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EVALUATION OF TILTH IN DEEP PLOWED SOLONETZIC AND RELATED SOILS

by

GARY D. BUCKLAND

A THESIS

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Date October 14, 1983

ABSTRACT

Morphological, micromorphological and analytical features of deep plowed Solonetzic and related soils were evaluated at several locations in east-central Alberta. Emphasis was placed on tilth related features of Ap horizons.

The majority of soils examined were classified in the Solonetz order. Where relief was hummocky, however, a substantial portion of the soils observed were Chernozemic. In most instances the Ap horizon of the normally tilled soils was granular in structure and fell into the mullgranic/mullgranoidic fabric sequence. At one location the Ap horizon was mullgranoidic iunctic in composition. Eluvial horizons, where present, exhibited banded fabrics. Transitional AB horizons exhibited blocky structures and, micromorphologically, were porphyroskelic with insepic plasma separations. Humified organic matter was frequently observed in the AB horizons and may be a relic of previous Na-humate translocation or may reflect current humification of this zone. B horizons were typically porphyroskelic with a variety of observed plasma fabrics: mosepic, masepic or skelsepic plasma separations, or a combination of the three were predominant within the s-matrix. A tendency towards higher plasma concentrations with depth suggests solodization is occurring in the upper B horizons. The blocky mesostructure of the B horizons was reflected in the observation of craze, skew and joint planes separating adjacent units.

Deep plowing resulted in redistribution of genetic materials and created a unique soil fabric in the Ap horizon. Mullgranic/ mullgranoidic material was mixed with porphyroskelic material to produce mixed complex mullgranoidic/porphyroskelic fabrics to minimum depths of 75 mm. At greater depths intact zones of the two modal fabrics were observed.

The new fabric in the Ap horizons of the deep plowed soils has many characteristics distinctly different from the soil fabric present in the normally tilled soils. Inclusion of the porphyroskelic B horizon material was reflected in higher values of Ca^{2+}, Mg^{2+} and Na^{+}, particularly in the Solonetzic soils examined. Exchange acidity and soil reaction were appreciably altered by deep plowing. Total C and total N were significantly lower in the deep plowed Ap horizons. The deep plowed Ap horizons had higher total clay and fine clay contents with the increase in both these constituents primarily reflecting an increase in the smectite component of the phyllosilicates.

Tilth related properties were altered by deep plowing. Modulus of rupture was significantly higher in the deep plowed Ap horizons at sites dominated by Solonetzic soils. Mean weight diameter and aggregate stability generally decreased upon deep plowing. The plastic limit was significantly lower on the deep plowed soils which resulted in an increased plasticity index.

Response of various crops to deep plowing was evaluated on the various geomorphic soil sequences observed. Response of wheat, oats and barley was generally positive at all locations, however, the degree of response was greater where Solonetzic soils dominated the landscape. A higher soil reaction and reduced exchange acidity is implicated in crop response phenomenon; other chemical criteria were generally inadequate in explaining crop response. Changes in the soil-water-plant regime are implicated in contributing to crop response, however, this area requires further research under Alberta dryland conditions.

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1. INTRODUCTION

Deep plowing evolved as a means for improving the productivity of Solonetzic soils during the 1950's in the USSR (Botov, 1959) and shortly thereafter the practice was transferred to North America (Cairns, 1962; Pair and Lewis, 1960). Since the mid-1970's deep plowing has been widely used in parts of Alberta, primarily on a test basis, to evaluate its feasibility for widespread use (Hermans, 1981).

Many studies have been conducted on deep plowed Solonetzic soils in North America, most of which revolve around elucidating mechanisms or factors contributing to crop response. Improved soil-water-plant relationships are implicated in crop response phenomenon (Cary _et al._, 1967; Eck and Taylor, 1969; Mech _et al._, 1967; Rasmussen _et al._, 1972) as are changes in soil chemical constituents (Cairns, 1972a, 1972b; Harker _et al._, 1977; Lavado and Cairns, 1980). Criteria used thus far, however, appear to have met with limited success in predicting crop response.

In Europe several criteria are used to evaluate the ameliorative potential and methods of ameliorating Solonetzic soils. Criteria are primarily morphometric and analytical in nature, but in all instances they reflect the soil classification system under use (Obrejanu and Sandu, 1971; Pak, 1971; Szabolcs, 1967, 1971). In essence they observe the evolutionary stage (and thus classification) of a soil, evaluate it in terms of their knowledge of the evolutionary sequence, and make recommendations on this basis.

A portion of this study is devoted to an analysis of the geomorphic soil sequence present, as evaluated by morphological, micromorphological and chemical techniques. The sum of these properties, namely the classification of the soil(s), is believed to be related to crop response upon deep plowing. Thus, a portion of this study is also devoted to an analysis of crop response to deep plowing, as related to the geomorphic soil sequence present.

Studies conducted thus far on deep plowed Solonetzic soils indicate relatively pronounced changes may occur within the Ap horizons. Frequently, an undesirable physical condition (poor tilth) is encountered (Bowser and Cairns, 1967; Cairns, 1976a; Lavado and Cairns, 1980): conditions which are potentially deleterious to crop growth. Several authors (Cairns, 1976a; Mech _et_ _al_., 1967) point out the importance of developing management practices designed to cope with, or improve, the resultant physical condition in the seedbed of deep plowed soils. A portion of this study is further devoted to characterization of physical properties of deep plowed Ap horizons, as they reflect soil tilth. Although tilth is expressed in terms of physical conditions, chemical and mineralogical characteristics may also influence the tilth of a soil. Thus, chemical and mineralogical characteristics and their relationship to physical conditions are also evaluated.

2. AN OVERVIEW OF SOLONETZIC SOILS

2.1 Genesis of Solonetzic Soils

Classical theories on the genesis of Solonetzic soils were advanced by Gedroits (1912, as cited by Pawluk, 1982) and de Sigmond (1938) and since have been refined by many researchers. Three classical processes have been identified; namely salinization, solonization and solodization. Although not necessarily exclusive of one another, these processes form a convenient basis for explaining Solonetz forming processes (Pawluk, 1982). Figure 1 is a schematic representation of profiles and processes in the Solonetz evolutionary sequence.

2.1.1 Salinization

Solonetzic soils are believed to have developed from parent material which became salinized through the influence of shallow groundwater. Salinization likely occurred during the recession of the last Wisconsin glaciation, as excess meltwater gave rise to fairly extensive groundwater flow systems (Pawluk, 1978). Within most Solonetzic areas, groundwater flow is through sedimentary deposits of marine or brackish origin which are generally overlain by thin morainal deposits (Odynsky, 1945). Providing the flow systems are fairly extensive and deep (intermediate or regional flow systems, as defined by Toth, 1963) large quantities of salt are dissolved and transported along the flow path. Groundwater composition is variable, however, in extensive flow systems Na^+ and SO_4^{2-} tend to predominate in discharge areas (Cheboratev, 1955; Le Breton and Jones, 1963; Pawluk, 1978).

Groundwater response to anistropy and/or hydraulic pressure

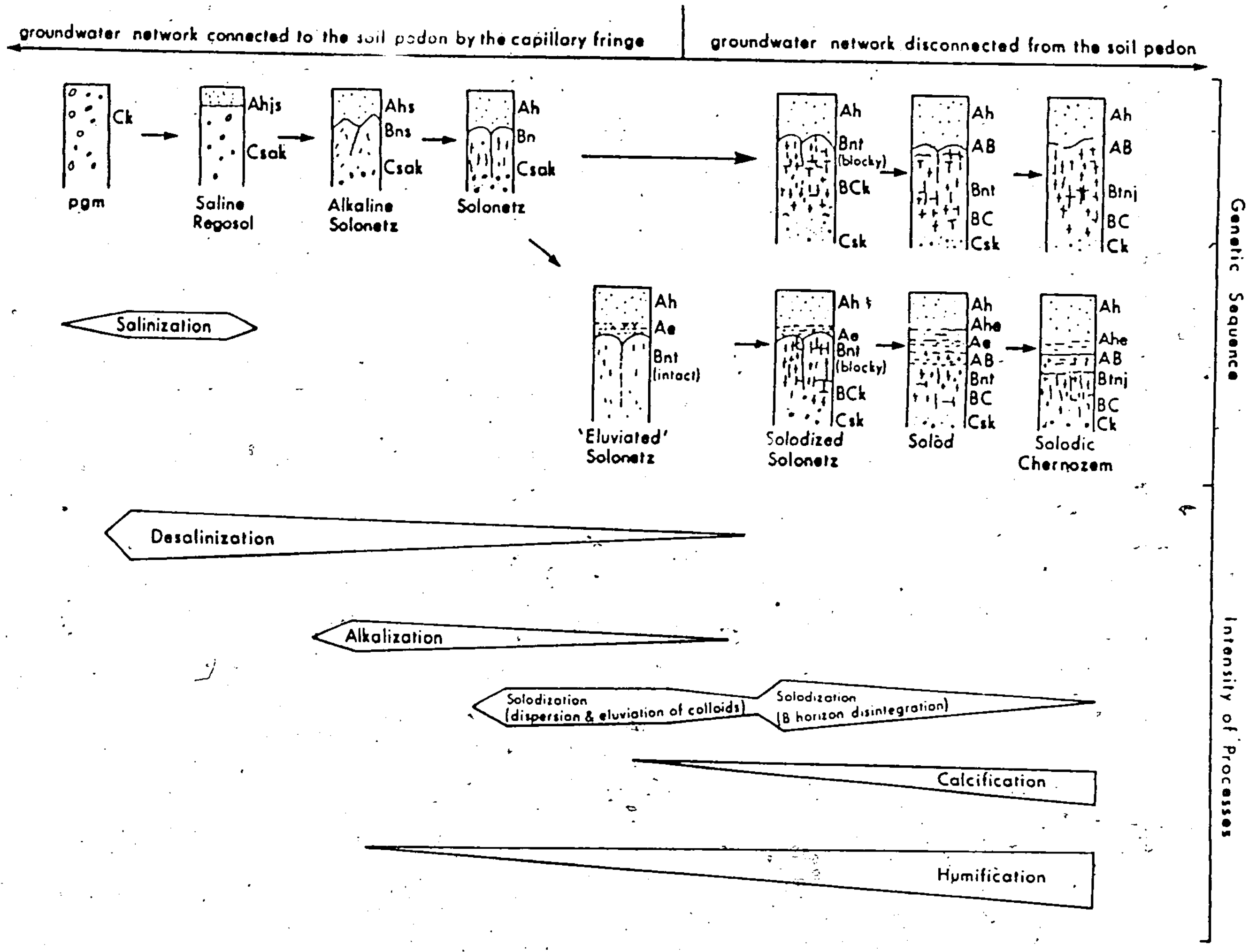


Figure 1. Processes and evolutionary sequence of Solonetzic soils (From Pawluk 1982).

within the flow media results in discharge of saline groundwater at or near the soil surface. Continued hydraulic discharge or upward capillary movement driven by evaporation results in concentration of salts at the ground surface.

2.1.2 Solonization

Pawluk (1982) lists three prerequisites for Solonetzic soils to form from an initially salinized parent material:

(1) The accumulated soluble salts must contain an appreciable amount of Na^+.

(2) Expansible clay minerals must be present in sufficient quantities.

(3) Desalinization must occur gradually.

De Sigmond (1938) first postulated that exchangeable Na^+ levels must be 12 to 15% or more of the total exchangeable cations for the formation of Solonetzic soils. Levels of exchangeable Na^+ as low as 7% (Dahlman, 1965) and 5 to 8% (Szabolcs, 1965) may affect the colloidal activity of clays. Exchangeable Mg^{2+} has been observed in high levels in Solonetzic soils with otherwise uniformly low exchangeable Na^+ (Bentley and Rost, 1947; Ehrlich and Smith, 1958; Ellis and Caldwell, 1935; Kelley, 1934; Kellogg, 1934; Mitchell and Riechen, 1937; Reeder and Odynsky, 1964; and others), however, the exact role of Mg^{2+} is at present controversial. Regardless of which cations are involved, they must adversely affect the stability of the clay-water system.

The effect which various cations have on the clay-water system is largely dependent upon the suite of clay minerals present. Expansible phyllosilicates are particularly susceptible to swelling and dispersion under the influence of Na^+. At low electrolyte concentrations and low to moderate ESP levels (10 to 30%) montmorillonite and vermiculite are particularly susceptible to dispersion and movement relative to kaolinite (Frenkel et al., 1978). Smectite minerals are commonly high and frequently the dominant phyllosilicates in parent materials and/or Solonetzic soils in Alberta (Arshad and Pawluk, 1966b; Brunelle et al., 1976; Dudas and Pawluk, 1982; Pawluk and Bayrock, 1969), in the northwestern United States (Sandoval and Reichman, 1971) and in the USSR (Travnikova, 1976). Although expansible phyllosilicates sufficiently high in exchangeable Na^+ may be present, dispersion and particle migration is minimal in the presence of soil solution high in electrolyte (Frenkel et al., 1978; McNeal et al., 1966; Rowell, 1963; Rowell et al., 1969); hence, the requirement for desalinization.

Desalinization is thought to have occurred as a result of two concurrent processes, namely, improved drainage through the development of integrated sinks and a shift towards a more humid climate (Pawluk, 1982). The former reduces the degree of influence of saline groundwaters while the latter reduces upward capillary salt flux and promotes leaching.

With these three prerequisites met the stage for solonization is set. As downward leaching continues the electrolyte concentration becomes sufficiently low to promote clay dispersion and translocation. The critical electrolyte level where clay disperses is highly dependent upon both the mineralogical composition and exchangeable cation suite. De Sigmond (1938) reports total salt levels from 0.10 to 0.15% will result in dispersion if ESP is in the range of 12 to 15%. Rowell et al. (1969) report electrolyte concentrations from 10^{-1} to 10^{-3} moles/L for ESP's ranging from 70 to 50%, respectively, will result in suspension dispersion of montmorillonitic soils.

Concurrent with dispersion is alkaline hydrolysis, according to the following reaction (Barshad, 1960):

$$\text{Na-clay} + \text{HOH} \rightleftharpoons \text{H-clay} + \text{NaOH}$$

$$\text{NaOH} + \text{CO}_3^{2-} \rightleftharpoons \text{Na}^+ + \text{HCO}_3^-$$

Under the resultant alkaline environment dissolved and peptized organic matter is leached along with clays to form a dark stained, columnar B horizon.

Maintenance of relatively high Na^+ concentrations in the soil solution and on the exchange complex will continue to promote dispersion and eluviation/illuviation. Sodium, however, is preferentially leached relative to other common cations such that some mechanism must be present to reintroduce Na^+ and maintain a dispersed soil system. Gradual desalinization is believed responsible for repeated Na^+ recharge into the upper solum. Assuming continuity is maintained between the water table and the soil surface, Na^+ will accumulate during dry periods of high matric potential at the soil surface (due to evapotranspiration or freezing), while Na^+ and clays will be leached during periods of high precipitation (Szabolcs, 1971; Landsburg, 1981). Under such conditions strong eluvial/illuvial features may develop.

2.1.3 Solodization

Solodization, or the breakdown of the B horizon, is thought to occur as a consequence of diminishing groundwater influence within the soil solum. This may result from a continued drop in the water table and/or textural differences between Ae and Bnt horizons which reduce the potential for capillary rise of saline groundwaters (de Sigmond, 1938; Landsburg, 1981; Szabolcs, 1971). In either case disconnection of groundwater from the upper solum reduces the amount of Na^+ recharged thereby increasing net leaching of Na^+.

After Na^+ removal becomes significant alkaline hydrolysis decreases in intensity and alkaline products are leached. A mildly acidic chemical regime develops (de Sigmond, 1938) which is more favourable to vegetative growth. Increased vegetative growth intensifies Ca^{2+} cycling from lower in the solum to the soil surface (calcification, Pawluk and Dumanski, 1969). This further enhances Na^+ removal. Humification of the surface horizon(s) is concurrent with increased vegetative growth (Pawluk and Dumanski, 1969).

Calcification and humification gradually result in (Bowser, 1961; Pawluk and Dumanski, 1969; de Sigmond, 1938):

(1) Breakdown of the columnar structure and development of a blocky mesostructure.

(2) Humification of eluvial horizons, if present.

(3) Gradual thickening of the A horizon at the expense of the B horizon.

(4) Development of a transitional AB horizon in place of the top of the weathered Bnt horizon.

The degree of expression of any of the above features will depend upon the amount of solodization that has taken place; that is, consideration for the length of time as well as the overall intensity. The soil thus evolves through the Solodized Solonetz→Solod→Solonetzic Chernozem sequence as groundwater influence decreases, desalinization continues and calcification and humification increase in intensity.

2.2 Properties of Solonetzic Soils

There are a number of stages which may be observed within the evolutionary sequence of Solonetzic soils, with each stage expected to reflect somewhat different properties. This, combined with a variety of parent materials from which Solonetz soils form results in a diverse array of morphological, physical, chemical and physicochemical properties. Only a brief account of properties is given here. More detailed accounts of various features are outlined in subsequent chapters.

2.2.1 Morphological Features

A unifying feature common to all Solonetzic soils is the Solonetz B horizon. This horizon generally has a columnar or prismatic structure and may have a blocky mesostructure. When dry it is hard to extremely hard and when wet it is plastic and sticky (Can. Soil Surv. Comm., 1978). Ped surfaces are frequently stained with illuvial Na-humates. Rooting patterns tend to be exped unless the soil is in an advanced stage of solodization (Bowser, 1961).

Morphological features of the A horizon are diverse. Thickness is highly variable and to a large extent is governed by groundwater conditions and relief. Shallow groundwater tables and steep slopes result in thin A horizons by limiting the depth of pedogenic processes and by soil removal through erosion, respectively. Mull Ah horizons with granular structure and soft or friable consistence are present in parkland and grassland ecosystems except on severely eroded soils. Platy Ae horizons with soft consistence are frequently encountered. Horizon boundaries between Ae and Bnt horizons are commonly abrupt.

Transitional AB horizons are usually present in the latter stages of development. Colours of the AB are similar to the overlying Ae while structure is generally similar to the blocky mesostructure observed in the Bnt below.

C horizons are massive and saline. Carbonates, salt crystals and gypsum rosettes are normally, though not always, encountered.

2.2.2 Chemical Properties

Since Solonetzic soils were at one time salinized, soluble salt content is generally higher than in associated Chernozemic soils. Distribution of salts with depth depends upon the balance between rate of leaching and groundwater introduction. As solodization proceeds the depth to which salts are leached increases (Bowser, 1961); hence, the depth to a saline horizon generally increases (within a given climatic zone) through the sequence Solonetz Solodized Solonetz Solod. Bowser et al. (1962) report low electrical conductivity (EC) values in A and B horizons of Solods and Chernozemic soils, with somewhat higher EC values in the B horizons of Solonetz and Solodized Solonetz soils (see Figure 2). Higher EC values were also found in the C horizons of the Solonetzic soils as compared with the associated Chernozemic soils. Similar findings have been reported elsewhere (Arshad and Pawluk, 1966a; Bentley and Rost, 1947; Landsburg, 1981; MacLean and Pawluk, 1975; Sandoval and Reichman, 1971).

Qualitative differences in the soil chemical suite are also presnt in different horizons at different genetic stages. Both soluble and exchangeable Na^+ increase with depth in Solonetzic soils (Figures 3 and 4, respectively). Maximum accumulation of soluble Na, relative to other

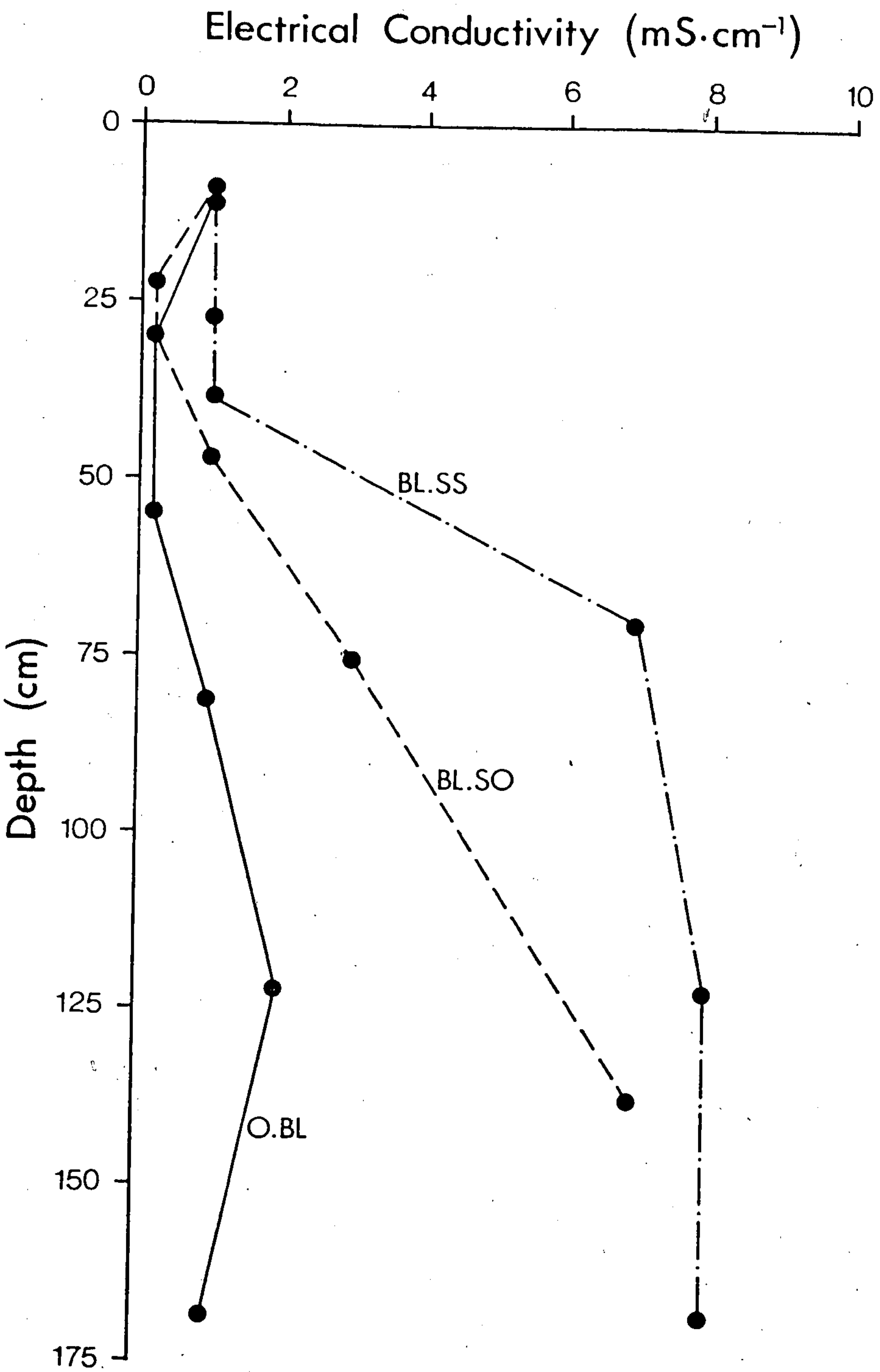


Figure 2. Distribution of total soluble salts with depth according to taxonomic classification (After Bowser _et al_ 1962).

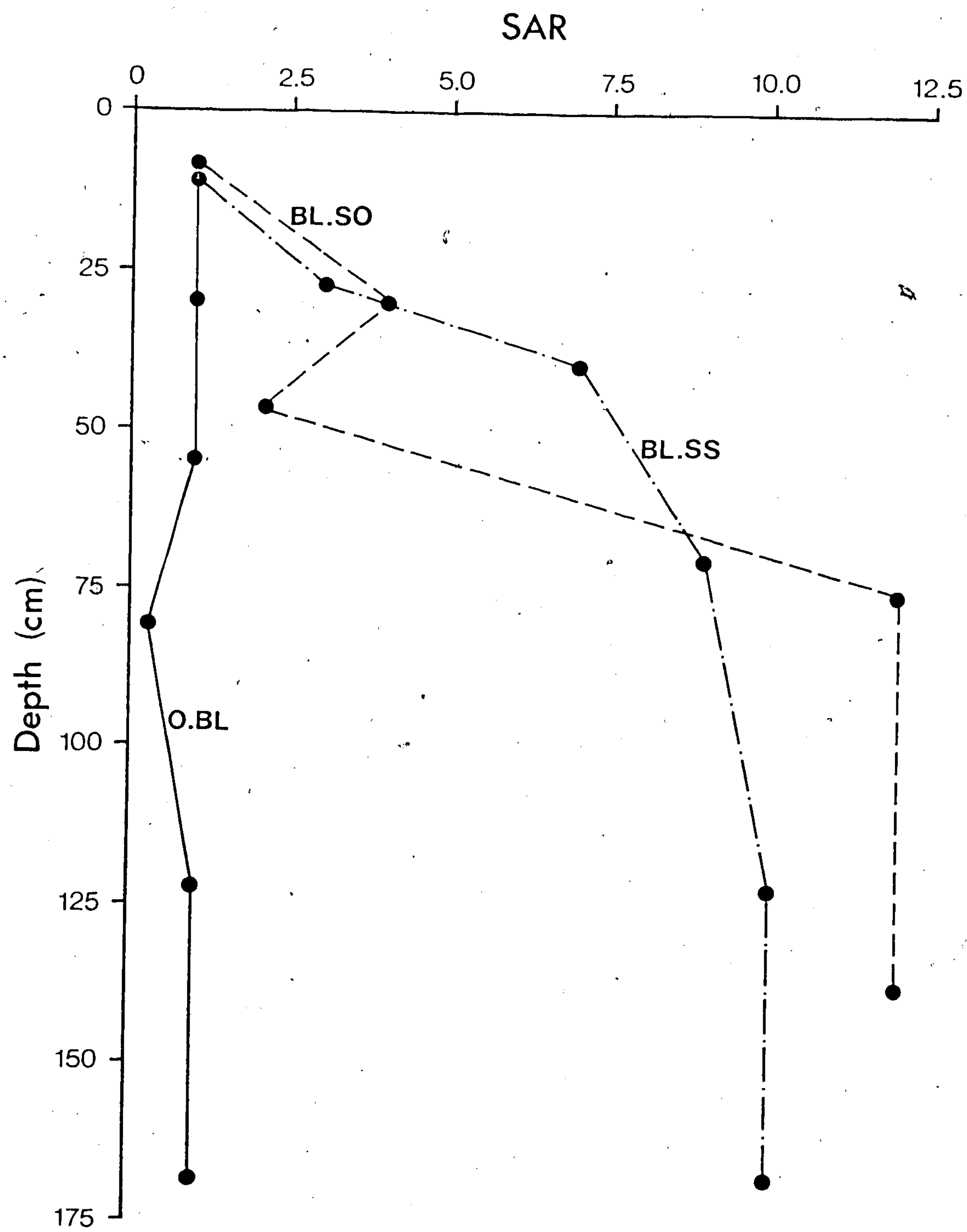


Figure 3. Sodium adsorption ratio (SAR) as a function of depth and soil classification (After Bowser _et al_ 1962).

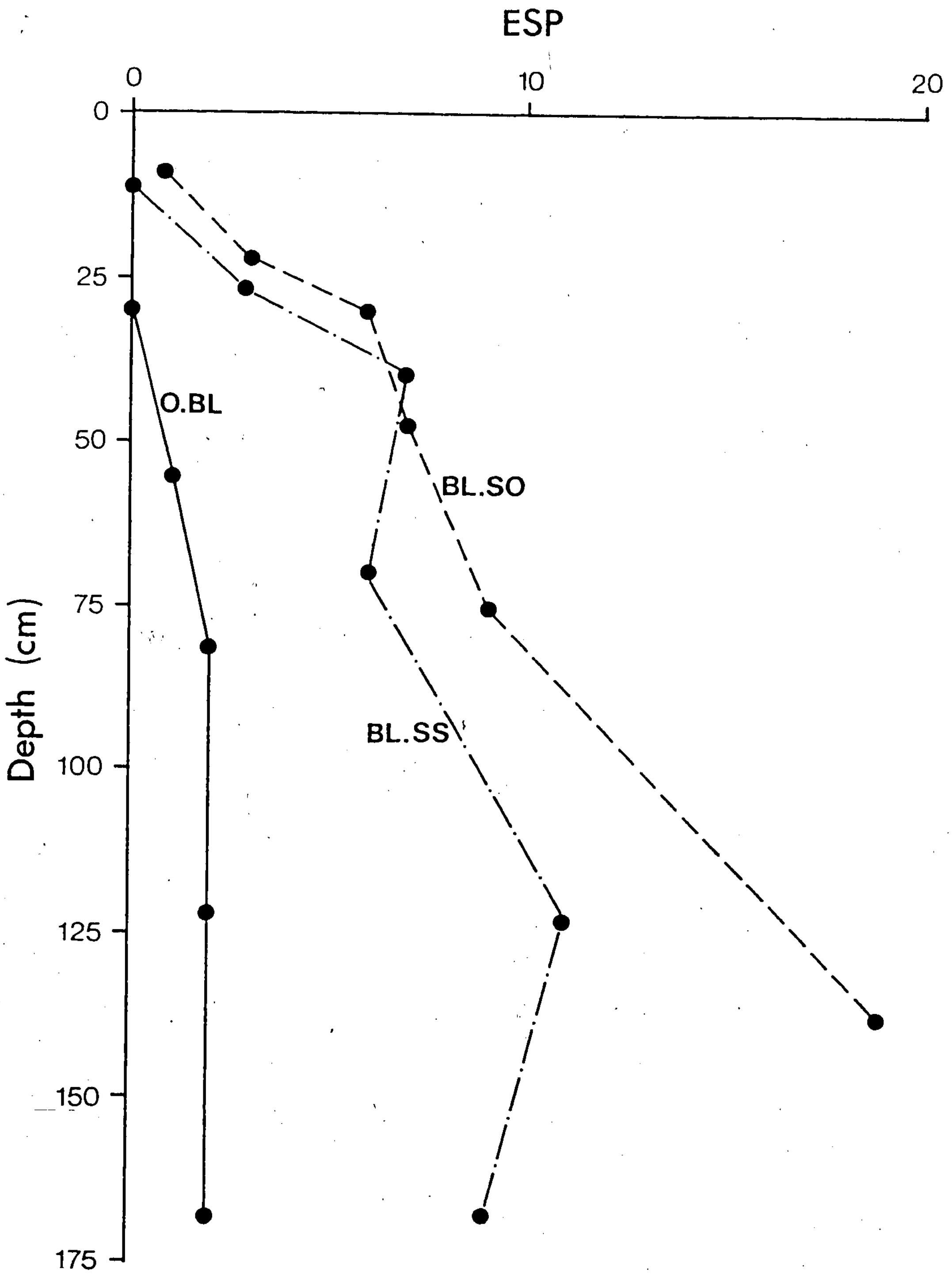


Figure 4. Exchangeable sodium percentage (ESP) as a function of depth and soil classification (After Bowser et al 1962).

cations, generally correspond to zones of maximum salt concentration (Bowser et al., 1962; Sandoval and Reichman, 1971). Likewise, soluble Ca^{2+} tends to increase with depth and attain a maximum in saline horizons. Values for Ca^{2+}, however, are generally lower than those for Na^{+} because of the lower solubility of Ca^{2+} salts. Magnesium normally exhibits trends similar to Ca^{2+}, although at lower concentrations. Exchangeable K^{+} is low and uniformly distributed with depth (Arshad and Pawluk, 1966a) with soluble K^{+} exhibiting similar trends.

Sulfate is by far the dominant anion reported in North America (Arshad and Pawluk, 1966a; Bowser et al., 1962; Sandoval and Reichman, 1971). European studies, however, frequently make reference to appreciable amounts of CO_3^{2-}, HCO_3^{-} and Cl^{-} relative to SO_4^{2-} (Sokolov and Kotin, 1961; Tursina, 1961; Szabolcs, 1965, 1971).

Soil reaction is variable and also reflects the evolutionary stages of soil genesis. An alkaline pH in the A horizon is indicative of shallow groundwater and minimal profile development (Pawluk and Dumanski, 1969). Acid conditions, whether measured by soil reaction (Figure 5) or exchange acidity are more frequently encountered in the A horizon and are associated with more advanced profile development. B and C horizons are weak to moderately alkaline, the former generally more so than the latter (de Sigmond, 1938; Bowser et al., 1962; Pawluk and Dumanski, 1969; Szabolcs, 1971).

2.2.3 Mineralogical Properties

Mineralogical properties of Solonetzic soils are also variable. The most important property, that of clay mineralogy, will be the only mineralogical fraction discussed. Pawluk (1982) suggests an appreciable

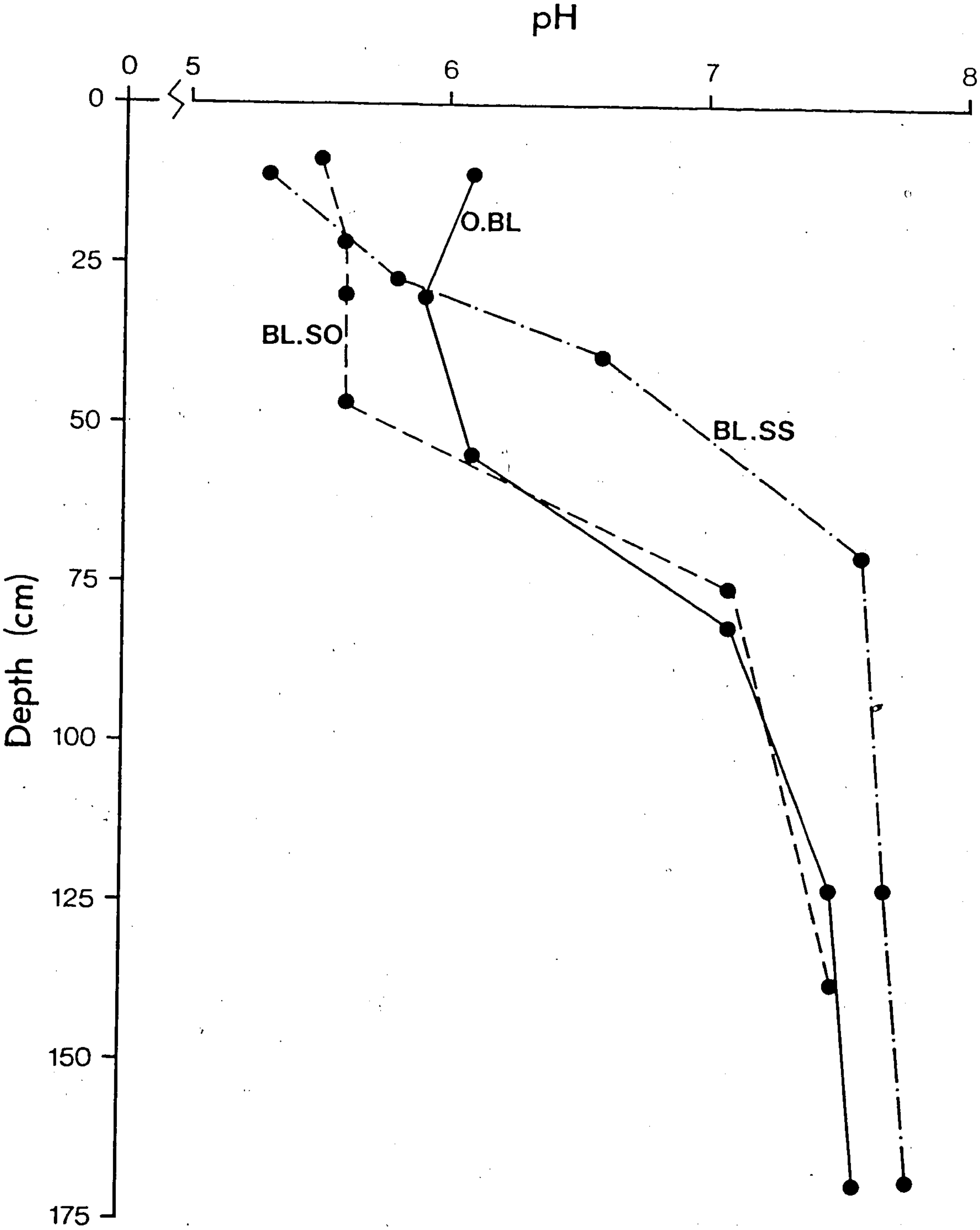


Figure 5. Soil reaction as a function of depth in Solonetzic and associated soils (After Bowser et al 1962).

amount of expansible clay minerals must be present for Solonetzic soils to form. A considerable amount of research supports this view point.

Van Schaik and Pawluk (1978) report approximately 50% of the total clay fraction in the C horizons of some Solonetzic soils is montmorillonite. Illite further comprises 25 to 30%. Corresponding values reported by Arshad and Pawluk (1966b) for C horizons are 40 and 25%, respectively. Similar values for montmorillonite are also reported by Brunelle et al. (1976).

Mica and/or kaolinite have been reported as subdominant phyllosilicates (Arshad, 1964; Mathieu, 1960; Sandoval and Reichman, 1971). On account of its ubiquitous nature, clay sized quartz is also present (Arshad, 1964; Brunnelle et al., 1976).

Size and charge density of phyllosilicates to a large extent govern their distribution with depth in Solonetzic soils. Smectite minerals are expansible, smaller in size and higher in charge density and therefore are more susceptible to dispersion and migration under the influence of Na^+. Brunelle et al. (1976) report as much as 35% more montmorillonite in Bnt horizons than in overlying eluvial horizons. In most cases montmorillonite was higher in Bnt than in the underlying C horizons. Higher illite content in the A and B hoirzons relative to the C horizon suggested illitization had occurred. The remaining clay fraction consisted of kaolinite, chlorite, amorphous material and quartz. These components were higher in eluvial horizons, which suggests their increase is due to negative enrichment.

2.2.4 Physical Properties

To a large extent physical properties of Solonetzic soils result from interactions between the soil chemical and mineralogical suites. The simple fact that exchangeable Na^+ promotes swelling and dispersion of smectite minerals results in many unique characteristic features.

The most obvious physical feature is particle size distribution (Figure 6). Textural differences between A and B horizons generally increase from Solonetz to Solodized Solonetz stages. Differences in clay content as great as 28% have been reported between Ae and Bnt horizons of Solodized Solonetz soils (Bowser et al., 1962). Differences in clay content between A and B horizons for Solodized Solonetz as compared to Solods is not as pronounced, although illuviation tends to occur further down the pedon and become distributed over a wider depth (Bowser et al., 1962).

Preferential movement of the fine clay fraction appears to occur relative to the coarse clay fraction. Bowser et al. (1962) and Brunelle et al. (1976) report more pronounced differences in fine clay content than total clay content between horizons. In some instances three times as much fine clay was found in Bnt horizons than in overlying Ae horizons. Fine clay within the Bnt was frequently found in quantities double that of the underlying C.

Clay illuviation and resultant shrink-swell cycles are undoubtedly responsible, in part, for high bulk densities in Solonetzic B horizons. Arshad (1964), Brunelle et al. (1976) and MacLean and Pawluk (1975) all report substantially higher bulk density values in Bnt horizons compared to overlying A horizons (see Figure 7). Bulk density differences between B and C horizons are generally less pronounced.

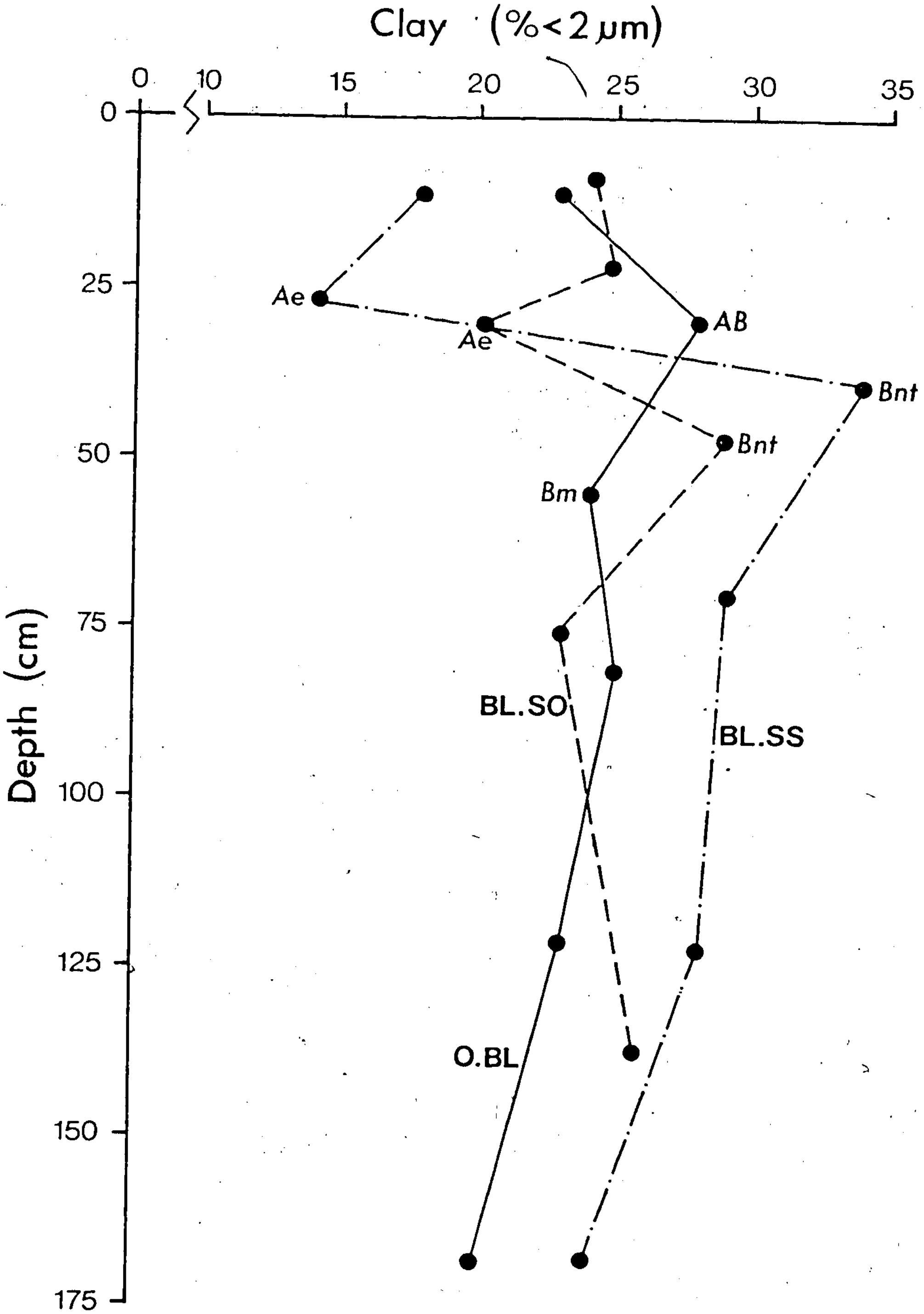


Figure 6. Distribution of the clay fraction with depth in two Solonetzic and an associated Chernozemic soil (After Bowser et al 1962).

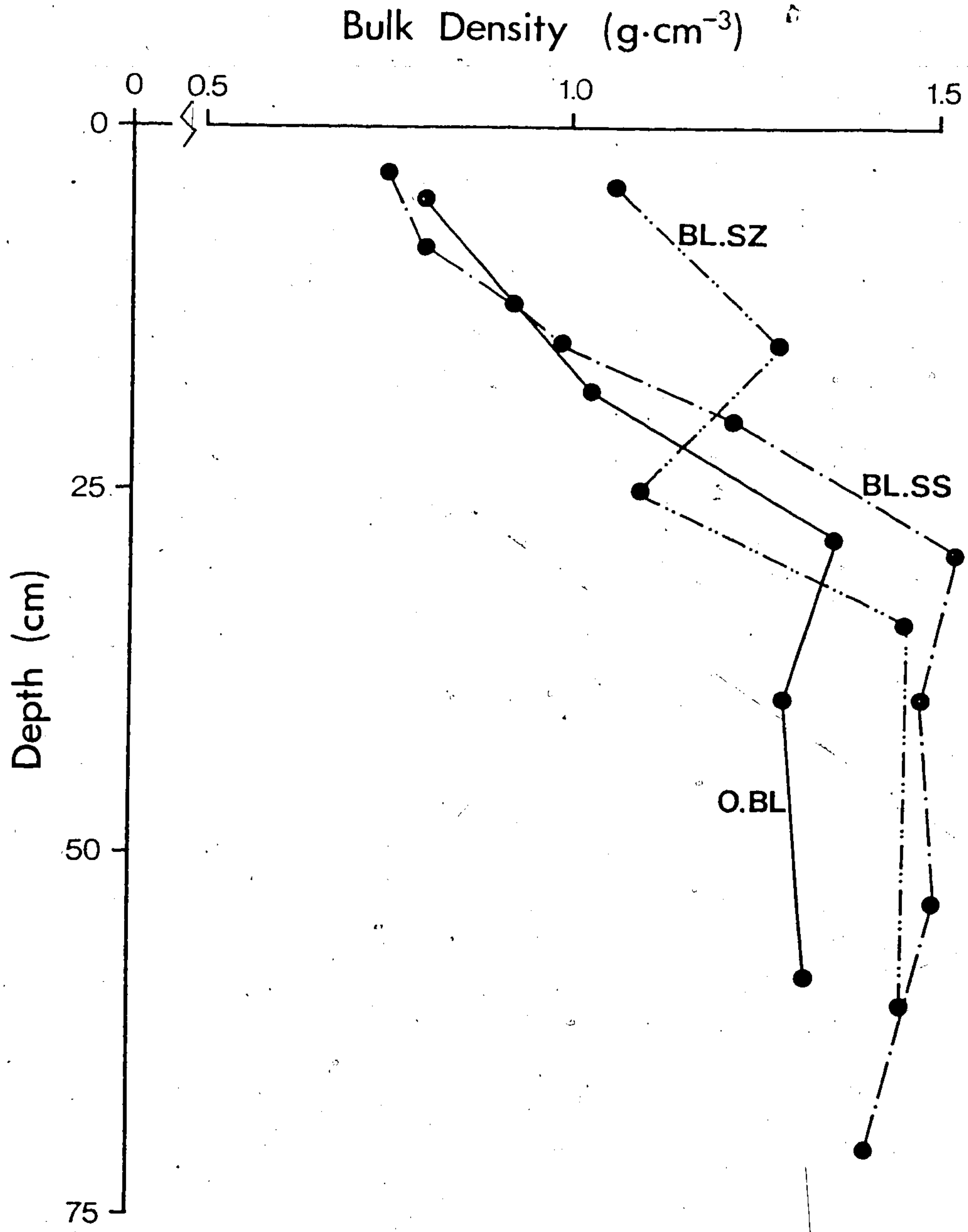


Figure 7. Soil bulk density as a function of depth and classification (After Arshad 1964).

Hydraulic conductivity of Solonetzic B horizons is variable and somewhat reflects the degree of solodization: values, however, are generally much lower than those for Chernozemic B horizons (Bowser et al., 1962, Figure 8). Stratified according to horizons, hydraulic conductivities generally follow a sequence A > C > B, although exceptions do occur (van Schaik and Pawluk, 1978). Anistropy may be present, particularly in Ae horizons. Development of a platy structure results in a marked preference for lateral flow relative to vertical flow (Landsburg, 1981).

2.3 Classification of Solonetzic and Related Soils

Classification of salt affected soils, particularly those affected by sodium, is variable and to a large extent depends upon the reasons for developing such a classification system. Most classification systems have a genetic bias: that is, they describe soil classes as they reflect soil genetic horizons which evolve through specific soil forming processes. On the other hand, some classification systems characterize soil properties in light of agronomic use. In some instances the two merge to form a system based on common origin, yet with the potential for assessing agricultural utilization. A brief discussion of the major classification schemes dealing with salt and/or sodium affected soils follows.

2.3.1 Canadian Taxonomy

In the Canadian soil classification scheme (Can. Soil Surv. Comm., 1978) the definition of the Solonetz order is based on B horizon properties. The Solonetzic B horizon "has columnar or prismatic

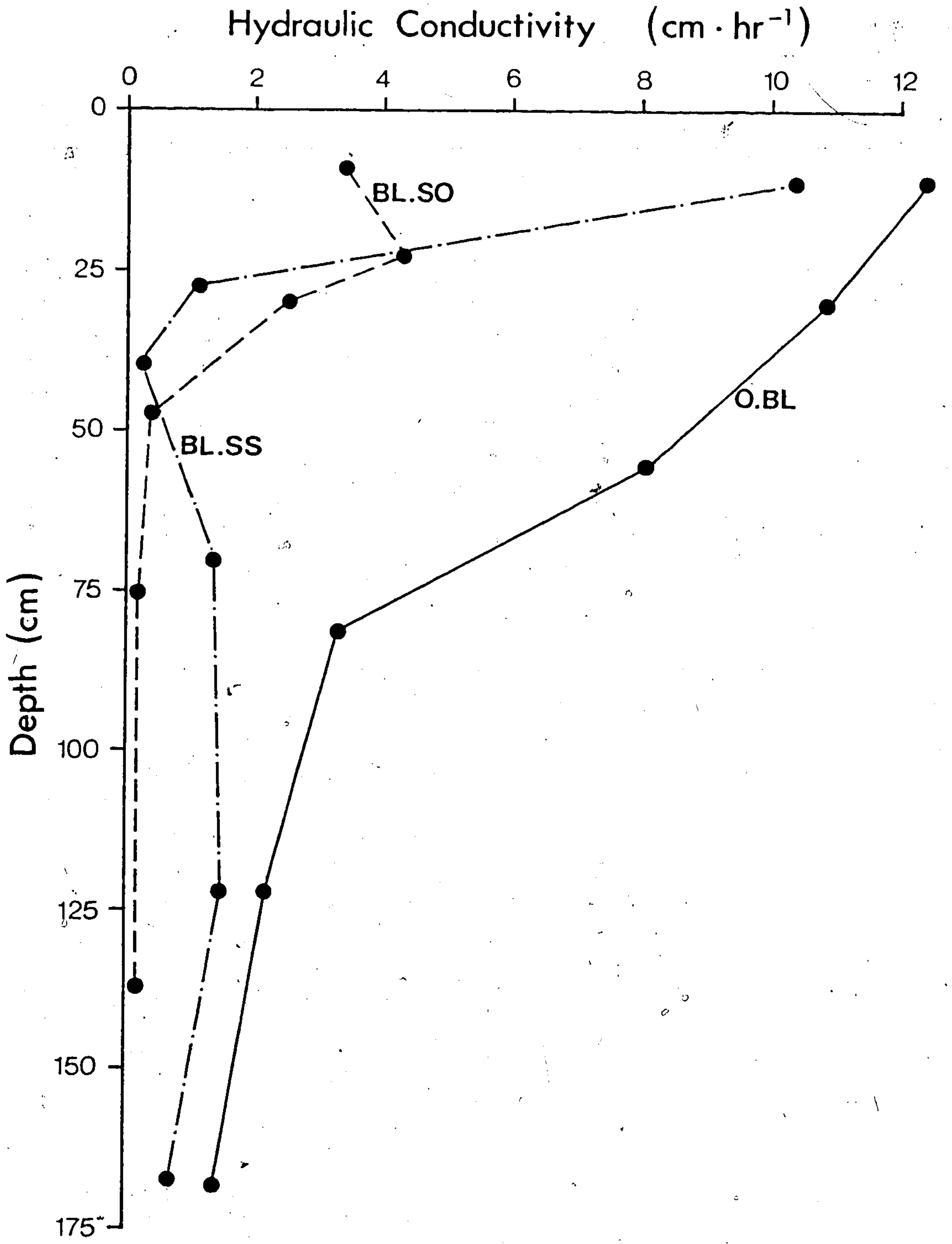


Figure 8. Soil hydraulic conductivity as influenced by depth and soil classification (After Bowser et al 1962).

structure, is hard to extremely hard when dry, and has a ratio of exchangeable Ca^{2+} to Na^{+} of 10 or less". Although chemical criteria are somewhat different than those of other classification systems, the morphological similarity is relatively consistent.

Differentiation into great groups is based on the degree of expression of eluvial (Ae) horizons and disintegration of the upper Bnt horizon. Great groups recognized are Solonetz, Solodized Solonetz and Solod. Horizon sequences for these groups are, respectively: no pronounced Ae horizon (<2 cm thick); an Ae horizon ≥2 cm thick; and an Ae horizon at least 2 cm thick with a distinct transitional AB or BA horizon. In essence the great groups reflect evolutionary stages. Recognition of an Ae horizon, followed by a transitional AB (or BA) horizon, is intended to reflect the degree of solodization.

Subgroup differentiation primarily reflects climatic/vegetative zonation and groundwater regime. Surface colour and depth to mottle/gley features, respectively, are used to delineate subgroups. In one instance chemical criteria are used for recognition of a subgroup: the Alkaline Solonetz has a surface pH 8.5.

2.3.2 United States Classification

2.3.2.1 U.S. Soil Survey Staff

The soil taxonomic system used in the United States (U.S. Soil Survey Staff, 1975) does not recognize salt affected soils at a high level of abstraction. Salt affected soils are those which contain salic, gypsic or natric horizons, the presence of which is recognized at the great group level.

Salic horizons, generally, are horizons which contain secondary enrichment of salts more soluble than gypsum. Gypsic horizons are similar, except the secondary enrichment is in the form of gypsum. Natric horizons have an $SAR \geq 13$ (or $ESP \geq 15$) and they exhibit prismatic, columnar or, rarely, blocky structures. In most instances it appears the natric horizon is very similar to the Solonetzic B horizon as defined by the Canada Soil Survey Committee (1978). More complete definitions of these horizons can be found in the source material (U.S. Soil Survey Staff, 1975).

2.3.2.2 U.S. Salinity Laboratory Staff

Classification of salt affected soils under this system results in three groupings (U.S. Salinity Laboratory Staff, 1954) based on soil chemical properties. Saline, saline-sodic and sodic groups are recognized. Differentiation is based on those criteria given in Table 1.

Table 1. Chemical classification of salt affected soils (after U.S. Salinity Laboratory Staff, 1954).

	Classification		
Property	Saline	Saline-Sodic	Sodic
EC (mS/cm)[1]	> 4	> 4	< 4
ESP	< 15	> 15	> 15
pH[2]	< 8.5	< 8.5	> 8.5

[1] Electrical conductivity of saturation extract at 25°C.

[2] pH values are general, rather than critical limits.

Saline soils are frequently recognized by the presence of white salt crusts on the soil surface. The dominant soluble salt is rarely Na^+, with the dominant anions being Cl^- and SO_4^{2-}. Low solubility salts, such as gypsum and alkaline carbonates may also be present. These soils are generally well flocculated and permeable because of the presence of excess electrolyte.

Saline-sodic soils are similar to saline soils in properties and composition except for the presence of appreciable Na^+. Reclamation of these soils requires removal of Na^+ concurrently with the removal of excess salts to prevent deterioration of soil structure and soil permeability.

Sodic soils differ from the previous two in having a low electrolyte concentration (EC<4). High Na^+, over time, results in distinctive eluvial/illuvial horizons and a columnar or prismatic B horizon of low permeability. Sodium is usually the dominant soluble cation.

2.3.3 Sodium Affected Soils of Hungary

In 1938 de Sigmond advanced a comprehensive classification system for sodium affected soils in Hungary. Those soils affected by Na^+ are grouped into a specific order and are subdivided on the basis of chemical and morphological criteria as they reflect genetic processes. Subdivision results in five "main types": Saline soils, Salty Alkali soils, Leached Alkali soils, Degraded Alkali soils and Regraded Alkali soils. Further differentiation into "sub-types" is also based on morphological and chemical criteria. A breakdown is given in Table 2.

According to de Sigmond saline soils contain excess soluble salts and consist primarily of Na^+ and Mg^{2+} in variable combination with

Table 2. Classification of sodium affected soils in Hungary. (After de Sigmond 1938).

Main Type		Sub-Type	
Name	Property	Name/Sub-type	Property
Saline Soils	High soluble salt content; high Na.	1	SO_4^{2-}
		2	Cl^-
		3	SO_4^{2-} & Cl^-
		4	SO_4^{2-} & CO_3^{2-}
		5	Cl^- & CO_3^{2-}
		6	SO_4^{2-}, Cl^- & CO_3^{2-}
		7	HCO_3^-
Salty Alkali Soils	Exchangeable Na >12%; Total Na >0.20%.		
Leached Alkali Soils	Columnar structure of B horizon; Definate eluvial/illuvial horizons; Gleyed horizon below solum.	Solonetz Soils Solonetz-like Soils	Definate structure. Weakly developed structure.
Degraded Alkali Soils	Appreciable gain of exchangeable H at the expense of Na; blocky structure develops in B horizon.		
Regraded Salty Alkali Soils	Secondary salinization of Leached Alkali or Degraded Alkali soils.	From Leached Alkali Soils From Degraded Alkali Soils	Absorbing complex unsaturated. Absorbing complex saturated.

Cl^-, SO_4^{2-}, CO_3^{2-} and HCO_3^-. Profile development is weak and is maintained by poor internal drainage or minimal leaching. Vegetation is typically halophytic. Division into sub-types is based on the quality of anionic constituents (Table 2).

Salty Alkali soils are similar in that profile development is generally weak, although distinct eluvial and illuvial horizons are occasionally present. Exchangeable Na^+ is $>12\%$ and total Na^+ is $>0.20\%$. Permeability of these soils is variable, with the more permeable members being lower in exchangeable Na. Vegetative cover is similar to that of saline soils.

Leached Alkali soils follow in sequence as leaching and salt removal continue. The B horizon has a well defined columnar structure and eluvial/illuvial horizons are pronounced. Total soluble salt content is low except in the lower horizons while exchangeable Na^+ content remains high in the upper horizons. C horizons are typically stratified on the basis of accumulations of carbonates or gypsum: the former occurs at greater depths due to lower solubility and a net downward movement. The D horizon (presumably "unaltered" parent rock) is normally gleyed. Vegetation tends to be xerophytic as opposed to halophytic because of decreasing salt content and moisture stress.

Degraded Alkali soils have thick A_1 (Ah) and A_2 (Ae) horizons. Sodium is lost from the upper solum, being displaced by H^+ which results in an acid reaction. The columnar structure breaks down into "nut-like clods" and is not as distinct as in the Leached Alkali soils. Mottled and gleyed horizons, marking water-table fluctuations, are frequently encountered in the subsoil.

Regraded Salty Alkali soils are those affected by secondary salinization. Morphological and physical characteristics are similar to those of Leached Alkali or Degraded Alkali soils with the exception that morphological features may be weakly expressed. According to de Sigmond these soils have undesirable properties associated with both high salt status and undesirable physical properties.

A modified classification system, having a genetic and agronomic bias, is reported by Abraham and Bocskai (1971). Solonetz soils have been subdivided into five major soil categories (soil types) according to morphological and chemical criteria. The five types recognized are Solonchak-Solonetz soils, Meadow Solonetz soils, Meadow Solonetz turning into Steppe soils, Solonized Meadow soils and Solod soils. Chemical limits for the five soil types are given in Table 3.

Solonchak-Solonetz soils have weakly developed columnar B horizons, are high in salt, strongly alkaline in reaction and are characterized by shallow water tables. Differentiation into subtypes is based on the dominant anion(s) present, as given in Table 4.

Meadow Solonetz soils are characterized by: a distinct eluvial A horizon of variable thickness; a columnar B horizon with a minimum ESP value of 15 or 25, depending upon depth; and C horizons which frequently contain accumulations of lime and occasionally exhibit gley features. Water soluble salt content is generally low in the A horizon but increases with depth. Subtypes are differentiated on the basis of A horizon thickness, as indicated in Table 5. Variants are further recognized according to salt quantity and composition. Thickness of the A horizon is deemed as important criteria for subdivision. Near neutral pH values (6.2 to 7.5) combined with low Na^+ and low total salt content result in a medium more condusive to plant growth. Hence, as

Table 3. Major chamical features of Solonetzic soils in Hungary (From Abraham and Bocskai, 1971).

For Table 3 see:

Abraham, L. and Bocskai, J. 1971. The utilization and amelioration of Solonetz soils in Hungary. p. 69 In I. Szabolcs (ed.) European Solonetz soils and their reclamation. Akademiai Kiado, Budapest.

stated by Abraham and Bocskai "the fertility of such soils is directly proportional to the thickness of the A horizon".

Table 4. Subtype differentiation of Solonchak-Solonetz soils in Hungary (after Abraham and Bocskai, 1971).

Subtype	Anion(s)
Carbonate solonchak-solonetz	CO_3^{2-}, HCO_3^-
Carbonate & sulphate solonchak-solonetz	$\geq 50\%$ SO_4^{2-}, CO_3^{2-}
Carbonate & chloride solonchak-solonetz	$\geq 30\%$ Cl^-, CO_3^{2-}, SO_4^{2-}

Table 5. Subtype differentiation of Meadow Solonetz soils in Hungary (after Abraham and Bocskai, 1971).

Subtype	Thickness of A Horizon (cm)
Shallow	<7
Medium	7 - 15
Deep	>15

Meadow Solonetz turning into Steppe soils comprise the third soil type. Deeper water tables result in increased eluviation and somewhat strong solodization in the upper B horizon. Soluble salt content is low except in the B horizon, while exchangeable Na^+ levels remain similar to those of the Meadow Solonetzes. Surface horizons are generally slightly acid to neutral (pH 6.2 to 7.0) and again form the basis for subtypes according to criteria in Table 6.

Table 6. Subtype differentiation of Meadow Solonetz soils grading towards Steppe soils in Hungary (after Abraham and Bocskai, 1971).

Subtype	Thickness of A Horizon (cm)
Medium	< 20
Deep	> 20

Variants separated on the basis of salt content and composition are also recognized.

Chemical limits for Solonetzic Meadow soils and Solods are given in Table 3. Specific descriptions, however, are not given for these two soil types.

2.3.4 Russian Soil Taxonomy

The classification system used in the USSR, as described by Rode (1962) is similar, though not identical, to that described by de Sigmond (1938). Salt affected soils are generally classified into three groups (or types) which recognize unity in origin. That is, soil properties reflect soil processes which in turn reflect soil forming factors. The three major groups recognized are Saline, Solonetz and Solod soils.

Saline soils, as the name implies, contain excess soluble salts. Profile development is weak with soils usually exhibiting "complete homogeneity of mechanical as well as total chemical composition of the aluminosilicate soil constituent throughout the profile". Subdivision of saline soils is based on two major constituents. Firstly, the depth and concentration of soluble salts as indicated in Table 7.

Table 7. Subdivision of saline soils in the USSR according to total salt content (after Rode, 1962).

Terminology	Soluble Salt Content (%)	Depth (cm)
Non-saline	<0.25	0 - 150
Weakly solonchakous	>0.25	80 - 150
Solonchakous	>0.25	30 - 80
Solonchakic	>0.25	5 - 30
Solonchak	>1.00	surface

Secondly, on the basis of the dominant anion(s) present, as indicated in Table 8.

Table 8. Subdivision of saline soils in the USSR according to salt composition (after Rode, 1962).

Terminology	Dominant Anion(s)*
Sulphate-soda	SO_4^{2-}, CO_3^{2-}
Chloride-sulphate	Cl^-, SO_4^{2-}
Sulphate-chloride	SO_4^{2-}, Cl^-
Chloride.	Cl^-

*In the case of more than one anion, the latter is dominant

Solonetz soils differ markedly from saline soils in their degree of profile development. These soils generally consist of a light gray surface of variable thickness underlain by an illuvial, columnar or prismatic B horizon. The B horizon generally breaks into "cuboidal" units, which characteristically have flat, humate stained ped faces. The Solonetz horizon is underlain by a horizon of salt accumulation. Calcium carbonate may be present in the middle to lower B horizon. Solonetz soils are highly variable and are subdivided on the basis of several criteria (Table 9).

Differentiation into subtypes is based on two properties. First, climatic zonation - Chernozem to Chestnut to Brown zone - as one moves to drier climates. Second, on the degree of moistening or, depth to groundwater table. Designations are Meadow Solonetz, Meadow Steppe Solonetz and Steppe Solonetz for groundwater tables at depths of < 5 m, 5-8 m and > 8 m, respectively. Further differentiation of subtypes into genera is based only on chemical criteria: total salt content; depth of salt accumulation; type of anion(s) present; and depth to carbonates or gypsum. More specific criteria are given in Table 9.

Division of genera into variants, in part, relates to thickness of the A horizon (or horizons overlying the Solonetz horizon). Shallow Solonetz, Medium Solonetz and Deep Solonetz are recognized when depth of the overlying A horizon is 7 cm, 7-15 cm and 15-25 cm, respectively (Rode, 1962; see Table 9). Rode further recognizes a Crusty Solonetz (A horizon ≤ 3 cm thick) although this is not indicated in Table 9. Additional B horizon properties, namely Na^+ content, degree of solodization and structure are listed in the table of Pak (1971) (see Table 9) but are not designated by Rode.

Solods represent a degraded stage of Solonetz soils. They owe their origin, in a relative sense, to increasing water table depth. Solod soils have a highly humified A horizon, generally 6-10 cm thick,

Table 9. Criteria used for classifying Solonetzic soils of the USSR into various groupings (From Pak, 1971).

For Table 9 see:

Pak, K.P. 1971. Solonetzes of the European part of the USSR and their reclamation. p. 141 In I. Szabolcs (ed.) European Solonetz soils and their reclamation. Akademiai Kiado, Budapest.

underlain by a whitish solodized horizon of variable thickness. Remnants of the former Solonetz horizon are often visible in the A horizon. Surface reaction of the upper horizons is usually weakly acid. Below the surface lies a distinct illuvial horizon which may exhibit a "residual" columnar structure. The lower portion of the illuvial horizon may be calcareous.

2.3.5 Classification, Properties and Solonetz Amelioration Potential

Several attempts have been made to group Solonetzic soils according to ameliorative potential. Most groupings are based on properties and hence, they reflect to some degree the classification scheme at hand.

European literature makes several references to classification and meliorative potential of Solonetz soils. Rode (1962) states "reclamation proceeds particularly on Steppe-Solonetz". Thus, a water-table depth >8 m facilitates reclamation. Reclamation of Meadow Solonetz soils is more difficult due to shallower groundwater and higher soluble salt content. In these soils leaching and drainage become integral parts of the reclamation procedure.

Rode further relates chemical properties, in part, to reclamation of Solonetz soils using gypsum. Greater amounts of gypsum are needed for reclaiming Soda-Solonetz than Medium Columnar Solonetz. This apparently is related to both the adverse effect of soda on colloids as well as depth of overlying A horizon. In all cases it is felt deep plowing should accompany gypsum application to destroy the Solonetz B horizon.

A further expansion on these characteristics is given by Szabolcs

(1971). Primary emphasis is given to groundwater and secondary emphasis to the soil chemical suite. A summary is given in Table 10. Where the groundwater is disconnected from the soil solum, as is the case with Steppe-Solonetz soils, deep plowing and chemical reclamation methods are successful, although agrotechnics are also strongly emphasized.

Agrotechnics appear to include ameliorative tillage as well as seeding to tolerant and/or reclaimer crops (Pak et al., 1964). Salt content in the upper solum is the criterion used to select a specific amelioration method.

In soils where the groundwater is temporarily linked with the soil solum (Meadow Solonetz, Solod soils turning into Steppe soils) similar methods are used. Gypsum applications and deep plowing are recommended, the latter particularly if water soluble salts are low and gypsum is high in the lower B and upper C horizons.

For Meadow Solonetz and Solod soils adequate drainage and leaching is essential, particularly when salts in high concentrations are near the surface. Chemical amendments are also recommended, particularly in fine textured soils.

In the U.S. Rasmussen and McNeal (1973) attempted to define the optimum depth of deep plowing and soil types responsive to deep plowing on the basis of hydraulic conductivity. The basis behind this research was thus: upon mixing horizons, the final weighted hydraulic conductivity will depend upon the relative thicknesses and hydraulic conductivities of those horizons incorporated in the mixing procedure. In deriving this procedure both electrolyte concentration and ESP were considered, as both have a pronounced influence on hydraulic

Table 10. Ameliorative groupings of Solonetzic soils (From Szabolcs, 1971).

For Table 10 see:

Szabolcs, I. 1971. Solonetz soils in Europe, their formation and properties with particular regard to utilization. p. 16 In I. Szabolcs (ed.) European Solonetz soils and their reclamation. Akademiai Kiado, Budapest.

conductivity.

In Alberta Cairns (1961) evaluated a Solonetz-Solodized Solonetz-Solod complex with regard to possible amelioration. In light of chemical properties determined Cairns assessed the suitability of three amelioration methods; gypsum application, application of elemental sulfur and deep plowing. Gypsum applications were deemed unsuitable due to the low solubility of gypsum and poor drainage. It was felt applications of S^o would further reduce an already acid pH as well as promote leaching of Ca^{2+}. Deep plowing appeared to be the most suitable amelioration method. Destruction of the B horizon and raising the surface pH could be accomplished in this manner. A minimum depth of 46 cm and a desirable depth of 61 cm were given to ensure incorporation of sufficient gypsum and carbonates to raise soil pH and promote chemical reclamation.

Carson et al. (1979) also attempted to assess the deep plowing potential of Solonetzic soils in Alberta on the basis of chemical properties. A various analytical methods were used including soluble salt analysis on saturation extracts and extractable cation analysis, using NH_4 Ac at various soil to extractant ratios. Results of the chemical analysis were discussed in light of known crop response, or lack thereof, on deep plowed soils. No clear relationship was found between any one chemical parameter and the degree of crop response. Low SAR or ESP values, and high Ca:Na ratios were inconsistent in predicting a favourable crop response. The reverse was also true. Sites which did respond well to deep plowing generally [illegible] acid Ap, although this was not universal.

Information available through standard soils surveys has also served as a basis for assessing areas suitable for deep plowing. Soil classification, texture, drainage, parent material, topography and stoniness are considered by Kjearsgaard (1980) to be important factors in governing deep plowing. Kjearsgaard's assessment is given in Table 11. He further points out that lime or salt horizons are normally present. If, however, depth to these horizons is in fact important, then soils in the Black soil zone are questionable with respect to plowability, as depth to these horizons may exceed penetration depth of the deep plows.

2.4 Distribution of Solonetzic and Related Soils

2.4.1 Geomorphic and Climatic Distribution

Salt affected soils, including Solonetzic soils, are distributed throughout all continents of the world. Hence, they may be associated with a variety of climatic conditions and landscape features. Broad generalizations, however, can be made with respect to climatic and geomorphic distribution.

Kovda (1965) and Szabolcs (1979) give an account of the climatic distribution of salt affected soils. These soils are generally found in cold or temperate regions although they also occur in subtropical and tropical regions. Generally speaking, climate is continental and arid or semi-arid. That is, at some time during the year there is a net precipitation deficit which discourages salt leaching and in fact may encourage salt accumulation.

Geomorphologically, salt affected soils are generally associated with alluvial plains or river and lake terraces. They are also found in depressional mountain plains or occasionally on mountain plateaus

Table 11. Soil survey information and deep plowing potential of soils (From Kjearsgaard 1980).

Characteristic	Can Be Plowed	Should Not be Plowed
Kind of soil (classification)	Solonetzic	Chernozemic, Regosolic, Gleysolic. Areas with >50% non Solonetzic soils.
Texture	loam, clay loam	sandy loams and coarser, areas with >40% coarse soils.
Surface Drainage	well drained	poorly drained ground water discharge areas
Parent Material	till, fluv-lac, lacustrine	Soft rock (bedrock), eolian, fluvial, areas with >30% soft rock.
Topography	<10% slopes	>10% slopes
Stones	<3% covered by stones (S2)	>3% covered by stones (S3)

(Kovda, 1965). Vegetative cover is variable and to a large extent reflects climatic zonation. Grasslands tend to predominate in the Chernozem zones (Steppe regions) while savanna type vegetation predominates in dry, equitorial regions. Salt affected soils are also found under deciduous/coniferous vegetation in Podzol zones of the north and are frequently associated with Brown and Chestnut soils of warmer regions, Red Earths of tropical regions and Sierozems of dry, subtropical regional (Kovda, 1965).

Salt accumulation is connected with well defined geomorphological and hydrogeological conditions. In arid and semi-arid regions the groundwater is usually somewhat mineralized (Szabolcs, 1979) particularly in relation to more humid areas (Kelley, 1951). Soluble salts within soils and groundwater is generally linked to underlying marine or brackish alluvial formations and shallow groundwater conditions. Kelley (1951) reports "much of the soluble salts found within soils of dry climates can be traced to secondary deposits [of shales and sandstones and the] chief cause of soluble salts is poor subsurface drainage". Within western Canada Solonetzic soils of semi-arid and sub-humid regions are generally associated with relatively level topography, relatively shallow, saline Cretaceous shales and restricted internal drainage (Bowser, 1961). Such findings are reported in studies of Arshad and Pawluk (1966a) and MacLean and Pawluk (1975).

Depth to the water table is important. Florea and Stoica (1958) report a critical water-table depth of 2.5 m. Water-table depths shallower than 2.5 m result in salinization of the soil surface by soluble salts ($NaCl$, Na_2SO_4, $MgSO_4$, $CaSO_4 \cdot 2H_2O$). The degree of salinization decreases as the water table deepens, with minimal salinization occurring at water table depths greater than 3.5-5.0 m. MacLean and Pawluk (1975) found Solonetzic soils in low lying areas where depth to the water table was generally between 0.5 and 2.0 m and discharging groundwater was very saline. Chernozemic soils were found primarily in upland areas where the water table for most of the year was greater than 2 m deep, although they were also found in low lying areas with shallower water tables. Low Na^+ groundwater and lateral flow above the water table appeared to relate to the occurrence of Chernozemic soils in low lying areas (MacLean and Pawluk, 1975).

2.4.2 Geographic Distribution

The approximate distribution of salt affected soils by continent or subcontinent is given in Table 12.

Table 12. Worldwide distribution of salt affected soils (after Szabolcs, 1979).

Continent	Extent of Salt Affected Soils (x 10^3 ha)
North America	15,755
Mexico and Central America	1,965
South America	129,163
Africa	80,538
South Asia	87,608
North and Central Asia	211,686
South East Asia	19,983
Australia	357,330
Europe	50,804

Salt affected soils therefore occupy a considerable extent of land area. A breakdown of the geographical distribution of Solonetzic soils (with structural B horizons) is given by Szabolcs (1979). A summary is given in Table 13.

In addition to those countries listed in Table 13, Solonetzic soils also occur in Spain, Austria, Greece, Italy and Portugal (Szabolcs, 1971). In Canada, the bulk of Solonetzic soils are found in Alberta. Approximately 4 million ha, or 30% of the arable land, is occupied by Solonetzic soils (Peters, 1978). In Saskatchewan there are approximately 1.5 million ha of land where Solonetzic soils predominate (Anderson and Ballantyne, 1982). Their presence is also reported in Manitoba, although chemically they may not satisfy the definition of Solonetz (Ehrlich and Smith, 1958).

2.5 Land Use of Solonetzic Soils

2.5.1 Land Use and Amelioration Methods

The nature of the areas in which Solonetzic soils occur is generally of low local relief and is climatically suitable for production of a variety of crops. In essence, the areas are arable and as such the major land use of Solonetzic soils is agricultural.

Under dryland conditions, a variety of crops have been or are currently grown on Solonetzic soils, depending upon prevailing climatic conditions. Field and forage crops such as wheat, oats, barley, rye, flax, rapeseed (canola), alfalfa, bromegrass, crested wheatgrass and a variety of other forages or forage mixtures are common in Alberta. This, undoubtedly, is also true of other areas, as field crops comprise a major land use in European countries (Abraham and Bocskai, 1971;

Table 13. Worldwide distribution of Solonetzic soils (modified from Szabolcs 1979).

Continent and Country	Approximate Land Area ($\times 10^3$ ha)
North America	
Canada	6,974
USA	2,590
South America	
Argentina	11,818
Bolivia	716
Brazil	362
Paraguay	1,894
Africa	
Angola	86
Chad	3,728
Liberia	44
Niger	111
Somalia	3,754
Asia	
Solomon Island	30,062
USSR	79,618 *
Australasia	38,111
Europe	
Bulgaria	20
Czechslovakia	7
France	75
Hungary	326
Romania	110
USSR	20,382
Yugoslavia	185

* Computed by difference, assuming total area in the USSR occupied by Solonetzic soils is 100,000,000 ha. (Pak 1971).

Obrejanu and Sandu, 1971). Not all land, however, is deemed suitable for cultivation. In Europe, those soils permanently linked with saline or alkaline groundwaters are generally restricted to pasture use or for growth of halophytic fodder crops unless adequate drainage is provided (Szabolcs, 1965).

Attempts have also been made to irrigate Solonetzic soils. Mixed success has been noted in Alberta (Palmer, 1982), the northwestern U.S. (Piper, 1982), and Europe (Abraham and Bocskai, 1971). Of particular interest is European utilization of Solonetzic soils for growing rice (Abraham and Bocskai, 1971; Obrejanu and Sandu, 1971), which involves inundation of the soils. Such attempts appear to have met with moderate success provided that adequate drainage prevents salinization of surrounding lands.

Land use has not been restricted to agricultural purposes. In Europe attempts have been made to establish tree plantations on Solonetzic soils, as well as utilize areas as fish stock ponds by inundating low lying areas (Abraham and Bocskai, 1971). Tree plantations met with limited success as trees are more susceptible to drought stress and have lower salt tolerance than field crops. Fish ponds were confined to areas with high water tables which were otherwise unsuitable for arable crops or pastures. Limited success was also realized with fish ponds, due to relatively low yields and salinization of surrounding areas.

Much of the land use of Solonetzic soils revolves around agricultural utilization, primarily because they "... mostly occur in areas where the agricultural potential is otherwise favourable ..." (Szabolcs, 1971). Their use as such, however, is generally hampered by undesirable physical properties and difficult management resulting therefrom. Furthermore, more productive soils typically occur in association with Solonetzic soils which adversely affects productivity of the entire area (Szabolcs, 1971). For these reasons considerable emphasis has been placed on amelioration methods designed to increase productivity. A multitude of amelioration methods have been attempted over the last 30 years. These methods can be classified into three general categories; agronomic, chemical and physical. Not all methods within a grouping are mutually exclusive and an integrated approach combining several techniques is frequently used.

Agronomic amelioration utilizes cropping practices designed to maintain or increase the indigenous fertility of the soil without drastically altering its properties. Growth of crops such as alfalfa or saline/alkaline tolerant forages is designed to improve soil conditions and prevent soil deterioration. Applicaton of manure and growth of plow-down crops also serves to improve surface conditions. Agronomic amelioration encompasses principles involving both physical and chemical treatment, however, since processes are biological the rate at which improvement progresses is generally slow.

Chemical treatment primarily involves the application of amendments designed to promote exchange and leaching of Na^+. Certain fertilizers, such as $(NH_4)_2SO_4$, NH_4NO_3, $Ca(NO_3)_2$ and K_2SO_4 have been used for this purpose (Cairns and van Schaik, 1968, Cairns <u>et</u> <u>al</u>., 1980; Carter <u>et</u> <u>al</u>., 1977; Obrejanu and Sandu, 1971). Acid or acid-forming compounds, such as S^o, H_2SO_4, HCl or FeS_2 have been used (McCready and Krouse, 1982; Obrejanu and Sandu, 1971; Pak <u>et</u> <u>al</u>., 1967). Other amendments utilized include gypsum, phosphogypsum, lignite dust, molasis, $FeSO_4$, $CaCl_2$ and $CaCO_3$ (Alzubaidi and Webster, 1982; Obrejanu and Sandu, 1971; Pak et al., 1967; Rasmussen et al., 1972; Raychaudhuri, 1965).

Physical treatment results in relatively drastic changes within the soil body. Subsurface drainage and leaching with irrigation water (Raychaudhuri, 1965; Paterson, 1982; Travis, 1982) are used to alter the soil hydrologic regime as well as encourage leaching of Na^+. Land levelling and the digo method (placement of low s[illegible]ften, gypsiferous and calcarious material over poorer quality mat[illegible] part alters the hydrologic regime although additional am[illegible]s also realized from the additional chemical effects. Profile disruption techniques including chiselling (Alzubaidi and Webster, 1982), subsoiling (Hermans, 1981; Lavado and Cairns, 1980; Rasmussen et al., 1972) and deep plowing (Anderson and Ballantyne, 1982; Alzubaidi and Webster, 1982; Bowser and Cairns, 1967; Cairns, 1962; Harker et al., 1977; Lavado and Cairns, 1980; Rasmussen et al., 1972; and others) have been shown to alter hydrologic, chemical and physical properties of Solonetzic soils. One of the most promising techniques, because of its drastic effect on profile characteristics, is deep plowing.

2.5.2 Deep Plowing

Deep plowing, as an amelioration technique, appears to have evolved during the early 1950's in the USSR. Development appears to have occurred almost simultaneously on three distinctly different types of soils with different goals intended. Deep plowing of Podzolic soils was initially devised to mix subsoil material with the relatively infertile A horizon while burying the less fertile Ae horizon (Botov, 1959;

Aodlin, 1960). Concurrently, deep plowing was evaluated for its ability to reduce capillary rise of saline groundwaters in irrigated areas by destroying the network of fine capillary pores (Fesko and Strugaleva, 1959). Deep plowing (or a similar tillage form) of Solonetzic soils was evaluated at approximately the same time (Maksimyuk, 1958; Botov, 1959). Shortly thereafter deep plowing or horizon mixing of Solonetzic soils was studied in the U.S. (Pair and Lewis, 1960) and Alberta (Cairns, 1962).

2.5.2.1 Theory

Deep plowing involves the destruction and reorganization of genetic horizons. As [illegible]d it attempts to increase crop productivity through the following means:

(1) Physically disrupt the B horizon.

(2) Incorporate Ca^{2+} salts within the disrupted B horizon.

(3) Incorporate carbonates within the Ap horizon.

Mechanical disruption of the B horizon and redistribution of soil constituents is intended to improve the physical and chemical condition of the soil such that crop growth is encouraged. Specifically, deep plowing should:

(1) Increase water transmission properties of the soil by reducing bulk density and increasing the proportion of noncapillary pores.

(2) Increase penetration depth of crops, through reduced bulk density and increased depth of water storage.

(3) Expedite salt leaching, particularly Na^{+}, due to increased depth of "effective" leaching and incorporation of Ca^{2+} salts.

(4) Encourage biological cycling of Ca^{2+} (calcification) through increased rooting depth of crops.

(5) Increase the general level of biological activity by reducing extremes in soil moisture.

Several researchers have examined the effect of deep plowing and/or deep tillage in light of these anticipated changes. Some of this research is summarized below. Those aspects not covered at this time may be found in the appropriate chapters to follow.

2.5.2.2 Soil-Water Relations

Several authors have reported changes in moisture movement, retention and extraction by crops after deep plowing or profile mixing. For the most part dramatic increases in water infiltration have been noted upon mechanical mixing or deep plowing soils (Pair and Lewis, 1960; Eck and Taylor, 1969; Rasmussen et al., 1972; Maksimyuk, 1958). Exceptions, however, have been noted and Mech et al. (1967) attribute a higher infiltration rate in the conventionally tilled soils, relative to the mechanically mixed soils, to possible lateral flow along an Ae horizon.

Increased infiltration, to some degree, has resulted in greater depth of water storage (Eck and Taylor, 1969; Rasmussen et al., 1972) and a more uniform distribution of moisture with depth (Burnatzki and Yarovenko, 1961). In addition, a greater total water storage results within the disturbed profile (Fehrenbacher et al., 1958; Cary et al., 1967; Eck and Taylor, 1969). Greater water storage is linked to increased infiltration but may also be due to reduced evaporation from the soil surface, as reported by Eck and Taylor (1969). Greater total water storage generally results in increased water extraction by vegetation (Cary et al., 1967; Mech et al., 1967; Eck and Taylor, 1969) although increased total water storage may be a result of increased clay content in some zones with no apparent difference between plant available moisture (Fehrenbacher et al., 1958).

2.5.2.3 Bulk Density

Bulk density is a property which influences water and root penetration in soils and has been addressed, in light of deep plowing, by several authors. Rasmussen et al. (1972) report reductions in bulk density for all horizons to a depth of 90 cm upon deep plowing a Solonetzic soil. After eight years bulk densities at depth still remained low. Sandoval (1978) also noted reductions in soil bulk density at depths of 15 to 91 cm five years after deep plowing a Solonetzic soil. Although bulk density generally decreased upon deep plowing, increases in the bulk density of the surface horizon (Ap) have been reported (Sandoval et al., 1972).

3. INTRODUCTION TO STUDY

Tilth is defined as "the physical condition of a soil as related to its ease of tillage, fitness as a seedbed and impedance to seedling emergence and root penetration" (Can. Dept. Agric., 1976). Deep plowing attempts to improve those aspects of tilth related to root penetration; that is, reducing bulk density and increasing water transmission properties improves root penetration characteristics. Another aspect of soil tilth, however, may deteriorate upon deep plowing. This aspect is soil suitability as a seedbed.

Several properties have been measured by various authors which reflect reduction in soil tilth. Reduced infiltration (Lavado and Cairns, 1980; Mech et al., 1967), increased soil hardness (Lavado and Cairns, 1980) and increased crust strength (Sandoval et al., 1972) are resultant properties which restrict crop growth. These properties are linked to certain changes in the Ap horizon, such as increased clay content (Rasmussen et al., 1972; Sandoval et al., 1972; Lavado and Cairns, 1980), increased extractable Na^+ (Cairns, 1976a; Lavado and Cairns, 1980) and a loss of organic matter as reflected in reduced C and N contents (Bowser and Cairns, 1967). No attempt, however, has been made to specifically measure, correlate and predict changes in soil tilth - as measured by physical parameters - with changes in the distribution of soil constituents caused by deep plowing. Several authors (Cairns, 1976; Mech et al., 1967) point out the importance of developing management practices designed to cope with, or improve, resultant physical conditions in the seedbed of deep plowed soils. Hence, an understanding of these physical conditions, those factors which affect them and those changes which impart them is essential.

3.1 Objectives

The objectives of this study are quite broad in overall scope. They follow in approximate order of importance.

(1) Quantify, in relative terms, physical, chemical and mineralogical characteristics of Ap horizons (deep plowed and conventionally tilled soils) which have some bearing on soil tilth, and determine the relationship between these properties.

(2) Substantiate and procure differences in fabric and composition through micromorphological investigations.

(3) Indicate soil management practices which may aid in alleviating adverse properties in the resultant deep plowed seedbeds.

(4) If possible, further elucidate the basis for crop response on deep plowed soils and develop criteria for predicting relative plowing success.

3.2 Design Strategy and Experimental Layout

Five sites in east-central Alberta were chosen for this study in June 1980. The sites were previously deep plowed as test sites under the deep plowing program conducted by the Plant Industry Division, Alberta Agriculture. Plowing was performed in 1975 or 1976 depending upon the site, with a three layer or single bottom plow (Table 14).

Deep plowing was performed in approximately 4 ha strips adjacent to an unplowed check strip (hereafter referred to as conventional tillage). A paired plot design was established on the deep plowed and

Table 14. Locations, cooperators and deep plowing status of the study sites.

Site	Legal Location	County	Cooperator	Year Plowed	Plow Type*
1	NE 9-46-16-W4	Flagstaff	W. Koehli	1975	3 Layer
2	NW31-45-14-W4	Flagstaff	K. Pollom	1975	3 Layer
3	NE12-42-16-W4	Flagstaff	G. Henderson	1976	3 Layer
4	SW 3-40-16-W4	Paintearth	E. Kneeland	1976	3 Layer
5	SW34-37-14-W4	Paintearth	R. Wairt	1976	Single Bottom

* All plows were manufactured by Kellough Brothers, Stettler, Alta.

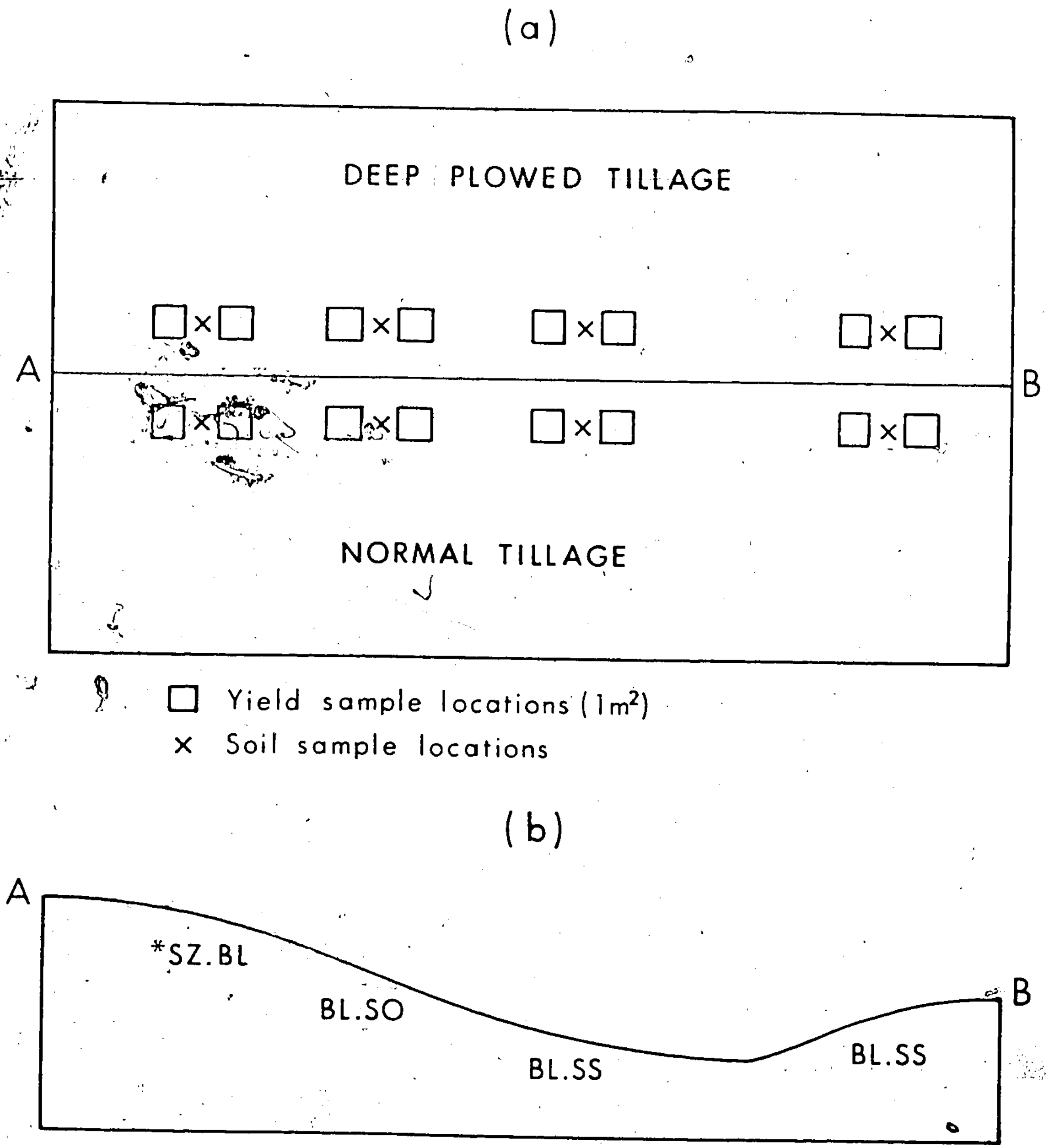


Figure 9. Field plot design showing (a) Relationship of paired plots within sites (b) Distribution of paired plots according to slope position and possible associated soils.

*Classification is according to the Canada Soil Survey Committee (1978).

adjacent conventionally tilled strip (Figure 9a) immediately prior to or after crop emergence in June, 1980. Plot locations were chained in for relocation the following year. Each paired plot consisted of two 1 m² crop sampling blocks, separated by a 1 m² soil sampling block, on each of the deep plowed and conventionally tilled strips. Individual paired plots were located as close together as possible on adjacent tillage treatments while still maintaining adequate distance from the dead furrow to eliminate edge effects. The rationale here was to minimize soil variability within paired plots on the assumption that the soil on the deep-plowed strip was, prior to deep plowing, very similar in nature to that presently on the check strip.

Four paired plots were established at each site. These were located, if possible, on different slope positions (Figure 9b) to encompass the range of soil types anticipated within the field. In this manner, changes in soil properties and crop yield characteristics could relate more closely to the geomorphic soil sequence present.

A more specific account of site characteristics, experimental design and analysis methods are found in the Materials and Methods section within the appropriate chapter.

4. BIOGEOGRAPHIC SETTING, MORPHOLOGY AND MICROMORPHOLOGY

4.1 Introduction

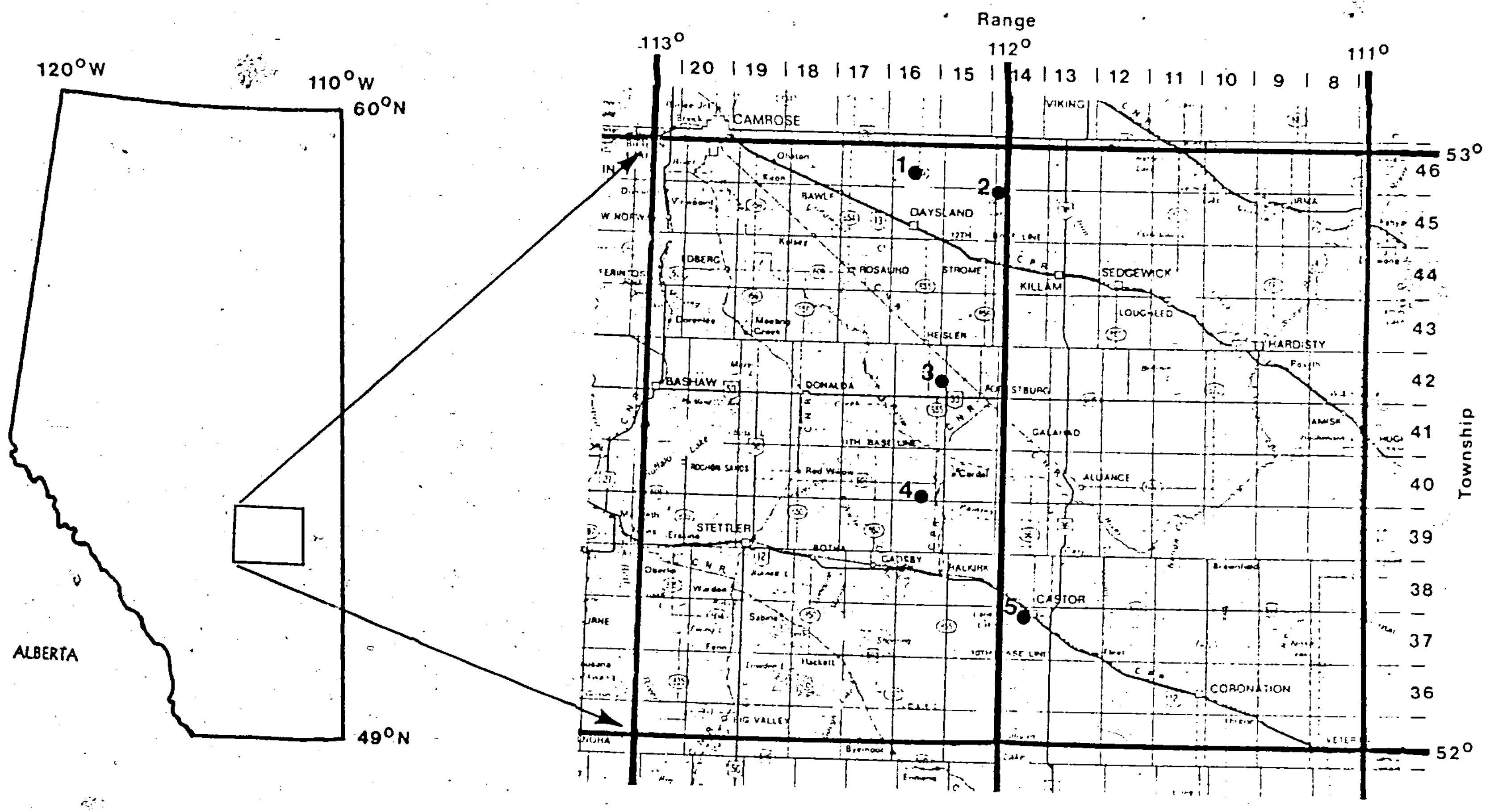
This chapter is devoted to biogeographic characterization of the study area and characterization of visual soil features. Characteristics of the study area, including climate, vegetation, geology and soils inventories are discussed in the literature review. Site specific characteristics are included in the initial discussion.

Morphological characteristics are examined, as they relate to soil processes and classification. Discussion of morphological features as they relate to crop response upon deep plowing is found in Chapter 6. Micromorphological investigations were undertaken to procure differences in soil fabric and composition as related to the geomorphic soil sequence present. Redistribution of genetic materials resulting from deep plowing is also examined.

4.2 Area Description

4.2.1 Location

The study area lies within east-central Alberta. More specifically, the five sites follow a general north-south transect along 112°W longitude between 52 and 53°N latitude (Figure 10). The northern most portion of the study area is slightly south of the Camrose-Viking area while the southern most portion lies within the Stettler-Castor-Coronation corridor. The entire area is contained within National Topographic System (NTS) sheets 83A (Red Deer) and 73D (Wainwright).



1● Approximate site location.

Figure 10. Location of the study area.

4.2.2 Climate

Climate throughout the study area is continental, characterized by long, cool summers (Koeppen climatic zone; Longley, 1968) and cold winters. The CLI classification indicates that for certain locations within the study area agriculture is limited by aridity or deficient soil moisture. This, however, is not true for the majority of the area (Environment Canada, 1976).

Mean annual precipitation for Camrose, Forestburg, Halkirk, Castor, Stettler and Coronation is given in Table 15. Annual precipitation is relatively uniform throughout the area. Slightly less precipitation occurs in the southern portion of the area relative to the northern area (370 mm to 390 mm vs. 390 mm to 400 mm). Lower precipitation is more apparent as one moves east, particularly in the southern region (420 mm vs. 327 mm for Stettler and Coronation, respectively).

Mean seasonal precipitation is also given in Table 15. Growing season precipitation ranges from 61% (Castor) to 70% (Halkirk) of mean annual precipitation. Corresponding values of growing season plus fall precipitation are 73% and 83% of mean annual precipitation, again for Castor and Halkirk, respectively. It is generally accepted the bulk of "effective" precipitation utilized by crops is that which occurs during the growing season and fall, as winter precipitation in this region is generally lost through evaporation or runoff (Bowser et al., 1947, 1951). June and July are high rainfall months, with approximately 120 to 160 mm falling during this period. April and October are months of low precipitation in the spring and fall, respectively.

Table 16 lists annual precipitation values from 1968 to 1978. The

Table 15. Mean monthly, seasonal and annual precipitation at various locations within the study area.

Month or Period	Camrose	Forestburg	Halkirk	Castor	Stettler	Coronation
	Meteorological Station					
	precipitation in mm					
September	34.5	32.7	38.6	32.2	37.6	36.3
October	14.7	14.3	21.6	15.5	16.5	18.0
Fall Total	49.2	47.0	60.2	47.7	54.1	54.3
November	15.2	14.7	9.4	20.3	16.8	15.8
December	15.5	18.0	11.4	23.6	16.3	18.3
January	17.8	18.9	12.2	25.0	20.8	20.8
February	17.5	13.7	10.7	15.1	20.1	18.0
March	12.7	16.9	14.0	20.2	18.8	20.3
Winter Total	78.7	82.2	57.7	104.2	92.8	93.2
April	17.0	18.5	19.6	22.5	19.6	22.6
May	36.8	47.8	48.8	41.0	35.8	29.0
June	68.8	85.4	81.8	76.5	79.2	54.6
July	75.7	68.0	71.7	50.0	77.7	68.6
August	63.8	55.8	59.4	48.6	61.0	50.3
Growing Season Total	262.1	275.5	280.7	238.6	273.3	225.1
Annual Precipitation	390.0	402.3	398.5	390.5	420.2	372.6
Years of Observations	20-24	9	21	9	25-29	25-29
Period of Observation	1941-70	1970-78	Pre 1947	1970-78	1941-70	1941-70
Source *	1	3,4,5,6	2	3,4,5,6	1	1

* 1 Canada Dept. Envir. 1975.
2 Canada Dept. Transp. 1947.
3 Canada Dept. Envir. 1972 (monthly records).
4 Alberta Envir. 1971, 1973-1977 (annual record for the respective year).
5 Canada Dept. Transp. 1970 (monthly records).
6 Canada Dept. Envir. 1978 (monthly records).

Table 16. Growing season and annual precipitation for years 1970 to 1979, at various locations throughout the study area.

Year	Period	Meteorological Station				
		Camrose	Forestburg	Castor	Stettler	Coronation
		precipitation in mm				
1970	Growing Season	261.9	301.5	209.9	378.0	167.6
	Annual	428.2	449.9	372.3	522.2	376.2
1971	Growing Season	216.7	198.1	201.9	183.9	210.3
	Annual	363.5	306.3	333.5	336.8	344.7
1972	Growing Season	-----	320.8	267.4	368.0	-----
	Annual	523.2	464.1	398.2	516.4	383.2
1973	Growing Season	572.8	376.9	401.8	411.0	394.2
	Annual	733.8	488.2	520.7	602.0	536.4
1974	Growing Season	280.4	267.0	267.1	294.4	296.4
	Annual	511.3	399.5	473.7	461.0	486.2
1975	Growing Season	297.2	299.5	244.2	341.9	300.5
	Annual	414.3	403.4	381.3	518.2	445.3
1976	Growing Season	229.1	204.5	180.1	279.4	233.2
	Annual	331.7	317.5	291.6	431.0	352.0
1977	Growing Season	318.5	265.2	165.3	-----	217.8
	Annual	463.1	404.9	330.0	-----	333.4
1978	Growing Season	313.2	246.3	209.7	390.5	233.6
	Annual	574.4	386.9	413.6	625.4	390.0
1979	Growing Season	375.4	255.6	182.9	263.3	240.3
	Annual	530.4	361.3	-----	380.2	316.5

Sources:
Canada Dept. Envir. 1972 (monthly records).
Alberta Envir. 1971, 1973-1977 (annual record for the respective year).
Canada Dept. Transp. 1970 (monthly records).
Canada Dept. Envir. 1978-1979 (monthly records for the respective year).

high and low years on record at Castor of 402 mm (1973) and 180 mm (1976), respectively, represent 133% and 75% of normal precipitation. Since the average moisture deficit in the area is approximately 203 mm (Laycock, 1960) the 1976 low represents an overall moisture deficit of approximatley 300 mm. Years of below normal precipitation thus may severely limit crop production, particularly in the southeastern portion of the study area.

Mean annual snowfall (Table 17) is higher in the south and southeastern portion of the area. Total snowfall ranges from 874 mm at Camrose to 1283 mm at Coronation. Generally, only a small portion (14-27%) of total annual precipitation is derived from snowfall. Mean fall snowfall (September and October) is low in all areas, indicating rainfall during this period is the major contributor to soil moisture reserves the following spring.

Although no mention has been made of rainfall intensity thus far, this factor is equally important. Timing and intensity often determine the effectiveness of precipitation, particularly that which occurs during the growing season. For the period May through August, one-day maximum precipitation, based on a 10 year return period, is 51 to 64 mm. For the same period, with a 25 year return period, one-day maximum precipitation is 64 to 76 mm (Longley, 1968). These values indicate a significant portion of growing season precipitation may occur during a single 24 hour period.

Table 18 lists temperature means at available locations. Little difference exists in monthly, seasonal or annual temperatures between stations. Mean annual temperature is approximately 2°C. January is the coldest month at approximately -15°C, while July, averaging 17°C,

Table 17. Mean monthly, seasonal and annual snowfall at various locations within the study area.

Month or Period	Meteorological Station					
	Camrose	Forestburg	Halkirk	Castor	Stettler	Coronation
	snowfall in mm					
September	15	6	28	13	15	36
October	51	25	107	59	69	102
Fall Total	66	31	135	72	84	138
November	125	122	89	183	145	152
December	147	180	109	244	160	196
January	168	189	117	250	203	226
February	170	115	104	148	183	193
March	119	162	135	202	185	218
Winter Total	729	768	554	1027	876	985
April	69	76	122	148	107	129
May	10	4	67	4	18	31
June	--	--	8	--	--	--
July	--	--	--	--	--	--
August	--	--	--	--	--	--
Growing Season Total	79	80	197	152	125	160
Annual Snowfall	874	879	887	1251	1085	1283
Years of Observations	20-24	9	21	9	25-29	25-29
Period of Observation	1941-70	1970-78	Pre 1947	1970-78	1941-70	1941-70
Source *	1	3,4,5,6	2	3,4,5,6	1	1

* 1 Canada Dept. Envir. 1975.
2 Canada Dept. Transp. 1947.
3 Canada Dept. Envir. 1972 (monthly records).
4 Alberta Envir. 1971, 1973-1977 (annual record for the respective year).
5 Canada Dept. Transp. 1970 (monthly records).
6 Canada Dept. Envir. 1978 (monthly records).

Table 18 . Mean monthly, seasonal and annual temperatures at various locations within the study area.

Month or Period	Camrose	Forestburg	Halkirk	Stettler	Coronation
	Meteorological Station				
	Temperature in °C				
September	10.3	11.7	8.9	10.6	10.7
October	4.2	6.3	3.3	5.1	4.8
Fall Average	7.3	9.0	6.1	7.9	7.8
November	-5.0	-3.3	-4.4	-4.2	-5.2
December	-12.1	- 9.6	-11.1	-10.1	-11.7
January	-17.3	-13.4	-16.0	-14.3	-16.2
February	-12.9	- 9.3	-12.2	-10.3	-12.2
March	- 7.1	- 4.9	- 5.6	- 5.8	- 7.1
Winter Average	-10.1	- [illegible]	- 9.9	- 8.9	-10.5
April	3.1	4.5	2.8	3.6	2.6
May	10.5	11.5	9.4	10.3	10.1
June	14.2	15.6	13.9	14.4	14.2
July	16.9	18.7	16.1	17.4	17.4
August	15.4	17.1	14.4	15.8	16.1
Growing Season Average	12.0	13.5	11.3	12.3	12.1
Annual Average	1.7	3.7	1.7	2.7	1.9
Years of Observations	20-24	-----	21	30	25-29
Period of Observations	1941-70	1941-70	Pre 1947	1941-70	1941-70
Source *	1	1	2	1	1

* 1 Canada Dept. Envir. 1975.
2 Canada Dept. Transp. 1947.

is the warmest month. The approximate number of degree days, from May 1 through September 30, is 2200 to 2400 (Longley, 1968).

4.2.3 Vegetation

The study area falls within the aspen parkland vegetative zone, which forms a transition between deciduous/coniferous forests of the north, and short and midgrass prairies to the south (Pettapiece, 1969). There is a gradual increase in the proportion of midgrass, mixed prairie grassland as one moves southward at the expense of tree cover.

In the northern area, the dominant tree cover is aspen poplar (Populus tremuloides) with willow (Salix spp.) commonly occurring in moist, non-saline depressions. White Spruce (Picea glauca) is occasionally associated with poplars in moister areas. More open areas consist of various shrubs and herbaceous vegetation intermixed with a variety of grasses. Rose species (Rosa spp.) are the most common shrubs while Canada Anenome (Anenome canadensis), Cinquefoil (Potentilla spp.), Goldenrod (Solidago spp.) and Common Yarrow (Achillea mil[illegible]ia) comprise the more conspicuous herbs. Smartweed (Polygonum [illegible]nifolium), Dock (Rumex spp.) and Water Parsnip (Sium suave) are frequently found in moister positions. Grasses include various admixtures of Wheat Grasses (Agropyron spp.), Blue Gramma Grass (Bouteloua syzigaehne), Rough Fescue (Festuca scabrella), June Grass (Koeleria cristala) and Bluegrasses (Poa spp.).

Towards the south of the study area the proportion of grassland increases and minor vegetative changes indicate a slightly drier climate. Gumweed (Grindelia squarrosa) appears along with Needle Grasses (Stipa spp.) while the proportion of Common Yarrow and Buffalo Bean

(*Thermopsis rhombifolia*) increases.

A more complete listing of the more common vegetation species and their habitat is given in Table 19.

Various weed species are well represented throughout the area. The best represented family is the Cruciferae, including Stinkweek (*Thlapsi arvense*), Common Peppergrass (*Lepidium densiflorum*), Shepherd's-purse (*Capsella bursa-pastoris*), Flixweed (*Descurainia sophia*), as well as several other less common species. Troublesome perennial weeds include Quack Grass (*Agropyron repens*), Canada Thistle (*Cirsium arvense*) and Common Dandelion (*Taraxacum officinale*). Green Foxtail (*Setaria viridis*) and Chickweek (*Stellaria media*) are more common in the northern area. Several other species are also present, as indicated in Table 20.

4.2.4 Geology

4.2.4.1 Bedrock Geology

The two major bedrock units within the study area are the Edmonton and Bearpaw Formations (Rutherford, 1939; Warren and Hume, 1939; Stalker, 1960). Both are of upper Cretaceous age with the former primarily brackish or freshwater in origin (Stalker, 1960) and the latter marine (Geol. Surv. Can., 1967; Green, 1972, as quoted by Hackbarth, 1975).

The Edmonton formation consists of argillaceous sandstones, bentonitic shales, carbonaceous shales, thin bentonitic beds and coal seams (Geol. Surv. Can., 1967). The Edmonton formation underlies the majority of the study area to the west and south (Rutherford, 1939; Warren and Hume, 1939). In the northeast region the Bearpaw

Table 19. Common vegetation species found throughout the study area.

Family	Genus and Species	Common Name	Habitat
Pinaceae	*Picea glauca*	White Spruce	[illegible]sional occupant of poplar bluffs.
Typhaceae	*Typha latifolia*	Common Cattail	Marshes and wet roadsides.
Gramineae	*Agropyron spp.*	Wheat Grass	Several species well represented. Common in relatively well-drained positions.
	Beckmannia syzigachne	Slough Grass	Marshes and wet roadsides.
	Bouteloua gracilis	Blue Grama Grass	Common in grassland.
	Bromus inermis	Awnless Brome	Disturbed areas, escaped cultivation.
	Festuca scabrella	Rough Fescue	Common in prairie grassland.
	Hordeum jubatum	Foxtail Barley	Common in low moist areas and saline flats.
	Koeleria cristata	June Grass	Common in prairie grassland.
	Poa spp.	Bluegrass	Several species fairly common in prairies or parkland. Moist or drier areas, depending upon species.
	Stipa spp.	Needle Grasses	Several species found in drier areas of the prairie grassland.
Cyperaceae	*Carex spp.*	Sedges	
Iridaceae	*Sisyrinchium spp.*	Blue-eyed Grass	Moist or wet areas, particularly common along fencelines in prairies.
Salicaceae	*Populus tremuloides*	Trembling Aspen	Most common tree species in the parkland area.
	Salix spp.	Willow	Moist, depressional areas.
Polygonaceae	*Polygonum lapathifolium*	Smartweed	Moist, depressional areas, low lying fields.
	Rumex spp.	Dock	Wet areas.
Ranunculaceae	*Anenome canadensis*	Canada Anenome	Roadsides, thickets. More common in the northern area.
	Ranunculus spp.	Buttercup	Moist and occassionally saline [illegible]
Rosaceae	*Potentilla spp.*	Cinquefoil	Fairly common in moist and dry grassland and wooded areas, depending upon species.
	Rosa spp.	Rose	Common in grassland and wooded areas, depending upon species.

Table 19. (continued). Common vegetation species found throughout the study area.

Family	Genus and Species	Common Name	Habitat
Leguminosae	*Astragalus spp.*	Milk Vetch	Moist, wooded areas as well as dry grassland, depending upon species.
	Caragana arborescens	Common Caragana	Farmyards and shelterbelts. Introduced.
	Lupinus spp.	Lupine	Common in prairie grassland and open woods.
	Medicago spp.	Medick (Alfalfa)	Disturbed areas and roadsides. Introduced.
	Melilotus spp.	Sweet Clover	Disturbed areas and roadsides. Introduced.
	Thermopsis rhombifolia	Buffalo Bean	Common in grasslands and roadsides.
	Trifolium spp.	Clover	Disturbed areas and roadsides. Introduced and native species which have escaped cultivation.
	Vicia americana	Vetch	Open woods and moist areas. More common in northern area.
Geraniaceae	*Geranium bicknellii*	Crane's-bill	Open woods, disturbed areas. More common in northern area.
Umbelliferae	*Heracleum lanatum*	Cow Parsnip	Open woods and moist areas. More common in northern area.
	Sium suave	Water Parsnip	Moist areas, sloughs. More common in northern area.
Rubiaceae	*Galium boreale*	Northern Bedstraw	Wooded areas and roadsides. More common in northern area.
Compositae	*Achillea millefolia*	Common Yarrow	Very common in native grassland.
	Aster spp.		Well represented genus with species in several habitats.
	Grindelia squarrosa	Gumweed	Dry prairies, disturbed areas and saline areas. Rare in northern area.
	Solidago spp.	Goldenrod	Several species common throughout study area.

formation appears. The Bearpaw consists of interbedded argillaceous sandstones, sandy and silty shales, thin, concretionary ironstone beds and bentonitic beds (Geol. Surv. Can., 1967). Both bedrock formations dip towards the west and southwest at approximately 3 to 4 m/km (Le Breton, 1971).

4.2.4.2 Physiography and Surficial Geology

The entire study area falls within the Torlea flats physiographic division and contiguous areas (Stalker, 1960). This is an area of low local relief with elevations ranging from approximately 700 to 820 m ASL. The area is characterized by shallow, small, frequently dry and saline lakes and sloughs (Stalker, 1960). One small river, the Battle River, transects this physiographic unit (Figure 10).

The area is dominated by glacial till deposits of relatively shallow thickness. Drift thickness in the Torlea flats ranges from 3 to 8 m in the northern region to less than 1.5 m in the southern and southeastern extremities (Stalker, 1960; Gravenor, 1956). Average thickness is 1.5 to 3.0 m. The thin glacial till deposits generally occur as relatively level to rolling ground moraine systems although localized areas of hummocky moraine are present. Relatively level lacustrine deposits and occasional, scattered hills are also present. The majority of the glacial material is derived locally from underlying sediment (Stalker, 1960).

Three till members have been described (Stalker, 1960). They differ primarily in age, degree of compaction and degree of influence by groundwater, rather than in composition. In ascending order, the three till members are Labuma, Maunsell and Buffalo Lake. This order generally corresponds to decreasing age, decreasing depth of burial below the water table, decreasing compaction, decreasing content of carbonaceous material and increasing permeability.

4.2.4.3 Hydrogeology

Hydrogeological conditions within the study area are described by Le Breton (1971) and Hackbarth (1975). The water table can be approximated by the land surface and is generally within 15 m of ground surface. Active groundwater flow is generally within 90 m of ground surface and as such is mainly within non-surficial deposits. Chemistry within the bedrock waters tends to be comprised of Na^+ and K^+ in combination with Cl^-, although SO_4^{2-} is proportionately higher in the southern region (Castor area). Groundwater composition in the drift materials consists of predominately Ca^{2+} and Mg^{2+} in combination with CO_3^{2-} and HCO_3^-, although the proportion of Na^+, K^+, Cl^- and SO_4^{2-} increases slightly when the drift is relatively shallow. Areas of thick drift generally represent groundwater recharge areas while discharge areas occur where underlying bedrock deposits are in close proximity to ground surface. Approximate groundwater composition is given in Table 21.

4.2.5 Soil Inventories

The area encompasses the Black soil zone in the north and grades into the Dark Brown soil zone in the south. The majority of the soils in the area are Chernozemic and Solonetzic with minor areas of Luvisolic and Gleysolic soils (Bowser et al., 1947, 1951; Wyatt et al., 1938, 1944). The majority of the soils have formed within medium textured

Table 21. Groundwater hydrology and hydrochemistry of selected well logs within the study area.

Adjacent Site	Well Location	Depth to Water (m)	Uppermost Formation	TDS at Water Surface (ppm)	Approximate Groundwater Composition (%)				
					Cations		Anions		
					$Na^+ + K^+$	Ca^{2+}	$CO_3^{2-} + HCO_3^-$	SO_4^{2-}	Cl^-
1&2	30-44-14-W4	12	Edmonton	1000	100	0	55	10	35
	24-46-16-W4	15	Bearpaw	1000	90	10	25	0	75
	24-46-16-W4	5	Bearpaw	1000	65	35	85	0	15
3	8-43-16-W4	--	Edmonton	1000	90	10	80	10	10
4	9-39-15-W4	15	Edmonton	2500	100	0	70	0	30
	10-39-15-W4	75	Edmonton	3000	90	10	20	0	80
	11-39-15-W4	215	Edmonton	5000	90	10	15	0	85
	11-39-15-W4	115	Edmonton	400[illegible]	90	10	15	0	85
5	4-38-15-W4	25	Horseshoe Canyon *	1500	100	0	30	55	15

Sources: Le Breton 1971; Hackbarth 1975.
* Horseshoe Canyon Formation appears to be synonomyous with the Edmonton Formation.

(loam to clay loam) morainal deposits although significant areas of soils, particularly in the south and southeast, have formed within till veneers underlain by modified Cretaceous sediments at shallow depth (Table 22). In addition to that information given in Soil Survey reports (Table 22), Bowser et al. (1962) examined features of soils within the area. A portion of their results were discussed in Chapter 2 (2.2).

4.3 Materials and Methods

4.3.1 Soil Morphology

Soil cores (75 mm diameter) to a depth of approximately 1 m were taken in the fall of 1980 following crop harvest. Eight cores were taken at each of the five sites, four in each of the deep plowed and conventionally tilled soils (see Figure 9). Horizons were discerned and colour (Munsell), texture, structure and consistence were described according to the Canada Soil Survey Committee (1978). Horizon designations were initially assigned in the field and were later modified pending the outcome of chemical analysis. Direct soil classification was not possible in some instances as cultivation destroyed diagnostic horizons. In these instances classification is inferred on the basis of other soil properties.

4.3.2 Soil Micromorphology

4.3.2.1 Thin Section Preparation

In the fall of 1980, 100 mm diameter cores were taken to a depth of 250 mm for micromorphological characterization. Cores were air dried for two months followed by oven drying at 50°C. The cores were impregnated using "Scotchcast" epoxy resin according to the method of

Table 22. Dominant soil complexes described in the vicinity of the various study sites.

Site	Legal Location	Soil Complex	Classification*	Parent Material	Reference
1	NE 9-46-16-W4	Daysland L.	BL.SO	morainal	Bowser _et al_ 1947
		Killam L.	BL.SS	morainal	
		Elnora L.	O.BL	morainal	
2	NW31-45-14-W4		BL.SS	morainal	Wyatt _et al_ 1944
3	NE12-42-16-W4	Killam L. (shallow phase)	BL.SS	morainal	Bowser _et al_ 1947
4	SW 3-40-16-W4	Torlea L.	DB.SS	residual	Bowser _et al_ 1951
		Gadsby L.	BL.SS	glacial-lacustrine	
5	SW34-37-14-W4		DB.SS	sorted residual	Wyatt _et al_ 1938

* Classification is according to the Canada Soil Survey Committee (1978).

Innes and Pluth (1971). After impregnation the cores were sectioned to produce 50 mm x 75 mm x 25 mm blocks in vertical increments of 75 mm. During sectioning the outer 25 mm was discarded as this was the most disturbed during sampling. The final thin sections, which measured [illegible] mm x 75 mm x 30 µm were prepared by the Soil Science Laboratory, Laval University, Quebec.

4.3.2.2 Descriptive Terminology

Micromorphological investigations were undertaken to describe soil fabrics according to related distribution and plasma separation and to describe soil voids. Definitions of descriptive terminology are those given by Brewer (1976) and Brewer and Pawluk (1975). The following definitions (Brewer, 1976) are basic to micromorphological descriptions.

Primary Ped: those peds in a soil which cannot be subdivided further to produce smaller peds. They represent the simplest peds in a soil material but may be grouped together to form larger peds.

s-matrix: that material comprising primary peds, which may consist of plasma, skeletal grains and voids.

Plasma: colloidal sized, relatively soluble, organic and inorganic material which is not bound up by skeletal grains.

Skeletal grains: grains larger than colloidal material, which are comprised of indigenous minerals.

Soil Fabrics According to Related Distribution (Brewer, 1976; Brewer and Pawluk, 1975).

Related distribution refers to the orientation of a group of like individuals with respect to a different group of like individuals. It can be described in terms of the relationship between plasma and skeletal grains or the relationship between matrix material and complex three-dimensional units. The various types recognized herein are:

Porphyroskelic fabric: the plasma occurs as a dense groundmass within which skeletal grains are imbedded.

Granic fabric sequence: unaccommodated, loosely packed, discrete units without coatings on or bridges between units. If the units exhibit some coalescence around the edges the term granoidic is used. Where the units are densely packed they may appear as a vughy groundmass and approach a porphyric type of fabric. Modifiers are typically added to describe the composition of the granic or granoidic units. Modifiers include ortho- (mineral grains), phyto- (partially decomposed plant fragments), humi- (highly decomposed, dark, moder-like organic units), matri- (matrix material) and mull- (mull-like units consisting of plasma plus skeletal grains with plasma birefringence masked by organic matter).

Fragmic fabric sequence: relatively densely packed, accommodated discrete units without coatings, on, or bridges between units. A patterned appearance generally results due to separation of units by horizontal and vertical joint planes. When adjacent units appear partially united, the term fragmic is replaced by fragmoidic. Densely packed units of this fabric sequence may also approach the porphyric type.

Iunctic fabric (formerly gefuric): f-matrix material forms loose infillings and bridges between framework members but does not entirely infill the areas nor does it entirely coat framework members. Bare surfaces of framework members commonly form walls of the larger voids.

Banded fabric: a succession of bands separated by a series of parallel, horizontal to subhorizontal, joint planes. These bands exhibit a gradation in colour and matrix from top to bottom. The top has a higher concentration of plasma and exhibits a darker colour than the bottom.

Isobanded fabric: as with banded fabric except the bands do not exhibit a change in density of matrix material or a gradation in colour throughout the thickness of the band.

Complex Fabrics (Brewer and Pawluk, 1975).

Designation of complex fabrics recognizes the presence of two or more modal fabric types within a given zone. They are recognized as mixed or separated.

Mixed complex fabrics: fabrics in which the component fabrics are inextricably intermixed; that is, they are intimately associated with one another such that they cannot be separated. An example is matri-mullgranoidic, in which mullgranoidic fabric is dominant yet matrigranoidic material is found in intimate association.

Separated complex fabrics: the component modal fabrics can be separated into distinct, recurring zones. An example is mullgranic/mullgranoidic fabric where sharp boundaries exist between a dominant mullgranoidic fabric and subdominant zones of mullgranic fabric. A double slash (//) indicates there is a gradual boundary between the two fabrics.

Plasmic Fabrics (Brewer, 1976).

Analysis of the plasmic structure involves the description and classification of elements of the s-matrix, with particular reference to the distribution and orientation of clay domains. Optical properties, particularly extinction patterns, are viewed under crossed nicols and are classified according to: visible plasma crystals; the kind and degree of orientation of plasma grains; the kind and degree of preferred orientation; and the kind and degree of development of plasma separations. Plasmic fabrics observed herein fall into the sepic class of Brewer (1976), and have "recognizable anisotropic domains with various patterns of preferred orientation". A brief account of those plasmic fabrics observed is outlined below.

Insepic fabric: striated plasma separations occur as isolated patches within a dominantly flecked plasma.

Mosepic fabric: striated plasma separations may adjoin each other but the appearance is otherwise flecked.

Vosepic fabric: a portion of the plasma separations are associated with the walls of voids, the remainder is flecked.

Skelsepic fabric: [illegible]ion of the plasma separations are associated with [illegible]ces of skeletal grains, the remainder is flecked.

Masepic fabric: elongated zones of striated plasma occur, the remainder is flecked.

Complex fabrics can be named where more than one plasmic fabric is present. For example, if plasma separations are dominantly flecked with minor zones of oriented plasma occurring subcutanically in association with skeletal grains, the appropriate term is skel-insepic.

Voids (Brewer, 1976).

Voids, which represent the pore fraction, are described with respect to their size, shape and arrangement. Only a minor description of those voids described is given here.

Vughs: randomly distributed and oriented voids of irregular size and shape; usually not interconnected with other voids.

Joint planes: these are planar voids elongated in two directions and limited in the third. They are generally random to interpedal, are parallel to subparallel, have a specific referred orientation and have relatively regular, smooth walls. An example is subparallel sets of joint planes in the banded fabric of an Ae horizon.

Skew planes: generally similar to joint planes except they lack any specific referred orientation; that is, they are random in orientation and distribution.

Craze planes: generally interpedal planar voids. They are complex, irregular and randomly oriented voids due to their association with accommodated peds.

4.3.2.3 Image Analysis (Density Slicing)

Image analysis was performed on selected thin sections to determine the extent of various genetic materials within a given thin section. Equipment utilized was supplied by the Alberta Remote Sensing Centre, Edmonton, and consisted of a light table, TV camera, density slicer and colour TV monitor. The image is converted by the density slicer into a video signal of up to 32 grey tones and is displayed on the TV monitor. The proportion of the various materials was determined by assigning a given density range or ranges to a given material. Density intervals were adjusted to reduce the amount of overlap between different genetic materials. A more complete description of the density slicing unit can be obtained by contacting personnel at the Alberta Remote Sensing Centre.

4.4 Discussion

4.4.1 Site Description

4.4.1.1 Landform

Sites 1 and 2 are located in an area dominated by hummocky to undulating morainal deposits. Plots at both these sites were placed along the slope. Plots occupied the crest, midslope and lower slope positions, similar to that shown in Figure 9b.

Level to rolling is the dominant surface expression at sites 3, 4 and 5. Surficial deposits generally consist of a relatively thin till veneer overlying modified, unconsolidated Cretaceous sediment. For sites 3 and 5 plots were established along the slope while at site 4 plots were on the slope contour. In all instances the plots occupied an approximate midslope position.

Data of McCracken (1979) indicating approximate depth to bedrock is given in Table 23.

4.4.1.2 Drainage

Table 23 also gives water-table depths at most study sites during a portion of 1978. For the most part groundwater is relatively shallow, particularly in the early summer months. Overall water-table depths are slightly shallower where the depth of till is shallow.

Table 23. Depth to bedrock and water table levels at the study sites during 1978 (After McCracken 1979).

Site	Water Table Well Number	Depth to Bedrock (m)	Depth to Water Table (m) March	June	August
1	1	>4.6	4.0	4.1	3.9
	2	4.1	3.5	2.9	1.9
	3	>4.6	3.1	3.3	3.0
2	N/A	N/A	N/A	N/A	N/A
3	1	>4.6	dry	5.7	---
	2	>6.1	dry	2.7	---
	3	>3.0	dry	4.3	---
4	1	2.1	dry	2.8	3.0
	2	2.4	dry	dry	3.0
	3	1.8	dry	4.5	4.5
5	1	2.0	dry	dry	1.2
	2	1.5	dry	2.3	---
	3	1.5	dry	2.4	2.5

N/A - not available

4.4.2 Soil Morphology

Horizon designations and morphological descriptions for conventionally tilled soils of sites 1 through 5 are given in Tables 24 through 28, respectively. Descriptions of the deep plowed soils are not given here, due to difficulty encountered in distinguishing features, the variability of those features and the resultant complexity of morphological descriptions.

Soil profiles at site 1 (Table 24) are found on the following slope positions: profile 1 - lower slope; 2 - lower slope; 3 - midslope; and 4 - upper slope. Because undisturbed Ah horizons, Ae horizons and/or AB horizons have not been destroyed by cultivation, subgroup classification is possible. For profiles 1 through 4, the respective classifications (Canada Soil Survey Committee, 1978) are: Orthic Black Chernozem; Black Solod; Black Solod; and Solonetzic Black Chernozem. In this classification chemical constraints (Appendix A, Table 61) have been considered and are reflected in horizon designations of Table 24.

The soils do not conform ideally to concepts of landscape features for Solonetzic regions. Bentley and Rost (1947) and Bowser (1961) describe a general sequence of O.BL → SZ.BL → BL.SO → BL.SS → BL.SZ as one moves downslope and the degree of groundwater influence increases. That is, advanced stages of Solonetz evolution are associated with better drained sites in higher topographic positions. Joffe (1936) and Ellis <u>et al.</u> (1970) as cited by Peters (1982) report the reverse to be true: weakly developed Solonetz profiles occupy the higher landscape positions while those in advanced stages of evolution (Solods) occupy lower slope positions. Increased leaching resulting from moisture redistribution to lower slopes is the rationale behind this

Table 24. Morphological descriptions of the soil profiles at site 1.

Profile	Horizon	Depth (cm)	Description
1	Ap	0-10	Black (10YR 2/1 m); loam; moderate granular; friable.
	Ah	10-25	Black (10YR 2/1m); loam; moderate to strong granular; friable.
	AB	25-43	Very dark grayish brown (10YR 3/2m); loam to clay loam; moderate blocky and moderate granular; firm.
	Bm	43-70	Dark yellowish brown (10YR 4/4m); loam to clay loam; weak to moderate blocky; firm.
	BC	70-91	Dark yellowish brown (10YR 4/4m); weak blocky to amorphous; firm.
	Cca	91+	Yellowish brown (10YR 5/4m); loam to clay loam; amorphous; firm.
2	Ap	0-13	Black (10YR 2/1m); sandy loam; moderate granular; friable.
	Krotovena	13-15	
	Ahe	15-28	Very dark grayish brown (10YR 3/2m); sandy loam; moderate granular to weak platy; friable.
	AB	28-41	Very dark grayish brown (10YR 3/2m); loam; moderate to strong blocky; very firm.
	Bnt	41-66	Dark brown (10YR 3/3m); clay loam; weak fine prismatic and moderate blocky; very firm.
	BCk	66-76	Dark brown (10YR 4/3m); loam; weak fine prismatic to amorphous; very firm.
	Ccas	76-97	Yellowish brown (10YR 5/4m); loam; amorphous; firm.
	Ccasa	97+	Yellowish brown (10YR 5/4m); loam; amorphous; firm.
3	Ap	0-11	Black (10YR 2/1m); loam; weak to moderate granular; friable.
	Ah	11-16	Black (10YR 2/1m); loam; moderate to strong granular; friable.
	Ae	16-20	Grayish brown (10YR 5/2m); loam; weak fine platy; friable.
	AB	20-26	Very dark grayish brown (10YR 3/2m); loam to clay loam; moderate fine to medium blocky; firm.
	Bnt_1	26-41	Dark brown (10YR 3/3m); weak columnar and moderate fine to medium blocky; very firm.
	Bnt_2	41-51	Dark brown (10YR 4/3m); clay loam; weak columnar; very firm.
	BCsk	51-61	Dark brown (10YR 4/3m); clay loam; weak columnar to amorphous; very firm.
	Ccas	61-87	Yellowish brown (10YR 5/4m); loam; amorphous; very firm.
	Ccasa	87+	Dark brown (10YR 4/3m); loam; amorphous; firm.
4	Ap	0-8	Very dark grayish brown (10YR 3/2m); loam; weak fine granular; friable.
	Ah	8-12	Black (10YR 2/1m); loam; weak fine granular; friable.
	Ahe	12-26	Very dark grayish brown (10YR 3/2m); loam; weak platy and weak coarse blocky; firm.
	AB	26-38	Dark brown (10YR 4/3m); loam to clay loam; weak blocky; firm.
	$Btnj_1$	38-51	Dark yellowish brown (10YR 4/4m); clay loam; weak columnar and moderate blocky; very firm.
	$Btnj_2$	51-65	Dark yellowish brown (10YR 4/4m); clay loam; weak prismatic and weak blocky; very firm.
	BCk	65-81	Dark yellowish brown (10YR 4/4m); loam to clay loam; weak blocky to amorphous; very firm.
	Ck	81-94	Dark yellowish brown (10YR 4/4m); loam; amorphous; firm.
	Csk	94+	Dark yellowish brown (10YR 4/4m); loam; amorphous; very firm.

type of catena.

The two schools of thought are likely both important in recognition of associated soils and their geomorphic relations. Geologic material is not homogeneous nor isotropic such that groundwater conditions can be accurately assessed on the basis of topographic information alone. On the same token, net leaching is not only a function of surface moisture but as well is strongly dependent upon internal drainage and groundwater flow. MacLean and Pawluk (1976) found the distribution of Solonetzic soils within a landscape cannot be explained entirely on the basis of topographic or hydrogeologic features alone and, even when hydrochemical features are evaluated, the catenary sequence of Solonetzic soils is highly variable. Several factors are undoubtedly responsible for the catenary sequence observed at site 1.

Morphological features given in Table 24 generally conform to those previously given within the region (Bowser <u>et</u> <u>al</u>., 1947, 1962). Solonetzic soils at this site are in an advanced stage of evolution, as indicated by blocky mesostructures in the B horizons and as reflected in the actual soil classification. Data in Table 23 indicate the water table is fairly deep and this is likely reflected in the soil profiles observed. The Orthic Black Chernozem observed in the lower slope position is not salt affected within sampling depth (Appendix A, Table 54), although its deep plowed counterpart is saline at 48 cm (Appendix A, Table 62). This implicates considerable variability in soil permeability which may reflect stratification of materials below sampling depth.

It is interesting to note the Solonetzic Black Chernozem in the upslope topographic position (profile 4, Table 24) morphologically exhibits strong Solonetzic features, including a columnar structure, very firm consistence when wet, extremely hard consistence when dry, and dark humate staining on ped surfaces. Chemical criteria, however, exclude this profile from the Solonetzic order (Appendix A, Table 61). Similar anomalies have been observed elsewhere in Alberta (Reeder and Odynsky, 1964) but not within this region.

The presence of Ah horizons underlying Ap horizons is unusual within cropped landscapes. This is possibly related to prior soil management. The check strip was located in close proximity to the legal field boundary relative to the center of the field. For many years tillage was accomplished with the use of a "one-way" tiller which, over time, could result in deposition of tilled A horizon material at the field extremeties at the expense of material in the center of the field.

Soil features at site 2 (Table 25) are similar in nature to those of site 1. Soil profiles and corresponding slope positions are: 1 - lower slope; 2 - lower slope: 3 - midslope; and 4 - upper slope. Soil classification for these profiles are: 1 - Orthic Black; 2 - Black Solodized Solonetz; 3 and 4 - Solonetzic Black Chernozem. Anomalies with respect to morphological and chemical criteria were not observed here, although as at site 1 an Orthic Black Chernozem was observed in the lower slope position. Both Solonetzic Black Chernozems exhibited only weak Solonetzic features.

Salts within the profiles generally occur at shallower depths relative to those soils at site 1. Although no groundwater information is available, this suggests the water-table depth may be shallower at site 2 relative to site 1. The presence of a Black Solodized Solonetz (profile 2) supports this viewpoint. In addition, the presence of

Table 25. Morphological descriptions of the soil profiles at site 2.

Profile	Horizon	Depth (cm)	Description
1	Ap	0-8	Very dark gray (10YR 3/1 d); loam; moderate granular; slightly hard.
	Bm	8-28	Dark yellowish brown (10YR 3/4 d); loam; weak to moderate blocky; hard.
	BCk	28-48	Dark brown (10YR 4/3 d); loam; weak blocky; hard.
	Cca	48-76	Brown (10YR 5/3 d); loam; amorphous; hard.
	$Ccas_1$	76-101	Dark Brown (10YR 4/3 d); loam; amorphous; hard.
	$Ccas_2$	101+	Pale brown (10YR 6/3 d); loam; amorphous; hard.
2	Ap	0-13	Black (10YR 2/1 m); loam; moderate fine granular; friable.
	Ae	13-20	Brown (10YR 5/3 d); loam to sandy loam; weak fine platy and moderate fine granular; slightly hard.
	Bnt	20-33	Dark brown (10YR 3/3 d); clay loam; moderate to strong columnar and strong medium to coarse blocky; extremely hard.
	BC	33-36	Brown (10YR 3/4 d); clay loam; moderate blocky; very hard.
	Ccasa	36-63	Yellowish-brown (10YR 5/4 d); loam; amorphous; very hard.
	Ccas	63-108	Yellowish-brown (10YR 5/4 d); loam; amorphous; very hard.
	Csa	108+	Brown (10YR 5/3 d); loam; amorphous; hard to very hard.
3	Ap	0-15	Black (10YR 2/1 m); loam; moderate fine granular; friable.
	Btnj	15-33	Dark brown (10YR 4/3 d); clay loam; moderate columnar and strong blocky; very hard.
	BCk	33-46	Brown (10YR 5/3 d); clay loam; moderate columnar and moderate blocky; very hard.
	$Ccas_1$	46-70	Yellowish-brown (10YR 5/4 d); loam; amorphous; very hard.
	$Ccas_2$	70-90	Yellowish-brown (10YR 5/6 m); loam; amorphous; friable.
	$Ccas_3$	90+	Brown (10YR 4/3 m); loam; amorphous; firm.
4	Ap	0-12	Black (10YR 2/1 m); moderate granular; friable.
	Ae	12-20	Brown (10YR 5/3 d); loam; weak coarse platy; slightly hard.
	AB	20-33	Dark brown (10YR 3/3 d); loam to clay loam; weak to moderate blocky; slightly hard.
	Btnj	33-53	Dark brown (10YR 4/3 d); clay loam; weak columnar and strong blocky; extremely hard.
	BCk	53-66	Yellowish-brown (10YR 5/4 d); loam to clay loam; weak prismatic and moderate blocky to amorphous; very hard.
	Cca	66+	Pale brown (10YR 6/3 d); loam to clay loam; amorphous; very hard.

soluble salts and carbonates in the same horizons implicates a relatively shallow, stable water table.

Morphological descriptions for soils observed at site 3 are given in Table 26. Unlike the previous two sites they are uniform in apparent horizon sequence and therefore classification, but differ markedly in lithology. With respect to location within the landscape, all soils are found within relatively level terrain.

Based on morphological, micromorphological and analytical features (see Chapter 5) the classification for these soils is as follows: profile 1 - Black Solod; Profiles 2, 3 and 4 - Black Solodized Solonetz or Black Solod. Differences in clay content (both total and fine clay) as well as differences observed in phyllosilicate distribution upon deep plowing suggest relatively intense eluviation from the Ap horizon and thus implicate the development of a Solodized Solonetz or Solod for profiles 2, 3 and 4. This, however, is at best subjective in lieu of distinguishing morphological criteria.

Stalker (1960) reports the presence of a discontinuous esker ridge within the immediate vicinity of site 3. This is supported upon visual observation of the field as well as the lithologic sequence in the soils examined. Profiles 2 and 3 have, within sampling depth, C horizon material (IIC) which is distinguishable as lenses or strata from overlying and/or underlying material in terms of colour, texture and/or structure. The IIC horizon material is higher in chroma than the underlying material (profile 3), coarser in texture than the overlying or underlying material (profiles 2 and 3) and may be single grained (profile 3). Such a lithologic sequence suggests a possible glacio-fluvial origin associated with internal ice flows. Gley features

Table 26. Morphological descriptions of the soil profiles at site 3.

Profile	Horizon	Depth (cm)	Description
1	Ap	0-12	Black (10YR 2/1 m); loam; moderate fine granular; friable.
	Ahe	12-16	Very dark grayish-brown (10YR 3/2 m); loam; weak fine platy and moderate fine granular; friable.
	Ae	16-20	Grayish-brown (10YR 5/2 d); sandy loam; weak to moderate fine platy; slightly hard.
	AB	20-29	Brown (10YR 4/2 d); loam; moderate to strong fine blocky; hard.
	Bnt	29-63	Yellowish-brown (10YR 5/4 d); clay loam; moderate columnar to strong blocky; very hard.
	BCk	63-70	Brown (10YR 5/3 d); clay loam; weak columnar and moderate coarse blocky; very hard.
	Ck	70-85	Light yellowish-brown (10YR 6/4 d); loam to clay loam; amorphous; very hard.
	IICsk	85+	Yellowish-brown (10YR 5/4 d); clay loam; amorphous; very hard.
2	Ap	0-14	Dark grayish-brown (10YR 4/2 d); clay loam; moderate fine granular; slightly hard.
	Bnt	14-35	Dark brown (10YR 4/3 d); clay loam; moderate columnar and strong fine to medium blocky; very hard.
	BCk	35-57	Brown (10YR 5/3 d); clay loam; weak columnar to amorphous; hard to very hard.
	IICcag	57-61	Gray (7.5YR 5/0 m); sandy loam; common, fine, prominent, strong brown (7.5YR 5/8 m) mottles; amorphous; firm.
	$IICsk_1$	61-83	Yellowish-brown (10YR 5/4 d); loam to sandy loam; amorphous; hard.
	$IICsk_2$	83+	Brown (10YR 5/3 d); loam; amorphous; hard.
3	Ap	0-14	Dark grayish-brown (10YR 4/2 d); loam; moderate fine granular; slightly hard.
	Bnts	14-33	Dark brown (10YR 4/3 d); clay loam; strong columnar and moderate to strong blocky; very hard.
	BCcas	33-53	Brown (10YR 5/3 d); loam; moderate columnar to amorphous; very hard.
	IICca	53-59	Brown (10YR 5/3 d); sandy loam to loamy sand; amorphous to single grained; slightly hard.
	IICcasa	59-73	Yellowish-brown (10YR 5/4 d); loam to sandy loam; amorphous; very hard.
	IIICsak	73-92	Very dark grayish-brown (10YR 3/2 d); clay loam; amorphous; very hard.
	IIICs	92+	Dark grayish-brown (10YR 4/2 d); clay loam; amorphous; very hard.
4	Ap	0-14	Dark gray (10YR 4/1 d); loam; moderate fine granular; slightly hard.
	Bnt	14-32	Very dark gray (10YR 3/1 m); clay loam; strong columnar and moderate blocky; very firm.
	BCsa	32-44	Dark grayish-brown (10YR 4/2 d); clay loam; moderate columnar to amorphous; hard.
	Ccas	44-69	Pale brown (10YR 6/3 d); loam to clay loam; amorphous; hard.
	IICk	69-84	Grayish-brown (10YR 5/2 d); clay loam; amorphous; extremely hard.
	IICs	84+	Pale brown (10YR 6/3 d); clay loam; amorphous; very hard.

observed in profile 2 further suggest this glacio-fluvial material may behave as a semi-confined aquifer for groundwater flow.

Coarse textured material, where present, is always overlain by soils developed in medium textured morainal material. Overlying depth of glacial till ranges from 53 to 85 cm. Directly underlying the glacial till within profiles 1 and 4 is modified Cretaceous sediment, which also underlies the glacio-fluvial material of profile 3. This modified Cretaceous sediment is clay loam in texture, very hard in consistence and exhibits well defined fine, subangular blocky units.

Salts occur at a shallow depth within the profiles, particularly in profiles 3 and 4 (Table 26 and Appendix A, Table 58). The presence of soluble salts in horizons overlying horizons which have accumulated carbonates (profiles 3 and 4) suggests an infusion of salts above net leaching depth. This implicates a relatively shallow, fluctuating groundwater table, although data of McCracken (1979, Table 23) indicate a relatively deep water table. It is possible that Solonetzic processes have resulted from lateral groundwater flow through the more pervious lenses and these lenses have piezometric heads independent of the topography.

Like site 3, soils at site 4 occur within a relatively uniform landscape. All profiles are on the midslope contour within rolling terrain. Diagnostic A horizons of profiles 1 and 2 may have been destroyed by cultivation, so their classification is tentative (Table 27). Analytical data in Chapter 5 suggest significant clay translocation such that profiles 1 and 2 appear to have evolved at least to the stage of Dark Brown Solodized Solonetz. The presence of salts at shallow depths and the columnar morphology of the Bnt horizons with a general

Table 27. Morphological descriptions of the soil profiles at site 4.

Profile	Horizon	Depth (cm)	Description
1	Ap	0-14	Dark brown (10YR 3/3 m); loam; weak fine granular; friable.
	Bnt	14-22	Dark brown (10YR 3/3 d); clay loam; moderate to strong columnar; extremely hard.
	Bntk	22-31	Yellowish-brown (10YR 5/4d); clay loam; moderate columnar; extremely hard.
	BCsak	31-58	Yellowish-brown (10YR 5/4 d); loam; weak columnar and moderate medium blocky upper, amorphous lower; hard.
	Csk	58-70	Yellowish-brown (10YR 5/4 d); loam; amorphous; hard. sand streaks present.
	Ccas	70+	Dark brown (10YR 4/3 d); loam; amorphous; hard.
2	Ap	0-10	Dark brown (10YR 3/3 m); sandy clay loam; weak to moderate fine granular; friable.
	Bnt	10-21	Dark yellowish-brown (10YR 3/4 m); sandy clay loam; moderate columnar and moderate subangular blocky; very firm.
	Cca	21-36	Dark brown (10YR 4/3 d); loam; amorphous; very hard.
	Ccasa	36-57	Dark brown (10YR 3/3 d); sandy loam; amorphous; hard.
	Csk	57-91	Brown (10YR 5/3 m); sandy loam; amorphous; firm.
	IICs	91-105	Light brownish-gray (10YR 6/2 m); sandy loam; amorphous; firm.
	IIICsa	105+	Dark yellowish-brown (10YR 4/4 m); clay loam; amorphous; very firm.
3	Ap	0-11	Dark brown (10YR 3/3 m); sandy loam; weak granular; very friable.
	Ae	11-24	Brown (10YR 5/3 m); sandy loam; weak platy and weak fine granular; very friable.
	Bnt	24-37	Dark yellowish-brown (10YR 4/4 d); sandy clay loam; strong columnar; very hard.
	Ccas	37-63	Dark brown (10YR 4/3 d); sandy clay loam; amorphous; hard.
	Csk	63+	Dark yellowish-brown (10YR 4/4 d); sandy loam; amorphous; hard.
4	Ap	0-13	Dark brown (10YR 3/3 m); sandy loam; weak fine granular; very friable.
	Ae	13-22	Grayish-brown (10YR 5/2 m); sandy loam to loamy sand; weak platy; friable.
	Bnt	22-39	Dark brown (10YR 3/3 d); sandy clay loam; moderate to strong columnar; very hard.
	BCk	39-53	Brown (10YR 5/3 d); sandy clay loam; weak columnar upper and amorphous lower; hard.
	Csk	53-68	Dark yellowish brown (10YR 4/4 m); sandy loam; amorphous; friable.
	IICcasa	68-93	Yellowish brown (10YR 5/4 m); sandy loam; amorphous; friable; gravelly.
	IIICcasag	93-110	Dark-yellowish brown (10YR 4/4 m); clay loam; amorphous; firm.
	IIICcag	110+	

absence of a blocky mesostructure support this classification. Based on observed horizon sequences, profiles 3 and 4 are Dark Brown Solodized Solonetz.

The sola of all soils have developed in loam to sandy loam morainal parent material. Coarse textured material underlies the sola of profiles 2 and 4 while sand lenses are present in the Csk horizon of profile 1 (Table 27). Modified Cretaceous sediments are found within sampling depth in profiles 2 and 4. Soluble salts at relatively shallow depth (31 cm+, Table 27 and Table 67, Appendix A) and gley features observed in profile 4 suggest the periodic occurrence of a relatively shallow water table.

Soils at site 5 (Table 28) also occur in the Dark Brown soil zone. All profiles occur in the midslope position in rolling terrain. The upper portion of the B horizon has, in three of the four profiles, been destroyed by cultivation. Analytical data (Chapter 5) is not as supportive for eluviation as those data for site 4 so classification is not given here. However, profiles described within the area (Wyatt et al., 1938, see Table 22) would fall into the Dark Brown Solodized Solonetz category.

All sola have developed in loamy textured glacial till. Modified Cretaceous sediment is encountered below the solum in three of the four profiles examined and is as shallow as 40 cm from ground surface (profile 4).

Morphologically, the B horizon is generally strongly developed columnar with a fairly well developed blocky mesostructure. The latter suggests some degree of Solodization has occurred. Infusion of salts in the lower solum of profiles 2 and 4 suggests a relatively shallow,

Table 28. Morphological descriptions of the soil profiles at site 5.

Profile	Horizon	Depth (cm)	Description
1	Ap+Bp	0-15	Very dark grayish brown (10YR 3/2 m); loam; weak to moderate granular; friable to firm.
	Bnt	15-29	Very dark grayish brown (10YR 3/2 m); loam to clay loam; strong columnar and moderate blocky; very firm.
	BC	29-33	Dark grayish brown (10YR 4/2 m); loam; weak blocky to amorphous; very firm.
	Csk	33-41	Dark grayish brown (10YR 4/2 m); loam; amorphous; very firm.
	Cs	41-60	Dark reddish gray (5YR 4/2 m); loam; amorphous; very firm.
	Csa	60-86	
	Csak	86-96	
	IICs	96+	Cretaceous sediment (shale).
2	Ap+Bp	0-10	Very dark grayish brown (10YR 3/2 m); loam; moderate fine granular; friable to firm.
	Bnt	10-24	Dark brown (10YR 4/3 m); loam to clay loam; weak columnar and moderate blocky; very firm.
	BCsk	24-34	Brown (10YR 5/3 d); loam; moderate blocky to amorphous; slightly hard.
	Ccasa	34-41	Pale brown (10YR 6/3 d); loam; amorphous; slightly hard.
	Ccas	41+	
3	Ap	0-9	Dark brown (10YR 3/3 m); loam; moderate fine granular; friable.
	Bnt	9-19	Dark yellowish brown (10YR 4/4 d); clay loam; moderate columnar and strong blocky; extremely hard.
	BC	19-24	Dark yellowish brown (10YR 4/4 d); loam to clay loam; weak blocky; hard.
	Ck	24-47	Yellowish brown (10YR 5/4 d) ; loam; amorphous; hard.
	Csak	47-62	
	Ccas	62-84	
	IIC	84+	Cretaceous sediment (shale).
4	Ap+Bp	0-14	Very dark grayish brown (10YR 3/2 m); loam; moderate fine granular upper and moderate to strong blocky lower; friable (upper) to very firm lower.
	Bntsk	14-25	Dark brown (10YR 4/3 d); clay loam; strong columnar and moderate to strong blocky; very hard.
	BCk	25-40	Brown (10YR 5/3 d); loam; moderate fine to medium blocky to amorphous; hard.
	IICcasa	40-53	Light brownish gray (10YR 6/2 d); loam to clay loam; amorphous; extremely hard; relatively unaltered bedrock material.
	IICcas	53+	

fluctuating groundwater table. This is supported by data of McCracken (Table 23) which indicates water tables as shallow as 1.2 m have been recorded.

Deep Plowed Soils

No attempt is given here to morphologically describe the deep plowed soils. Horizon sequences below deep plowing depth are indicated in Tables 62, 64, 66, 68 and 70, Appendix A, and are similar to those observed in conventionally tilled soils at equivalent depths. A brief summary with respect to plowing depth, however, is given here.

Plowing depth at site 1 was relatively consistent and fairly deep. Plow depth ranges from 48 to 59 cm. Although, based on the conventionally tilled profile sequences, these depths were insufficient to reach C horizon material, in most instances calcareous and saline C horizon material was observed immediately below deep plowing depth.

Depth of deep plowing was slightly shallower site 2, ranging from 38 to 48 cm. In most cases calcareous or saline C horizon material was not reached within plowing depth. In one instance a plowing depth of only 38 cm resulted in only partial disruption of an upper B horizon.

Plowing depth at site 3 ranged from 31 to 50 cm. In most instances this was sufficient to incorporate calcareous C horizon material (Table 66, Appendix A). In one instance this material was also saline.

In most instances plowing depth at site 4 was sufficient to reach calcareous and saline parent material, even though plowing depth was relatively shallow (23 to 43 cm). The shallowest plowing depth (23 cm) was sufficient to penetrate a calcareous BC horizon.

The overall shallowest, but most consistent depth of deep plowing was observed at site 5 where plowing depth ranged from 33 to 42 cm. In all instances calcareous and saline C horizon material was found immediately below plowing depth.

4.4.3 Soil Micromorphology

4.4.3.1 Fabric Analysis

Micromorphological descriptions for zones observed in both the conventionally tilled and deep plowed soils at the five sites are given in Tables 29 through 38. Descriptions are general in nature in that they describe all observed zones for a given tillage treatment and site. Not all zones are present within a given profile. For zone sequences observed within a given profile the reader is referred to Figures 11 through 20.

Descriptions for conventionally tilled and deep plowed soils at site 1 are given in Tables 29 and 30 with zone sequences indicated in Figures 11 and 12, respectively. Approximate horizon equivalents for those zone designations in Tables 29 and 30 are: I - Ap; Ia - Ah; Ib - Ahe; II - Ae; IIIa,b - AB; IVa,b,c - Bnt or Bm; A and A1 - anthropogenic material resulting from deep plowing.

Zone I, or Ap material, reflects the norm of A horizon material observed. This zone generally consists of partially fused mullgranic units with variable amounts of partially decomposed plant tissue (phytogranic units) interspersed within. The dominant natural process implied here is the accumulation of organic matter and its resultant intimate and complex association with mineral material. Zone Ia is similar to zone I except it occurs below cultivation depth and is present

Table 29. General micromorphological descriptions for zones occurring in the four conventionally tilled soil profiles at site 1.

Zone	Fabric	Description and Remarks
I	Granic//granoidic	Separated complex fabric: mullgranic units of irregular size and shape coalesce in areas to form zones of mullgranoidic fabric; degree of coalescence becomes more pronounced with depth; occasional phenoclasts; common partially decomposed plant tissue; inclusions of skel-mosepic porphyroskelic fabric commonly present when this zone directly overlies zone IV; always present.
Ia	Granic//granoidic	Separated complex fabric: mullgranic// mullgranoidic; as with I above except mull component more pronounced; normally absent.
Ib	Isobanded granoidic	Mullgranoidic: regular 5-7mm spacing of joint planes results in the appearance of isobanded fabric; mull component is similar to, or slightly weaker in expression than zone I; common.
II	Weak banded granoidic// porphyroskelic	Separated complex fabric: mull-matrigranoidic units coalesce in areas to form zones of porphyroskelic material; banding is discontinuous and rather weak; insepic plasma fabric masked by weak expression of mull component; gradually grades into III; normally absent.
III	Porphyroskelic	Insepic porphyroskelic: plasma fabric is weakly masked by the inclusion of highly humified organic matter; vughy; common.
IVa	Porphyroskelic	Skel-mosepic porphyroskelic: in some instances strongly striated zones occur resulting in a futher sub-dominant masepic plasmic fabric; vughy with numerous skew planes; common.
IVb	Porphyroskelic	Skel-masepic porphyroskelic: similar to IVa except domains are more strongly striated; mosepic plasma separations occasionally sub-dominant; vughy; numerous craze planes with units partially accommodated; normally absent.
IVc	Porphyroskelic	Skel-mosepic porphyroskelic: very similar to IVa except for the presence of highly humified organic matter imbedded in the s-matrix; normally absent.

For zone sequences see figure 11.

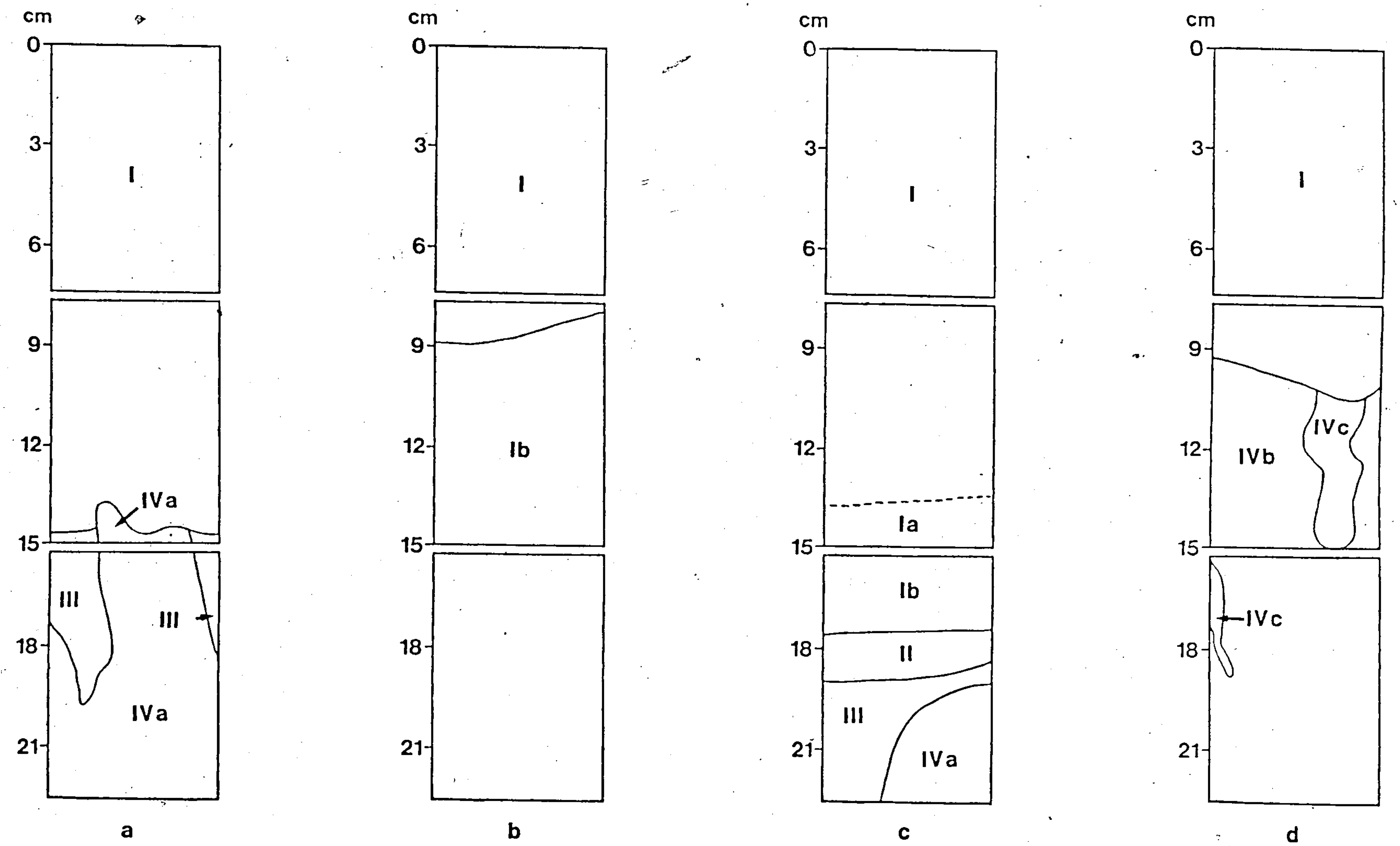


Figure 11. Micromorphological zones observed in the normally tilled soils at site 1. Profiles 1 - 4 (Table 24) are represented by figures a - d, respectively. Dashed line represents apparent tillage depth.

only in profile 3. Micromorphologically, this material is more isotropic and slightly denser than the overlying zone I. Zone Ib of profiles 2 and 3 exhibits a mullgranoidic fabric which is similar in nature to zone I. Regular 5 to 7 mm spacing of joint planes suggest this layer was at one time cultivated. Successive cultivations could be responsible for the isoband appearance of zone Ib. Pawluk and Dudas (1982) report a banded fabric separated by horizontal joint planes in the once culti[illegible] Ap of Chernozemic soil.

[illegible] II was found only in profile 3. Banded fabric and weak expression of plasma fabric in this zone suggest it is eluvial in nature. Similar descriptions for Ae horizons were reported by McMillan and Mitchell (1953) in various soils of Saskatchewan.

Zone III, observed in profiles 1 and 3, appears to represent a transitional AB horizon. Soil fabric is porphyroskelic with weak insepic plasmic fabric somewhat masked by weak humification of this zone.

B horizon material is represented by zone IV. Numerous skew, joint and/or craze planes were observed. Designation of zones as IVa,b,c, is based on plasma fabric orientation and the apparent degree of highly humified organic matter within the s-matrix. Zones IVa and IVc are similar in that plasma fabric is dominantly skel-mosepic, yet they differ in the amount of humic material within the s-matrix; humified organic matter is much more pronounced in zone IVc relative to zone IVa. Zone IVb is dominated by skel-mosepic plasma separations.

Zone IV was observed in profiles 1, 3 and 4. Skel-mosepic porphyroskelic material (IVa) is present in profiles 1 and 3. This fabric is not pronounced in that portion adjacent to overlying zones. That is, plasma tends to become more concentrated and pronounced with depth. Plasma concentration may reflect illuviation within this zone, yet only weak expression in the uppermost portion suggests clay removal from the upper B horizon is occurring. More pronounced plasma concentrations in zone IVb of profile 4 relative to profiles 1 and 3, suggest illuviation is intense and solodization has not proceeded to an advanced stage. Zone IVc, which was observed only in profile 4, has highly humified organic matter imbedded in the s-matrix. Both areas are located adjacent to vertical skew planes such that the humified material is probably the result of sodium humate translocation.

Zone sequences and implied horizon sequences do not conform well to those observed morphologically, even though sampling distance was within 2 metres. Agreement is found only with profile 3, which morphologically and micromorphologically exhibits characteristics of a Black Solod. Morphological characteristics of profile 4, which indicate the Btnj has strongly expressed Solonetzic features, are supported by the high plasma concentrations of zone IVb which were observed micromorphologically.

Micromorphological descriptions and zone sequences for the deep plowed soils at site 1 are given in Table 30 and Figure 12, respectively. For the most part zones observed are similar in nature to those observed in the conventionally tilled soils. Exceptions include a radical alteration in distribution of various materials with depth and the presence of anthropogenic material. Zones A and A1 represent this anthropogenic material which consists of an admixture of various materials in varying quantity.

Zone A represents a mixture of A and B horizon material (matri-

Table 30. General micromorphological descriptions for zones occurring in the deep plowed soils at site 1.

Zone	Fabric	Description and Remarks
A	Porphyroskelic-granoidic	Mixed complex fabric: matri-mullgranoidic; skel-mosepic porphyroskelic; proportion of either fabric type is highly variable, depending somewhat on packing density; plasma separations given are generally found in intimate association with the mullgranoidic fabric; masking of plasmic fabric by organic matter is weak to moderate; masepic plasma separations are occasionally sub-dominant; common partially decomposed plant residues; always present.
A1	Granoidic// porphyroskelic	Separated complex fabric: mull-matrigranoidic//skel-mosepic porphyroskelic; similar to fabric A but porphyroskelic material dominates and zones tend to be separated rather than mixed, although mixed zones are also present; mull component is weaker than in A; vughy; few skew planes and partially decomposed plant residues; common.
I	Granic//granoidic	Separated complex fabric: mullgranic// mullgranoidic; units are of variable size and shape and degree of coalescence governs fabric type; common partially decomposed plant residues; appears to be identical to zone I in the conventionally tilled soils except the degree of packing of mullgranic units is independant of depth; always present but proportion and depth of occurrence relative to other fabrics is highly variable.
III	Porphyroskelic	Insepic porphyroskelic: plasma separations normally masked by moderate inclusions of humified organic matter; normally absent.
IVa	Porphyroskelic	Skel-mosepic porphyroskelic: see conventional tillage, zone IVa (table 29).
IVb	Porphyroskelic	Skel-masepic porphyroskelic: see conventional tillage, zone IVb (table 29).
IVc	Porphyroskelic	Skel-mosepic porphyroskelic: see conventional tillage, zone IVc (table 29).

For zone sequences see figure 12.

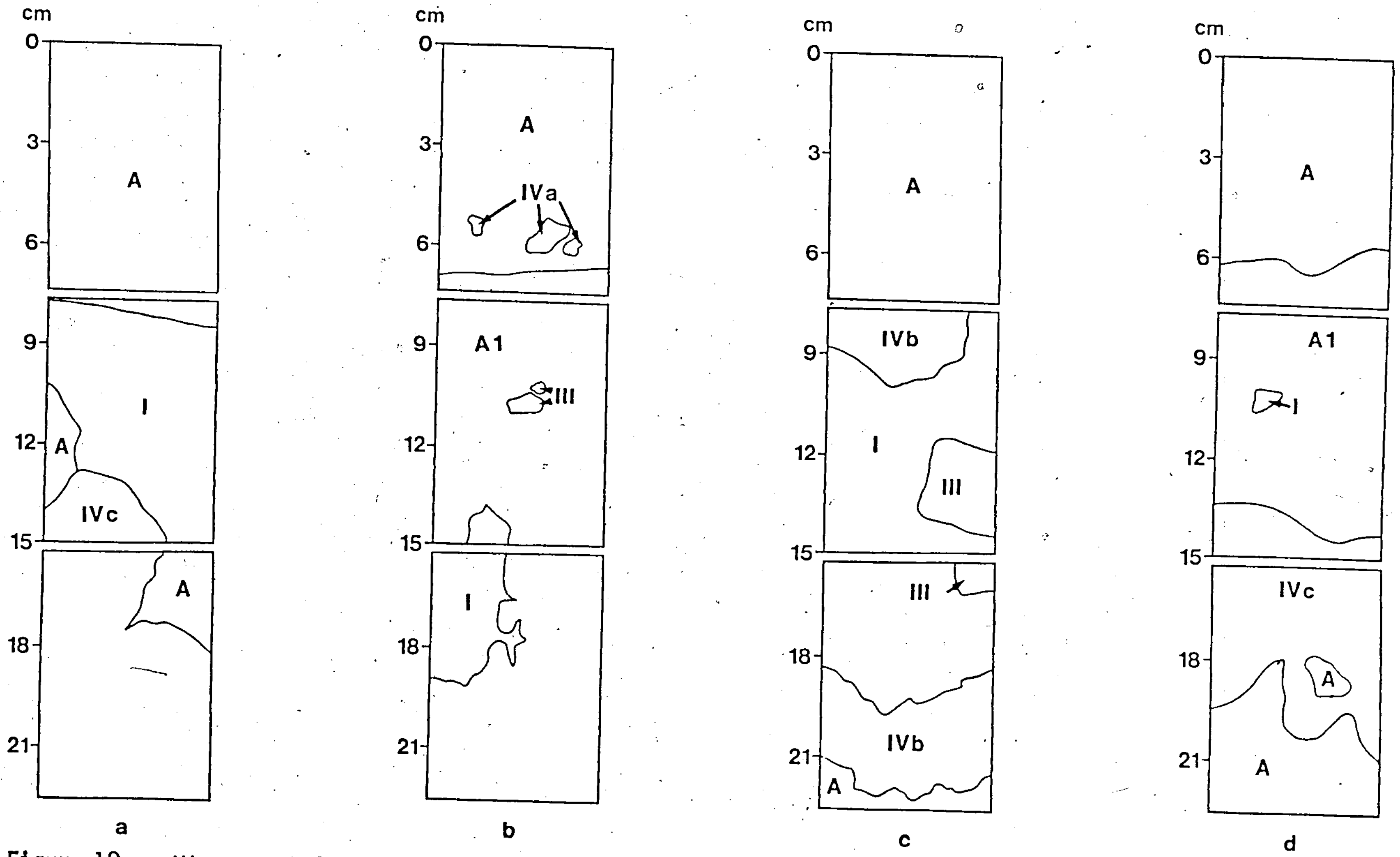


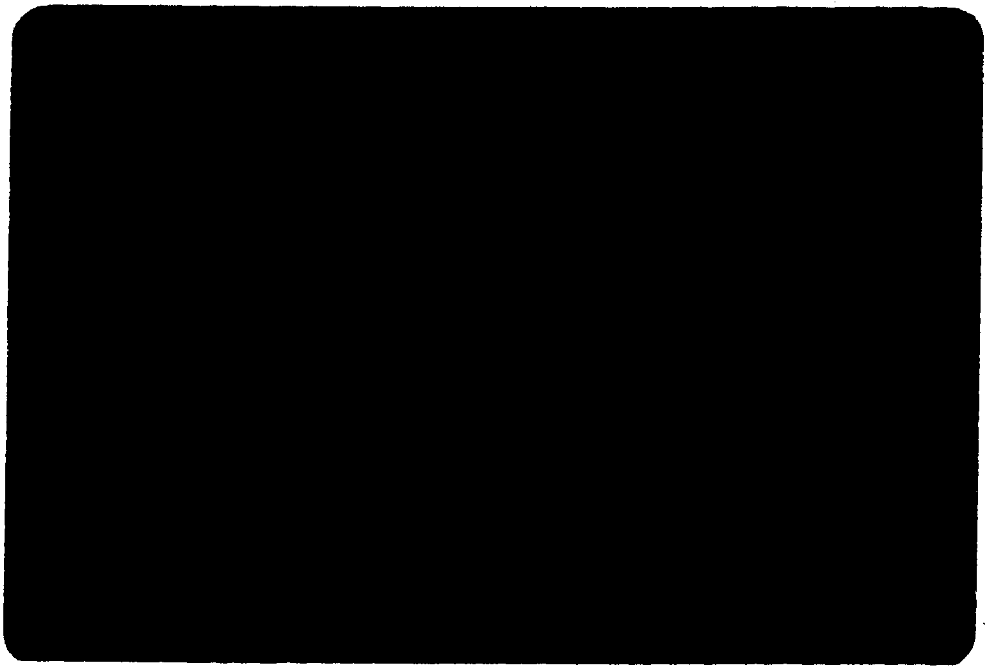
Figure 12. Micromorphological zones observed in the deep plowed soils at site 1. Profiles 1 - 4 are represented by figures a - d, respectively.

mullgranoidic) within which larger B horizon units are found (skel-mosepic porphyroskelic). The former represents granic units composed of mull and matrix material which occur in intimate association, while the latter is composed of small porphyroskelic units interspersed within the dominantly granoidic fabric. Zone A1, observed in profiles 2 and 4, differs from zone A in that minimal mixing of matri-mullgranoidic material and porphyroskelic material has occurred. The two fabrics occur as separable entities with a gradual boundary distinguishing the two separated fabrics. Unlike material in zone A, that found within zone A1 appears to have originated predominantly from non-Ap (or Ah) material. Plates 1 and 2 indicate the appearance of the mixed fabrics of the anthropogenic material.

It should be noted that Ap material (zone I) is not found at the immediate soil surface. Rather, it is found lower in the deep plowed profiles (profiles 1-3) and is virtually absent in profile 4. It therefore appears the action of the 3-layer topsoil saving plow is such that B horizon material is incorporated with A horizon material and these two materials, upon subsequent tillage, are mixed to form a more homogeneous soil mixture. Discrete areas of uniform material (zones I, III, IVa,b,c) remain, however, perhaps due in part to both stability and limited cultivation depth.

Zone sequences in the conventionally tilled soils at site 2 (Table 31 and Figure 13) are similar to those of site 1. Sampling depth, however, was insufficient to observe the nature of B horizon material.

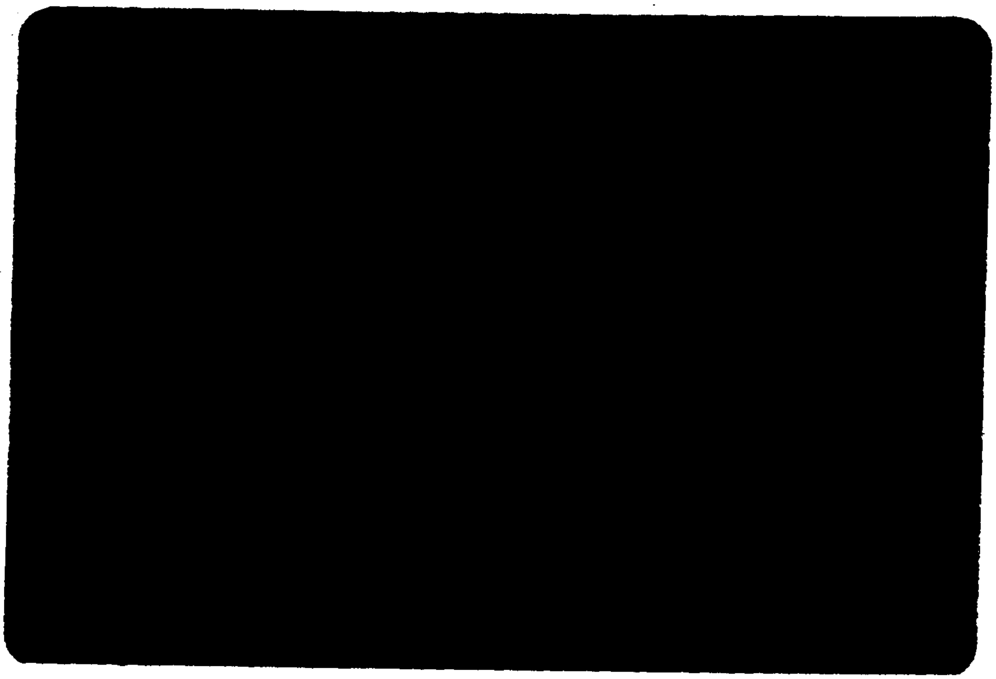
Zone I consists of mullgranic material exhibiting a variable degree of fusion to form a dominant mullgranoidic fabric. This zone corresponds to Ap material. Zone Ia, observed in profile 2, exhibits a



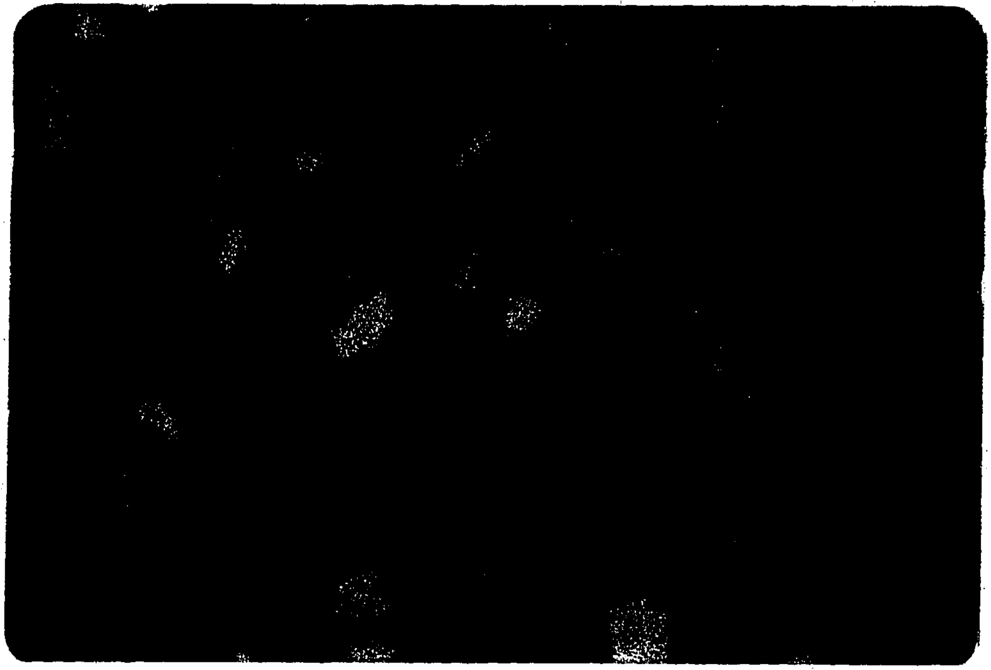
A) Zone A, Figure 12c, 3.0 cm depth; plain light; x 16.

B) Zone A, Figure 12c, 3.0 cm depth; partially crossed nicols; x 16.

Plate 1. Micrographs of anthropogenic material resulting from deep plowing.



A) Zone A, Figure 12c, 22.0 cm depth; plain light; x 10.



B) Contact between zones IVb and I, Figure 12c, 20.0 cm depth; partially crossed nicols; x 10.

Plate 2. Micrographs of fabric mixing resulting from deep plowing at site 1.

Table 31. General micromorphological descriptions for zones occurring in the conventionally tilled soil profiles at site 2.

Zone	Fabric	Description and Remarks
I	Granic//granoidic	Separated complex fabric: mullgranic units of irregular size and shape coalesce to form mullgranoidic fabric; mullgranic fabric is occasionally dominant; minor inclusions of insepic porphyroskelic material may be present; common to abundant partially decompose plant tissue; highly porous, with apparent porosity decreasing with depth; normally gradually grades into zone III; always present.
Ia	Granoidic	Mixed complex fabric: matri-mullgranoidic ; very similar to I except for lower organic matter; dense packing in some areas approach a porphyroskelic fabric; normally absent.
II	Weak banded granoidic// porphyroskelic	Separated complex intergrade: weakly banded matri-mullgranoidic//insepic porphyroskelic; organic matter slightly lower than in Ia; occasional joint planes with units partially accommodated; common undecomposed plant residues; normally absent.
III	Porphyroskelic	Insepic porphyroskelic: common inclusions of highly humified organic matter imbedded in s-matrix, decreasing with depth; vughy; common skew planes; common partially decomposed plant tissue.
IIIa	Porphyroskelic	Insepic porphyroskelic: similar to III except presence of organic matter is minimal; weak skelsepic plasma fabric occasionally present in lower portion of zone; normally absent (perhaps due to limiting depth of thin sections).

For zone sequences see figure 13.

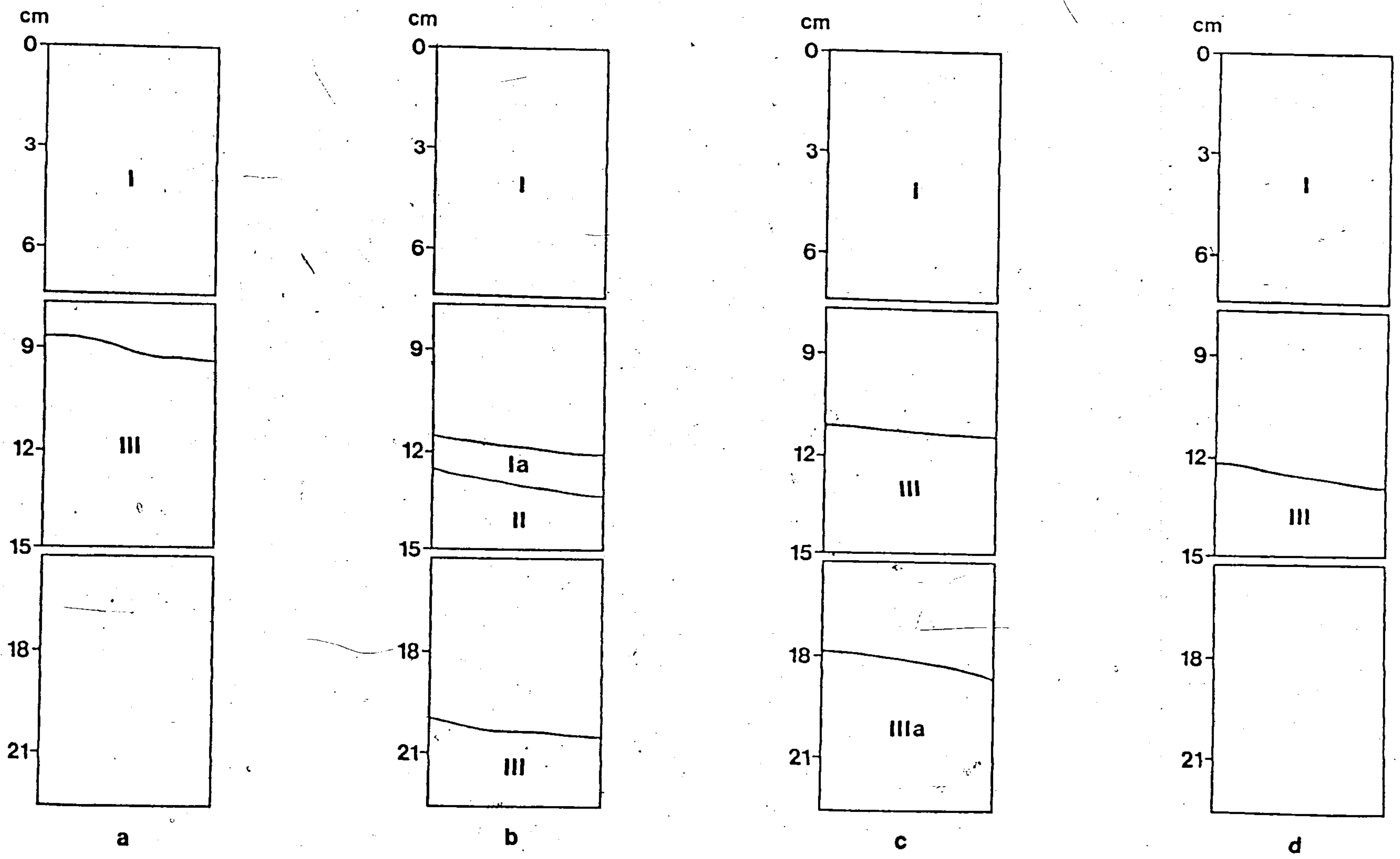


Figure 13. Micromorphological zones observed in the normally tilled soils at site 2. Profiles 1 - 4 (Table 25) are represented by figures a - d, respectively.

higher degree of coalescence of granic units, those of which are lower in apparent organic matter content than in the overlying zone I. This zone appears to exhibit weak eluvial features and therefore may correspond to a weakly humified and weakly eluviated Ahe horizon.

A distinct eluvial zone (II) is observed only in profile 2. This zone consists of insepic prophyroskelic material which is separated by horizontal joint planes to produce a banded fabric. Weak inclusions of organic matter are present which suggests this zone is undergoing gradual humification.

An apparent AB horizon is present in all four profiles and this horizon represents the lower boundary of micromorphological observation. Zone III is characterized by insepic porphyroskelic material. Moderate inclusions of humified organic matter, which gradually decrease with depth, suggest this zone is undergoing gradual humification. Zone IIIa underlies zone III in profile 3 and is similar to zone III although organic matter inclusions are weak. In the lower portion of this zone a weak skelsepic plasma fabric appears. This area may reflect the current zone of intense solodization if it corresponds to the upper Bnt horizon.

Again, micromorphological zone sequences do not conform well with morphological descriptions; Profile 2, however, is similar in both respects assuming zone III represents the upper Bnt horizon. It is possible the Bm horizon of profile 1 corresponds to zone III. Pawluk and Dudas (1982) report the Bmu horizon of a turbated Black Chernozem is dominated by insepic plasma fabric.

Deep plowed soils exhibit erratic distribution of materials with depth (Figure 14). Zones I, III and IIIa (Table 32) are similar in

Table 32. General micromorphological descriptions for zones occurring in the deep plowed soils at site 2.

Zone	Fabric	Description and Remarks
A	Porphyroskelic/ granoidic	Separated complex fabric: sharp boundary between porphyroskelic material of variable plasma fabric and mullgranoidic material; variable amount of matrix material interspersed within mullgranoidic fabric; highly porous; common partially decomposed plant tissue; normally absent.
A1	Granoidic// porphyroskelic	Separated and mixed complex fabric; matri-mullgranoidic//insepic porphyroskelic; similar to zone A except for proportion of fabric type; porous, normally present.
I	Granic//granoidic	Separated complex fabric: mullgranic// mullgranoidic: similar to zone I of conventionally tilled soils; variable amount of matrix material interspersed within mullgranic material; normally present.
III	Porphyroskelic	Insepic porphyroskelic: see zone III in conventionally tilled soils (table 31); always present.
IIIa	Porphyroskelic	Insepic porphyroskelic: see zone IIIa in conventionally tilled soils (table 31); normally absent.
IV	Porphyroskelic	Mosepic porphyroskelic: moderate inclusions of highly humified organic matter; vughy; normally present.
IVa	Porphyroskelic	Skel-ma-mosepic porphyroskelic: vughy; normally present.

For zone sequences see figure 14.

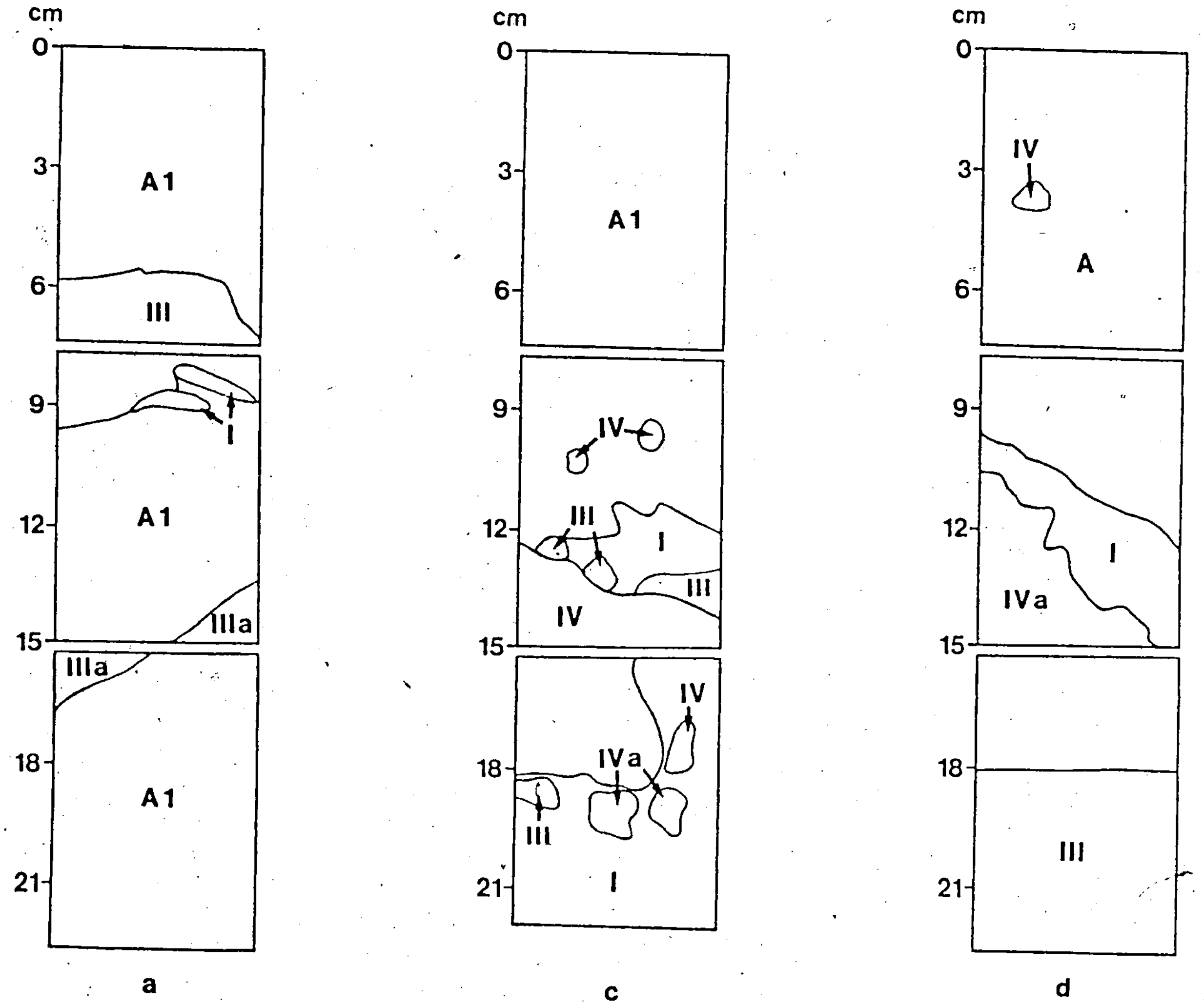


Figure 14. Micromorphological zones observed in the deep plowed soils at site 2. Profiles 1, 3 and 4 are represented by figures a, c and d, respectively.

composition to those observed in the conventionally tilled soils. Zones A and A1 reflect anthropogenic material derived from two or more genetic materials. Zone A consists of a porphyroskelic material of variable plasma composition interspersed within mullgranoidic material. The boundary between the two fabrics is sharp. This zone, overall, is highly porous (Table 32). In zone A1 the proportion of the two fabric types is reversed; matri-mullgranoidic fabric is subdominant to insepic porphyroskelic fabric. In addition, the boundary between the two fabrics is not as pronounced.

Apparent B horizon material (zones IV and IVa) is present in profiles 3 and 4. Both zones have dominant mosepic plasma separations with zone IVa exhibiting subdominant skelsepic and masepic plasma separations. Morphologically (Table 25) it appears this fabric is derived from Btnj horizons.

Micromorphological descriptions and zone sequences for the conventionally tilled soils at site 3 are given in Table 33 and Figure 18, respectively. In all instances zone I is observed which consists of mullgranic units partially fused to form mullgranoidic fabric. Within this zone partially decomposed plant residues are abundant.

Zones IIIa and IIIb exhibit weak insepic plasma separations. Zone IIIb differs from zone IIIa in having a greater concentration of humified organic matter in the s-matrix. Zone IIIb is only present in profile 4 and forms the boundary adjacent to a relatively large vertical skew plane which appears to demarcate adjacent columnar peds.

Zones IV, IVa and IVb are all porphyroskelic but exhibit variable plasma separations. Zone IV of profiles 2 and 4 exhibits a mo-skelsepic plasma fabric. It is interesting to note zone IV in profile 2 is

Table 33. General micromorphological descriptions for zones occurring in the conventionally tilled soil profiles at site 3.

Zone	Fabric	Description and Remarks
I	Granic//granoidic	Separated complex fabric: mullgranic// mullgranoidic; fine mullgranic units of irregular shape coalesce in areas to form zones of mullgranoidic fabric; abundant undecomposed and partially decomposed plant fragments; few skew planes; occasional phenoclasts; highly porous; always present.
IIIa	Porphyroskelic	Weak insepic porphyroskelic: plasma fabric weakly masked by inclusions of highly humified organic matter; vughy; normally absent.
IIIb	Porphyroskelic	Insepic porphyroskelic: similar to III except plasma fabric is strongly masked by humified organic matter imbedded in the s-matrix; this is a dense area which is adjacent to a large, vertical craze plane; normally absent.
IV	Porphyroskelic	Mo-skelsepic porphyroskelic: proportion of mosepic to skelsepic plasma fabric is variable and either may be dominant in a given thin section; minor insepic and/or masepic plasma fabrics occasionally occur ; vughy; few craze planes with units partially accommodated, gradually decreasing with depth; normally present.
IVa	Porphyroskelic	Mosepic porphyroskelic: minor masepic and skelsepic components may also be present; plasma fabric somewhat masked by highly humified organic matter; vughy; common skew planes and craze planes with units frequently partially accommodated; walls of vertical craze planes occasionally lined with mullgranoidic material; normally present.
IVb	Porphyroskelic	Skel-insepic porphyroskelic: vughy; few craze planes with units partially accommodated; where present, gradually grades into zone IV; normally absent.

For zone sequences see figure 15.

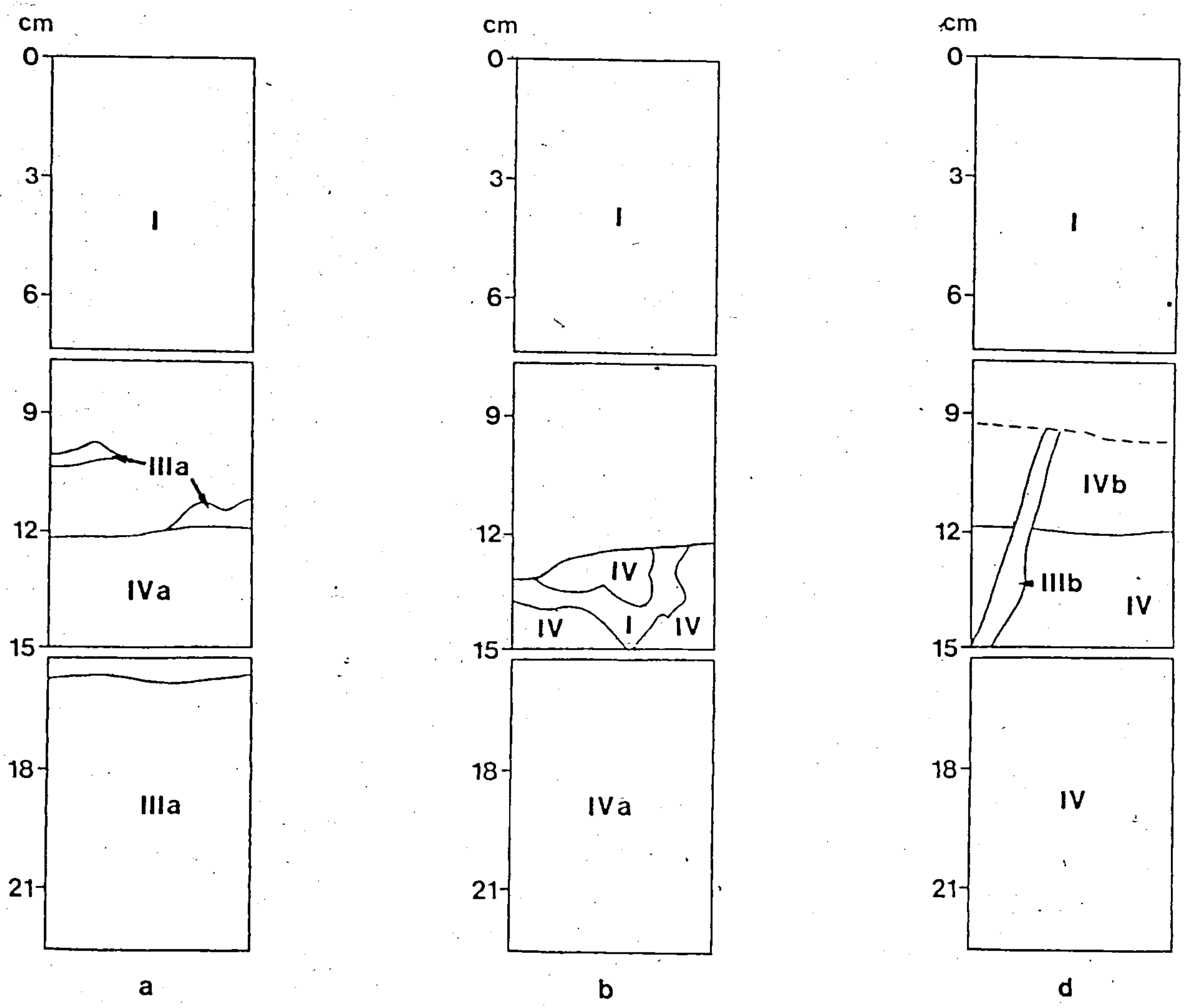


Figure 15 Micromorphological zones observed in the normally tilled soils at site 3. Profiles 1, 2 and 4 (Table 26) are represented by figures a, b and d, respectively. Dashed line represents apparent tillage depth.

separated by a thin band of zone I. This suggests cultivation has been sufficiently deep to incorporate some B horizon material within the Ap.

Underlying zone IV in profile 2 is zone IVa, which exhibits less pronounced plasma separations (mosepic). Zone IVb directly overlies zone IV in profile 4. The skel-insepic plasma fabric (zone IVb) observed here may reflect some degree of degradation of an upper Bnt horizon.

An anomaly observed at this site is the presence of insepic porphyroskelic material (IIIa) underlying mosepic porphyroskelic material (IVa) at shallow depth (profile 1). Thus far porphyroskelic material with relatively weakly expressed plasma separations has been associated with solodized material and as such has overlain material with more pronounced plasma concentrations. It appears that conventional tillage may have redistributed genetic horizons in a manner similar to that of profile 2. This would also explain the rather erratic distribution of zone IIIa above zone IVa, in otherwise Ap (zone I) material.

With the exception of profile 1, micromorphological sequences agree with morphological observations. That is, Ap material (zone I) directly overlies Bnt material (zone IV or IVb), with eluvial or transitional horizons generally absent.

Descriptions and zone sequences for the deep plowed soils are given in Table 34 and Figure 16. Again, a dramatic redistribution of genetic materials is indicated in Figure 16. Zone types inclusive of zones I, IV and IVb are similar to those described for the conventionally tilled soils. Zones A and A1 are anthropogenic in origin and consist of separate areas of mullgranoidic and mo-skelsepic

Table 34. General micromorphological descriptions for zones occurring in the deep plowed soils at site 3.

Zone	Fabric	Description and Remarks
A	Granoidic/ porphyroskelic	Separated complex fabric: mulgranoidic/ mo-skelsepic porphyroskelic; insepic or masepic plasma fabrics may also occur in some areas; higher density and some mixing of the two fabrics is often associated with the surface 5-10mm, which in some instances could be considered a crust; highly porous, particularly in the uppermost 50mm; occasional skew planes; abundant decomposed and partially decomposed plant tissue; always present.
A1	Porphyroskelic/ granoidic	Separated complex fabric: very similar to A except the relative dominance of the two fabrics is reversed; generally less porous than A; normally absent.
I	Granoidic	Mulgranoidic: very similar to I in the conventionally tilled soils except the degree of coalescence between mulgranic units is more pronounced and this zone is not associated with the soil surface; occasional inclusions of porphyroskelic material with variable plasma separations ; always present.
IV	Porphyroskelic	Mo-skelsepic porphyroskelic: as with zone IV in the conventionally tilled soils: this fabric type occurs as areas interspersed within zones A, A1 or I; normally present.
IVb	Porphyroskelic	Skel-insepic porphyroskelic: as with zone IVb in the conventionally tilled soils; also interspersed within zones A, A1 and I; always present.

For zone sequences see figure 16.

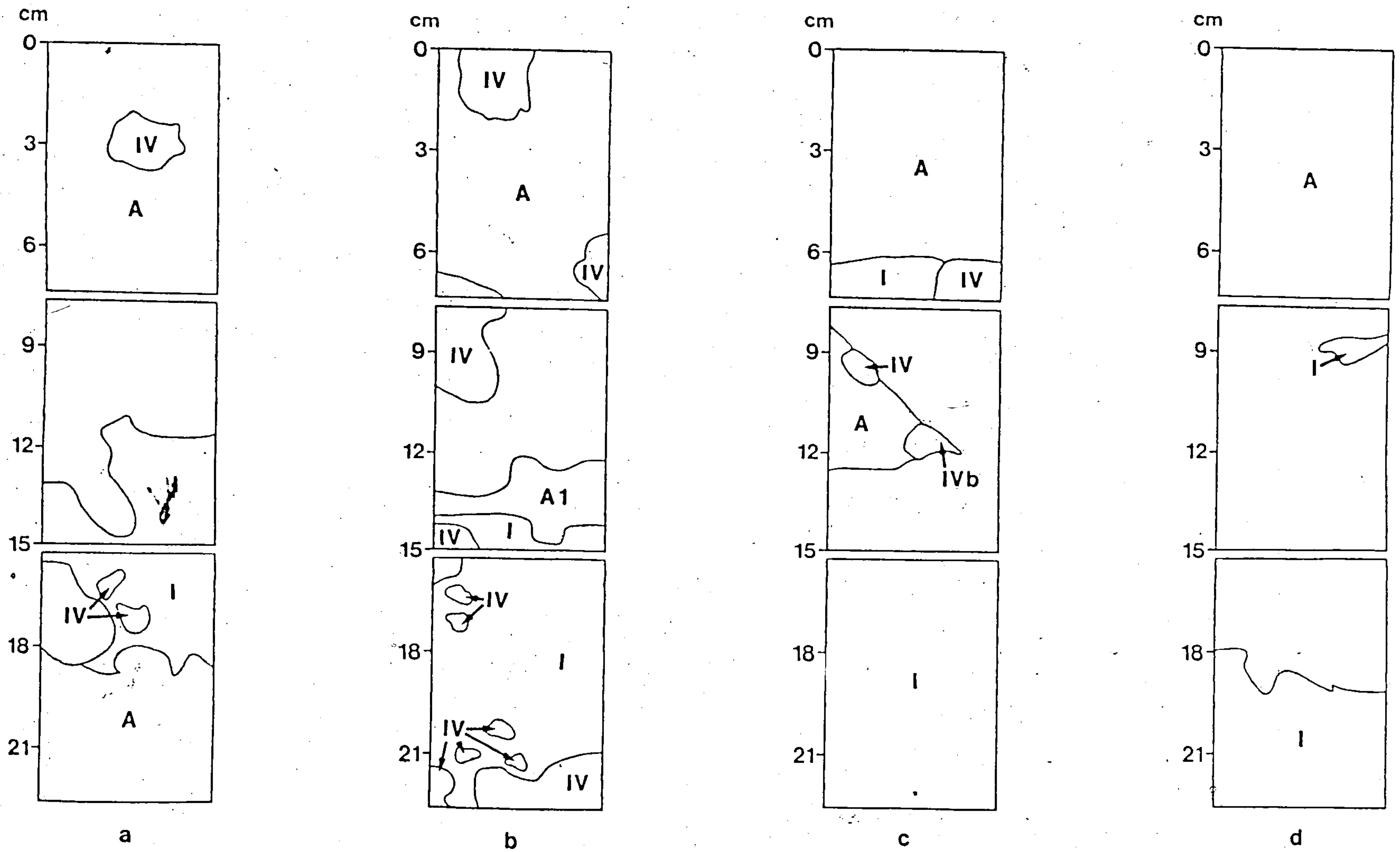


Figure 16. Micromorphological zones observed in the deep plowed soils at site 3. Profiles 1 - 4 are represented by figures a - d, respectively.

porphyroskelic fabrics. Differentiation of zones A and A1 is based on the proportion of the two observed constituent fabrics: porphyroskelic material is dominant to mullgranoidic material in zone A while the reverse is true for zone A1.

One fundamental difference exists between those soils described thus far and those at site 4. Surface horizons of the conventionally tilled soils (Table 35 and Figure 17) are coarse textured and are characterized by mullgranoidic junctic porphyric intergrades. Here, zone I consists of coarse ortho-f-members (sand grains) between which mullgranoidic material forms bridges. Porphyric intergrades result when packing of units becomes pronounced. This type of fabric reflects relatively intense degradation, either through genetic processes or cultural practices. The relatively coarse nature of the parent material (Table 27) would undoubtedly enhance both.

Underlying this zone is either of zones Ia or Ib, but more commonly the latter. Zone Ib exhibits a weaker expression of the mull component and is occasionally dissected by skew planes, but is otherwise similar to zone I. It probably represents a weakly eluvial horizon relative to zone I, although the entire A horizon appears to be strongly eluviated (see also Chapter 5). Zone Ib is present in all profiles. Zone Ia is present only in profile 2. The mull component of the mullgranoidic material is more pronounced in this zone relative to zone I which may reflect either an undisturbed Ah horizon or an Ap horizon which has not been cultivated recently.

Zone II is an eluvial horizon characterized by weak, discontinuous banding. It is present only in profile 4. Some humification of zone II appears to have occurred.

Table 35. General micromorphological descriptions for zones occurring in the conventionally tilled soil profiles at site 4.

Zone	Fabric	Description and Remarks
I	Granoidic iunctic	Mullgranoidic iunctic: fine mullgranoidic units of irregular size and shape form bridges between large ortho-f-members; in some zones dense packing of mullgranoidic units approach a porphyric fabric to give zones of iunctic porphyric intergrades; numerous packing voids; common partially decomposed plant fragments; always present.
Ia	Granoidic iunctic	Mullgranoidic iunctic: as with I, except higher organic matter and generally a slightly greater packing density, resulting in a greater proportion of iunctic porphyric intergrades; normally absent.
Ib	Granoidic iunctic	Mullgranoidic iunctic: mull component less pronounced than in I; occasional skew planes which are frequently lined with material from I or Ia; plant residues less common; always present.
II	Weak banded granoidic iunctic	Weak banded mullgranoidic iunctic: very similar to Ia, except for the presence of weak, discontinuous banding; normally absent.
III	Porphyroskelic	Insepic porphyroskelic: plasma fabric weakly expressed between coarse ortho-f-members; occasional weak masking of insepic plasma fabric by organic matter; occasional skew planes and partially decomposed plant tissue; gradually grades into IV; normally present.
IV	Porphyroskelic	Mo-skelsepic porphyroskelic: proportion of mosepic to skelsepic plasma fabric is somewhat variable; in some zones masepic or vosepic plasma is present, although not as the dominant fabric; vughy; skew planes common with units partially accommodated; few partially decomposed plant fragments; always present.

For zone sequences see figure 17.

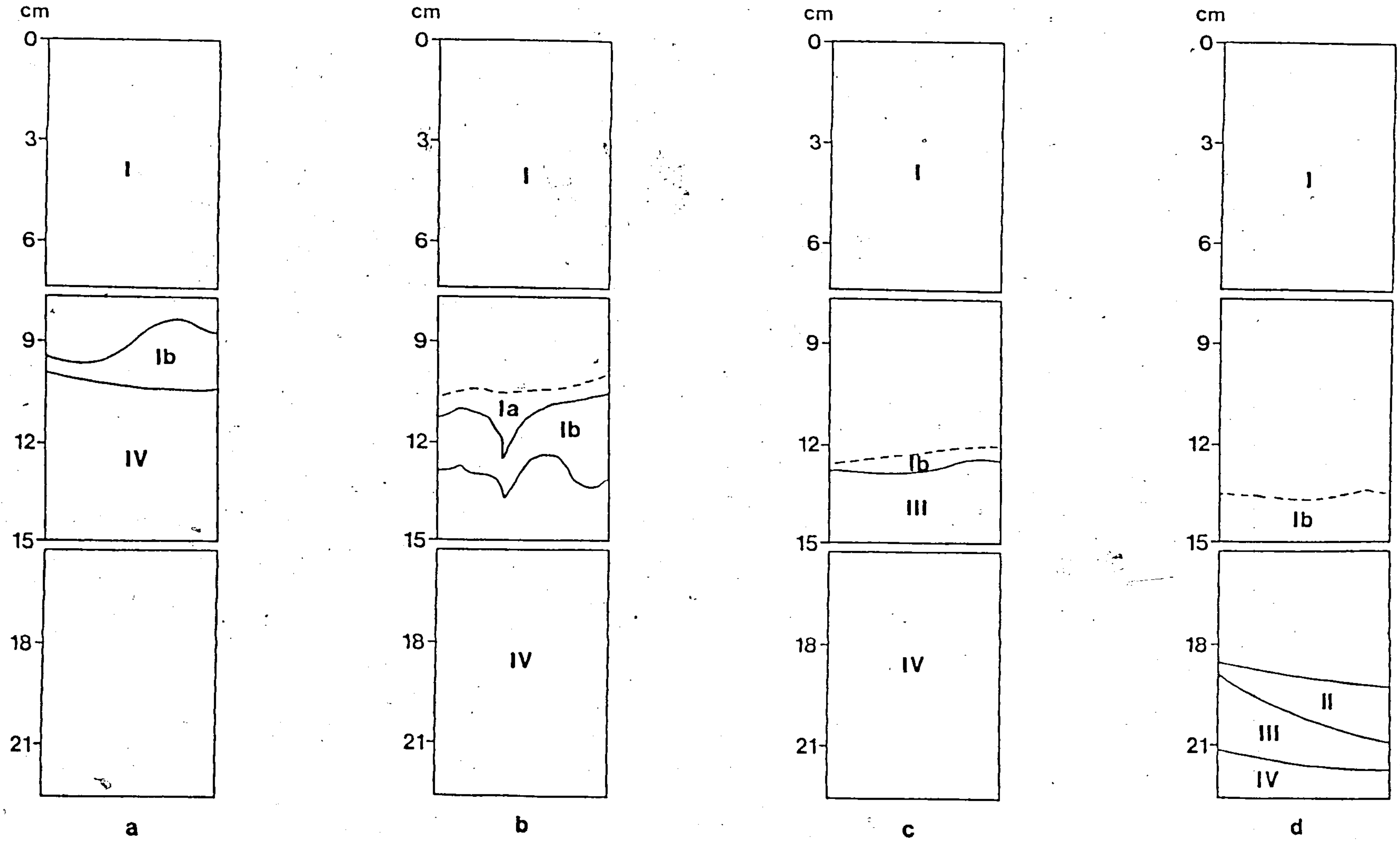


Figure 17. Micromorphological zones observed in the normally tilled soils at site 4. Profiles 1 - 4 (Table 27) are represented by figures a - d, respectively. Dashed line indicates apparent tillage depth.

Insepic porphyroskelic fabric (zone III) underlies zone Ib in profile 3 and zone II in profile 4. Weak expression of plasma separations between coarse ortho-f-members, combined with weak humification of this zone suggest it is a transitional horizon.

Porphyroskelic B horizon material is present in all profiles. It is somewhat variable in plasma composition but tends to be dominated by mo-skelsepic. Skew planes are common with units partially accommodated.

Results of observations on deep plowed soils are given in Table 36 and Figure 18. Zones I and IV are similar in composition to those in the conventionally tilled soils but differ in their distribution with depth. Zone A, as in other deep plowed soils, is anthropogenic in origin. Here it consists of matri-mullgranoidic units interspersed between ortho-framework members. Plasma fabric of the matrigranoidic units tends to be mo-skelsepic in nature. Zone C, present as a crust in profiles 2, 3 and 4 is similar to zone A except that packing is much more pronounced such that iunctic porphyric intergrades are more common. Additionally, there appears to be a gradation towards finer ortho-f-members with depth through zone C. This may reflect redistribution of the ortho-f-members upon raindrop impact.

Zone IVa, which was not observed in the conventionally tilled soils, is found in profiles 1, 3 and 4. Stronger plasma concentrations, indicated by skel-masepic plasma separations, suggest this zone is illuvial in nature. It is likely this zone is derived from a lower portion of the Bnt horizon, below the depth observed in the conventionally tilled soils.

Micromorphological descriptions for zones observed in the

Table 36. General micromorphological descriptions for zones occurring in the deep plowed soils at site 4.

Zone	Fabric	Description and Remarks
C	Granoidic iunctic porphyroskelic	Mixed complex fabric: matri-mullgranoidic units are packed between coarse ortho-f-members in varying degrees to form the two fabric end members and intergrades; weak masking of skel-insepic plasma fabric by organic matter; ma-skelsepic plasma separations occasionally observed in the center depth of the crust; proportion of fine ortho-f-members generally increases with depth; normally present.
A	Granoidic iunctic	Matri-mullgranoidic units of irregular size and shape form bridges between large ortho-f-members; dense packing in some areas results in zones of iunctic porphyric intergrades; plasma is variable in composition but generally is mo-skelsepic which is weakly masked by organic matter; occasional undecomposed or partially decomposed plant tissue; always present.
I	Granoidic iunctic	Mullgranoidic iunctic: as with A above except mull component much more pronounced and no visible plasma separations; always presest.
IV	Porphyroskelic	Vughy mo-skelsepic porphyroskelic: skew planes common with units frequently partially accommodated; normally present.
IVa	Porphyroskelic	Vughy skel-masepic or ma-skelsepic porphyroskelic; skew planes common with units frequently partially accommodated; normally present.

For zone sequences see figure 18.

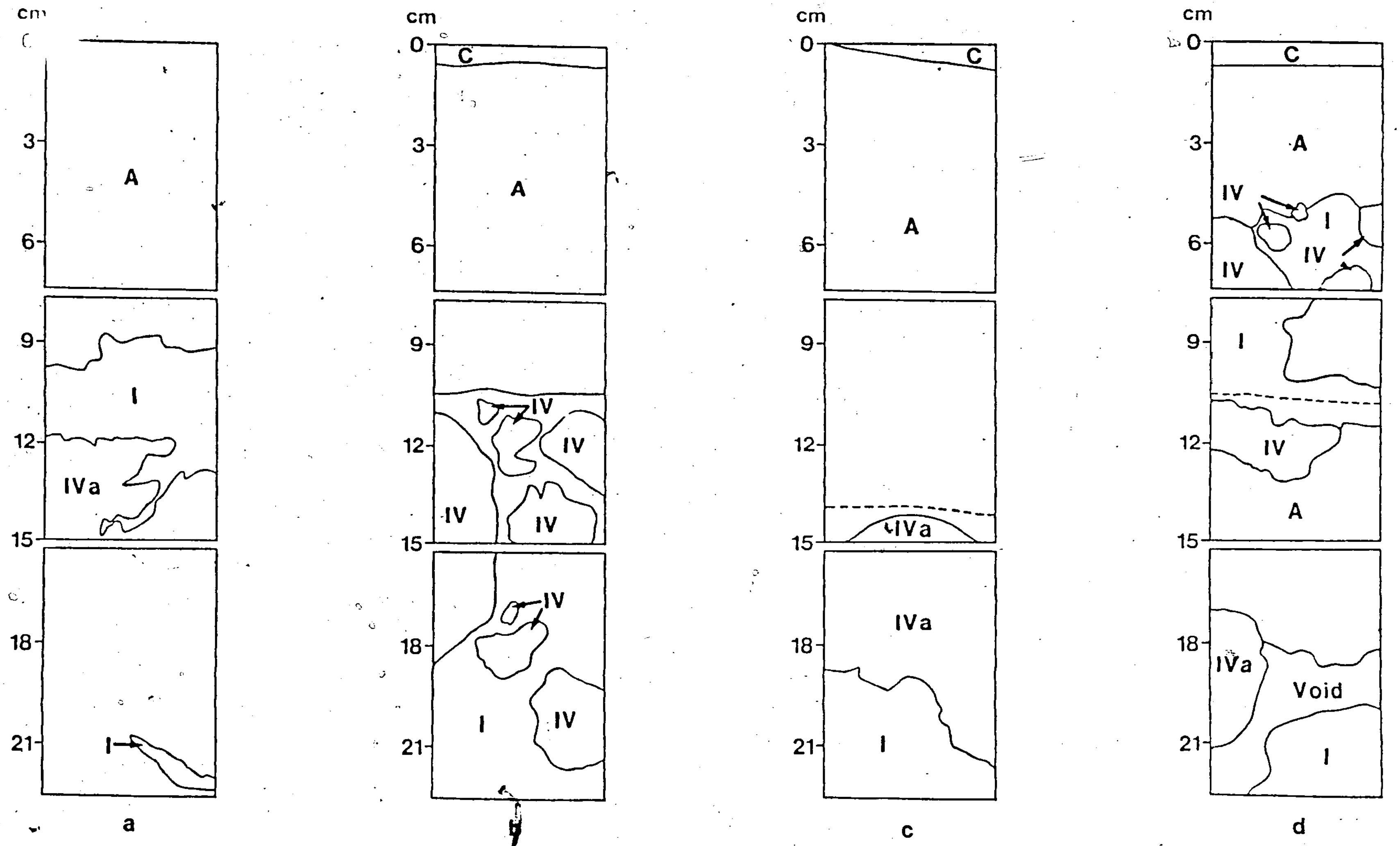


Figure 18. Micromorphological zones observed in the deep plowed soils at site 4. Profiles 1 - 4 are represented by figures a - d, respectively. Dashed line indicates apparent current tillage depth.

conventionally tilled soils at site 5 are given in Table 37 and corresponding zone sequences are given in Figure 19. Zone I represents the norm for the cultivated Ap and generally exhibits the mullgranic//mullgranoidic sequence although densely packed areas grading to porphyric are occasionally present. Separated mullgranoidic//insepic porphyroskelic fabric (zone Ia) was observed in profile 1. This zone may comprise cultivated material from former Ae and/or AB horizons mixed within the current Ap horizon.

Zone III of profiles 1 and 3 consists of porphyroskelic fabric exhibiting skel-insepic plasma separations with moderate inclusions of humified organic matter. This zone probably reflects the upper, partially solodized surface of the Bnt horizon.

Two types of Bnt horizon material are noted. Both are porphyroskelic in fabric type (zones IV and IVa) and are dominantly skel-mosepic in plasmic fabric. The difference is that masepic plasma separations are significant, though subdominant in zone IVa. Both zones are suggestive of illuviation, zone IVa perhaps more so.

Descriptions and sequences for deep plowed soils at site 5 are given in Table 38 and Figure 20, respectively. Unlike deep plowed soils of previous sites no unaltered Ap material was found within sampling depth. The surface is comprised of anthropogenic (A or A1) material of a mixed complex nature. The proportion of mullgranoidic to porphyroskelic fabric distinguishes between zones A and A1 (Table 38). In both instances the boundary between the two fabric types is sharp.

Material derived from the B horizon occurs in discrete, small areas (profiles 2 and 3) or as the dominant material in large areas (profile 4). Plasma fabrics are similar to those observed in the conventionally tilled soils.

Table 37. General micromorphological descriptions for zones occurring in the conventionally tilled soil profiles at site 5.

Zone	Fabric	Description and Remarks
I	Granic//granoidic	Separated complex fabric: muligranic units of variable size and shape coalesce to form zones of muligranoidic fabric; proportion of granoidic fabric increases with depth, and in some instances approaches a porphyroskelic fabric; common partially decomposed plant residues; occasional inclusions of porphyroskelic material; porous; always present.
Ia	Granoidic// porphyroskelic	Separated complex fabric: muligranoidic// insepic porphyroskelic: common partially decomposed plant residues; fairly porous; normally absent.
III	Porphyroskelic	Skel-insepic porphyroskelic: moderate inclusions of humified organic matter imbedded in s-matrix; normally present.
IV	Porphyroskelic	Skel-mosepic porphyroskelic: moderate amounts of humified organic matter within the s-matrix; normally present, but amount may not warrant specific zonation.
IVa	Porphyroskelic	Ma-skel-mosepic porphyroskelic: minor vosepic plasma separations also occur in areas; humic material imbedded in s-matrix; plasma becomes less concentrated with depth; vughy; numerous skew planes, occasionally containing roots; normally present.

For zone sequences see figure 19.

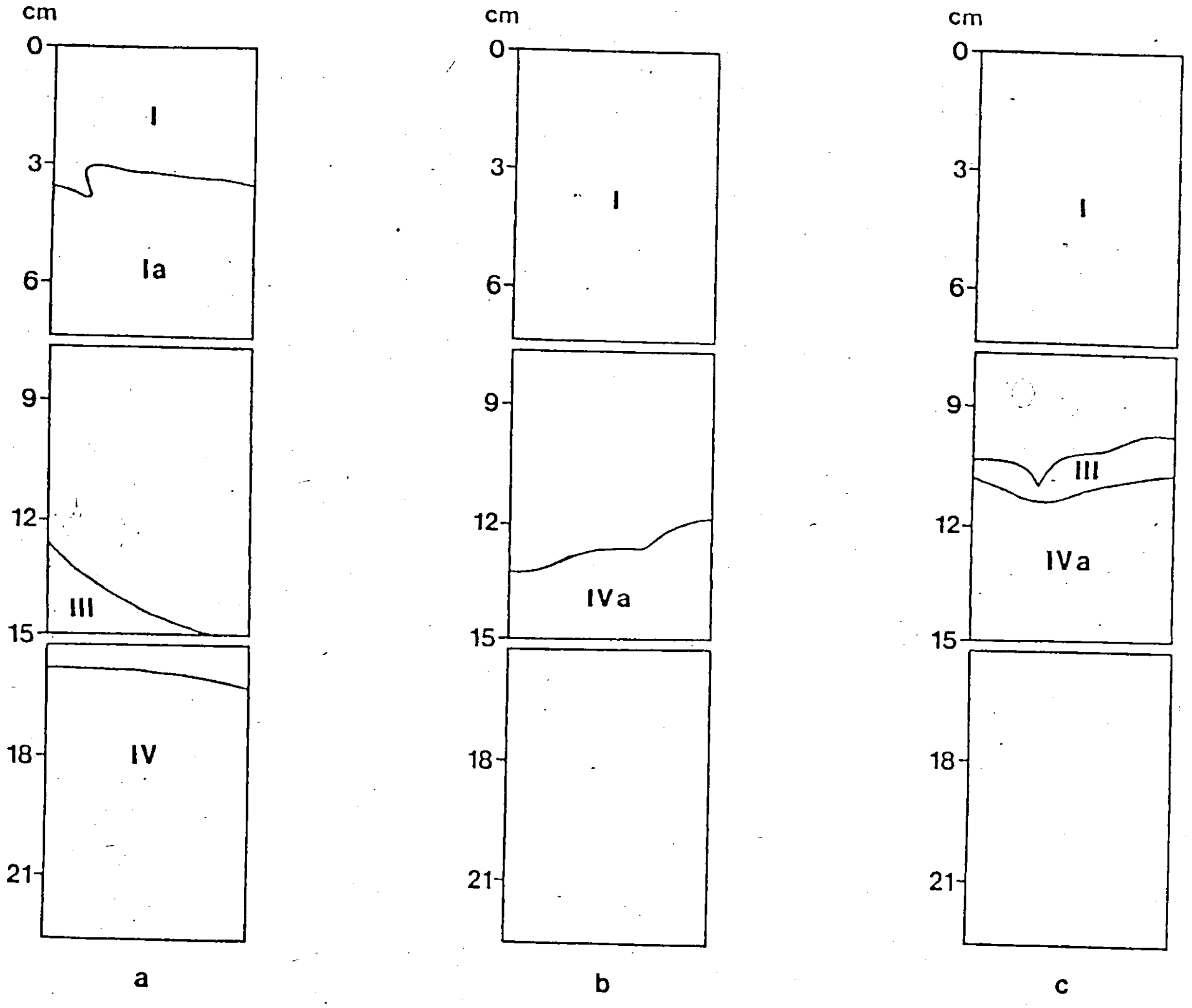


Figure 19. Micromorphological zones observed in the normally tilled soils at site 5. Profiles 1 - 3 (Table 28) are represented by figures a - c, respectively.

Table 38. General micromorphological descriptions for zones occurring in the deep plowed soils at site 5.

Zone	Fabric	Description and Remarks
A	Granoidic/ porphyroskelic	Separated complex fabric: muligranoidic fabric interspersed within areas of porphyroskelic material; the latter generally characterized by skel-mosepic plasma separations but areas of insepic plasma fabric also occur; generally porous; common partially decomposed plant tissue; always present.
A1	Porphyroskelic/ granoidic	Separated complex fabric: identical to zone A with the exception of fabric proportions; normally absent.
IV	Porphyroskelic	Skel-mosepic porphyroskelic: see zone IV, conventional tillage (table 37); occasional plant fragments found in skew planes; normally absent.
IVa	Porphyroskelic	Ma-skel-mosepic porphyroskelic: see zone IVa, conventional tillage (table 37); normally present.

For zone sequences see figure 20.

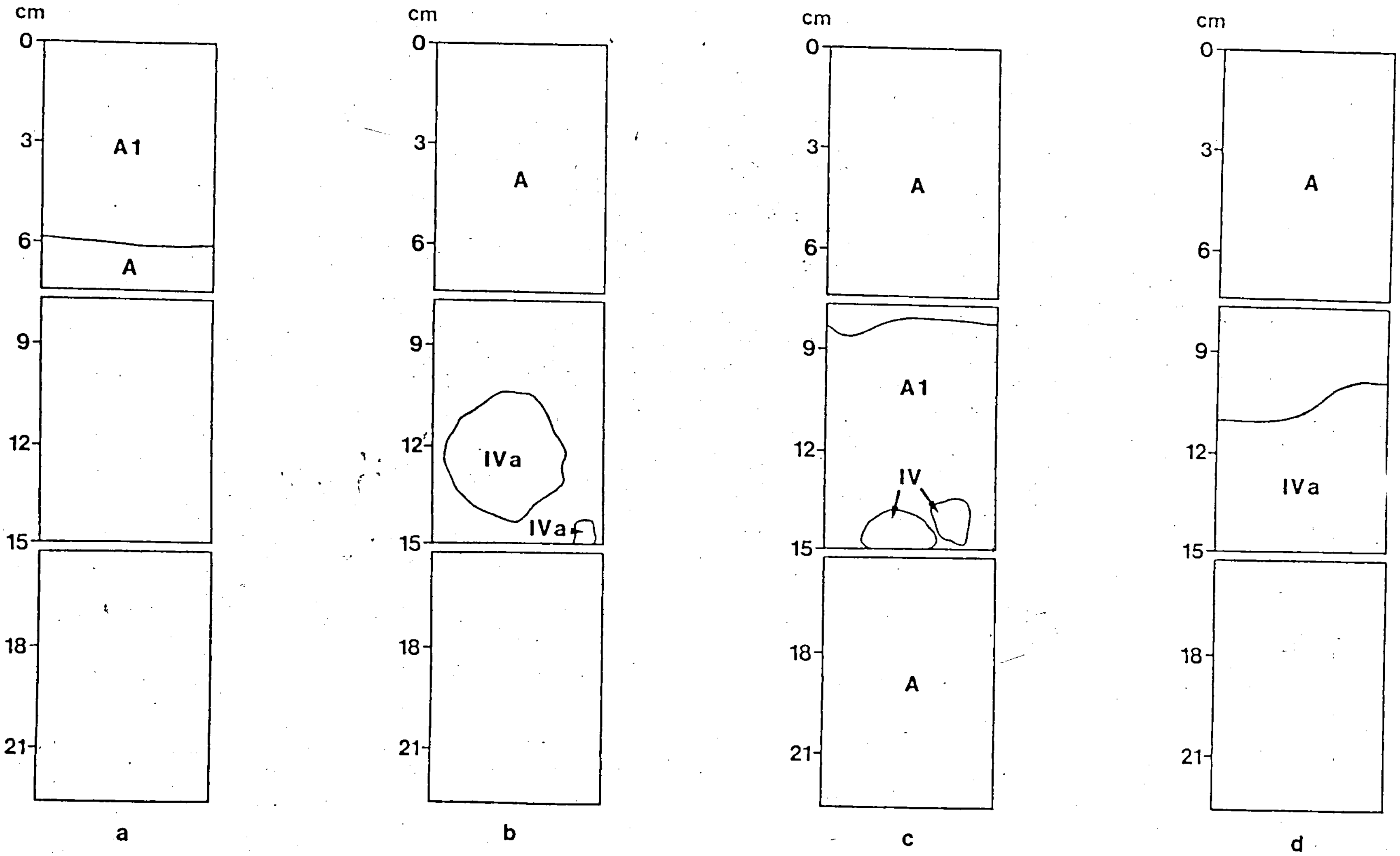


Figure 20. Micromorphological zones observed in the deep plowed soils at site 5. Profiles 1 - 4 are represented by figures a - d, respectively.

4.4.3.2 Image Analysis

In many instances micromorphological observations revealed clearly distinct areas of different genetic materials. Density slicing was performed to determine the extent of various materials within a given thin section, expressed as a percent of total thin section area. Emphasis was placed on distinguishing A horizon material (mullgranoidic or mullgranoidic iunctic fabrics) from B horizon material (porphyroskelic fabric) particularly in the deep plowed soils. Results are given in Table 39 and should be viewed with reference to Figures 11 to 20, as indicated in Table 39. Plate 3 illustrates the enhanced images of a conventionally tilled and deep plowed soil at site 1.

In all instances the surface 75 mm of the conventionally tilled soils consists entirely of A horizon material, whereas that of the deep plowed soils consists of an admixture of various anthropogenic materials. Deep plowing has a variable effect on material within the 75 to 150 mm depth. In some instances (sites 1 and 2) the proportion of strictly B horizon material has increased, while in others (sites 3 and 4) it has decreased. If, however, the amount of B horizon material contained within the anthropogenic zones is considered, deep plowing overall increases the amount of non-A horizon material at depths of 75 to 150 mm. In most instances the amount of A horizon material found at depths of 150 to 225 mm is increased by deep plowing (sites 2, 3 and 4). The only exception is where the initial A horizon occurs within this depth (site 1).

It should be noted that values in Table 39 are by no means exact. Overlap in "apparent" density between obviously different materials was encountered in most thin sections. Three factors contribute to the

Table 39. Approximate distribution of soil materials with depth, as determined by density slicing

		Normal Tillage			Deep Plowed Tillage			
Site	Depth (cm)	Reference figure	A horizon material	B horizon material	Reference figure	A horizon material	B horizon material	Mixed material
1	0.0- 7.5	11c	100	---	12c	---	---	100
	7.5-15.0		100	---		62	38	---
	15.0-22.5		66[1]	34		54[2]	46	---
2	0.0- 7.5	13c	100	---	14c	---	---	100
	7.5-15.0		61	39		---	45[1]	55[4]
	15.0-22.5		---	100[1,3]		34	66[1]	---
3	0.0- 7.5	15a	100	---	16a	---	8	92
	7.5-15.0		59	41		50	---	50
	15.0-22.5		---	100		29	---	71[5]
4	0.0- 7.5	17b	100	---	18b	---	---	100
	7.5-15.0		59	41		---	34	66[4]
	15.0-22.5		---	100		64	36	---
5	0.0- 7.5	19b	100	---	20b	---	---	100
	7.5-15.0		100[6]	---		---	---	100[6]
	15.0-22.5		---	100		---	---	100

---

[1] includes AB (zone III) material.

[2] includes some mixed (zone A) material.

[3] zone III was distinguishable from zone IIIa (respective values are 46 and 54%).

[4] includes A horizon (zone I) material.

[5] includes B horizon (zone IV) material.

[6] not possible to distinguish between Ap material (zone I or A) and Bnt material (zone IVa).

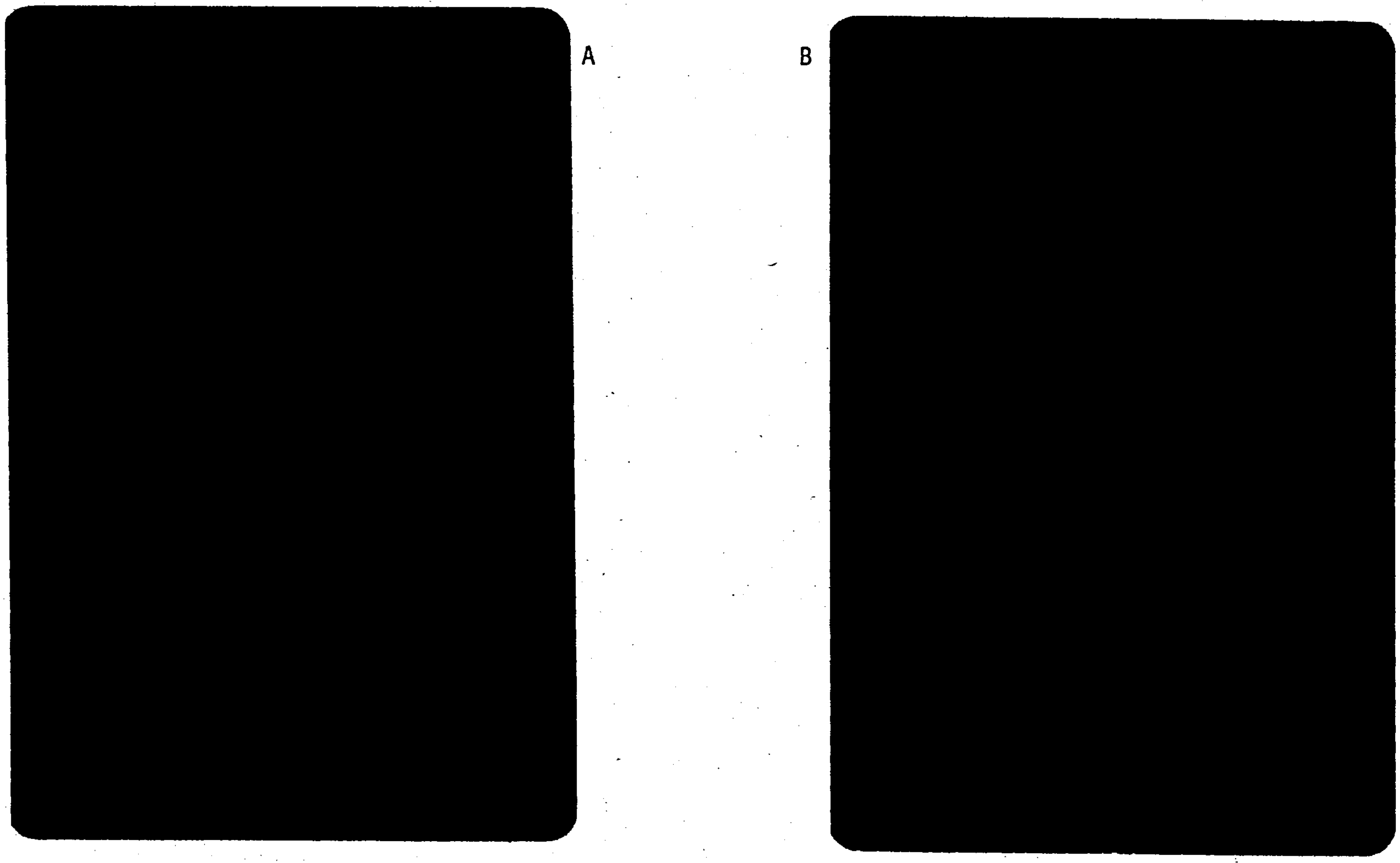


Plate 3. Image analysis of zone sequences at site 1. Profile 3, 15.0 - 22.5 cm depth.
A) Normally tilled soil (Figure 11c). B) Deep plowed soil (Figure 12c).

observed overlap; real density, colour and thin section thickness. Real density and soil colour in various combinations often resulted in the same perceived density as determined by the image analysis technique used. This is particularly true of the soil sequences examined at site 5 where differences between A and B horizon materials could be not resolved. Genetic materials low in real density but darker in colour (Ap) resulted in the same apparent density as materials higher in density but lighter in colour (Bnt). Thickness of thin sections modifies the result by altering both colour and density. Thinner areas of thin sections have lower densities and are lighter in colour. This is indicated in plate 3A, where the Bnt horizon exhibits the same colouration (perceived density) as the larger skew plane interstices.

4.5 Summary

Morphological and micromorphological features of deep plowed and conventionally tilled soils were examined. The bulk of the soils examined were Solonetzic, according the the guidelines outlined by the Canada Soil Survey Committee (1978). Only at sites 1 and 2 where relief is hummocky were Chernozemic soils encountered. Those Solonetzic soils observed exhibited moderate to strong columnar structures in the B horizon and in most instances exhibited a blocky mesostructure. The blocky mesostructure is an indication some degree of solodization has occurred in these soils. Intact eluvial horizons were observed in some soils at sites 1 to 4, however, none were observed at site 5. Differences in other features (discussed in Chapter 5) suggest eluvation/illuviation has occurred in Solonetzic soils lacking an Ae horizon. It is, therefore, postulated the Ae horizon has, in most instances, been destroyed by cultivation and those soils lacking an Ae horizon are in an intermediate stage of evolution (Solodized Solonetz) as opposed to an early stage of evolution (Solonetz).

The surface horizon (Ap) in the conventionally tilled soils was dominated by the granic fabric sequence which is dominantly mull in composition. Similar descriptions are given by Pawluk and Dudas (1982) for the Ap horizon of a Chernozemic soil. At site 4 mullgranoidic iunctic fabric was observed in the conventionally tilled Ap horizons. This fabric is indicative of relatively severe degradation of the surface. It may reflect soil management, genetic processes, an intially coarse parent material or a combination of all three. Smectite redistribution (Chapter 5) suggests intense eluviation.

Banded fabrics were observed in certain profiles at sites 1, 2 and 4. Where observed, banded fabrics were generally, though not always, underlain by insepic porphyroskelic fabric. The latter appears to be associated with transitional AB horizons and occasionally with the zone of weathering in the upper Bnt horizon. Humified organic matter was frequently encountered in the s-matrix of the insepic porphyroskelic fabric. This may reflect sodium humate illuviation under previous, more alkaline conditions or gradual humification of this zone.

Porphyroskelic fabric was observed in all B horizons examined. Plasma fabrics were variable but generally consisted of mosepic, skelsepic or masepic plasma separations in variable combinations. Brewer (1976) attributes skelsepic, vosepic and masepic plasmic fabrics to forces associated with wetting and drying of soil materials. Since wetting and drying is implicated in the formation of columnar structures in Solonetzic soils (Bowser, 1961) this is the likely origin of these fabrics. The origin of insepic and mosepic fabrics is not as certain. They may, to some degree, be inherited from sedimentary rock material, with less intense shrink-swell cycles being responsible for development of mosepic plasmic fabric (Brewer, 1976). Insepic fabrics observed were typically associated with transitional AB horizons and apparent weathering zones in Bnt horizons such that their origin in the upper sola of Solonetzic soils may be partially eluvial in nature. Craze and skew planes were frequently observed in B horizons. Where adjacent peds were found to be partially accommodated reflects the blocky mesostructure observed morphologically.

Deep plowing altered the distribution with depth of soil fabrics in addition to creating a unique soil fabric. Former Ap material (mullgranoidic or mullgranoidic iunctic sequences) was replaced by mixed complex mullgranoidic//porphyroskelic material to mimimum depths of 75 mm. These areas (designated A or A1) are largely confined to shallower depths and therefore may owe their origin to subsequent post deep plowing tillage; larger porphyroskelic units have been broken down and mixed with former Ap material to form more intimately associated mixtures that appear fairly homogeneous when viewed macroscopically. Observed micromorphologically, this mixture can be separated into distinctly different modal fabrics. It should be noted this anthropogenic fabric is also found at depth such that it may also result from the mixing action of the deep plows.

Relatively intact, larger areas of porphyroskelic fabric are found distributed throughout depth in all deep plowed soils examined. This material appears to be derived from AB or Bnt horizons, although material from lower depths cannot be ruled out due to the relatively shallow depth of micromorphological investigations (225 mm). Chemical properties of deep plowed soils (Appendix A) suggest C horizon material was, in most instances, incorporated within the disturbed upper sola.

At sites 1 to 4 original Ap material (mullgranoidic or similar fabric) is observed within sampling depth in all deep plowed profiles, but not at the immediate soil surface. Botov (1959) reports downward losses of Ap material are the result of an incorrect setting for the first layer plowshare of the 3-layer plow. Variable topsoil thickness and consistence of the B horizon causing uplift of the plow may also contribute to Ap losses.

At site 5 mullgranoidic fabric is not observed in any of the deep plowed profiles. This supports the tillage action of the two types of plows used. The topsoil saving feature of the 3-layer plow, used at sites 1 to 4, is indicated by preservation of at least zones of unaltered Ap material while the more complete mixing action of the single-bottom plow (no intact zones of Ap material) is indicated at site 5.

5. ANALYTICAL PROPERTIES OF SOIL SEEDBEDS

5.1 Introduction

Considerable research has been devoted to the study of changes in chemical and physical properties of Solonetzic soils through deep plowing. Although this is true, little emphasis has been placed on the effect of these various changes on the overall suitability of the soil as a medium for seed germination and seedling establishment. Furthermore, no attempt has been made to specifically measure and relate various chemical, physical and mineralogical properties of deep plowed seedbeds to crop establishment patterns. This chapter is devoted to analytical characterization of the seedbeds of conventionally tilled and deep plowed Solonetzic soils and the apparent relationships between the various properties measured. The relationships of these properties, where applicable, to crop establishment and growth patterns are discussed in Chapter 6.

5.2 Literature Review

5.2.1 Effect of Deep Plowing on Chemical Properties

The bulk of research on deep plowing of Solonetzic soils has focused on changes in soil chemical properties within plowing depth. Various changes in soluble, extractable and exchangeable ions are reported by several authors. A summary of these changes, specific to Ap horizons, follows.

5.2.1.1 Soil Solution Properties

Numerous researchers have examined changes in soil solution properties resulting from deep plowing. The measured effect of deep plowing on a given constituent has generally been consistent. That is, the direction of change reported by one author is generally supported by another author. A summary of the relative changes of various soil solution properties is given in Table 40.

According to these studies soil reaction (pH) is consistently increased by deep plowing (Alzubaidi and Webster, 1982; Ballantyne, 1983; Bowser and Cairns, 1967; Cairns, 1962; Harker et al., 1977; Lavado and Cairns, 1980). Measured increases range from a low of 0.3 pH units (Ballantyne, 1983) to a high of 2.8 pH units (Lavado and Cairns, 1980). Increased pH values are a direct result of incorporation of calcareous material and/or incorporation of alkaline material from the lower solum. Increased lime equivalent in deep plowed Ap horizons has been reported (Ballantyne, 1983; Lavado and Cairns, 1980), while other studies indicate alkaline B horizon material is incorporated within the Ap (Bowser and Cairns, 1967).

Changes in total salt content following deep plowing have been variable (Table 40). In some instances electrical conductivity (EC) of the Ap has increased (Alzubaidi and Webster, 1982; Ballantyne, 1983; Harker et al., 1977; Sandoval et al., 1972); in others it has decreased (Bowser and Cairns, 1967; Rasmussen et al., 1972) while in still others no change has been reported. Significant increases as high as 2.7 mS/cm are reported (Harker et al., 1977) while significant decreases of 2.3 mS/cm are also reported (Bowser and Cairns, 1967). What factors have affected the direction of change of total soluble salts

Table 40. Changes in soil solution properties of Ap horizons after mechanically disturbing Soloneztic soils.

Source	Relative Change in Property *								
	pH	EC	SP	Ca	Na	Mg	K	SAR	Ca:Na
Alzubaidi & Webster 1982	↑	↑	-	-	-	-	-	↓	↑
Ballantyne 1983	↑	↑	-	↑	↓	nc	-	-	-
Bowser & Cairns 1967	↑	↓	-	↑	↓	↓	nc	-	-
Cairns 1962	↑	nc	nc	-	-	-	-	-	-
Harker *et al* 1977[1]	↑	↑	↑	↑	↑	↑	nc	-	↑
Lavado & Cairns 1980	↑	-	-	-	-	-	-	-	-
Rasmussen *et al* 1972	-	↓	-	-	-	-	-	-	-
Sandoval 1978	-	nc	-	-		-	-	↓	-
Sandoval *et al* 1972	-	↑	-	-	-	-	-	↓	-

* ↑ - increase; ↓ - decrease; nc - no change.

[1] results given are from field studies.

are not specified. Net leaching, time, initial salt status and soil variability will all affect the measured direction and magnitude of salt fluxes. These factors would be reflected in the intensity of Solonetzic soil formation and the degree of solodization that has developed at the specific sites.

Upon deep plowing saturation percent (SP) was found to increase by Cairns (1962) but no change is reported by Harker et al. (1977). Several factors may affect saturation percent, including clay quantity and quality, exchangeable Na and organic matter content. The increased SP reported by Cairns (1962) accompanies an increase in clay content.

Soluble Ca^{2+}, in all instances, has increased in the Ap horizon upon deep plowing (Table 40). Ballantyne (1983) reports an increase of 13% in soluble Ca^{2+} upon deep plowing Solonetzic soils in Saskatchewan. Bowser and Cairns (1967) report a significant increase of 0.14 me/100 g of soluble Ca^{2+} upon deep plowing a Duagh Solonetz (BL.SZ). A similar increase of 7.1 me/L on the same soil series is reported by Harker et al. (1977).

Results of soluble Na^{+} are less consistent than those for soluble Ca^{2+}. Harker et al. (1977) report a significant increase in soluble Na^{+} from 21.2 to 48.9 me/L upon deep plowing. On the other hand, decreases are reported by Ballantyne (1983), Bowser and Cairns (1967) and Sandoval (1978). Respective changes are from 42 to 31% soluble Na^{+}, 1.38 to 0.38 me Na^{+}/100 g and approximately 8 to 5 me Na^{+}/L.

Although soluble Na^{+} may increase, soluble Ca:Na ratios generally increase upon deep plowing. Alzubaidi and Webster (1982) and Harker et al. (1977) report increased Ca:Na ratios upon deep plowing. In the former study a substantial increase in this ratio from 0.05 to 3.24 is reported while the latter reports a slight increase from 0.08 to 0.18. Incorporation of C horizon material high in Ca^{2+} followed by at least moderate leaching should favour an increase in this ratio because of the ease with which Na^+ is exchanged and leached relative to Ca^{2+}.

Little emphasis is placed on soluble Mg^{2+} and K^+ changes upon deep plowing, except as they may influence crop nutrition (Carter et al., 1979). However, Harker et al. (1977) report an increase in soluble Mg^{2+}, Bowser and Cairns (1967) report a decrease and Ballantyne (1983) reports no change. Studies of Harker et al. (1977) and Bowser and Cairns (1967) indicate no change is observed in soluble K^+ levels.

The SAR in all reported instances has decreased in the Ap horizon upon deep plowing. Reported reductions range from 13 (Alzubaidi and Webster, 1982) to 3 (Sandoval, 1978) with intermediate values also reported (Sandoval et al., 1972).

5.2.1.2 Exchangeable/Extractable Analysis

To a large extent changes observed in extractable or exchangeable cations follow those changes observed in the respective soluble constituents. A summary is given in Table 41.

Bowser and Cairns (1967), Cairns (1962) and Lavado and Cairns (1980) all report significant increases in extractable or exchangeable Ca^{2+}. Respective increases are 9.3 me/100 g (exchangeable), 4.7 me/100 g (extractable) and 7.76 to 14.16 me/100 g (extractable). Those increases reported by Bowser and Cairns (1967) and Cairns (1962) parallel increases observed in soluble Ca^{2+}.

In two reported instances exchangeable/extractable Na^+ has

Table 41 . Changes in various chemical properties of Ap horizons after mechanically disturbing Solonetzic soils.

	Relative Change in Property *									
	Extractable/Exchangeable							Organic Matter		
Source	Ca	Na	Mg	K	Ca:Na	ESP	CEC	OM	C	N
Alzubaidi & Webster 1982	-	-	-	-	-	↓	-	-	-	-
Ballantyne 1983	-	-	-	-	-	-	-	-	↓	↓
Bowser & Cairns 1967	↑	↓	nc	nc	↑	-	↑	-	↓	↓
Cairns 1962	-	-	-	-	-	-	-	↓	-	-
Lavado & Cairns 1980	↑	↑	↑	nc	↑	-	-	↓	-	-
Rasmussen _et al_ 1972	-	-	-	-	-	↓	-	-	-	-
Pair & Lewis 1960	-	-	-	-	-	↓	-	-	-	-

* ↑ - increase; ↓ - decrease; nc - no change.

decreased upon deep plowing. Bowser and Cairns (1967) report a significant reduction in exchangeable Na^+ from 5.2 to 1.2 me/100 g while Cairns (1962) reports a moderate reduction from 5.0 to 3.3 me/100 g extractable Na^+. Contrary to these results, Lavado and Cairns (1980) found significant increases in extractable Na^+ as high as 3.68 me/100 g.

Exchangeable sodium percentage (ESP) has in all instances decreased in Ap horizons upon deep plowing (Table 41). A significant decrease from 11.7 to 2.4 is reported by Alzubaidi and Webster (1982). Reductions in ESP from 21 to 1 (Pair and Lewis, 1960) and 12 to 5 (Rasmussen _et al_., 1972) have also occurred.

Extractable Ca:Na ratios have also been examined in Solonetzic soils. This ratio has not been found to change unidirectionally upon deep plowing. Bowser and Cairns (1967) report a significant increase in this ratio from 2.0 to 16.3, while other studies report a variety of changes with varying directions (Cairns, 1976a; Lavado and Cairns, 1980). Plowing of low Ca^{2+}, C horizon material appears to have little effect on this ratio (Lavado and Cairns, 1980). This ratio is of interest in that a post deep plowing ratio of 4 or more appears necessary to maintain a sufficiently stable seedbed with adequate tilth (Cairns, 1976a).

Extractable or exchangeable Mg^{2+} and K^+ have received less emphasis that Na^+ or Ca^{2+}. Only in one instance have these values changed upon deep plowing; an increase in extractable Mg^{2+} is reported by Lavado and Cairns (1980).

Cation exchange capacity was found to increase from 23 to 27 me/100 g upon deep plowing (Bowser and Cairns, 1967). No explanation is given for this increase, although it is probably the result of an increase in clay content observed in the same study.

It is interesting to note conflicting chemical results are reported by various authors who have deep plowed the same soil series. Changes in the Duagh soil series (BL.SZ) upon deep plowing are reported by several authors. Results of Bowser and Cairns (1967) generally agree with those of Cairns (1962) except for soluble Mg^{2+}. Of particular note is the deviation in certain data of Harker et al. (1977) relative to the other two studies. Significant increases in EC and soluble Na^+ are reported by Harker et al. whereas either no change or significant decreases are reported in the other two studies. Several factors were relatively uniform throughout the three studies, including the period between observations (6 or 7 years) and the methods of analysis. Differences do exist between the method of profile disruption, but this is not consistent between the opposing results. The discrepancy may result from differences due to the period and time of sampling, as influenced by seasonal or short term climatic trends, or the inherent variability of Solonetzic soils. Total salt content and soluble Na^+ tend to increase over the summer months in the Duagh Solonetz (Landsburg, 1981) such that the increase in these two properties reported by Harker et al. may reflect a July sampling date.

5.2.1.3 Organic Matter Related Properties

Deep plowing, whether performed with or without a plow with topsoil saving features, has a detrimental effect on soil organic matter content within Ap horizons (Table 41). Bowser and Cairns (1967) report significant reductions in carbon and nitrogen contents;

respective changes were 3.43 to 1.89% and 0.29 to 0.17%. Similar, yet smaller reductions, are reported by Ballantyne (1983) who found organic C to decrease from 1.25 to 0.96% and N to decrease from 0.13 to 0.11% five years after deep plowing. Slightly larger reductions in C and N are reported in the year immediately following deep plowing (Ballantyne, 1983).

Organic matter (OM) content itself is reduced upon deep plowing. Cairns (1962) indicates a slight drop in OM from 4.83 to 4.28% occurs in the Ap horizon. More pronounced decreases are reported by Lavado and Cairns (1980) where OM content was reduced from 36 to 52% of original levels. Data of Lavado and Cairns (1980) further suggest the magnitude of this decrease is similar whether a topsoil saving plow or a single bottom plow is used.

5.2.2 Effect of Deep Plowing on Physical Properties

Table 42 summarizes literature available relating to changes in soil physical properties upon deep plowing Solonetzic soils. Results tend to be more consistent than those reported for soil chemical properties.

Both total clay and fine clay increase in the Ap horizon upon deep plowing (Ballantyne, 1983; Bowser and Cairns, 1967; Cairns, 1962; Lavado and Cairns, 1980; Rasmussen et al., 1972). The mean reported change in total clay is 4.1%, with a range of -0.1% (Lavado and Cairns, 1980) to 8.0% (Ballantyne, 1983). In both studies where fine clay is examined the reported increase is 7.0% (Ballantyne, 1983; Bowser and Cairns, 1967).

Water stable aggregates have been found to increase in content upon deep plowing. Bowser and Cairns (1967) attribute a significant

Table 42. Changes in physical properties of Solonetzic Ap horizons following mechanical disruption.

Source	Total Clay	Fine Clay	Aggregate Stability	Strength	Infiltration	Shrinkage	Bulk Density	Water Retention -1/3	-15
	Relative Change in Property *								
Ballantyne 1983	↑	↑	-	-	-	-	-	-	-
Bowser & Cairns 1967	-	↑	↑	↑	↑	-	-	-	-
Cairns 1962	↑	-	-	-	-	-	-	-	-
Lavado & Cairns 1980	↑	-	-	↑	↓	↑	-	-	-
Rasmussen _et al_ 1972	↑	-	-	-	↑	-	nc	↑	↓
Sandoval _et al_ 1972	-	-	-	↓	-	-	↑	-	-

* ↑ - increase; ↓ - decrease; nc - no change.

increase in water stable aggregates from 47 to 66% to upward redistribution of clay and downward redistribution of salts.

Some variability is reported in changes in soil strength in the Ap horizon upon deep plowing. Sandoval et al. (1972) report a slight reduction in breaking strength from 1.1 to 0.8 kg/cm^2 five years after deep plowing. Contrary to this are increases in breaking strength reported by Bowser and Cairns (1967) and Lavado and Cairns (1980). In the former study breaking strength increased from 4 to 9 kg/cm^2 while in the latter study significant increases as high as 8.23 kg/cm^2 are reported. Slightly larger increases in breaking strength appear to occur with the use of a single moldboard plow as compared to the use of a topsoil-saving plow (Lavado and Cairns, 1980).

Conflicting results are also reported with respect to changes in water infiltration rate upon deep plowing. On disturbed soil samples Bowser and Cairns (1967) report a significant increase in infiltration from 1.6 to 3.4 mL/cm^2/5 min. Contrary to this are results of Lavado and Cairns (1980) who report significant 5 to 8 fold reductions in infiltration.

Soil shrinkage has been examined only in one study (Lavado and Cairns, 1980). In all soils examined shrinkage was significantly increased by deep plowing, in some instances by as much as 8.24%.

Bulk density of deep plowed Ap horizons has also been examined. Sandoval et al. (1972) report a slight increase in bulk density from 1.45 to 1.60 g/cm^3 due to deep plowing while another study (Rasmussen et al., 1972) reports no changes.

Slight alterations of water-retention properties in Ap horizons due to deep plowing are reported by Rasmussen et al. (1972). Water retention at -1/3 bar tension increased slightly while that of 15 bars tension decreased slightly. The overall result was an increase in the available water of 3% (by weight).

From the foregoing it is apparent that deep plowing results in some rather pronounced changes in chemical and physical properties of Ap horizons. Whether these changes are beneficial or detrimental, however, depends upon the study. Certain studies indicate some aspects of tilth are improved, while others indicate the opposite.

5.3 Materials and Methods

In the fall of 1980, at the time of morphological and micromorphological sampling, Ap samples were procured for laboratory analysis. Four samples were obtained for each of the tillage treatments (conventional and deep plowed) at each of the five sites (refer to Figure 9, Chapter 3 for sample locations). Depth of sampling in the deep plowed soils was equivalent to Ap depths observed in the conventionally tilled soils. All samples were air dried and ground to pass a 2 mm sieve. Unless otherwise specified, the following analyses were conducted in duplicate on the fine earth (2 mm) samples.

5.3.1 Chemical Properties

Soluble metallic cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), pH, EC and saturation percent were determined by the saturation paste method (U.S. Soil Salinity Staff, 1954). Soluble Ca^{2+} and Mg^{2+} were determined on saturation extracts by atomic absorption spectroscopy (AAS) while soluble Na^{+} and K^{+} were determined by flame photometry. Extractable metallic cations were determined from a 1:40 NH_4Ac extract

(1 M, pH 7) by AAS.

Total exchange capacity (TEC) was determined on samples saturated with NH_4Ac and removed of excess electrolyte by leaching with n-propanol. The NH_4Ac was displaced with NaAc and the former was measured with the use of an ammonium electrode (Anonymous, 1980). Exchangeable Na^+ was determined by correcting extractable Na^+ for soluble Na^+, using saturation percent to convert soluble Na^+ from a volume basis to a weight basis. ESP was ca[illegible]m exchangeable Na^+ and TEC values. Exchange acidity was [illegible] by extraction with 1.0 M $Ba(Ac)_2$ and back titrating with standardized NaOH using phenolphthalein indicator (Russel and Stanford, 1958). Soil reaction in 0.01 M $CaCl_2$ was determined by the method of Peech (1965). Total C was determined by dry combustion with a Leco induction furnace (McKeague, 1978). Semi-micro Kjeldahl, excluding NO_3^- and NO_2^-, was used to determine total N (McKeague, 1978).

5.3.2 Mineralogical Properties

The clay separates (2 um) were separated for mineralogical analysis by gravity sedimentation (Jackson, 1979) following ultrasonic dispersion (Genrich and Bremner, 1974). X-ray diffractograms, for qualitative determination of clay mineralogy were obtained using a Phillips diffractometer equipped with Cu K x-radiation. Oriented samples, prepared by the paste method (Theisen and Harward, 1962), were subjected to the following seven relative humidity (RH)/temperature/solvate treatments on Ca^{2+} or K^+ saturated samples (McKeague, 1978):

Ca saturated, 54% RH

Ca saturated, ethylene glycol solvated

Ca saturated, glycerol solvated

K saturated, 105°C, 0% RH

K saturated, 105°C, 54% RH

K saturated, 300°C, 0% RH

K saturated, 550°C, 0% RH

Quantitative estimations of the phyllosilicates present were conducted by a variety of methods. Percent smectite was estimated from clay CEC, assuming smectite has an average CEC of 110 me/100 g (Borchardt, 1977). Smectite estimates were checked using surface area rminations (Carter et al., 1965). The assumed surface area of smectite was 820 m^2/g. Mica content is based on the K content of a 0.1% Ca^{2+} saturated clay suspension, as determined by ICP-AES with suspension aspiration (Spiers et al., 1983). The mica was assumed to contain 10% K_2O (Jackson, 1979). Kaolinite plus chlorite was obtained by difference. These two minerals were separated on the basis of 3.59 Å and 3.54 Å peak intensities, respectively, using equations of Griffin (1971) and diffractogram peaks from the Ca saturated, ethylene glycol solvated treatment.

The following assumptions are inherent in the above approach to quantify the clay mineralogy (Griffin, 1971): (1) the reported phyllosilicates, namely smectite, mica, kaolinite and chlorite are the only minerals present; (2) the refracting ability of the minerals is consistent; and (3) there is a 1:1 linear relationship between the ratio of the second order peak of kaolinite (3.59 Å) and the fourth order peak of chlorite (3.54 Å). This approach ignores the presence of minerals such as quartz and feldspars and also excludes amorphous clay materials. It, therefore, represents an analysis of the phyllosilicate composition rather than an analysis of the total clay fraction composition. With the exception of five samples, phyllosilicate mineralogy was not performed in duplicate.

5.3.3 Physical Properties

Particle size distribution was performed using the pipette method (Toogood and Peters, 1953). All samples were pretreated with H_2O_2 to remove colloidal organic matter. Where total salt content was sufficiently high to cause flocculation, repeated washings and centrifugations were performed until a suspension remained after standing for 24 hours. Where necessary, carbonates were removed with the addition of 1 M NaAc buffered to pH 5 with acetic acid (McKeague, 1978).

Sand fractionation was performed by the procedure of Day (1965) using sand separated for particle size distribution analysis. An Allen-Bradley sonic sifter equipped with standard sieves was used to separate the various sand fractions.

Soil moisture retention characteristics were determined with the use of a pressure plate apparatus (Richards, 1965) on disturbed samples. Mass water content was determined at tensions of 1/3, 1, 3 and 15 bars.

Mean weight diameters of aggregates were measured according to the wet sieving procedure (Kemper and Chepil, 1965) with the following exceptions. Sieving was performed on samples previously air dried and ground to pass a 2 mm sieve. Sieve sizes of 1.0, 0.5, 0.25 and

0.12 mm were used. Triplicate 60 g samples were immersed in a dry state and sieving was performed for 30 minutes in distilled water.

Aggregate stability was determined from data obtained through the sand fractionation and wet sieving procedures previously described. This involved correction of aggregates for sand > 60 mesh (0.25 mm), since sand > 60 mesh is not considered as aggregates (Kemper, 1965). The equation used for calculating aggregate stability (AS) was as follows (Kemper, 1965):

$$\% \ AS = 100 \left[\frac{(AGG+S) - S}{SAMP - S}\right]$$

where AGG+S refers to the total weight of soil material retained on all sieves during wet sieving.

S is the proportional weight of sand > 60 mesh contained within the original 60 g wet sieving sample, as calculated from sand fractionation and particle size distribution data.

SAMP is the initial oven dry weight (approximately 60 g) of the sample used for wet sieving.

Modulus of rupture was determined on five replicate samples by the method of Richards (1953) as described by Reeve (1965).

Soil consistence, as measured by the Atterberg limits, was determined according to the method described by Sowers (1965). The one point method was used for determining the liquid limit. Duplicate determinations were conducted on 50% of the samples. Activities (Skempton, 1953) were calculated by dividing the plasticity index by percent clay.

5.3.4 Statistical Analysis Techniques

Statistical analyses were performed on most properties measured in the Ap samples. The analyses conducted were designed to: (1) determine the overall effect of deep plowing on properties of the Ap layer, inclusive of all sites; (2) determine the effect of deep plowing on Ap properties within a given site; (3) determine differences in Ap properties between sites; (4) determine the linear relationship between various analytical Ap properties; and (5) assess the variability of analytical properties on a per site per treatment basis. In most instances APL statistical packages accessed through the University of Alberta computer were used. The SPSS package was used to complete certain simple correlations.

The overall effect of deep plowing was assessed using a standard two-way analyses of variance (ANOVA) with application of the F-statistic (Steel and Torrie, 1980). These ANOVA involved sources of variation of tillage treatment, site, tillage treatment x site and error. In all instances the F-statistic was computed using mean square error (MS_E) as the valid error mean square, regardless of whether the tillage x site interaction was significant. This decision was based on using the guidelines of Hicks (1964) to determine the error mean square (EMS).

The effect of deep plowing within a given site was analyzed using a one-way ANOVA and the resulting F-statistic, using observations specific to that given site only; that is, within site tillage effects were assessed on the basis of the eight observations (four conventional tillage, four deep plowed) and ensuing variability. The outcome of this test is the same as would have occurred had t-tests been performed to compare tillage treatments (Hardin, 1982)[1]. The advantage of using this approach is that the effect of deep plowing within a given site is assessed on the basis of soil variability within that site only. Since plots within a site were located to encompass maximum anticipated soil variability, it was deemed undesirable to underestimate or overestimate treatment effects at given site because greater or lesser variability was present at another site.

Statistical differences between sites within a given tillage treatment were determined only if warranted by a significant F-statistic for site, as determined by the two-way ANOVA. The Student-Newman-Keuls (SNK) procedure was used on means which were "logically grouped" (Winer, 1971) to provide for comparisons of all site means within a given tillage treatment. The standard error of means (SEM) used for computation of required differences is determined as follows (Winer, 1971):

$$\mathrm{SEM} = MS_E/n$$

where MS_E = mean square error for all cells in the experiment

n = the number of within cell observations

The above approach assumes homogeniety of variance between both tillage treatments. Degrees of freedom (DF) of the SEM, for determination of SNK values, are found as follows:

$$\mathrm{DF} = pq(n-1)$$

where p = number of tillage treatments (=2)

q = number of sites (=5)

n = number of within cell observations (=4)

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[1] Hardin, R.T., Professor, Department of Animal Science, University of Alberta, Edmonton.

Thus, the DF for the SEM was 30.

Simple correlations between various Ap properties using the entire data set, were completed as were determination of standard deviations (Steel and Torrie, 1980).

ANOVA tables and correlation matricies are contained in Appendices B and C, respectively. Means and standard deviations of the various Ap properties, determined on individual cells, are contained within Appendix D.

5.4 Results and Discussion

5.4.1 Chemical Properties

A comparison of soil solution properties in the Ap horizons, as affected by tillage, is given in Table 43. The overall effect of deep plowing was to significantly increase pH, EC, soluble Ca^{2+}, Mg^{2+}, Na^{+} and SAR in the Ap horizons. Soluble K^{+} also increased slightly, though not significantly. Statistically, the saturation percent was significantly decreased.

Although the conventionally tilled values for soil solution properties vary somewhat from site to site, for the most part the various sites responded to deep plowing in approximately the same manner. A notable exception is at site 2, where EC, soluble Ca^{2+} and soluble Na^{+} were not markedly changed by deep plowing. A shallow plowing depth (38 to 48 cm) and the predominance of Chernozemic soils at this site (see Chapter 4) undoubtedly influenced redistribution of these constituents. Since site 1 is similar to site 2 in that Chernozemic soils occupy at least 50% of the sampled areas, non-significant changes were anticipated here as well. However, since plowing depth was

Table 43. Salinity status in the Ap horizons as determined on saturation extracts.

Site	pH	EC	SP	Ca	Na	Mg	K	SAR
				Soluble Cations (me/l)				
Conventional Tillage								
1	a 6.3	0.3	a 58	1.3	1.3	0.6	b 0.09	b 1.3
2	b 5.2	0.4	a 59	2.3	1.2	1.3	a 0.33	b 1.0
3	ab 5.9	0.5	a 60	0.7	4.5	0.4	b 0.07	a 5.5
4	ab 5.6	0.3	b 50	0.6	2.6	0.3	b 0.09	ab 3.7
5	a 6.2	0.6	ab 53	1.2	4.6	0.5	b 0.11	a 4.9
Overall Mean	5.8	0.4	56	1.2	2.9	0.6	0.14	3.3
Deep Plowed								
1	ab 7.2 *	b 1.1 **	ab 51	5.4 **	b 4.7 *	b 2.8	b 0.19	b 2.3
2	c 6.4 **	b 0.7	a 57	4.2	b 1.7	b 2.3	a 0.38	b 1.0
3	bc 6.9 **	a 2.1 *	a 56	7.1 *	a 15.8	a 4.4	b 0.15	a 6.4
4	a 7.9 **	b 1.2 **	b 46	2.6 **	a 10.7	b 0.9	b 0.12 *	a 8.0 **
5	ab 7.5 **	ab 1.5 **	a 56	4.1 **	a 14.1 **	b 1.3	b 0.16	a 8.6 *
Overall Mean	7.2 **	1.3 **	53 *	4.7 **	9.4 **	2.4 **	0.20	5.3 **

*, ** Significantly different, within similar levels, from normal tillage at P=.05 and P=.01, respectively.
Values within columns and within tillage not preceeded by the same letter are significantly different at P=.05.

deeper and salts were generally found at shallower depths in the C horizon underlying the deep plowed zone at site 1 (Table 62, Appendix A), significant changes were observed in some properties.

Although rather substantial increases in soluble Na^+ were observed at sites 3 and 4, the inherent variability of Ap properties, particularly in the conventionally tilled soils (Table 98, Appendix D), resulted in non-significant changes at these two sites. Soils are fairly uniform in so far as classification within the Solonetzic order is concerned (Tables 26 and 27, Chapter 4), such that morphological similarity does not necessarily imply chemical similarity.

Extractable and exchangeable cations for the Ap horizons are given in Table 44. Results here generally correspond to those for soil solution properties, in that pH, Ca^{2+}, Mg^{2+}, Na^+ and ESP are significantly increased, on an overall basis, by deep plowing. Of additional significance is the reduction in exchange acidity. Total exchange capacity, extractable K^+ and extractable Ca:Na remained unchanged by deep plowing.

On the basis of data contained in Table 44 grouping of the sites appears practical. Sites 1 and 2 have, in the conventionally tilled soils, high extractable Ca^{2+} and Mg^{2+}, low extractable Na^+, low ESP and high Ca:Na ratios relative to sites 3, 4 and 5. Upon deep plowing, extractable Ca^{2+}, Mg^{2+} and Na^+ were, for the most part, significantly increased at sites 3, 4 and 5 but not at sites 1 and 2. In addition, increases in ESP and extractable Ca:Na are more pronounced at sites 3, 4 and 5. Differences in these initial values and relative changes upon deep plowing further coincide with soil classification at these sites. At least 50% of the soils samples at sites 1 and 2 are Chernozemic while

Table 44. Exchangeable and extractable properties in the Ap horizons.

Site	pH in 0.01 M $CaCl_2$	Exchangeable Properties (me/100g)				Extractable Cations (me/100g)				
		Exchange Acidity	TEC	Na	ESP	Ca	Na	Mg	K	Ca:Na
Conventional Tillage										
1	5.1	8.77	a 22.62	bc 1.20	b 5.4	12.5	ab 1.28	a 4.16	0.72	b 10.6
2	5.2	8.22	b 19.46	c 0.38	b 1.9	9.7	b 0.45	ab 3.21	0.86	a 24.2
3	5.1	10.00	c 15.34	bc 1.13	b 8.1	4.4	ab 1.39	bc 1.72	0.50	b 5.6
4	4.6	7.39	d 11.26	ab 1.50	a 13.5	3.8	ab 1.63	c 1.12	0.54	b 2.5
5	5.3	5.47	c 14.29	a 2.28	a 16.0	8.7	a 2.52	ab 2.78	0.92	b 3.4
Overall Mean	5.0	8.11	16.59	1.30	9.0	7.8	1.46	2.60	0.71	9.3
Deep Plowed										
1	a 6.9**	1.19**	b 17.66**	c 0.72	c 4.1	17.3	c 0.95	a 6.09*	0.61	a 20.8
2	b 6.0	3.38*	a 21.26	c 0.60	c 2.8	13.9	c 0.69	ab 4.84	0.81	a 21.2
3	a 7.3**	0.63**	b 16.96	b 1.93	b 11.4	28.7*	b 2.81	a 6.33**	0.75	b 9.4
4	a 7.5**	0.08**	c 13.08	a 2.94*	a 22.4	24.1*	ab 3.43*	b 3.73**	0.61	b 6.8**
5	a 7.5**	0.24**	b 17.31*	a 3.46*	a 20.1	21.8**	a 4.24*	ab 4.64*	0.73	b 5.4
Overall Mean	7.1**	1.05**	17.25	1.93**	12.2**	21.1**	2.42**	5.13**	0.70	12.7

*, ** Significantly different, within similar levels, from normal tillage at P=.05 and P=.01, respectively.
Values within columns and within tillage not preceeded by the same letter are significantly different at P=.05.

those at sites 3, 4 and 5 are all Solonetzic. As well, horizons of salt accumulation are found at greater depth at sites 1 and 2 relative to sites 3, 4 and 5 (Appendix A).

Organic matter related properties of total carbon (C) and total nitrogen (N) are given in Table 45. Deep plowing significantly decreased both properties at all sites, which agrees with findings reported elsewhere (Bowser and Cairns, 1967). Relative reductions in total C range from 55% (site 1) to 33% (site 5) with an overall mean reduction of 43%. Decreases in total N range from 56% (site 3) to 35% (site 2) with an overall mean reduction of 46%. Generally speaking, greater relative reductions in total C and N occur at those sites initially higher in value for these two properties; that is, the percent reduction following deep plowing is higher at sites 1, 2 and 3 relative to sites 4 and 5.

No apparent difference exists between the topsoil saving features of the single bottom plow (site 5) and the topsoil saving plow (sites 1 to 4). In fact, relative losses of total C and N were slightly lower at site 5 relative to site 4. Lavado and Cairns (1980) provide data comparing both plow types at these two sites. They found little difference between the two plow types and attribute this to malfunction of the topsoil saving plow. Improper setting of the topsoil saving plow may cause significant losses of Ap material (Botov, 1959).

Reductions in total C and N reflect both dilution of Ap material with subsurface material, as well as an actual loss of Ap material from the surface. Dilution is apparent both in micromorphological observations (Chapter 4) and the chemical analysis previously discussed. Actual loss was also apparent micromorphologically but was

Table 45. Organic matter properties of the Ap horizons as affected by tillage treatment.

	Conventional Tillage			Deep Plowed Tillage		
Site	Total Carbon (%)	Total Nitrogen (%)	C:N	Total Carbon (%)	Total Nitrogen (%)	C:N
1	a 3.30	a 0.288	11.5	b 1.49**	b 0.129**	11.6
2	a 3.38	a 0.287	11.8	a 2.17**	a 0.187**	11.6
3	a 2.99	a 0.254	11.7	b 1.46**	b 0.111**	13.4
4	b 2.13	b 0.185	11.5	b 1.30**	b 0.107**	12.1
5	b 2.27	b 0.207	10.9	b 1.52**	b 0.126**	12.1
Overall Mean	2.81	0.244	11.5	1.59**	0.132**	12.2

*, ** Significantly different, within similar levels, from normal tillage at P=.05 and P=.01, respectively.

Values within columns and within tillage not preceeded by the same letter are significantly different at P=.05.

additionally noted morphologically, as in many instances depth of deep plowing was located by observation of a thin band (1 to 2 cm) of Ap material at the bottom of the dead furrow.

Carbon to nitrogen ratios remained unaltered by deep plowing (Table 45). Ratios at sites 3 and 5, however, are slightly higher in the deep plowed soils relative to the conventionally tilled soils. Reaction with dilute HCl confirmed the presence of traces of carbonates in the deep plowed soils at these two sites. Although inorganic C was present at sites 3 and 5, the amounts probably have a negligible effect on total C values reported for these sites, as the linear correlation between total C and total N is 0.98*[1] (Table 97, Appendix C).

5.4.2 Phyllosilicate Mineralogy

Table 46 gives results of phyllosilicate mineralogy of the Ap horizons. Deep plowing has an overall effect of increasing the smectite content and decreasing the amount of kaolinite and chlorite present. Mica content remains unchanged by deep plowing.

Smectite, which is comprised of both montmorillonite and biedellite (results determined from XRD patterns but not shown) is the dominant phyllosilicate group in all deep plowed soils and in all conventionally tilled soils except site 4. Dominance of smectite minerals in the clay fraction of Alberta Solonetzic soils is reported elsewhere (Brunelle <u>et al.</u>, 1976). Increased smectite in the deep plowed Ap horizons is undoubtedly due to incorporation of subsurface material within this

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[1] Here, and in subsequent statements, the asterisk (*) signifies the correlation coefficient is significant at the 5% level. Using the 40 sample data set, a correlation ± 0.33 with 38 degrees of freedom (error) is significant at the 5% level (Steel and Torrie, 1980).

Table 46. Phyllosilicates in the Ap horizons, expressed as a percent of the <2um fraction.

Site	Mica	Smectite	Kaolinite	Chlorite
	Phyllosilicate Group (%)			
Conventional Tillage				
1	a 29	a 44	b 18	b 9
2	b 27	a 44	b 19	b 11
3	b 26	a 40	b 22	b 13
4	d 21	b 29	a 32	a 18
5	c 24	a 45	b 20	b 12
Overall Mean	25	40	22	13
Deep Plowed Tillage				
1	a 27 *	57 **	11 **	5 **
2	b 25	53 **	14 **	8 **
3	b 25	55 **	12 **	8 *
4	b 24 *	54 **	14 **	9 *
5	b 24	53	14	9
Overall Mean	25	54 **	13 **	8 **

*, ** Significantly different, within similar levels, from normal tillage at P=.05 and P=.01, respectively.

Values within columns and within tillage not preceeded by the same letter are significantly different at P=.05.

zone, particularly that derived from the lower B horizon. The nature of smectite minerals, with their smaller size and high charge density (Borchardt, 1977) make them particularly susceptible to dispersion and migration under the influence of Na^+. Upon deep plowing, smectite is reintroduced to the soil surface.

Kaolinite and chlorite are both lower in content in the deep plowed soils relative to the conventionally tilled soils. Higher values in the conventionally tilled soils likely reflects negative enrichment through smectite eluviation during the course of genesis (Brunelle et al., 1976).

Site 4 exhibits trends dissimilar to those of other sites. Kaolinite is the dominant phyllosilicate in the conventionally tilled soils at this site, rather than smectite. Chlorite is also significantly higher and mica significantly lower. These factors, particularly the relative balance of smectite versus kaolinite plus chlorite, suggest intense eluviation at site 4. Observation of a mullgranoidic junctic fabric at this site (Chapter 4) supports this conclusion. Since the phyllosilicate composition is consistent between sites in the deep plowed soils it is unlikely parent material phyllosilicate composition is responsible for the observed differences.

5.4.3 Physical Properties

Particle size distribution of the Ap horizons is given in Table 47. There was an overall significant increase in fine clay and total clay at the expense of sand and silt in the deep plowed soils. Increases in clay and fine clay in the deep plowed soils result from incorporation of subsurface material within the Ap, while the reduction in sand and silt is due to dilution. The increase in clay was also clearly evident in the

Table 47. Particle size distribution in the Ap horizons of conventionally tilled and deep plowed soils.

Site	Particle Size Class (%)				
	Sand	Silt	Clay	Fine Clay	Fine Clay: Total Clay
Conventional Tillage					
1	b 42.8	a 39.9	a 17.2	a 8.4	a 0.50
2	b 44.1	ab 34.5	a 21.4	a 9.3	ab 0.44
3	b 44.7	a 35.9	a 19.4	ab 6.3	b 0.31
4	a 62.1	b 26.9	b 11.0	b 3.5	b 0.31
5	b 48.4	ab 33.9	a 17.6	a 9.5	a 0.55
Overall Mean	48.4	34.2	17.3	7.4	0.42
Deep Plowed Tillage					
1	b 46.8	28.8	a 24.4 *	12.5 *	0.51
2	b 43.1	29.9 *	a 27.0	13.1 *	0.49
3	b 39.5	33.3	a 27.1	11.3 *	0.42
4	a 54.4	27.8	b 17.8	9.0 *	0.51 *
5	b 42.0 **	34.0	a 24.0 **	11.7	0.49
Overall Mean	45.2 *	30.8 *	24.1 **	11.5 **	0.48 *

*, ** Significantly different, within similar levels, from normal tillage at P=.05 and P=.01, respectively.

Values within columns and within tillage not preceeded by the same letter are significantly different at P=.05.

micromorphological observations (Chapter 4).

The overall fine clay:total clay ratio was significantly increased by deep plowing, although on an individual site basis the change was somewhat inconsistent. Changes in this ratio suggest the fine clay fraction is preferentially eluviated during the genesis of Solonetzic soils. A higher simple correlation between smectite and fine clay (r = 0.80*) relative to the other phyllosilicates (Table 92, Appendix C) indicates that smectite, which is generally high in charge density and small in size (Borchardt, 1977) relative to the other reported phyllosilicates, is the primary phyllosilicate susceptible to dispersion and eluvation. This is further supported in that those sites in which a significant increase in fine clay upon deep plowing was found also show a significant increase in smectite content (Table 46). In support of the intense eluviation observed at site 4 is the significantly different composition in sand, clay and fine clay relative to the other sites (Table 47).

Size distribution of the sand fraction is given in Table 48. The major fraction of the sand is fine sand with subdominant amounts of medium sand and very fine sand. Very little coarse and very coarse sand is present. The only notable difference between the various sites is the higher proportion of medium sand at site 4 relative to the other sites. Fine sand and very fine sand at site 4 are proportionately reduced.

The overall effect of deep plowing on soil moisture retention characteristics (Table 49) was to increase moisture retention at all tensions examined. For the most part retention at all tensions was increased by the same amount, resulting in an upward shift in the soil

Table 48. Distribution of the sand fractions in the Ap horizons.

	Sand Size Class* (% of total sand)				
Site	VCS	CS	MS	FS	VFS
Conventional Tillage					
1	3.0	9.1	22.6	39.9	25.4
2	2.4	8.6	21.1	40.5	27.5
3	2.6	9.1	24.3	40.7	23.3
4	1.3	10.5	34.8	35.1	18.3
5	2.4	7.1	18.8	44.2	27.6
Deep Plowed Tillage					
1	2.9	9.5	23.1	40.3	24.3
2	2.5	8.3	21.7	41.0	26.5
3	2.1	7.1	22.7	42.7	25.5
4	1.8	10.0	33.3	36.0	19.0
5	2.6	7.7	19.3	43.5	27.0

* Classes are according to the Canada Soil Survey Committee (1978), as follows:

VCS-very coarse sand	2.0 mm - 1.0 mm
CS-coarse sand	1.0 mm - 0.5 mm
MS-medium sand	0.5 mm - 0.25 mm
FS-fine sand	0.25 mm - 0.10 mm
VFS-very fine sand	0.10 mm - 0.05 mm

Table 49. Soil moisture retention characteristics in Ap horizons at the various sites as affected by tillage.

Site	Soil Moisture at Specified Tension (bars) (% by weight) -1/3	-1	-3	-15	Available Water
Conventional Tillage					
1	a 23.9	a 19.4	a 15.9	a 13.9	10.0
2	a 23.6	a 19.5	a 15.8	a 13.5	10.0
3	a 22.0	a 17.4	a 13.5	a 11.1	10.8
4	b 16.3	b 12.5	b 9.6	b 8.1	8.2
5	a 21.6	b 16.7	a 13.8	a 12.2	9.3
Overall Mean	21.5	17.1	13.7	11.8	9.7
Deep Plowed Tillage					
1	21.3	b 17.5	b 14.3	b 12.8	8.5
2	22.4	ab 19.4	b 16.4	b 14.1	8.3
3	23.3	ab 19.5	b 17.1 *	b 14.4 *	8.8
4	19.5	b 15.9	b 14.1	b 12.0	7.5
5	27.2 **	a 22.8 **	a 21.1 **	a 17.9 **	9.3
Overall Mean	22.7 **	19.0 **	16.6 **	14.3 **	8.5 **

*,** Significantly different, within similar levels, from normal tillage at P=.05 and P=.01, respectively.

Values within columns and within tillage not preceeded by the same letter are significantly different at P=.05.

moisture characteristic curve with little change in the shape of the curve. Retention at -15 bars, however, increased more than that at -1/3 bar, resulting in a slight, but significant decrease in overall available water.

The only significant difference between sites, within the conventionally tilled soils, is lower moisture retention at site 4. Within the deep plowed Ap horizons, significantly higher moisture retention occurs at most tensions at site 5 relative to the other sites, even though moisture retention in the conventionally tilled soils was approximately equal. This may be the result of the use of a single bottom plow at site 5, which, theoretically, should result in a greater proportion of B horizon material at the soil surface.

Of those factors affecting soil moisture retention, particle size distribution and organic matter content are, in the absence of structure, generally considered to be the most important. Simple correlations between these two properties (Tables 96 and 97, Appendix C) reveal the following. Moisture retention is negatively correlated with sand, with correlations tending to be more significant at lower tensions (-0.69* versus -0.77* for tensions of -15 and -1/3 bar, respectively). Similar, but positive correlations between both clay and fine clay and moisture retention were observed. Correlations ranged between 0.60* and 0.70*. Noteworthy is a gradation in the correlation values which show more significant correlations at higher tensions (Table 96, Appendix C). This suggests clay content has an increasing influence on soil water retention as the soil dries. Correlations between any particle size fraction and available water are and for the most part insignificant.

Correlations between moisture retention and total C and total N are poor (Table 97, Appendix C). Maximum correlations of 0.19 and 0.16 were found between moisture retention at -1/3 bar and total C and total N, respectively. Despite these poor correlations, available water is significantly correlated with total C and total N. Respective correlations are 0.56* and 0.54*.

Soil strength, as measured by the modulus of rupture, was significantly increased by deep plowing, although on an individual site basis this increase was significant only at sites 3, 4 and 5 (Table 50). This again suggests the soils at sites 1 and 2 (dominantly Chernozemic) are responding differently to deep plowing relative to the soils at sites 3, 4 and 5 (Solonetzic).

Modulus of rupture is weakly correlated with clay (r = 0.38*) and fine clay (r = 0.30). Previous studies (Ibanga et al., 1980) indicate modulus of rupture is directly related to clay content, although the reported relationship tends to be curvilinear. No significant relationship exists between silt and modulus of rupture (r = -0.10) although direct relationships (Lemos and Lutz, 1957) and inverse relationships (Ibanga et al., 1980) are reported in the literature.

Stronger correlations are found with the various Na related properties and modulus of rupture, including ESP (r = 0.51*), exchangeable Na^+ (r = 0.62*), SAR (r = 0.60*), soluble Na^+ (r = 0.78*) and extractable Na^+ (r = 0.69*) (Table 94, Appendix C). All these correlations are similar, although it is interesting to note the correlation of modulus of rupture with ESP is low relative to the other Na properties. Several authors have indicated a positive relationship between ESP and modulus of rupture (Richards, 1953; Reeve et al.,

Table 50. Selected physical properties in the Ap horizons as affected by tillage.

Site	Modulus of Rupture (mbar)	Mean Weight Diameter (mm)	Aggregate Stability (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Activity
Conventional Tillage							
1	251	.3897	a 39.2	[illegible] 35	a 28	a 7	a 0.36
2	261	.3801	a 37.7	a 34	a 28	a 6	a 0.28
3	252	.3260	ab 29.0	b 30	a 29	b 1	b 0.06
4	250	.3402	b 24.8	c 23	ab 25	b 1	b 0.04
5	375	.3354	ab 30.1	bc 27	b 21	a 6	a 0.34
Overall Mean	278	.3543	32.2	30	26	4	0.22
Deep Plowed							
1	b 545	.3366	29.4	a 32	b 20 **	ab 13 *	0.52
2	b 352	.3428	31.7	a 34	a 23 **	ab 10 **	0.38 *
3	a 2761 *	.3121	25.9	a 32	b 18 **	a 14 **	0.53 **
4	a 1917 *	.3412	28.4	b 26	b 18 **	b 8 *	0.40 **
5	a 1852 **	.3011	23.6	a 33 **	b 20	ab 13 **	0.53 *
Overall Mean	1485 **	.3268 *	27.8 *	31	20 **	11 **	0.47 **

*, ** Significantly different, within similar levels, from normal tillage at P=.05 and P=.01, respectively.
Values within columns and within tillage not preceeded by the same letter are significantly different at P=.05.

1954), with high correlations (regression coefficients) reported by Reeve et al., although these coefficients are somewhat specific to soil type. No clear explanation exists for the higher correlation of modulus of rupture with soluble Na^+ relative to ESP, unless absolute Na^+ content, rather than relative Na^+ content, has a greater influence on soil strength.

The correlation between extractable Ca^{2+} and modulus of rupture ($r = 0.81^*$) is particularly surprising. Although Ca^{2+} is an important agent in stabilizing soil aggregates through its complexation with organic constituents (Harris et al., 1966; Emerson, 1959) it has not been related to soil strength (as measured by modulus of rupture). This finding is opposed to previous research which indicates Ca^{2+} levels are important in maintaining tilth of deep plowed seedbeds (Cairns, 1976a), and in particular Ca:Na ratios (Cairns, 1976a; Lavado and Cairns, 1980), which are negatively correlated ($r = -0.11$) in this study. The higher Ca^{2+} values have possibly stabilized the soil material upon drying the briquettes for modulus of rupture determinations, after the soil material has initially slaked during wetting due to the presence of Na^+.

Changes in mean weight diameter (MWD) due to deep plowing are also indicated in Table 50. On an overall basis, deep plowing significantly decreased MWD of water stable aggregates, although on an individual site basis no significant changes occurred. Differences between sites are not apparent although in the conventionally tilled Ap horizons sites 1 and 2 have slightly higher values relative to sites 3, 4, and 5.

Mean weight diameter is not strongly correlated with any other measured soil property. Moderate negative correlations (r = -0.37* to -0.48*) exist with the various Na related properties (Table 94, Appendix C). Correlations of 0.41* and 0.45* are present between MWD and total C and N, respectively (Table 97, Appendix C). Similar relationships between organic matter and MWD are reported by Toogood (1978). Poor correlations between MWD and particle size (Table 96, Appendix C) agree with other findings (Toogood, 1978).

Aggregate stability (AS) is significantly reduced in the Ap horizons by deep plowing (Table 50). A decrease was observed at all but site 4, although on an individual site basis the reduction was not significant. The slight increase in AS observed at site 4 possibly reflects the initial poor structural characteristics (mullgranoidic iunctic fabric) present in the conventionally tilled Ap horizons.

Aggregate stability is not correlated with any particle size class (Table 96, Appendix C), nor any phyllosilicate property (Table 95, Appendix C). Moderate negative correlations exist between AS and the various Na^+ properties, ranging from -0.49* with soluble Na^+ to -0.57* with extractable Na^+ (Table 94, Appendix C). Reduced aggregation of the <50 μm fraction with increasing exchangeable Na^+ has been reported (Martin and Richards, 1959). Exchange acidity is moderately correlated with AS (r = 0.50*) although previous research indicates exchangeable H^+ has little influence on aggregation of the <50 μm fraction (Martin and Richards, 1959). A strong relationship exists between AS and MWD (r = 0.81*, Table 93), however, the former is corrected for sand > 60 mesh while the latter is not, so that the relationship, as expected, is not perfect.

The effect of deep plowing on soil consistence, as measured by the

Atterberg limits, is given in Table 50. Deep plowing reduced the overall plastic limit (PL) and had no effect on the liquid limit (LL) which resulted in an increase in the plasticity index (PI). Although initial and final values are somewhat different between sites, the relative effect of deep plowing is consistent between the various sites.

Moderate correlations exist between the various Atterberg limits and particle size fractions. Both the LL and PI are positively correlated with clay and fine clay; respective correlations with the LL are 0.66* and 0.60*, while those with the PI are 0.75* and 0.77*, respectively (Tab[illegible]pendix C). The PL is weakly correlated with all particle size [illegible] Table 95). Odell et al. (1960) also found strong relationships [illegible]ween clay content and the LL and PI as well as a lesser influence of clay on the PL.

The various chemical evaluations of soil Na are moderately correlated with the Atterberg limits (Table 94, Appendix C). The LL is positively correlated only with ESP (r = 0.53*) while the PI is correlated only with SAR (r = 0.53*). All of the soil Na properties are negatively correlated with the PL, ranging from r = -0.52* (SAR) to r = -0.63* (soluble Na^+). Of note is the strong positive correlation of 0.91* between total exchange capacity (TEC) and LL. A slightly lower, yet significant correlation between these two properties is reported elsewhere (Odell et al., 1960). Also of interest is the relatively high correlation of extractable Mg^{2+} with the PI (r = 0.88*, Table 94).

Certain phyllosilicate characteristics correlate with the PI (Table 95). Correlations between clay CEC, clay surface area and PI are 0.80* and 0.74*, respectively. Since smectite content is based on clay CEC the correlation between smectite and PI is also 0.80*.

Smectite minerals, notably montmorillonite, have much higher LL and PI values than other reported phyllosilicates (Cornell, 1951, as cited by Lambe and Whitman, 1969; White, 1949; Seed et al., 1964) and therefore in a soil containing even a small proportion of smectite minerals consistence is influenced primarily by the smectite minerals present (Seed et al., 1964; Odell et al., 1960). The relationship between Mg content in the clay separate and PI (r = 0.85*) suggests the montmorillonite component of the smectite group is responsible for the observed correlation between smectite and PI (Mg is the prime octahedral constituent in montmorillonite, Borchardt, 1977). This is further supported by the high correlation between Mg content of the clay separate and smectite content (r = 0.94*, Table 88).

The plastic limit (PL) is strongly related to properties reflecting soil organic matter content. Respective correlations between total C, total N and the PL are 0.88* and 0.87* (Table 97). Baver et al. (1972) report PL values which were 25% higher (absolute) in a soil containing 7% organic matter compared to the same soil in which the organic matter was removed using H_2O_2. Since other properties are not well correlated with the PL, it appears the PL is to a large extent governed by soil organic matter.

Activities, or the ratio of the PI to total clay (Skempton, 1953) are given in Table 50. Deep plowing significantly increased activity on an overall basis as well as at four of the five sites. Increased activities are undoubtedly a function of the increased smectite content, although activities as high as 7.0 are reported for montmorillonite dominated samples (Skempton, 1953). The correlation between activity and smectite is 0.75* (Table 95).

5.5 Summary

Analytical features either directly or indirectly related to soil tilth were examined in Ap horizons of conventionally tilled and deep plowed soils. Some marked changes in most soil properties examined resulted from deep plowing. Different responses to deep plowing were frequently observed depending upon whether the sampled landscape was dominated by soils of the Solonetz or Chernozem order.

At those sites comprised entirely of Solonetzic soils, soluble and extractable Ca^{2+}, Mg^{2+} and Na^{+} were generally, though not always, significantly increased by deep plowing. Where Chernozemic soils occupied 50% or more of the sampled landscape, changes in these properties were generally less pronounced. Exchangeable Na^{+}, ESP and SAR generally increased as a result of deep plowing Solonetz dominated landscapes, although significance levels were variable. Increases in soil pH and EC and reductions in exchange acidity were significant in most instances and were independent of soil type. The effect of deep plowing on total exchange capacity and Ca:Na ratios was variable and independent of soil order, while no effect was observed with respect to soluble and extractable K^{+}. Both total C and total N were significantly lower on the deep plowed soils at all locations. Reductions in these two properties do not appear to be related to the type of plow used, however, slightly greater reductions occurred where total C and N were initially higher in the conventionally tilled Ap horizons.

Phyllosilicate mineralogy of Ap horizons was altered by deep plowing in the bulk of soils examined and was not dependent upon soil order. Smectite content was significantly increased by deep plowing while kaolinite and chlorite were significantly reduced through dilution.

Mica content, for the most part, remained unchanged.

Particle size distribution was also influenced by deep plowing. Sand and silt content, on an overall basis, were significantly reduced in the deep plowed Ap horizons, although on an individual site basis the direction and significance of the change was variable. Total clay and fine clay increased upon deep plowing at all locations, however, the significance of the increase was variable. Significant increases in fine clay were more apparent than increases in total clay, which parallels, and is highly correlated with ($r = 0.84^*$), the increase in smectite content. Size distribution of the sand fraction remained unchanged by deep plowing.

Moisture retention at a given tension was significantly higher in the deep plowed soils when expressed on an overall basis. On a site specific basis, however, changes were generally insignificant and occasionally retention was lower in the deep plowed soils. Moisture retention at -15 bars was increased more so than retention at -1/3 bar which resulted in an overall significant decrease in available water. Moisture retention at any given tension was positively correlated with clay content and, as the tension increased, correlations increased. This perhaps indicates that clay content becomes increasingly important in retention of soil moisture as the soil dries. Available water is moderately correlated with only total C and total N, even though retention at a given tension is weakly correlated with these two properties.

Modulus of rupture was significantly increased by deep plowing at those sites dominated by Solonetzic soils; the observed increases were approximately an order of magnitude. No change was observed at those sites where Chernozemic soils occupied a significant portion of the landscape. Both mean weight diameter and aggregate stability remained unchanged by deep plowing on an individual site basis, however, on an overall basis these two properties were significantly lower on the deep plowed soils.

Certain changes were also noted with respect to soil consistence. Although the liquid limit, for the most part, was unaffected by deep plowing, the plastic limit was significantly reduced. The plastic limit is highly correlated with total C and total N, such that the observed decrease probably reflects a loss of organic matter. The drop in the plastic limit resulted in a significant increase in the plasticity index at all locations. Activities also increased upon deep plowing most sites, and this appears to be related to the increased smectite content, and probably the montmorillonite component contained therein.

6. CROP RESPONSE

6.1 Introduction

The effect of deep plowing on crop yields has been studied by many researchers. For the most part, moderate to pronounced crop yield increases are reported (Bowser and Cairns, 1967; Cairns, 1962, 1970, 1971; Eck and Taylor, 1969; Harker et al., 1977; Hermans, 1981, 1982; Karkanis and Cairns, 1981; Krogman and MacKay, 1980; Lavado and Cairns, 1980; Mech et al., 1969; Sandoval, 1978; Sandoval et al., 19[illegible]), however, yield depressions resulting from deep plowing have been observed within some of these studies. The emphasis in the above studies has been on changes in the entire soil pedon and the effects these changes have on total crop yield. Few studies have been devoted to an analysis of crop response characteristics other than total yield and even fewer to an analysis of the influence of seedbed properties on crop growth characteristics.

This chapter is devoted to an analysis of crop response characteristics on deep plowed Solonetzic and associated soils. The relationship between various seedbed properties (Chapter 5) and crop growth characteristics is discussed, where applicable. The relationship of the geomorphic soil sequence present (Chapter 4) to crop response is also evaluated.

6.2 Literature Review

Changes in soil properties contributing to crop response can be grouped into two general categories: (1) increased soil moisture storage and extraction; and (2) changes in the soil chemical suite, particularly increased Ca^{2+} derived from various sources. The two are not mutually exclusive in that the relative balance of Ca^{2+} and Na^+ has a marked effect on water movement (Frenkel et al., 1978; Harron, 1979).

6.2.1 Soil-Water Relations

Changes in soil-water relations upon deep plowing was briefly introduced in Chapter 2. Expansion on the previous summary is required to fully appreciate the contribution that these aspects make to crop growth and yield.

Pair and Lewis (1960) report infiltration rates for a Sebree soil (presumably Solonetz) which was thoroughly mixed to a depth of 122 cm. Mean infiltration rates increased from 0.025 cm/hr to 1.07 cm/hr upon deep plowing. This change resulted in a total of 729 cm of water infiltrating into the mixed soil during a 729 hr period (approximately 30 days), compared with only 33 cm of water in the undisturbed soil. A reduction in ESP from 34.77 to 8.24 upon mixing was the factor identified for the marked increase in infiltration.

On a [illegible]ic soil in the USSR, Burnatski and Yarovenko (1961) found [illegible] uniform distribution of soil moisture with depth following winter precipitation when depth of tillage was increased from 25 to 35 cm. More uniform distribution was attributed to breaking of a plowsole in addition to improved soil structure and corresponding increased infiltration.

Also in the USSR, Maksimyuk (1958) evaluated the effect of deep tillage on water infiltration properties of a Solonchak-like Solonetz. The soil was deep spaded and subjected to successive leachings. Only

2.1 hours were required for a given amount of water to infiltrate into the deep spaded soil, while 14.4 hours were required for an equivalent amount of water to infiltrate into the virgin soil. After five leachings, infiltration time increased to 9.15 and 33.0 hrs for the deep spaded and virgin soil, respectively. This reduction in infiltration with time was attributed to soil swelling.

In Texas, Eck and Taylor (1969) evaluated the effects of thorough profile mixing to depths of 90 and 150 cm on a Pullman SiCL (Reddish Chestnut soil). Grain sorghum was grown under irrigated and stressed (dryland) conditions. Profile modification was found to increase the amount and depth of water storage and reduce evaporation in the stressed treatments. Depth of root penetration by the sorghum increased as a result of profile mixing. Water use efficiency (WUE) increased as a result of greater water storage and extraction at depth, particularly under stressed conditions. Under the stressed conditions, WUE increased by 41.3% for grain production and 25.2% for total dry matter production. The overall result was significantly higher grain and stover yields under stressed conditions. For the 90 and 150 cm modified treatments, respective increases in grain yields, relative to the check, were 66 and 81%. Little change was noted in grain or stover yields on the irrigated treatments.

Cary et al. (1967) evaluated soil water distribution and extraction by alfalfa on a Freeman SiL (Mollic Haploxeralf) as affected by profile modification. Significantly greater water storage at the beginning of the cropping year and greater water extraction at the end of the cropping year was observed when the profile was disturbed to a depth of 122 cm and replaced in a mixed state or in the original horizon

APPENDIX D

Means and Standard Deviations of the Various Ap Horizon Properties

Table 98. Basic statistics for the soil solution properties as determined on saturation extracts.

Property	Statistic	Site 1		Site 2		Site 3		Site 4		Site 5	
		Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed
Property											
pH	$\bar{X}$	6.3	7.3	5.2	6.4	5.9	7.0	5.6	7.9	6.2	7.5
	s	0.39	0.51	0.32	0.53	0.39	0.19	0.43	0.28	0.62	0.15
EC (mS/cm)	$\bar{X}$	0.3	1.1	0.4	0.7	0.5	2.1	0.3	1.2	0.6	1.5
	s	0.05	0.32	0.16	0.33	0.48	1.11	0.14	0.22	0.29	0.4
SP	$\bar{X}$	58	51	59	57	60	56	50	46	53	56
	s	5.9	1.5	4.3	4.5	3.3	3.4	2.5	6.7	3.0	2.4
Cation (me/l)											
Ca	$\bar{X}$	1.3	5.5	2.3	4.2	0.8	7.1	0.7	2.6	1.3	4.1
	s	0.29	1.43	0.90	2.01	0.13	4.46	0.13	0.53	0.77	1.11
Na	$\bar{X}$	1.3	4.7	1.3	1.7	4.5	15.9	2.6	10.7	4.7	14.1
	s	0.45	2.42	0.57	0.74	3.81	8.71	1.19	2.36	.07	3.85
Mg	$\bar{X}$	0.6	2.9	1.3	2.3	0.5	4.7	0.3	1.0	0.6	1.3
	s	0.15	0.24	0.21	1.37	0.17	3.43	0.15	0.10	0.37	0.33
K	$\bar{X}$	0.09	0.19	0.33	0.39	0.08	0.15	0.09	0.12	0.11	0.17
	s	0.099	0.070	0.063	0.286	0.019	0.078	0.018	0.010	0.085	0.077
SAR	$\bar{X}$	1.3	2.3	1.0	1.0	5.5	6.5	3.7	8.0	4.9	8.7
	s	0.39	1.10	0.57	0.38	4.32	1.48	1.53	1.23	0.69	2.04

Means ($\bar{X}$) and sample standard deviations (s) are based on four replicates per site per treatment.

Table 99. Basic statistics of the extractable and exchangeable chemical properties in the Ap horizons.

Property	Statistic	Site 1		Site 2		Site 3		Site 4		Site 5	
		Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed
Extractable chemistry (me/100g)											
Ca	$\overline{X}$	12.5	17.3	9.7	13.9	4.4	28.7	3.8	24.1	8.7	21.8
	s	2.25	5.80	2.74	3.04	1.90	19.31	0.58	11.46	2.76	4.70
Na	$\overline{X}$	1.28	0.95	0.46	0.69	1.39	2.81	1.64	3.43	2.52	4.24
	s	0.319	0.397	0.158	0.238	1.091	0.915	0.428	1.011	0.287	1.039
Mg	$\overline{X}$	4.16	6.09	3.21	4.84	1.72	6.34	1.12	3.74	2.78	4.64
	s	0.837	0.85	0.596	1.615	0.543	1.081	0.055	1.109	1.085	0.839
K	$\overline{X}$	0.72	0.61	0.87	0.81	0.51	0.75	0.54	0.61	0.92	0.73
	s	0.242	0.200	0.273	0.399	0.148	0.254	0.047	0.308	0.443	0.173
Ca:Na	$\overline{X}$	10.6	20.8	24.2	21.2	5.6	9.4	2.5	6.8	3.5	5.5
	s	4.34	10.79	12.01	4.37	5.50	3.80	0.98	1.62	0.89	2.15
Exchangeable chemistry (me/100g)											
pH in $CaCl_2$	$\overline{X}$	5.1	6.9	5.2	6.1	4.6	7.3	4.7	7.5	5.4	7.5
	s	0.19	0.37	0.54	0.90	0.21	0.42	0.17	0.17	0.69	0.13
Exchange Acidity	$\overline{X}$	9.29	1.30	8.93	3.09	8.80	0.53	6.85	0.07	6.71	0.27
	s	2.352	0.831	3.772	2.791	1.912	0.908	1.180	0.072	3.429	0.077
TEC	$\overline{X}$	22.62	17.66	19.46	21.26	15.34	16.96	11.26	13.09	14.30	17.31
	s	2.152	1.033	1.468	1.092	3.131	0.335	0.922	3.015	1.496	0.866
Na	$\overline{X}$	1.2	0.72	0.38	0.60	1.13	1.93	1.50	2.95	2.28	3.47
	s	0.297	0.290	0.122	0.241	0.864	0.464	0.379	0.889	0.194	0.872
ESP	$\overline{X}$	5.4	4.2	1.9	2.9	8.1	11.4	13.5	22.5	16.0	20.2
	s	1.59	1.83	0.43	1.27	6.91	2.87	4.04	3.81	1.32	5.54

Means ($\overline{X}$) and sample standard deviations (s) are based on four replicates per treatment per site.

Table100. Basic statistics for the organic matter related properties in the Ap horizons.

		Site 1		Site 2		Site 3		Site 4		Site 5	
Property	Statistic	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed
Total Carbon (%)	$\bar{X}$	3.30	1.49	3.38	2.18	2.99	1.46	2.13	1.30	2.27	1.52
	s	0.47	0.18	0.28	0.13	0.64	0.12	0.15	0.22	0.24	0.09
Total Nitrogen (%)	$\bar{X}$	0.288	0.129	0.287	0.187	0.255	0.111	0.185	0.107	0.207	0.127
	s	0.041	0.014	0.024	0.012	0.046	0.016	0.018	0.019	0.017	0.017
C:N	$\bar{X}$	11.5	11.6	11.8	11.7	11.7	13.4	11.5	12.2	10.9	12.1
	s	1.1	1.0	0.1	0.4	0.5	2.2	0.4	0.7	0.3	1.3

Means ($\bar{X}$) and sample standard deviations (s) are based on four replicates per site per treatment.

Table 101. Basic statistics for the mineralogy and chemistry of the clay separates.

		Site 1		Site 2		Site 3		Site 4		Site 5	
Property	Statistic	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed
Phyllosilicate*											
Mica	$\bar{X}$	29	27	27	25	26	25	21	24	24	24
	s	1.41	0.96	0.58	1.50	0.58	1.50	1.15	1.00	0.58	0.96
Smectite	$\bar{X}$	44	57	44	53	40	55	29	54	45	53
	s	1.71	2.99	2.63	2.16	2.65	5.72	2.87	6.13	7.68	1.26
Kaolinite	$\bar{X}$	18	11	19	14	22	12	32	14	20	14
	s	1.83	2.22	2.06	0.96	1.26	3.20	2.83	2.63	5.50	0.50
Chlorite	$\bar{X}$	9	5	11	8	13	8	18	9	12	9
	s	0.96	0.96	0.58	1.00	2.99	1.73	4.99	3.42	3.56	0.50
Clay Chemistry											
K (%)	$\bar{X}$	2.40	2.23	2.20	2.09	2.11	2.08	1.75	1.94	1.94	2.00
	s	0.137	0.101	0.033	0.103	0.060	0.112	0.060	0.078	0.051	0.098
Mg (%)	$\bar{X}$	1.12	1.39	1.08	1.33	0.96	1.41	0.81	1.29	1.03	1.41
	s	0.080	0.052	0.096	0.045	0.066	0.105	0.030	0.185	0.104	0.063
Fe (%)	$\bar{X}$	7.26	8.18	6.96	7.73	7.40	7.92	6.64	7.56	7.16	7.73
	s	0.340	0.223	0.417	0.159	0.486	0.355	0.298	0.211	0.363	0.316
Al (%)	$\bar{X}$	12.36	14.17	11.97	13.90	11.96	13.29	11.57	13.54	12.40	13.58
	s	0.543	0.126	0.553	0.339	0.563	0.573	0.607	0.180	0.454	0.334
Si (%)	$\bar{X}$	23.55	24.29	23.81	25.50	24.73	23.55	22.88	22.89	23.25	22.73
	s	0.411	0.670	0.565	0.274	0.755	0.435	0.383	1.183	1.149	2.028
Surface properties											
CEC (me/100g)	$\bar{X}$	48.1	62.5	48.6	58.3	43.5	61.0	32.1	59.4	49.1	58.4
	s	1.97	3.09	2.87	2.33	2.75	6.26	3.06	6.75	8.42	1.42
SA (m^2/g)	$\bar{X}$	385	495	379	464	343	444	340	463	425	481
	s	22.9	9.1	29.9	36.7	38.7	18.2	23.9	15.7	43.8	14.4

Means ($\bar{X}$) and sample standard deviations (s) are based on four replicates per treatment per site.

* Expressed as a percent of the <2um fraction. The four phyllosilicates listed are assumed to be 100% of the <2um fraction.

Table 102. Basic statistics for particle size distribution in the Ap horizons.

Property	Statistic	Site 1		Site 2		Site 3		Site 4		Site 5	
		Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed
Particle size distribution (%)											
Sand	$\bar{X}$	42.9	46.8	44.1	43.1	44.7	39.5	62.1	54.4	48.5	42.0
	s	7.9	2.2	3.7	3.1	4.1	2.8	7.0	4.8	1.4	1.9
Silt	$\bar{X}$	39.9	28.8	34.5	29.9	35.9	33.4	26.9	27.8	34.0	34.0
	s	6.4	4.4	2.7	1.6	5.7	1.7	7.3	4.8	2.1	2.6
Clay	$\bar{X}$	17.2	24.5	21.4	27.0	19.4	27.2	11.0	17.8	17.6	24.0
	s	2.0	4.4	1.6	4.4	5.6	3.4	0.9	5.7	3.2	1.2
Fine Clay	$\bar{X}$	8.5	12.5	9.4	13.2	6.4	11.3	3.5	9.0	9.5	11.7
	s	0.8	2.8	1.1	1.8	3.6	0.7	1.6	2.5	2.1	1.0
Fine Clay/ Total Clay	$\bar{X}$	0.50	0.51	0.44	0.49	0.32	0.42	0.31	0.51	0.55	0.49
	s	0.08	0.05	0.04	0.03	0.11	0.03	0.12	0.07	0.14	0.06
Sand fraction (%)											
VCS	$\bar{X}$	3.0	3.0	2.4	2.5	2.6	2.2	1.4	1.8	2.4	2.6
	s	0.7	0.3	0.2	0.2	0.9	0.2	0.5	0.7	0.1	0.6
CS	$\bar{X}$	9.1	9.5	8.6	8.3	9.1	7.1	10.5	10.0	7.2	7.7
	s	1.2	0.9	0.3	0.7	1.0	0.5	4.8	6.2	0.3	0.8
MS	$\bar{X}$	22.7	23.1	21.1	21.8	24.3	22.7	34.8	33.3	18.8	19.3
	s	0.3	2.4	0.4	0.8	1.0	1.0	8.7	10.7	0.7	1.3
FS	$\bar{X}$	40.0	40.3	40.6	41.0	40.8	42.7	35.1	36.0	44.2	43.6
	s	1.9	0.5	0.7	0.3	1.2	1.5	7.9	11.5	0.9	2.0
VFS	$\bar{X}$	25.4	24.3	27.5	26.5	23.4	25.6	18.3	19.0	27.6	27.0
	s	1.2	3.1	0.3	1.2	1.7	1.8	5.5	6.2	1.2	1.5

Means ($\bar{X}$) and sample standard deviations (s) are based on four replicates per site per treatment.

Table 103. Basic statistics for the physical properties in the Ap horizons.

		Site 1		Site 2		Site 3		Site 4		Site 5	
Property	Statistic	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed
Soil water retention (% by weight)											
-300 mbar	$\bar{X}$	24.0	21.3	23.6	22.4	22.0	23.3	16.3	19.5	21.6	27.2
	s	3.0	1.5	2.4	1.6	2.7	1.6	1.3	5.1	1.1	1.9
-1 bar	$\bar{X}$	19.5	17.5	19.6	19.4	17.4	19.5	12.5	15.9	16.7	22.9
	s	2.2	1.4	1.8	1.3	1.9	1.9	1.0	4.3	1.6	1.4
-3 bar	$\bar{X}$	15.9	14.4	15.8	16.4	13.5	17.2	9.7	14.1	13.8	21.1
	s	1.8	1.3	1.8	1.2	1.8	1.9	0.8	4.5	2.2	1.9
-15 bar	$\bar{X}$	13.9	12.8	13.5	14.1	11.2	14.4	8.1	12.0	12.2	17.9
	s	1.5	1.3	1.7	1.2	1.4	1.8	0.7	3.9	2.2	1.7
Available Water	$\bar{X}$	10.1	8.5	10.1	8.3	10.9	8.9	8.2	7.5	9.4	9.3
	s	1.7	0.4	1.2	2.3	1.6	0.4	0.9	1.6	1.3	0.8
Selected physical properties											
Modulus of Rupture(mbar)	$\bar{X}$	251	545	261	352	252	2761	250	1917	375	1852
	s	70	241	28	91	23	1815	23	1256	206	445
Mean Weight Diameter(mm)	$\bar{X}$	0.3897	0.3367	0.3801	0.3429	0.3260	0.3122	0.3403	0.3412	0.3403	0.3412
	s	0.0613	0.0301	0.0514	0.0358	0.0175	0.0041	0.0395	0.0788	0.0395	0.0788
Aggregate Stability(%)	$\bar{X}$	39.2	29.4	37.7	31.8	29.0	25.9	24.9	28.5	30.1	23.6
	s	6.0	4.9	1.9	5.1	2.4	1.0	5.2	9.7	4.4	3.9
Liquid Limit(%)	$\bar{X}$	35	32	34	34	30	32	23	26	27	33
	s	4.1	1.4	2.2	2.4	3.9	2.1	1.7	4.0	1.9	1.8
Plastic Limit(%)	$\bar{X}$	28	20	28	23	29	18	25	18	21	20
	s	3.8	0.6	2.0	0.5	3.1	2.5	1.6	1.0	1.3	1.3
Plasticity Index(%)	$\bar{X}$	7	13	6	10	1	14	1	8	6	13
	s	4.4	1.0	0.8	1.9	1.3	3.6	1.0	4.6	2.2	2.9
Activity	$\bar{X}$	0.36	0.52	0.28	0.38	0.06	0.53	0.04	0.40	0.34	0.53
	s	0.06	0.00	0.00	0.00	0.00	0.03	0.01	0.03	0.01	0.01

Means ($\bar{X}$) and sample standard deviations (s) are based on four replicates per site per treatment.

Table 104. Basic statistics for crop yield properties during 1980.

Property	Statistic	Site 1 Normal Tillage	Site 1 Deep Plowed	Site 2 Normal Tillage	Site 2 Deep Plowed	Site 3 Normal Tillage	Site 3 Deep Plowed	Site 4 Normal Tillage	Site 4 Deep Plowed	Site 5 Normal Tillage	Site 5 Deep Plowed
		----Oats----		---Wheat----		----Oats----		---Wheat----		----Oats----	
Total Dry Matter (g/m^2)	$\bar{X}$	776	804	955	1034	716	787	355	704	458	591
	s	161	119	93	59	250	207	81	149	89	139
Grain Yield (g/m^2)	$\bar{X}$	370	397	322	376	326	357	139	266	193	280
	s	85	61	36	25	116	83	34	39	73	54
Straw Yield (g/m^2)	$\bar{X}$	407	407	633	658	390	431	216	438	265	311
	s	116	135	67	38	138	131	48	110	68	131
Emergence (plants/m^2)	$\bar{X}$	162	172	205	198	170	184	180	217	---	---
	s	26	31	37	36	24	19	74	64	---	---
Stem Counts (stems/m^2)	$\bar{X}$	281	267	534	595	212	196	247	421	300	234
	s	62	24	54	82	41	50	67	76	53	28
Tillering (tillers/plant)	$\bar{X}$	1.77	1.59	2.69	3.08	1.24	1.08	1.58	2.03	----	----
	s	0.43	0.28	0.61	0.67	0.15	0.29	0.56	0.49	----	----
Single Stem Yield (g/head)	$\bar{X}$	1.32	1.49	0.61	0.64	1.51	1.85	0.58	0.64	0.66	1.21
	s	0.14	0.22	0.11	0.07	0.30	0.28	0.13	0.11	0.27	0.25

Means ($\bar{X}$) and sample standard deviations (s) are based on eight replicates per site per treatment.

Table 105. Basic statistics for crop yield properties during 1981.

		Site 1		Site 2		Site 3		Site 4		Site 5	
Property	Statistic	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed	Normal Tillage	Deep Plowed
		---Barley---		----Oats----		---Barley---		---Wheat----		---Fallow---	
Total Dry Matter (g/m^2)	$\bar{X}$	377	448	522	422	196	474	108	300	---	---
	s	55	78	128	71	24	85	17	46	---	---
Grain Yield (g/m^2)	$\bar{X}$	195	246	240	201	86	194	47	140	---	---
	s	39	40	60	40	11	41	9	24	---	---
Straw Yield (g/m^2)	$\bar{X}$	181	202	282	221	110	279	61	161	---	---
	s	24	39	74	37	14	45	8	22	---	---
Emergence (plants/m^2)	$\bar{X}$	174	139	222	114	171	200	211	229	---	---
	s	69	15	49	37	18	51	18	39	---	---
Stem Counts (stems/m^2)	$\bar{X}$	167	215	364	237	183	230	---	---	---	---
	s	38	32	102	36	22	34	---	---	---	---
Tillering (tillers/plant)	$\bar{X}$	1.12	1.56	1.64	2.29	1.08	1.18	----	----	----	----
	s	0.55	0.29	0.28	0.82	0.17	0.21	----	----	----	----
Single Stem Yield (g/head)	$\bar{X}$	1.18	1.15	0.67	1.86	0.47	0.84	----	----	----	----
	s	0.13	0.11	0.09	0.18	0.02	0.09	----	----	----	----

Means ($\bar{X}$) and sample standard deviations (s) are based on eight replicates per site per treatment.

APPENDIX E

Weekly and Cumulative Precipitation During 1980 and 1981 at Selected Locations

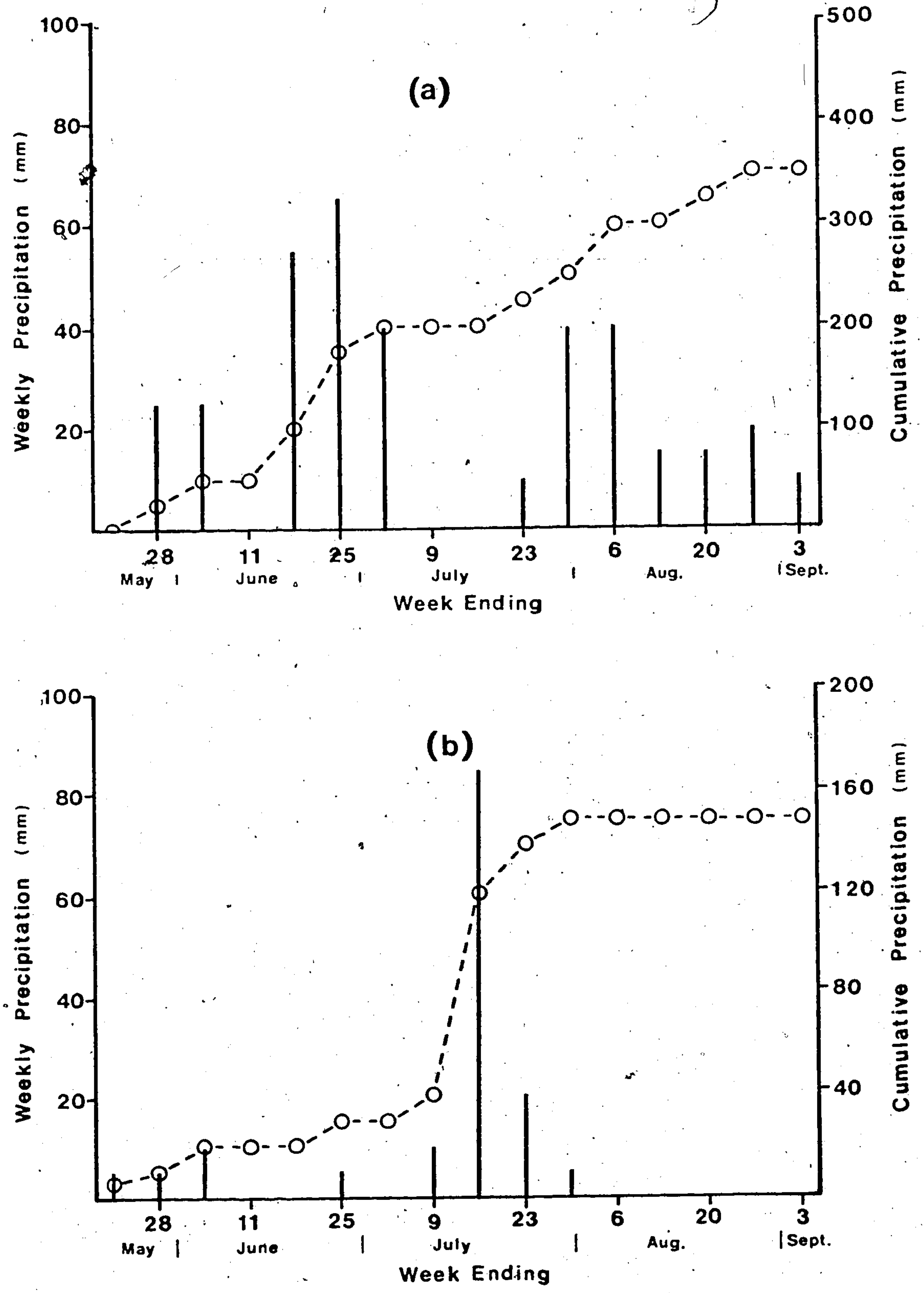

Figure 29. Weekly and cumulative growing season precipitation at site 2.a) 1980 b) 1981.