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# Properties and characterization of vertisols developed on limestone in a semi-arid environment

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Cracking soils, or vertisols, occupy a large and important part of the agricultural land in Jordan where rain-fed agriculture is practised. Six sites were selected in places where vertisols occur on limestone parent material, including different precipitation zones. The physico-chemical properties of these soils were studied in order to understand the genesis and behaviour of these soils. The climate is Mediterranean characterized by a hot dry summer and cool winter. Smectite/vermiculite, kaolinite, illite, palygorskite and quartz were the dominant clay minerals in the studied soils. The soils were subjected to different cycles of soil formation as follows: humid; arid to less humid; and to arid again.



Keywords: vertisols; smectite; semi-arid environment; calcareous; limestone parent material

## Introduction

Vertisols are soils with a high clay content that expand and contract markedly with changes in moisture content. These soils exhibit minimal horizon differentiation as a result of pedoturbation (Ahmad, 1983). They are also very plastic and sticky when wet. Clay content in vertisols may be as high as 80%, or as low as 30%. Vertisols exhibit open cracks at a depth of up to 50 cm that are at least 1 cm wide and extend upward to the surface or the base of the plough layer or surface crust (Soil Survey Staff, 1975). It was found that the average depth of cracks is inversely related to the moisture level in the soil. Also, width is affected by the length of the drying period, history of the soil and clay content (El-Abedine & Robinson, 1971).

Cracking soils, or vertisols, occupy a large and important part of the agricultural land in Jordan where rain-fed agriculture is practised (Taimeh & Khresat, 1988). This is because this type of soil is deep and occupies flat areas that receive more than 300 mm annual precipitation. Vertisols are typically developed on alluvial material in flat inland areas (Jenny, 1980). These soils occur in climatic zones with strongly contrasted seasonal climates, one of which is remarkably dry. During the wet winter season

 

(November–March) they are almost saturated, and become very dry and desiccated throughout the soil profile in the summer season (June–September).

Although these soils are considered among the most productive (Acquaye *et al.*, 1992), some of their physical properties such as the limited available water, shrink–swell movement and deep cracking, and compaction still pose a problem (Duchaufour, 1982).

Smectite and 'mixed layer' clays have been reported to comprise an important part of the clay fraction in most areas where vertisols have been studied. In Jordan, smectite dominated the clay minerals for basalt-derived soils, while smectite/vermiculite interstratified mineral dominated the clay minerals for limestone-derived soils (Taimeh & Khresat, 1988). Vertisols in Jordan were subjected to four episodes of climatic changes since deposition of the parent material. The four episodes, arranged chronologically, were: humid (40,000–20,000 years B.P.); arid (20,000–13,000 years B.P.); sub-humid (13,000–7000 years B.P.); and arid (7000 years B.P.–present) (Rognon & Williams, 1977).

The objectives of this study were to enhance our understanding of these soils; to measure those characteristics which have an impact on their agricultural utilization; to determine the genesis of these soils; and to classify these soils according to the USDA system.

## Materials and methods

Six sites were selected where vertisols occur on limestone parent material (Fig. 1). The sites represent the major areas for cereal production in Jordan. All of the study sites occur on the same landform (Highland Dissected Limestone Plateau), but under different precipitation zones. The climate is Mediterranean characterized by a hot dry summer and cool moist winter. Winter starts around mid November and summer around the beginning of May. Mean annual precipitation varies from one site to another (Table 1) and its distribution during the season varies greatly. Mean winter temperature varies from 6°C to 10°C, and mean summer temperature varies from 23°C to 27°C. Relative humidity varies from 43% in early summer to ~73% in winter (Meteorological Department, 1988). The soil temperature regime of the study area is thermic and the soil moisture regime is xeric to aridic (Xeric aridic transitional regime).

Samples were taken from soil-pit profiles after these profiles had been described according to Guthrie & Witty (1982). Particle-size distribution analyses was determined on natural unground samples using the method of Gee & Bauder (1986). Bulk density was determined on natural clods by the saran resin method (Brasher *et al.*, 1966). Organic matter was determined by the potassium dichromate method (Nelson & Sommers, 1982). Soil pH was determined on 1:1 soil:water extracts (McLean, 1982). Soluble salts were determined by measuring the electrical conductivity in 1:1 soil:water extracts (Rhoades, 1982). Extractable cations were determined by using the flame photometer and the versenate titration method (Thomas, 1982). Cation exchange capacity was determined according to the method of Polemio Rhoades (1977). Free iron oxides were measured using the orthophenathroline calorimetric method (Jackson, 1973). Calcium carbonate equivalent values were obtained by the acid neutralization method (Richards, 1954).

X-ray diffraction patterns were obtained for clay and silt fractions using Mg saturation, Mg saturation + ehtyleneglycol solvation for clay and silt fractions, and potassium saturation plus heating at 550°C for 4 h for the clay fraction only. Phillips X-ray diffraction apparatus, model PW II 3/90, was used to read the X-ray diffraction patterns (Jackson, 1973).

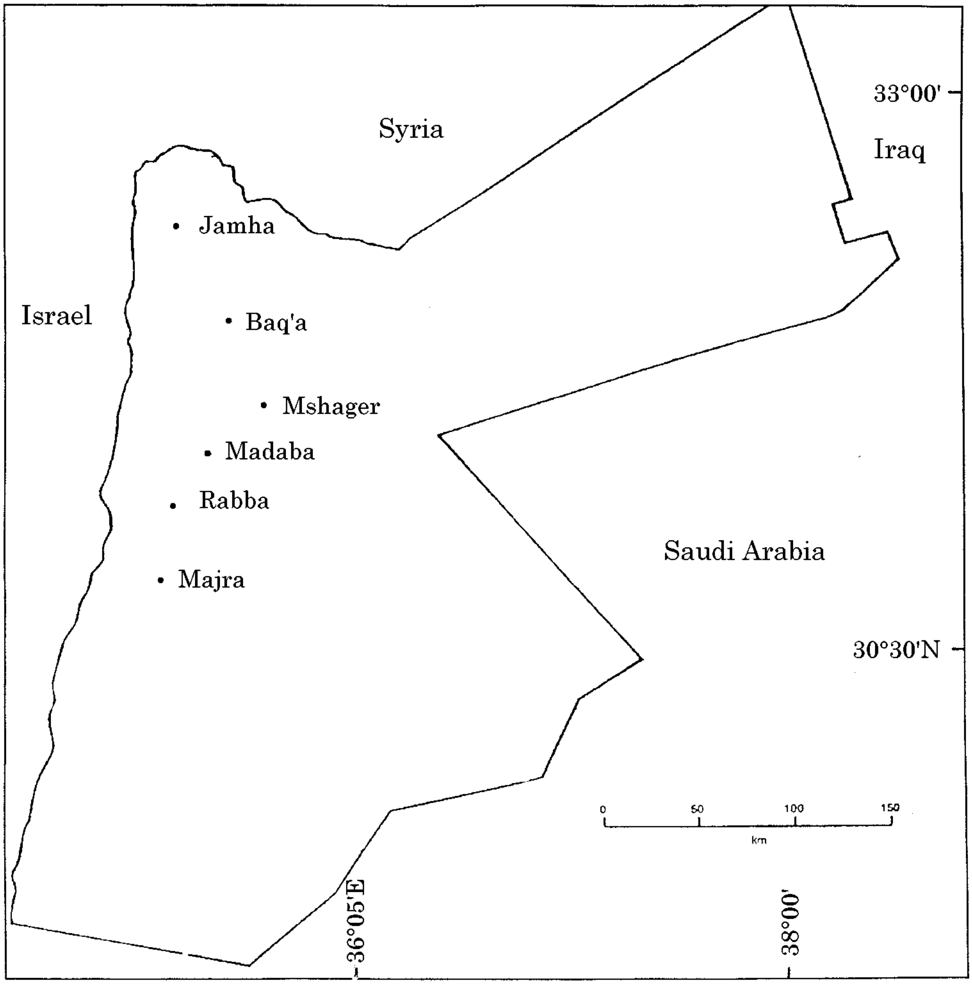


Figure 1. Location of the study sites.

## Results and discussion

The studied sites were calcareous since they are colluvium originating from limestone. The carbonate was mainly concentrated in the clay and silt fractions (Table 2). The carbonate distribution indicates that the carbonate is mainly concentrated in the silt fraction followed by clay in the surface horizons, and in subsurface soils most of the carbonate is concentrated in the clay fraction. There were higher accumulations of carbonate in the subsoil. Total carbonates in Jamha, Rabba and Majra soils were uniformly distributed throughout the soil profiles. Carbonate associated with the clay fraction increased with depth, indicating carbonate leaching. However, Mshager soil does not show this trend. This is attributed to the upland geomorphic position and low effective precipitation at this site. Carbonate associated with silt increased towards the surface, while carbonates associated with the sand fraction were uniformly distributed. Mshagar and Madaba soils' total carbonate remained uniform in the upper 100 cm; below that it increased with depth.

Soil pH values in all the studied soils increased gradually with depth (Table 3). This

Table 1. *Classification of studied soils, rainfall for the area and topography*

| Soil | USDA classification | Rainfall (mm year$^{-1}$) | Slope |
|---|---|---|---|
| Jamha | Very fine, smectitic, thermic, Typic Haploxerert | 500 | 1 |
| Rabba | Fine, smectitic, thermic, Entic Haploxerert | 300 | 1 |
| Majra | Fine, smectitic, thermic, Chromic Haploxerert | 300 | 2 |
| Mshager | Very fine, smectitic, thermic, Chromic Haploxerert | 370 | 1–2 |
| Madaba | Very fine, smectitic, thermic, Chromic Haploxerert | 300 | 1 |
| Baq'a | Very fine, smectitic, thermic, Chromic Haploxerert | 350 | 1–2 |

increase in pH with depth was attributed to the increase of carbonates for all these soils. High sodium content also contributed to higher pH values.

Overall maximum organic matter content for the surface horizons is 1·2% (Table 3). Organic matter content in Baq'a soil exceeded 1% for the surface horizon which meets the requirement of the mollic epipedon, but the churning nature is more significant, therefore it was classified as a vertisol.

Electrical conductivity values showed that the highest value was 0·64 ds m$^{-1}$ in Baq'a soil. The average electrical conductivity of the other soils was 0·22 ds m$^{-1}$ indicating that these soils are not saline. The electrical conductivity values increase with depth suggesting leaching (Table 2). These soils were probably subjected to higher leaching during humid past climates (Taimeh, 1984).

Calcium was the most dominant extractable cation followed by magnesium, sodium and potassium (Table 4). Extractable calcium in all the studied soils showed accumulation on the soil surface and decreased slightly with depth. Magnesium was uniformly distributed for most of the studied soils. Slight differences were found between surface and subsurface horizons. Extractable calcium and magnesium increased as rainfall increased. Extractable sodium increased with depth in all studied sites, and decreased as rainfall increased. Extractable sodium in Mshager and Baq'a soils was higher than other soils. This is attributed to the high clay content of these soils which restricts leaching. Extractable potassium behaved oppositely to extractable sodium, with surface horizons having higher extractable potassium. The increase in extractable potassium in the surface horizons could be related to the presence of illite minerals which are abundant in the silt fraction reflecting the dominance of rather aridic conditions. Moreover, extractable potassium increased as rainfall decreased.

The total soil cation exchange capacity in Rabba, Majra, Mshager and Madaba soils decreased slightly with depth. This could be due to the effect of organic matter. The cation exchange capacity for clay showed different values among soil horizons (Table 3). This variation is attributed to the different amounts of dominant clay minerals resulting from illuviation.

Clay contents in Rabba, Jamha and Majra soils increased with depth (Table 5). The difference in clay content between surface and subsurface soils does not account for the presence of an argillic horizon. Silt content increased towards the soil surface indicating

Table 2. *Carbonate distribution* (%) *in the studied profiles*

| Horizon | Depth (cm) | Carbonate distribution (%) | | | | |
|---|---|---|---|---|---|---|
| | | Coarse sand | Very fine sand | Silt | Clay | Total |
| Jamha soil | | | | | | |
| Ap | 0–20 | 0·1 | 0·1 | 1·8 | 1·7 | 3·7 |
| Bw | 20–50 | 0·1 | 0·1 | 0·6 | 1·9 | 2·4 |
| Bss1 | 50–95 | 0·1 | 0·1 | 1·7 | 2·1 | 3·7 |
| Bss2 | 95–135 | 0·1 | 0·1 | 1·1 | 2·7 | 3·7 |
| Rabba soil | | | | | | |
| Ap | 0–20 | 0·2 | 0·6 | 15·8 | 5·6 | 22·0 |
| Bw | 20–60 | 0·2 | 0·4 | 12·7 | 9·0 | 22·0 |
| Bss1 | 60–120 | 0·3 | 0·5 | 13·6 | 6·2 | 23·2 |
| Bss2 | 120–160 | 0·1 | 0·5 | 7·5 | 14·8 | 22·0 |
| Majra soil | | | | | | |
| Ap | 0–15 | 0·2 | 0·2 | 7·5 | 3·7 | 11·0 |
| Bw | 15–50 | 0·2 | 0·2 | 6·2 | 4·3 | 11·0 |
| Bss1 | 50–110 | 0·2 | 0·2 | 10·2 | 7·9 | 12·2 |
| Bss2 | 110–150 | 0·2 | 0·2 | 5·2 | 9·0 | 14·6 |
| Mshagar soil | | | | | | |
| Ap | 0–20 | 0·4 | 0·1 | 8·2 | 8·2 | 18·3 |
| Bw | 20–60 | 0·1 | 0·3 | 9·3 | 8·6 | 18·3 |
| Bss1 | 60–110 | 0·3 | 0·4 | 12·1 | 4·2 | 19·5 |
| Bss2 | 110–160 | 0·1 | 0·3 | 11·1 | 9·6 | 22·0 |
| Madaba soil | | | | | | |
| Ap | 0–30 | 0·1 | 0·4 | 7·5 | 8·0 | 17·1 |
| Bw1 | 30–90 | 0·1 | 0·4 | 8·0 | 8·4 | 17·1 |
| Bw2 | 90–130 | 0·1 | 0·3 | 7·1 | 10·5 | 18·3 |
| Bss | 130–160 | 0·1 | 0·6 | 15·6 | 7·9 | 24·4 |
| Baq’a soil | | | | | | |
| Ap | 0–40 | 0·2 | 0·3 | 10·0 | 12·6 | 23·2 |
| Bw | 40–100 | 0·2 | 0·1 | 6·9 | 15·4 | 22·0 |
| 2Bss1 | 100–170 | 0·2 | 0·2 | 11·6 | 12·9 | 24·4 |
| 2Bss2 | 170–210 | 0·2 | 0·2 | 7·7 | 11·9 | 19·5 |
| 3Bssk1 | 210–270 | 0·1 | 0·1 | 2·4 | 14·7 | 17·1 |
| 3Bssk2 | 270–350 | 0·2 | 0·1 | 1·9 | 12·6 | 14·6 |

accumulation of silt on the surface, and this is attributed to increased aeolian activity. Sand fractions were uniformly distributed throughout the soil profiles. Clay and silt content for Baq’a soil was uniformly distributed in the upper 100 cm, afterwhich it decreased and remained uniform to a depth of 210 cm. Below this depth, clay increased and remained uniform to a depth of 350 cm. This suggested that this soil can be divided into three zones, each one belonging to a different depositional environment.

Bulk density increased with depth for all the studied soils (Table 5). The minimum bulk density was observed at Ap horizon. This might be due to the effect of organic matter and loosening of the soil material. The increase in bulk density with depth is attributed to lower organic matter, more compaction and less aggregation. Coefficient

Table 3. *Selected chemical properties of the studied soils*

| Horizon | Depth (cm) | pH | OM (%) | CEC (cmol(+) kg$^{-1}$) | Fe oxide (%) | EC (ds m$^{-1}$) |
|---|---|---|---|---|---|---|
| Jamha soil | | | | | | |
| Ap | 0–20 | 7·5 | 0·8 | 56 | 2·3 | 0·25 |
| Bw | 20–50 | 7·7 | 0·7 | 55 | 2·1 | 0·19 |
| Bss1 | 50–95 | 7·8 | 0·5 | 53 | 2·3 | 0·16 |
| Bss2 | 95–135 | 7·8 | 0·4 | 54 | 1·9 | 0·21 |
| Rabba soil | | | | | | |
| Ap | 0–20 | 7·9 | 0·4 | 41 | 2·9 | 0·20 |
| Bw | 20–60 | 7·9 | 0·4 | 39 | 3·1 | 0·16 |
| Bss1 | 60–120 | 8·0 | 0·3 | 45 | 2·9 | 0·19 |
| Bss2 | 120–160 | 8·0 | 0·1 | 36 | 2·5 | 0·21 |
| Majra soil | | | | | | |
| Ap | 0–15 | 7·9 | 0·6 | 42 | 3·1 | 0·13 |
| Bw | 15–50 | 7·9 | 0·6 | 43 | 3·4 | 0·17 |
| Bss1 | 50–110 | 8·0 | 0·5 | 39 | 3·3 | 0·17 |
| Bss2 | 110–150 | 7·9 | 0·3 | 38 | 2·7 | 0·21 |
| Mshagar soil | | | | | | |
| Ap | 0–20 | 7·8 | 0·6 | 43 | 2·7 | 0·15 |
| Bw | 20–60 | 7·9 | 0·4 | 42 | 2·5 | 0·18 |
| Bss1 | 60–110 | 8·0 | 0·2 | 48 | 2·7 | 0·19 |
| Bss2 | 110–160 | 8·1 | 0·2 | 38 | 2·7 | 0·18 |
| Madaba soil | | | | | | |
| Ap | 0–30 | 7·9 | 0·6 | 48 | 2·7 | 0·13 |
| Bw1 | 30–90 | 8·1 | 0·4 | 40 | 2·5 | 0·16 |
| Bw2 | 90–130 | 8·1 | 0·3 | 37 | 3·3 | 0·17 |
| Bss | 130–160 | 8·1 | 0·2 | 36 | 3·3 | 0·19 |
| Baq'a soil | | | | | | |
| Ap | 0–40 | 7·6 | 1·2 | 44 | 3·4 | 0·44 |
| Bw | 40–100 | 8·1 | 0·4 | 38 | 3·1 | 0·47 |
| 2Bss1 | 100–170 | 8·2 | 0·5 | 40 | 3·3 | 0·55 |
| 2Bss2 | 170–210 | 8·2 | 0·2 | 40 | 3·6 | 0·42 |
| 3Bssk1 | 210–270 | 8·2 | 0·2 | 42 | 4·2 | 0·32 |
| 3Bssk2 | 270–350 | 8·2 | 0·2 | 45 | 4·0 | 0·64 |

OM = organic matter; CEC = cation exchange capacity; EC = electrical conductivity.

of linear extensibility (COLE) values exceeded 0·09 in all the studied soils reflecting a high shrink–swell potential.

X-ray diffraction analysis indicated the presence of the following minerals, arranged in descending order of abundance: smectite/vermiculite, illite, palygorskite and quartz. The degree of interlayering increased with depth. Illite content decreased with depth. Kaolinite, however, decreased with depth except for vertisols occurring within the 350–400 mm rainfall zone where it was uniformly distributed with depth. Quartz, plagioclase, kaolinite, palygorskite vermiculite/illite and smectite/vermiculite were identified in the silt fraction of the surface horizons. The presence of palygorskite and plagioclase at the surface indicates the weakness of chemical weathering and is

Table 4. *Extractable cations of the studied soils*

| Horizon | Depth (cm) | Ca | Mg | K | Na |
|---|---|---|---|---|---|
| | | cmol(+) kg$^{-1}$ | | | |
| Jamha soil | | | | | |
| AP | 0–21 | 46·9 | 8·8 | 0·6 | 0·5 |
| Bw | 21–85 | 48·0 | 9·9 | 0·3 | 0·6 |
| Bss1 | 85–133 | 47·6 | 6·3 | 0·4 | 0·7 |
| Bss2 | 133–175 | 46·9 | 8·8 | 0·3 | 0·9 |
| Rabba soil | | | | | |
| AP | 0–20 | 44·9 | 5·7 | 0·9 | 0·4 |
| Bw | 20–50 | 39·1 | 7·7 | 0·5 | 0·5 |
| Bss1 | 50–95 | 39·1 | 6·2 | 0·4 | 0·8 |
| Bss2 | 95–135 | 46·2 | 7·0 | 0·5 | 1·2 |
| Majra soil | | | | | |
| AP | 0–15 | 45·0 | 5·7 | 0·8 | 0·4 |
| Bw | 15–50 | 46·8 | 6·6 | 0·4 | 0·5 |
| Bss1 | 50–110 | 47·0 | 6·7 | 0·4 | 0·8 |
| Bss2 | 110–150 | 47·4 | 7·0 | 0·4 | 1·2 |
| Mshagar soil | | | | | |
| AP | 0–20 | 46·4 | 8·4 | 1·3 | 0·8 |
| Bw | 20–60 | 46·8 | 9·0 | 0·6 | 0·4 |
| Bss1 | 60–110 | 46·9 | 9·7 | 0·5 | 0·8 |
| Bss2 | 110–160 | 47·3 | 9·0 | 0·5 | 1·2 |
| Madaba soil | | | | | |
| AP | 0–30 | 46·4 | 8·6 | 1·4 | 0·3 |
| Bw1 | 30–90 | 46·4 | 9·2 | 0·7 | 0·5 |
| Bw2 | 90–130 | 46·9 | 10·2 | 0·8 | 0·8 |
| Bss | 130–160 | 46·9 | 10·6 | 0·7 | 0·8 |
| Baq'a soil | | | | | |
| AP | 0–40 | 46·5 | 9·4 | 3·6 | 0·8 |
| Bw | 40–100 | 46·9 | 10·6 | 0·8 | 2·9 |
| 2Bss1 | 100–170 | 46·3 | 10·5 | 0·9 | 4·8 |
| 2Bss2 | 170–210 | 46·2 | 10·9 | 1·0 | 5·3 |
| 3Bssk1 | 210–270 | 47·1 | 11·8 | 1·0 | 5·4 |
| 3Bssk2 | 270–350 | 46·6 | 11·3 | 1·0 | 5·5 |

attributed to aeolian activities.

The high degree of clay interlayering with depth is attributed to weathering in a previous climate, since the prevailing climate allows only limited weathering and leaching. The presence of some minerals, such as palygorskite, illite and plagioclase, especially at the surface, suggests that these minerals were transported by wind.

## Soil genesis and classification

The results obtained from physical, chemical and mineralogical analysis were used to produce a conceptual model of vertisols development derived from limestone of the

Table 5. *Particle-size distribution (carbonate free), bulk density and coefficient of linear extensibility (COLE) values of the studied soils*

| Horizon | Depth (cm) | Carbonate free (%) | | | | | Bulk density | | COLE |
|---|---|---|---|---|---|---|---|---|---|
| | | CI | Si | Vfs | Fs | Cs | Dry | Moist | |
| Jamha soil | | | | | | | | | |
| AP | 0−20 | 62·3 | 36·7 | 0·7 | 0·1 | 0·2 | 1·65 | 1·25 | 0·10 |
| Bw | 20−50 | 67·1 | 32·1 | 0·5 | 0·1 | 0·2 | 1·72 | 1·30 | 0·10 |
| Bss1 | 50−95 | 63·9 | 32·7 | 0·4 | 0·1 | 2·9 | 1·82 | 1·32 | 0·11 |
| Bss2 | 95−135 | 66·5 | 32·8 | 0·4 | 0·1 | 0·2 | 1·70 | 1·32 | 0·09 |
| Rabba soil | | | | | | | | | |
| AP | 0−20 | 32·7 | 64·0 | 3·0 | 0·2 | 0·1 | 1·80 | 1·49 | 0·07 |
| Bw | 20−60 | 35·9 | 61·0 | 2·5 | 0·3 | 0·3 | 1·87 | 1·42 | 0·10 |
| Bss1 | 60−120 | 38·4 | 58·1 | 2·9 | 0·4 | 0·2 | 1·88 | 1·45 | 0·09 |
| Bss2 | 120−160 | 63·5 | 33·3 | 3·0 | 0·1 | 0·1 | 1·92 | 1·48 | 0·09 |
| Majra soil | | | | | | | | | |
| AP | 0−15 | 34·8 | 60·1 | 3·8 | 0·5 | 0·8 | 1·93 | 1·38 | 0·12 |
| Bw | 15−50 | 36·5 | 48·3 | 3·6 | 0·5 | 1·1 | 1·85 | 1·40 | 0·10 |
| Bss1 | 50−110 | 39·9 | 55·4 | 3·0 | 0·4 | 1·3 | 1·89 | 1·40 | 0·11 |
| Bss2 | 110−150 | 50·9 | 45·0 | 2·5 | 0·4 | 1·2 | 1·84 | 1·37 | 0·10 |
| Mshgar soil | | | | | | | | | |
| AP | 0−20 | 55·1 | 42·1 | 2·4 | 0·2 | 0·2 | 1·78 | 1·30 | 0·11 |
| Bw | 20−60 | 60·6 | 36·8 | 2·0 | 0·1 | 0·5 | 1·82 | 1·31 | 0·12 |
| Bss1 | 60−110 | 62·1 | 34·9 | 2·4 | 0·4 | 0·2 | 1·88 | 1·38 | 0·11 |
| Bss2 | 110−160 | 46·2 | 50·9 | 2·1 | 0·2 | 0·6 | 1·91 | 1·42 | 0·10 |
| Madaba soil | | | | | | | | | |
| AP | 0−30 | 60·9 | 36·7 | 2·1 | 0·1 | 0·2 | 1·63 | 1·18 | 0·11 |
| Bw1 | 30−90 | 63·3 | 34·0 | 2·5 | 0·1 | 0·1 | 1·71 | 1·36 | 0·08 |
| Bw2 | 90−130 | 67·9 | 29·3 | 2·5 | 0·1 | 0·2 | 1·73 | 1·35 | 0·09 |
| Bss | 130−160 | 39·7 | 57·6 | 2·4 | 0·2 | 0·1 | 1·83 | 1·41 | 0·09 |
| Baq'a soil | | | | | | | | | |
| AP | 0−40 | 66·4 | 31·2 | 1·6 | 0·6 | 0·2 | 1·59 | 1·23 | 0·09 |
| Bw | 40−100 | 66·0 | 31·7 | 1·3 | 0·5 | 0·5 | 1·75 | 1·29 | 0·11 |
| 2Bss1 | 100−170 | 48·9 | 48·7 | 1·3 | 0·6 | 0·5 | 1·79 | 1·31 | 0·11 |
| 2Bss2 | 170−210 | 48·3 | 49·3 | 1·2 | 0·6 | 0·6 | 1·88 | 1·35 | 0·12 |
| 3Bssk1 | 210−270 | 70·6 | 26·7 | 1·3 | 0·7 | 0·7 | 1·65 | 1·29 | 0·09 |
| 3Bssk2 | 270−350 | 72·6 | 23·4 | 1·6 | 1·2 | 1·2 | 1·72 | 1·27 | 0·11 |

Vfs = very fine sand; Fs = fine sand; Cs = coarse sand.

upper cretaceous age. The following sequence gives the chronological sequence of development. *Stage 1:* this stage proceeded when the parent material was subjected to strong chemical weathering in a humid climate characterized by high rate of clay formation. The high clay content, which originated from limestone, might be considered as sufficient evidence for intensive weathering. Also, the occurrence of carbonate concretion in the subsurface of the studied soils is indicative of a wetter climate. *Stage 2:* climate shifted from humid to arid. Intensive colluvial activity signified this stage. This is substantiated by the occurrence of rounded edge limestone gravels in the lower parts of the studied soils. *Stage 3:* climate shifted again to humid, but it was less humid than the first stage. This was indicated by the relatively low clay content in the upper solum of the studied soils. Also, leaching of carbonates associated with the clay fraction was active during this stage. *Stage 4:* climate changed gradually towards aridic. The arid climate initiated the accumulation of calcareous silt in the surface horizons and the occurrence of quartz, illite, plagioclase and palygorskite in silt fraction on the surface horizons.

The chronological sequence of development for the studied soils is in accordance with the results of a paleoclimatic study by Taimeh (1984).

All of the studied soils were classified according to the USDA soil classification system (Table 1).

## Summary and conclusions

Gilgai microrelief was absent in all the studied soils. The parallel-ped structure was present in all the studied soils. All the sites were classified as vertisols. The limit between Chromic Haploxerert and Typic Haploxerert was rainfall of 450 mm year$^{-1}$.

Climate played a significant role in the development of these soils. These soils were subjected to different cycles of soil formation as follows: humid; arid to less humid; and to arid again.

Jamha and Baq'a soils probably were subjected to more intensive chemical weathering than other soils. This is attributed to the landscape position for Baq'a soil and higher precipitation for Jamha soil. Mshager and Madaba soils had a similar pattern of soil development as those mentioned above, except that these soils consist of two solum separated at the depth of 110 cm and 130 cm, respectively.

Many workers in soil genesis and classification consider these soils as young and immature. However, based on the different pedogenic processes that took place in these vertisols, it is believed that soils should not be considered as such.

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