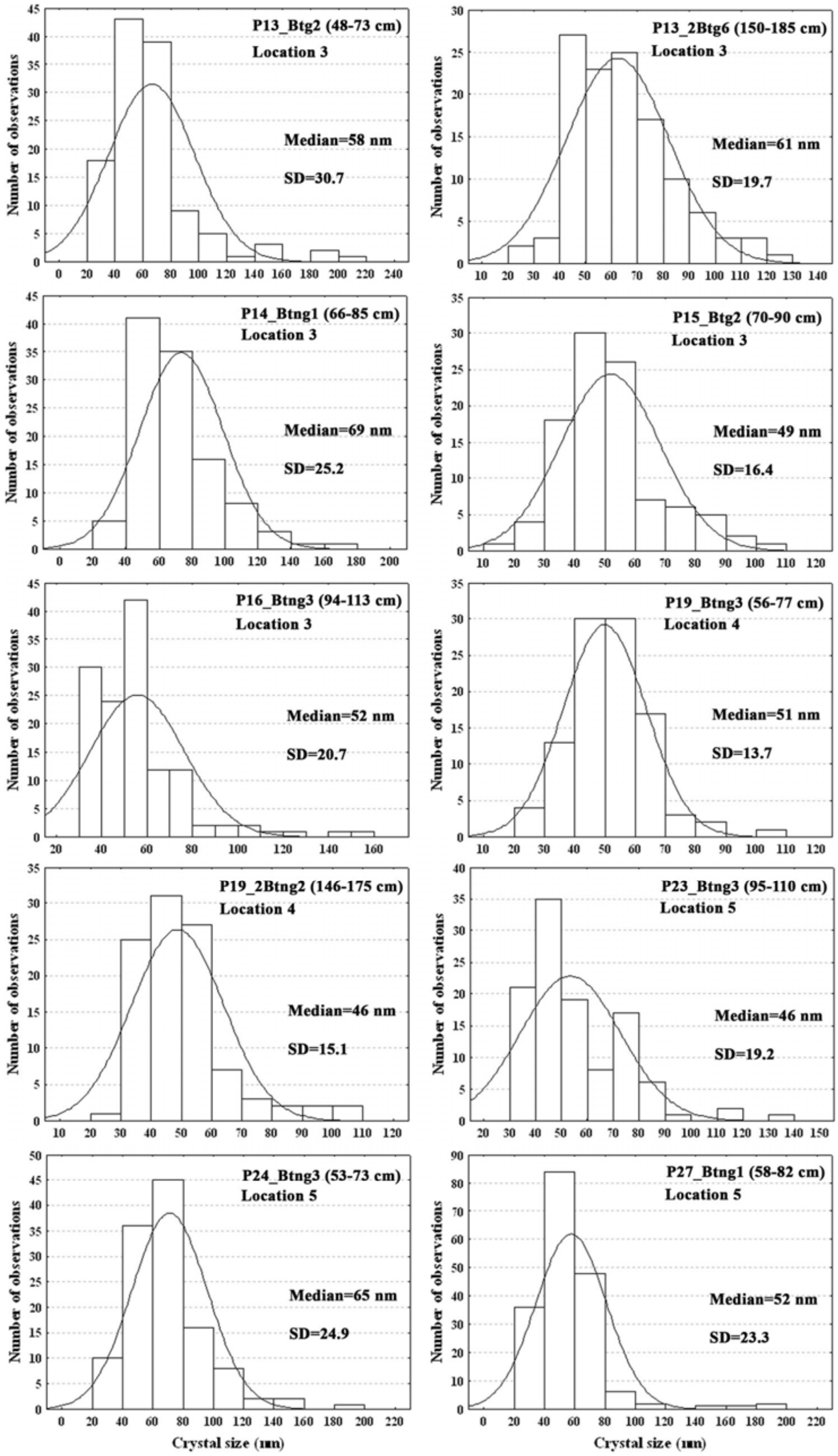


Figure 44 (Continued)

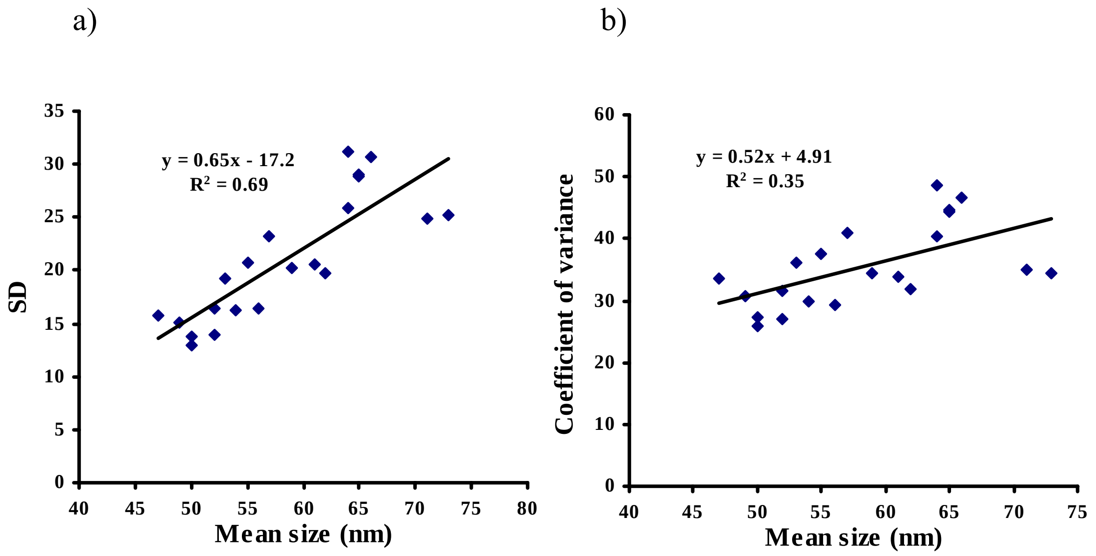


Figure 45 (a) The relationship between the mean of kaolin crystal size and standard deviation and (b) The relationship between the mean of kaolin crystal size and coefficient of variation for salt affected soils in this study.

5. Synthesis

Minerals in these salt affected soils consist predominantly of quartz and clay minerals kaolin, smectite, illite and vermiculite occurring in various proportions. Small amount of calcite, halite, feldspar and iron oxides (Goethite, Hematite and Lepidocrocite) occurs in some samples. Halite occurred in surface horizons due to the high salt accumulation (the surface contains a salt crust). Halite and calcite occurred in some BC and C horizons is consistent with the geological condition of the area.

Minerals in clay fraction are predominantly kaolin and smectite with trace of illite and interstratifile minerals. The different amounts of quartz present in the clay fraction tend to be associated with soil texture.

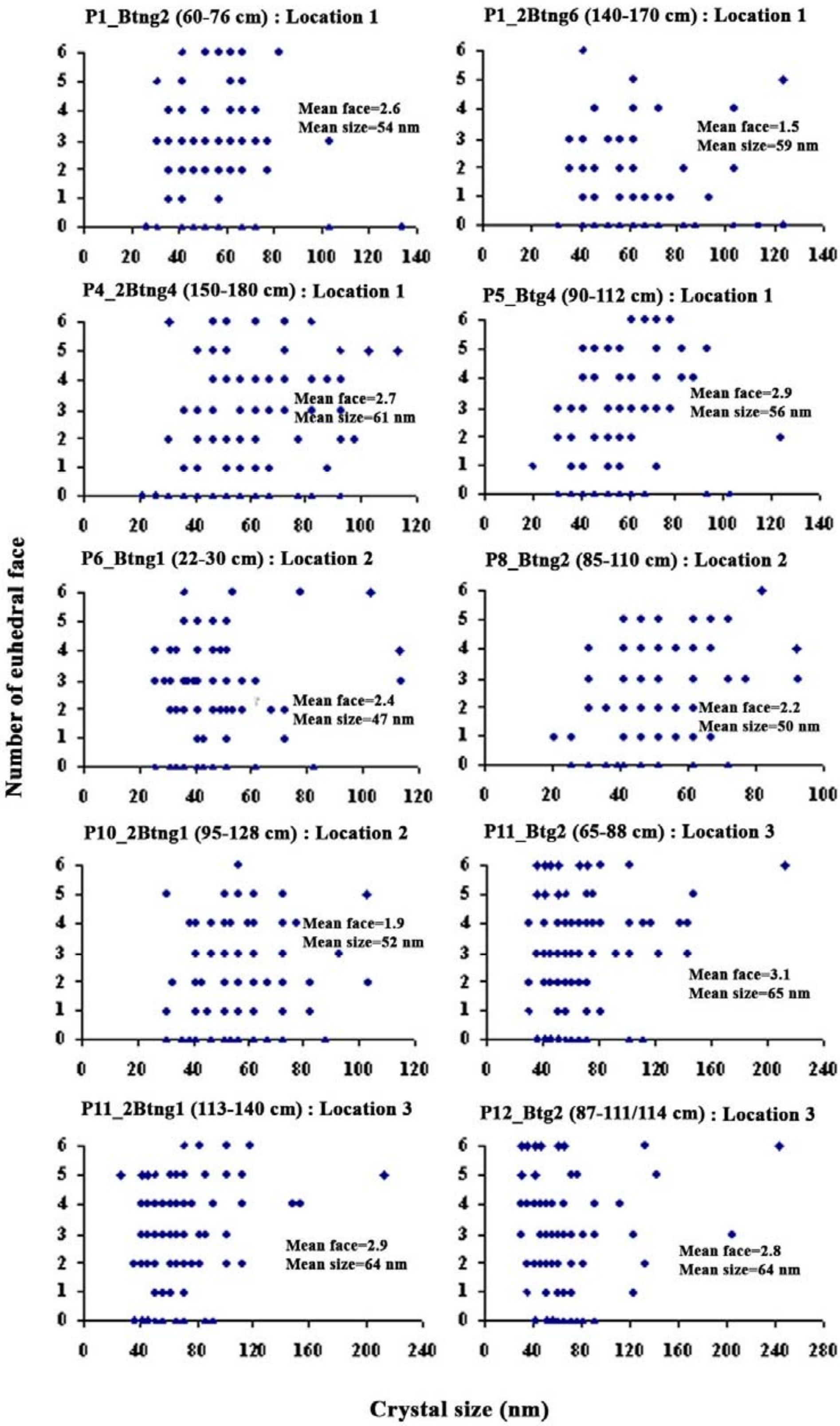
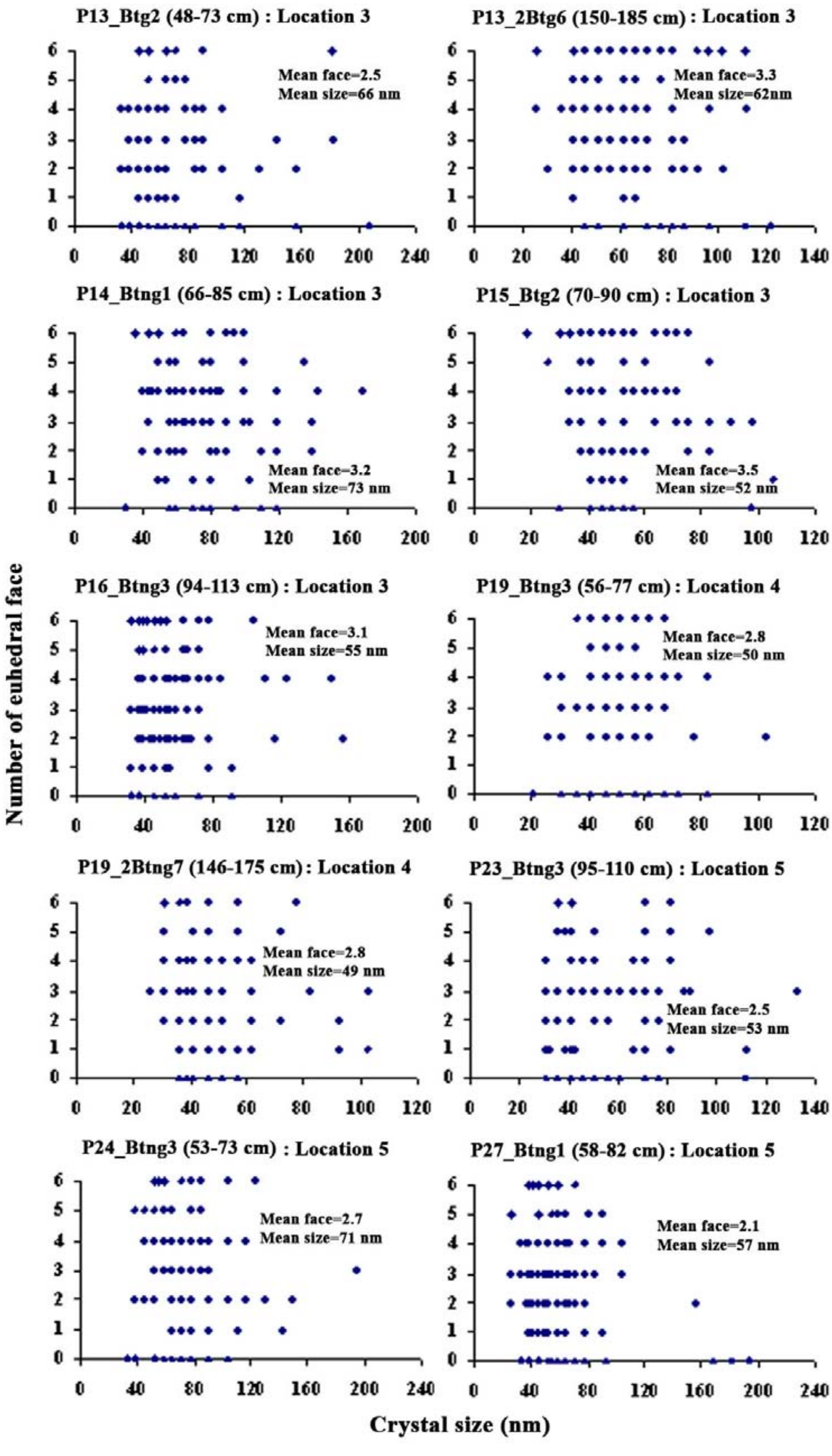


Figure 46 The relationship between the number of euhedral face and kaolin size for salt affected soils in this study.



<u>Figure 46</u> (Continued)

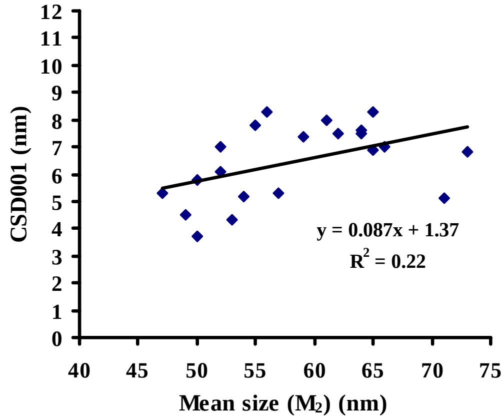


Figure 47 The relationship between CSD001 of kaolin and mean crystal size determined by TEM for salt affected soils in this study.

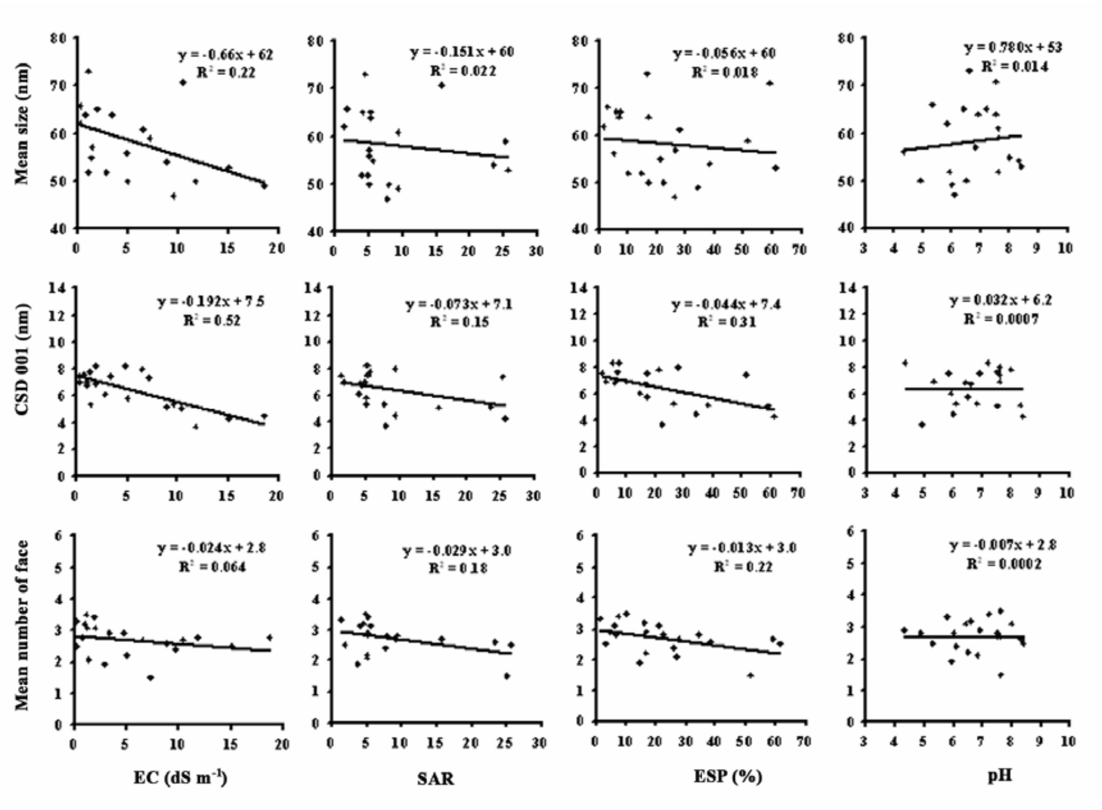


Figure 48 Values of EC, ESP, SAR, pH related to measures of the size and shape of kaolin crystal for salt affected soils in this study; (a) EC, ESP, SAR, pH related to mean size of kaolin crystals determine by TEM, (b) EC, ESP, SAR, pH related to crystal size (CSD001) determinde by XRD, (c) EC, ESP, SAR, pH related to the mean number of euhedral faces of kaolin crystals.