SOIL GENESIS IN RELATION TO GROUNDWATER REGIMES IN A HUMMOCKY GROUND MORAINE AREA NEAR HAMIOTA, MANITOBA

A Thesis
Submitted to the Faculty
of
Graduate Studies
The University of Manitoba
by
BASHIR HASHIM AL-TAWEEL

In Partial Fulfillment of the
Requirements for the Degree

of

DOCTOR OF PHILOSOPHY
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TO MY MOTHER

ABSTRACT

The influence of groundwater flow systems, levels and chemistry on soil distribution and profile development in two hummocky moraine areas near Hamiota in southwestern Manitoba was studied during a 3 year period. Emphasis was placed on determining the hydrological and pedogenic characteristics along transects of two toposequences. To characterize the groundwater regime, 15 observation wells and five piezometer nests were installed along the three transects. Water table levels were recorded and water samples were obtained from observation wells, while hydraulic heads were obtained from piezometers. The water table data were used for the construction of groundwater fluctuation patterns and water samples were used to determine the groundwater chemistry. Hydraulic head data were used to determine 1) the direction of hydraulic gradients at every piezometer nest; and 2) to interpret the pattern of groundwater flow within the studied transects.

To determine the pedogenic characteristics, seven soil profiles were sampled in detail and detailed soil survey maps prepared of two sites. Disturbed samples from the soil profiles and from underlying materials along the transects were used for physical and chemical analysis. Undisturbed samples from the soil profiles were used for micromorphological and sub-micromorphological characterization. Special emphasis was given to soluble salts and carbonate features. The hydrological characteristics were described and related to pedogenic characteristics of the soil along the transects from upper or transient depressions down the slope to the lower depressions.

The pedogenic, hydrologic, and hydrochemical data indicated that: 1) Determination of the water table fluctuation depth aided in the evaluation of soil development in this hummocky moraine area. This was particularly true around and in the depressions. 2) Leached or leached and eluviated soils occurred in areas where the dominant groundwater gradient at depth (5 to 6 m) was downward, while in the saline and non-saline ring soil areas, the gradients were mainly upward. 3) The soluble salts were of secondary and probably of shallow origin and were probably translocated from the adjacent areas through till materials by local flow system to the saline zones. In these zones, the saline groundwater as a result of its upward gradient at shallow depth below the water table and in the unsaturated soil zone was believed to be responsible for the accumulation of soluble salts. The distribution pattern of these soluble salts above the carbonate layer, such that the more soluble thenardite accumulation was commonly found at or near the soil surface with the gypsum accumulation below the thenardite, confirmed the hypothesis of their groundwater origin. 4) The pedogenic carbonate accumulation in the saline and non-saline zones was probably the result of shallow carbonated groundwater flow from the nearby sloughs.

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1. INTRODUCTION

In the prairie provinces, glacial till deposits with knoll and depression topography are quite extensive. This topography has a very clear influence on profile development. The influence of topography on soil development and soil distribution has been studied by many workers, but at times it appears difficult to predict the soil profile type distribution in apparently similar topography. This is particularly true around and in the depressions. To help overcome this difficulty it appears that groundwater information is needed. Some recent studies in western Canada suggest that groundwater characteristics are important in explaining soil profile type and distribution, but these studies were generally on a small scale and the soil profile investigations were largely confined to physical and chemical analysis.

The present study, conducted on a large scale, was designed to determine the pedogenic characteristics of soils along a toposequence from upper or transient depressions down the slope to lower depressions and to relate them to the groundwater flow patterns, groundwater depths and groundwater chemistry. Special emphasis was given to soluble salt and carbonate movement.

The pedogenic characteristics were determined by means of soil macromorphological, micromorphological, submicromorphological, physical and chemical analysis, while groundwater characteristics were obtained through monitoring groundwater levels and chemistry with time.

To establish a clear interrelationship between soil distribution, groundwater fluctuation and topography, detailed soil and topographic maps were prepared.

The study was carried out at two sites near Hamiota, Manitoba which are part of the Oak River Basin of southwest Manitoba. Specifically, these sites were selected because of the typical knoll and depression topography and because of previous hydrogeological information available for the area.

2. REVIEW OF LITERATURE

Three topics were covered in the Literature Review. The first included the soil forming factors and soil forming processes. All soil forming factors were reviewed but parent material and topography were given special emphasis. The soil forming processes were discussed under three headings: translocation and characteristics of soluble salts, carbonates, and clays. The second topic included groundwater flow and groundwater chemistry, and the third topic dealt with the relationship between groundwater properties and soil formation.

2.1 Soil

2.1.1 Soil Forming Factors

Parent material. As one of the factors of soil formation, parent material is important because it determines soil texture and to a large degree the chemical composition of the soil. It may also contribute to undesirable soil conditions such as poor internal drainage (i.e. fine textured soils), excessive quantities of soluble salts, or of lime carbonate, or extreme acidity or alkalinity.

The parent material of soils may be of many kinds in one region or they may be few in number. Variation, to a large measure, are due to the regional geology of the area and to the geological agencies responsible for their deposition.

In the Interior Plains Region of western Canada, large tracts of glacial till form the parent materials of the agricultural soils. Much of this till is uniform in texture being loam to clay loam, and the chemical composition is also fairly uniform in a broad sense but nevertheless significant differences in composition of the till are recognized and their influence on soil formation has been noted by soil scientists. The variation in chemical composition can be attributed chiefly to the respective quantities of limestone, shale, and igneous-like rocks that are found in the till. This, in turn, can be related to the nature of the underlying bedrock over which glacier passed.

St. Arnaud (1976) published a map which shows the carbonate content of glacial parent material in the prairie provinces. It is clear from the map that the calcium carbonate equivalent increases from west to east being 1 to 6% in Alberta and>40% in south central Manitoba. In eastern Saskatchewan and southwest Manitoba, the calcium carbonate equivalent percent of the till ranges between 16 and 25. It is also known that calcite:dolomite ratios vary, but no comprehensive study to determine the calcite:dolomite ratio for the prairie provinces has been conducted to date.

Considerable information[1] on the $CaCO_3$ equivalent and calcite:dolomite ratios is available for Manitoba soil parent

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[1] Unpublished data on $CaCO_3$ equivalent and calcite:dolomite ratios for some Manitoba Soils. Department of Soil Science, University of Manitoba, Manitoba.

materials. From this data it appears that the $CaCO_3$ content of the upper 2 m of unaltered till in southwestern Manitoba is 16 to 20% and the calcite:dolomite ratio is 1:1. Similar calcite:dolomite ratios were found in southeast Saskatchewan (Acton and Fehrenbacher, 1976), but the sampling depth was generally shallower (1 m).

The influence of the carbonate content of soil parent material on profile development has been studied by many workers. In Saskatchewan, Acton and Fehrenbacher (1976), found that as the carbonate content decreased, the thickness of the soil profile increased. Similarly, Ehrlich (1955), in Manitoba, concluded that the high carbonate content of soil parent material restricted soil profile development. For example, in the Isafold association which was sampled in the inter-lake region of Manitoba, the calcium carbonate equivalent was around 50% and the thickness of soil solum in the well drained position was 15 cm, whereas under similar climatic conditions the thickness of the solum of the Newdale association in west central Manitoba, developed from less calcareous parent material (around 18% $CaCO_3$ equivalent) was 43 cm.

Another important characteristic of the glacial till is the soluble salt content. From the data available, the EC_e of the brown till in west central Manitoba taken from well drained positions is approximately 1 mS/cm. The EC_e of the glacial till in southwestern Manitoba is somewhat higher than 1 mS/cm (Eilers, 1974). On the other hand, St. Arnaud (1979) found that EC_e values of Battleford till[2] which was analyzed for the Weyburn soil association (NW 3-27-6 W3) in Saskatchewan ranged from 4 to 6 mS/cm. From those results, it is difficult to infer the soluble salt content of unaltered parent material because of the high mobility of soluble salts. The ionic distribution pattern of the salts in the brown till is Mg^{++}, Na^{+}, Ca^{++}, and SO_4^{--} and that they all occur in important quantities. This was mentioned by Robertson (1955) as a part of his characterization of the Newdale soil association (west central Manitoba) and Acton (1971; p. 111) as part of his characterization of glacial till material near Wapella in eastern Saskatchewan. Similarly, as is the case with inorganic carbonate, soluble salts have a negative effect on the soil profile development. According to Sandoval and Shoesmith (1961), the extreme hydromorphic condition and high salinity in the parent material retarded the development of chernozemic soils in the northern Red River Valley in North Dakota.

Topography. Locally, topography is perhaps the factor that most frequently causes soil differences. It refers to the features of the surface of land-differences in relief or height between one place and another and the direction (aspect), steepness (% slope), and frequency of slopes. Various combinaations of these features occur from place to place forming

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[2] The Battleford till is the uppermost till in central and eastern Saskatchewan and it is believed to be similar to the uppermost till in west central Manitoba.

the land forms of an area.

An early and clear exposition of the relationship between soil profile development and topography was given by Ellis (1938) in the publication entitled "The Soils of Manitoba" (Figure 1). He described the water relationships of soils on a level topography as being normal for the region; on knob and basin topography he described locally arid conditions on the knolls because of run-off, and locally humid conditions in the depressions because of the additional water received from upper slope positions. Ellis also presented a schematic illustration which portrayed the soil profile types on the various positions of the slope. In the sketch he showed that the soils on the knolls were found to be much shallower than on the mid slope position, and that the depth of the solum increased gradually down the slope towards the depressions. In and around depressions, Ellis stated that the soils were generally strongly leached and eluviated types.

In a study in Saskatchewan, Acton and Fehrenbacher (1971) also concluded that topography of morainic areas had a pronounced effect on soil formation along a slope. They reported that the penetration of water and ultimately the nature of soil development along the slope was closely related to the configuration of the slope. Soils with relatively thin Ah and Bm horizons occurred on knoll positions where infiltration of water was minimal. These horizons were thicker in the midslope positions where water penetration was deeper and in the lower slope and toe-slope positions further thickening of soil

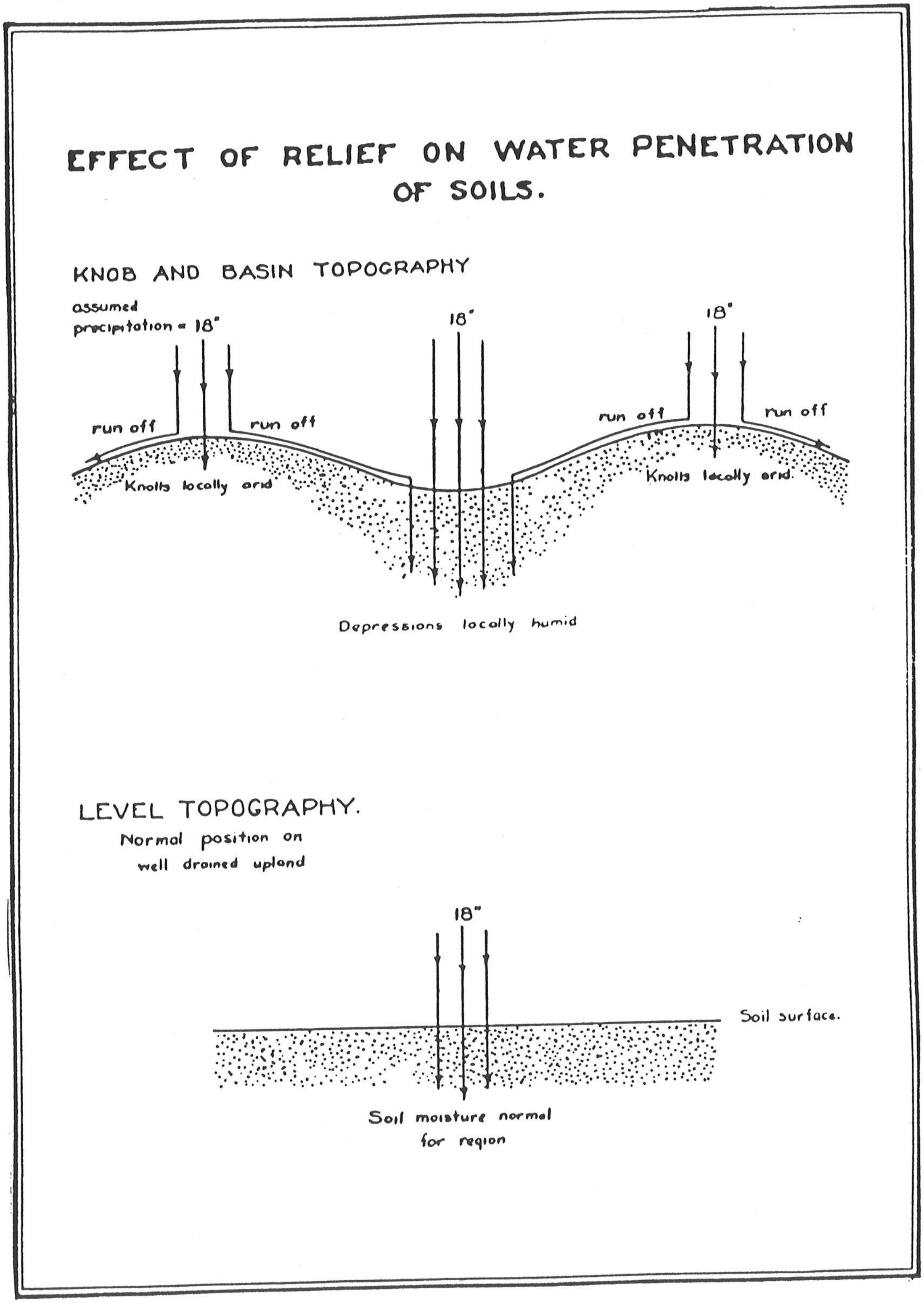

Figure 1. The effect of relief on water penetration in soils (after Ellis, 1938).

profile took place accompanied by processes of degradation, eluviation, and illuviation.

In a few cases workers discuss groundwater under topography but in most cases they do not talk about groundwater as a soil forming factor. However, Ellis (1938) had a very good appreciation of the important role of groundwater in controlling soil forming processes in Manitoba soils. He stated that, in the Aspen Grove or the northern black earth region, excessive soil moisture conditions have been responsible for the occurrence of local soil types such as saline soils, "meadow" soils, and "swamp podzols".

Recently, MacLean and Pawluk (1975), working near Vegreville, Alberta, found that water table depths$\geq$2 m permitted the formation of Chernozemic soils despite being located in a groundwater discharge area. Alkaline Solonetz, Saline Carbonated Gleyed Regosols and Saline Black Solonetz soils occurred where the water table was usually within 0.5 m of the surface. Moreover, Jenny (1980; p.280) stated that when the groundwater table lies at depths lower than 2.5 m in sands and 3.5 m in clays, capillary rise did not reach the A and B horizons. It appears that if the water table is below a certain depth, it does not affect the formation of solum horizons.

Vegetation. Vegetation is considered the most effective biotic factor besides animals and microbes that contribute to soil genesis (Jenny, 1980; p. 341). Moreover, this factor is often treated under two general classes as trees and grasses and the corresponding soils under the different vegetation being forest and grassland, respectively.

The most measurable result of different vegetation is the content and distribution of organic matter in the soil profile. According to Simonson (1959) who discussed the role of organic matter in horizon differentiation through four changes (i.e. addition, removal, transfers, and transformation), the addition and losses of organic matter are small to desert soils while the rates of additions and decay are both higher in chernozems.

In his discussion of the effect of vegetation as a forming factor for Manitoba soils, Ellis (1938) combined vegetation and climate in one interrelated factor. He mentioned that grassland vegetation may add organic matter both within the soil and as grass mat on the surface. This distribution of organic matter explains the high organic matter content in the upper portion of and within (e.g. B horizon) the profile of grassland soils. On the other hand, organic matter is added mainly on the forest soil in the form of litter. This distribution of organic matter gives rise to lower fertility in the case of forest soils and relatively high fertility in the grassland soils.

The role of organic matter in soil formation has been discussed by several authors. Jenny (1941) has discussed the role of organic matter in the formation of stable soil aggregates. The strong effect of aggregation in erosion prevention is well proven (Wischmeier and Mannering, 1969). The important role of many fats, waxes, and other components of soil humus to slow degradation by encasing the inorganic particles with a protective colloid was suggested by Smeek (1970). Another property of soil humus noted by Kononova (1961) is the buffering capacity which enables soils rich in humus to suppress the effect of soil acidity and consequent chemical attack of mineral colloids. In addition to that, in the forest soils, organic acids which are released and become complexed with inorganic constituents enhance the eluviation process due to the high solubility and mobility of the organic complexes.

In the southern region of the interior plains, the grassland areas are characterized by Brown, Dark Brown, and Black soil zones, while in the aspen grove areas where trees have been established for a certain time, degradation of Black soils is apparent (Ellis, 1938).

Climate. Climate is considered to be the most influential global factor of soil formation through 1) its control of some of the chemical and physical reactions taking place in the soil, 2) its control of the organic factor, and 3) its control to some extent of the factors of relief and time through erosion and deposition of soil materials. However, regarding the climatic aspects which affect soil development, precipitation and temperature are considered the most effective measurable features (Buol _et_ _al_., 1980).

Precipitation, as any increase in moisture supply results in (a) increase in organic content in soils through its effect on plant growth and other organisms, (b) leaching, and transport of material from upper to lower part of the soil, and

(c) physically, possible rupturing of soil material through freezing. Moreover, the rate of soil reactions in which water is important depends mainly upon some other factors such as: temperature, pH, and redox potential (Buol _et_ _al_., 1980).

Temperature affects the rate of chemical and physical reactions, and organic matter decomposition. These rates, according to Foth and Turk (1972), are greater in the grassland than in the forest soils. Furthermore, according to Vant Hoffs' law, for every 10 °C rise in temperature the speed of chemical reactions increases by a factor of 2 or 3.

When considering the influence of precipitation on soil development, it is important to consider the redistribution of moisture (snow melt and rainwater) that occurs in a knoll and depression topography. In south central Saskatchewan, where the climate is considered to be semi-arid to subhumid, the surface runoff to depressional areas was calculated by Meyboom (1967) to be around 3% of total recharge water. In another study by Shjeflo (1968), which dealt with evapotranspiration and water budget of prairie potholes in North Dakota, most of the snowmelt water ran off and collected in the depressions and also a considerable portion of the rain ended up in the depressions.

Time. Soil age refers to the length of time that a given soil has been under the influence of the various soil-forming factors. In the prairie areas of western Canada, the deglaciation period which determines the age of the soil is estimated to be between 11,000 to 19,000 year BP with deglaciation occurring earlier in southern Alberta and Saskatchewan than in Manitoba (Prest, 1970). In south western Manitoba and southeastern Saskatchewan, Christansen (1978) considers deglaciation to have occurred about 14,000 years ago.

2.1.2 Soil Forming Processes

Translocation of Salts

Genesis of translocated salts. The accumulation processes of soluble salts in soils differ between regions. In arid and semi-arid regions, salinization occurs mainly as a result of: (1) upward movement of shallow saline groundwater to the surface by capillary action with consequent evaporation; or (2) when the groundwater is deep and the land is irrigated at regular intervals with saline groundwater; or (3) by redistribution of salts originally present in the soil parent material. In these areas, because of limited precipitation, salts are concentrated at shallow depth in the solum. According to Buringh (1970), the depth at which the salt accumulation occurs depends on the quantity of water that percolates through the soil. In regions with a higher effective rainfall (e.g. 300 mm) gypsum and more soluble salt may accumulate at a depth of 90 and 130 cm, respectively, whereas in more desertic regions, these salts accumulate in the upper few centimeters of the soil.

Pratt (1952), who studied the saline soils of the aspen grove and grassland region of western Manitoba in a subhumid climate, found that the general source of soluble salts which occur in the poorly drained soils was the soil minerals in the surrounding higher land. He stated that the salts were translocated from higher positions in the landscape to the lowland areas by runoff and seepage. In another study, St. Arnaud (1978) found at a site near Cutbank, Saskatchewan, where the soils were dominantly Chernozemic and the topography was characterized by ridge and swale pattern, the following trend of salinity distribution along the studied transect: 1) The surface horizons were leached free of soluble salts along the entire transect; 2) In the upper and mid-slope positions, salinity in the C horizons increased with depth, reaching a maximum of 6 to 8 mS/cm in the 2 to 4 m zone and then decreased to 4 to 6 mS/cm; and 3) The depressions were deeply leached with no evidence of salts down to 8 to 9m. This distribution of soluble salts, according to that author, suggests that the removal of soluble salts in depressional areas is a more important aspect of water redistribution in the landscape than is lateral movement within the soil itself. Ballantyne (1962), in his study of salt accumulation in Black Chernozemic soils of southeastern Saskatchewan, in a region characterized by knoll and depression topography, found that: 1) downward movement of salts occurred in soil profiles in the knoll and upperslope positions, and 2) the maximum accumulation occurred first within the profile solum in the knoll and upper slope positions and then at the surface of soils in the lower position. The significant increase in salinity in the lower slopes was assumed to be related to the lateral movement of saline water from the knoll and upper slope position. The salinity distribution along transects presented by St. Arnaud and Ballantyne are different in spite of rather similar topography. These results suggest different hydrological conditions at the two sites.

Characteristics of translocated salts. The structure of saline horizons is either loose or compact depending on the dominant salt. According to Buringh (1960), $MgSO_4$ gives rise to loose fluffy soil layer while with NaCl, the soil is usually compact. Soluble salts also accumulate as aggregates (pure or mixed with clay) (Tursina *et al.*, 1980) and sometimes as salt flecks (Sandoval and Shoesmith, 1961).

In the Western Upland area of Manitoba and Saskatchewan, the most common soluble ions in the saline soils are Mg^{++}, Na^{+}, Ca^{++}, and SO_4^{--} (Acton, 1971; Pratt, 1952; Robertson, 1955; Rozkowski, 1967).

From the micromorphological point of view, Brewer (1964) reported that soluble salts were found as fine or coarse crystals, groups of large crystals (e.g. crystal chamber[3]) or cutanic material. Altaie (1969), working in northeast Iraq, found gypsum as a common salt in all the above crystalline forms.

Using sub-micromorphological techniques (scanning electron microscopy), more details regarding crystal forms and features of soluble salts, especially sulfates, have been reported by Tursina (1980), Mermut and St. Arnaud (1981b), and Stoops (1978). Stoops in particular gave a detailed descrip-

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[3] Micromorphological term by Brewer (1964), see Glossary, page 273.

tion of several crystal forms of authigenic sulfate minerals in soils which are found under different climatic (i.e. arid to tropical) and geomorphological conditions. His description of two sulfate minerals is as follows:

Gypsum ($CaSO_4.2H_2O$) occurs in coarse or fine lenticular or discoid crystals in Gypsiorthids (Iraq), in short prismatic forms in acid sulfate soils, fibrous in Calciorthid (Egypt), elongated prismatic in polder soils (Tchad), short prismatic crystals from Torriorthent (Peru), rosette-like aggregates of gypsum prisms in cat-clay (Nigeria). Weathered lenticular crystals often give rise to a comb-like shape corresponding to cleavage planes of the mineral crystals.

Thenardite (Na_2SO_4) is commonly found in salt lakes and playas where it can be formed directly from the salt solution or as a dehydration product of mirabellite ($Na_2SO_4.10\ H_2O$). It is found as efflorescences of prismatic crystals in Konya Basin (Turkey) and in alluvial soils in Peru. Tursina (1980) reported that circular-rhomboidal thenardite crystals are a common form in solonchack soils in USSR.

Translocated Inorganic Carbonate

Genesis of translocated carbonates. The movement of carbonate within a soil body may lead to the complete removal of carbonates from the entire profile, as is common in more humid areas, or removal from the solum and reprecipitation of the carbonate in the C horizon as is commonly observed in more arid and semi-arid regions.

According to St. Arnaud and Herbillon (1973), who studied the occurrence and genesis of secondary magnesium-bearing calcites of several chernozemic and solonetzic soils from Saskatchewan, the conditions and processes which led to their formation and which could be applied to most pedogenic carbonate formation were as follows: (1) the dissolution of original carbonates in upper soil horizon, following the solubility principles of carbonate minerals which suggests that calcite should be leached before dolomite, (2) the translocation of dissolved ions and reprecipitation in the lower horizons, and (3) variation in P_{CO_2} levels, moisture movement and the drying out of the soils which provide the conditions necessary to formation of magnesium-bearing calcites formation. Regarding the last point, the authors gave more theoretical details which could be applied to field conditions. For instance, when the solubilization of calcite and dolomite occurs in the upper horizons and if moisture, temperature and P_{CO_2} levels remain constant, an eventual equilibrium will be established between the solid and liquid phases. Following that, if the moisture front is forced downward due to additional rainfall, the soil solution enters a zone of lower P_{CO_2} and becomes supersaturated with respect to both calcite and dolomite. This supersaturation condition leads to the reprecipitation of calcite or magnesium-bearing calcite.

Dealing with the situation when the groundwater is relatively shallow, capillary rise of water could carry dissolved carbonates to be precipitated near the surface. These conditions are reported to be common in the imperfectly and poorly drained soils (e.g. calcium carbonate solonchacks) of eastern North Dakota (Redmond and McClelland, 1959).

The ultimate stage of accumulation of calcium carbonate or of calcium and magnesium carbonate is the formation of a calcic horizon. This accumulation may be in the C horizon, but it may also be in mollic, argillic, or natric horizons, or duripans (U.S.D.A., 1975).

Characteristics of translocated carbonates. Distribution and characteristics of the calcic horizon differ in different climatic conditions. In arid regions, when the amount of rainfall is very limited and the parent material is calcareous, the calcic horizon is often the only horizon in soil and its position usually is near the soil surface (Buringh, 1960). In the steppe regions, calcic horizons may develop under A1 (Ah) horizons or mollic epipedons and could be as thick as 1 m. On the other hand, when calcic horizons are formed by capillary movement of bicarbonate rich groundwater, their soils may occupy depressions. If water is ponded in such depressions, a soil having a calcic horizon frequently appears around the deeper depressions (U.S.D.A., p. 46, 1975).

In the field, a horizon of pedogenic carbonate accumulation is characterized by the presence of whitish lime spots, often as lime powder or small concretions (Buringh, 1970). Furthermore, according to Sehgal and Stoops (1972), the most common pedogenic calcite accumulation in arid and semi-arid regions of Punjab, India, occurs as nodules. On the other hand, Gile et al. (1965) characterized the pedogenic carbonate accumulation in the desertic and desertic grassland areas of New Mexico and found that the accumulations commonly occurred as pebble coatings and inter-pebble fillings in the gravelly soils and as filaments, faint coatings, and nodules in the non-gravelly soils. In Manitoba, the pedogenic carbonate accumulations occur in medium and fine textured soils as fine powdery material in Cca horizons, and as carbonatic streaks, nodules or concretions within and/or below the solum. Moreover, in the gravelly soils these accumulations take place mainly as pebble coatings (Smith, personal communication[4]).

Although several authors indicate that the secondary carbonates accumulated as calcite (Redmond and McClelland, 1959; Rostad and St. Arnaud, 1970; St. Arnaud, 1979), it has also been reported by Sherman et al. (1962) that dolomite could form pedogenically by slow conversion of calcite by the action of magnesium salts which are mainly sulfates in the fluctuating groundwater. Another point to be mentioned is the grain size of secondary carbonate. Rostad and St. Arnaud (1970) found that the secondary carbonate occurs mainly as clay and fine silt.

The formation and characteristics of Mg-calcite have been given special attention by geologists and pedologists. Chave (1952) and Goldsmith et al. (1955) have given evidence that a series of carbonates have been found under present day condi-

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[4] Smith, R.E., Manitoba Soil Survey.

tions with a composition intermediate between calcite and dolomite. These minerals were deposited in marine environments and were commonly of organic origin. Graf and Goldsmith (1955) studied the stability field of Mg-calcite under metamorphic environments and found that with increasing temperatures from 50 to 800°C, in the presence of adequate CO_2 pressure, mole percent $MgCO_3$ increased from 6 to 22. They concluded that under earth-surface temperatures, the substitution of Mg^{++} in calcite should be very small. On the other hand, Goldsmith et al. (1955), Goldsmith and Graf (1958) found that Mg/Ca ratio in the precipitating solution controls the composition of the formed carbonate minerals. This finding has been studied in a wide variety of metamorphic rocks as well as synthetic magnesium calcite. Furthermore, these authors distinguished magnesium calcite from pure calcite by the position of the strong third order reflection of the "$d_{211(104)}$" in X-ray diffractograms. The $d_{211(104)}$ reflection is shifted with the reference to its position in pure calcite to higher diffraction angles depending on the Mg-content in the calcite structure.

In soil, magnesium calcite was mentioned for the first time by Sherman et al. (1962) by the name "dolomitic calcite" when they studied the dolomitization process in the soils of Red River Valley in North Dakota. In all the studied soils, dolomitic carbonates occurred on slopes of minor depressions and in that part of the profile affected by fluctuating water table. In western Canada, the occurrence and distribution of Mg- calcite in a soil sequence of Chernozemic and Solonezic soils in central Saskatchewan was first reported by St. Arnaud and Herbillon (1973). They found that (1) low Mg-calcite[5] formed mainly in the upland Chernozemic soils and (2) high magnesium[6] calcite formed mainly in the C horizons of Solonetizic and depressional Chernozemic soils of the same area. In addition they found that Mg-calcite was concentrated in clay and fine silt fraction of Cca horizons.

St. Arnaud (1979) stated that the calcite/dolomite ratio in the parent material, drainage condition, rainfall pattern, and salinity levels have a significant effect on Mg-calcite formation. In particular, he pointed out the importance of Mg-content of the soil solution. According to St. Arnaud, the build-up of Mg^{++} in soil solution originates from the dissolution of dolomite in the upper part of the soil which leads to a higher Mg concentration in the soil solution and subsequent precipitation of it as Mg-calcite in the Cca horizon. He found the formation of Mg- calcite was very much related to the depth of leaching in soil. If the leaching is much below the Cca horizon, the secondary carbonates are Mg- free and if the leaching is restricted to relatively shallow depth (2-4 m) as in the upslope positions, the build up of soluble salts and the increase of soluble Mg/Ca results in a higher content of Mg-calcite. St. Arnaud concluded that if the ratio of soluble Mg/Ca was 1 then Mg- calcite was found in the secondary carbonates. He found that the Mg/Ca ratio was greater than 1 gener-

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[5] Low $Mg^{++} < 8$ mole % $MgCO_3$.

[6] High $Mg^{++} > 8$ mole % $MgCO_3$.

ally in saline soils.

Micromorphologically, pedogenic soil carbonates which consist commonly of calcite usually occurred in one or more of three different forms: (1) Crystallites[7] - small intercalary crystals scattered through and embedded in the plasma of the S-matrix. This form is common in a calcareous parent material. (2) Intercalary crystals - larger crystals than crystallites formed by addition of material leached from above horizons during soil formation. (3) Calcans and Neocalcans - crystallization at a drying surface of a void or skeleton grain. These forms are found either due to leaching from overlying horizon or diffusion towards the void surface from S-matrix. (4) Fine-grained nodules - these features are considered to be formed partially by a diffusion process but other processes are probably also important. According to Brewer (1972), there is a progression in the development of these forms of carbonate with time. Moreover, the succession of calcareous material in which crystallites are the common form to a calcic horizon with usually high amount of nodules is a common sequence towards this development.

Several micromorphological studies have been conducted regarding the genesis, forms, and relationship of several features of secondary carbonate in soil in various climatic areas. Sehgal and Stoops (1972), during their characterization of pedogenic calcite accumulation in arid and semi-arid regions

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[7] See Glossary for micromorphological terms, page 273.

of Punjab (India), characterized the calcitic accumulation in a sequence of soils ranging from Camborthids[8] through to more strongly developed Calciorthids[8] in alluvial parent material. They found the following forms of secondary carbonate in the sola of Camborthids: (1) Microcrystalline interfluorescence, (2) Neocalcitans, and (3) Spongy calcitic nodules (characterized by irregular shape, 100 to 200 micron size, and yellowish color). In the deep horizons (Ck) of Camborthids and sola of Calciorthids, soft diffuse calcitic nodules with crystic plasmic fabric are a form of secondary carbonate indicative of a more advanced stage of development. Yarilova (1969), working in the USSR, found several carbonatic, mainly calcitic forms in various chernozemic soils in different regions of USSR. In the typical thick meadow-steppe chernozem, three forms were found: (1) microgranular calcite (0.5-1.5 micron in size), (2) calcitans, especially in the lower part of the profile, and (3) small grained (0.01-0.1 mm in size, isometric, fan-shaped, or elongated grains), and needle shaped calcite (lublinite). In the "calcareous-illuvial horizon" of the podzolized chernozemic soil while in the ordinary chernozems, the calcite is micro-granular and occurs within the plasmic material.

Mermut and St. Arnaud (1981a) studied micromorphologically the nature and distribution of carbonates in calcareous horizons of several Saskatchewan Chernozemic and Luvisolic soils. Their finding could be summarized as: (1) Carbonatic

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[8] U.S. Taxonomy terminology (1975).

plasma contains microcrystalline carbonates often of pedogenic origin. (2)Several cutanic accumulation forms (dominantly calcitic) were most pronounced in Cca horizons of well drained soils. These cutanic forms are: (a) grain calcans (in the upper part of the maximum carbonate accumulation zone), (b) free and embedded grain calciargillans (in the coarser textured soils), and (d) quasicalcans whose formation seems to be stimulated by saline condition. (3) Carbonatic glaebules (e.g. nodules) were found in three forms: (a) Glaebules with sharp boundaries were associated with a dry environment. (b) Glaebules with diffuse boundaries were related to a relatively humid condition. (c) Sesquioxidic-carbonate glaebules which occurred in soils affected by poor drainage. (4) Carbonatic crystallaria (intercalary crystals) were generally found in finer textural soils. In a following paper by the same authors (Mermut and St. Arnaud, 1981b), studies of microcrystalline pedogenic carbonates in a calcitic plasma, grain calcans, neocalcans, and carbonatic glaebules were carried out to disclose further the nature of carbonates in soils using sub-micromorphological techniques (i.e. scanning electron microscope "SEM" and electron probe). Their main conclusions were: the size of calcitic equidimensional crystals in the calcitic plasma was 0.3 to 1.0μm, while the crystals were found to be 2 to 3μm in size and were rounded when the calcite was mixed with clay. On the other hand, when the calcite occurred as elongated and rod types occurring sometimes as a bundle of fibers, it was found to be magnesium calcite.

Translocation of Clay

Genesis of translocated clay. Migration of clay begins with: 1) dispersion of aggregates in the A horizon, when Ca^{++} is displaced to some degree by H^+ or Na^+, 2) by migration of humus molecules, and 3) by mechanical disruption of the clay suspension occurs through flocculation by Ca^{++} and Mg^{++} of subsoil carbonate, by rise in pH with soil depth, and by interaction with oxides (Jenny, 1980). According to USDA (1975), the flocculation of migrated clay in the B horizon (i.e. argillic horizon) takes place on the ped surfaces and in the pores as clay skins. Alternating, wet and dry periods are essential in the above process.

Characteristics of translocated clay. An argillic horizon (Bt) is considered to be the ultimate stage of clay illuviation. It is either found below an eluvial horizon or at the surface if the soil has been partially truncated. The most important feature in the field that one can observe in this horizon is the clay skin (i.e. oriented clay coatings on the surfaces of pores and peds) (U.S.D.A., 1975).

From micromorphological point of view, the interpretation of the clayey features with relation to their genesis are well recognized. Brewer (1972) mentioned that the known characteristics of layer lattice clay minerals that are pertinent to such interpretation are their: 1) platy shape, 2) suspension characteristics and 3) preferred parallel orientation of drying and optical properties with respect to micas.

Among the clay features which one can relate to the translocation of clay in soil are:

Argillans: are coatings of clay minerals on the surface of voids, grains or peds in the soil material. These argillans are commonly associated with iron oxides or hydroxides (i.e. gerriargillans) or with organic compounds (i.e. organo argillans) (Brewer, 1964). Their formation is considered either due to eluviation of clay size materials from surface horizons to be deposited in an illuvial subsurface horizon (Brewer, 1972), due to a reorientation of clay minerals in situ by wetting and drying processes (Acton, 1971) or a combination of both (Smith and Buol, 1968).

Argillans have been reported in Chernozemic soils (Acton, 1961, St. Arnaud and Whiteside, 1964, Yarilova, 1969, Pettapiece and Zwarich, 1970), in Luvisolic soils, (St. Arnaud and Whiteside, 1964, Smith and Buol, 1968, McKeague et al., 1974, Bresson, 1973) and in Aridisols[10] (Hendricks, 1973, and Steven, 1973).

The stages of argillan development has received considerable attention by different workers. Hendricks (1973) found that there was an increase in the development of oriented grain cutans in the B horizon and a decrease in the A horizon. These findings were for a sequence of the following soils: Typic Torrifluvent, Typic Cambiorthid and Typic Hapliargid, which had been developed on alluvium in southern Arizona. Pettapiece and Zwarich (1970) conducted a similar study on soils

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[10] U.S. Soil Taxonomy terminology (1975).

showing progressively more profile development on a sequence of soils: Orthic Black, Orthic Dark Grey to Grey Wooded (Gray Luvisol) in Manitoba. One of their conclusions was that an increase in ped density and clay cutan formation occurred in the Bt horizons of Grey Wooded and Orthic Dark Grey as compared to Btj horizon of the Orthic Black.

Plasmic fabric: includes the kind and degree of preferred orientation of clay mineral particles which is due to pressure, differential movement, or deposition from suspension. However, in the soil thin sections, only the last one is usually observable (Brewer, 1972).

Papules: are relatively small bodies of strongly oriented clay mineral grains which are commonly interpreted as broken argillans.

Clay laminae and nodules: Clay Laminae are elongated zones of strongly oriented clay mineral grains. Clay nodules are a concentration of clay minerals lacking skeleton grains. These two features occur in the S-matrix, and until now there was a difficulty in interpretation for their genesis and existence (Brewer, 1972).

2.2 Groundwater

Groundwater is defined as that portion of total precipitation which, at any particular time, is either passing through or standing in the soil or the underlying strata and is free to move under the influence of gravity (U.S. Soil Sci. Soc., 1973). In this section, two topics are discussed, namely groundwater flow and groundwater chemistry.

2.2.1 Groundwater Flow

To understand the causes behind the groundwater flow in the soil and underlying material, it is necessary to define fluid potential. According to Hubbert (1940), fluid potential is defined as a physical quantity, capable of measurement at every point in a flow system, whose properties are such that flow always occurs from regions of higher potential values to those of lower potential values regardless of the direction in space. Fluid potential can be expressed as hydraulic head, which at a given point, is the height of water column that can be supported at that point (pressure head) plus the height of that point above standard datum (elevation head).

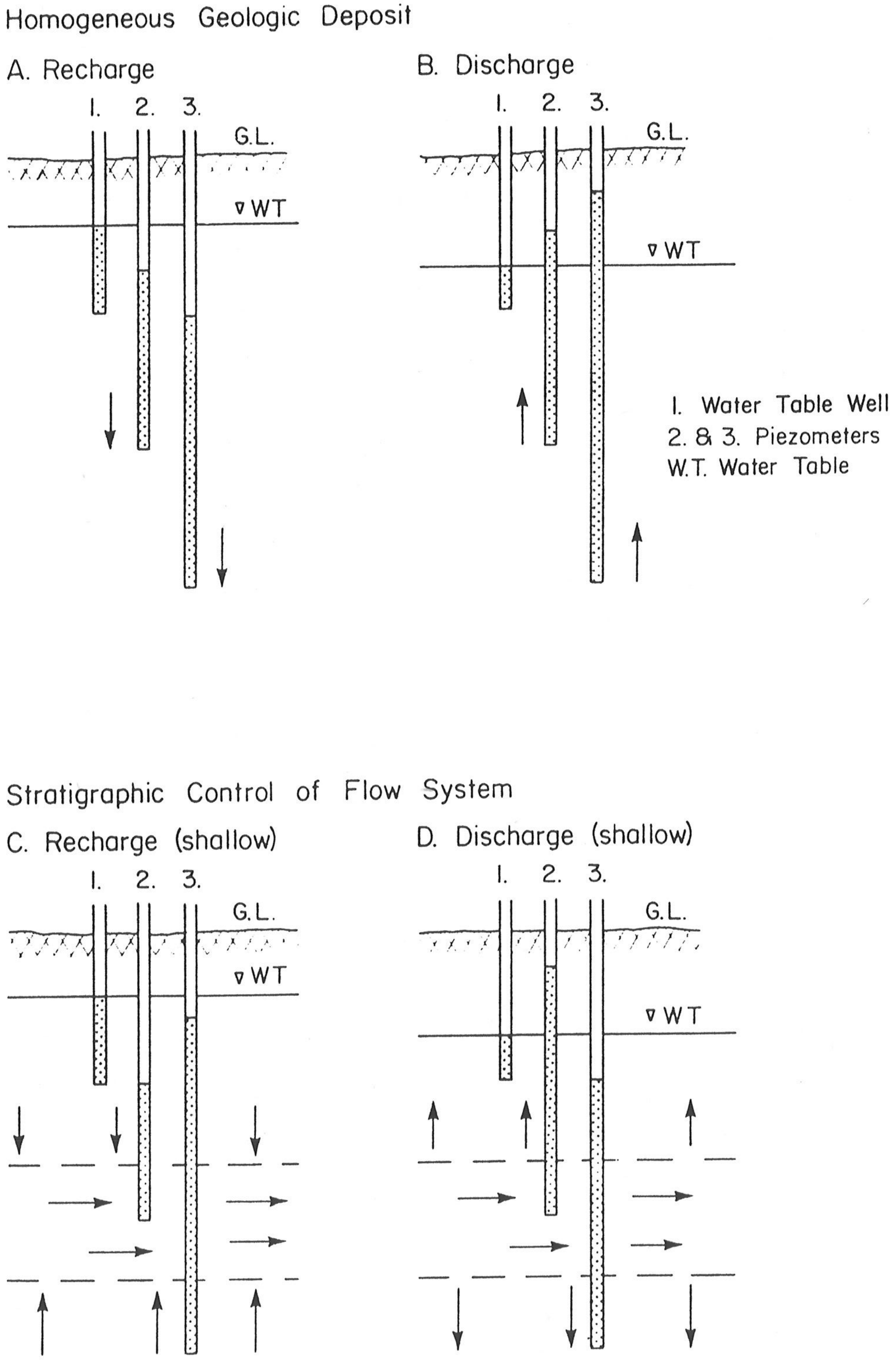
The water level in a piezometer is expressed as height above standard datum (usually sea level). This water level is a direct measure of groundwater potential (hydraulic head) at the point of piezometer end. More than one piezometer at a single site constitutes a piezometer nest which allows vertical hydraulic gradients to be measured.

Eilers (1973) presented a schematic illustration of piezometer nests in different hydrogeological conditions to facilitate interpretation of hydraulic head data (Figure 2). According to the above author, when the geologic deposits were homogeneous and the water levels (hydraulic head) in the piezometers nest are below the water table levels (Figure 2A); this indicates groundwater recharge (i.e. the direction of groundwater movement is downward from the water table zone). On the other hand, when piezometer water levels are above the water table (Figure 2B), it indicates groundwater discharge (i.e. groundwater movement is upward toward the water table zone). In non-homogeneous material (i.e. stratigraphic changes), the flow system may be distorted. These stratigraphic changes may be reflected in the vertical hydraulic heads of piezometers in a single nest (Figure 2C and 2D).

According to MacLean (1974), piezometers nests are usually situated in a line at right angles to a river. This is because the flow parallel to the river is normally small compared to flow towards the river, and can be neglected during the construction of equipotential lines. Flow nets are composed of equipotential lines at right angles in homogeneous and isotropic materials. However, in non-homogeneous materials, refraction of equipotential lines and flow lines occurs at lithological contacts according to the tangent law of refraction (Hubbert, 1940):

$$\frac{\text{Tan } \theta_1}{\text{Tan } \theta_2} = \frac{K_1}{K_2}$$ where K_1 and K_2 are

hydraulic conductivities of the materials and θ is the angle between the equipotential lines and lithological boundary.



Arrows indicate general direction of groundwater flow.

Figure 2. Schematic of Piezometer Nests to Facilitate Interpretation of Hydraulic Head Data. (after Eilers, 1973)

According to Toth (1962), the small drainage basin[11] is considered to be an important landscape segment for the study of groundwater in central Alberta as well as in the southern part of Saskatchewan and Manitoba. This land is usually treated as a separate unit of flow in the groundwater regime. In Figure 3, small drainage basins can theoretically be divided into two types of areas: the discharge area which is downslope from the midline and the recharge area which is upslope from the midline (Toth, 1962).

Three different flow systems may be superimposed on one another to comprise the general groundwater flow systems of a theoretical basin: the regional, intermediate and local systems (Figure 4). A system of groundwater flow is considered to be regional if its recharge area occupies the water divide and its discharge area lies at the bottom of the basin. The major characteristics of an intermediate system of groundwater flow is that, although its recharge and discharge areas do not occupy the highest and lowest elevated places, respectively, in the basin, one or more topographic highs and lows may be located between them. A local system of groundwater flow has its recharge area at a topographic high and its discharge area at a topographic low that are located adjacent to each other. Furthermore, the local system is of special importance to soil

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[11] Defined as: an area bounded by topographic highs, its lowest part being occupied by an impounded body of surface water or by outlet of a relatively low order stream and having similar physiographic condition over the whole of its surface (Toth, 1963).

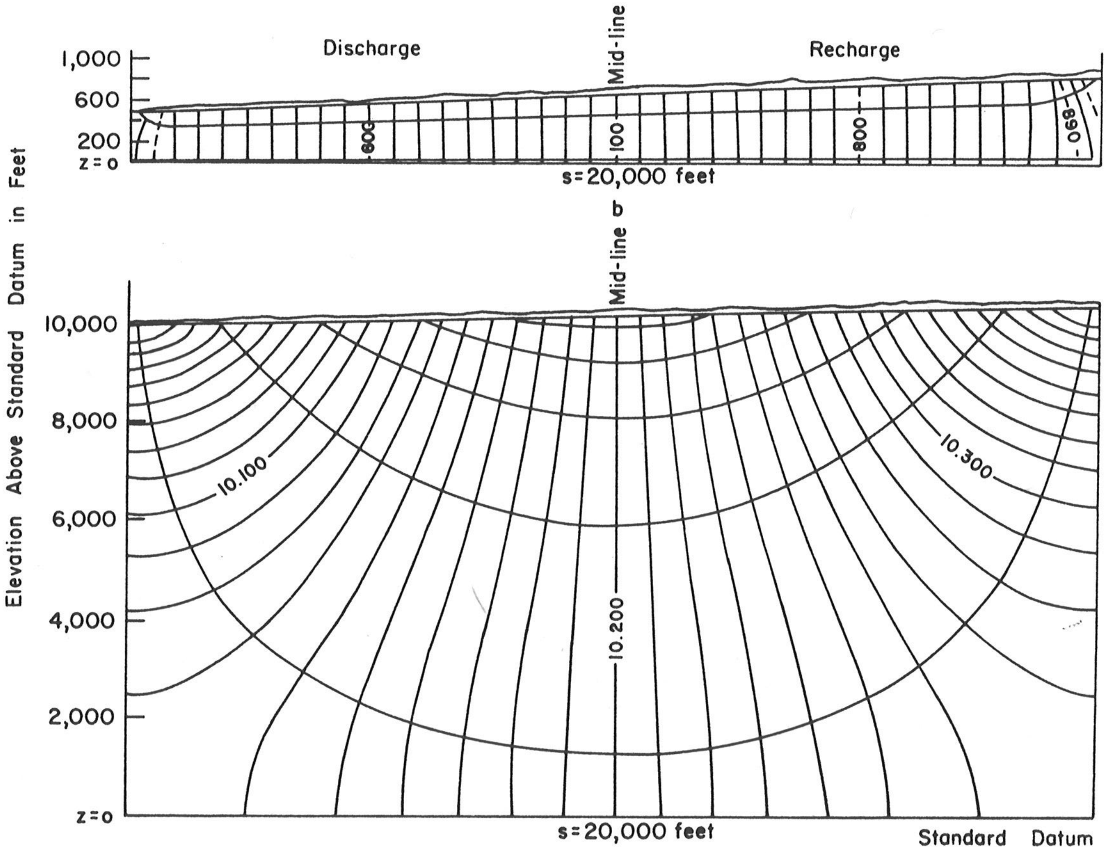

Figure 3. Two-dimensional Theoretical Potential Distributions and Flow Patterns for Different Depths to the Horizontal Impermeable Boundary (after Toth, 1962).

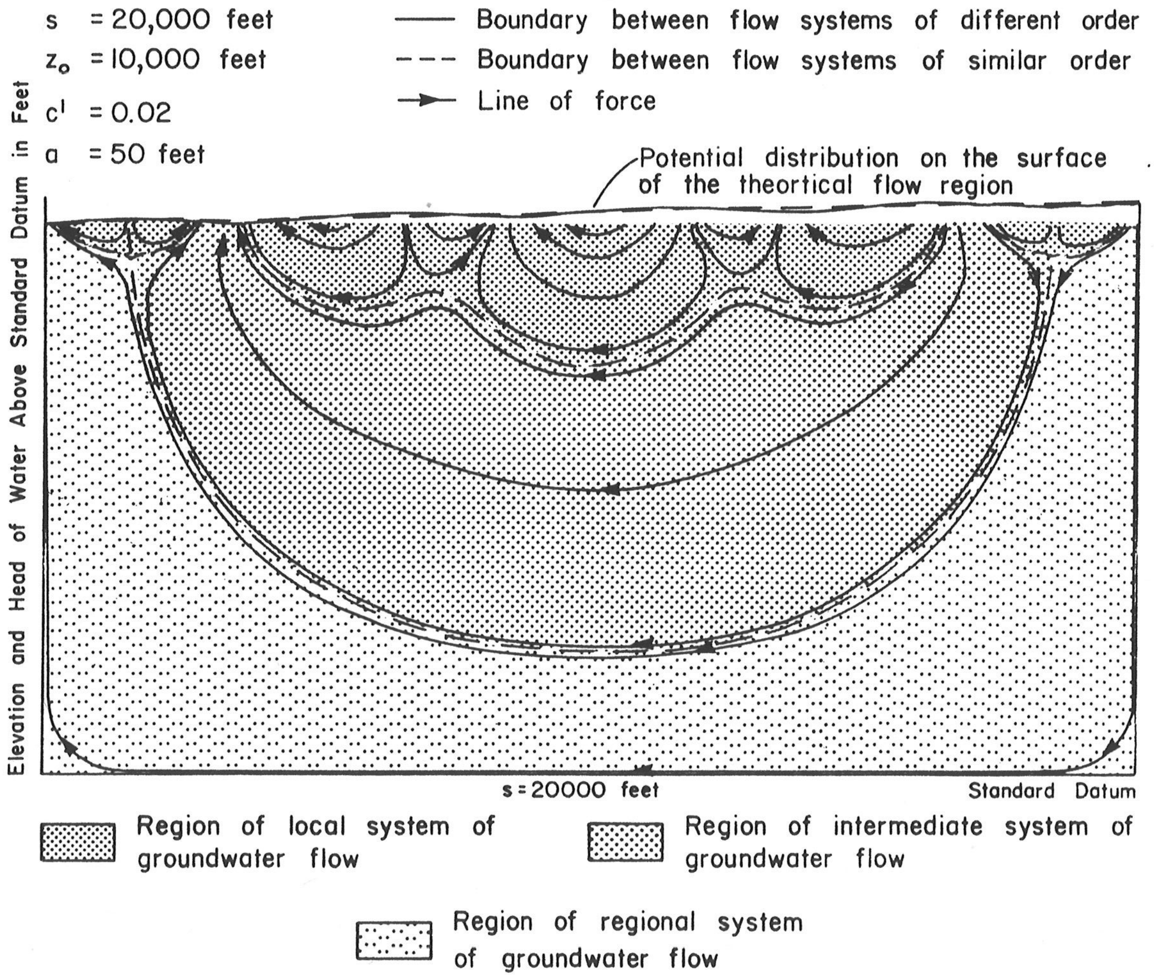

Figure 4. Theoretical Flow Distribution in a Composite, Homogeneous, and Isotropic Drainage Basin (after Toth, 1963).

scientists because of its potential influence on soil profile development. The local systems are separated by subvertical boundaries and the systems of different order are separated by subhorizontal boundaries. On the other side, the location and extent of recharge and discharge areas are important features of groundwater movement. Moreover, the higher the topographic relief, the greater is the importance of local flow systems in the study area.

In the Canadian prairies, Lissey (1968) concluded that sloughs were the centers of hydrologic activity. The reason behind this consideration was because the actual transfer of water to and from the zone of saturation was confined to topographic depressions, while the interdepressional regions remained hydrologically inactive as far as the transfer of groundwater was concerned. Furthermore, in these prairie areas, the predominant local flow system was described by Lissey as "simple" (i.e. one recharge slough and one adjacent lower discharge slough (Figure 5). As a result of groundwater movement in the system, the water table occupied different positions at different times during the year starting with stage 1, which was predominant in the early spring and ending with stage 4, which represented the ultimate recession of groundwater. Lissey (1968) referred to this simple flow system as a local flow system. This differs from Toth's (1962) local flow system in that both recharge and discharge ends terminate in depressions.

The unsaturated flow processes of infiltration and

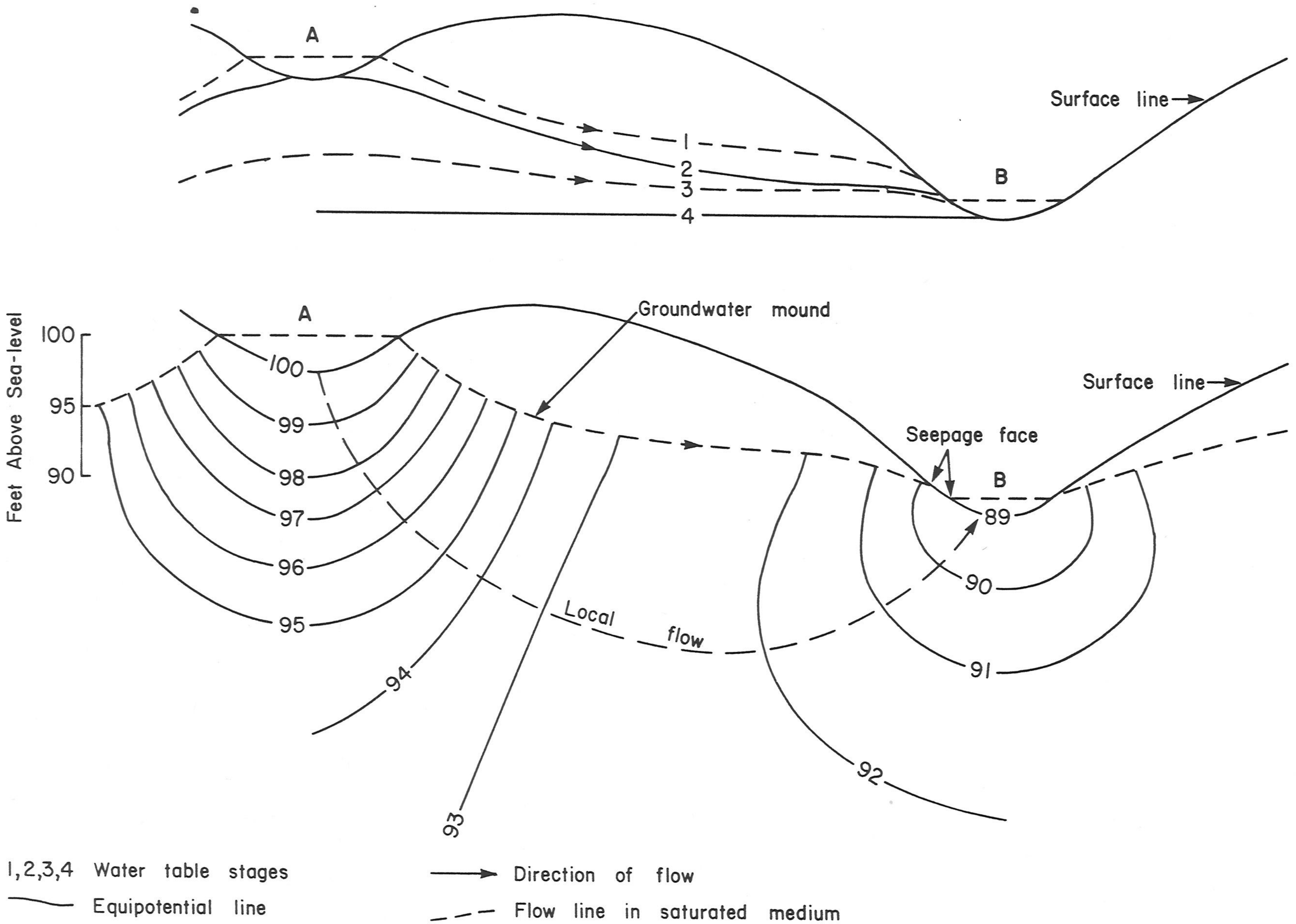

Figure 5. Development of Local Flow Systems. (after Lissey, 1968).

evaporation are considered to be in physical continuity with the parallel saturated processes of recharge and discharge. According to Freeze (1969) and Freeze and Banner (1970), water table fluctuations result when the rate of groundwater recharge or discharge is not matched by unsaturated flow rate created by infiltration or evaporation, respectively. However, this equilibrium rarely happens and because the water movement near the soil surface is of a transient character (i.e. the discontinuous nature of rainfall and evaporation), the water table fluctuates most of the time.

Factors Affecting Groundwater Flow

Climate. Temperature and precipitation affect the movement of groundwater. Temperature, on one hand, determines the evapotranspiration, and precipitation, on the other hand, determines the amount of infiltration of the water through the soil. These features and the intensity of their action also depend on soil physical properties, such as texture or permeability.

In the Canadian prairies, specifically in the knoll and depression topography, the amount of precipitation (snow and rain) available for infiltration is considered to be lower at the knoll position than in depressions due to run-off of water from the knolls to the depressions (Ellis, 1938). This run-off occurs mainly as snow melt water in spring and as water from heavy rains in summer and fall. Moreover, Shjeflo (1968) gave some ideas regarding the amount of run-off from snow melt or rainfall in a pothole area in North Dakota (see page 12).

Another important influence on the groundwater movement in the frost affected area of northern latitudes is the thermal gradient, especially under freezing and thawing conditions. Many workers reported this fact (Wills _et_ _al_., 1964; Ferguson _et_ _al_., 1964; Cary, 1966; Hoekstra, 1966; Benz _et_ _al_., 1966; Cary, 1971). Their conclusions could be framed as such: If temperature gradients were present in a soil system, water moved upward from the groundwater table which was higher in temperature to the freezing front in response to matric potential gradients and vapour pressure differences. The drop in level of groundwater related positively to the frozen layer thickness; this happened usually in winter time, whereas in summer or early spring the water table was in its highest level.

Vegetation. The vegetation may affect, in a different degree, the discharge and recharge processes by decreasing evaporation and increasing infiltration. According to Meyboom (1966) who studied and described groundwater flow that was associated with a ring of willows in a slough developed within the hummocky moraine of south central Saskatchewan, the groundwater flow system is of the local type and is influenced by: (1) In winter, the hydrological condition is of normal downward flow. (2) A spring condition develops which is characterized mainly by a groundwater mound underneath the slough. (3) In summer and fall, a condition develops which is characterized by an inverted water table relief owing to a cone of depression around the phreatophytic willows and phreatophytes in the dry slough bed.

Geology. Groundwater movement is affected by two important geologic factors. The first is the geomorphology of the area which control the location, size, type and extent of depressions occurring in the area. Hitchon (1969), in a study of a western Canadian Sedimentary Basin concluded that major upland topographic features are major recharge regions and that major lowlands are major regional discharge areas.

If the topography is more complex and the basin depressions are progressively lower in elevation, an additional interrupted flow is recognized which can be considered as intermediate or regional flow and transitional sloughs will develop which have discharge and recharge at opposite ends at the same time. These flow systems exist in the Shoal Lake area of the Oak River Basin (Lissey, 1968; Lissey and Wyder, 1966). If the basin depressions are not progressively lower in elevation, both local and intermediate flow systems are established when the regional water table is high (Figure 6).

The second factor is permeability variations with depth within the saturated medium. The important consequences of a permeability contrast are concentration of flow in the more permeable medium and diffraction of flow lines at the contact.

Surficial Features as Indicators of Groundwater Flow Conditions.

Although there are several approaches which have been used to study groundwater flow such as: (1) mathematical, which is based on well defined physical laws, (2) piezometric analysis which involves actual measurement of potentials in the field

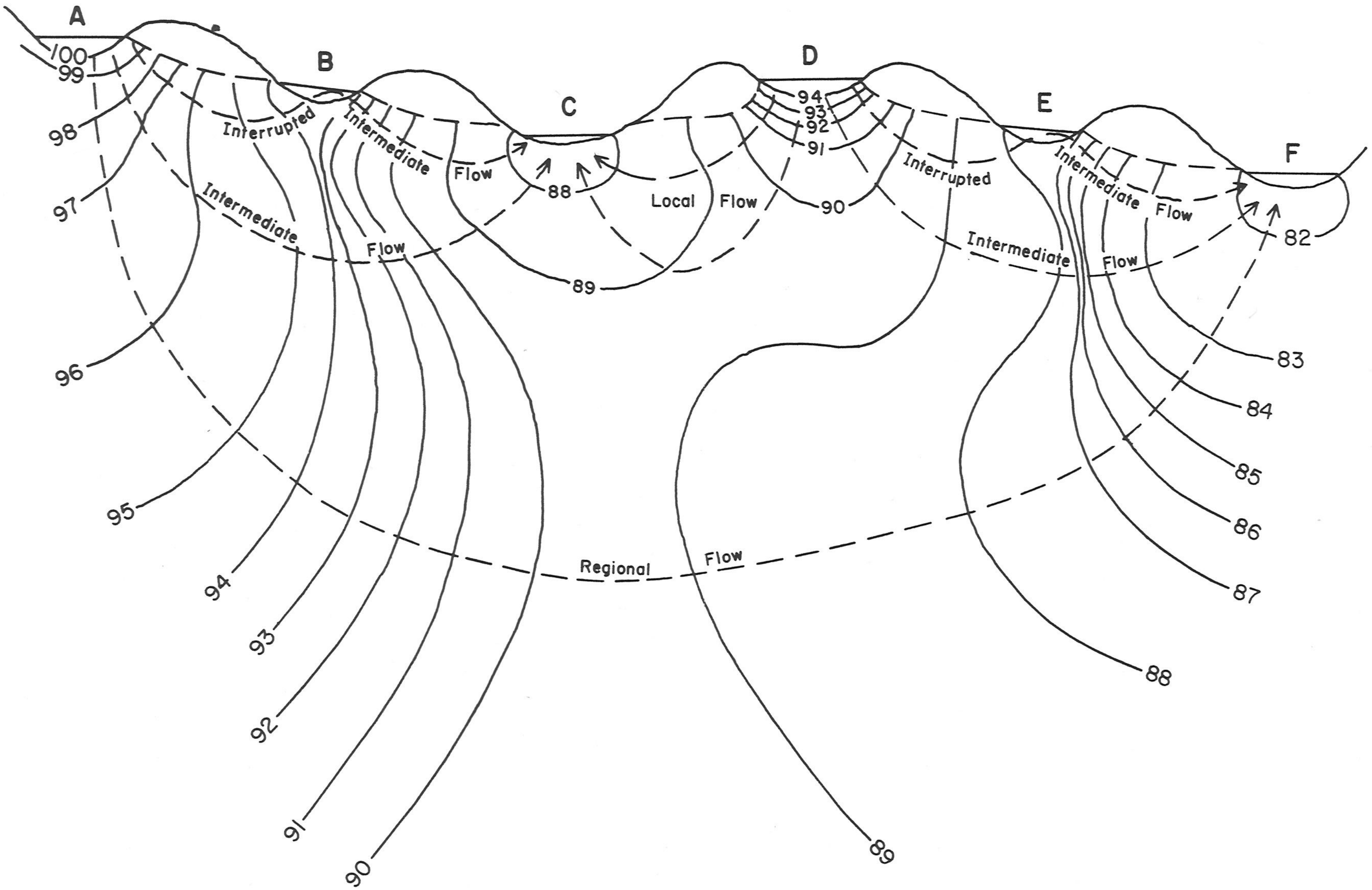

Figure 6. Devolopment of Intermediate Flow Systems (After Lissey, 1968).

from which flow directions can be derived, (3) surficial features as indicators of groundwater characteristics, (4) hydrogeochemical, in which groundwater chemistry is used in the interpretation of groundwater flow, and (5) stream hydrographs to calculate groundwater discharge (MacLean, 1974), the third approach will be discussed here after because of its application in the study area.

The surficial features are attributed by several workers mainly to environmental factors such as: climate, geomorphology and geology (Toth, 1966, 1971; MacLean and Pawluk, 1975). Toth (1966) studied the surficial features in Trochu area of Alberta. From his study, the most common, observable, and/or measurable features that he has found are: groundwater levels, chemical characteristics of water, natural vegetation, salt precipitates, and moist and dry depressions. These surficial features are discussed below.

Groundwater level can be observed or inferred from observation wells, piezometers and moist depressions. These features have been used for the construction of water level maps or groundwater fluctuation patterns using observation wells, or hydraulic flow nets using nests of piezometers.

Chemical properties of groundwater depend on the chemical characteristics of soil and subsoil material which groundwater is passing through. These properties could be used for preparing maps and/or diagrams showing the ionic distribution of groundwater within different positions in the landscape.

This would be useful to evaluate the alteration of its chemistry within the flow path.

Natural vegetation and its use as an indicator of groundwater conditions , is reported by several authors (Meyboom, 1966, 1967; Lissey, 1968; Habib *et al*., 1971). According to Meyboom (1967) and Lissey (1968), who used plant communities as indicators of groundwater quality, sloughs interpreted as recharge ones, have few concentric zones of glycophytes (plants of non-saline and alkaline soils) with rapid transition of plant communities from the central wet area to the adjacent dry upland; sloughs interpreted as discharge have few zones of Halophytes (plants of saline soil) such as: prairie bulrush (*Scirpus paludosus*) and foxtail (*Hordeum jubatum*) with a gradual transition from central wet area to the adjacent dry upland. Habib *et al*. (1971) supported the concept of using natural vegetation as an indicator for soil and groundwater salinity and depth; it was mentioned during his comprehensive study of native vegetation in Iraq that almost all halophytes are found with groundwater depth ranging from 0.6 to 2.0 m.

Salt precipitates commonly occur as a result of groundwater discharge in areas with shallow water tables. The quality of these salts and their distribution in the soil profile are mainly related to groundwater chemistry and/or physicochemical properties of soil and subsoil materials (MacLean, 1974; MacLean and Pawluk, 1975; Toth, 1971).

Moist and dry depressions: These important phenomena have been used as groundwater indicators as the moist depressions included mainly sloughs, marshes which are characterized by open water or highly moist bottom with a ring shaped pattern of phreatophytes (water loving trees and shrubs; e.g. willows, poplar, etc.). The dry depressions are obviously drier because they are situated on the highest position in the landscape which are ultimately interpreted as a recharge aspect.

2.2.2 Groundwater Chemistry

Almost all groundwater originates as rain or snow melt which infiltrates through the soil and underlying geological material and becomes part of the groundwater system. As the water moves through the soil and geological material, its chemistry can be greatly altered. The kind and degree of alteration is related to factors such as: (1) geology (bedrock or surface deposits), (2) climate (mainly rainfall and temperature), and (3) hydrology (groundwater flow condition and permeability of soil and subsoil deposits) (MacLean, 1974; Rozkowski, 1967).

Geologic factors: refer to the mineralogy of the bedrock or surficial deposits through which groundwater flows. Back (1966) mentioned that the distribution, solubility and adsorption capacity of the minerals in the deposits is one of the main factors which controls the amount of dissolved solids in the groundwater. It has been noted (Cheboratev, 1955; Schoeller, 1959) that as the flow path increases, there is a tendency for the dominant cation to change from Ca^{++} to Mg^{++} to Na^{+} and for the dominant anion to change from HCO_3^- to SO_4^{--} to Cl-. This tendency is due to the differences in ionic potential (charge ÷ ionic radius), in which Ca^{++} and Mg^{++} are retained and Na^+ is released (to be more soluble). Change in anions occurs mainly because of solubility differences in combination with the dominant cations. Rozbowski (1967) conducted a hydrogical study of glacial tills in the Moose Mountain area of Saskatchewan and found that Ca^{++}, and Mg^{++}, Na^+, SO_4^{--} and HCO_3^- were the common ions in groundwater of the tills. These ions could be considered also common in the till materials of prairie regions (Eilers, 1973; Greenlee *et al*., 1968).

Climatic factors: rainfall through its chemical composition and amount could heavily influence the groundwater chemical composition. An acidic character of rainwater, which could dissolve more solids (Back, 1966), together with a low amount of rainfall (MacLean, 1974) results in concentration of the dissolved ions in the groundwater. Moreover, temperature, a second factor, interacts with rainfall through its effect on evapotranspiration and its influence on solubilities of the minerals and rate of reactions within soil materials. According to Rozkowski (1967), the excess of evapotranspiration over precipitation in the semi-arid climate of Saskatchewan causes the increase of total solids in both surface and shallow groundwater.

Hydrologic factors: are considered to be a group of factors which determine the chemical composition of groundwater. First the type of flow system (local, intermediate or regional) determines the length of flow path in which the dominant ionic system will be established and second, the permeability and hydraulic gradient determine the time of contact of groundwater with the host material. These above interrelationships are supported by several workers (Meyboom, 1960; Toth, 1966; Lissey, 1968; Eilers, 1973; Leskiw, 1971). In addition to that, Rozkowski (1967) characterizes the ionic grouping for groundwater in recharge, discharge, or lateral flow zones in a small local basin in hummocky moraine of southern Saskatchewan to be SO_4-Ca-Mg, SO_4-Mg, and SO_4-Mg-Ca type, respectively. Recently, Freeze and Cherry (1979) proposed four classes of groundwater according to their total dissolved solids (TDS) using 10,000 mg/L (ppm) as a limit to consider the groundwater to be <u>saline</u>. Moreover, these authors stated that the groundwater composition in glacial deposits of North America could be classified into three types: Type I with 100 mg/L TDS in which Na^+, Ca^{++}, and/or Mg^{++} are the dominant cation and HCO_3^- is the dominant anion, Type II with 100 meq/L TDS in which Ca^{++} and Mg^{++} are the dominant cation and HCO_3 is the dominant anion and Type III with 1,000 to 10,000 meq/L TDS in which Na^+, Mg^{++}, Ca^{++}, HCO_3^-, and SO_4^{--} generally occur with SO_4^- as a dominant anion.

2.3 Soils and Their Relationship to Groundwater

The presence or absence of groundwater in the soil could be observed through soil profile properties. In semi-arid, subhumid, and humid regions, when groundwater invades the soil profile, at least seasonally, many physical and chemical properties may be altered by: (a) anaerobic or reducing reactions, (b) vertical and lateral movement of groundwater which may carry the soluble materials within the flow path, and (c) soil temperature which tends to be colder in the saturated soil which 1) affects the solubility of some minerals (Jenny, 1980) and 2) influences vertical movement of groundwater especially in frozen conditions (Willis et al., 1963; Benz et al., 1968).

Because the groundwater flow is generally slow compared with surface water, soluble salts and other soluble materials can accumulate at least locally as minor amounts in the low lying areas of the landscape. This could happen especially in the arid and semi-arid climates where the potential evapotranspiration is much higher than precipitation in spite of the presence of shallow groundwater. However, the accumulations of soluble salts and carbonates are a common soil feature which is related to groundwater. According to Muratova (1958) who studied salt accumulation processes in the soil and groundwater in Mil'sk Plain of U.S.S.R., soluble salt accumulation in the parent material and groundwater is explained by the combination of physical and geographic condition, such as: (1) levelness of the location, (2) high temperature which results in high evaporation, and (3) absence of natural drainage and runoff. However, Muratova stated that salt accumulation in soils is affected primarily by groundwater when water table reaches a critical depth. In addition to that, the vertical redistribution of salts in the soil profile is explained by differences in salt solubility, exchange reactions, activity of living organisms, and drainage condition. Ballantyne (1962) and Greenlee *et al*. (1968) concluded that the occurrence of soil salinity in southern Alberta and Saskatchewan is due mainly to discharging phenomena of groundwater in the lower portion of the slope. The origin of these salts is suggested to be, according to the latter author, from bedrock and to a lesser extent from till material which has more been leached to lower portion of slope through lateral groundwater movement.

Secondary accumulation of carbonate and more soluble salts in soils in relation to groundwater levels have been studied in eastern North Dakota by Redmond and McClelland (1959). They found that calcium carbonate solonchacks which occurred in association with Chernozems and Humic Gley soils appeared to be related genetically to the capillary rise of saline groundwater accompanied by high evaporation rate at the soil surface.

Several observed relationships between groundwater movement and its effect on the genesis of different soil orders have been reported by different workers within various parts of western Canada. Pawluk *et al*. (1969) found in the Edmonton area of Alberta, the following relationship between soil profile type and groundwater regimes.

1. The Orthic Black Chernozem and Solodic Black Chernozems occur in either midline or recharge area;
2. The Black Solod appears to be in a recharge area;
3. Black Solonetz is located in the lower part of midline or highest parts of the discharge area; and
4. Saline Black Solonetz occurs in a groundwater dis-

charge area. This shows clearly that salinity increases in the landscape follow the change from groundwater recharge to groundwater discharge conditions.

Leskiw (1971) studied the soil-groundwater relationship using surficial features as indicators for soil conditions. He found the following relationship: (1) carbonated saline gleyed Regosols - Black Solonetz - Solodic Black is a common sequence in the discharge area accompanied by high to low amount of water leaving the saturated zone; (2) humic eluviated gleysols - Gleyed eluviated Black - eluviated Black is a common sequence in the recharge area with high to low amount of water entering the saturated zone; (3) carbonated Gleysols - Rego Black and Carbonated Eluviated Black could be expected in the midline area between recharge and discharge.

In a study area near Deloraine, Manitoba, the following soil-groundwater relation was found by Eilers (1973):

(1) A definite relationship exists between groundwater flow and soil genesis (leached and eluviated soils are typical of groundwater recharge areas while saline and carbonated soils are typical of discharge areas).

(2) The soluble salts in the soil and groundwater in the area above the Souris Escarpment are derived for the most part from the glacial till and the soils below the Escarpment are affected by sodium salts from underlying Riding Mountain formation (Eilers, 1973).

3. PHYSIOGRAPHY OF HAMIOTA AREA

3.1 Location of the Studied Area

The area investigated is located in the Oak River Basin of South Western Manitoba (Figure 7). This basin is an important part of the Assiniboine River drainage system which lies in the interior region of North America. This basin was used in hydrogeological studies by Lissey (1968) and Parry (1968) and is considered to be representative of the prairie area in western Manitoba.

The area studied consists of two sites: Site 1 is located 5 km south of Hamiota and Site 2 is 4 km east and 0.8 km south of Hamiota (Figure 8).

3.2 Geology

3.2.1 Bed Rock Geology

The two sites lie within the Virden Map sheet area (NTS 62F) and are entirely underlain by Upper Cretaceous Shale of the Riding Mountain formation which consists of two facies: (i) light grey hard siliceous shale which is less permeable with depth (Odanah member) overlying (ii) soft greenish clay shale which is relatively compact and highly impermeable (Millwood member) (Wickenden, 1945).

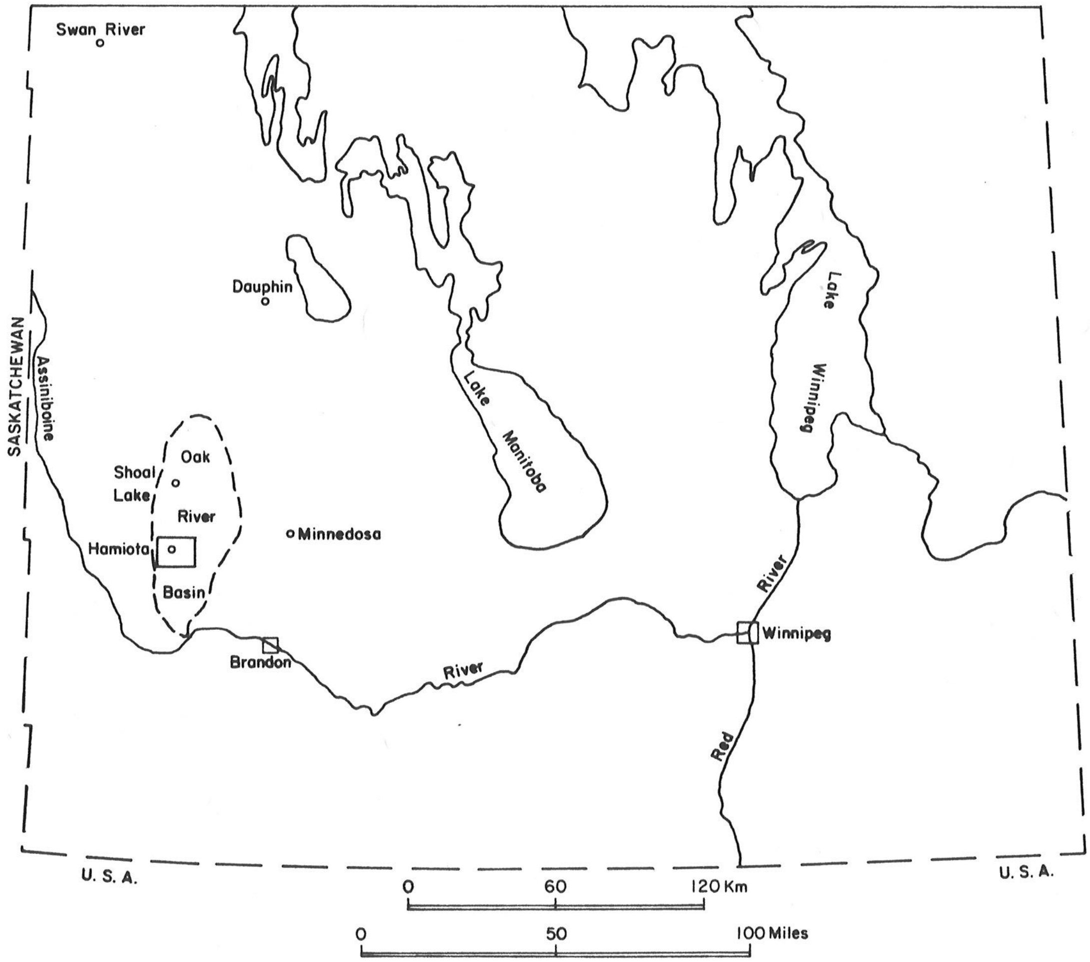

Figure 7.Location of Study Area in the Oak River Basin, Manitoba.

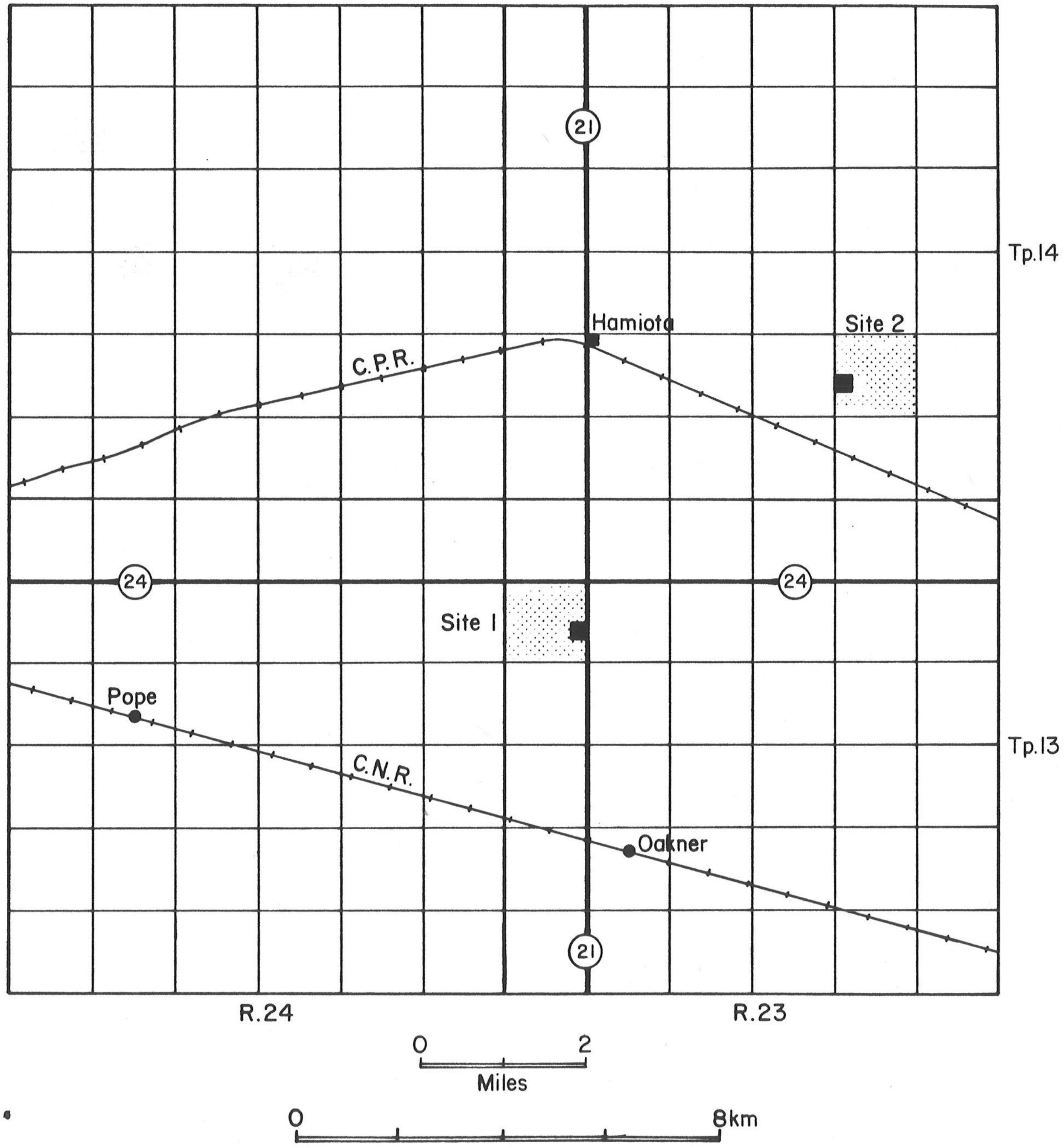

Figure 8. Location of Sites 1 and 2 in the Study Area.

3.2.2 Surficial Geology

The surficial deposits are glacial till of last Wisconsinan deglaciation (14,000 years ago) (Christiansen, 1978) which consists of heterogeneous mixture of boulders, cobbles, gravel, sand, silt and clay. The bedrock source of the till is granite, limestone and shale. The deposits are loam to clay loam in texture and moderately to strongly calcareous. At Site 2, Lissey (1968) found 7 m of oxidized till over 14 m of unoxidized (dark) till over shale bedrock. More detailed information was presented in Section 4.5 page 73.

3.3 Topography and Drainage

The topography of the study areas was characterized during the present study as low relief (<3m) undulating landscape with numerous undrained depressions. The slopes were irregular ranging from 2 and 5%. Some integrated drainage in the form of meltwater channels were present in the area.

3.4 Climate

The climate of the Oak River Basin in which the two sites are located has been designated by Koppen and Geiger (1936) as Dfb, subhumid with summer precipitation maximum. Due to its location in the center of the continent, winter temperatures are lower and summer temperatures are higher than the world average for the same latitude (Smith and Michalyna, 1973). At Hamiota, which is the closest station to the study sites, the mean annual temperature (30 years records) is 1.5°C with a range of -4.4°C to 7.4°C. The mean total precipitation for the same period is 433.2 mm (fainfall: 342.1 mm; snowfall: 91.1 mm) (Table 1) (Atmospheric Environment Service, 1975).

The Black Chernozemic Newdale loam, in which the two sites are located, has a MAST[12] $\sim$ 4.5° C and MSST[13] $\sim$ 13.5° C (Mills *et al.*, 1977). The soil temperature distribution with time and in different locations in the studied area are illustrated in Tables 35 to 37 (Appendix K, p. 293).

Soil temperature regime and soil moisture regime are considered to be important parameters in soil classification, when determined for the study area according to Baier and Russelo (1970). The soil temperature regime in Boreal, cold to moderately cold since MAST is 2 to 8° C and MSST is 8 to $<$15° C, while the soil moisture regime is humid since the moisture control section is not dry in any part as long as 90 consecutive days in most years and very slight deficits occur in the growing season (water deficits 2.5 to 6.4 cm) (Clayton *et al.*, 1977).

3.5 Vegetation, Agriculture and Present Land Use

The Oak River Basin is within the Aspen Parkland prairie region which consists mainly of grassland and to a lesser ex-

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[12] MAST = Mean Annual Soil Tempreature at 50 cm depth.

[13] MSST = Mean Summer Soil Temperature at 50 cm depth.

TABLE 1. Mean monthly temperature, total precipitation, rainfall and snowfall for Hamiota for a 30-year period 1940-1971 (adapted from Atmospheric Environment Service, 1975

Temp. °C & prec. mm	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Temp (Mean)	-18.8	-15.8	-8.7	2.7	10.2	15.5	18.9	17.5	11.3	5.3	-5.7	-14.6	1.5
Prec.(Total)	17.0	13.7	17.0	26.2	41.9	82.3	69.1	65.3	43.7	22.4	18.8	15.7	433.2
rain	trace	0.3	2.0	17.5	40.6	82.3	69.1	65.3	43.7	18.5	2.5	0.3	342.1
snow	17.0	13.5	15.0	8.6	1.3	0.0	0.0	0.0	0.3	3.6	16.3	15.5	91.1

tent trees around the depressions or in locally humid positions (Ellis, 1937; Bird, 1961).

From the point of view of agriculture, most of the arable area is used for growing wheat (*Triticum* spp.) and to a lesser extent rapeseed (*Brassica campestris*), barley (*Hordeum vulgare*) and flax (*Linum usitatissimum*).

3.6 Groundwater Regime

Lissey (1968) stated that the regional groundwater flow system controlled the permanent transitional sloughs in the Shoal Lake area. He further stated that the local flow systems were important when the variations in topography become pronounced.

Groundwater flow patterns in Sites 1 and 2 were previously studied by Lissey (1968) and at Site 1 by Parry (1968). Using the concept of interrupted flow and transitional sloughs of Lissey (1968) and the conclusions of Meyboom (1966, 1967) on the evaluation of flow system and hydrologic characteristics of phreatophytic vegetation, the following first approximations could be drawn:

1. In Site 1, the slough in the study area is considered to be a through-flow slough (transitional slough), with interrupted flow discharging in the north and recharging in the south when viewed on an intermediate or regional scale. In addition to this, lateral flow could be expected in this area between recharge and discharge sites in the landscape.

2. In Site 2, the sloughs appear to be of the recharging character mainly because of the relatively rapid downward

movement of surface water during the spring-early summer period. Moreover, some other local indications of discharge and/or lateral flow condition could be expected in the landscape near the sloughs; however, more detailed results and discussion regarding the hydrologic system of the study area will be presented in the following chapters.

4. FIELD INVESTIGATION

4.1 Site Selection

The area chosen for the study was one on which considerable hydrological work was previously conducted by Lissey (1968) and Parry (1968). These authors considered the areas as typical of ground moraine areas of western Canada.

The two sites selected in the Hamiota area are considered to give a typical soil - toposequence on one hand and a soil - groundwater sequence on the other. Specifically, sites were selected that contained saline soils as part of the sequence, leached and eluviated soils in depressions, non-eluviated soils in the depressions as well as well drained leached soils in knoll and midslope positions. One of the sites selected contained a slough studied by Parry (1968).

The first site (Figure 8, p. 50) is located in an area sloping upward from the slough (SE¼ 30-13-23W1) which was described by Parry (1968) and Lissey (1968) as a transitional type. It was used together with the associated soil toposequence (Figure 9) as two important parameters for this study; its area is estimated to be around 2500 m^2. The second site (Site 2) is much larger in area (around 16,000 m^2) and is more complex. It consists of several sloughs of a recharge character and a few different soil-toposequences of which two were used for the study (Figures 8 and 9). This

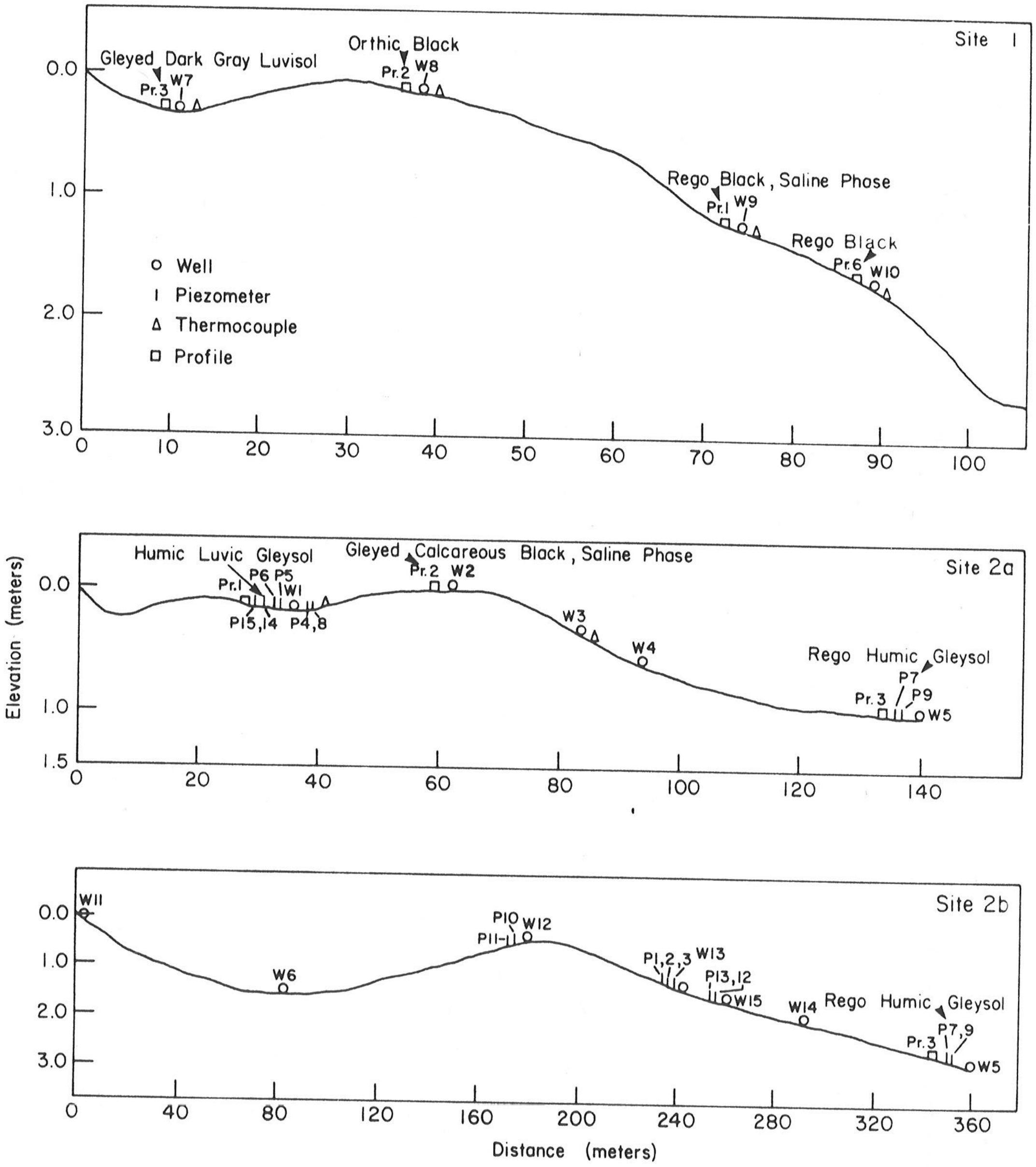


Figure 9 Wells, Piezometers, Thermocouples and Profiles Along Three Transects at Site 1 and 2.

Figure 10a. Saline and non-saline ring around the main slough at Site 1.

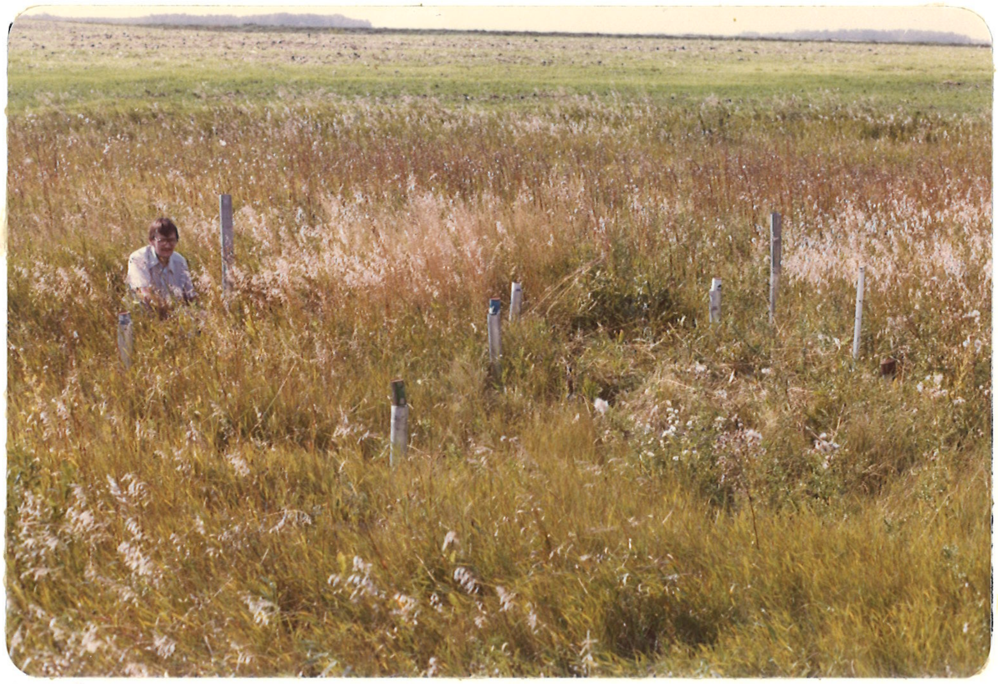


Figure 10b. Well 1 and piezometers 4, 5, 6, 8, 14 and 15 at Site 2.

site is located in undulating landscape (SW$\frac{1}{4}$ 11-14-23w1).

4.2 Site Instrumentation

Fifteen observation wells and 15 piezometers were installed at the two sites using soil and presumed hygrological variation with topography as parameters for the location of the wells and piezometers nests (Figures 11 and 13). Wells 1 to 6 and 11 to 15, Site 2 and Wells 7 to 10, Site 1 were installed in October 1978. The piezometers were installed only in Site 2 (Figure 13) and were grouped in nests of two to six piezometers near well sites (Figures 9 and 10b). Detailed information regarding the time of installation of the wells and piezometers times is given in Table 2.

Observation wells were installed using a truck mounted hydraulic auger. Once the auger reached the desired depth, p.v.c. (polyvinyl chloride) pipes or galvanized steel rain downspouts were inserted into the holes. The depths of wells are given in Table 2. The holes were then backfilled with augered material (Figure 15). Temporary extension tubes were added to wells for the winter period to facilitate the taking of the readings. The piezometers were constructed from p.v.c. tubing with 2.05 cm internal diameter. The lower end of each piezometer is slotted and placed at depths of 2.5 to 6.0 m. A sufficient amount of coarse sand was poured into the hole to cover the lower 20 cm of the pipe; then a sufficient amount of wet concrete mixture to fill a 60 cm depth followed and finally the remainder of the hole was backfilled with the augered out soil material. Again, like the observation wells, extensions

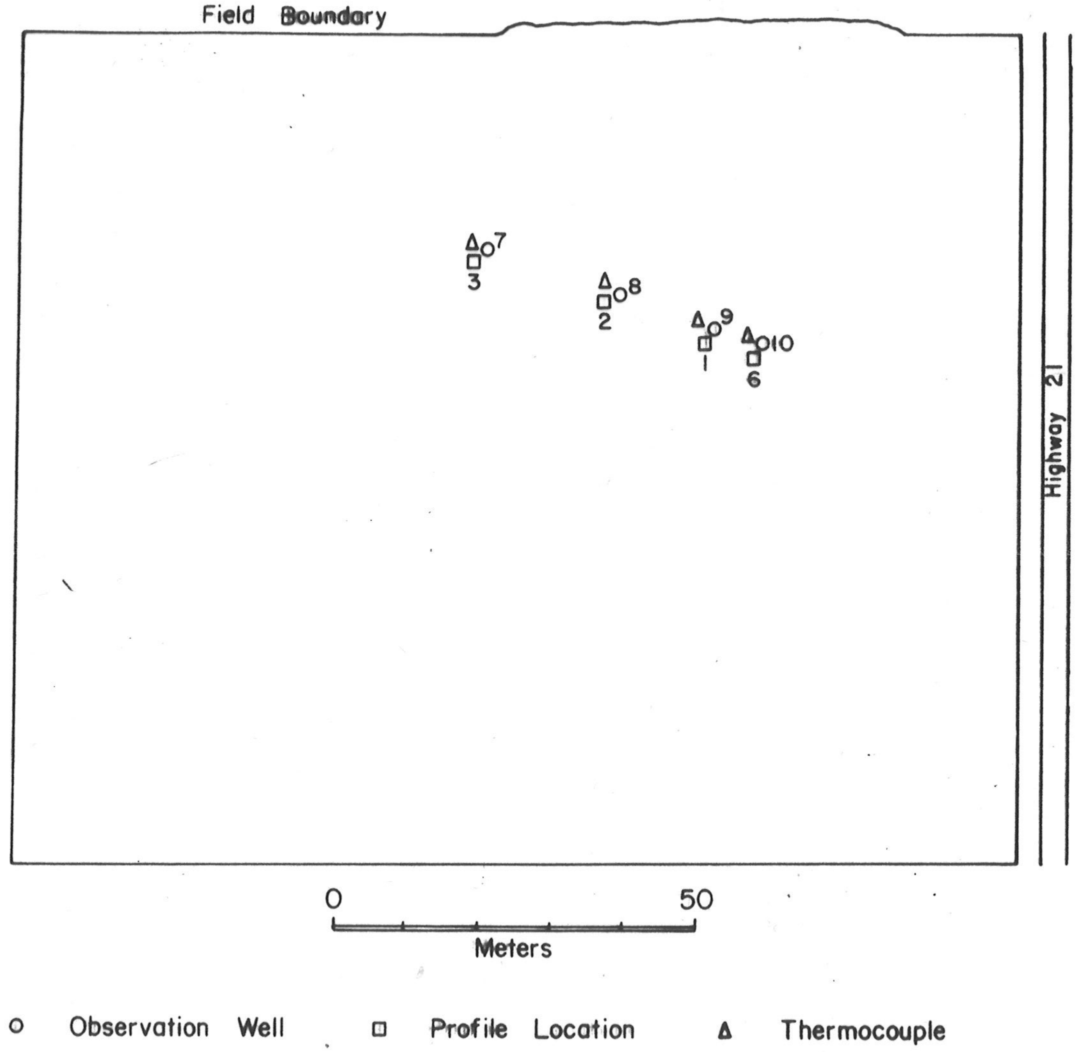
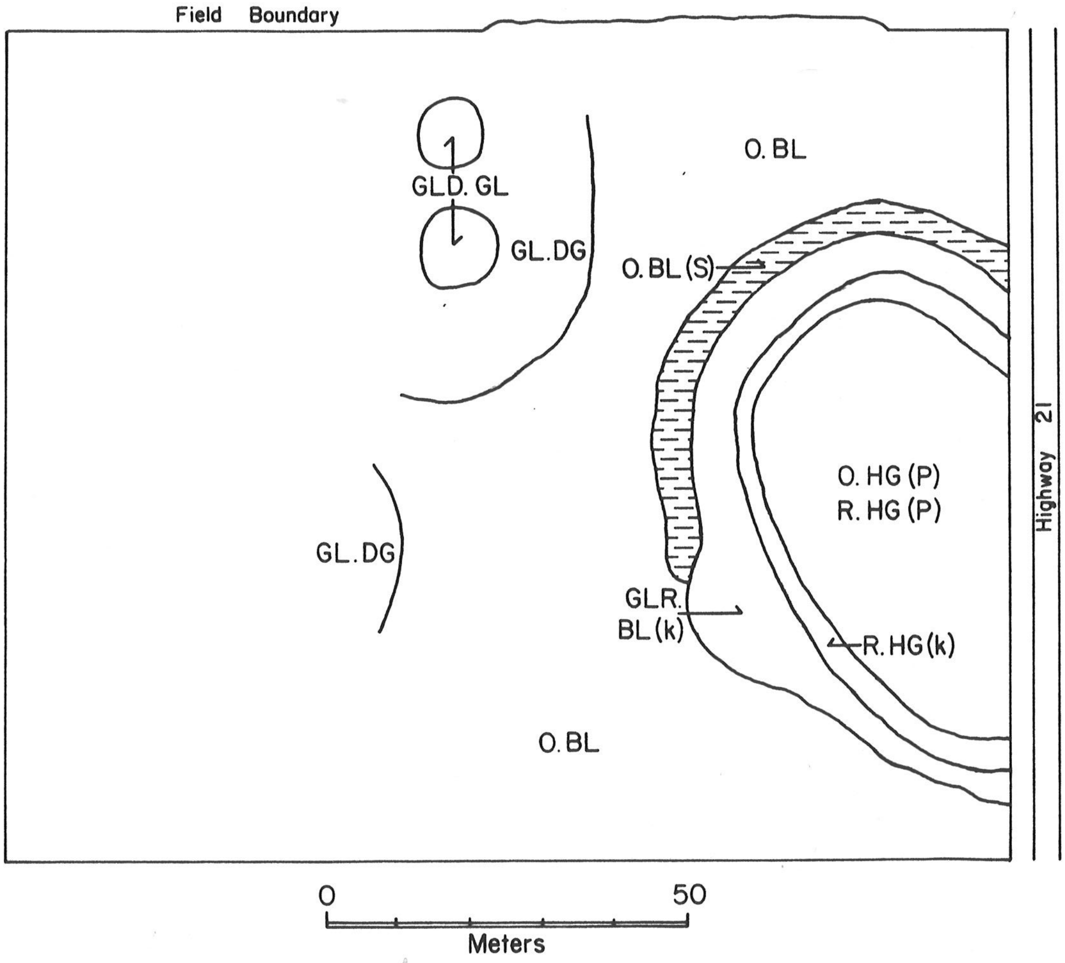


Figure 11. Location of Wells, Profiles and Thermocouples at Site I.
SE 30-13-23W1



Black Chernozemic

O. BL	Orthic Black
O. BL (S)	Orthic Black (saline phase)
R. BL	Rego Black
GLR. BL (K)	Gleyed Rego Black (carbonate phase)

Dark Gray Chernozemic

GL. DG	Gleyed Dark Gray

Humic Gleysol

O. HG (P)	Orthic Humic Gleysol (peaty phase)
R. HG (P)	Rego Humic Gleysol (peaty phase)
R. HG (K)	Rego Humic Gleysol (carbonate phase)

Gray Luvisol

GLD. GL.	Gleyed Dark Gray Luvisol
▤	Saline Phase

Figure 12. Soil Map of Site I (South of Hamiota). SE 30-13-23W1

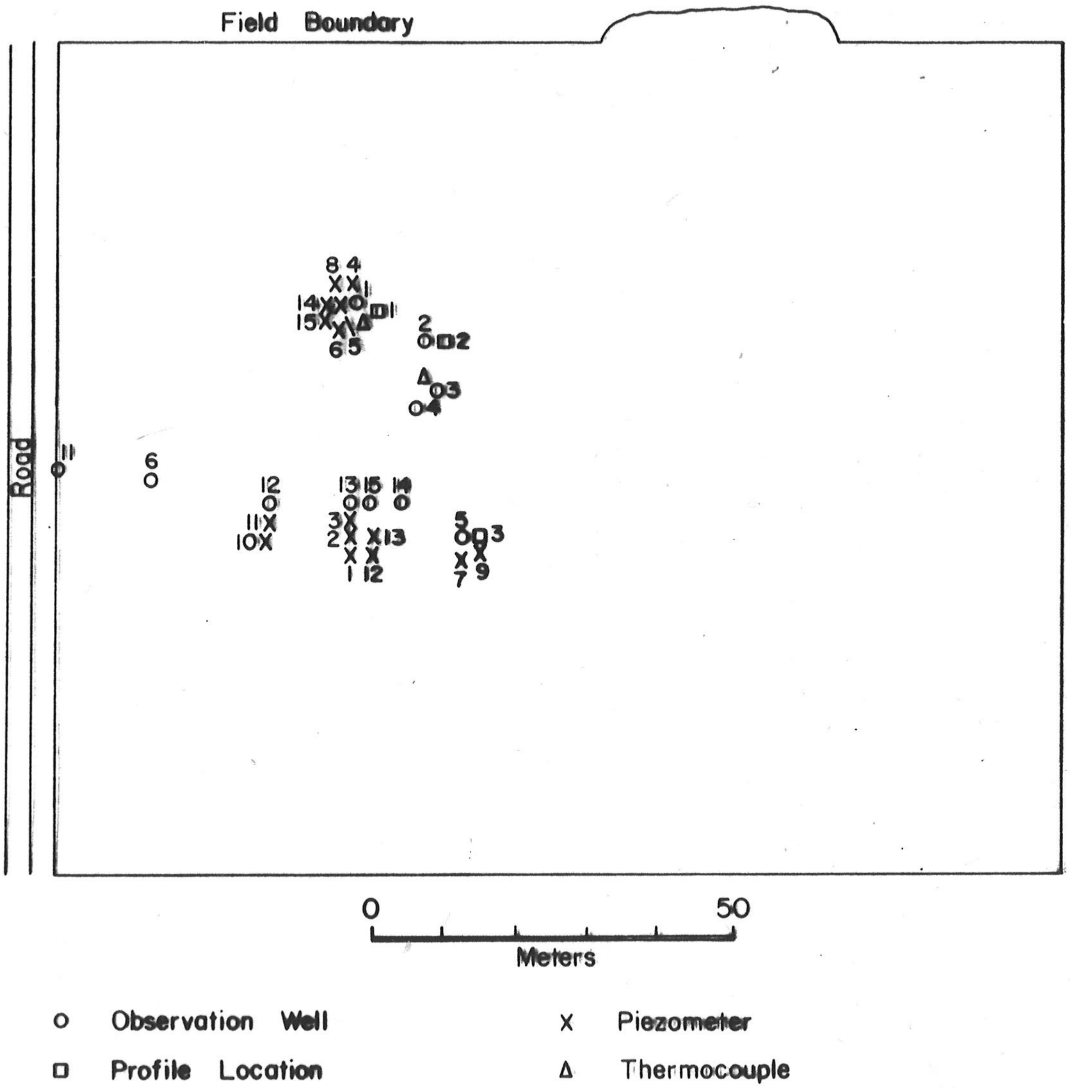
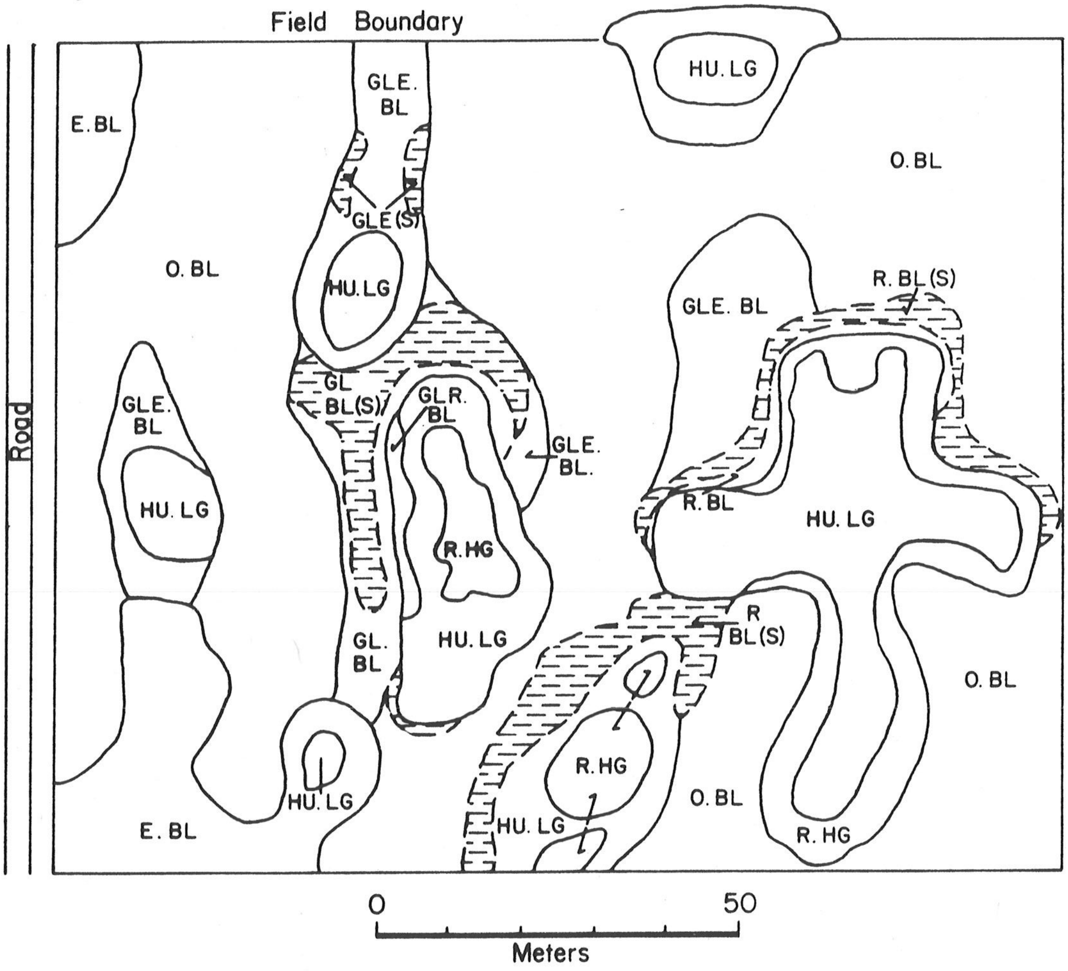


Figure 13. Location of Wells, Piezometers, Profiles and Thermocouples at Site 2. SW 11-14-23W1



Black Chernozemic

O. BL	Orthic Black
R. BL	Rego Black
R. BL (S)	Rego Black (saline phase)
E. BL	Eluviated Black
GL. BL	Gleyed Black
GL. BL (S)	Gleyed Black (saline phase)
GLR.´BL	Gleyed Rego Black
GLE. BL	Gleyed Eluviated Black
GLE. (S)	Gleyed (saline phase)

Humic Gleysol

R. HG	Rego Humic Gleysol

Luvic Gleysol

HU. LG	Humic Luvic Gleysol
▤	Saline Subgroup

Figure 14.Soil Map of Site 2 (East of Hamiota).
SW 11-14-23W1

TABLE 2. Depths and dates of installation of wells and piezometers (in cm).

Location	Well #	Installation Date				Piezometer # and location		Installation Date		
		1978	1979	1980				1980		
		October	October	April	October			July	August	October
Site 2	1	202	(351)			Site 2	1	325		
	2	278	(480)				2	535		
	3	244	244				3	417		
	4	243	243				4	300		
	5	196	196				5	500		
	6	279	279				6	400		
Site 1	7	255	(521)				7	350		
	8	290	(521)				8		600	
	9	258	(420)				9		600	
	10	190	190		(290)		10		600	
Site 2	11		573				11		450	
	12		573				12		600	
	13		527				13		350	
	14		415				14			352
	15			410			15			259

( ) = Well depths increased from those originally reported for October 1978.

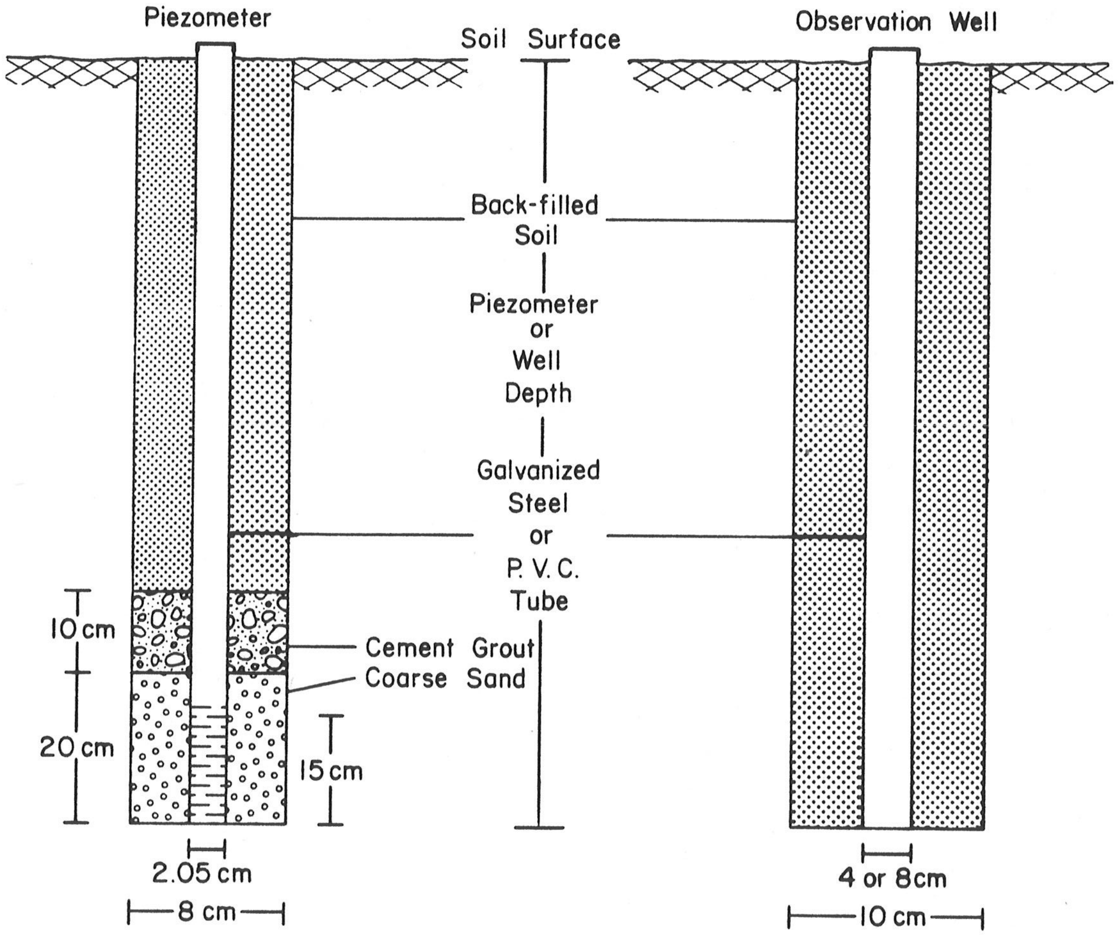


Figure 15. Design of Wells and Piezometers Installed in the Study Area.

(100 cm in length) were added above the ground surface. These extensions facilitated reading the water table depth from the wells and hydraulic heads from piezometers during winter when there was a deep snow cover on the ground surface and during the spring when the water level rose above ground surface.

The location of thermocouples to measure soil temperature are shown in Figures 11, p. 60 and 13, p. 62 . Soil temperature was measured on soils occurring in various topographic positions. In Site 1, four thermocouples were installed near Wells 7, 8, 9 and 10. Meanwhile, only two thermocouples were installed in Site 2 near Wells 1 and 3. All these thermocouples were installed in late October 1978 to read temperatures at depths of 2.5, 5, 10, 20, 50, 100 and 150 cm. Temperatures were monitored with a portable potentiometer.

4.3 Sampling, Mapping and Records

Intensive work was done to collect soil and groundwater samples from the two study sites. Pits of about 1.5 m deep were dug and the soil in each pit was described and photographed. The soil sampling sites are shown in Figure 9, p. 57 . Disturbed samples from each horizon and subhorizon were taken for chemical, physical and mineralogical characterization. Undisturbed soil samples were taken for micromorphological studies. Additional soil samples (0 to 15 cm and 15 to 30 cm) were collected from the ring of saline soils around the depressions and deep parent material samples were collected and described when some wells and piezometers were being installed. Water samples were collected from observation wells starting in

July 1979 and ending in November 1980 on an irregular basis. The samples were analyzed shortly after sampling for pH, electrical conductivity and carbonate ions and then were stored in glass bottles in a refrigerator for further chemical analysis.

A soil map, a topographic map and vegetation map were prepared for each site. To prepare the soil map, a detailed soil survey was carried out using a grid system for the location of soil inspection holes (Figures 64 and 65; Appendix A, p. 201). Topographic mapping was done for the Site 2 only with a survey level using the ground elevation at Well 1 as a bench mark assuming its elevation to be 100 m above datum and using 0.2 m as the contour interval (Figure 17). For Site 1, a topographic map prepared by Parry (1968) using 1.0 ft (0.3 m) as the contour interval (Figure 16) was used.

Vegetation mapping was carried out by ground observations in the studied areas. Aerial photographs from 1977 were enlarged to provide a base for vegetation mapping.

In the main slough (moist depression) of Site 1, the central part was occupied by permanent water body surrounded by two vegetation rings, the inner of which consists mainly of catails (_Typa latifolia_) and the outer consists of willows (_Salix_ sp.) and various grasses with some wild roses (_Rosa_ sp.) and wild oats (_Avena fatua_) (Figure 18). At Site 2, almost all the sloughs are moist depressions with a temporary water surface in the spring.

The distribution pattern of native vegetation was relatively uniform throughout the area and consisted of several rings of vegetation in every studied slough. These units are dominated mainly by sedges (*Carex* sp.) with some wild mint (*Mentha glabrior*) and other herbaceous species in the centers surrounded by a willow ring and then an area of grasslike plants, herbs and low shrubs, e.g. sedge (*Carex* sp.), wild roses (*Rosa* sp.), quackgrass (*Agropyron* sp.), wild oats (*Avena fatua*) and wild mustard (*Sinapis arvensis*). On the other hand, there is only one upland dry depression located in the northern part of the area which still has a grove of Aspen poplar (*Populas tremuloides*) (Figure 19).

Records of water table depths were started in May 1979 for Wells 1 to 10, November 1979 for Wells 11 to 15 and continued almost every month until the end of 1981. Hydraulic heads were recorded from piezometers from July 1980 for piezometers 1 to 7 and from August 1980 for piezometers 8 to 13 and October 1980 for piezometers 14 and 15. These readings were taken almost every month except in winter time. Soil temperature readings began in November 1978. Reading schedule was similar to that followed for the wells and piezometers.

4.4 Soils

With the aid of aerial photographs and on site soil examinations, a detailed soil map (Scale 1:1000) was prepared of the two sites (Figures 12, p. 61 and 14, p. 63). The soils in the area are part of the Newdale Association (undulating phase) developed on medium to moderately fine textured, moderately calcareous mixed morainal till (Ehrlich *et al.*, 1956).

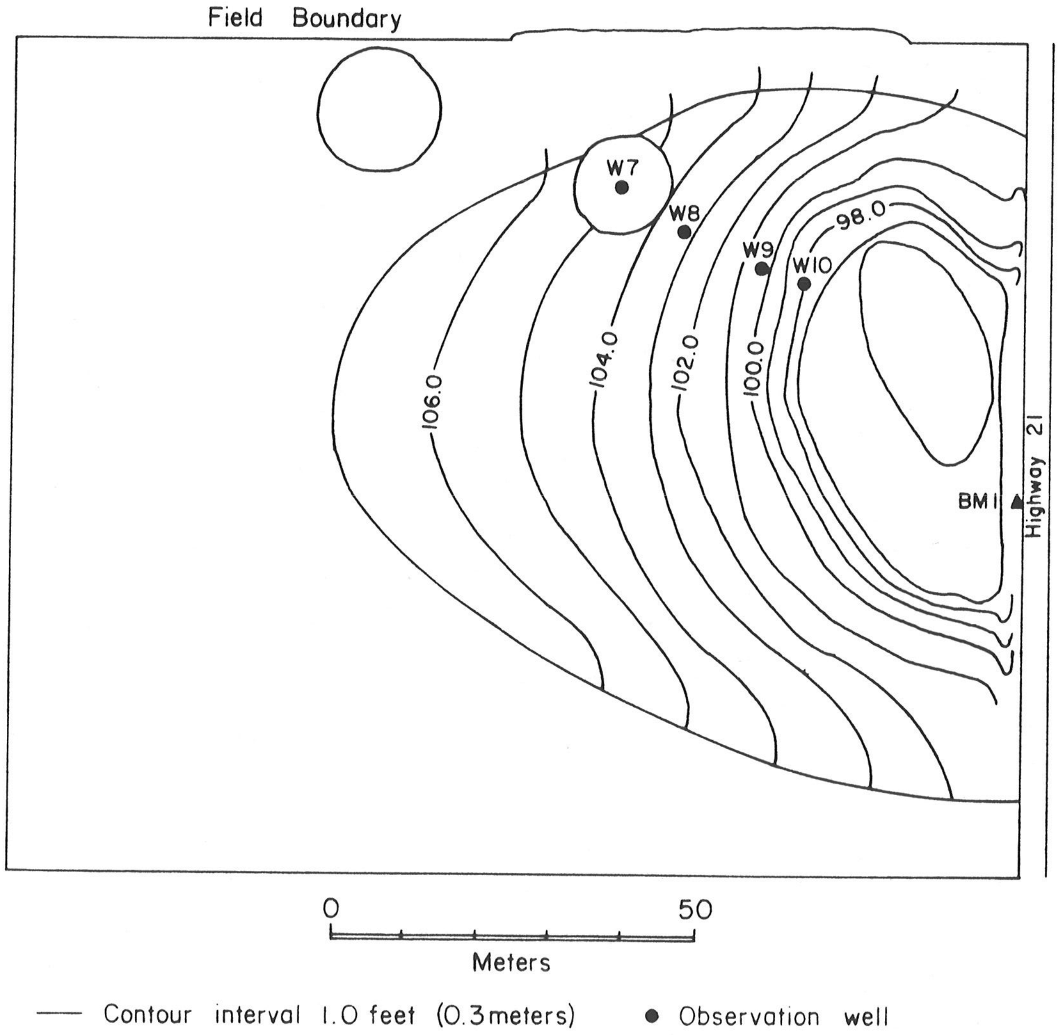


Figure 16 Topographic Map of Site 1 (South of Hamiota).
SE 30-13-23W1 (after Parry, 1968)

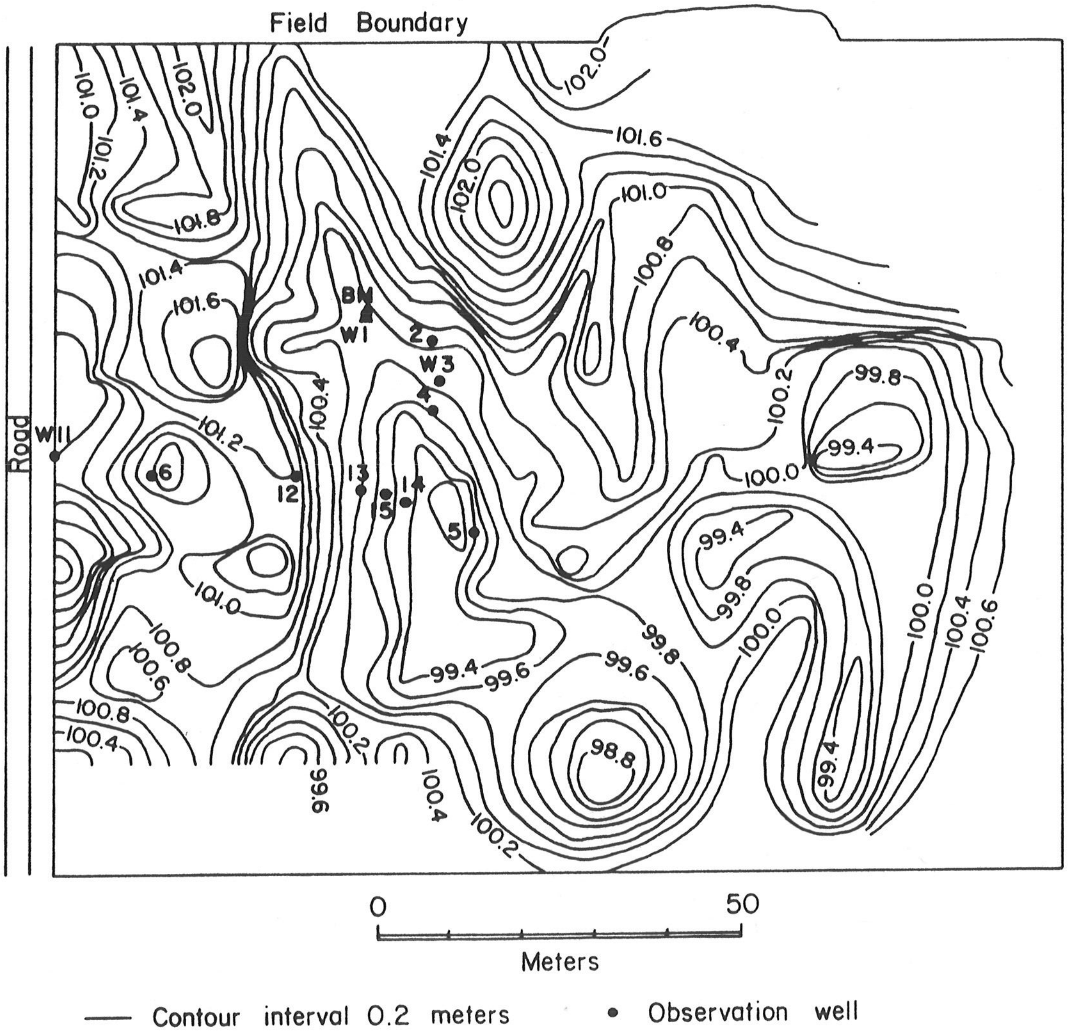


Figure.17 Topographic Map of Site 2 (East of Hamiota).
SW 11-14-23W1

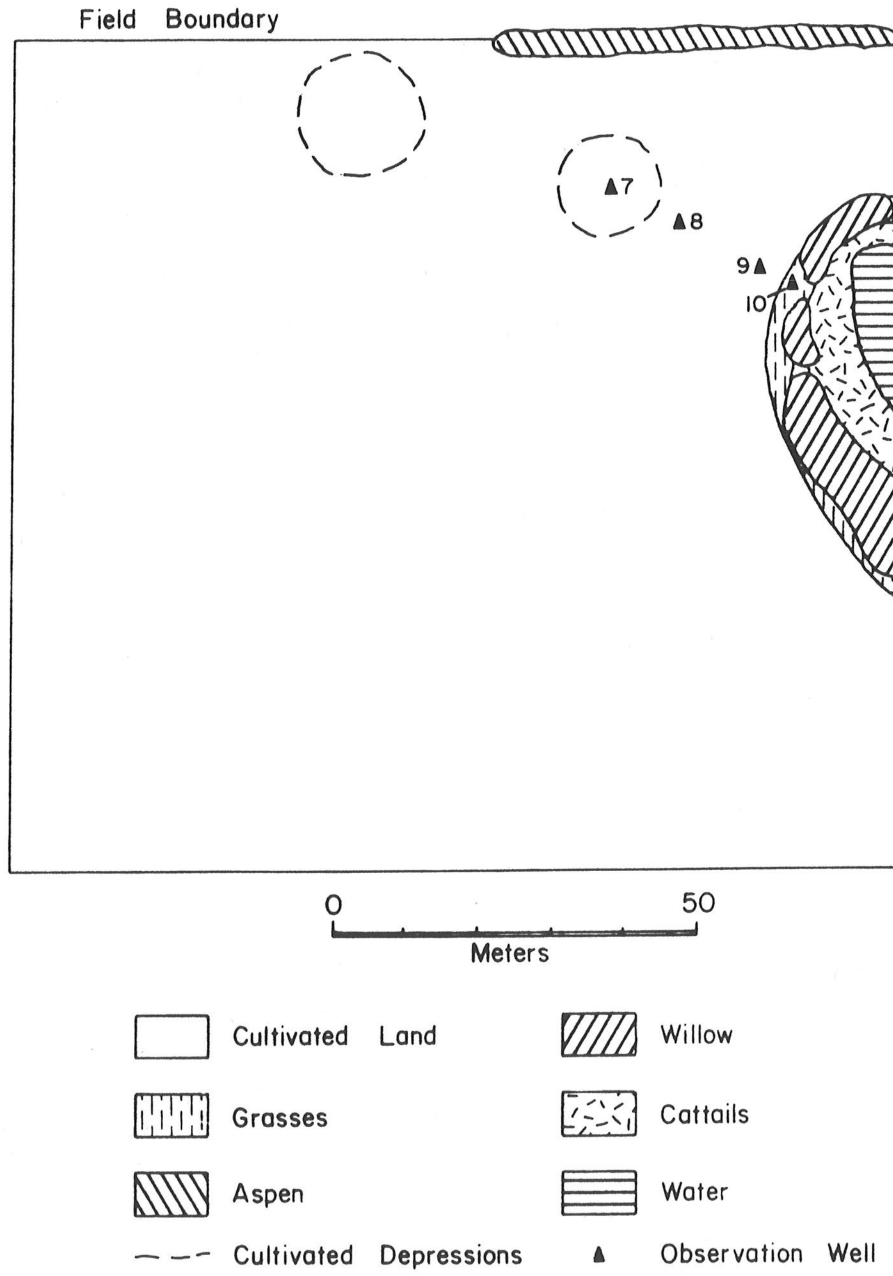


Figure.18 Vegetation Map of Site 1 (South of Hamiota).
SE 30-13-23W1.

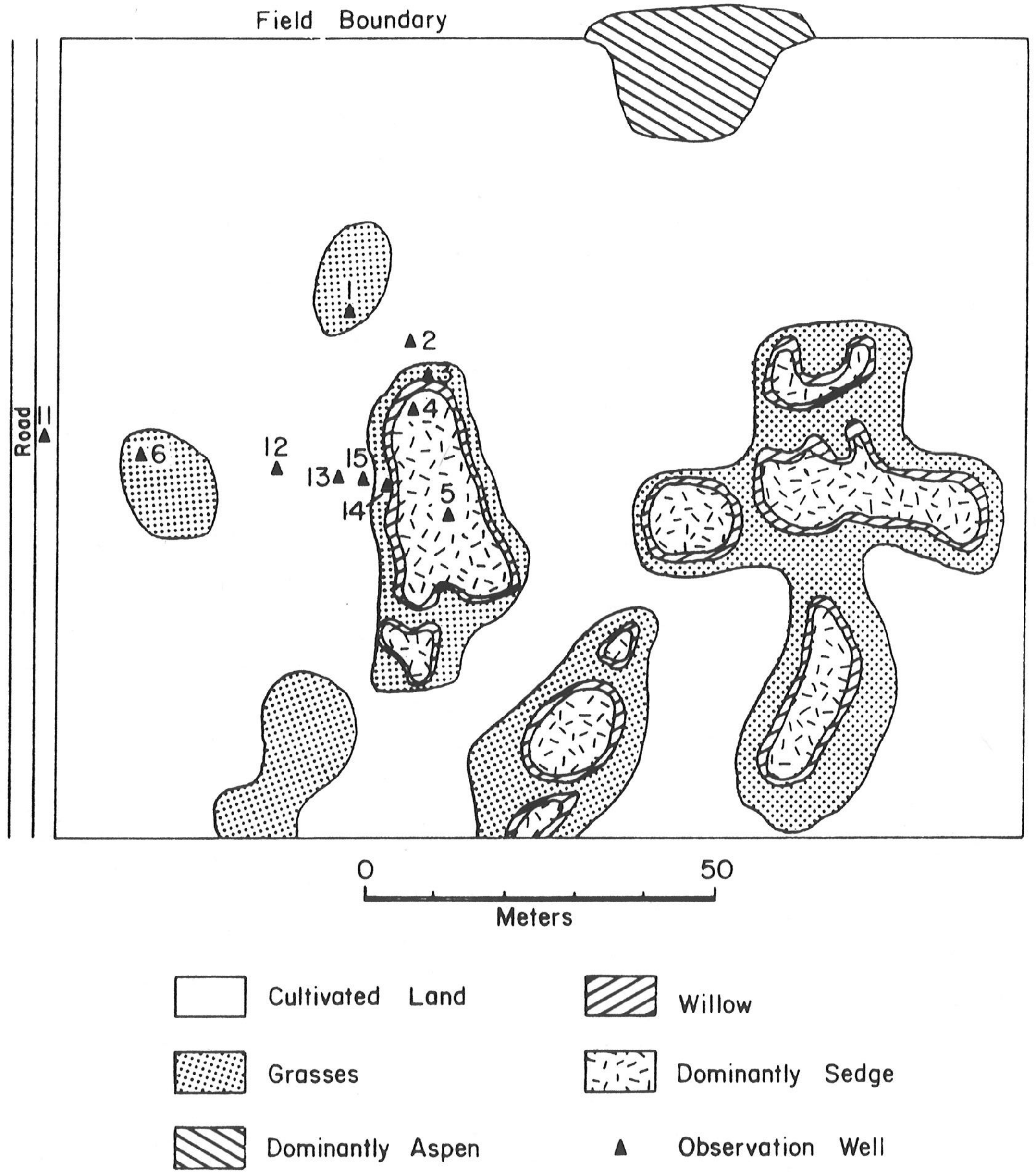


Figure.19 Vegetation Map of Site 2 (East of Hamiota).
SW 11-14-23W1.

Most of the soils are classified as well to moderately well drained soils, although the soils in or around the depressions are imperfectly or poorly drained. Soils within Site 1 are dominantly Orthic Black and Gleyed Dark Gray Chernozems which together with the Gleyed Dark Gray Luvisol of the upland depression are found above the 100 ft. contour (Figure 20). The main slough area which lies below the 100 ft. contour is occupied by the carbonated phase of the Orthic Gleysols and Rego Humic Gleysols. At Site 2, Orthic, Eluviated, Gleyed Eluviated and Gleyed Blacks are the soil subgroups occurring in the cultivated area and Humic Luvic Gleysol, and Rego Humic Gleysol occupy mainly the slough area (Figure 21). These two groups of soil are roughly separated by the 100 m topographic contour line.

Although most of soils in the study areas are well drained, an important phenomenon of sulfate salt accumulation has developed as "salinity rings" around the sloughs which most of the time are separated by "non-saline rings" (Figure 10a, p. 58). This is an indication of upward movement of groundwater within the dominant recharge system of the studied soils. More details will be presented in the Chapter of Results and Discussion. The macromorphological description of a representative soil profiles are in Appendix B, p. 206.

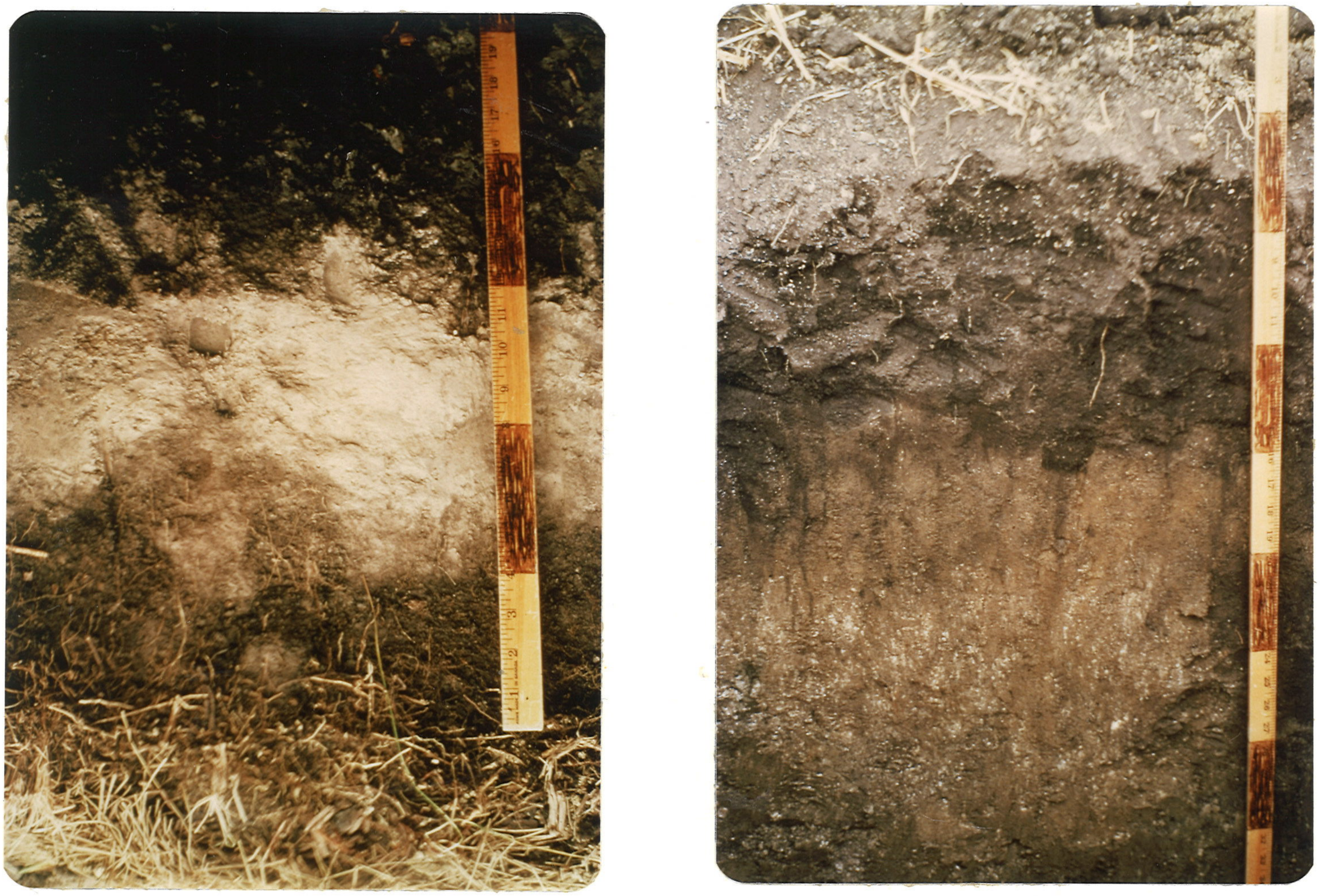
4.5 Surficial Deposits

In the study area, the deep drill samples taken at 40 cm intervals were mostly obtained between 2 and 6 m., are characterized as C horizon. At most of the drilling sites

Profile 2 (Orthic Black)

Profile 3 (Gleyed Dark Grey Luvisol)

Figure 20. Profiles 2 and 3 at Site 1.



Profile 1 (Humic Luvic Gleysol)

Profile 2 (Gleyed Calcareous Black"saline phase")

Figure 21. Profiles 1 and 2 at Site 2.

two till materials were encountered and in some cases a fluvial deposit at the contact, (e.g.: Well 8). The upper till material which extends to 3.5 m depth is mainly loam-clay loam in texture and is brownish in color. Below the brown till is the more compact, fine textured and dark gray till. Both tills are moderately calcareous, and are slightly saline in the discharge areas. More details regarding chemical, mineralogical composition of these materials will be presented in the following chapters. The macromorphological descriptions of the surficial deposits are presented in Appendix C, p. 225.

5. METHOD OF ANALYSIS

5.1 Soil Analysis

5.1.1 Chemical Analysis

The chemical methods used in the laboratory for the determination of pH, electrical conductivity, cations and anions, cation exchange capacity, calcium carbonate equivalent, calcite, dolomite, and organic carbon were followed as described in the following sections.

The soil solutions for chemical determinations were extracted from saturation soil pastes which were prepared according to the method described by the USDA (1960).

Soil reaction (pH): was determined in H_2O by the aid of Beckman Zeromatic pH meter and Fisher digital pH/ion meter using a single glass electrode cell and following the method described by USDA (1960).

Electrical conductivity (EC_e): was determined by using a conductivity bridge and conductivity cell of 1 cm^{-1} cell constant. The results were expressed in mS/cm at 25°C (USDA, 1960).

Soluble cations (Ca^{++}, Mg^{++}, Na^+ and K^+): were determined by using a Perkin Elmer atomic absorption spectrophotometer.

Soluble anions

Carbonate and bicarbonate[14]: were determined in a saturated soil extract using previously boiled distilled water for dilution to avoid the effect of CO_2 gas on the pH measurement of soil solution. These analyses were done by automatic titration with standard sulphuric acid solution (0.05 N) using pH 8 as end point for CO_3^{--} and pH 4 as end point for HCO_3^-.

Sulphate[14]: was determined by using the centrifuge method. The method involved the mixing of 1 mL of N $CaCl_2$ and 5 mL acetone with 4 mL of soil paste extract in 15 mL centrifuge tubes. The contents were then centrifuged after flocculation had taken place. After decantation of the supernatant liquid the precipitate was dissolved in distilled water and titrated with EDTA using the method of Cheng and Bray (1951) for the determination of calcium.

Chloride[14]: was determined by using a potentiometric method. The method involved pipetting 2 mL aliquots of the soil extract in a beaker and diluting to 50 mL with distilled water. The solution was then titrated with standard 0.05 N $AgNO_3$ using a Radiometer automatic titrator with mercurous sulphate and silver billet electrodes to the end point of +70 mV.

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[14] These ions are determined according to laboratory methods of the Manitoba Soil Survey, 1972, compiled by G.J. Beke.

Cation exchange capacity: was determined using the method of USDA (1960) using N ammonium acetate as the extraction solution.

Calcium carbonate equivalent, calcite and dolomite: determinations were made by using the manometric CO_2-pressure method (Skinner, 1959).

Organic carbon: Total organic carbon was determined by the modified wet oxidation method of Walkley and Black (1934) using an automatic titrator with the following setting: end point = 375 mV using platinum and calomel electrodes.

5.1.2 Physical Analysis

Particle size distribution: was determined by using the pipette method of Kilmer and Alexander (1949) with sodium polymetaphosphate as the dispersing agent.

Soil temperature: was determined by thermocouples using a portable potentiometer (see Section 6.5, p. 171 for more details).

5.1.3 Mineralogical Analysis

Clay Mineralogy

Preseparation treatments: The destruction of calcium carbonate, removal of organic matter and dissolution of soluble salts were done according to the method of Kittrick and Hope (1963) and Jackson (1956).

Particle size separation: The separation of the sand fraction from silt and clay was done by wet sieving, using a 50µm sieve. For the separation of clay from silt the dispersion-flocculation method of Jackson (1956) was applied, using 2% Na_2CO_3 for dispersion of the silt and clay suspension and 2% HCl for flocculation of the clay fraction. Further separations of the clay fraction were made with a centrifuge.

X-ray diffraction analysis. Samples for X-ray diffraction were prepared as described by Jackson (1956). Representative horizons from Profiles 1, 2 and 3, Site 1, were analyzed. Two sets of slides were prepared for the fine clay fraction and two other sets for the coarse clay fraction from each selected horizon. The first set of every fraction consisted of glycerol-magnesium saturated clay and the second of potassium-saturated clay. Diffractograms were obtained from the magnesium and potassium-saturated clays and also from the potassium-saturated clays after they had been heated for 2 hours at 550°C.

The equipment used for the X-ray diffraction analysis consisted of a Philips PW 1010 generator, a Philips PW 1050 goniometer and Philips PW 1051 recorder. The generator was operated at 36 kV, 8 mA with $CoK\alpha$ radiation and the ratemeter settings were: 4 and 8 for fine and coarse clay, respectively; the time constant was 8 s.

Interpretation methods. The qualitative identification of clay minerals was done by comparing the reflection of the

X-ray diffractograms with data of DeConinck (1974), Grim (1968) and Jackson (1956).

The following identification guide of clay minerals represents the main criteria used to identify the minerals in the samples. A semi-quantitative table based on relative peak intensities was prepared to show the composition of the clay mineral fractions (Table 11, p. 116).

Montmorillonite and Vermiculite

The two minerals are distinguished by the following features:

1. on saturation with K$^+$	Basal spacing
vermiculite	10 Å
montmorillonite	12-13 Å

2. Mg^{++} + glycerol	Basal spacing
vermiculite	14 Å
montmorillonite	18 Å

3. on heating: vermiculite normally collapses at lower temperature than montmorillonite.

Illite

Illite has a basal spacing of 10.1 Å, giving an integral series of: 10.1, 5.05, 3.33, 2.5 Å; this series does not show any change either with different saturating cations or on heating. The 10.1 and 3.33 Å peaks are normally the strongest ones.

Mixed Layer Minerals

1. Often irregular mixed layers are characterized by

the presence of first order broad reflection, forming a "bridge" between the peaks of the two simple minerals. This is typically the result of weathering of a micaeous mineral to a vermiculitic mineral (De Coninck, 1974). However, the second order reflection can usually be distinguished but higher orders are generally weak (broad haloes).

2. Generally, the most probable combination of the regular mixed layers minerals are: montmorillonite-illite and to a lesser extent vermiculite-illite with the following basal spacing:

	K^+-Saturation	Mg^{++} + glycerol
montmorillonite-illite	24 Å	28 Å
vermiculite-illite	24 Å	24 Å

3. On heating, the mixed layer minerals collapse in a similar manner to single minerals depending on the weathering stage.

Feldspars

According to De Coninck (1974) and Brown (1961), feldspars cover a wide range of reflections, the most common in decreasing order of importance are: 3.1-3.3, 3.52, 3.68-3.72, 4.05, 6.5 A.

Quartz

The most typical reflection is a 4.26 Å, together with the 3.34 Å which is often a compound peak including besides quartz normally the higher orders of mica and 14.0 Å minerals.

Mg - Content of Calcite

The soil carbonate concretion[15] samples used in this study were taken predominantly from Cca and Ck horizons. Carbonated and/or salinized Ah or Ap horizons were also selected from seven saline, non-saline and eluviated profiles representing three different soil orders (Chernozemic, Gleysolic and Luvisolic). Carbonate concretions were also selected from some deep till samples. All carbonate samples were selected with the aid of a binocular microscope. For comparison purposes, three carbonate pebbles, approximately 2.5 cm in diameter, were selected from most of the above mentioned horizons. The pebbles were broken and the fresh interior parts of the pebbles were used for mineralogical analysis. This step was taken in order to see if there was any mineralogical relationship between the soil concretions and carbonate pebbles from the same horizon. Samples of calcite and dolomite, obtained from the Department of Earth Sciences (University of Manitoba), served as working standards for despacing calibrations. Pure fluorite powder was used as an internal standard for the carbonate pebbles and quartz was used as an internal standard for calcite and dolomite in the soil concretion samples. The soil concretions samples, pebbles with fluorite, and working standards of calcite and dolomite were crushed separately to fine powder and

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[15] Local concentration of calcium carbonate in the form of grain or nodule of varying size, shape, hardness, and color (U.S. Soil Sci. Soc., 1973).

X-ray slides for them were made with the aid of ethanol.

X-ray diffractograms of the samples were obtained using the Phillips X-ray unit with Co Kα radiation and a scanning rate of 0.125°/min as suggested by St. Arnaud and Herbillon (1973). The shift of the d211(104) peak of calcite in the soil concretions and pebble diffractograms was compared with the working standard, and on the basis of the relationship between diffraction angles and Mg contents established by Goldsmith and Graf (1958) (Figure 22), the mole percent of $MgCO_3$ in $CaCO_3$ was obtained for all the samples. The area under the calcitic and dolomitic peaks of the diffractograms was determined with a compensating planimeter Type KP-23 in order to determine the calcite-total carbonate ratio.

5.1.4 Micromorphological Analysis

Sampling Procedure

The sampling was done by the use of stainless steel rings of 5 cm diameter and 5 cm height or directly using undisturbed soil peds approximately 5x5x5 cm. The rings were pressed into the pit wall at each horizon and the cores were cut out carefully from the wall with a knife when they were almost filled. Forty-one undisturbed samples were obtained representing the soil horizons of Profiles 1, 2, 3, and 6, Site 1 and Profiles 1 and 2, Site 2.

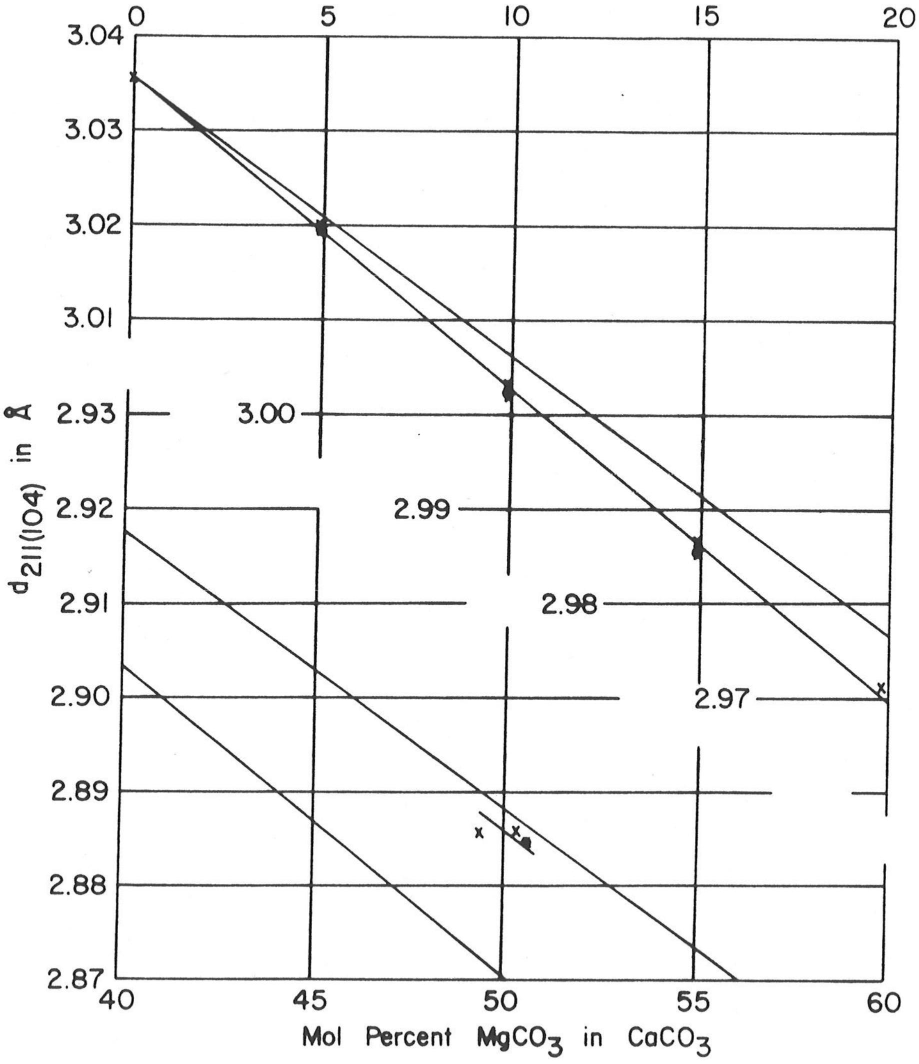

Figure. 22 Variation of $d_{211(104)}$ for the Ca-Mg Carbonates. Crosses Indicate Measurements Made With the X-ray Diffractometer. The Small Dot is the Literature Value for Calcite. The Straight Line Through the Plotted Points was Computed From the Analogous a_0 and c_0 Lines in Figs. 2 and 3 (after Goldsmith *et al.*, 1958).

Preparation of Thin Sections

After air-drying the undisturbed soil samples, the samples were trimmed to an approximate size of 30x25x25 mm. The clods were placed in 150 mL size aluminum foil cups and the horizon and orientation of the samples were marked on the cups. The samples were then placed in a vacuum desiccator similar to a part of the vacuum impregnation apparatus used by Brewer (1964). A liquid nitrogen container connected to a vapour trap jar was added in order to condense most of the vapours and gases. After preparing the epoxy resin and hardener (Epo-Tek 301) using a ratio of 3 to 1 by volume, the mixture was placed in 50 mL container, and transferred immediately to the separatory funnel which had been fitted to the desiccator. The epoxy mixture was added slowly to the sample under vacuum until the samples were completely covered. The samples were maintained under vacuum until impregnation appeared complete (about 15 min), as evidenced by the absence of bubbling. The vacuum was released slowly and the samples were removed and placed in a cold water bath to slow down the reaction and remove the resultant heat.

After their polymerization and hardening was almost complete, which takes about 24 hr, the samples were cut into two equal parts. One was kept in reserve and from the other a slice of 30x20x3 mm was cut by diamond saw and examined carefully for good impregnation.

This slice was ground and polished using different textural grades of silicon carbide (grade 220, 400 and 1200) on a square glass plate (30x30x0.4 cm) and an electrical grinder polisher and the polished section was mounted on a slide (26x45x1 mm) by using epoxy cement and two "Bulldog" paper clamps to hold the soil section firmly in place. After setting of the epoxy, which takes about 24 hr, the next stage was the grinding of the unmounted side of the section until the appearance of the greyish colour under the polarizing microscope, which is characteristic of the first order of the quartz grains. This stage was carried out with a diamond disk grinder and manually by the use of the square glass plate and different grades of silicon carbide powder. For all the procedures of cutting, grinding, polishing, and cleaning, kerosene was used for cooling and lubrication. Finally, the thin section was cleaned, using an ultrasonic cleaner then covered with a cover slip and labelled.

Description and Interpretation Methods

The micromorphological description and interpretation were carried out according to:

-Babel, U. (1964) for the description and classification of organic matter and humus forms,

-Beckman, W. and Geyger, E. (1967) for the description of aggregates and structures,

-Brewer, R. (1964) for the description and classification of voids, plasmic fabric of organic poor surface and subsurface horizons, pedological features,

-Brewer, R. and Pawluk, S. (1975) for the classification of plasmic fabric of organic-rich surface horizons,

-Brewer, R. (1972) for the interpretation of the micromorphological data, and

-Stoops, G. and Jongerius, A. (1975) for the classification of the related distribution of the fine and coarse particles.

5.1.5 Sub-Micromorphological Analysis

The application of SEM[16] technique was done essentially to identify: (1) the clay mineral arrangement especially in Bt and BC horizons; (2) neoformed crystallized minerals, mainly evaporites such as gypsum and carbonates such as calcites; and (3) to study the plasmic fabric and pedological features of calcareous and non-calcareous A, B and C horizons from different profiles of Sites 1 and 2. Sixteen undisturbed samples representing 16 soil horizons (Ah, Ahk, AC, ACk, Bmks, Bt, Btg, Ccas, Ck and Ckg) were selected after careful study was made with a binocular microscope to identify the features to be studied. The selected peds were mounted on small metal stubs with silver dag suspension and coated by thin films of carbon and gold, respectively and finally electron micrographs were taken with magnificaiton varying from about 100X to 10,000X.

5.2 Groundwater Analysis

5.2.1 Groundwater Chemistry

Using the same methods of analysis previously used for saturated soil extracts, electrical conductivity (ECw), soil reaction (pH), anion, and cation determinations were made on the ground water samples.

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[16] Scanning Electron Microscope.

5.2.2 Groundwater Depth

Depth of water in the piezometers and wells was determined by the aid of stiff tygon tube (6 mm diameter) calibrated in units of 1 cm. The tube was inserted into the wells or piezometers while air was forced through the tube. Detection of a bubbling noise indicated when groundwater contact had been made and the depth was then read directly at the top of piezometer or well.

5.2.3 Groundwater Sampling

Water samples from each well were collected nine times in 1979 (two samples) and 1980 (seven samples). The sampling method which proved to be practical consisted of using the stiff tygon tube. The tube was inserted into the well and water was drawn up into the tube by a vacuum which was applied by mouth to the top end of the tube. Sufficient vacuum was applied to raise the level of water in the tube 3 to 5 m above the initial water level in the well. The tube was then removed from the well and 100 to 200 mL samples were placed in glass bottles for chemical analysis.

5.2.4 Estimation of Hydraulic Heads in the Unsaturated Zones

The estimation of total heads along the soil transects were done in three steps: (A) by estimating that the moisture contents at 50 cm depth were less than field capacity in the area where the crops were actively growing, and water table level was ranging between 150-450 cm (B) by converting the moisture content to moisture tension, then the moisture tension to pressure heads expressed as heights of water (i.e.

1/3 atmosphere = 344 cm of water); and (C) by summation of the pressure head values and the corresponding elevation head values, the total head values were calculated which gave an estimate of the maximum hydraulic heads at the measuring sites.

5.2.5 Interpretation of Hydraulic Head Data

The hydraulic head data (Table 14, page 173) were interpreted based on the analysis and procedures developed by Meyboom (1966), Freeze and Witherspoon (1968), and Freeze and Cherry (1979). The vertical direction of groundwater flow was determined by comparing the hydraulic heads of piezometers in each nest. The horizontal direction of groundwater flow was determined by comparing water level differences between piezometer nests.

6. RESULTS AND DISCUSSION

The data in this Chapter are discussed under headings which relate to a specific property or set of properties. In Chapter 7, a more general discussion is presented in which all the data obtained in the study is interrelated to achieve a better overall assessment of the objectives of the study. To follow the locations of profiles, wells, piezometers and thermocouples in the studied sites, see Figure 9, p. 57.

6.1 Physical and Chemical Properties of Soil in the Study Area

Physical-chemical properties of Profiles 1, 2, 3, and 6, Site 1, and Profiles 1, 2, and 3, Site 2, are presented in Tables 3 to 10 pages 98 to 105, and Tables 16 to 22 in Appendix D, pages 238 to 244, and in Figures 23 to 30 pages 106 to 113. Some data on samples of glacial materials, taken from greater depths (2 to 6 m) at most soil profile sampling sites are presented at the bottom of Tables 3 to 10, pages 98 to 105 under the heading Underlying Glacial Drift.

The C horizons of all soil profiles fall into the same textural classes, namely loam to clay loam. This suggests that all soils developed on similar parent material. The carbonate contents and calcite/dolomite ratios also support this conclusion. The color of the till at about 3 m changes from brown to dark gray. The dark gray till is more compact than movement of clay from the surface horizon and the formation of an argillic (Bt) horizon as described in Soil Taxonomy (U.S.D.A., 1975; page 93) are met. Some of the conditions are: (1) removal of soluble salts and carbonates from A and B horizons, (2) the drying out of the soil and subsequent rewetting which leads to the dispersion of clay, and (3) the passage of sufficient water through the soil to move the dispersed clay. Profile 2, Site 1 (Orthic Black) also exhibits an argillic horizon but less developed than in the two previously discussed soil profiles. This profile which occurs in the upper slope position is leached of soluble salts and carbonate and is in a topographic position such that considerable water moves through the soil, thus resulting in clay movement.

The soils that occur in the saline ring (Profile 1, Site 1 Rego Black, Saline phase ; and Profile 2, Site 2 ; Gleyed Calcareous Black, Saline phase) and at the edge of the slough Profile 6, Site 1 Rego Humic Gleysol) show little or no clay movement. This is to be expected in soils in which soluble salts and carbonate are not leached out.

It is interesting to speculate as to why Profile 3, Site 2 (Rego Humic Gleysol), which occurs in a large low depression, shows no evidence of clay movement. In this topographic position, considerable water ponds in the spring as a result of snow melt and much of this water infiltrates and reaches the water table in the spring and early summer (see discussion on groundwater fluctuation, page 146), but apparently all the conditions required for clay movement are not met. One of these is probably the lack of complete drying out of the soil profile because of a relatively high water table throughout the year.

6.1.3 Electrical Conductivity and Extractable Salts

On the basis of the electrical conductivity values of profile and underlying glacial till samples (Figures 23, 26 and 27, pages 106; 109 and 110 and Tables 16 to 22; Appendix D , p.237) the following grouping is made:

(1) Non-saline soils: include the soils of upper depressions, (Profile 3, Site 1 "Gleyed Dark Gray Luvisol" and Profile 1, Site 2 "Humic Luvic Gleysol"), knoll and mid slope soils (Profile 2, Site 1 "Orthic Black"), slough edge soil (Profile 6, Site 1 "Rego Black"), and the soil of lower depressions (Profile 3, Site 2 "Rego Humic Gleysol"). The EC_e values for these soils is less than **2.0 mS/cm and in** some profiles less than o.2 mS/cm. In Site 2 the soils in the upper depressions (Profile 1 "Humic Luvic Gleysol") are characterized by a low salinity (around 0.5 mS/cm) to a depth of 4.0 m and then increase to 2 mS/cm in the dark gray till. These low values of EC_e for these soils are not unusual since they are highly leached and eluviated. The soils in the knoll and mid slope positions (e.g. Profile 2, Site 1 "Orthic Black") are similar to the previous soil group (i.e. upper depressional soils) except the leaching depth is shallower. The soils at the slough edge (Profile 6, Site 1 "Rego Black") are characterized by a low salinity at depth which is probably due to influence of relatively fresh water from or nearby the slough.

The soils at lower depressions (Profile 3, Site 2 "Rego Humic Gleysol") are leached throughout their depth. However, the relative increase in salinity at the surface of the last two groups of soils were consistent with some upward movement of soil moisture and consequent accumulation of salts.

(2) Saline: in the soils of the saline ring (Profile 1, Site 1 "Rego Black, saline phase" and Profile 2, Site 2 "Gleyed Calcareous Black, saline phase") the EC_e in the first 50 cm is 3.9 to 4.9 mS/cm for Profile 1 and 5.2 to 7.1 mS/cm for Profile 2. Moreover, the highest salinity is found in the lower part of surface horizons (e.g. Aps of Profile 2, Site 2 "Gleyed Calcareous Black, saline phase"). This accumulation of salt in the upper 50 cm salinity can probably be attributed to upward movement of saline groundwater (Table 31, p.288) during the dry summer period. It is interesting to note that the dark gray till has EC_e values of about 3 mS/cm which is considerably higher than what is found in the brown till. The reason for the different salt levels is not apparent at this time.

In the soil horizon extracts, SO_4^{--} and HCO_3^- are the dominant anions and Ca^{++} and Mg^{++} are the dominant cations in almost all the profiles. Furthermore, in the soils of upper depressions and at the slough edge, HCO_3^- is the dominant anion to about 4 m and beyond 4 m SO_4^{--} becomes the dominant anion. Under the knoll and mid slope position (Well 12, Site 2), HCO_3^- is dominant in the till material to the depth of 6 m, while Profile 2, Site 1 (Orthic Black) is characterized by

HCO_3^- as dominant anion in the upper 80 cm followed by SO_4^{--} domination until 7 m. These results could be explained by a deeper leaching depth for soluble salts in the position of Well 12 compared with Profile 2, Site 1 (Orthic Black).

On the other hand, the salt ring soils and underlying till are characterized by SO_4^- salinity at 3 m depth and deeper and the upper 1.2 m which probably is of secondary origin (upward movement of groundwater). Similarly, the deep till samples of Well 13, Site 2 are characterized by sulfate salinity.

From the other side of ionic spectrum, the dominance of either Mg^{++} or Ca^{++} has been found to be related to the leaching stage of the profile such that Ca^{++} appear to be dominant in the most leached and/or eluviated profiles (e.g. upper depressional, knoll and mid slope, slough edge and lower depressional profiles) and underlying second till, while Mg^{++} dominates in the least leached ones (i.e. salt ring profiles). These findings could be related also to the limited solubility of $CaSO_4$ in the saline horizons and the dissolution of $CaCO_3$ in the leached profiles.

From the above discussion of ionic distribution in the horizons, one can conclude that: in the non-saline profiles (Profile 3, Site 1), the dominant cations are Ca^{++} followed by Mg^{++} and anions are HCO_3^- followed by SO_4^-, while in the saline profiles (Profile 1, Site 1 and Profile 2, Site 2) the dominant cations are Mg^{++} followed by Ca^{++} and anions are SO_4^{--} followed by HCO_3^-.

6.1.4 pH (soil reaction)

The pH values of mineral soil horizons and underlying glacial till samples range between 7.4 and 8.6, depending mainly on the $CaCO_3$ content and PCO_2 in the soil horizons or underlying materials.

6.1.5 Organic Carbon Content (for the profiles of Site 1 only)

Organic carbon % decreases with depth which is a normal distribution pattern. Organic carbon content ranges from 7.7% in the Ah of Profile 6 to nil in most of the Ck horizons.

6.1.6 Cation Exchange Capacity (for the profiles of Site 1 only)

The C.E.C. values generally decrease with depth ranging from 44.4 meq/100 g in the Ah horizon of Profile 6 to 7.5 meq/100 g in the Ae horizon of Profile 3. The decrease can be attributed mainly to organic matter and clay content which are related linearly to the cation exchange capacity.

TABLE 3. Physical and chemical characteristics of Profile 1, Site 1 (Rego Black, saline phase).

		Particle Size Distribution (%)														
		Sand 50-2000 µm														
Horizon	Depth cm	V.C.S.	C.S.	M.S.	F.S.	V.F.S.	TS*	Silt 2-50 µm	Clay < 2 µm	Texture U.S.D.A.	% $CaCO_3$ equiv.	% Calcite	% Dolomite	Calcite / Dolomite	% O.C.	C.E.C. meq/100 g
Apks	0- 15	2	4	9	12	11	38	36	26	L	1.10	0.00	1.01	0.00	4.0	33.7
AC	15- 26	2	6	15	12	11	46	27	27	SCL	2.72	1.68	0.96	1.75	1.2	25.9
Cks1	26- 40	1	3	9	17	15	45	20	35	CL	12.05	7.38	4.30	1.72		20.2
Ccas	40- 50	1	1	5	9	14	30	39	31	CL	21.96	17.41	4.19	4.15		17.7
Ckgjs2	50- 60	2	4	10	16	15	47	26	27	SCL	16.94	11.56	4.96	2.33		16.0
Ckgj3	60- 70	3	6	13	18	14	54	27	19	FSL	12.65	8.09	4.20	1.13		13.7
Ckg4	70-100	3	4	7	11	11	36	38	26	L	13.07	9.94	7.50	1.32		19.0
Ckg5	100-115	3	6	10	13	11	43	27	30	CL	14.03	7.52	5.99	1.25		19.5
Ckg6	130-150	3	6	9	11	11	40	34	26	L	14.68	7.98	6.18	1.29		19.1
Ckg7	150-180	2	5	9	12	11	39	35	26	L	15.04	9.25	5.33	1.73		19.6
Underlying glacial drift																
	a 280-320										14.32	5.49	8.14	0.67		
	a 360-400										12.98	4.22	8.07	0.52		
	b 480-520										11.43	4.11	6.74	0.61		

*TS = Total Sand.

a = Brown till; b = Dark gray till.

a,b Samples obtained by deep drilling.

TABLE 4. Physical and chemical characteristics of Profile 2, Site 1 (Orthic Black).

		Particle Size Distribution (%)														
		Sand 50-2000 µm														
Horizon	Depth cm	V.C.S.	C.S.	M.S.	F.S.	V.F.S.	TS[*]	Silt 2-50 µm	Clay <2 µm	Texture U.S.D.A.	% $CaCO_3$ equiv.	% Calcite	% Dolomite	Calcite / Dolomite	% O.C.	C.E.C. meq/100 g
Ap	0- 18	1	4	8	11	11	35	36	29	CL					5.0	35.9
Ahe	18- 30	1	4	8	10	11	34	45	21	L					3.6	28.7
Bt	30- 50	2	3	8	9	7	29	35	36	CL					1.1	29.6
BC	50- 60	4	4	7	9	9	33	35	32	CL	3.85	1.11	2.52	0.44	0.8	26.4
Ck1	60- 80	2	3	7	12	13	37	47	16	L	12.07	7.01	4.66	1.50		22.8
Ck2	80-100	2	3	7	11	11	34	34	32	CL	16.94	11.90	4.65	2.56		20.4
Ck3	100-125	2	5	8	10	11	36	37	37	L	15.91	10.41	5.06	2.06		20.6
Ck4	125-150	3	5	8	12	12	40	34	26	L	14.31	9.26	4.65	1.99		20.8
Underlying glacial drift																
	[c] 200-240										17.96	6.65	10.17	0.65		
	[c] 280-320										12.34	3.05	8.56	0.36		
	[c] 360-400										13.48	3.57	9.13	0.39		
	[c] 480-520										12.82	4.71	7.48	0.63		
	[c] 560-600										12.34	4.27	7.44	0.57		
	[b] 640-680										13.33	5.33	7.37	0.72		

[*] TS = Total Sand.

b = Dark gray till; c = Stratified material.

b,c Samples obtained by deep drilling.

TABLE 5 . Physical and chemical characteristics of Profile 3, Site 1 (Gleyed Dark Gray Luvisol).

Horizon	Depth cm	Particle Size Distribution (%)								Texture U.S.D.A.	% CaCO$_3$ equiv.	% Calcite	% Dolomite	Calcite / Dolomite	% O.C.	C.E.C. meq/100 g
		Sand 50-2000 µm						Silt 2-50 µm	Clay <2 µm							
		V.C.S.	C.S.	M.S.	F.S.	V.F.S.	TS*									
Ap	0- 20	1	3	6	8	8	26	49	25	L					4.9	33.6
Ahe	20- 28	3	7	14	20	15	59	21	20	SL					4.0	24.4
Aeg	28- 43	0	0	1	30	13	44	44	12	L					0.6	7.5
Btgl	43- 63	1	4	7	8	6	26	26	48	C					0.8	30.7
Bt2	63- 83	1	3	6	8	6	24	36	40	C					0.8	33.1
Bt3	83- 93	1	3	6	9	7	26	34	40	C					0.9	29.6
Btj4	93-115	2	5	7	8	9	31	34	35	CL					0.7	29.8
BC1	115-135	2	5	9	12	11	39	32	29	CL	6.33	1.85	4.12	0.45	0.6	25.7
BC2	135-155	1	4	9	14	13	41	31	28	CL	10.17	4.82	4.93	0.98	0.3	20.0
Ckgl	155-180	2	5	9	13	12	41	29	30	CL	12.15	6.47	5.23	1.24		22.1
Ckg2	180-240	2	4	7	15	13	41	27	32	CL	13.03	7.34	5.24	1.40		19.6
Ckg3	240-260	4	6	10	14	11	45	34	21	L	13.95	9.25	4.33	2.14		16.8

*TS = Total Sand.

TABLE 6. Physical and chemical characteristics of Profile 6, Site 1 (Rego Black).

		Particle Size Distribution (%)														
		Sand 50-2000 µm														
Horizon	Depth cm	V.C.S.	C.S.	M.S.	F.S.	V.F.S.	TS*	Silt 2-50 µm	Clay < 2 µm	Texture U.S.D.A.	% $CaCO_3$ equiv.	% Calcite	% Dolomite	Calcite / Dolomite	% O.C.	C.E.C. meq/100 g
Ah	0- 8	2	4	4	6	8	24	43	33	CL	0.00	0.00	0.00	0.00	7.7	44.3
Ahk1	8- 28	2	5	8	10	8	33	36	31	CL	2.56	0.00	2.36	0.00	6.2	39.2
Ahk2	28- 48	2	4	9	11	10	36	32	32	CL	2.32	0.00	2.14	0.00	5.2	40.1
AC	48- 64	3	5	11	13	10	42	26	32	CL	16.34	13.06	2.32	5.63	1.3	21.8
Ccag	64- 90	4	6	12	16	19	57	35	8	SL	24.85	20.71	4.51	4.59		17.0
Underlying glacial drift																
	a 240-270										16.56	5.62	10.07	0.56		
	a 270-300										15.94	5.68	9.45	0.60		

*TS = Total Sand.

a = Brown till samples obtained by deep drilling.

TABLE 7. Physical and chemical characteristics of Profile 1, Site 2(Humic Luvic Gleysol).

		Particle Size Distribution (%)														
		Sand 50-2000 µm														
Horizon	Depth cm	V.C.S.	C.S.	M.S.	F.S.	V.F.S.	TS*	Silt 2-50 µm	Clay < 2 µm	Texture U.S.D.A.	% $CaCO_3$ equiv.	% Calcite	% Dolomite	Calcite / Dolomite	% O.C.	C.E.C. meq/100 g
Ahe	0- 14	0	1	2	3	6	12	52	36	SiCL						
Aeg	14- 26	2	4	6	7	10	29	56	15	Sil						
AB	26- 34	2	4	7	10	10	33	27	40	CL						
Btg1	34- 54	1	4	9	12	12	38	23	39	CL						
Btg2	54- 72	1	4	9	13	13	40	8	52	C						
BC	72- 92	2	5	8	11	15	41	21	38	CL	9.99	3.82	5.68	0.67		
Ckg1	92-132	3	5	9	11	15	43	35	22	L	20.54	9.99	9.72	1.03		
Underlying glacial drift																
a	132-292	5	6	9	12	11	43	25	32	CL	17.22	8.08	8.42	0.96		
b	292-348	4	5	8	11	16	44	33	23	L	15.63	7.25	7.72	0.94		
b	400-500	5	6	10	14	12	47	31	22	L	17.37	8.13	8.52	0.95		

*TS = Total Sand.

a = Brown till; b = Dark gray till.

a,b Samples obtained by deep drilling.

TABLE 8. Physical and chemical characteristics of Profile 2, Site 2 (Gleyed Black, saline phase).

Horizon	Depth cm	Particle Size Distribution (%)								Texture U.S.D.A.	% $CaCO_3$ equiv.	% Calcite	% Dolomite	Calcite / Dolomite	% O.C.	C.E.C. meq/100 g
		Sand 50-2000 μm						Silt 2-50 μm	Clay < 2 μm							
		V.C.S.	C.S.	M.S.	F.S.	V.F.S.	TS*									
Apks	0- 6	2	3	7	9	12	33	36	31	CL	trace					
Aps	6- 15	2	3	7	9	12	33	37	30	CL						
Ahs	15- 30	2	4	8	9	9	32	36	32	CL						
Bmks	30- 48	3	6	10	11	10	40	25	35	CL	trace					
Ckgjs1	48- 58	5	7	12	14	14	52	22	26	SCL	2.88	0.0	2.66	0.0		
Ckgjs2	58- 88	2	4	8	12	12	38	37	25	L	16.76	8.53	7.58	1.12		
Ckgjs3	88-100	2	4	8	12	15	41	36	23	L	22.49	12.42	9.28	1.34		
Underlying glacial drift																
	a 100-120										21.0	12.9	7.5	1.72		
	a 120-145										18.1	8.9	8.5	1.05		
	a 145-170										17.0	8.0	8.3	0.96		
	a 170-200										17.4	7.3	9.2	0.79		
	a 250-300										15.8	6.2	8.8	0.70		
	b 360-385										14.5	4.5	9.2	0.49		
	b 385-405										15.2	5.0	9.4	0.53		

*TS = Total Sand.

a = Brown till; b = Dark gray till.

a,b Samples obtained by deep drilling.

TABLE 9. Physical and chemical characteristics of Profile 3, Site 2 (Rego Humic Gleysol).

Horizon	Depth cm	Particle Size Distribution (%)								Texture U.S.D.A.	% $CaCO_3$ equiv.	% Calcite	% Dolomite	Calcite/Dolomite	% O.C.	C.E.C. meq/100 g
		Sand 50-2000 µm						Silt 2-50 µm	Clay < 2 µm							
		V.C.S.	C.S.	M.S.	F.S.	V.F.S.	TS*									
Ah1	0- 5	1	2	3	6	6	18	47	33	SiCL						
Ah2	5- 25	1	2	6	6	7	22	45	33	CL						
Ahk	25- 50	1	2	5	5	5	18	36	46	C	1.75	0.0	1.61	0.0		
AC	50- 77	1	1	3	3	6	14	46	40	SiCL	6.09	2.92	2.99	0.98		
Ckg1	77- 90	0	1	1	2	6	10	52	38	SiCL	10.90	4.28	6.09	0.70		
Ckg2	90-105	0	1	1	2	10	14	50	36	SiCL	12.59	4.47	7.48	0.60		
Underlying glacial drift																
	a 125-200	3	6	9	13	11	42	36	22	L	14.34	5.17	8.65	0.60		
	b 300-350	5	6	10	12	13	46	33	21	L	16.23	5.52	9.87	0.56		

*TS = Total Sand.

a = Brown till; b = Dark gray till

a,b Samples obtained by deep drilling.

TABLE 10. Chemical characteristics of glacial till samples at Wells 12 and 13, Site 2.

			Soluble Cations meq/L					Soluble anions meq/L								
Depth cm	pH	EC_e mS/cm	Na	K	Ca	Mg	Total	CL	SO_4	CO_3	HCO_3	Total	% $CaCO_3$ equiv.	% Calcite	% Dolomite	$\frac{\text{Calcite}}{\text{Dolomite}}$
Well 12																
a160-200	8.6	0.47	0.61	0.54	1.35	4.03	6.53	0.69	0.71	0.00	2.89	4.29	14.53	6.09	7.77	0.78
a280-320	8.5	0.45	0.43	0.54	1.80	3.37	6.14	0.50	0.71	0.00	2.68	4.10	14.36	6.94	6.83	1.02
a360-400	8.5	0.52	0.61	0.56	3.14	2.47	6.78	1.39	0.58	0.00	3.06	5.03	16.95	7.19	9.00	0.80
b480-520	8.4	0.77	0.74	0.54	3.09	1.81	6.18	0.99	0.44	0.00	2.96	4.39	16.41	6.94	8.72	0.79
b560-600	8.5	0.84	1.26	0.74	6.99	3.70	12.69	0.99	1.80	0.00	2.96	5.75	19.53	6.87	11.66	0.59
Well 13																
a200-240	8.2	3.80	4.56	0.87	23.95	40.30	69.68	0.79	69.21	0.00	2.67	72.67	15.78	5.05	9.89	0.51
a280-320	8.2	3.25	3.22	0.84	22.95	30.43	57.44	0.79	58.45	0.00	2.77	62.01	17.18	5.08	11.16	0.45
a360-400	8.3	3.05	3.09	1.10	20.96	29.60	54.75	0.79	53.65	0.00	2.77	57.21	16.88	4.89	11.05	0.44
b480-520	8.2	2.85	2.43	1.18	23.95	19.74	47.30	0.99	47.68	0.00	2.68	51.35	16.95	6.01	10.08	0.60

a = Brown till; b = Dark grey till.

a,b Samples obtained by deep drilling.

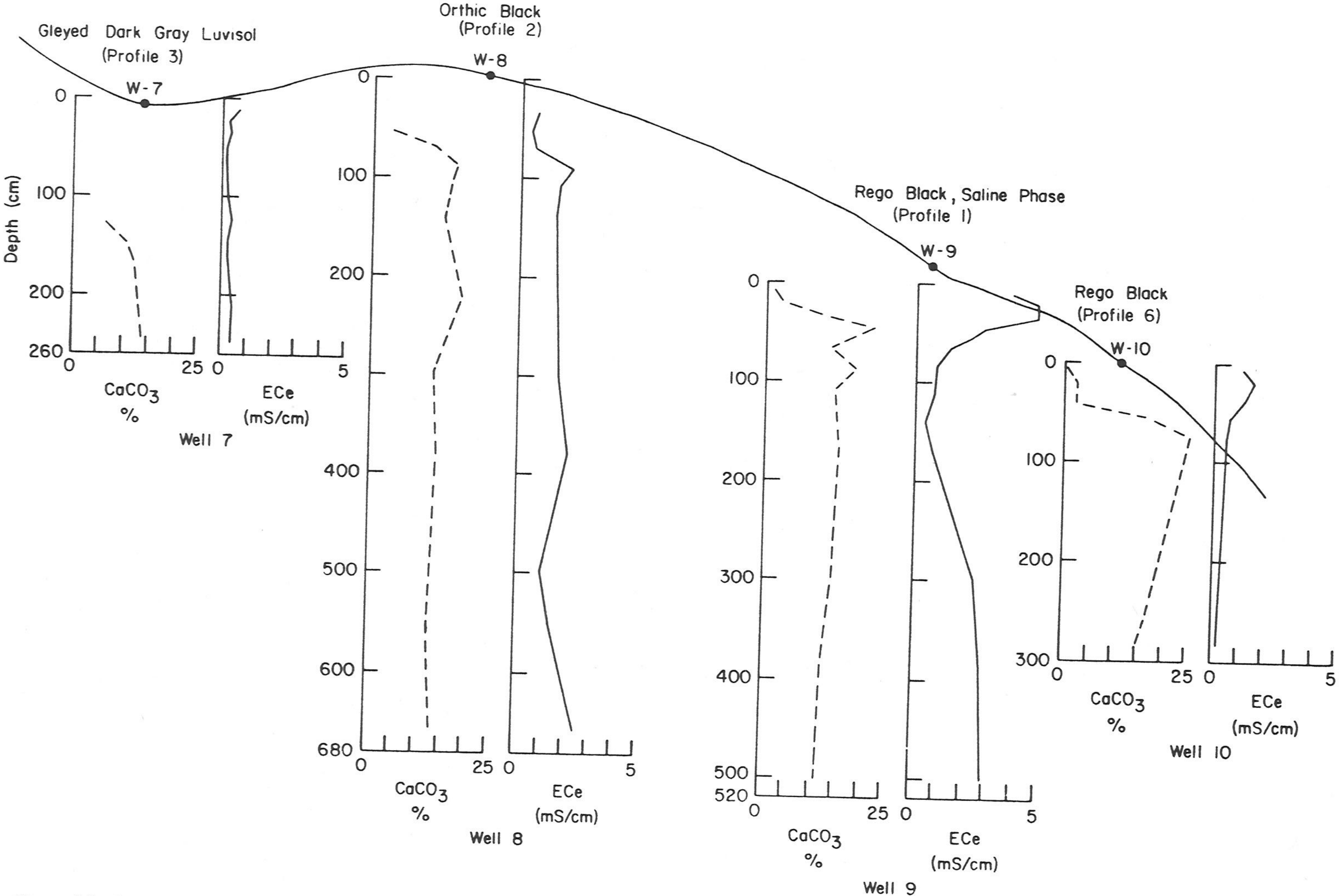


Figure 23 Calcium Carbonate Equivalent and Salinity (ECe) Distribution in Soil and Underlying Glacial Till With Depth Along Transect From Well 7 to 10, Site I.

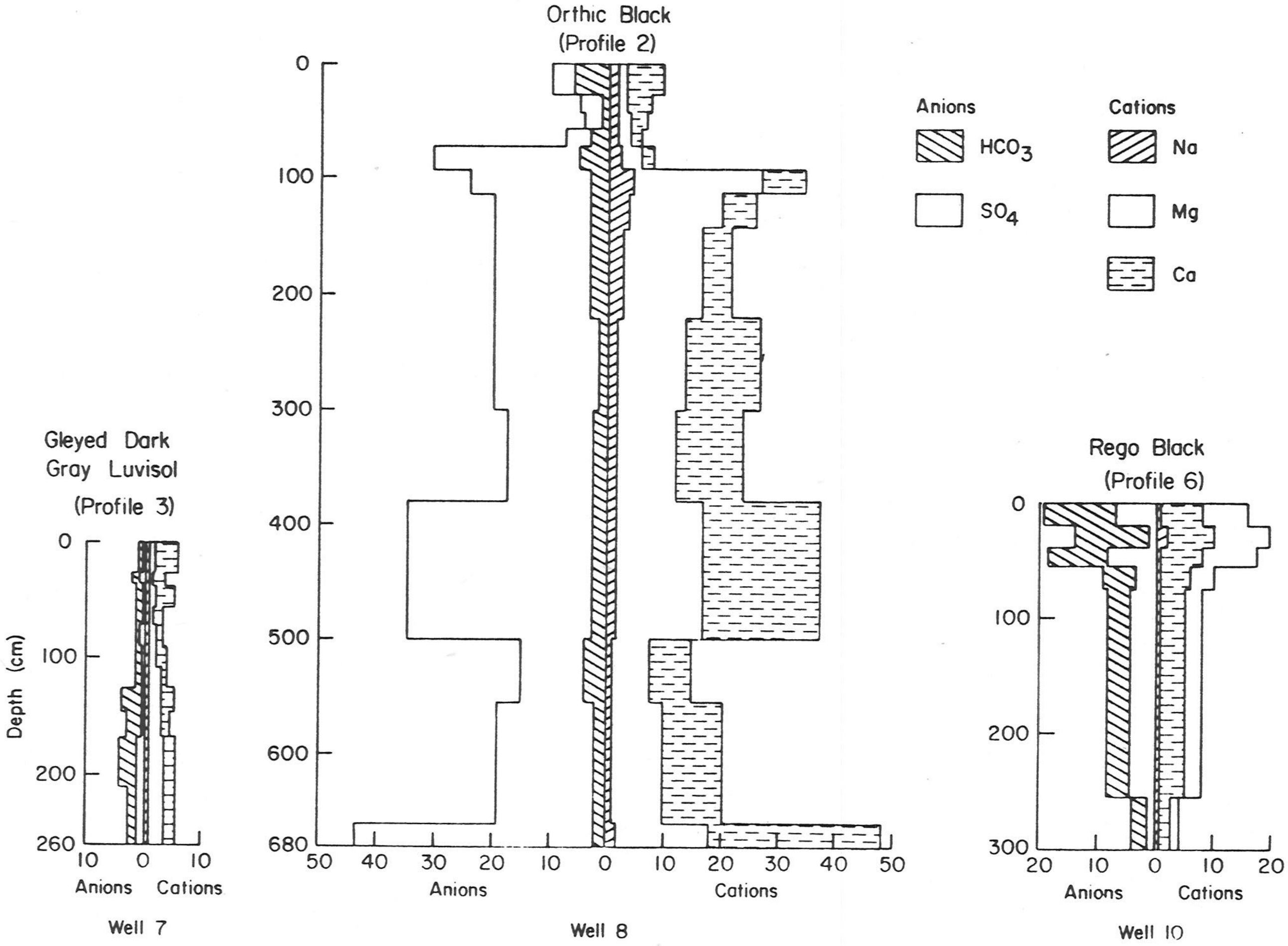


Figure 24 Anion and Cation Distribution (meq/l) in Soils and Underlying Glacial Till With Depth Near Wells 7, 8 and 10, Site 1.

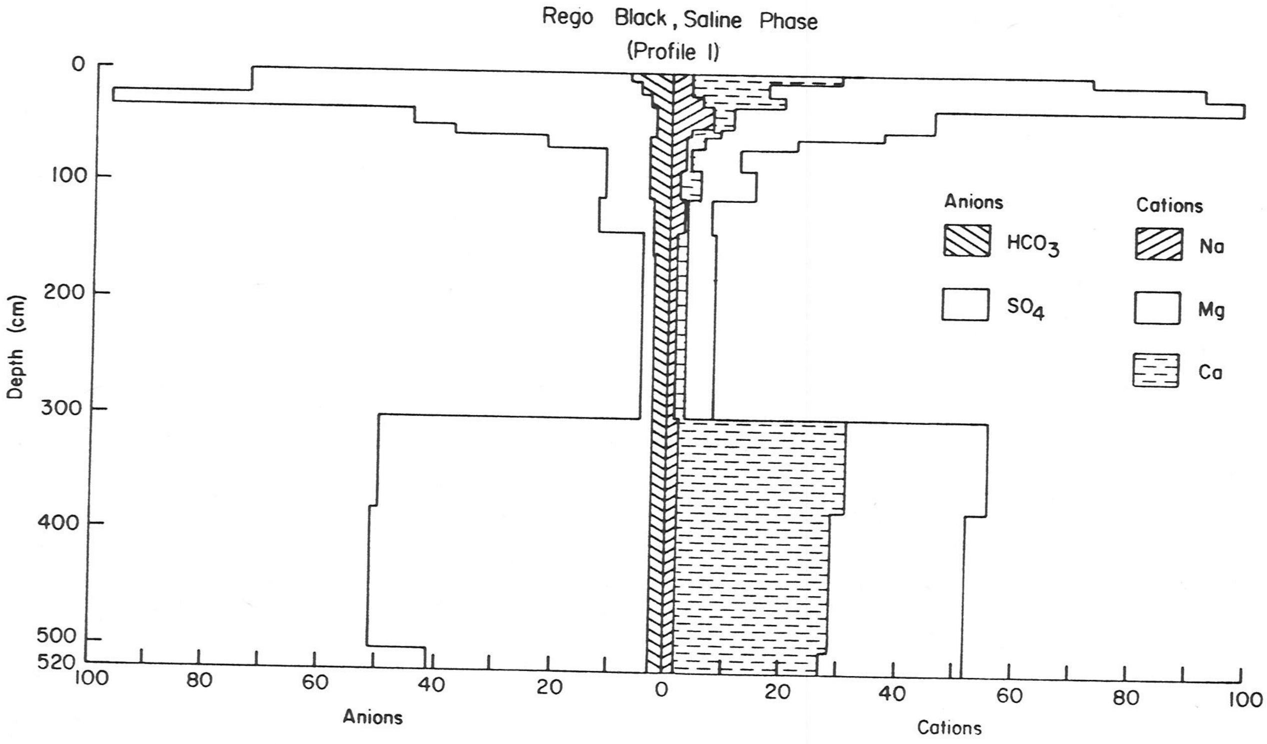


Figure 25 Anion and Cation Distribution (meq/l) in Soil and Underlying Glacial Till With Depth Near Well 9, Site I.

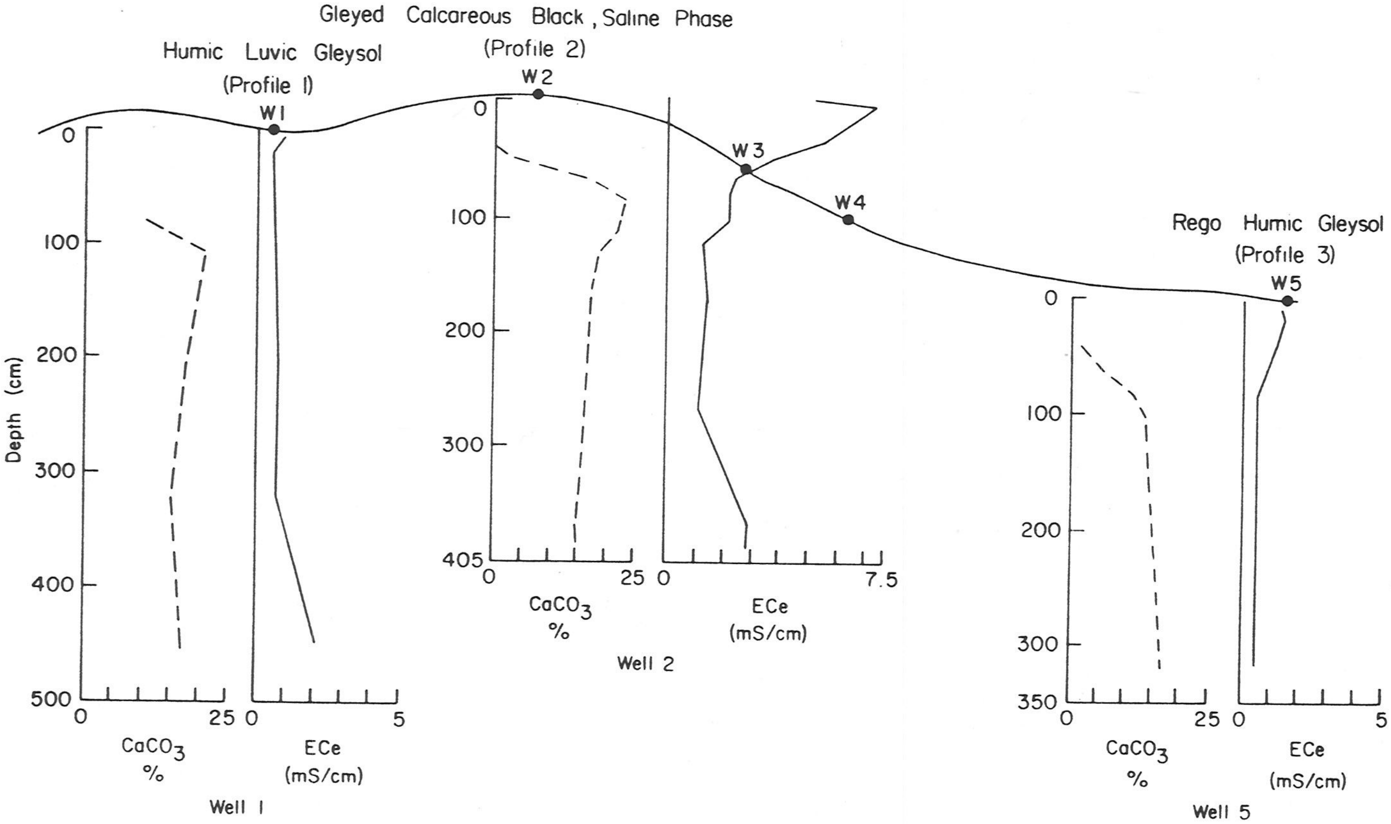


Figure 26 Calcium Carbonate Equivalent and Salinity (ECe) Distribution in Soil and Underlying Glacial Till With Depth Near Well 1 to 5, Site 2.

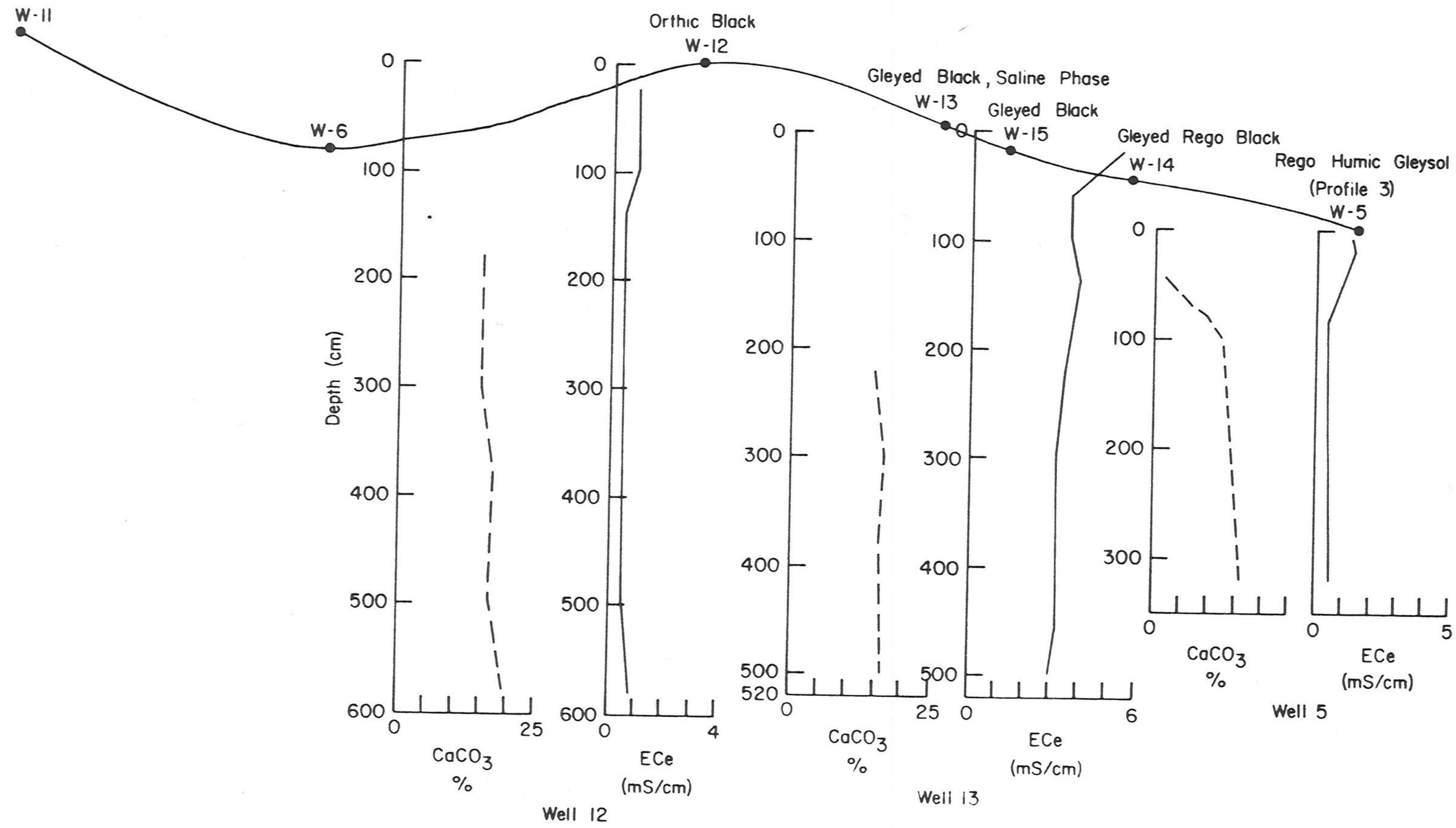


Figure. 27 Calcium Carbonate Equivalent and Salinity (ECe) Distribution in Soil and Underlying Glacial Till With Depth Along Transect From Well 1 to 5, Site 2.

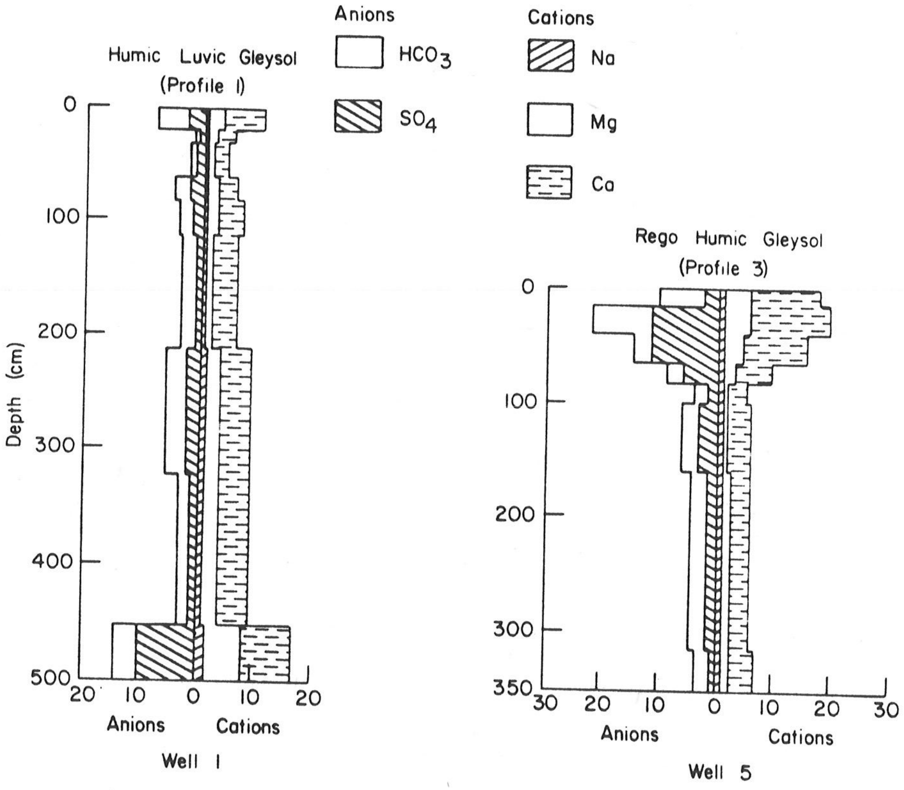
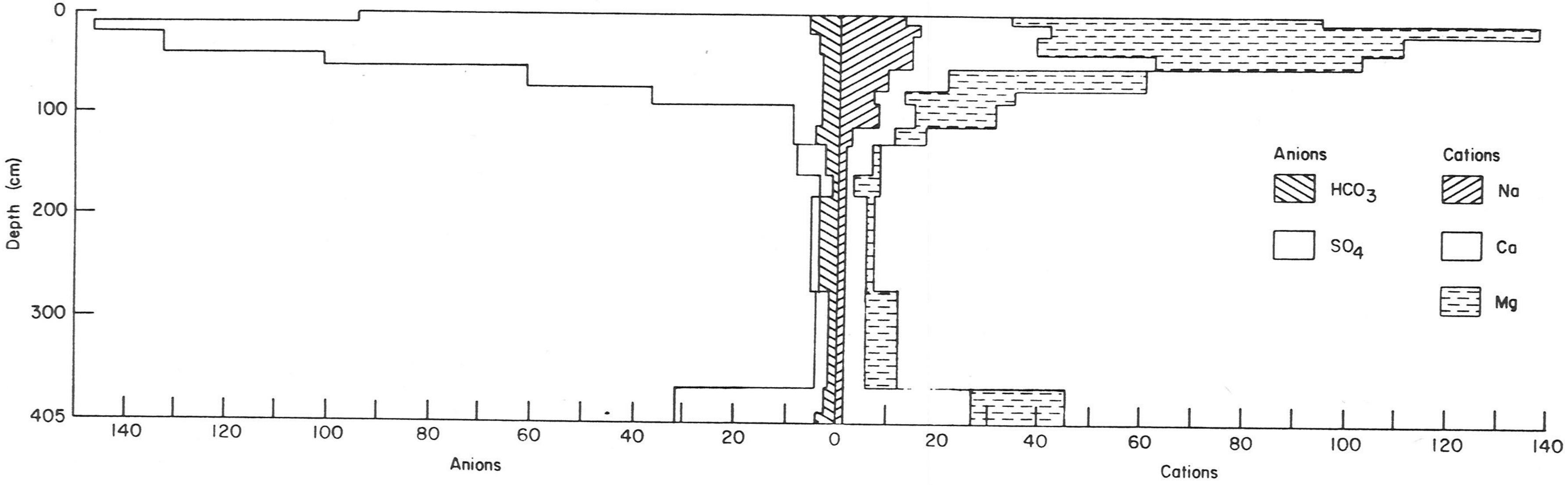


Figure 28 Anion and Cation Distribution (meq/l) in Soils and Underlying Glacial Till With Depth Near Wells 1 and 5, Site 2.



Gleyed Calcareous Black, Saline Phase

(Profile 2)

Figure 29 Anion and Cation Distribution (meq/l) in Soil and Underlying Glacial Till With Depth Near Well 2, Site 2.

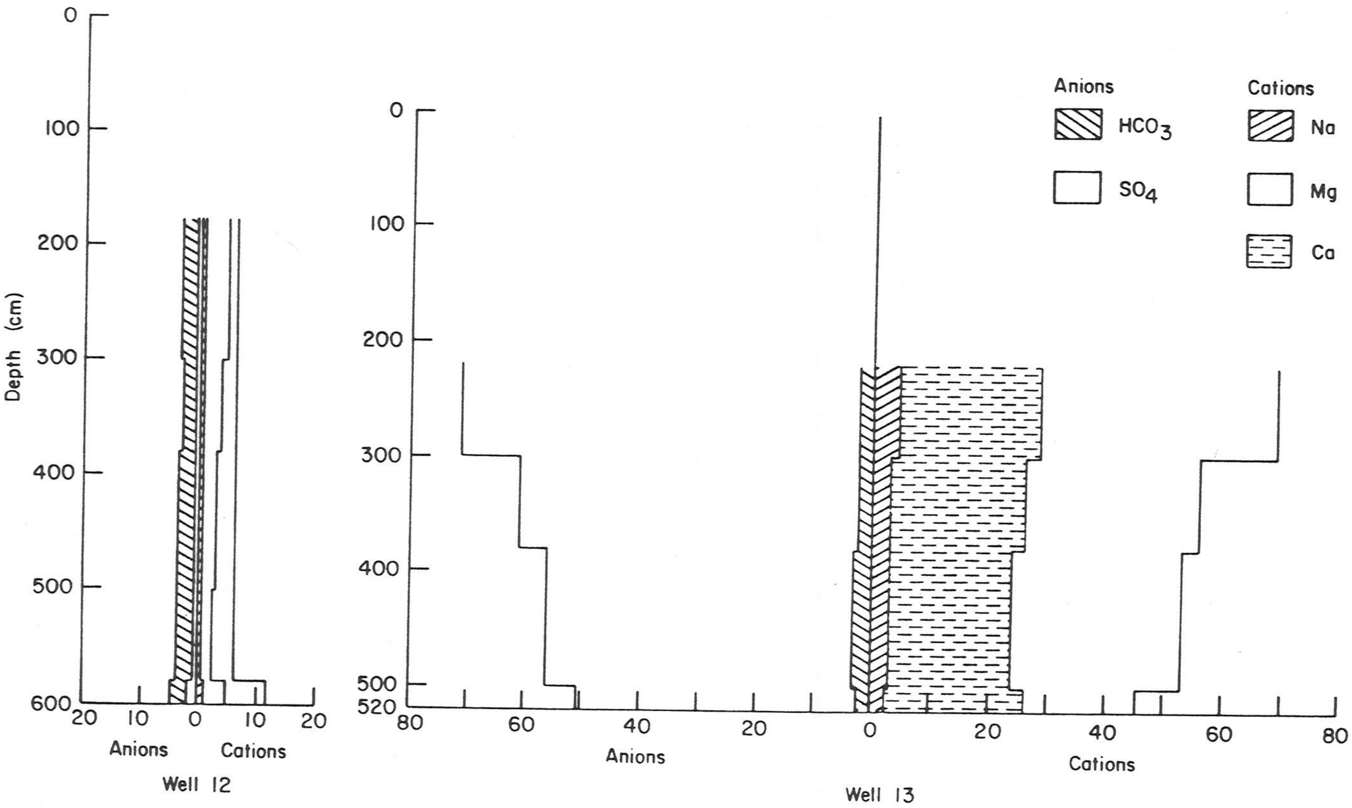


Figure.30 Anion and Cation Distribution (meq/l) in the Glacial Till Below 200 cm, Near Wells 12 and 13, Site 2.

6.2 Mineralogical Properties of the Studied Soil Sequences

6.2.1 Clay Mineralogy of Selected Soil Horizons from Site 1

The mineralogical composition by X-ray diffraction of the fine and coarse clay fractions is summarized in Table 11 and illustrated in Figures 31 and 32.

Coarse Clay Fraction (2 to 0.2 μm)

Montmorillonite (18.0 Å) is found in appreciable amounts in the C horizon of all three profiles which could indicate the initial amount of that mineral in the parent material, while the amount in the A or B horizons is almost negligible, which could indicate the weatherability of this mineral to illite (See Figure 31 for montmorillonite and illite peaks). Illite seems to remain almost constant within and among the profiles. The first and/or second order reflections of Mg-saturated vermiculite (14 and 7 Å) are quite prominent in the B and C horizons and to a lesser extent in the A horizons, which could indicate that vermiculite has a high resistance to weathering processes in the soil profiles. Interstratified layer silicate minerals seem to occur only in small amounts with an irregular manner of stacking. These minerals are characterized by the presence of a first order broad reflection which lies in a position between the reflection of the individual minerals (Jackson, 1956, p.220). Kaolinite is found in low amounts in all soils and is believed to represent the original amount present in the unaltered parent material. Quartz peaks are prominant in all samples whereas only trace amounts of feldspar are present.

Fine Clay Fraction (<0.2 µm)

The principal clay minerals in the fine fraction are montmorillonite and, to a lesser extent, illite. Montmorillonite occurs equally in B and C horizons of all profiles, while illite as well as kaolinite remain relatively constant within and among the profiles. Montmorillonite shows an increase with depth in Profiles 1 (Rego Black, Saline phase) and 3 (Gleyed Dark Gray Luvisol), while interstratified[18] layer minerals show a decrease. Meanwhile, Profile 2 (Orthic Black) is characterized by a steady trend to slight decrease with depth for montmorillonite and interstratified layer minerals. These results could indicate relatively higher weathering in Profiles 1 and 3 than in Profile 2.

Another interesting point to be mentioned arises from a comparison of 18 Å peak on the Mg diffractogram and the 10 Å peak on the K-550 diffractogram. In the A horizons, the 18 Å peaks are much diminished indicating the presence of disordered poorly crystallized partially expanding minerals which are

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[18] Interstratified or mixed layer minerals are clearly characterized mainly by broadened peaks and/or plateaus between 10 and 18 Å (Jackson, 1956; p. 220; Al-Rawi *et al.*, 1969).

TABLE 11. Mineralogical composition of the fine and coarse clay fractions of selected horizons from Site 1.

Profile and horizon	Size of clay fraction	**Mon.	Verm.	Illite	Kao.	Mix.	Qtz.	Fel.
Profile 1 Apks 0- 15 cm	fine	*3	1	3	1	2	T	
	coarse	T	2	3	1	T	4	T
Ccas 40- 50 cm	fine	5	T	2	1	2	T	
	coarse	1	1	2	1	1	4	T
Profile 2 Ahe 18- 30 cm	fine	5	1	2	1	1	T	
	coarse	1	1	3	T	T	5	T
Bt 30- 50 cm	fine	6	T	2	1	1	T	
	coarse	T	2	2	1	1	4	T
Ck2 80-100 cm	fine	6	T	2	1	1	T	
	coarse	1	1	2	1	T	5	T
Profile 3 Ahe 20- 28 cm	fine	4	1	2	1	1	1	
	coarse	T	T	3	1	T	5	T
Aegj 28- 43 cm	fine	4		2	1	2	1	
	coarse	T	1	3	1	T	5	T
Bt1 43- 63 cm	fine	6		2	1	1	T	
	coarse	1	1	2	1	1	4	T
BC 115-135 cm	fine	6		1	1	2	1	
	coarse	1	1	1	1	1	5	T
Ckg2 180-240 cm	fine	5		2	1	1	1	
	coarse	2	1	2	1	T	4	T

*Relative peak intensity scale of 10 for a semi-quantitative examination by the aid of X-ray diffractograms.

**Mon. = montmorillonite; Verm. = vermiculite; Kao = kaolinite; Mix. = mixed layer minerals; Qtz. = quartz; Fel. = feldspar; T = trace.

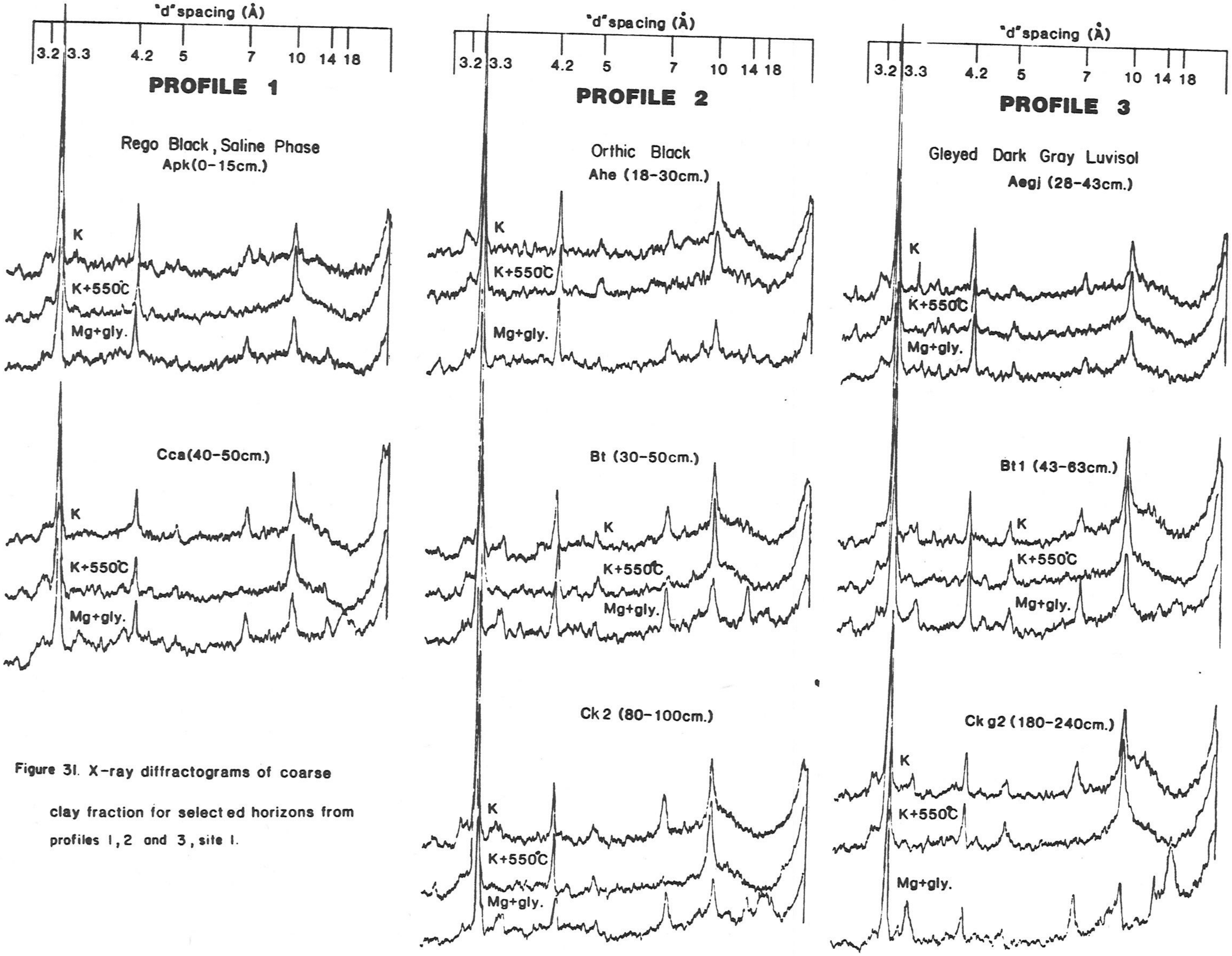

Figure 31. X-ray diffractograms of coarse clay fraction for selected horizons from profiles 1, 2 and 3, site 1.

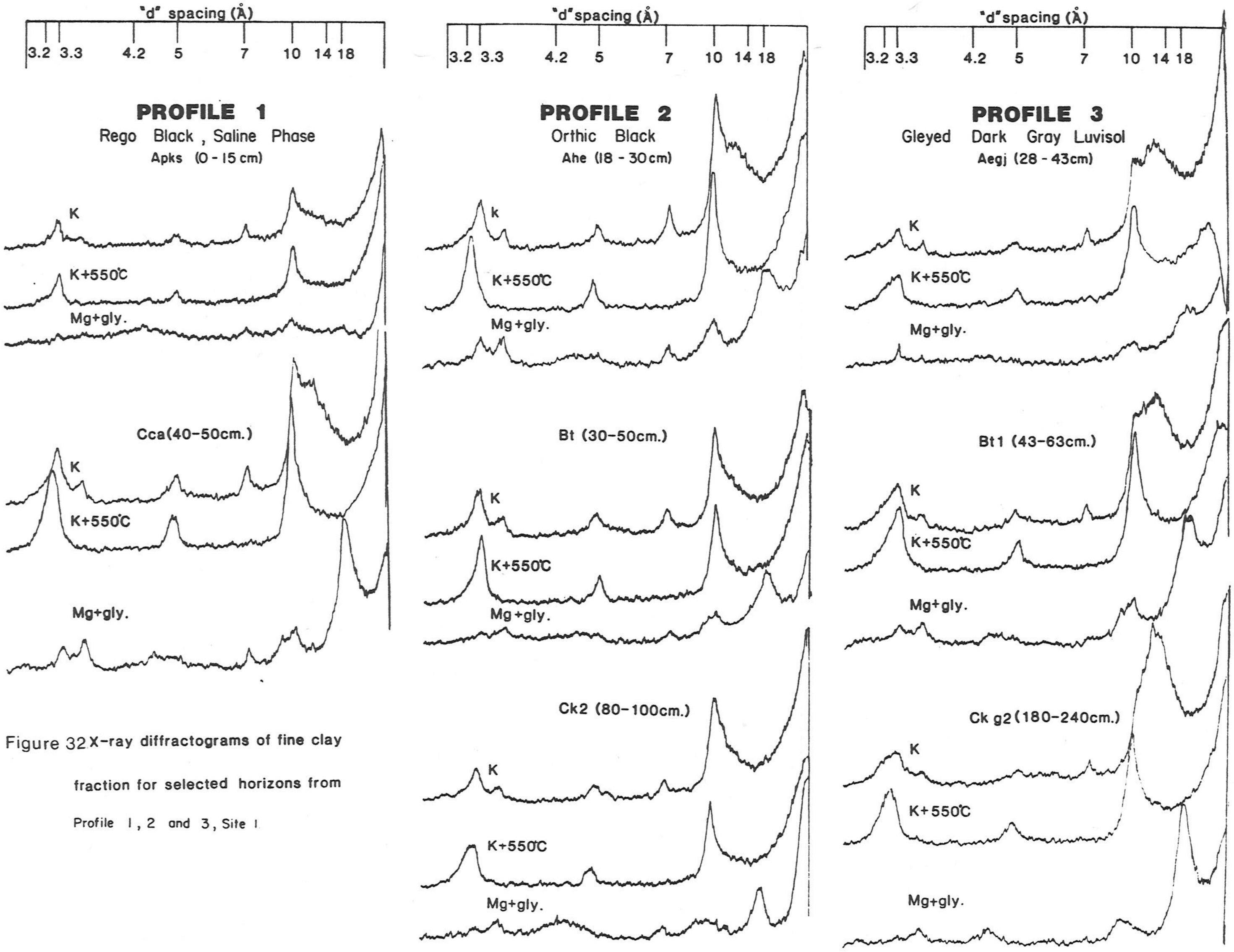

Figure 32 X-ray diffractograms of fine clay fraction for selected horizons from Profile 1, 2 and 3, Site I

probably weathered montmorillonite.

General Discussion on Pedogenesis in Relation to Clay Mineralogy

Dealing with the sequence of studied profiles (Rego Black (Saline phase), Orthic Black, and Gleyed Dark Gray Luvisol), the dominant clay minerals in the coarse and fine fractions are montmorillonite and illite with a ratio around 3:1 in most studied horizons. These findings are similar to those of St. Arnaud and Mortland (1963) who studied the characteristics of clay fractions in a sequence of four soils in Saskatchewan (Orthic Black, Orthic Dark Gray, Dark Gray Wooded and Orthic Gray Wooded) and to those of Beke (1964) who studied the clay mineralogy of Orthic Black, Orthic Dark Gray, and Orthic Gray Wooded soils in north central Manitoba. Preferential illuviation of montmorillonite in the fine clay is indicated in Gleyed Dark Gray Luvisol Soil (see 18 Å peak in Aegj and Btl, "Figure 32"). This was not the case in a comparable soil of the Saskatchewan sequence which suggested to the authors that montmorillonite moves as an interstratified mineral with illite.

Examining the overall picture of clay mineralogy in Profiles 1, 2 and 3, the following conclusion may be drawn: the original mineralogy of the clay in the C horizons is characterized by the dominance of montmorillonite and, to a lesser extent, illite. Profile 1 (Rego Black, Saline phase) shows high alteration of these minerals in the surface horizon as indicated by K-550 diffractograms. This alteration may be related to saline status of the soil and groundwater in this profile with appreciable amount of Na^+. Profile 2 (Orthic Black) shows little pedogenic activity since the mineralogy of the B and C horizons remain almost the same, but there is some increase in layer silicates in the Ahe. Particularly in the fine clay fraction (see 10 Å peak of K + 550°C diffractogram, Figure 32).

As for Profile 3 (Gleyed Dark Gray Luvisol), after the weathering of the parent material has started, it is believed that as a result, montmorillonite decreases in Btl and, to a much higher extent, in Aegj keeping in mind the high amounts of this mineral which have been eluviated from A to B horizon. Moreover, interstratified layer minerals have been formed in A and B horizons as a result of this weathering process.

6.2.2 Mg-Calcite of Soil and Underlying Material Samples

After the examination of X-ray diffractograms of carbonate concretions and pebbles selected from some horizons of the soil profiles and from some underlying glacial till samples (Figures 33 and 34 show representative diffractograms), two aspects of the calcite and dolomite peaks namely the shifting peaks and areas under the peaks were used to determine: (1) mol % $MgCO_3$ in calcite as a measure of Mg-substitution in calcite, and (2) ratio of $\frac{\text{calcite}}{\text{calcite + dolomite}}$.

From the data in Table 12 (page 125) and Tables 23, 24 (Appendix E, p.245), the following observations are made:

(1) although all the samples fall within the low-Mg calcite range of 0 to 8 mol % $MgCO_3$ (Winland, 1969), there is

a fair amount[19] of Mg-calcite (as high as 4.1 mol % $MgCO_3$) to a depth of 60 cm in Profile 1, Site 1; to the 200 cm depth of Profile 2, Site 1 (as high as 1.8 mol % $MgCO_3$); and to the 90 cm depth of Profile 6, Site 1 (as high as 2.4 mol % $MgCO_3$). In Profile 2, Site 2, the Mg-calcite content is the highest among the studied profiles (as high as 4.4 mol % $MgCO_3$) to 400 cm depth, while the samples at Well 13, Site 2 are found to be as high as 1.4 mol % $MgCO_3$ to 80 cm depth. Moreover, there is a significant relation which could be described as linear between Mg content of calcite and salinity (EC_e) on the one hand and soluble Mg^{++}/Ca^{++} on the other (Table 12). These relations are obvious in the salt-affected soils (formed due to upward movement of saline groundwater), except for Profile 6. This may be related to the effect of the fresh water slough nearby. Meanwhile, Profile 3, Site 1 and Profiles 1 and 3 and samples of Well 12, Site 2 are characterized by lower Mg contents (<1 mol % $MgCo_3$) and irregular distribution patterns with depth. Some of these findings are different from those of St. Arnaud (1979). In his study area, the soils are characterized mostly by stronger leaching than the soils in the Hamiota area, plus the salinity is of groundwater origin in the latter area. These characteristics result in deeper accumulation of salinity and secondary carbonate in Saskatchewan soils, and consequently a higher Mg-calcite and soluble Mg/Ca. Moreover, his ratio of ≥ 1 for Mg/Ca is not found in

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[19] Fair amount of Mg-calcite means calcite with ≥ 1 mol % $MgCO_3$.

any of underlying glacial till samples at Site 1.

(2) A shifting of 2.88 Å peak of dolomite to the lower angle, especially in soil profile samples from the midslope and depressional position samples suggests the "calcitization" of dolomite (Figure 33); however, more detailed studies are required in order to verify this observation.

(3) Ratios > 0.5 for the area under the peak of

$$\frac{\text{calcite}}{\text{calcite + dolomite}}$$ mean calcite is more important than dolomite in the carbonate sample and vise versa. The ratio for the carbonate concretions decreases with depth in the saline profiles (i.e. Profile 1, Site 1 "Rego Black, Saline phase" and Profiles 2 "Gleyed Calcareous Black, Saline phase) and 13, Site 2) and underlying glacial till, being > 0.5 in approximately the upper 200 cm and < 0.5 below 200 cm which does mean the domination of calcite above 200 cm and dolomite below 200 cm (Tables 23 and 24, Appendix E , page 245). The C horizon samples of Profile 2, Site 1 (Orthic Black) and the samples from Well 12, Site 2 (both taken from a knoll position) are characterized by an irregular trend of ratio figures. The profiles in the depressional areas show ratios which increase with depth (i.e. calcite is more dominant); in Profile 3, (Site 1 (Gleyed Dark Gray Luvisol) while in Profiles 1 (Humic Luvic Gleysol) and 3 (Rego Humic Gleysol), Site 2, the ratios are < 0.5 throughout the sampling depth. These ratios of calcite-dolomite suggest that calcite is dominant to certain extent within and above the recalcification zone of salt affected profiles

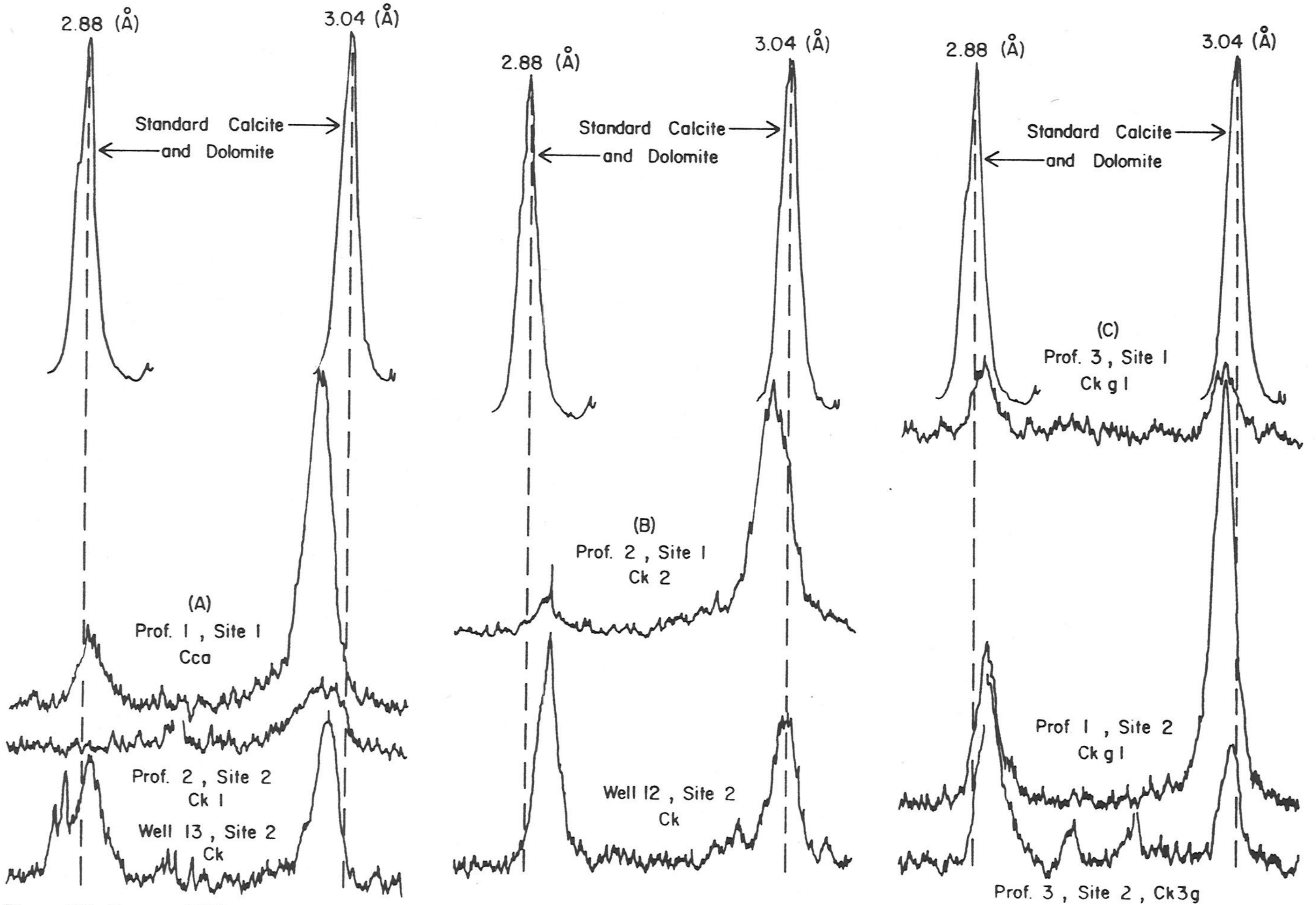

Figure 33 X-ray Diffractograms of Standard Carbonate Minerals and Carbonate Concretionary Material From Selected Ck and Cca Horizons. Saline Soils (A), Non-saline Soils (B) and Eluviated Soils (C).

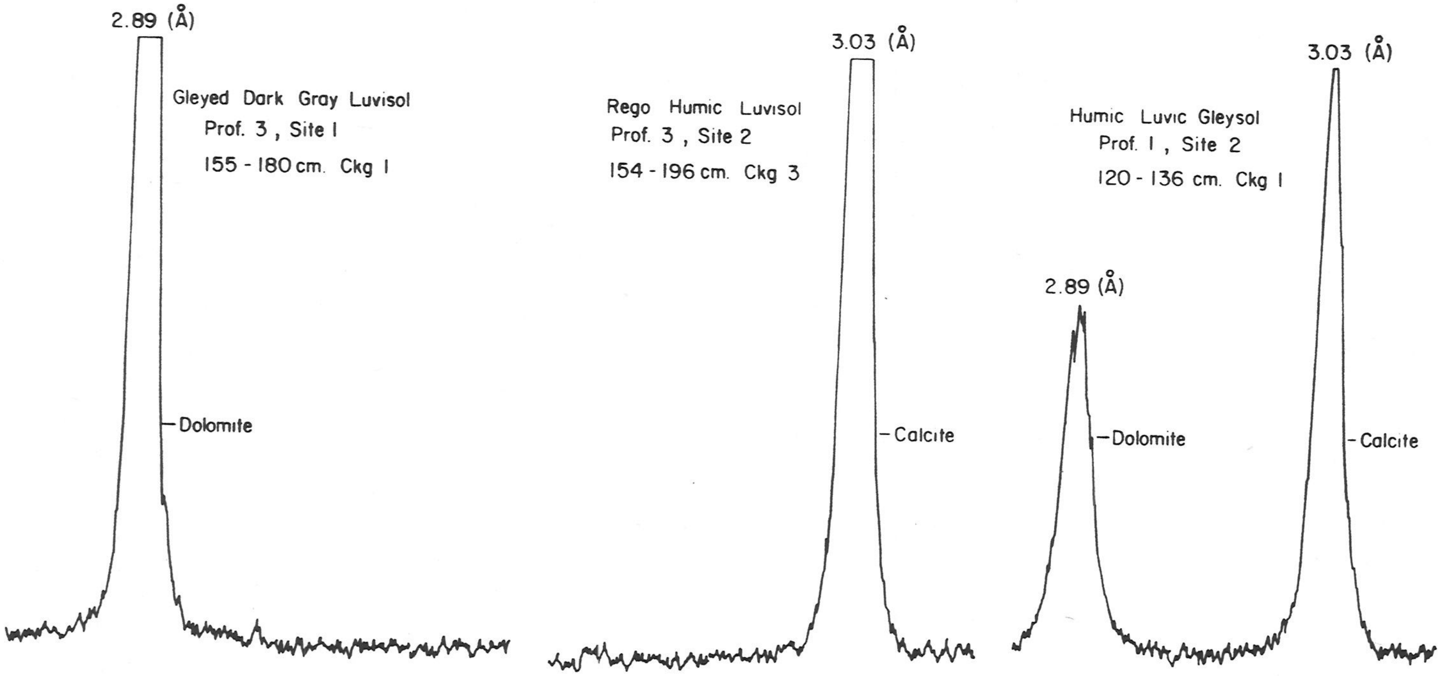

Figure 34 X-ray Diffractograms of Carbonate Pebbles From Selected Horizons of Eluviated or Leached Profiles.

TABLE 12. Mol % $MgCO_3$ in calcite, EC_e and soluble Mg^{++}/Ca^{++} for some carbonatic samples from Sites 1 and 2.

Soil samples from profiles and well sites			Mol % $MgCO_3$ in calcite	EC_e mS/cm	Soluble $\frac{Mg^{++}}{Ca^{++}}$
<u>Site 1</u>					
Prof. 1	26- 40	Cksl	2.4	4.90	5.65
	40- 50	Ccas	3.3	2.75	5.06
	50- 60	Ckgs2	4.1	2.30	5.09
	150-180	Ckg7	0.5	0.53	2.19
	a 240-280		0.6	2.60	0.85
	a 320-360		0.6	2.75	0.98
	b 400-440		0.6	2.85	0.96
	b 520-560		0.0	2.95	0.95
Prof. 2	60- 80	Ck1	1.8	0.48	1.65
	80-100	Ck2	1.8	1.95	2.87
	c 160-200		1.2	0.92	0.86
	c 320-360		0.4	1.40	0.81
	c 400-440		0.0	1.42	0.80
	c 600-640		0.0	1.40	0.60
Prof. 3	155-180	Ckg1	0.0	0.35	0.44
	a 225-238		0.5	0.40	0.39
	a 262-275		0.5	0.27	--
Prof. 6	64- 90	Ck1	2.4	0.57	0.65
	a 270-300		0.1	0.37	0.48
<u>Site 2</u>					
Prof. 1	120-136	Ckg1	0.6	0.52	0.38
	a 221-235		0.1	0.68	0.52
	b 458-499		0.4	2.06	0.73
Prof. 2	48- 58	Ckgjsl	4.4	3.70	3.29
	a 100-120		2.6	2.24	1.54
	a 170-200		1.4	1.44	1.20
	a 250-300		1.2	1.08	1.14
	b 360-385		1.2	2.89	0.75
	b 385-405		1.2	2.87	0.80
Prof. 3	a154-196		0.4	0.43	0.50
	a235-265		0.0	0.50	--
	b463-487		0.7	--	--
Well 12	a 80-120		1.0	1.04	--
	a320-360		0.4	0.47	0.93
	b552-592		0.4	0.84	0.53
Well 13	a 40- 80		1.4	3.65	--
	a120-160		1.0	4.02	--
	b240-280		0.1	3.30	1.51
	b440-480		0.2	3.08	1.10

a = Brown till; b = Dark gray till; c = Stratified material

Samples a,b,c were obtained by deep drilling.

and dolomite is dominant below that depth, which is in good agreement with the chemical and micromorphological analysis (see pages 92 & 127). For the rest of the samples (i.e. profiles and underlying samples) no consistent agreement has been found.

(4) There is little or no Mg-calcite in the pebbles of most of the horizons with the exception of those of Profile 1, Site 1 (Rego Black, Saline phase). In this profile, there is 2.5 mol % $MgCO_3$ in calcite of dolomitic limestone pebbles in the upper 50 cm. These values are identical to or close to the values obtained for the carbonate concretions obtained from the same horizon which may suggest a highly altered stage of the pebbles. On the other hand, by looking at the calcite-dolomite ratios (Tables 12, and Tables 23, 24, in Appendix E, p. 245), the tendency for highly dolomitic or calcitic pebbles has been found. However, a few samples show a mixture of calcitic-dolomitic mineralogy (Figure 33). Nevertheless, an explanation has not been found for the high ratio of dolomite pebbles in saline Profile 1, Site 1.

6.3 Micro-Submicromorphological Characteristics of the Studied Soil Sequences

6.3.1 Micromorphological Characteristics[19]

From the detailed micromorphological description in Appendix F, p. 248. The following interpretations have been made for representative soil horizons of the two studied soil sequences at Sites 1 and 2.

Microstructure[20] is spongy or irregular jointed in the Ap and Ah horizons (Figure 35c) with the exception of Ahk horizon of Profile 6, Site 1 (Rego Black) which shows cracked structure and the Ahe horizon of Profile 3, Site 1 (Gleyed Dark Gray Luvisol) which shows plate-like trend of jointed structure. The AC and AB horizons show an irregular jointed structure. The Ae horizons show an irregular jointed with plate-like structure in the upper part of the horizons and regular jointed structure in the lower part of the horizon (Figure 35a and b).

All B and C horizons show an irregular jointed structure except the Bt1 and Bt2 of Profile 3, Site 1 (Gleyed Dark Gray Luvisol) which show regular jointed structure (Figure 36a), and the Ccas horizon of Profile 1, Site 1 (Rego Black, Saline phase) which shows porous structure (Figure 36b). The Bmks and Ck horizons of Profile 2, Site 2 (Gleyed Calcareous Black, Saline phase) exhibit porous structure.

These observations are in aggreement with the field description (i.e. macromorphological description) considering

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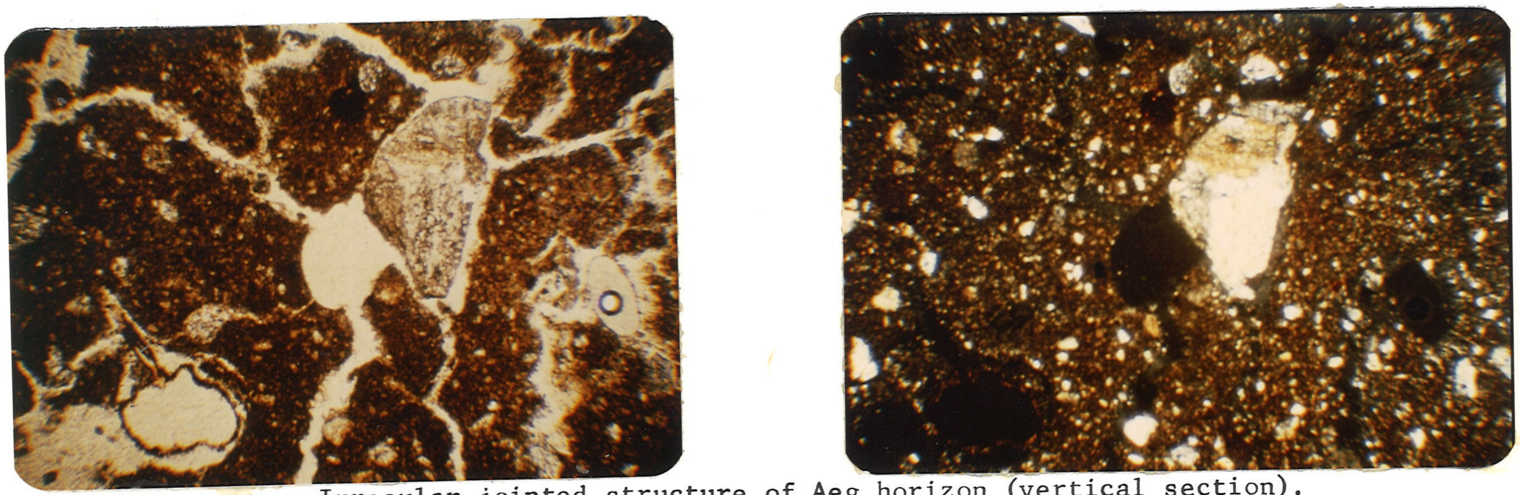
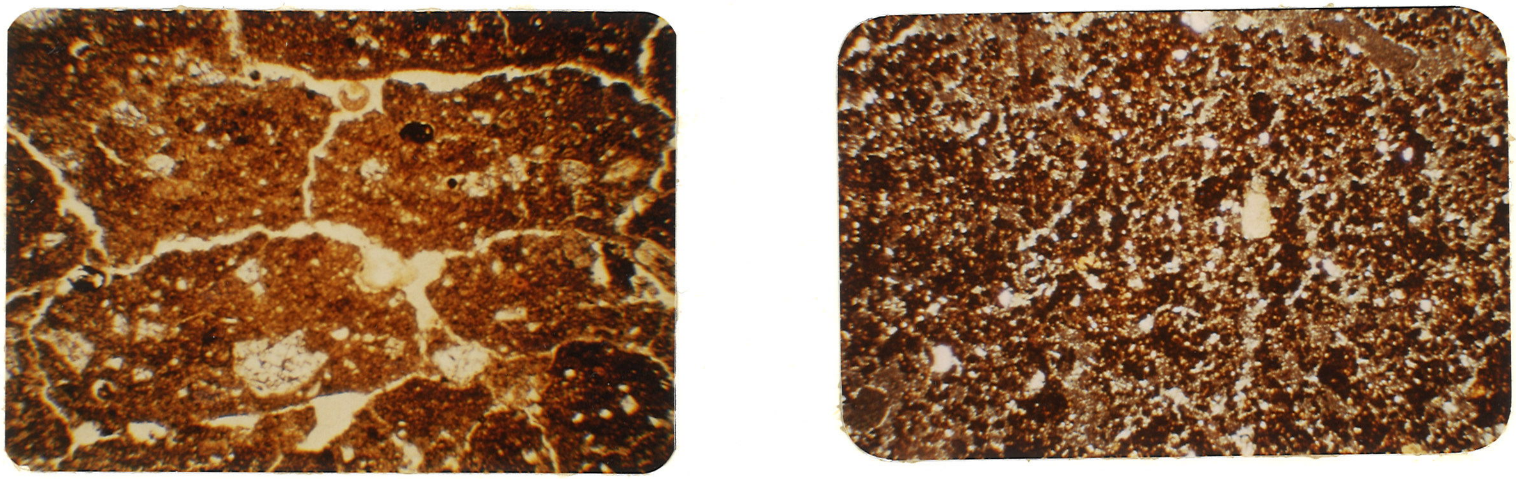
[19] See Appendix G, page 272 for glossary of micromorphological terms.

[20] Microstructure description according to Beckman and Greyger (1967).



a. Irregular jointed structure of Aeg horizon (vertical section). Plain light, "left" and crossed polarizer "right", X25.



b. Regular jointed structure of Aeg horizon (horizontal section). Plain light, X25.

c. Spongy structure of Ahs horizon. Plain light, X25.

Figure 35. Microstructure of A horizons, a and b "Humic Luvic Gleysols" and c "Rego Black, saline phase".

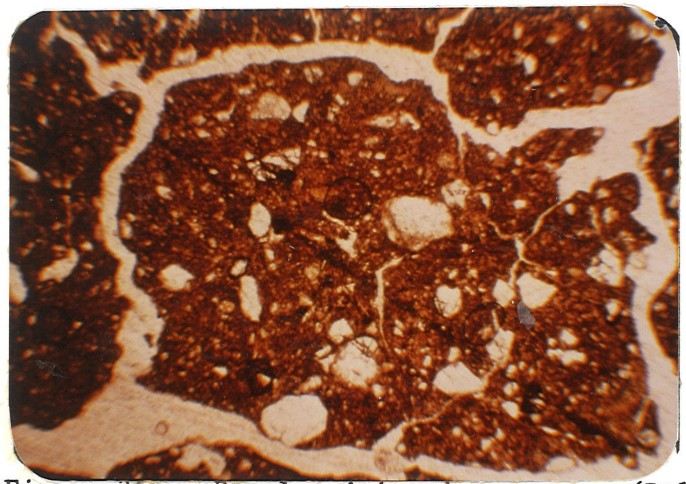


Figure 36a. Regular jointed structure (Bt1 "Gleyed Dark Gray Luvisol"). Plain light, X25.

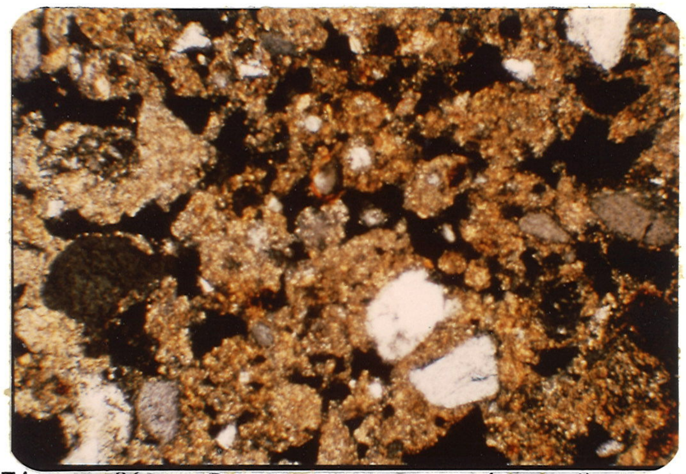


Figure 36b. Porous structure (Ccas "Rego Black, saline phase"). Crossed polarizer, X100.

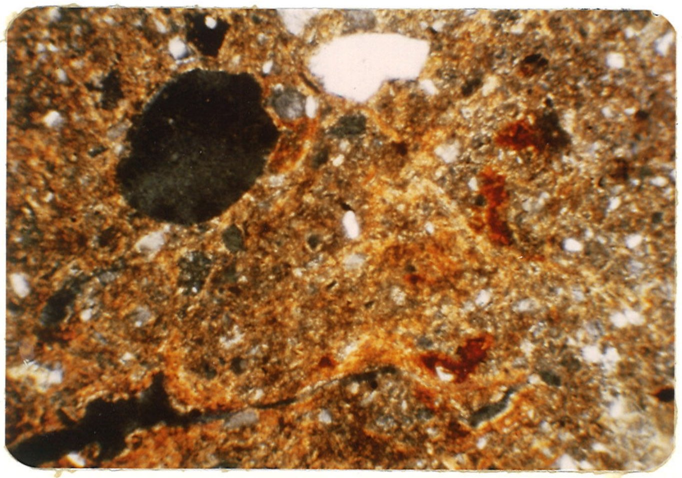


Figure 36c. Double space porphyric related distribution (Bt1 "Gleyed Dark Gray Luvisol"). Crossed polarizer, X100.

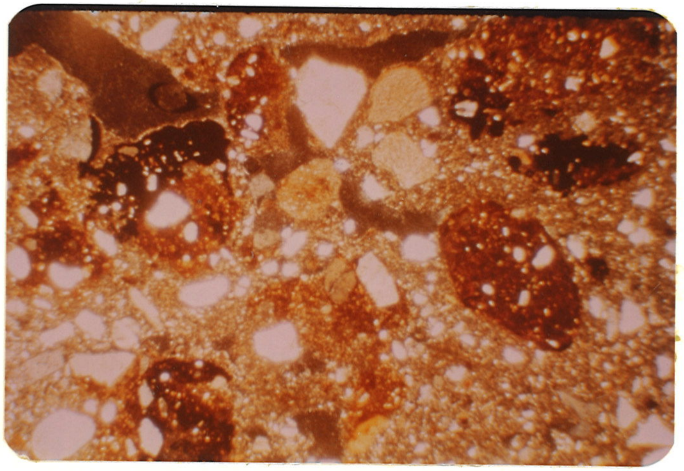


Figure 36d. Orthic and inherited iron nodules (Aegj "Gleyed Dark Gray Luvisol"). Crossed polarizer, X25.

the mechanical effect of freezing and thawing on the soil structure (i.e. plate-like) particularly in the upper part of soil profiles (Pawluk and Brewer, 1975).

Void pattern[21] is characterized mostly by the presence of planar voids and vughs, to a certain extent channels and rarely vesicles and chambers. These different kinds of voids, especially the planar ones, could be related partly to the mechanical action of frost and/or the heterogeneity of soil materials (Brewer, 1964). Within the Bt horizons, the void pattern is dominantly channels (Figure 36a).

The soil material[22] is characterized by a high c/f20µm (i.e. coarse over fine material with 20 µm size limit) ratio for most A and C horizons and the related distribution is single space porphyric (Stoops and Jongerius, 1975). Most of the B horizons, especially the Bt's are characterized by lower c/f ratio (approximately 3/7) and consequently double space porphyric related distribution (Figure 36c).

The coarse material of non-calcareous horizons (specifically A and B horizons) consists dominantly of quartz, quartzite, and subdominantly of plagioclase, orthoclase, microcline, biotite, pyroxenes, amphiboles, opaque minerals, alterites, siliceous rock fragments, and rarely garnet. Within carbonate horizons, the coarse materials are characterized by the

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[21] Void pattern description according to Brewer (1964).

[22] The coarse and fine material and their $c/f_{20\ \mu m}$ related distribution are described according to Stoops and Jongerius (1975).

presence of primary calcite and dolomite minerals, carbonate fragments, and pedogenic calcite crystals in addition to materials of non-carbonatic horizons.

The size of the coarse materials in all horizons are mostly fine-very fine sand, except within the C horizons which have a highly homogeneous silt.

The fine material of non-calcareous Ap and Ah consists mostly of clay and organoferric compounds. The Ae horizons consist of silt, clay, and ferric compounds in the fine material.

The calcareous A and C horizons are characterized by a fine material composed of clay, organic, and/or ferric compounds and pellitic to aleuritic calcite.

The Bt fine material of and Bm horizons are dominantly clay and ferruginous compounds.

Plasmic fabric of: (a) non-calcareous Ap and Ah horizons are humic-mull granic[23]; (b) Ae horizons are silasepic to skelvosepic,[24] (c) the calcareous A and C horizons are mostly crystic plasmic fabric, (d) Bt and Bm horizons are mainly lattisepic for the former and Voskelsepic for the latter.

Organic material[25] is relatively high, mostly strongly decomposed and present in the plasmic material of upper horizons in

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[23] Plasmic fabric of organic-rich surface horizons are described according to Brewer and Pawluk (1975).

[24] Plasmic fabric of organic-poor surface and subsurface horizons are described according to Brewer (1964).

[25] Organic materials are described according to Babel (1964).

all profiles, while with depth their amount decreases sharply and their distribution becomes more clustered and within pedological features.

Pedological features.[26] Translocation of fine material is of relatively minor significance in several horizons (e.g. Ap horizon of Profile 6, Site 1 "Rego Black"). However, a) orthic iron nodules (Figures 36d and 37b) are the most common pedogenic features occupying most horizons in all profiles of Sites 1 and 2, b) orthic calcitic nodules are concentrated in Cca, Ck4 of Profile 1, Site 1 (Rego Black) (Figure 37a) and Ccag Ck1 of Profile 6, Site 1 (Rego Black). Inherited calcite nodules are present in the deepest studied horizons of all profiles (about 125 cm deep). Generally, the orthic nodules occur close to the level of the water table in the different profiles in the two studied soil sequences.

The cutanic and/or subcutanic features of iron (ferrans; neoferrans), calcite (calcitans; neocalcitans), and clay (ferriargillans; organo-argillans) occur mostly at or near void surfaces for cutans and neocutans, respectively in various depths, concentrations, and strengths. Ferrans, and to a greater extent, neoferrans (Figure 37c and d) occur in appreciable amounts and as strongly developed features within deeper Ck horizons of the studied profiles except Profile 1, Site 2 in which their occurrence started near the surface horizons and Profile 2, Site 2 in which no detection has been made in

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[26] Pedological features are described according to Brewer (1964).

the studied horizons.

Calcitans and neocalcitans are found to be weakly to moderately developed, mostly above and in the Ck horizons especially within salt-affected profiles (i.e. Profile 1, Site 1 and Profile 2, Site 2) (Figure 38a and b).

The clayey cutanic materials are complexed with ferric compounds or organic materials and consequently present as ferriargillans and organo-argillans, respectively. These two features are present individually or in combination with Bt and BC horizons of Profiles 2 and 3, Site 1 and Profile 1, Site 2. However, in Bmks of Profile 2, Site 2, the ferruginous clayey materials are characterized by aggregate-like to weakly oriented, randomly distributed ferriargillans within voids or around grains (Figure 39a). Grain ferriargillans occur commonly in the lower part of the Bt and BC horizons (see page 260).

Clayey cutanic features (i.e. ferriargillans and organo-argillans) tend to become more oriented and more frequent with increasing leaching and eluviation depth. For example, in the S. matrix of Bmks of Profile 2, Site 2 (Gleyed Calcareous Black, saline phase) the clayey materials are mostly clustered (Figure 39a) while in the Bt horizons of Profile 3, Site 1 (Gleyed Dark Gray Luvisol) and Profile 1, Site 2 (Humic Luvic Gleysol), the clayey materials become highly oriented and more frequent (Figure 39b, c, and d).

Calcite crystallaria and isotubules occurred mostly in the calcareous horizons of Profiles 1, 3, and 6 at Site 1

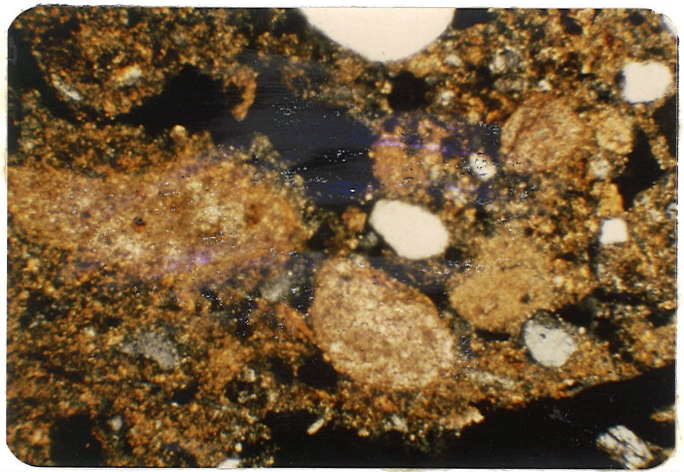


Figure 37a. Calcite nodules (Ccas "Rego Black, saline phase"). Crossed polarizer, X100.

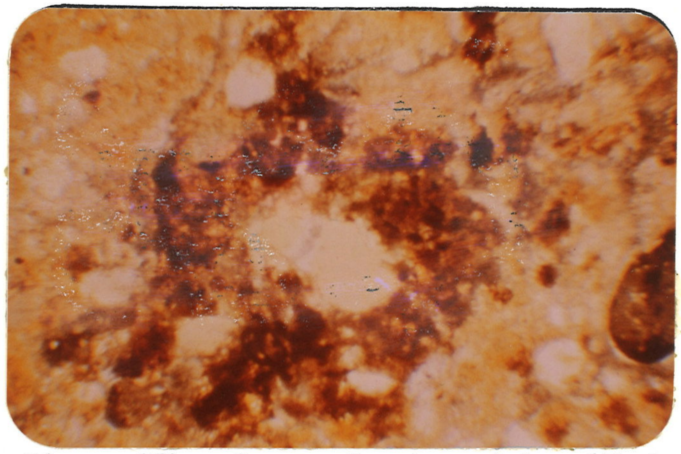


Figure 37b. Organo ferric nodules (Cksl "Rego Black, saline phase"). Plain light, X100.

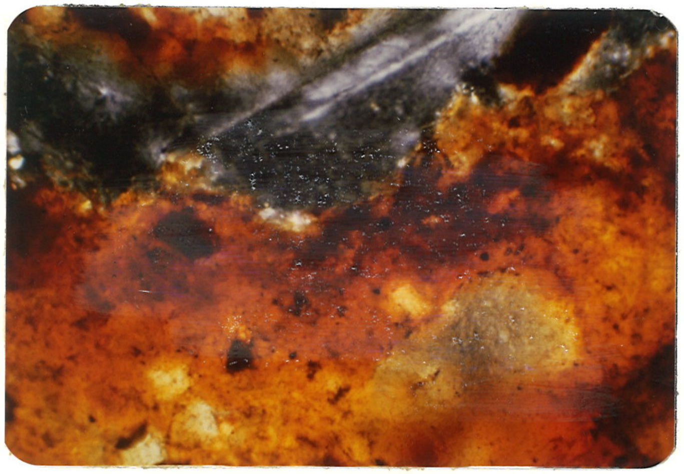


Figure 37c. Neoferrans (Ckg6 "Rego Black, saline phase"). Crossed polarizer, X250.

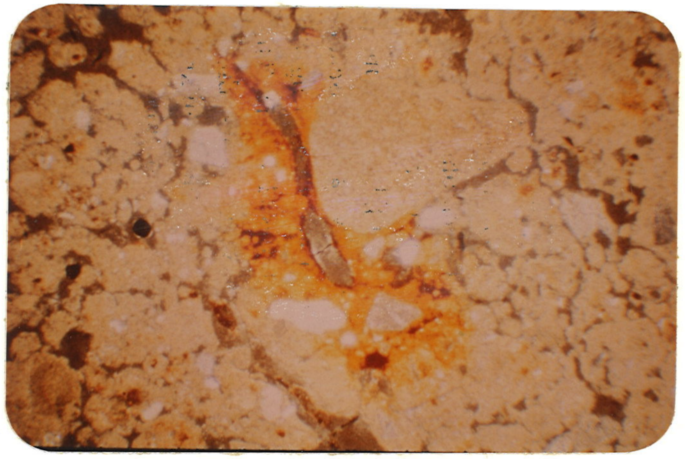


Figure 37d. Ferrans and neoferrans (Cksl "Rego Black, saline phase"). Crossed polarizer, X25.

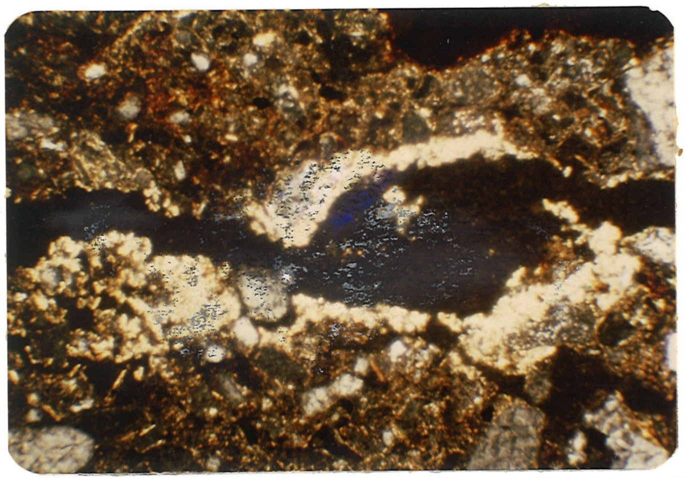


Figure 38a. Calcitans (AC "Rego Black, saline phase"). Crossed polarizer, X100.

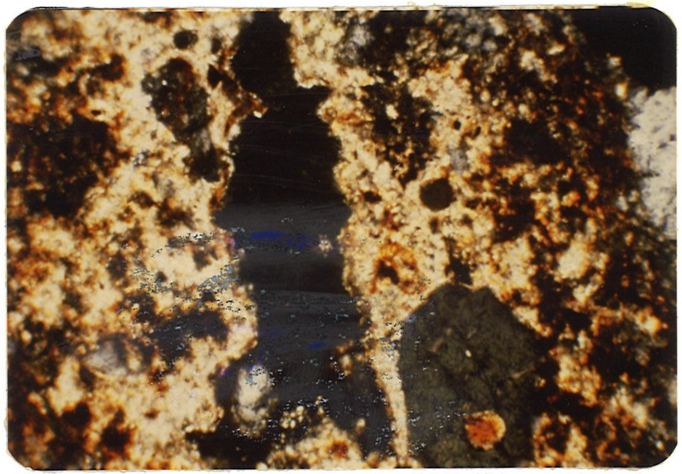


Figure 38b. Neocalcitans (AC "Rego Black, saline phase"). Crossed polarizer, X250.

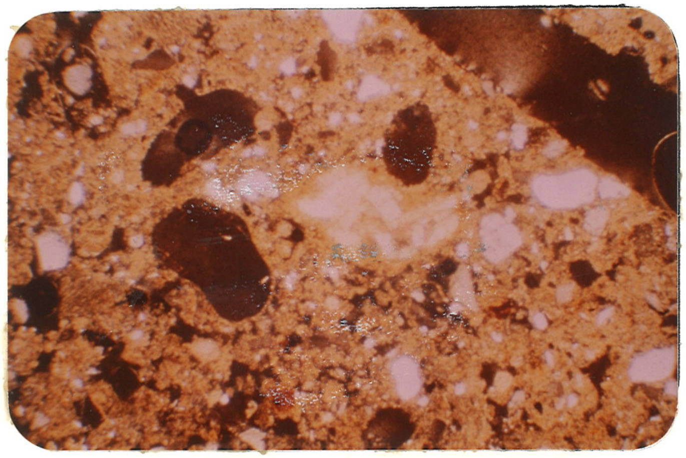


Figure 38c. Calcite intercalary crystals (Ccas "Rego Black, saline phase"). Crossed polarizer, X250.

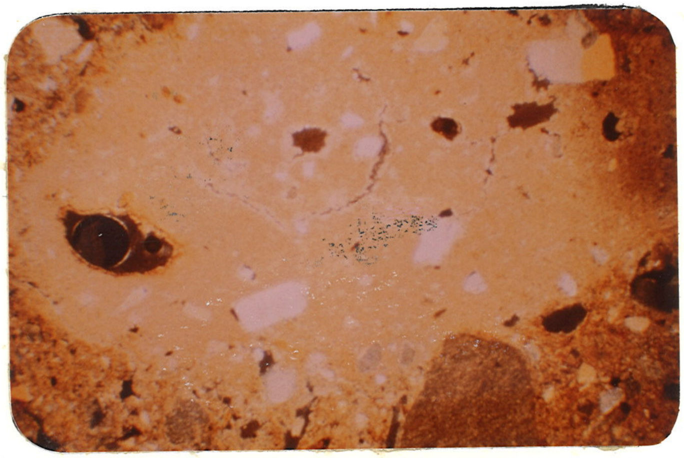


Figure 38d. Calcitic isotubule cross section (BC "Gleyed Dark Gray Luvisol"). Crossed polarizer, X100.

(Figure 38c and d). These features were concluded to be of pedogenic origin because of 1) the similarity in plasmic composition within the calcitic features and surrounding materials and 2) their $c/f_{20\mu m}$ related distribution is porphyric which is comparable to the related distribution of the host soil materials.

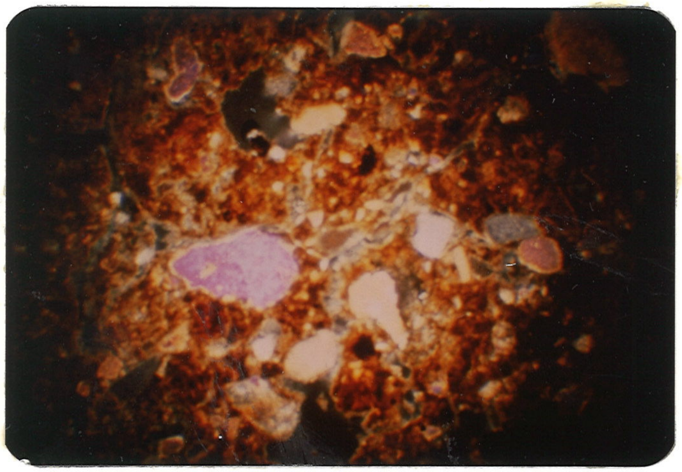


Figure 39a. Accumulation of ferrugenous clayey material (Bmks "Gleyed Calcareous Black, Crossed polarizer, X25. saline phase")

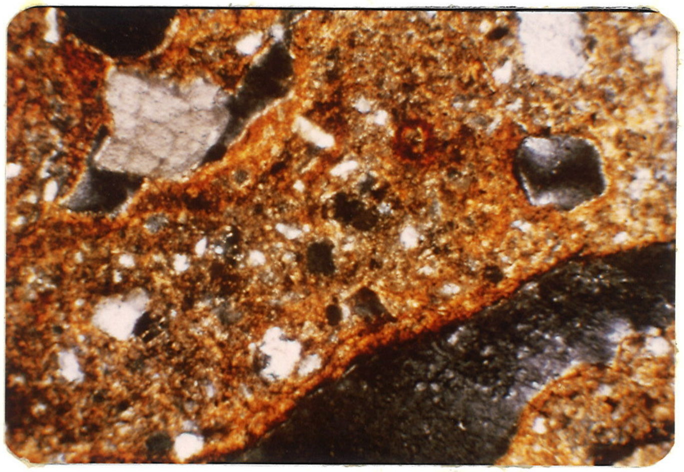


Figure 39b. Weakly-moderately oriented ferriargillans (Btl "Gleyed Dark Gray Luvisol"). Crossed polarizer, X100.

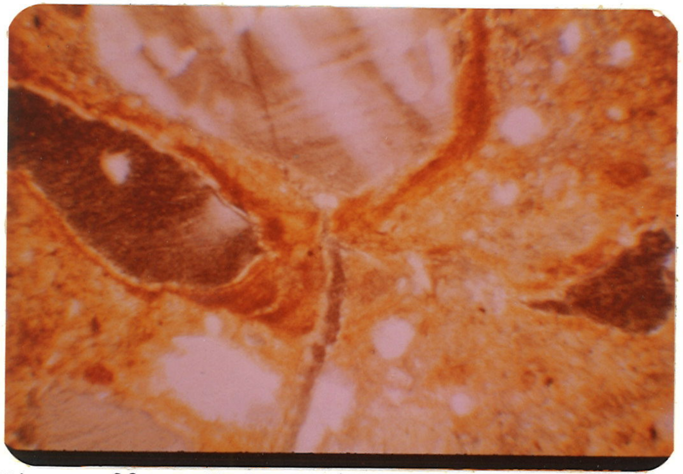


Figure 39c. Moderately oriented ferriargillans around void and quartz grain (Btl "Gleyed Dark Gray Luvisol"). Crossed polarizer, X100.

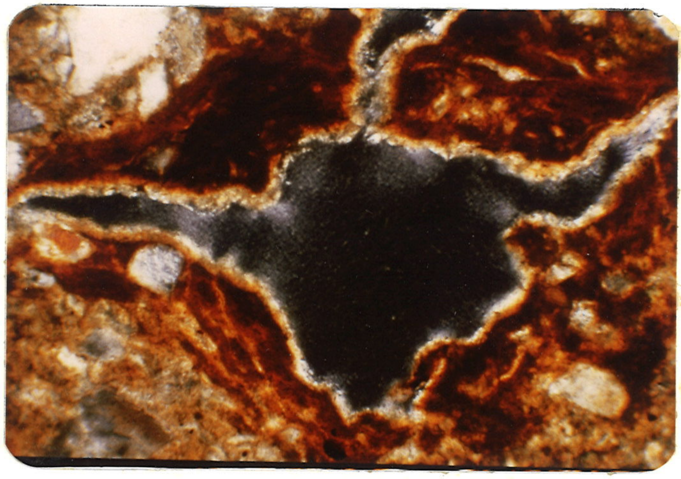


Figure 39d. Strongly developed ferriargillans (Btgl "Humic Luvic Gleysol"). Crossed polarizer, X100.

6.3.2 Submicromorphological Features of Selected Soil Horizons by the Aid of SEM

Undisturbed peds from the Aps, AC and Ccas horizons of Profile 1, Site 1 (Rego Black, saline phase) were used to a) identify and determine the nature of soluble salts, and b) to describe the soil fabric and carbonatic cutanic material for Cks and Ccas horizons. The Bmks sample (Profile 2, Site 2, Gleyed Calcareous Black, saline phase) was selected for the same purpose. Two other samples from Btgl of Profile 3, Site 1 (Gleyed Dark Gray Luvisols) and Ckg5 of Profile 1, Site 1 (Rego Black, saline phase) were selected to study the soil fabric and cutanic features in the former horizon and specific clayey features in both horizons.

A description of the identified evaporite minerals, soil fabric, and features which were found in the studied samples is as follows:

Evaporite Minerals

Gypsum $CaSO_4.2H_2O$. This mineral is found to be crystallized and concentrated in different forms in the subsurface horizons of the studied saline profiles. In the AC horizon (15 to 40 cm) of the Rego Black (saline phase), Site 1, the gypsum crystals occur as pockets of (a) numerous fine hexagonal crystals of 2 to 4 μm in diameter with strongly developed crystal faces (Figure 40), and (b) fine crystals (2 to 4 μm) with rounded to oval shape. In addition, a cave-like feature with a comb-like structure of gypsiferous material was found (Figure 41). The last two types of formation appear to be related to successive dissolution stages of the fine hexagonal gypsum crystals within their pockets.

In the Bmks horizon (30 to 48 cm) of Gleyed Calcareous Black (saline phase), Site 2, the crystal forms were found to be (a) prismatic to prism-like elongated crystals, and (b) mass of weakly discernible crystals (Figure 42). The identity of these crystals as gypsum was verified by using the X-ray technique (Stoops _et_ _al_., 1978) for the interpretation of forms and features of gypsum crystals and gypsiferous materials.

Thenardite Na_2So_4. This meta stable mineral appears in the Ap horizon (0 to 15 cm) of Profile 2, Site 2 (Gleyed Calcareous Black, saline phase), mainly as fine (10 to 20 μm), irregular crystals. These crystals are often stacked to each other forming a concretion-like aggregate (75 μm size). Moreover, the larger crystals (∿50μm) occur mainly as individual elongated rhomboidal thenardite crystals (Figure 43). The identity of these crystals as thenardite were verified by using the figures of Tursina _et_ _al_ (1980) and Driessen and Schoorl (1973).

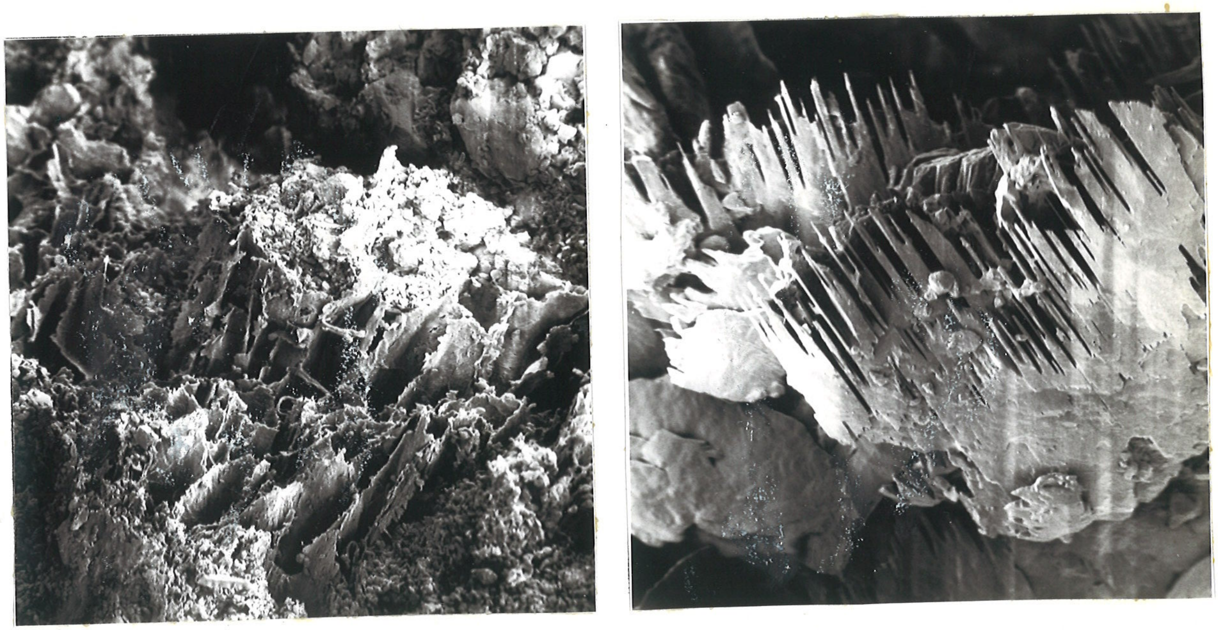
Pedogenic Accumulation of Calcite (Calcitans)

In the Ccas horizon (40 to 50 cm) of the Rego Black "saline phase", Site 1, the calcitic pedologic features (calcitans) are considered to be weakly to moderately developed since the orientation level of the calcitic material was weakly developed on the void surface (Figure 44). The grain size fraction of these materials appear to be of fine-very

X750

X3750

Figure 40. SEM photograph of lenticular-hexagonal gypsum microlites (AC "Rego Black, saline phase").



X150

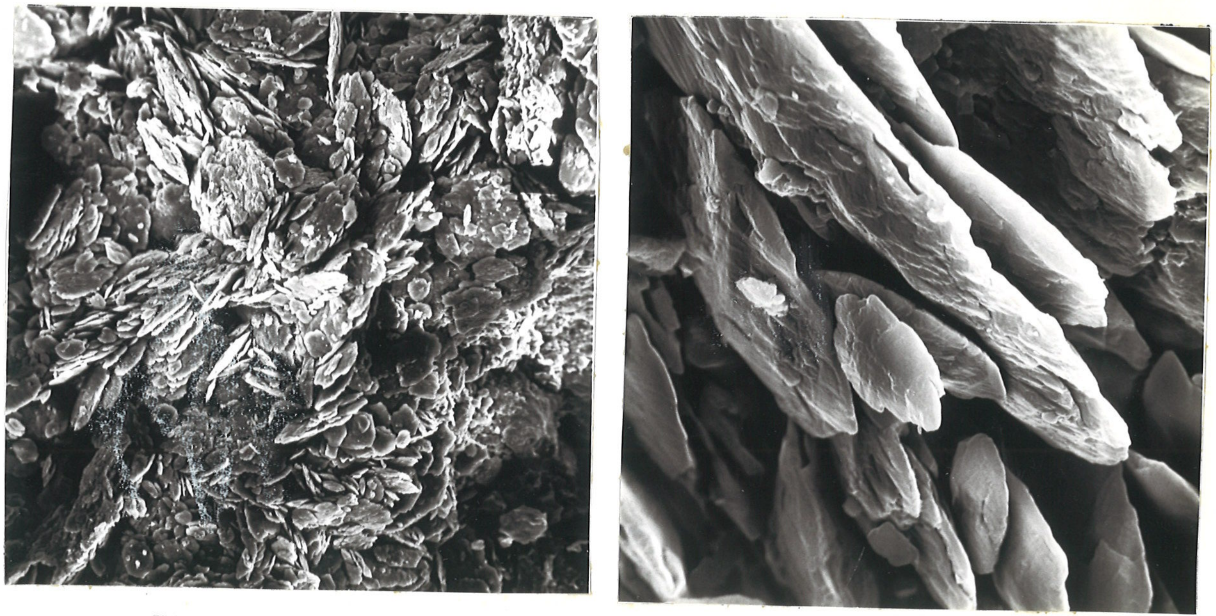
X375

Figure 41. SEM photograph of cave like with comb-structure in weathered gypsiferrous material (AC "Rego Black, saline phase").

X1500

X750

Figure 42. SEM photograph of prismatic and closely packed features in agypsiferous material (Ahs "Gleyed Calcareous Black,saline phase").



X150

X1500

Figure 43. SEM photograph of concretion-like aggregates and acicular crystals of thenardite (Apks "Rego Black, saline phase").

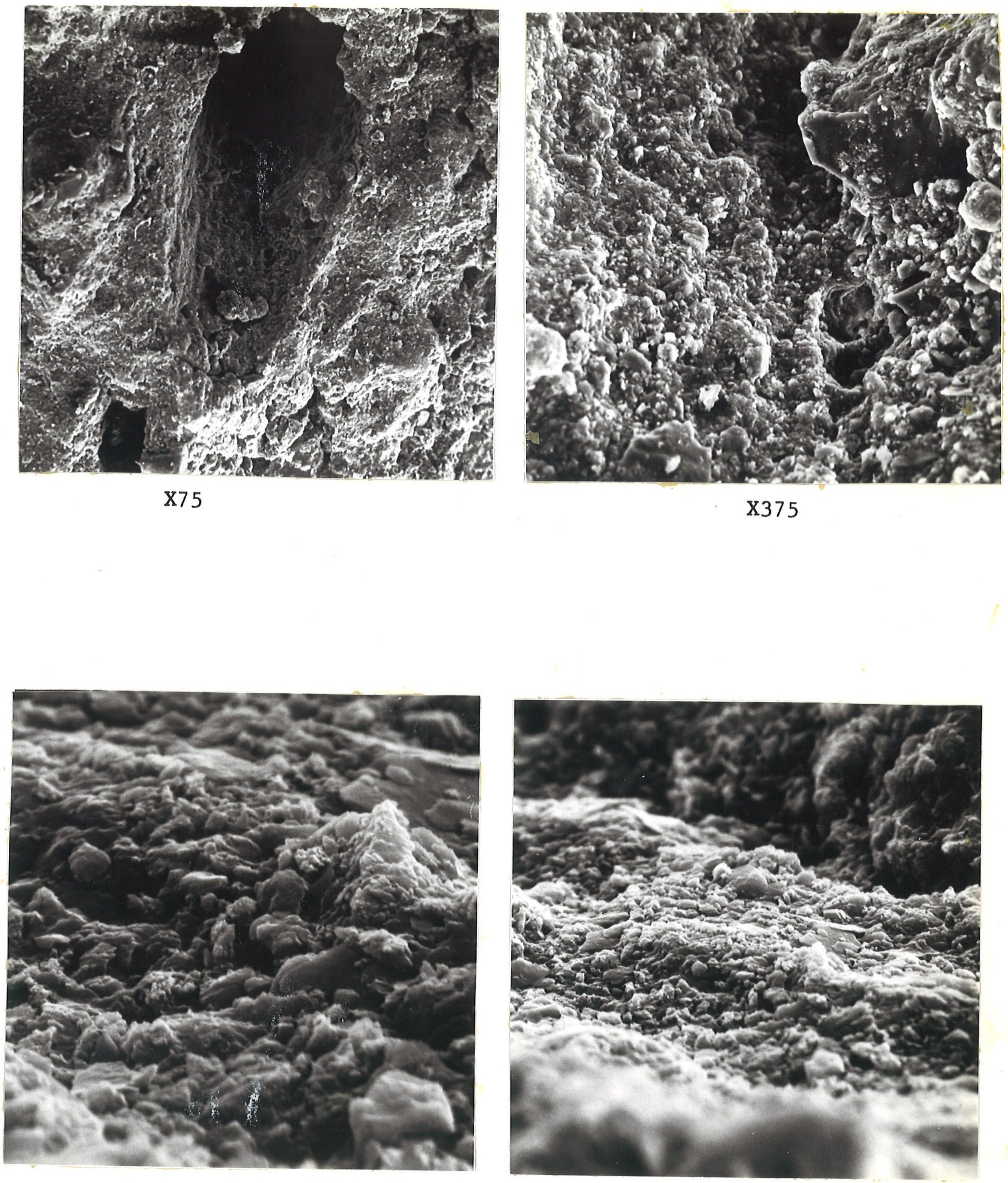
fine silt to coarse clay.

Discussion on the accumulation of thenardite, gypsum and carbonates

The detailed examination of the samples from several horizons indicate that thenardite and gypsum crystals and calcitic features are of pedogenic origin, and may be formed due to upward movement of the saline groundwater in both studied sites. These minerals and pedological features are distributed according to their solubility starting with the most soluble thenardite (Na_2SO_4) at the surface horizon (0 to 15 cm), gypsum ($CaSO_4.2H_2O$) concentration in the horizons below 15 to 40 cm and calcite accumulation, which is the least soluble of the three salts, is found mostly in the Ccas horizon (40 to 50 cm). This distribution pattern is typical for an evaporation sequence from saline groundwater of carbonate-sulphate composition. The distribution pattern of the salts obtained in one present study is comparable to one reported by Tursina *et al.* (1980).

Soil Fabric and Argillans in Bt Horizon

During the examination of a vertical cut of several channels in the Btgl horizon of Gleyed Dark Gray Luvisol, there appears to be a very fine and oriented clay (i.e. argillans) covering the channel wall and several grain surfaces giving rise to a skel-vosepic plasmic fabric. From the orientation level, these argillans seem to be in moderately-well developed stage (Figure 45).



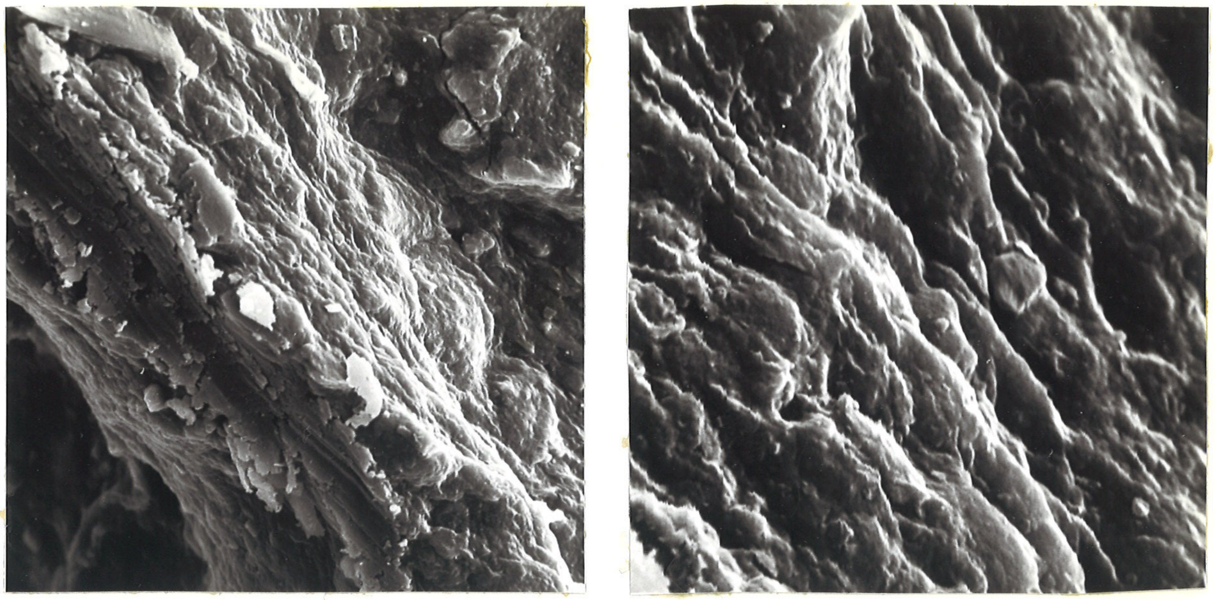
X75

X375

X3750

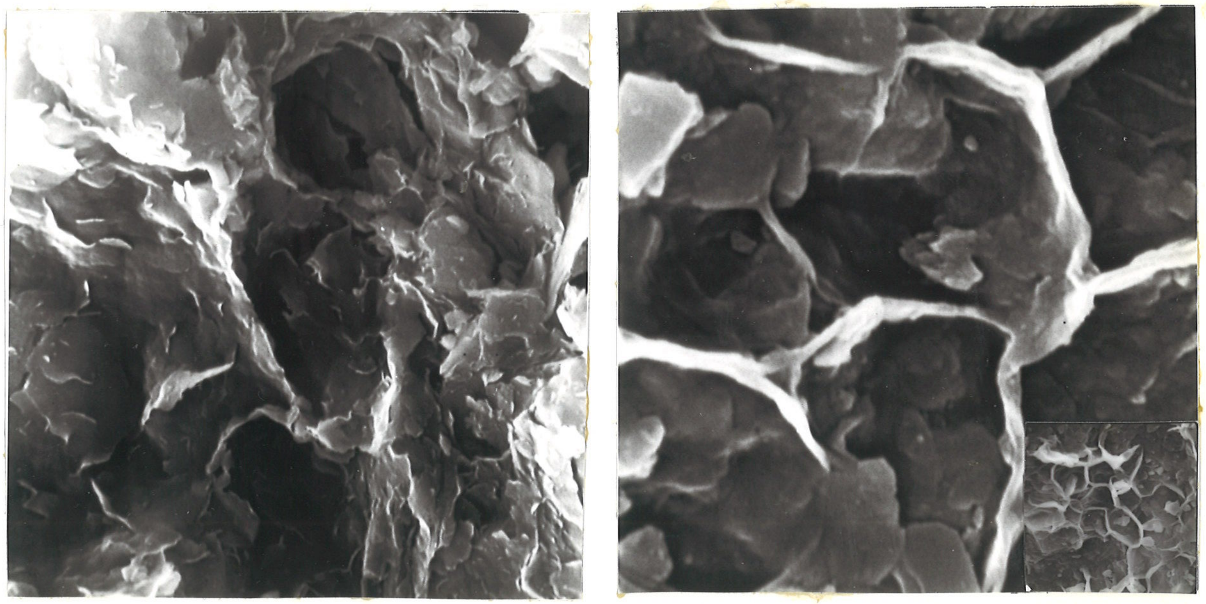
X1500

Figure 44. SEM photographs of moderately developed calcitans on void wall (Ccas "Rego Black, saline phase").



X750 X3750

Figure 45. SEM photographs of the surface of channel argillan (Btgl "Gleyed Dark Grey Luvisol").



(A) (B)

X7500 7500X 400X

Figure 46. SEM photographs of hexagonal-like clayey features associated with gleization.

A - (Btgl "Gleyed Dark Grey Luvisol) and B - (Ckg5 "Rego Black, saline phase").

Specific Clayey Features Associated with Gleization

During the examination of several Bt and Ck horizons of the Gleyed Dark Gray Luvisols, Rego Black, and Orthic Black Profiles, features of either 1) ellipsoidal chain-like or 2) hexagonal network were found. These features are composed of clay size materials and are characterized by parallel orientation within the link pattern or hexagonal network (Figure 46). The development of these features were associated with "gleyed" horizons. The above features were comparable with photographs of ferrugenous and/or mangefirrous compounds as reported by Jamagne and Jeanson (1978). Additional microprobe analysis are required for a more complete interpretation of the composition of these features.

6.4 Groundwater Fluctuation, Flow, and Chemistry

6.4.1 Water Table Fluctuation

Water Table Fluctuation with Annual Seasons

The water table levels for 15 obwervation wells at Sites 1 and 2 for a 3 year period (1979 to 1981) appear in Table 25, Appendix H, page 280 and Figures 47 to 54, pages 147 to 154 From the table and figures, one can infer a certain cyclical sequence of events in water table levels in each year. Although the times at which the events occur varies from year to year, the variations are not large and for discussion purposes, the sequence of events in the year 1980 are used (Figures 48, 51, and 53). The sequence is as follows:

a. In spring: (1) the snow melt water ponds in the depressions; (2) after the soil thaws in the depressions the ponded water moves into the soil and a water mound builds up under the depressions resulting in a water table level that is above or very close to the surface, particularly in the lower depressions (Wells 5 and 6). However, the large slough of Site 1 is occupied permanently by surface water; (3) the water mounds in the upper depressions (Well 7) usually are less pronounced than under the lower depressions and they dissipate quickly; and (4) during the spring period the water levels show a slight or no change under mid-slope and knoll positions.

b. In summer: the next stage of groundwater movement is the dissipation of the groundwater mounds under the sloughs. This is due to downward and lateral flow of the groundwater as well

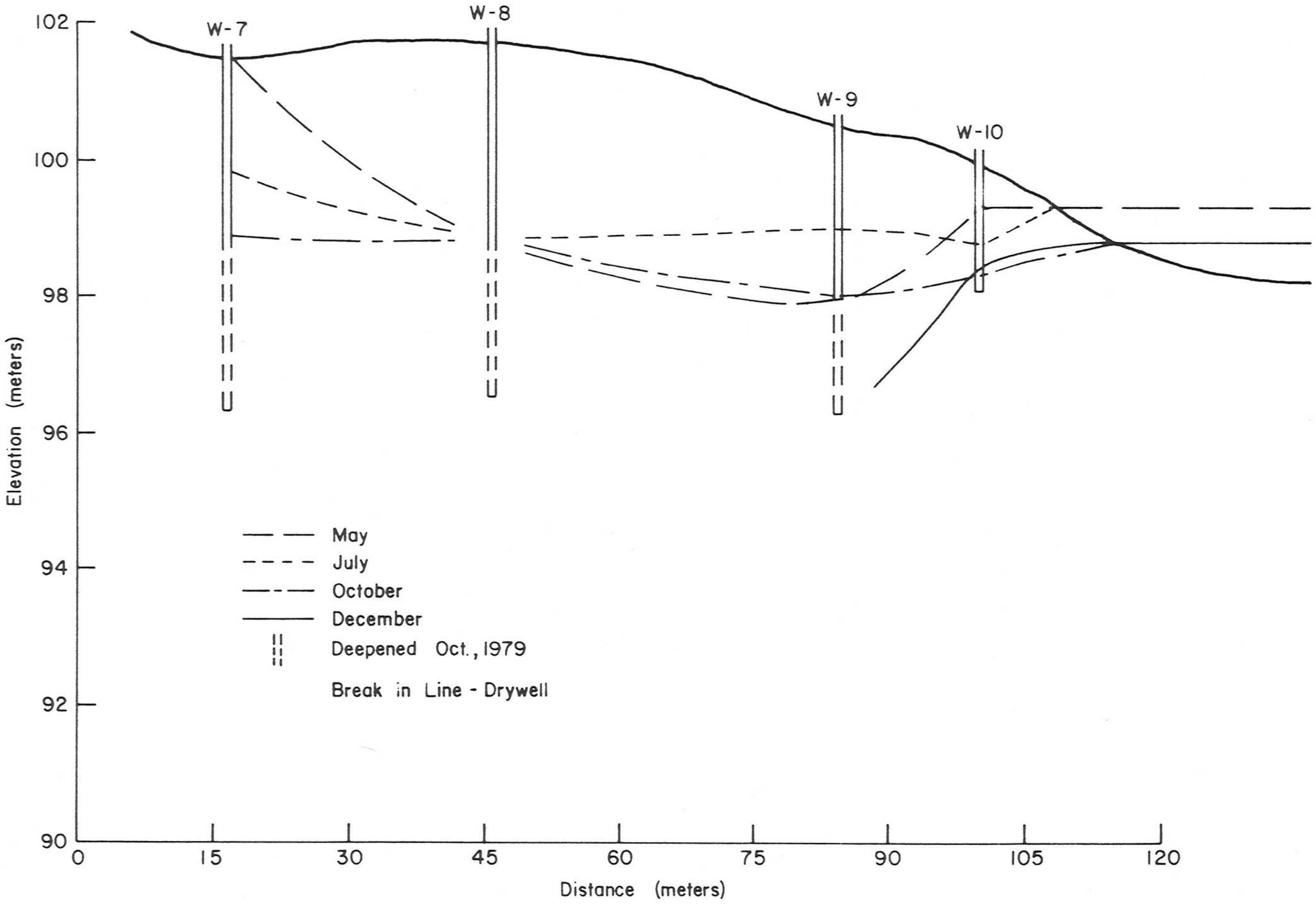


Figure 47 Water Table Patterns Along Transect From Well 7 to 10, Site 1 for 1979.

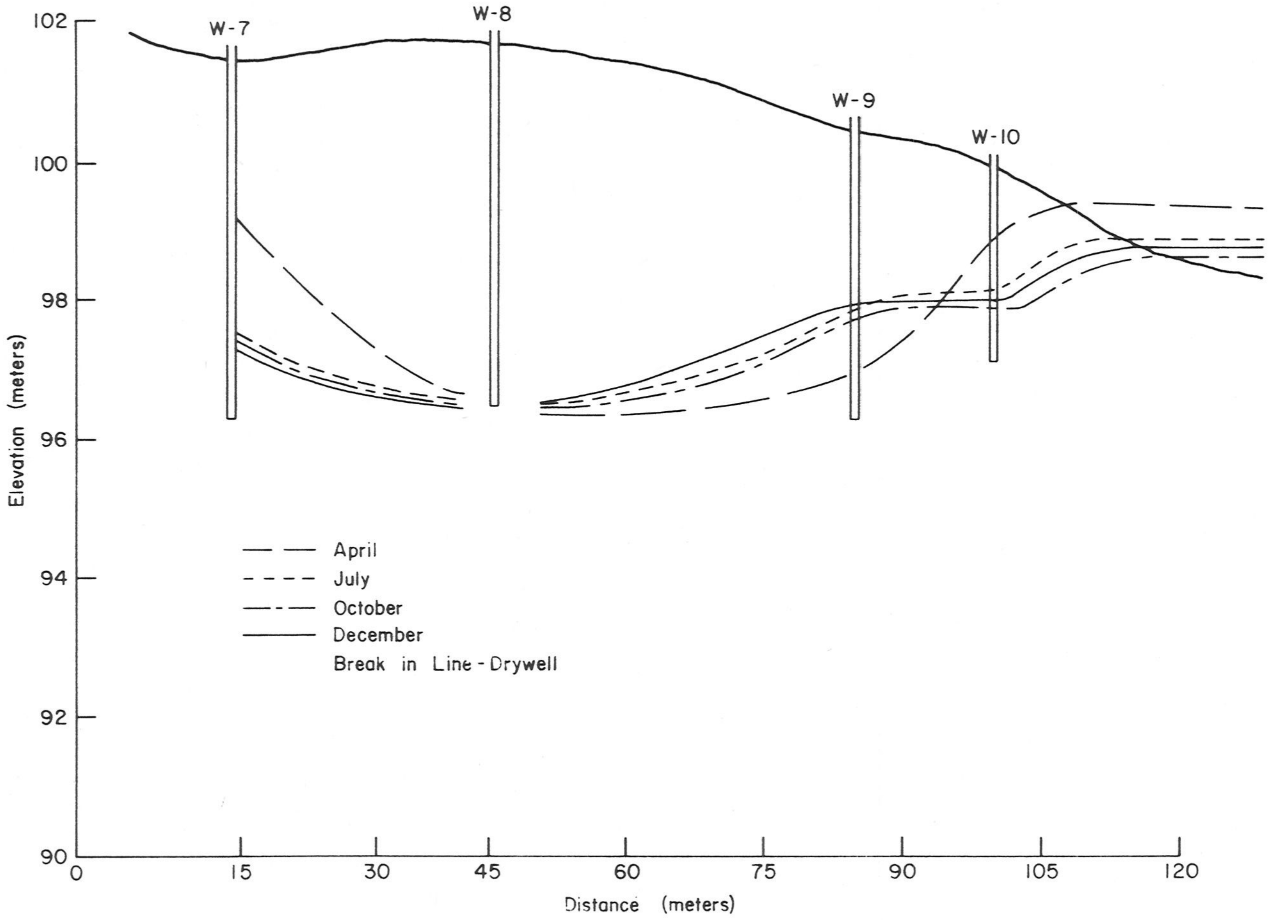


Figure 48 Water Table Pattern Along Transect From Wells 7 to 10, Site 1 for 1980.

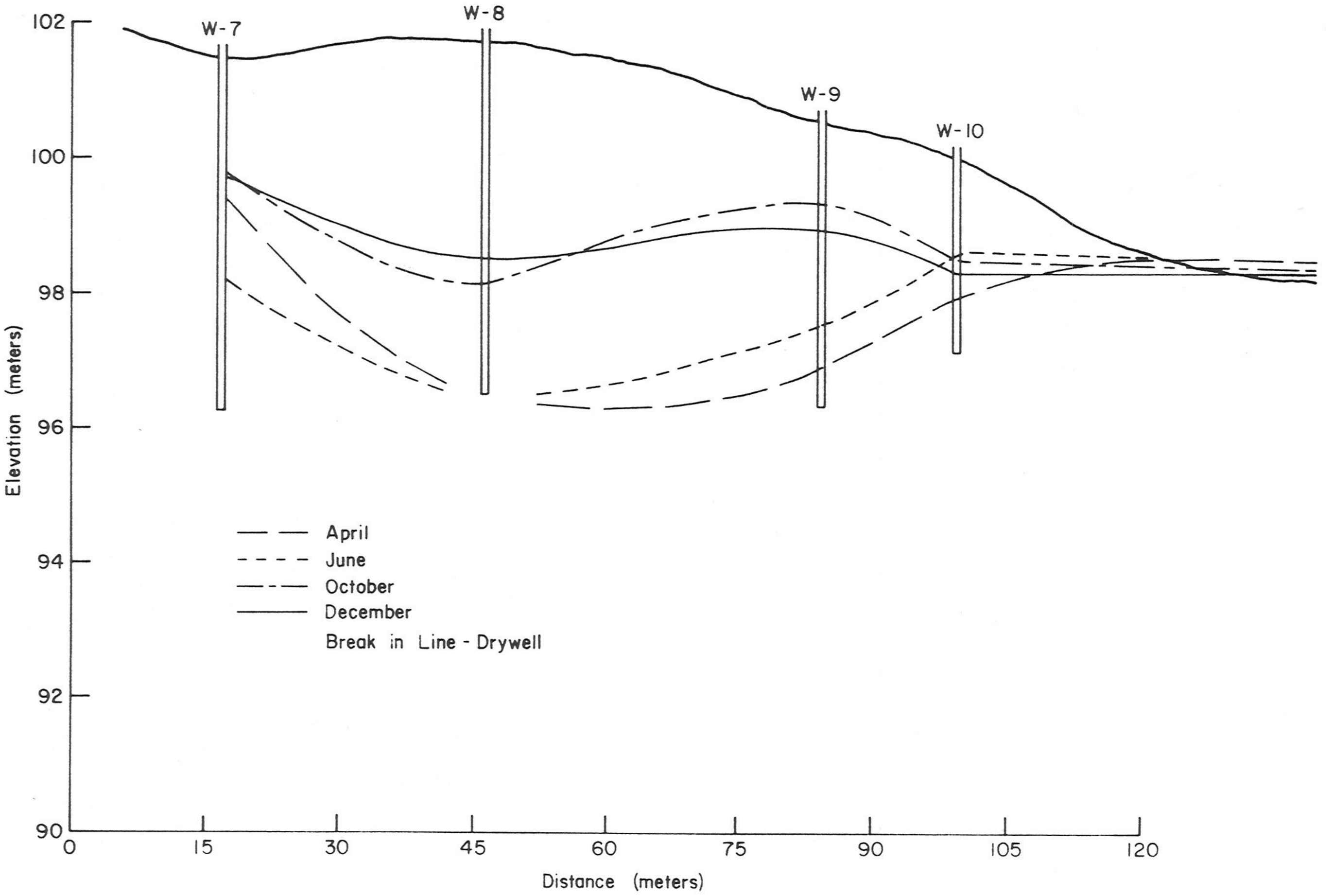


Figure 49 Water Table Patterns Along Transect From Well 7 to 10, Site I for 1981.

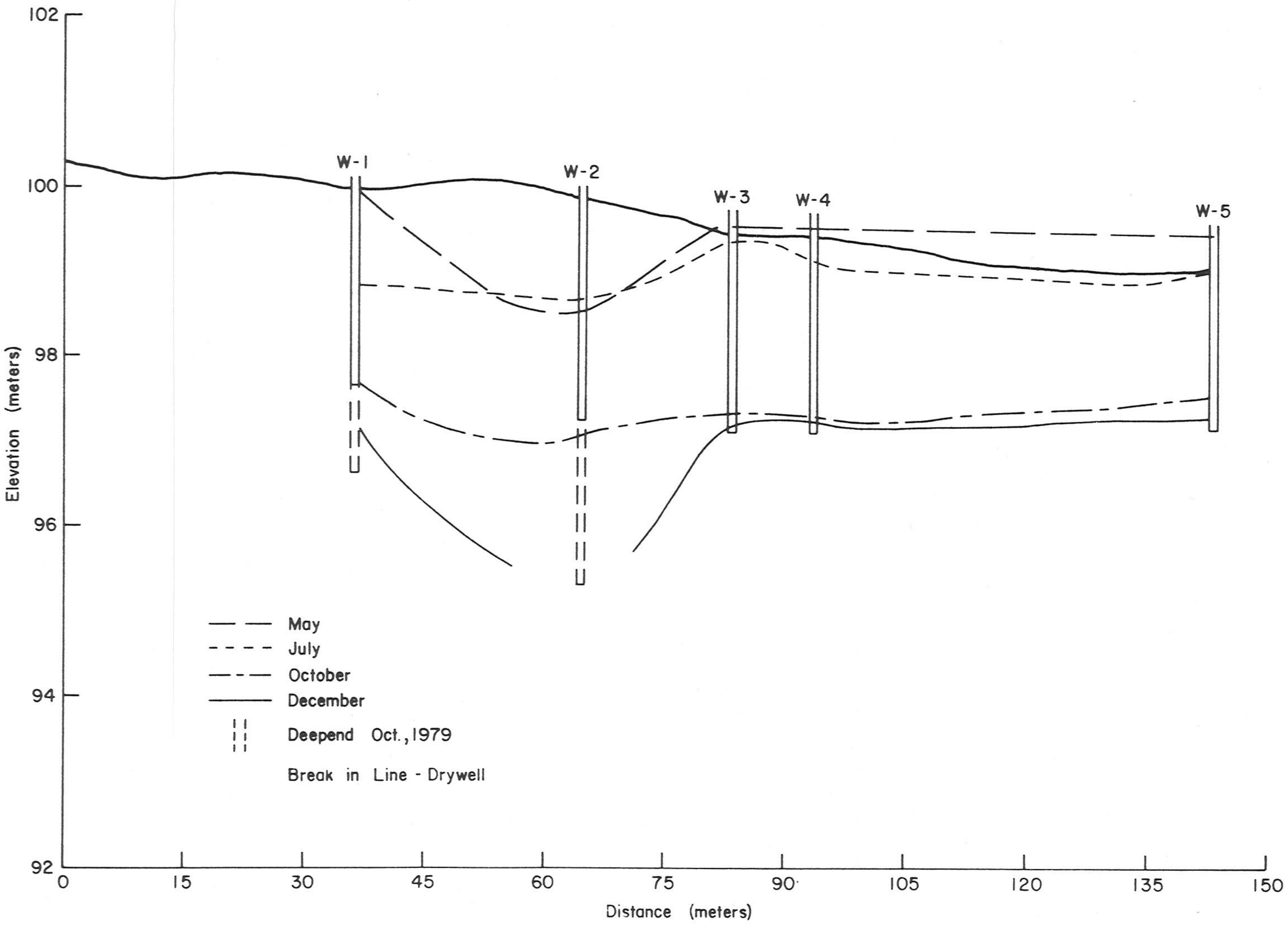


Figure 50 Water Table Patterns Along Transect From Well 1 to 5, Site 2 for 1979.

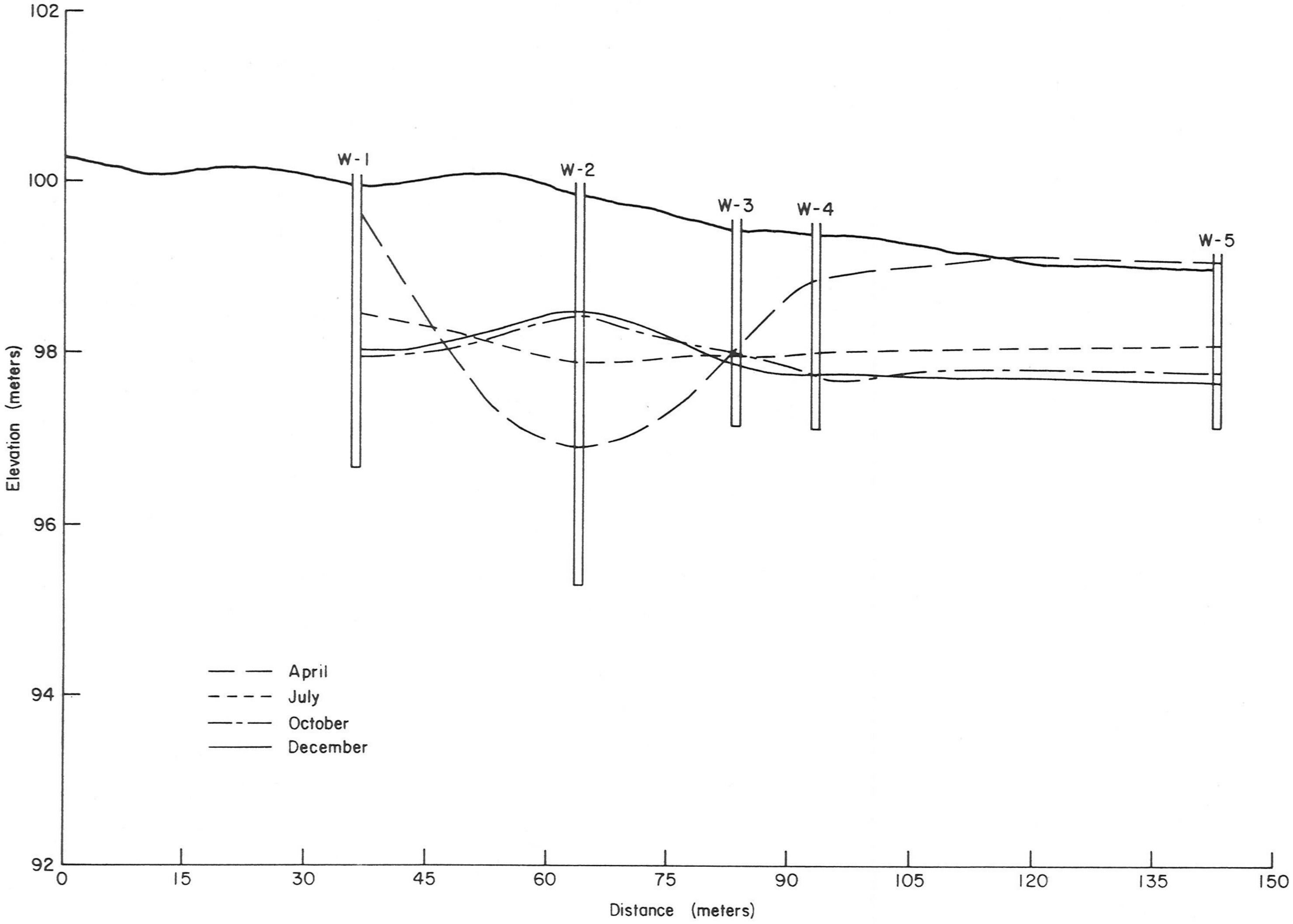


Figure 51 Water Table Patterns Along Transect From Well 1 to 5, Site 2 for 1980.

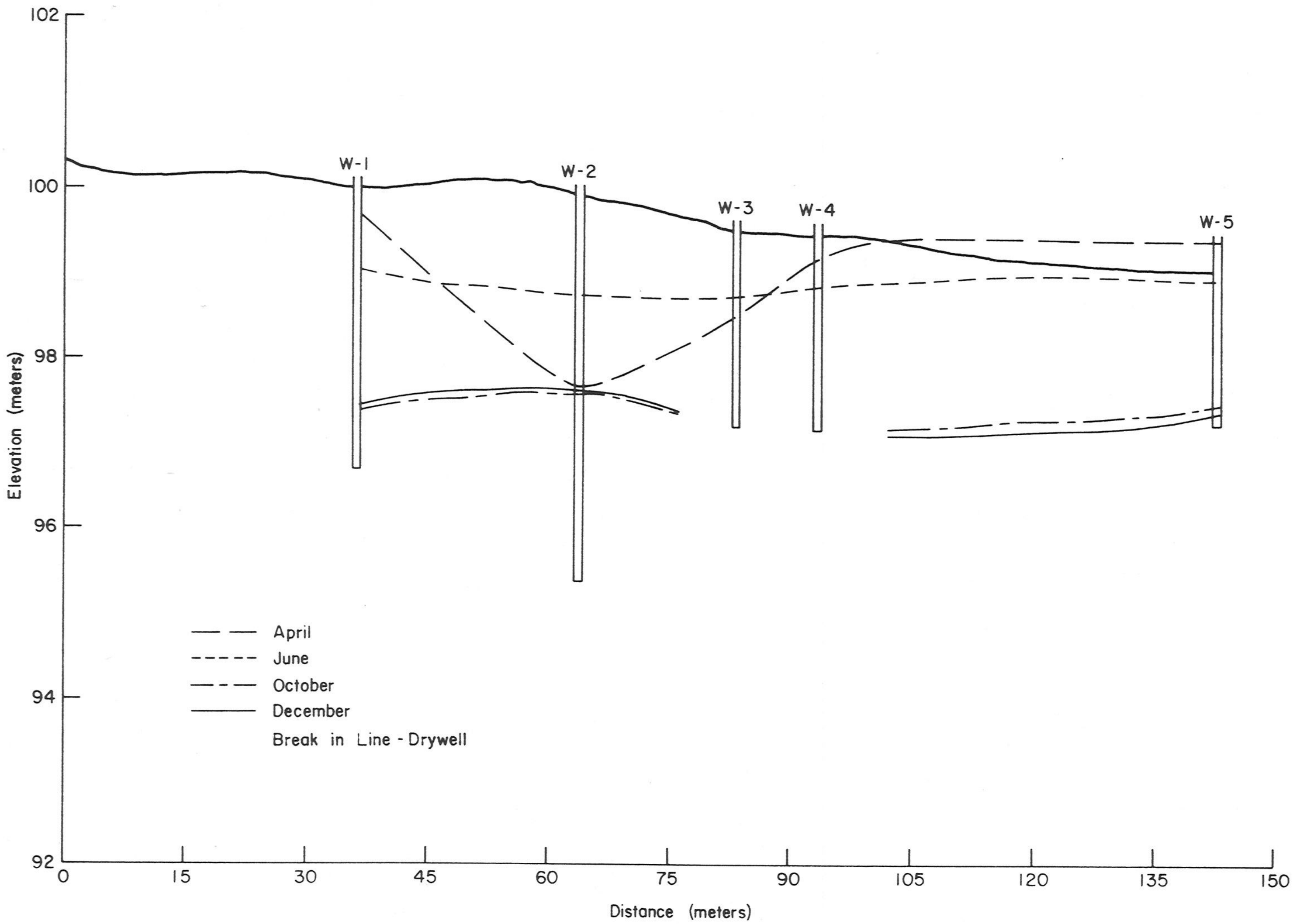


Figure 52 Water Table Patterns Along Transect From Well 1 to 5, Site 2 for 1981.

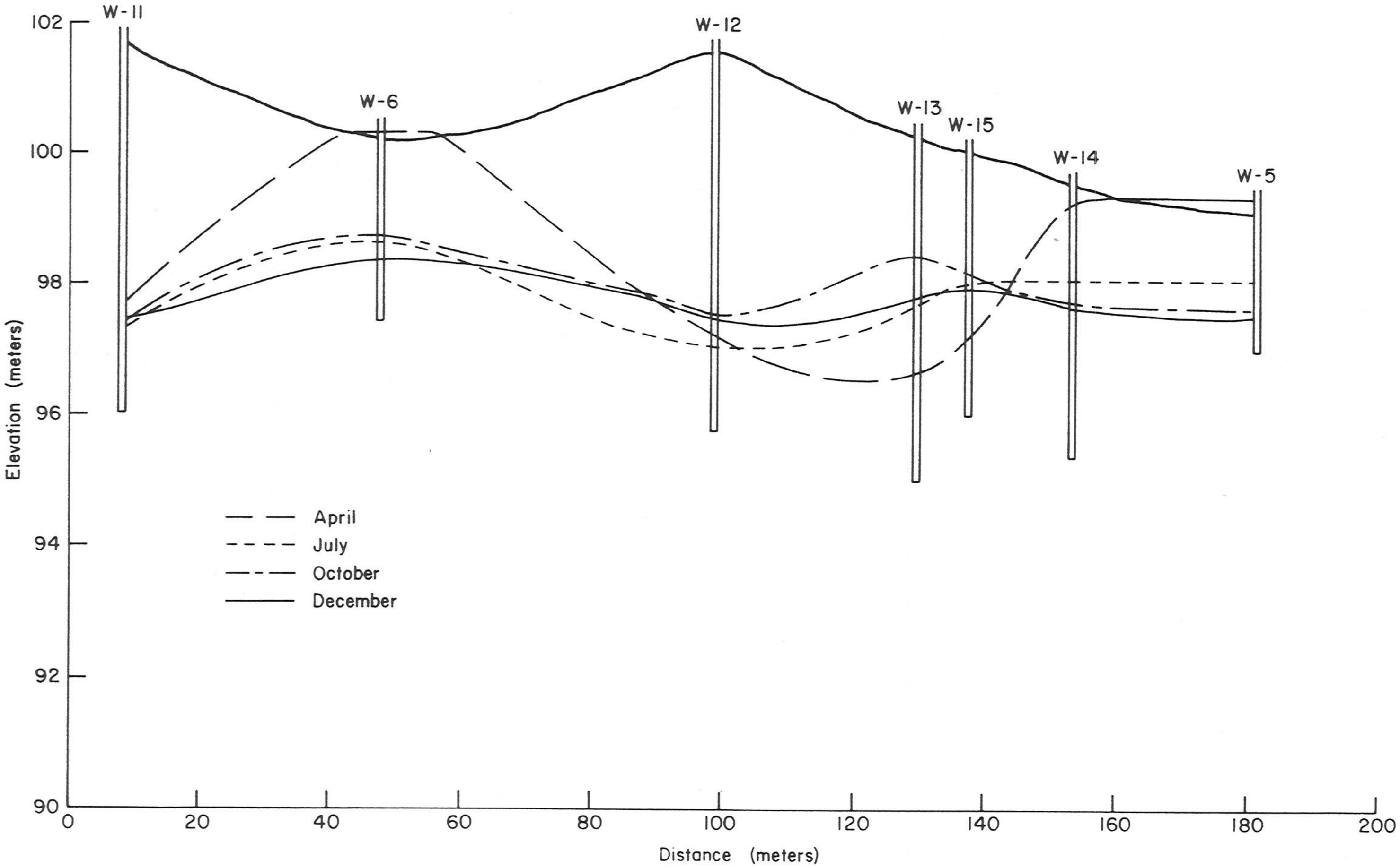


Figure.53 Water Table Patterns Along Transect From Well 11 to 5, Site 2 for 1980.

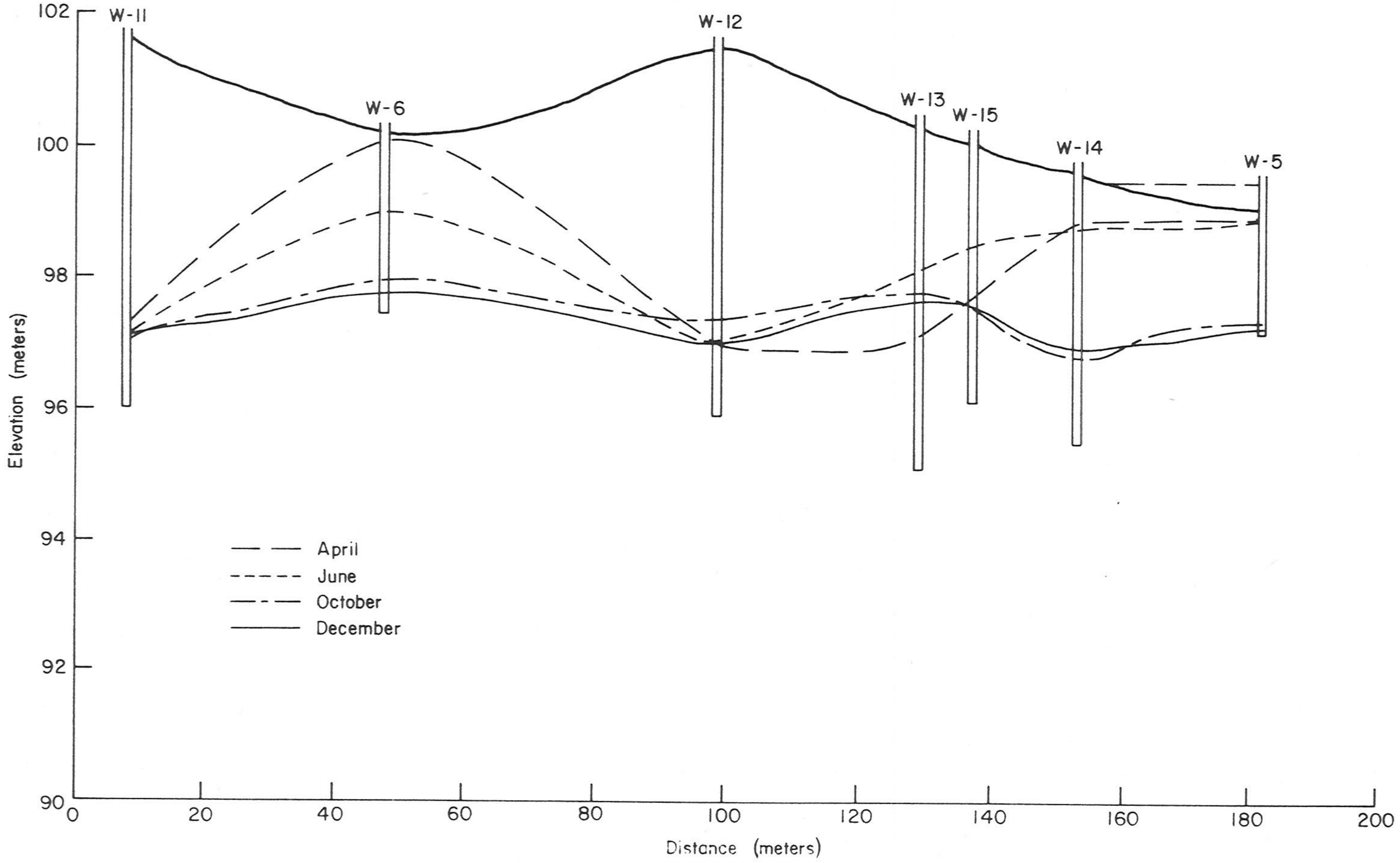


Figure.54 Water Table Patterns Along Transect From Well 11 to 5, Site 2 for 1981.

as evaporation and transpiration. For example, in Well 1 in April, the water table was at 27 cm but dropped to 173 cm in July while the water level rose from 312 cm in April to around 140 cm in July in Well 2, which is located in a higher position as a result of lateral movement of water from under the nearby depression.

c. In fall and winter: the water table flattens out and recedes to its lowest level in the cycle (Figures 51 and 53, October and December patterns).

In the spring a repeat cycle starts with the ponding of water in the depression. Heavy rainfall during the summer could result in ponding of water in the sloughs.

Grouping of wells according to water table levels.

To further study the characteristics of the groundwater, the wells were grouped into six classes (Table 13) on the basis of similarity in hydrological position in the landscape and chemical characteristics of the groundwater.

The wells in the lower and transient sloughs, and at the slough edge are characterized by a maximum water table around April to May. This is due to the effect of ponded water during spring time. On the other hand, the minimum water table levels occur in December.

For the non-saline well (Well 15), the highest water table occurs in June and the lowest in August to September. For the salt ring wells (Wells 2, 9, and 13), the highest water table occurred in June and July 1979 (for Wells 2 and 9

TABLE 13. The monthly period of maximum and minimum water table levels for six well groups for the 3 year period (1979-1981).

Well groups	Well numbers	Times of maxima	Times of minima
Lower slough	4, 5	April-May	December
Transient slough (upper sloughs included)	1, 6, 7	April-May	December
Slough edge	3, 10, 14	April-May	December
Non-saline ring	15	June	Aug.-Sept.
Saline ring	2, 9, 13	May-Sept.	June-Oct.
Knoll + midslope	8, 11, 12	Sept.-Nov.	May-Aug.

only), July to August in 1980 and May to July 1981. The lowest water table was reached usually around the month of December for 1979 and 1981 and around April in 1980. This relative delay in the water table rise in the year 1980 compared with the other two years can be most likely attributed to higher rainfall (96.3 mm) during the month of July in 1980 as compared with 52.5 in 1979 and 49.0 in 1981 for the same month.

The water level data from the wells located at the knoll and midslope positions (i.e. Wells 8, 11, and 12) are limited. This was because Well 8 was dry for much of the time and late installation of Wells 11 and 12. Nevertheless, the water table levels in these two topographic positions are considerably lower than in other positions. The levels in Wells 11 and 12 are generally about 4 m (see Table 25, p.281) below the surface and the water table shows very little fluctuation with time. The water level in Well 8 is also very low, being deeper than 4 m in 1979 and deeper than 6.5 m in 1980 and most of 1981.

The sudden rise of groundwater table in October 1981 in Well 8 could be related to a heavy rainfall prior to and during October (September: 47 mm and October: 39 mm). In 1980, there was 13 mm of precipitation in October, but the water table did not rise significantly as that year the land was heavily cropped and the fall rains just replaced the water in the soil moisture profile. This was not the case in 1981 when the land was in summer fallow and the soil had a high moisture content prior to the heavy rain.

6.4.2 Groundwater Flow

Vertical hydraulic gradient at the piezometer nests.

The hydraulic head measurements for the 2 year period of 1980 and 1981 for the 15 piezometers located around Wells 1, 5, 12, 13, and 15 at Site 2 are summarized in Table 14. From these data, the following conclusions regarding hydraulic gradients along the studied transects are made:

a. Centre of large slough (Piezometers 7 and 9) near Well 5. In the early spring when the soil is frozen, water ponds in the depression and the water table is at about 2 m which is the lowest level reached in late winter. In the early spring there is no perceptible gradient in the depression. In the late spring, the gradients are variable at a depth but frequently downward with rapid infiltration of ponded water, particularly in the willow ring area (at outer edge of depression) where the soil does not freeze to the same depth as in the centre of depression because it is protected by a thick snow cover that is trapped by the willows. In summer, the water table declines as a result of evapotranspiration and a small upward gradient develops at depth. In fall and winter, when the water table is low (about 1.5 m deep), plants are inactive and occasional fall rain results in small and variable gradients.

b. Centre of transient slough (Piezometers 4, 5, 6, 8, 14, and 15) near Well 1. Piezometer 6 gave results that were usually anomalous and were therefore disregarded. Piezometer 4 terminates in a small sand lens and may be subject to some

TABLE 14. Hydraulic head data from piezometers 1 to 15 for the period 1980 to 1981.

Well site	Ground elevation m	Piezometer (p) and their depths in m		Hydraulic Head m												
				23 Jul 1980	11 Aug 1980	16 Sept 1980	30 Sept 1980	4 Nov 1980	2 Dec 1980	15 Apr 1981	19 May 1981	5 Jun 1981	14 Jul 1981	10 Sept 1981	28 Oct 1981	10 Dec 1981
W-1	100.00	p 15	2.59	+	+	+	+	97.82	97.83	99.36	98.71	98.56	98.22	97.33	dry	dry
		p 4	3.00	98.17	97.97	97.68	97.80	97.80	97.83	99.57	98.72	98.57	98.25	97.42	97.17	97.20
		p 14	3.52	+	+	+	+	97.82	97.82	99.58	98.72	98.59	98.26	97.47	97.19	97.23
		p 6	4.00	98.13	97.92	97.80	97.82	97.84	97.80	99.12	98.65	98.55	98.22	97.44	97.14	97.15
		p 5	5.00	98.16	97.98	97.84	97.87	97.82	97.77	99.25	98.67	98.56	98.25	97.54	97.22	97.20
		p 8	6.00	+	+	97.85	97.88	97.84	97.78	99.24	98.66	98.57	98.27	97.54	97.23	97.21
W-5	99.05	p 7	3.50	97.53	98.29	97.79	97.78	97.69	97.64	99.04	99.03	98.82	97.85	97.13	97.30	97.22
		p 9	6.00	+	+	97.88	97.79	97.72	97.65	99.88	99.03	98.80	97.94	97.19	97.30	97.18
W-12	101.36	p 11	4.50	+	+	97.30	97.39	97.35	97.25	96.88	m	dry	97.05	97.22	97.11	dry
		p 10	6.00	+	+	97.34	97.43	97.38	97.29	96.94	m	96.94	97.07	97.25	97.19	97.98
W-13	100.33	p 1	3.25	97.87	97.93	98.32	98.36	98.21	98.04	97.12	98.04	98.19	97.99	97.48	97.65	97.71
		p 3	4.17	97.80	97.92	98.36	98.34	98.16	98.00	ff	97.93	98.23	98.02	97.47	97.57	97.64
		p 2	5.35	97.81	97.91	98.29	98.34	98.14	97.93	ff	97.52	97.96	97.98	97.54	97.57	97.60
W-15	100.07	p 13	3.50	+	+	98.29	98.26	98.06	97.96	ff	m	98.43	98.05	97.26	97.39	97.55
		p 12	6.00	+	+	98.28	98.13	98.11	98.00	97.74	m	98.36	98.18	97.39	97.30	97.45

ff = frozen
\+ = not installed at sampling time
m = missing

lateral flow. From the piezometers readings, the following interpretations are made:

In early spring, when the soil is frozen, about 10 cm of water is ponded in the depression and the water table is at about 2 m. The hydraulic head is highest at 3 m with an upward gradient above and a downward gradient below, indicating entry of water in the sand lens. In late spring, when the soil thaws, the water infiltrates and the water table rises to a peak of about 50 cm below the surface. The gradient at this time is strongly downward at depth and upward near the surface as plants use water. In summer, fall, and winter the water table continues to decline to reach a minimum of about 3 m below the surface while gradients are low and often upward in summer changing to neutral and then to slightly downward in fall and winter.

c. <u>The outer edge of large slough</u> (Piezometers 1, 2, and 3 & 8, 12, and 13) near Wells 13 and 15. In spring, when the soil is frozen, the water table is at about 3 m and declining. The gradient at depth is upward. In early summer the water table rises slowly with the maximum occurring later at longer distances from the slough; the depth ranges from 40 cm to about 2.5 m. Meanwhile, there is a downward gradient at depth during the passage of the water table maximum, but upward before and after, which indicates that most of the lateral movement takes place at shallow depths. By inference, the gradient in the unsaturated zone must be always upward. In late summer, fall, and winter the water table declines with some fluctuations due to fall rains and the gradients are generally downward in the fall and upward in winter.

d. *Knoll position* (Piezometer 10 and 11) near Well 12. In spring, when the soil is frozen the water table is low as it is in summer and fall (about 4 to 5 m deep), with some declining trend. There is a small gradual rise in summer and fall, which may be due to the lateral movement of groundwater from neighboring sloughs. Meanwhile, the rain water that infiltrates in the soil must be lost again by evapotranspiration. In winter, there is a gradual decline of water table to about 50 cm below the maximum. The gradient at depth is upward over the four seasons.

Groundwater flow pattern

The flow pattern within the studied transects (Figures 56 & 57 p. 165 & 166 shows that: (a) on June 5, 1981, there was a general outflow at depth (below the water table) from the sloughs to the areas between the sloughs (e.g. knoll position), while at shallow depths the unsaturated flow direction was generally upward and (b) on July 14, 1981, there was a reversed flow pattern at depth at Well Sites 13, 15, and 14 toward a higher knoll position on one hand and toward the large slough (i.e. Well Site 5) on the other. At shallow depths, the flow pattern remained generally upward due to lower water potentials toward the soil surface caused mainly by evapotranspiration within the whole transect.

Groundwater flow and its influence on soil genesis.

Site 1. Parry (1968) produced a diagram showing the groundwater flow conditions around the large slough (Figure 55) and discussed the groundwater movement from and into the slough within shallow and deeper depth. From Parry's figure and discussion, the following conclusions may be reached:

a. There is a general flow (i.e. regional) into the slough from the north and general outflow to the south. This inflow-outflow system is indicated by piezometeric heads within the slough itself. Near the north and south edges of the slough piezometeric heads were found to be lower than the level of water in the slough, indicating outflow. Although the inflow-outflow system in the till material is nearly vertical, Parry mentioned that lower hydraulic heads in the sand than in the till immediately above the sand indicates the presence of lateral flow.

b. From the shallow piezometers, the direction of local flow is nearly upward toward the water table in the north end of the slough. However, from the water table data (e.g. Figure 55), the water table was high at the north end of the slough and low at the south end. Moreover, there is a depression in the water table around the slough where the water table rises away from the slough or slopes away from the slough. This depression is believed to be caused by consumptive water use by phreatophytes and by evaporation from soil surface.

The soils in the studied transect range from Gleysols near the edge of the slough through Rego Blacks and then to

Orthic Blacks toward the higher area. Moreover, the morphological characterization (macro and micro) indicates that there is a high accumulation of secondary carbonate and some soluble salts within 50 to 100 cm from the soil surface in the non-saline zone of the transect (see Figure 23, p.106) and within the upper meter from the soil surface in the saline zone.

The general distribution pattern of soluble salts and carbonate accumulation could be described as follows: the soluble salts occupy the upper part of the accumulation zone in the profile while carbonates are concentrated in the lower part of the accumulation zone. This distribution pattern indicates the groundwater origin of these accumulations in the sense that the least soluble carbonate precipitates first due to upward movement of groundwater in the unsaturated zone followed by the more soluble salts above the carbonate layer. In addition to this, the upward movement of groundwater toward the water table maintains the critical depth of water table during the summer-fall period for the accumulation of soluble salts and carbonate at the present level (i.e. within 1 m).

Site 2. Looking over the groundwater flow conditions and soil distribution pattern within the two studied transects (Figures 56 and 57), the following points are made:

a. Transect from Wells 1 to 5. The soil at Well 1 (Humic Luvic Gleysol) is highly leached and eluviated, which could be attributed to a net downward movement of groundwater during the spring and short drying period in the upper part of the soil which is essential for the development of Bt

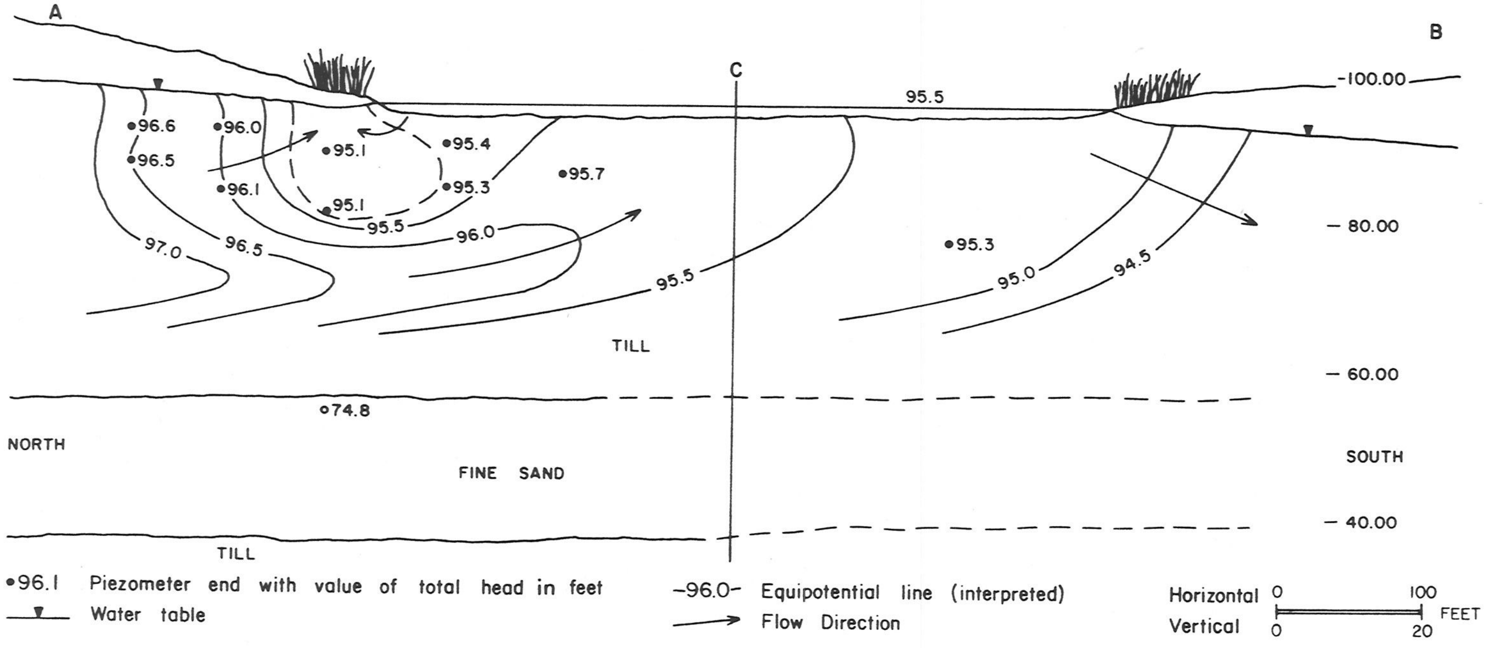


Figure.55 Flow Conditions Along Section A - B in Slough A, August 29 1967 (after Parry, 1968).

horizon. These conditions could be applied to the soil around Well 5 except that the soil does not become dry enough with depth for the eluviation process to begin. On the other hand, the soils around Well 2 developed a surface salinity (ECe around 6.0 mS/cm within upper 50 cm) which could be related to saline and shallow groundwater particularly during dry periods. However, as in Figure 56, the upward movement of groundwater within the unsaturated zone should be considered in continuity to the discharging system of saturated flow. This upward movement of saline groundwater is considered the main cause of salt accumulation in the saline horizons.

b. Transect from Well 11 to 5. The soil around Well 6 is similar to the soils around Well 1 (Humic Luvic Gleysol); consequently, by inference there must be a downward movement of groundwater particularly during the spring period. Dealing with soils and underlying materials around Well 12, where the water table is fairly low (<4m) throughout the year, there is a shallow concentration of soluble salts as a result of the redistribution of these salts in the soil material. However, the low ECe values (<1.0 mS/cm) between 1 and 6 m could be attributed to the original content of soluble salts in these materials which is in this case low. In the saline zone (around Well 13), where the saline groundwater is shallower during dry seasons (∿2 m) and the flow pattern in the unsaturated zone is upward or toward the saline zone from the east part of the transect (Figure 57), there is a surface accumulation of soluble salts within 50 cm. However, the high salinity

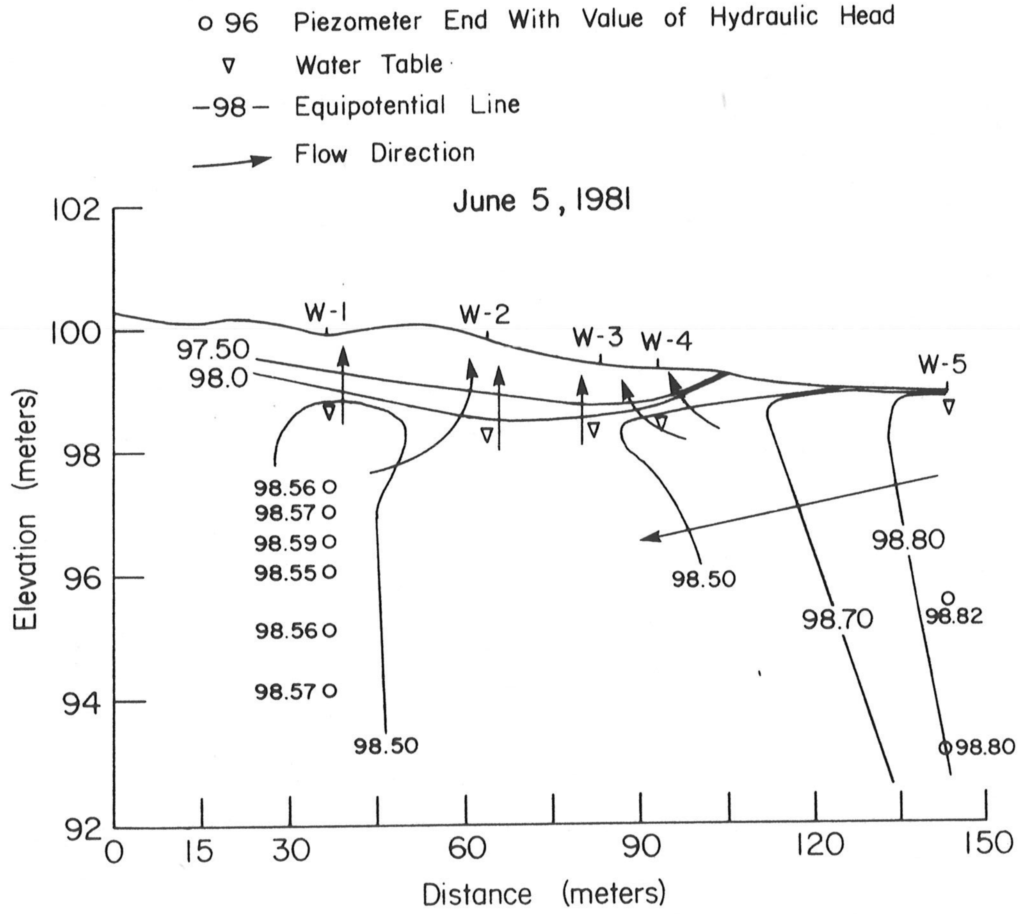


Figure.56 Groundwater Flow Conditions Along Transect From Wells 1 to 5 at Site 2.

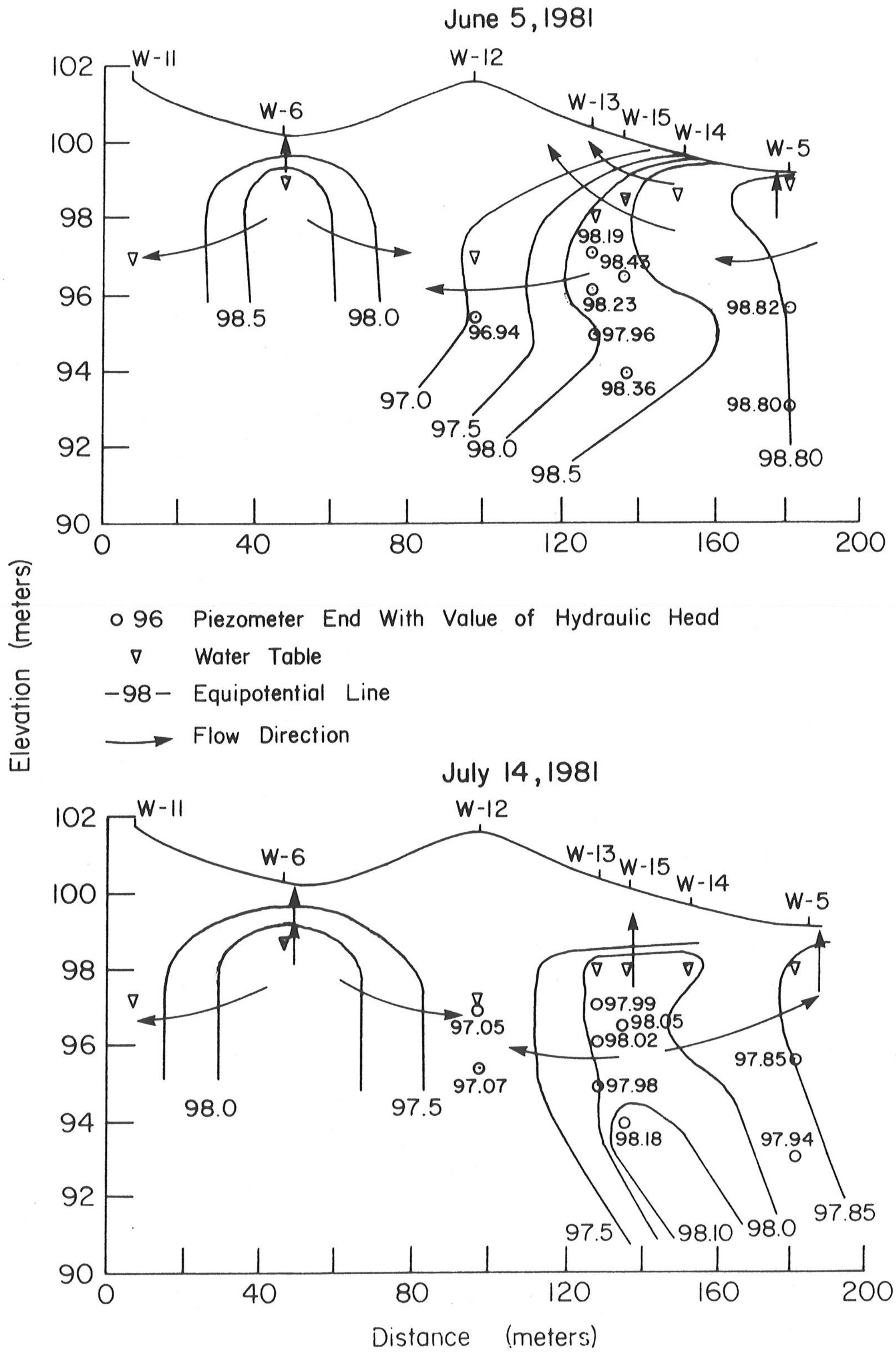


Figure.57 Groundwater Flow Conditions Along Transect From Wells 11 to 5, Site 2

(3 mS/cm) at depth can be attributed to the net upward movement of saline groundwater in this zone (∿ 2 to 5 m deep).

6.4.3 Groundwater Chemistry

The groundwater chemistry along the soil transects was studied to determine the change in salt level and ionic grouping with time. The chemical data for 8 months in 1979 to 1980 for most of the observation wells at Sites 1 and 2 are presented in Tables 26 to 33 (see Appendix I, p. 282). A grouping of wells was made on the basis of salinity and ionic distribution and a summary of the chemical composition of the groundwater appears in Table 15.

Non-saline wells (Wells 1, 3, 4, 5, 6, 7, 10, 12, 14, and 15): The values for ECw for the groundwater samples vary from 0.4 to 1.1 mS/cm with a mean value for 7 months of 0.64 mS/cm. The ECw values for any single well in this group remained relatively constant for the above period. The ionic distribution in a decreasing order of magnitude in the above wells is HCO_3^- - Ca^{++} - Mg^{++}.

Saline wells (Wells 2, 9, and 13): The ECw for the groundwater of Wells 2, 9 and 13 varies between 1.6 to 3.4 mS/cm with a mean value for 8 months of 2.69 mS/cm. The maximum ECw reading was in May to June (Tables 26 to 33, Appendix I, p. 283-290 for Wells 2 and 9, while for Well 13, the maximum reading was in September to November. The ionic distribution is characterized by SO_4^{--} with the dominance of either Ca^{++} or Mg^{++}; these results agree with the finding regarding chemical composition of natural water of Chebotarev (1955).

There is an indication of decreasing salinity in 1980 compared with 1979 for the non-saline group of wells (e.g.

TABLE 15. Summary of the chemical composition of the groundwater from non-saline and saline areas.

ECw and ion concentration	Non-saline area (Wells 1, 3, 4, 5, 6, 7, 10, 12, 14 and 15)		Saline area (Wells 2, 9 and 13)	
	Range	Mean	Range	Mean
ECw mS/cm	0.37- 1.08	0.64	1.60 - 3.37	2.69
Ca^{++} meq/L	1.65- 8.48	3.85	5.30 -32.68	20.98
Mg^{++} meq/L	0.82- 7.89	2.94	10.69 -32.89	21.58
Na^{+} meq/L	0.06- 1.17	0.32	1.06 - 4.09	1.98
K^{+} meq/L	0.04- 0.54	0.23	0.14 - 0.54	0.37
SO_4^{--} meq/L	0.99-14.42	3.11	20.10 -57.90	40.23
Cl meq/L	0.00- 0.85	0.23	0.17 - 2.90	0.66
CO_3^{--} meq/L	0.00- 0.57	0.13	0.00 - 0.33	0.05
HCO_3^{-} meq/L	2.00- 9.04	4.56	nil - 5.92	3.62

ECw for Well 4 was 0.96 mS/cm in September 1979 and 0.5 mS/cm in September 1980) (Tables 26-33, Appendix I, p. 283). On the other hand, the salinity increases for the saline group of discharge character (e.g. ECw for Well 2 and 1.70 mS/cm in September 1979 and 2.35 mS/cm in September 1980). These results could be related to the higher precipitation in 1980 compared with 1979 (Table 34, Appendix J, p. 291). This high precipitation may lead to more dissolution and translocation of salts from the recharge areas to be concentrated in the discharge areas within the same soil cross section. Similar findings have been mentioned by (Lissey, 1968; and Toth, 1966).

6.5 Seasonal Soil Temperature at the Studied Area

Soil temperature data for 2.5, 5, 10, 20, 50, 100, and 150 cm depths in six different locations in the study area (Figure 9, p. 57) appear in Tables 35 to 37 (Appendix K, p. 293). Air temperatures were determined at each site when soil temperatures were recorded. From an examination of thermographs plotted for the 3 year study period (Figures 58 to 63) the following generalizations can be made:

(1) An obvious feature of the soil temperature data lies in the narrow range of temperatures in the depressional areas (Figures 61, 62, and 63) compared with the non-depressional areas. This is probably because of the higher moisture contents in the depressions compared with other areas in the study sites.

(2) In spring (March-April), frozen soil[27] of non-depressional areas prevents snow melt and spring rains from infiltrating and as a result, most of the water moves downslope to the lower positions of the landscape (sloughs). Furthermore, when the slough bottom thaws, a groundwater mound forms beneath the slough. The above hypothesis could not be confirmed because of lack of short term temperature readings (i.e. weekly or biweekly) in the freezing-thawing period and the lack of thermocouples in some sloughs. However, groundwater patterns within the study period (Figure 54, p. 154) have helped to draw the above generalization.

(3) The effect of the soil thermal gradient on the groundwater movement may have been important in all temperature sites, e.g. the soil temperature minimum of March 1980 was the lowest in more than 3 years, while the groundwater level at that time was the lowest within the study period (Table 25, Appendix H, p. 281). This could suggest upward movement of groundwater toward the frost layer in the soil which reaches more than 150 cm deep for all soil temperature sites. Thawing of this ground ice would result in an addition of water to water table in the spring. Similar results have been obtained by Hockstra (1966), Benz *et al*. (1968), and Cary (1971).

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[27] Frost period about 5 months from December to April (see Appendix K, p. 293 for more details).

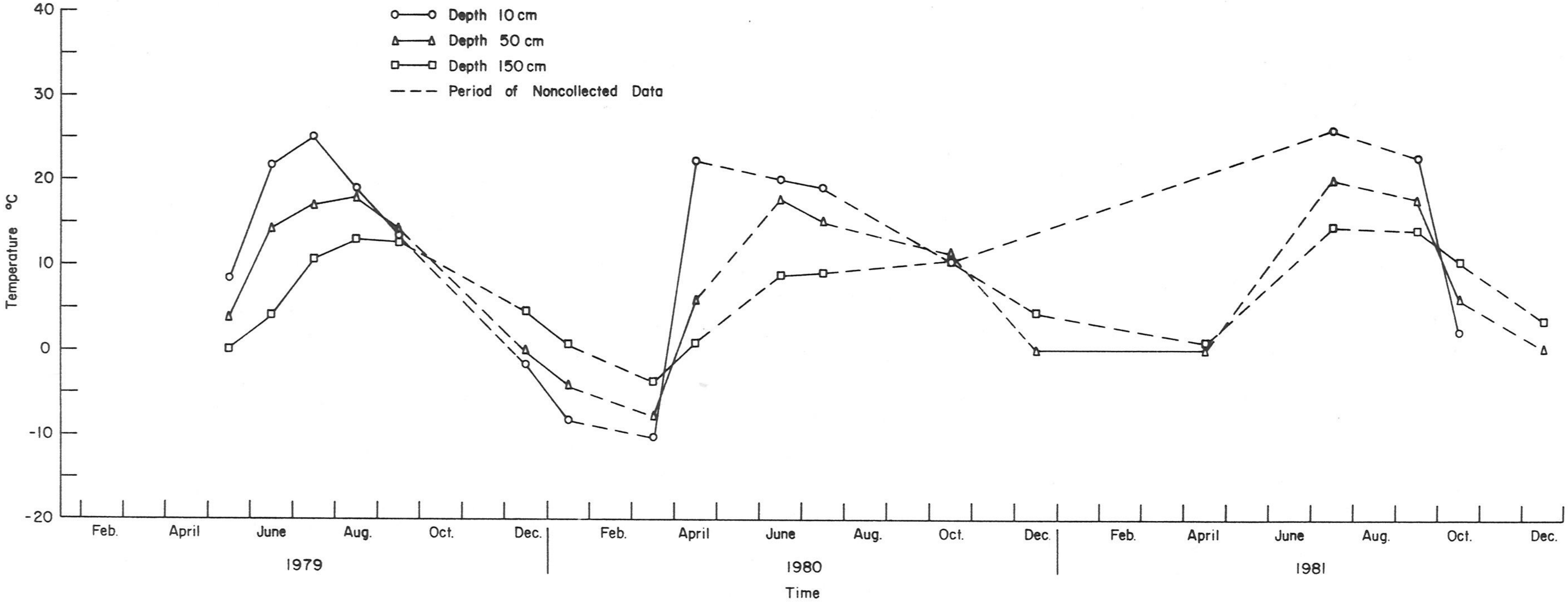

Figure.58 Seasonal Variation of Soil Temperature in the Mid-slope Position Near Profile 1 (Rego Black, saline Phace), Site 1.

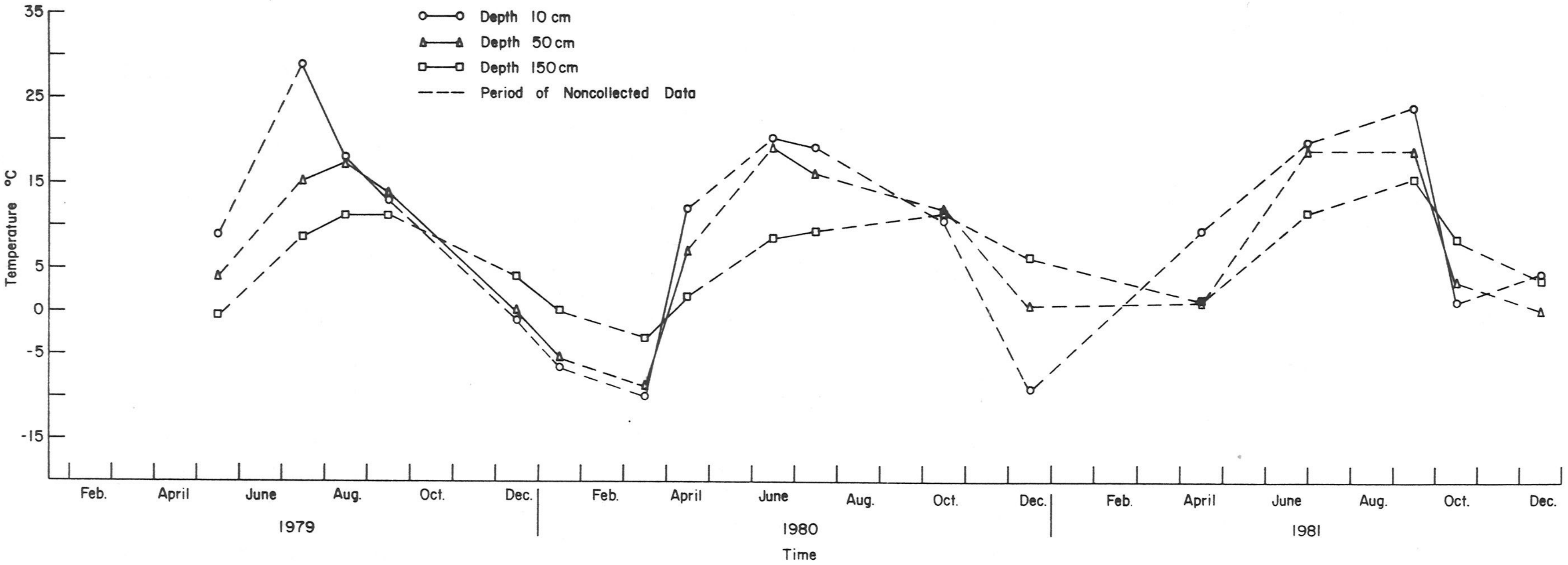

Figure 59 Seasonal Variation of Soil Temperature in the Knoll Position Near Profile 2 (Orthic Black), Site 1.

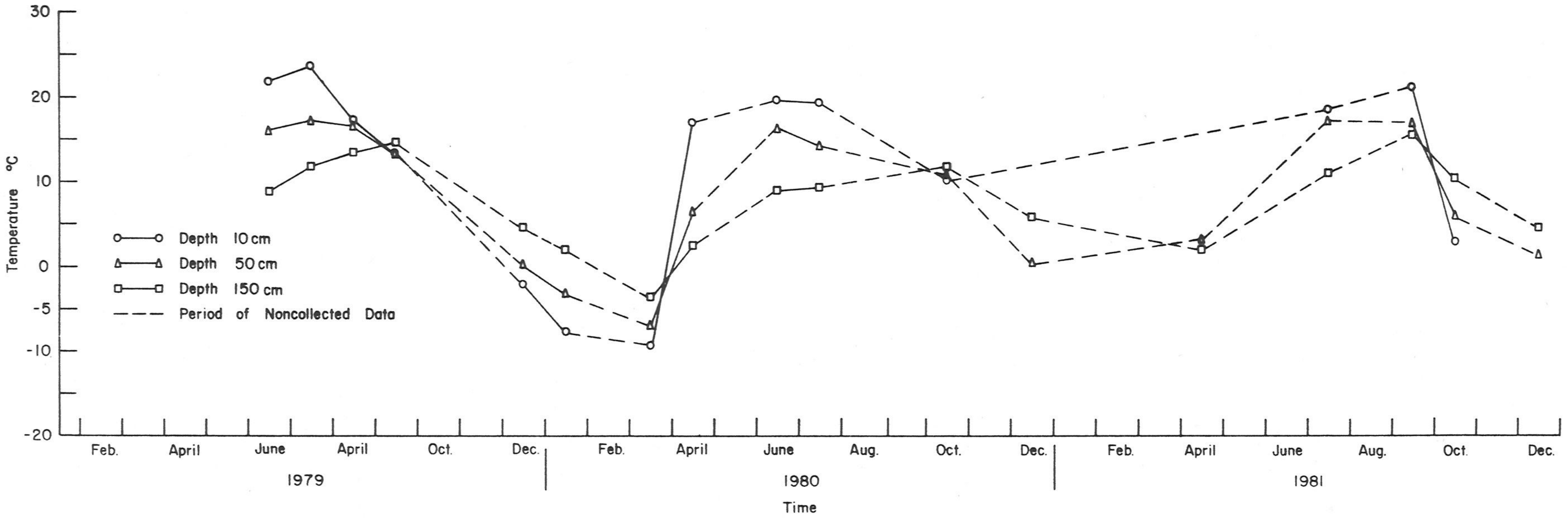

Figure 60 Seasonal Variation of Soil Temperature in the Upper Depression Near Profile 3 (Gleyed Dark Gray Luvisol), Site 1

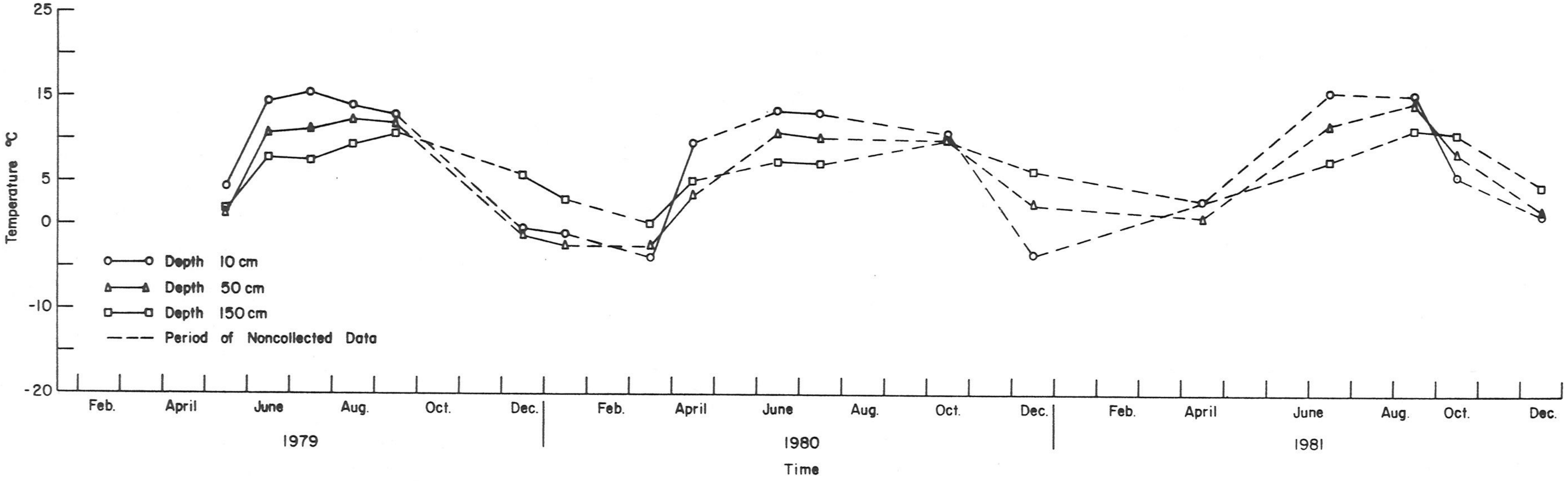

Figure.61 Seasonal Variation of Soil Temperature in the Lower Slope Position Near Profile 6(Rego Black).Site1.

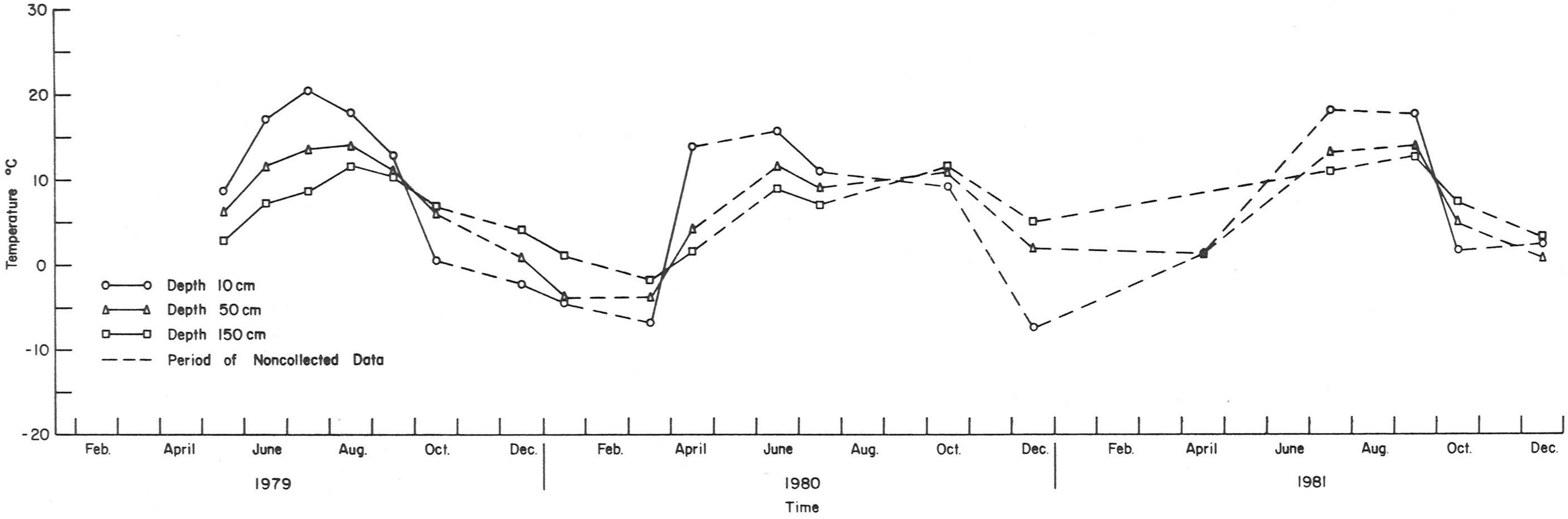

Figure.62 Seasonal Variation of Soil Temperature in the Upper Depression Near Profile I (Humic Luvic Gly sol). Site 2.

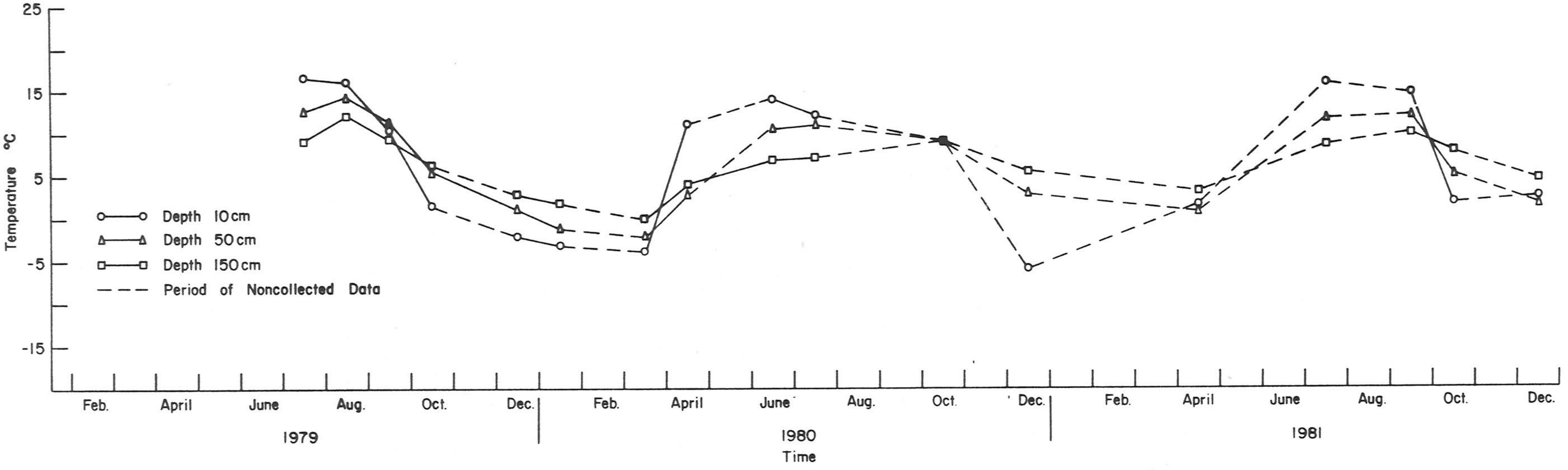

Figure.63 Seasonal Variation of Soil Temperature in the Lower Depression Near Profile 3 (Rego Humic Gleysol), Site 2

7. GENERAL DISCUSSION

7.1 Groundwater Flow Conditions in Relation to Topography

The two sites used in the study, were characterized by low relief knoll and depression topography with numerous undrained sloughs and aspen parkland vegetation. According to Lissey (1968), the two sites are situated in a regional recharge area; however, the local differences in topography have created local groundwater flow systems. The local flow systems are influenced mainly by the presence of sloughs in the landscape. Indeed, Lissey considered the sloughs as focal points in the Canadian prairies where the actual transfer of water to and from the zone of saturation is confined.

From Figure 57 (p. 167) which shows the flow condition at Site 2 along the transect from Wells 11 to 5 in early June and mid July 1981, it can be concluded that there was a lateral flow below the water table from the sloughs to the area between the sloughs. A similar situation existed along the transect from Wells 1 to 5 (Figure 56, p. 166). For Site 1, using Parry's groundwater flow diagram (Figure 55, p. 164) for the transitional slough, as well as for Site 2, the hydraulic gradient at a shallow depth below the water table together with the unsaturated flow direction is generally upward. This upward movement of groundwater particularly in the unsaturated zone is responsible mainly for the formation of saline zones as will be discussed below.

7.2 The Soil Development and Distribution at Sites 1 and 2 in Relation to Groundwater Regimes

7.2.1 Depressional Area Soils

At Site 1, the soil at the upper depression was a Gleyed Dark Gray Luvisol, while the soils of lower depressions (about 2.5 m lower than the upper depression) were Rego Humic and Orthic Humic Gleysols (Figure 12, page 61). The Luvisol probably developed due to a strong downward gradient of groundwater in spring-early summer (e.g. in 1980, the water table was at 209 cm in late spring and dropped to 393 cm in mid June). The fact that the water table for much of the summer period was below 2 m resulted in the drying out of the soil above the water table which facilitated the dispersion and eluviation of clay and the formation of the Ae and Bt horizons. The soils in the lower slough developed under the influence of permanent surface water or a very high water table level most of the year. Consequently, the soils in the lower depression were developed under very restricted leaching conditions and under anaerobic conditions which resulted in the formation of Gleysolic soils.

At Site 2, the reasons behind the development of Luvic Gleysols in the sloughs (transient depressions) around Wells 1 and 6, on one hand, and Humic Gleysols around Well 5 (Figure 14, p. 63), were probably similar to a certain extent to the ones discussed for Site 1. For example, in late April 1980, the water table depth was 27 cm at Well 1 and 10 cm of water was ponded around Well 6 but by mid June the water table levels were down to 125 cm for Well 1 and 148 cm in Well 6. Meanwhile, the water table at Well 5 dropped from 5 cm of ponded water to 41 cm for the same period. This 1 m drop in groundwater level for Wells 1 and 6 in the spring to early summer period probably resulted in a leaching of soluble salts and carbonate and some eluviation of clay in the soils around these wells. Around Well 5, the drop of groundwater level was less than 50 cm for the same period which resulted in the absence of enough dryness in the upper part of the soil profile in which restricted the eluviation of clay to the lower horizon. Indeed, the Humic Gleysol soil around Well 5 is leached of carbonates to about 50 cm but shows evidence of little clay eluviation.

7.2.2 Knoll Soils

The soils on the knoll were classified as Orthic Black at both Sites 1 and 2 (at Wells 8 and 12, respectively). The formation of the Orthic Black Soils which located on the knolls was not affected by groundwater. Indeed the water table depth at these 2 soil sites was more than 4 m for most of the study period (Table 25, Appendix H, p. 281). This water table depth could be considered deep enough to not affect the soil horizons formation. However, the formation of a shallow solum in this position is probably due to the infiltration of rain water accompanied by leaching of soluble salts and carbonate to about 1 m. Some eluviation of clay also occurred on the soil at Well 8.

7.2.3 Saline and Non-Saline Soils around depressions

These soils do reflect the groundwater regime showing zones of salt accumulation, commonly gypsum,located within 5 m of the edge of the sloughs and range from Orthic to Rego Black "saline phase" in the saline zone and Rego Black to Gleyed Rego Black in the non-saline zone of Site 1. At Site 2, the soils were dominantly saline phases of Gleyed Calcareous Black to Rego Black in the saline zones while in the non-saline zones, Gleyed Black to Rego Black were the common soils.

The genesis of these soils was influenced by a relatively shallow water table and by the upward hydraulic gradient above the water table. For example, the water table depths in the saline zone (Well 9, Site 1 and Wells 2 and 13, Site 2) rose from about 350 cm in late April to around 200 cm in summer, while in the non-saline soils (Well 15, Site 2), the water table rose from 250 cm to 160 cm for the same period. The rise of water tables to those depths together with the upward hydraulic gradient near and above the groundwater table resulted in the precipitation of soluble salts and/or carbonates in the saline and non-saline zones. The salts near the surface in the saline zone are due to the high salinity of groundwater (2 to 3 mS/cm). Meanwhile, in the non-saline zone, because of low salinity (0.5 mS/cm) of the groundwater the salt accumulation is hardly noted.

The soluble salts and carbonates in the saline zone maybe of relatively recent origin since they are found in some soils that have weak to moderately developed Bm horizons (Figures 12 and 14).

The Bm horizons presumably formed after the original salts and carbonates were leached out and that in more recent times due to a change in the groundwater regime, resalinization and recarbonation of the A and B horizons has occurred. The fact that the Carbonate accumulation occurs below the more soluble salt accumulation zone indicates that both the Carbonates and salts originated from groundwater.

7.3 Origin, Mobility and Accumulation of Soluble Salts and Carbonates

Looking at the EC_w values and ionic distribution pattern of groundwater in the wells along the studied transects from July 1979 to November 1980 (Tables 26 to 33, Pages 283 to 290)and the EC_e, $CaCO_3$ and ionic distribution in the soils and underlying materials (Figures 23 to 30, p. 106 to 113) the following points can be made:

Site 1. Since there is an inflow of groundwater to the slough from the north side (Figure 55, p. 184) it is likely that the infiltrating water, mainly from snow melt and rain, penetrates the soil and underlying material of the higher areas and transports the salts towards the slough. These dissolved salts, together with the salts dissolved within the flow path of probably local system, then discharge near the slough and gives rise to a ring of saline soils in the cultivated field near the edge of the slough. This explanation could be applied to the soluble salts accumulation; however, for the carbonate accumulation, the source of carbonates appears to be from the shallow groundwater flow from the slough. The water in the slough is non-saline but highly carbonated. The carbonates in the non-saline ring near the slough edge also originate from the groundwater under the slough.

Site 2. In the transect along Wells 1 to 5, the flow direction at depth in early June 1981 is from the sloughs to the area between the sloughs where the saline zones are located (Figure 56, p. 166). This local flow system appears to be the main source of soluble salts to the saline zone. Dealing with the carbonate accumulation in the saline zone, the upward movement of groundwater at shallow depth from the slough toward the saline area is probably responsible for their precipitation.

In the transect along Wells 11 to 5, the groundwater flow direction at depth during spring to early summer is from the sloughs to the area between the sloughs, while in midsummer and later there is a reversed flow pattern at a depth under Well Sites 13, 15, and 14 toward a higher knoll position on one hand and toward the large slough on the other (Figure 57, p. 167; Table 14, p. 159). Again, by applying the previous explanation for the translocation of soluble ions, these ions could be moved at depth laterally from the slough area to the area between the sloughs, then by shallow upward movement of saline groundwater, the salt accumulations were formed. As in the previously discussed transect of this site, the carbonate accumulation in the saline zone is of shallow groundwater origin from the nearby slough.

From a micromorphological and mineralogical point of view, the horizons of secondary carbonate accumulation in the saline and non-saline rings are considered to be moderately to highly developed because of the presence of calcitic nodules, calcans, and the crystic plasmic fabric. Because of the low solubility of carbonates, these formations most likely developed over a long period of time. Meanwhile, the forms and features of the accumulated soluble salt indicate a relatively short cycle of development (i.e. washed down in the soil in response to rainy season and accumulation in the dry season). This conclusion is based on the presence of meta-stable thenardite and the occurrence of different weathering stages of gypsum (see Sections 6.3.1, p. 127 and 6.3.2, p. 138).

7.4 Applicability of the Findings in Relation to Groundwater Flow Soil Distribution and Topography

In the hummocky till land form of southwest Manitoba, topography is considered to be an important soil factor for the prediction of the soil profile type distribution from the knoll to the depression. Often, however, the relationship between topography and soil distribution is insufficient to explain the soil development and soil distribution particularly in the depressional area or immediately adjacent to the depressions. Information about the water table depth and fluctuation along the transect throughout the year helps to explain the soil distribution. For instance, the soils around Well 7, Site 1 (i.e. Gleyed Dark Gray Luvisols) are developed with a greater drop in groundwater in spring-summer period (about 2 to 4 m) while the soils around Wells 1 and 5, Site 2 are Humic Luvic Gleysols and Humic Gleysols, respectively, with a shallower water table for the same period (i.e. .06 to about 2 m for Well 1 and from 0.65 m of ponded water to about 1 m for Well 5).

Another interesting point is the formation of saline zones in the study area. Because of the groundwater origin of the soluble salts in these zones, the change in groundwater behaviour in response to various factors (wet or dry years, cultural practices) could influence the formation and extent of these zones. The presence of a relatively non-saline zone adjacent to the sloughs is a common feature in the studied areas. These zones are formed probably as a result of a lateral and upward flow of fresh slough water.

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APPENDICES

APPENDIX A

(Location of soil inspection holes and profiles at sites 1 and 2)

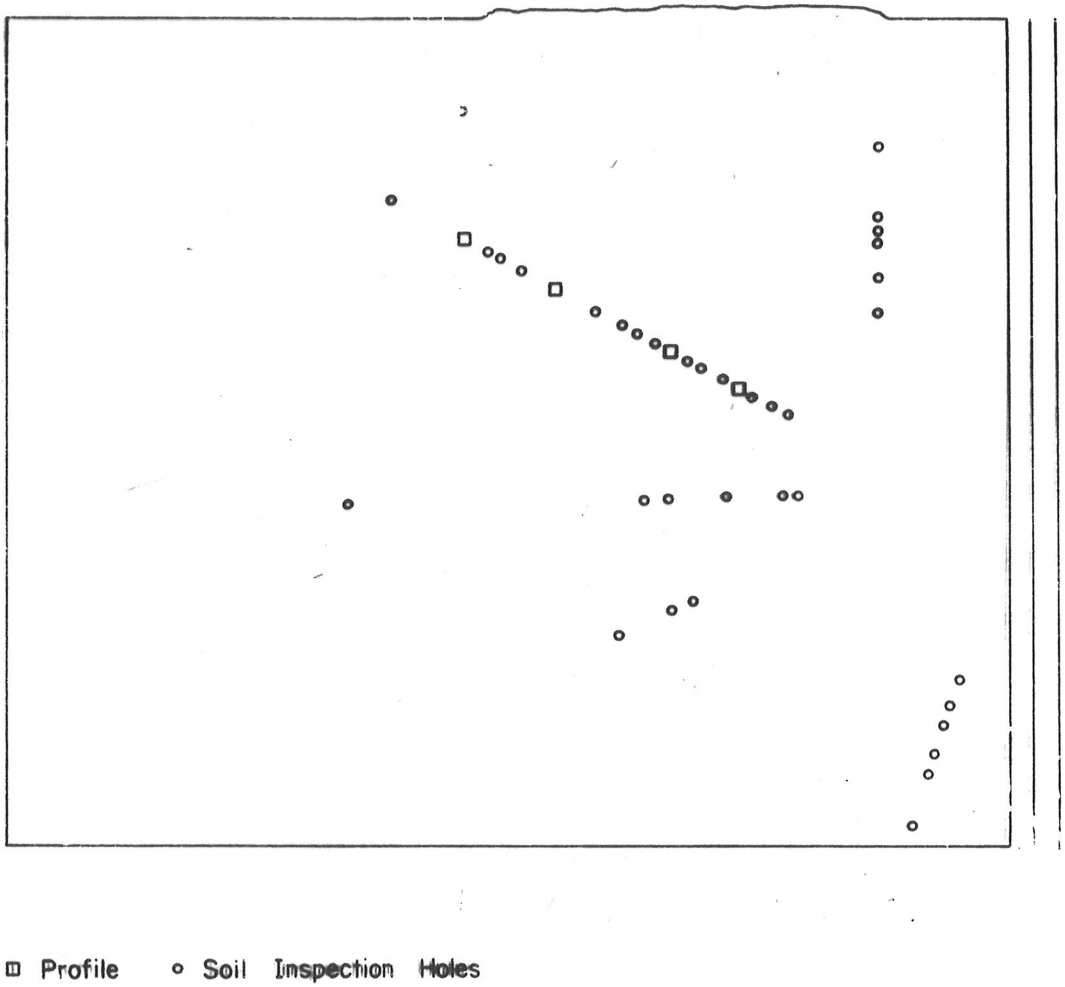
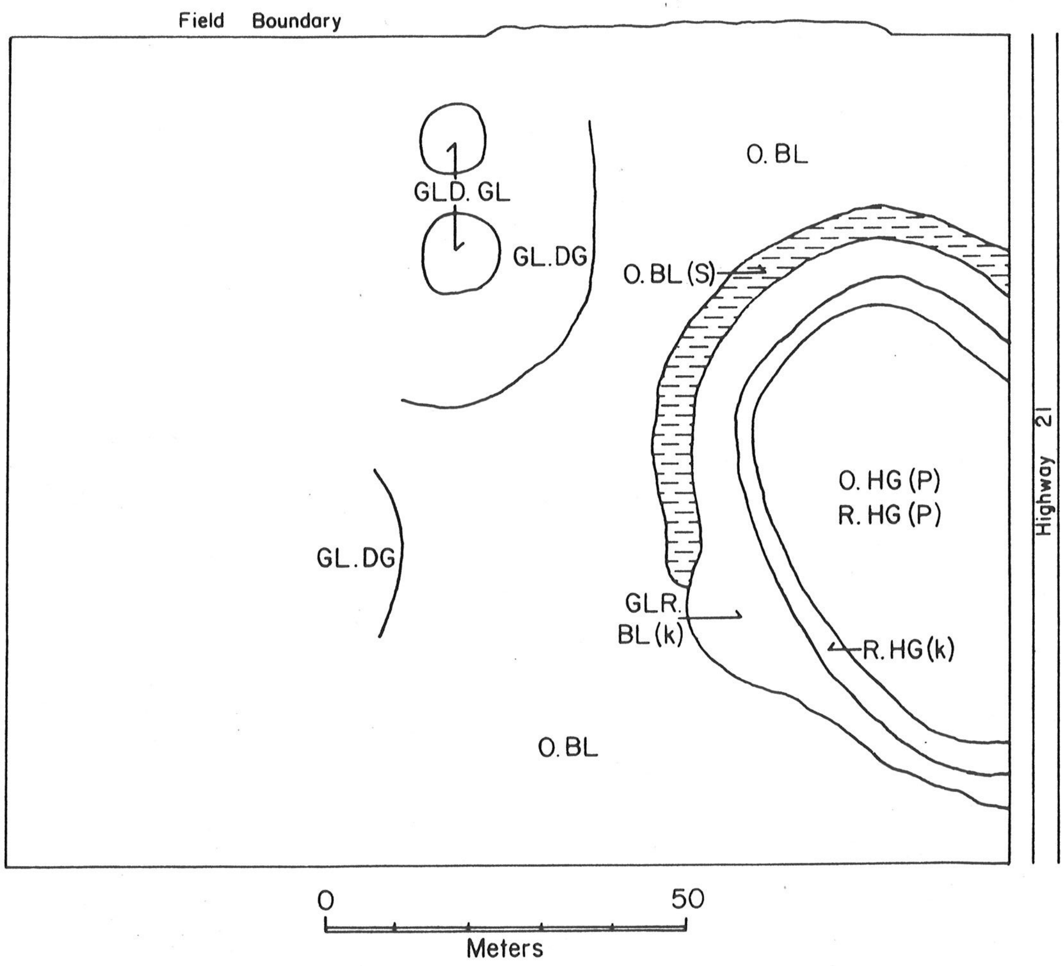


Figure 64. Location of Soil Inspection Holes and Profiles at Site I



Black Chernozemic

O. BL	Orthic Black
O. BL (S)	Orthic Black (saline phase)
R. BL	Rego Black
GLR. BL (K)	Gleyed Rego Black (carbonate phase)

Dark Gray Chernozemic

GL. DG	Gleyed Dark Gray

Humic Gleysol

O. HG (P)	Orthic Humic Gleysol (peaty phase)
R. HG (P)	Rego Humic Gleysol (peaty phase)
R. HG (K)	Rego Humic Gleysol (carbonate phase)

Gray Luvisol

GLD. GL.	Gleyed Dark Gray Luvisol
▤	Saline Phase

Figure.12 Soil Map of Site 1 (South of Hamiota). SE 30-13-23W1.

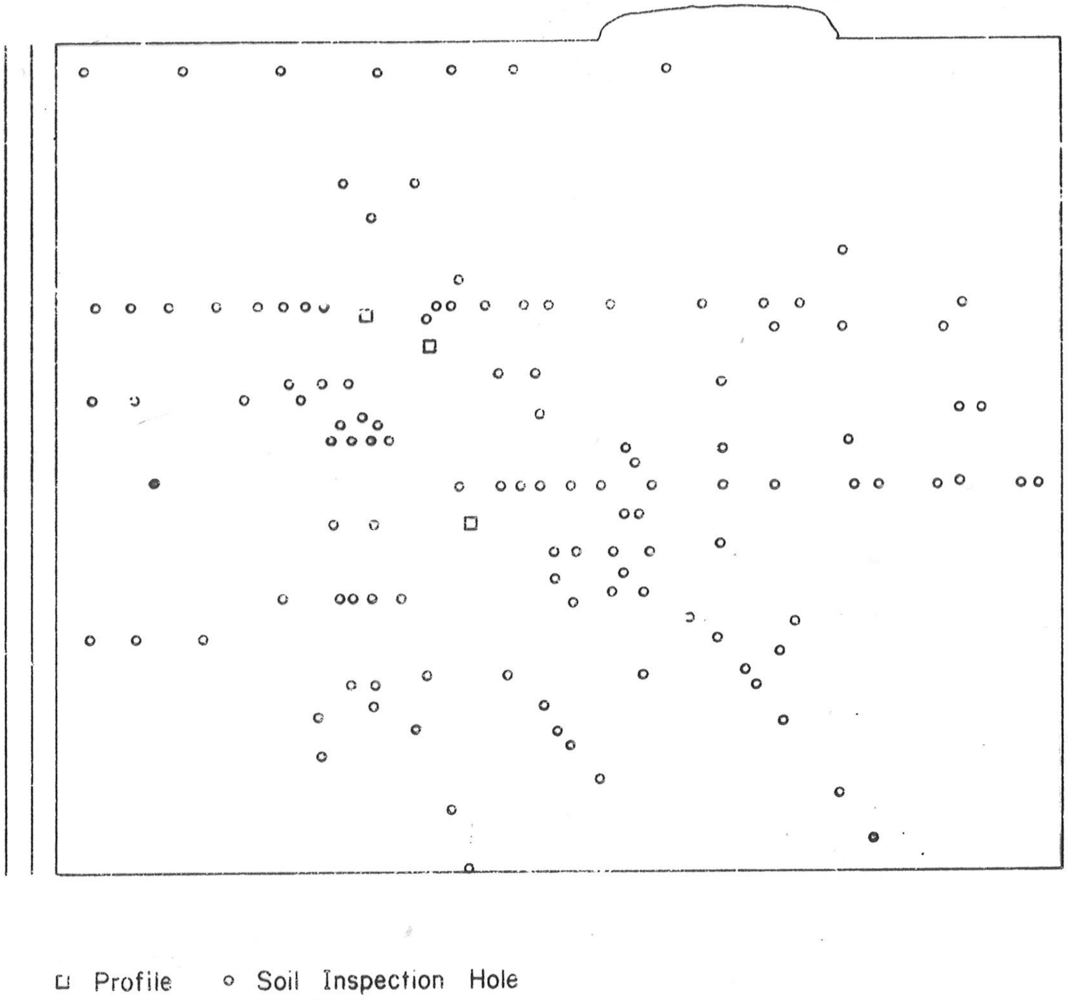
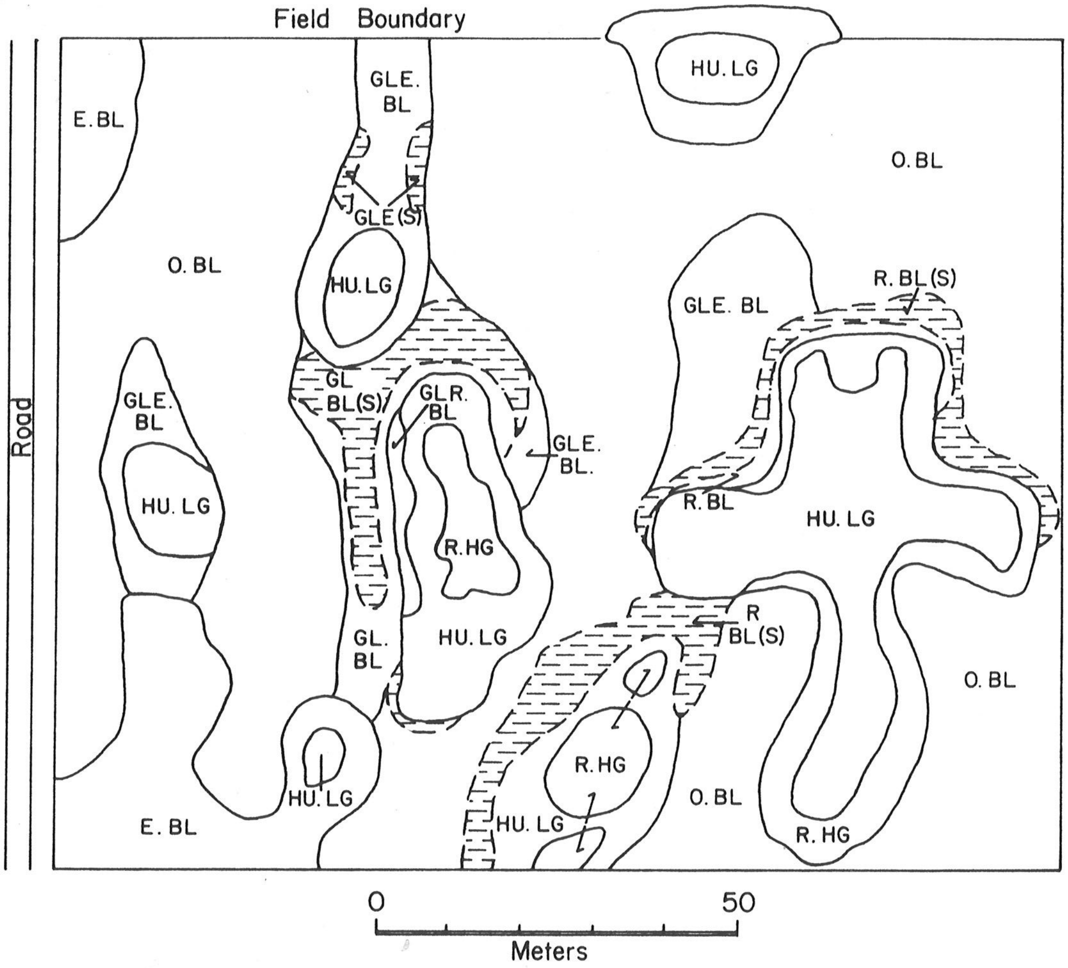


Figure 65. Location of Soil Inspection Holes and Profiles at Site 2.



Black Chernozemic

O. BL	Orthic Black
R. BL	Rego Black
R. BL (S)	Rego Black (saline phase)
E. BL	Eluviated Black
GL. BL	Gleyed Black
GL. BL (S)	Gleyed Black (saline phase)
GLR. BL	Gleyed Rego Black
GLE. BL	Gleyed Eluviated Black
GLE. (S)	Gleyed (saline phase)

Humic Gleysol

R. HG	Rego Humic Gleysol

Luvic Gleysol

HU. LG	Humic Luvic Gleysol
▤	Saline Subgroup

Figure.14 Soil Map of Site 2 (East of Hamiota).
SW 11-14-23W1

APPENDIX B

(Macromorphological description of soil profiles)

Site 1: South of Hamiota

Profile 1: Rego Black (saline phase)

Location	SE $\frac{1}{4}$ 30-13-23W1
Vegetation	Cultivated land.
Drainage	Moderately well drained.
Parent Material	Fine loamy and fine silty, moderately to very strongly calcareous mixed morainal till.
Topography	Undulating, profile sampled at toe position.
Mineral Soil Family Criteria	Fine loamy; mixed non-clay; strongly calcareous; cold; subhumid.

Horizon	Depth cm	Description
Apks	0-15	Black (2.5Y 2/0, moist) very dark gray (10YR 3/1, dry) loam; moderate medium granular; friable (moist); slightly effervescent; moderately saline; gradual irregular boundary.
AC	15-26	Brown-dark brown (10 YR 4/3, moist) dark olive gray (5Y 3/2, dry) sandy clay loam; weak to moderate fine subangular blocky breaking to moderate medium granular, friable (moist); slightly effervescent; moderately saline; clear irregular boundary.

Horizon	Depth cm	Description
Cks1	26-40	Grayish brown to light brownish gray (2.5Y 5.5/2, moist) pale olive to olive (5Y 5.5/3, dry) clay loam; weak to moderate medium to coarse subangular blocky breaking to moderate medium granular; friable (moist); moderately effervescent; irregular boundary.
Ccas	40-50	Light brownish gray (2.5 6/2, moist) pale olive (5Y 6/3, dry) clay loam, weak medium to coarse subangular blocky breaking to moderate medium to coarse granular; friable (moist); strongly effervescent; common random spotted accumulation of secondary carbonate; diffuse irregular boundary.
Ckgjs2	50-60	Brown (5Y 5/3, moist) pale olive (5Y 6/3, dry) sandy clay loam; few fine faint mottles; weak to moderate medium to coarse subangular blocky breaking to moderate medium to coarse granular; friable (moist); moderately to strongly effervescent; few random spotted accumulations of secondary carbonate; clear irregular boundary.
Ckgj3	60-70	Olive brown (2.5Y 4/4, moist) pale olive (5Y 6/3, dry) fine sandy loam;

Horizon	Depth cm	Description
		few fine faint mottles; weak to moderate medium to coarse subangular blocky breaking to moderate medium to coarse granular; friable (moist); moderately to strongly effervescent; clear irregular boundary.
Ckg4	70-80	Olive brown (8.5Y 4/4, moist) olive (5Y 5/3 dry) loam; few fine to medium faint mottles; moderate medium pseudoplaty breaking to weak to moderate fine to medium subangular blocky, friable (moist); moderately to strongly effervescent; diffuse irregular boundary.
Ckg5	100-115	Olive brown (2.5Y 4/4, moist) pale olive-olive (5Y 5.5/3, dry) clay loam; few fine to medium mottles; moderate medium pseudoplaty breaking to weak to moderate fine to medium subangular blocky; friable (moist); moderately to strongly effervescent; diffuse irregular boundary.
Ckg6	130-180	Olive brown (2.5Y 4/4, moist) pale olive to olive (5Y 5.5/3, dry) loam; moderate medium pseudoplaty breaking to weak to moderate fine to medium subangular blocky; friable (moist).

Profile 2: Orthic Black

Location : SE ½ 30-13-23W1

Vegetation : Cultivated land.

Drainage : Well drained.

Parent Material : Fine loamy and fine silty, moderately to very strongly calcareous mixed morainal till.

Topography : Undulating, profile sampled at knoll position.

Mineral Soil Family Criteria : Fine loamy; mixed non-clay, strongly calcareous, cold, subhumid.

Horizon	Depth cm	Description
Ap	0-18	Very dark gray (10YR 3/1, moist) dark gray to very dark gray (10YR 3.5/1, dry) clay loam moderately medium granular; friable (moist); clear irregular boundary.
Ahe	18-30	Very dark brown (10YR 2/2, moist) very dark grayish brown (2.5Y 3/2, dry) loam, weak medium platy breaking to moderate fine to medium subangular blocky; friable (moist); clear irregular boundary.
Bt	30-50	Very dark gray to very dark grayish brown (10YR 3/1.5, moist) very dark grayish brown (2.5Y 3/2, dry) clay loam; very weak medium prismatic

Horizon	Depth cm	Description
		breaking to moderate to strong fine to medium angular blocky; firm (moist); clear irregular boundary.
BC	50-60	Dark grayish brown to very dark grayish brown (10YR 3.5/2, moist) very dark grayish brown (2.5Y 3/2, dry) clay loam; weak to moderate coarse angular blocky; friable (moist); gradual irregular boundary.
Ck1	60-80	Dark grayish brown to olive brown (2.5Y 4/3, moist) gray brown (2.5Y 5/2, dry) loam; weak coarse pseudoplaty breaking to moderate fine to medium subangular blocky; friable (moist); slightly to moderately effervescent; diffuse irregular boundary.
Ck2	80-100	Olive brown (2.5Y 4/4, moist) light brownish gray to grayish brown (2.5Y 5.5/8, dry) clay loam; moderate coarse pseudoplaty breaking to moderate fine to medium subangular blocky; friable (moist); moderately effervescent; diffuse irregular boundary.
Ck3	100-150	Olive brown (2.5Y 4/4, moist) light olive gray to olive gray (5Y 5.5/3, dry) loam; moderate coarse pseudoplaty

Horizon	Depth cm	Description
		breaking to moderate fine to medium subangular blocky; friable (moist); moderately effervescent.

Profile 3: Gleyed Dark Gray Luvisol

Location	:	SE ¼ 30-15-23W1
Vegetation	:	Cultivated land.
Drainage	:	Poorly drained.
Parent Material	:	Fine loamy and fine silty, moderately to very strongly calcareous, mixed morainal till.
Topography	:	Undulating, profile sampled from upper depression.
Mineral Soil Family Criteria	:	Fine loamy, mixed non clay, weakly to strongly calcareous, cold, subaquic.

Horizon	Depth cm	Description
Ap	0-20	Black (10YR 2/1, moist) dark gray (10 YR 4/1, dry) loam; weak medium to coarse platy breaking to moderate medium to coarse granular; friable (moist); diffuse irregular boundary.
Ahe	20-28	Black (10 YR 2/1, moist) gray (10YR 5/1, dry) sandy loam to sandy clay loam, moderate medium platy breaking to moderate medium to coarse granular,

Horizon	Depth cm	Description
		friable (moist); clear irregular boundary.
Aegj	28-43	Olive gray (10YR 5/2, moist) light gray (10YR 6.5/1, dry) loam; few fine distinct mottles (10YR 4/3, moist); moderate medium platy breaking to weak to moderate medium subangular blocky; friable (moist); abrupt wary boundary.
Btgl	43-63	Very dark gray (10YR 3/1, moist) very dark grayish brown (2.5Y 3/2, dry) clay; moderate coarse angular blocky; firm (moist); clay films concentration; diffuse irregular boundary.
Bt2	63-83	Very dark gray (10YR 3/1, moist) very dark grayish brown (2.5Y 3/2, dry) clay; moderate medium to coarse angular blocky; firm (moist); clay film concentration; gradual irregular boundary.
Bt3	83-93	Black (10YR 2/1, moist "exped") dark olive gray (10YR 3/2, moist "inped") very dark grayish brown (2.5Y 3/2, dry); clay; moderate fine to medium angular blocky; firm (moist); clay film concentration; clear irregular boundary.

Horizon	Depth cm	Description
Btj4	93-115	Black (10YR 2/1, moist "exped") dark grayish brown (2.5Y 4/2, moist "inped") grayish brown (2.5Y 5/2, dry); clay loam, moderate medium angular blocky; firm (moist); clay film concentration is less important; gradual irregular boundary
BCk1	115-135	Dark grayish brown to olive brown (2.5Y 4/3, moist) grayish brown (2.5Y 5/2, dry) clay loam; weak medium angular blocky breaking to weak medium granular; friable (moist); very weak effervescence; gradual irregular boundary.
BCk2	135-155	Olive brown (2.5Y 4/4, moist) pale olive to olive (5Y 5.5/3, dry) clay loam; weak medium angular blocky breaking to weak medium granular; friable (moist); weak effervescence; gradual irregular boundary.
Ckg1	155-180	Olive (5Y 4/3, moist) pale olive (5Y 6/3, dry) clay loam; few fine distinct mottles brown to dark brown (7.5Yr 4/4, moist); moderate effervescence; common fine irregular white spotted secondary carbonate (10YR

Horizon	Depth cm	Description
		8/1 moist)
Ckg2	180-240	Olive brown (2.5Y 4/4, moist) pale olive to olive (5Y 5.5/3 dry) clay loam; few fine distinct mottles brown to dark brown (7.5YR 4/4, moist); strong effervescence; many fine irregular white spotted secondary carbonate (10YR 8/1, moist).
Ckg3	240-260	Light olive brown (2.5Y 5/4, moist) light gray (2.5Y 7/2, dry) loam; few fine distinct strong brown mottles (7.5YR 5/8, moist); strong effervescence; many fine distinct spotted white secondary carbonate (10YR 8/1, moist).

Profile 6: Rego Black

Location : SE¼ 30-13-23W1

Vegetation : Cultivated land.

Drainage : Moderately well drained.

Parent Material : Fine loamy and fine silty, moderately to very strongly calcareous, mixed morainal till.

Topography : Undulating, profile sampled at lower slope position.

Mineral Soil Family Criteria : Fine loamy mixed non clay, strongly calcareous, cold, subhumid.

Horizon	Depth cm	Description
LFH	8- 0	Very dark gray (10YR 3/1, dry).
Ah	0- 15	Black (10YR 2/1, moist) very dark gray (10YR 3/1, dry) clay loam; moderate medium platy breaking to moderate medium subangular blocky; friable (moist); diffuse wavy boundary.
Ahk	15- 45	Black (10YR 2/1, moist) very dark gray (10YR 3/1, dry) clay loam; moderate medium platy breaking to moderate medium subangular blocky; friable (moist); clear wavy boundary.
AC	45-60	Black (10YR 2/1, moist) light gray (2.5Y 7/0, dry) clay loam; weak medium platy breaking to moderate medium subangular blocky; friable (moist); diffuse wavy boundary.
Ccag	60-80	Light brownish gray to grayish brown (2.5Y 5.5/2, moist) gray to light brownish gray (2.5Y 6/1, dry) sandy loam; weak medium platy breaking to moderate medium subangular blocky; friable (moist); moderately effervescent; diffuse irregular boundary.
Ckgl	80-110	Olive brown (2.5Y 4/4, moist) gray to light brownish gray (2.5Y 6/1, dry) clay loam; weak medium platy breaking

Horizon	Depth cm	Description
		to moderate medium subangular blocky; friable (moist); strong effervescent; diffuse irregular boundary.
Ckg2	110-150	Olive brown (2.5Y 4/4, moist) gray to light brownish gray (2.5Y 6/1, dry) loam; weak medium platy breaking to moderate medium subangular blocky; friable (moist); moderately effervescent.

Site 2: East of Hamiota

Profile 1: Humic Luvic Gleysol

Location : SW ¼ 11-14-23W1

Vegetation : Grasses, forbs and shrubs (slough grass, rose thistle).

Drainage : Imperfectly drained.

Parent Material : Fine loamy and fine silty, moderately to very strongly calcareous mixed morainal till.

Topography : Undulating, profile sampled from upper depression.

Mineral Soil Family Criteria : Fine loamy, mixed non clay, strongly calcareous, cold, subaquic.

Horizon	Depth cm	Description
LFH	8- 0	Weak; moderate and well decomposed plant material.
Ahe	0- 14	Very dark gray (10YR 3/1, moist) dark

Horizon	Depth cm	Description
		gray to very dark gray (10YR 3.5/1, dry) silty clay loam; weak fine to medium platy breaking to weak to moderate fine to medium granular; slightly hard (dry); clear irregular boundary.
Aeg	14- 26	Light gray to gray (10YR 6/1, moist) white to light gray (10YR 7.5/1, dry) silt loam; common medium distinct 10YR 6/4 mottles; moist (exped); weak to moderate fine platy; common very fine pores; (dendritic cracks and fissures); slightly hard (dry); clear irregular boundary.
AB	26- 34	Gray (10YR 5/1, moist) white to light gray (10YR 7.5/1, dry) clay loam; few medium distinct mottles (10YR 6/4, moist) (exped); weak to moderate fine platy; common very fine pores; (dendritic vesiclar "inped"); slightly hard (dry); gradual irregular boundary.
Btgl	34- 54	Dark gray to very dark gray (10YR 3.5/1, moist) gray (10YR 5/1, dry) clay loam; weak medium angular blocky; common fine pores (dendritic vesiclar "inped"); common thin clay film concentration on ped faces (10YR 4/1, moist); few very

Horizon	Depth cm	Description
		fine random pores; firm (moist); gradual irregular boundary.
Btg2	54- 72	Dark yellowish brown (10YR 4/4, moist) olive (5Y 6/3, dry) clay; weak fine columnar breaking to moderate medium subangular blocky; continuous moderately thick clay film concentration on ped faces (10YR 6/1, moist); firm (moist); clear irregular boundary.
BC	72- 92	Gray (10YR 5/1, moist) olive (5Y 5/3, dry) clay loam; common fine distinct fine inped mottles (10YR 5/6, moist); weak medium pseudo platy breaking to weak medium subangular blocky; firm (moist); gradual irregular boundary.
Ckg1	92-132	Light gray to gray (10YR 5/6, moist) pale olive (5Y 6/3, dry) loam; common medium distinct mottles (10YR 5/6, moist); weak to moderate medium pseudo-platy; common very fine to medium pores (discontinuous "inped"); friable (moist); gradual irregular boundary.
Ckg2	132-292	Light gray to gray (10YR 6/1, moist) light yellowish brown (2.5 6/4, dry) clay loam; friable (moist).
Ckg3	292-348	Light gray to gray (10YR 6/1, moist);

Horizon	Depth cm	Description
		light yellowish brown (8.5Y 6/4, dry); loam; friable (moist).

Profile 2: Gleyed Calcareous Black (Saline phase)

Location : SW ¼ 11-14-23W1

Vegetation : Cultivated

Drainage : Moderately well drained.

Parent Material : Fine loamy and fine silty, calcareous and saline mixed morainal till.

Topography : Undulating, profile sampled at toe position.

Mineral Soil Family Criteria : Fine loamy, mixed non clay, strongly calcareous, cold, subhumid.

Horizon	Depth cm	Description
Apks	0- 6	Black (10YR 2/1, moist) very dark gray (10YR 3/1, dry) clay loam; weak to moderate fine to medium granular; few very fine random pores (discontinuous vesicular "inped"); friable (moist); common medium oblong concentration of soluble salts (2.5Y 8/0, moist); weak effervescence; gradual smooth boundary.
Aps	6- 15	Black (10YR 2/1, moist) very dark gray (10YR 3/1, dry) clay loam; moderate fine to medium granular; few very fine random pores (discontinuous vesicular "inped"); friable (moist); common medium oblong

Horizon	Depth cm	Description
		concentration of soluble salts (2.5Y 8/0, moist); gradual smooth boundary.
Ahs	15- 30	Black (10YR 2/1, moist) very dark gray (10YR 3/1, dry) clay loam; moderate fine to medium granular; friable (moist); common fine spherical salt concentration (10YR 7/1, moist); clear irregular boundary (range maximum = 20 cm and minimum 10 cm).
Bmks	30- 48	Dark grayish brown to brown (10YR 4/2.5, moist) dark grayish brown (2.5Y 4/2, dry) clay loam; moderate fine subangular blocky; friable (moist); few fine spherical salt concentration (10YR 7/1, moist); weak effervescence; clear irregular boundary (range maximum 20 and minimum 15 cm).
Ckgjsl	48- 58	Grayish brown to dark grayish brown (10YR 4.5/2, moist) grayish brown (2.5Y 5/2, dry) sandy clay loam; few medium distinct strong brown mottles (7.5YR 5/6, moist); weak to moderate fine subangular blocky; friable (moist); few fine subangular blocky; friable (moist); few fine spherical iron-manganese concretions (Black 10YR 2/1);

Horizon	Depth cm	Description
		moderate effervescence; common random spotted accumulation of secondary carbonate: white (10YR 8/1, moist); diffuse irregular boundary.
Ckgjs2	58- 88	Grayish brown (10YR 5/2, moist) light olive gray (5Y 6/2, dry) loam; few medium distinct strong brown mottles (7.5YR 5/6, moist); weak to moderate fine subangular blocky;friable (moist); moderate effervescence; few medium spotted accumulation of secondary carbonate: white (10YR 8/1, moist); diffuse irregular boundary.
Ckgj3	88-100	Light brown gray to grayish brown (10YR 5.5/2, moist) light olive gray (5Y 6/2, dry) loam; common medium distinct yellowish brown mottles (10YR 5/4, moist); weak to moderate fine subangular blocky; friable (moist); moderate effervescence; few medium spotted accumulation of secondary carbonate; white (10YR 8/1, moist).

Profile 3: Rego Humic Gleysol

Location	: SW ¼ 11-14-23W1
Vegetation	: Grasses and forbs "sedges and sloughgrass".

Profile 3: Rego Humic Gleysol

Drainage : Poorly drained.

Parent Material : Fine loamy and fine silty, moderately calcareous; mixed morainal till.

Topography : Undulating, profile sampled from lower depression.

Mineral Soil Family Criteria : Fine loamy mixed non clay, strongly calcareous, cold, perhumid.

Horizon	Depth cm	Description
Oh	5- 0	Black (10YR 2/1, moist) very dark grayish brown (10YR 3/2, dry) fine fiber and non woody humic; compacted; herbaceous material.
Ah1	0- 5	Black (10YR 2/1, moist) very dark gray (10YR 3/1, dry) silty clay loam; massive breaking to weak fine to medium granular; firm (moist); diffuse irregular boundary.
Ah2	5- 25	Black (10YR 2/1, moist) very dark gray (10YR 3/1, dry) clay loam; moderate medium granular with some tendency of blocky structure in the lower part of the horizon; friable (moist); diffuse irregular boundary.
Ahk3	25- 50	Black (10YR 2/1, moist) very dark grayish brown (2.5Y 3/2, dry) clay; moderate

Horizon	Depth cm	Description
		fine to medium subangular blocky; firm (moist); weak effervescence; diffuse irregular boundary.
ACk	50- 77	Very dark gray (10YR 3/1, moist) dark gray (5Y 4/1, dry) silty clay loam; weak fine subangular blocky; common fine vertical pores (continuous simple tubular); firm (moist); moderately effervescence; gradual irregular boundary.
Ckgl	77- 90	Very dark grayish brown (2.5Y 3/2, moist) olive gray (5Y 5/2, dry) silty clay loam; common medium distinct mottles (10YR 5/4); massive; firm (moist); strong effervescence; diffuse irregular boundary.
Ckg2	90-105	Olive gray to olive (5Y 4/2.5, moist) light olive gray (5Y 5/2, dry) silty clay loam; common medium distinct mottles (10YR 5/4, moist); massive; firm (moist); strong effervescence.

APPENDIX C

(Macromorphological descriptions of
Surficial deposits)

Site 1: South of Hamiota

Deep Drilling Samples : Location : Well 9 near Profile 1

Layer depth (cm)	Description
160-200	Dark grayish brown (10YR 4/2, moist) olive (5Y 5/3, dry) clay loam to sandy clay loam till; few fine faint mottles; few fine and medium pebbles; strong effervescence.
200-240	Dark grayish brown (10YR 4/2, moist) pale olive (5Y 6/3, dry) clay loam to sandy clay loam till; few fine faint mottles; few fine and medium pebbles; strong effervescence.
240-280	Grayish brown to dark grayish brown (10YR 4.5/2, moist) olive (5Y 5/3, dry) clay loam to sandy clay loam till; few fine faint mottles; few fine and medium pebbles; strong effervescence.
280-320	Dark grayish brown (10YR 4/2, moist) olive (5Y 5/3, dry) clay loam to sandy clay loam till; common fine to medium faint mottles; few medium pebbles; strong effervescence.
320-360	Dark grayish brown (10YR 4/2, moist) olive gray (5Y 5/2 dry) clay loam to sandy clay loam till; common medium distinct mottles; few medium pebbles

Layer depth (cm)	Description
	strong effervescence.
360-400	Dark grayish brown to very dark grayish brown (2.5Y 5/2, moist) grayish brown to light olive brown (2.5Y 5/3, dry) clay loam to sandy clay till; compact; common medium distinct mottles; common medium pebbles; strong effervescence; moist condition although below water table level.
400-520	Dark grayish brown to very dark grayish brown (2.5Y 3.5/2, moist) grayish brown (2.5Y 5/2, dry) clay loam to sandy clay loam till; more compact than above; common medium distinct mottles; common medium pebbles; strong effervescence; moist condiitons although below water table level.
520-560	Very dark grayish brown (2.5Y 3/2, moist) grayish brown (2.5Y 5/2, dry) clay loam to sandy clay loam till; very compact; many medium distinct mottles; common medium pebbles; strong effervescence; moist although below water table level.

Deep Drilling Samples. Location: Well 8 near Profile 2

Layer depth (cm)	Description
160-200	Brown to dark brown (10YR 4/3, moist)

Layer depth (cm)	Description
	olive (5Y 5/3, dry) moderately stratified sandy till; clay loam; strong effervescence.
200-280	Brown (10YR 5/3, moist) pale yellow (2.5Y 7/4, dry) highly stratified sandy till (1st max stratification around 250 cm deep); silt loam-clay loam; few fine pebbles; strong effervescence.
280-320	Dark grayish brown (10YR 4/2, moist) light yellowish brown (2.5Y 6/4, dry) stratified sandy till; silt loam to clay loam; few fine pebbles; strong effervescence.
320-360	Grayish brown to dark grayish brown (10YR 4.5/2, moist) light gray to light brownish gray (2.5Y 6.5/2, dry) stratified sandy till; silt loam to clay loam; few fine pebbles; strong effervescence.
360-440	Brown to dark brown (10YR 6/3, moist) light yellowish brown (2.5Y 6/4, dry) highly stratified sandy till (2nd max stratification around 400 cm deep); silt loam to very fine sandy loam; few fine pebbles; strong effervescence.

Layer depth (cm)	Description
440-480	Dark brown (10YR 3/3, moist) light yellowish brown (2.5Y 6/4, dry) clay loam to sandy clay loam till; common medium pebbles; strong effervescence.
480-520	Brown (10YR 4.5/3, moist) grayish brown to light olive brown (2.5Y 5/3, dry) clay loam to sandy loam till; common medium pebbles; strong effervescence.
520-560	Dark brown (10YR 3/3, moist) grayish brown (2.5Y 3/3, dry) clay loam to sandy clay loam till; common medium pebbles; strong effervescence.
560-600	Very dark grayish brown (2.5Y 3/2, moist) grayish brown to light brownish gray (2.5Y 5.5/2 dry) clay loam to sandy loam till; common medium pebbles; strong effervescence.
600-640	Very dark grayish brown (2.5Y 3/2, moist) grayish brown (2.5Y 5/2, dry) clay loam to sandy loam till; common medium pebbles; strong effervescence.
640-680	Very dark grayish brown (2.5Y 3/2, moist) grayish brown (2.5Y 5/2, dry) clay loam to silt loam till; common medium pebbles; strong effervescence.

Site 2: East of Hamiota

Deep drilling Samples. Location: Well 1 near Profile 1

Layer depth (cm)	Description
400-500	Olive brown (2.5Y 4/4, moist) light brownish gray to light yellowish brown (2.5 6/3, dry) gritty tills; clay loam; many coarse orominant mottles "exped"; brown to dark brown (7.5 4/4, moist) and few fine medium distinct inped mottles; strong effervescence.
450-500	Very dark gray (5Y 3/1, moist) olive gray (5Y 5/2, dry) clay loam to clay till; many coarse prominent mottles; brown to dark brown (7.5YR 4/4, moist).

Deep Drilling Samples. Location: Well 2 near Profile 2

Layer depth (cm)	Description
100-120	Olive brown (2.5Y 4/4, moist) light gray (5Y 7/2, dry) loam to clay loam till; few fine distinct mottles; brown (7.5YR 4/4, moist); many medium spotted and fillaments secondary carbonate accumulation; few medium manganese concretions; few fine pebbles; strong effervescence.
120-145	Dark grayish brown to olive brown (2.5Y 4/3 - 5Y 4/4, moist) pale olive

Layer depth (cm)	Description
120-145	to olive (5Y 6/3, dry) loam to clay loam till; few medium to coarse distinct mottles; brown (7.5YR 4/4); stratified few medium to coarse carbonate accumulation; few medium manganese oxide concretions; few medium to coarse pebbles; strong effervescence.
145-200	Dark grayish brown to olive brown (8.5 4/4, moist) pale olive (5Y 6/3, dry) loam to clay loam till; few medium distinct mottles; brown (7.5YR 4/4, moist); few medium concentration stratified carbonate accumulation; few fine manganese oxide concretions; few fine to medium pebbles; strong effervescence.
250-300	Olive brown (2.5 4/4, moist) pale olive (5Y 6/3, dry) clay loam till; many medium to coarse distinct mottles; strong brown (7.5YR 5/6, moist); few fine pebbles; strong effervescence.
360-385	Grayish brown to dark grayish brown (2.5Y 4.5/2, moist) pale olive (5Y 6/3, dry); stratified calcareous till; sandy loam to loamy sands; few fine to medium faint mottles; brown (7.5YR 5/4, moist); few fine to medium pebbles; strong

Layer depth (cm)	Description
	effervescence.
385-405	Dark grayish brown (2.5Y 4/2, moist) olive (5Y 5/3, dry) clay loam to silty clay loam till; many fine to medium pebbles.
Deep Drilling Samples. Location: Well 5 near Profile 3	
125-200	Brown to dark brown (10YR 4/3, moist) pale olive (5Y 6/3, dry) clay loam till; few common fine distinct mottles; brown to black brown (7.5YR 4/4, moist); and less than %5 grayish brown (2.5Y 5/2, moist); moderate to strong effervescence.
235-265	Light yellowish brown to light olive brown (2.5Y 4.5/4, moist) pale olive (5Y 6/3, dry) clay loamtill; few fine distinct mottles; brown to dark brown (7.5YR 4/4, moist); strong effervescence.
265-270	Dark brown (10YR 3.5/3, moist) light brownish gray to light yellowish brown (2.5 6/3, dry) sandy loam till; few fine distinct mottles; brown to dark brown (7.5YR 4/4, moist); strong effervescence.
270-300	Brown to dark brown (10YR 4/3, moist)

Layer depth (cm)	Description
	light olive gray (5Y 6/2, dry) clay loam till; common fine distinct mottles; brown to dark brown (7.5YR 4/4, moist); strong effervescence.
300-350	Very dark grayish brown (2.5Y 3/2, moist) light olive gray (5Y 6/2, dry) clay loam till; common fine distinct mottles; brown to dark brown (7.5YR 4/4, moist); strong effervescence.

Drilling Samples. Location: Well 12

Layer depth (cm)	Description
0- 40	Dark gray to very dark gray (10YR 3.5/1, moist) very dark gray (10YR 3/1, dry) loam to clay loam "gritty".
40- 80	Black (10YR 2/1, moist) very dark gray (10YR 3/1, dry); gritty loam to clay loam; weak effervescence in the last 10 cm.
80-120	Dark grayish brown to very dark grayish brown (2.5Y 3.5/2, moist) grayish brown (2.5Y 5/2, dry) gritty till; clay loam; few fine faint mottles; few fine pebbles; weal to moderate effervescence.
120-240	Dark brown (10YR 3/3, moist) light brownish gray to grayish brown

Layer depth (cm)	Description
	(2.5Y 5.5/2, dry) gritty till; clay loam; few fine faint mottles; few fine pebbles; strong effervescence.
240-480	Dark brown (10YR 3/3, moist) pale olive to olive (5Y 5.5/3, dry) gritty till; clay loam; few fine faint mottles; few fine pebbles; strong effervescence.
480-600	Very dark grayish (2.5Y 3/2, moist) pale olive (5Y 6/3, dry) gritty till; clay loam; few fine faint mottles; few fine pebbles; strong effervescence.

Drilling Samples. Location: Well 13

Layer depth (cm)	Description
0- 40	Black (10YR 2/1, moist) very dark gray (10YR 3/1, dry) clay loam; few medium oblong soluble salt accumulation included gypsum.
40- 80	Dark grayish brown (2.5Y 4/2, moist) light brownish gray (2.5Y 6/2, dry) clay loam; few fine pebbles; common fine to medium spherical soluble salt accumulation included few gypsum.
80-120	Brown to dark brown (10YR 4/3, moist) light brownish gray (2.5Y 6/2, dry) clay loam till; many fine to medium spherical soluble salt accumulation

Layer depth (cm)	Description
	included few gypsum; few fine pebbles; strong effervescence.
120-200	Brown to dark brown (10YR 4/3, moist) pale yellow to pale olive (5Y 6.5/3, dry) clay loam till; few fine faint mottles; few fine pebbles; strong effervescence.
200-320	Brown to dark brown (10YR 4/3, moist) pale yellow to light yellowish brown (2.5Y 6.5/4, dry) clay loam till; few fine faint mottles; few fine pebbles; strong effervescence.
320-360	Dark brown (10YR 3/3, moist) pale yellow to light yellowish brown (2.5Y 6.5/4, dry) loam to clay loam till; common medium distinct mottles; strong effervescence.
360-400	Dark brown (10YR 3/3, moist) pale yellow to pale olive (5Y 6.5/3, dry) weakly stratified till; fine loamy sand; strong effervescence.
400-440	Dark yellowish brown (10YR 4/4, moist) pale yellow to light yellowish brown (2.5Y 6.5/4, dry) stratified till; sand to fine sandy loam; strong effervescence.

Layer depth (cm)	Description
440-480	Very dark grayish brown (2.5Y 3/2, moist) pale olive (5Y 6/3, dry) stratified till; upper layer of fine loamy sand followed by 2nd layer of weakly compact clay loam; strong effervescence.
480-520	Dark grayish brown to very dark grayish brown (2.5Y 3.5/2, moist) olive gray (5Y 5/2, dry) moderately compact clay loam till; strong effervescence.

APPENDIX D

(Analyses data for the saturation extract of soil and underlying material samples from the study sites)

TABLE 16. Chemical analysis of the saturation extract of Profile 1, Site 1 (Rego Black, Saline phase).

				Soluble Cations meq/L					Soluble Anions meq/L				
Horizon	Depth cm	pH	EC_e mS/cm	Na	K	Ca	Mg	Total	Cl	SO_4	CO_3	HCO_3	Total
Apks	0- 15	8.1	3.85	2.65	1.07	26.45	41.12	71.29	1.09	65.58	1.78	7.65	76.05
AC	15- 26	8.2	4.90	5.09	0.66	11.48	79.83	92.06	1.39	91.70	0.38	6.12	99.59
Cks1	26- 40	8.3	4.90	5.83	0.89	13.97	78.95	99.64	1.39	92.56	0.00	4.59	98.54
Ccas	40- 50	8.3	2.75	2.91	0.56	6.99	35.36	45.82	0.09	42.74	0.38	3.15	46.36
Ckgjs2	50- 60	8.2	2.30	2.69	0.59	5.49	27.96	36.73	0.09	34.31	0.00	3.82	38.22
Ckgj3	60- 70	8.2	1.50	1.96	0.46	3.49	15.62	21.53	0.69	18.05	0.00	3.82	22.56
Ckg4	70-100	8.5	0.90	1.43	0.51	2.00	8.22	12.16	0.40	7.79	0.00	4.21	12.4
Ckg5	100-115	8.5	0.95	1.91	0.64	2.54	9.37	14.46	0.40	9.15	0.00	4.21	13.76
Ckg6	130-150	8.3	0.47	0.87	0.64	1.70	4.11	7.32	0.40	1.53	0.00	3.63	5.56
Ckg7	150-180	8.4	0.53	0.78	0.64	1.95	4.28	7.65	0.40	2.89	0.00	3.63	6.92
Underlying glacial drift													
	a 280-320	8.3	2.72	2.00	1.38	28.94	24.67	56.99	0.30	47.48	0.00	2.68	50.46
	a 360-400	8.3	2.85	1.78	1.43	26.95	26.31	56.47	0.69	47.70	0.00	2.68	51.07
	b 480-520	8.3	2.90	1.74	1.30	25.95	24.67	53.66	0.40	48.86	0.00	2.48	51.74

a = Brown till; b = Dark gray till.
a,b Samples obtained by deep drilling.

TABLE 17 . Chemical characteristics to the saturation extract of Profile 2, Site 1 (Orthic Black).

Horizon	Depth cm	pH	EC_e mS/cm	Soluble Cations meq/L Na	K	Ca	Mg	Total	Soluble Anions meq/L Cl	SO_4	CO_3	HCO_3	Total
Ap	0- 18	8.3	0.65	0.23	0.69	6.49	2.38	9.79	0.50	4.15	0.29	6.50	11.44
Ahe	18- 30	8.0	0.50	0.30	0.21	4.54	2.30	7.35	0.30	2.01	0.00	4.11	6.42
Bt	30- 50	8.2	0.47	0.74	0.25	2.59	2.47	6.05	1.39	3.03	0.00	1.82	6.24
BC	50- 60	8.5	0.37	0.56	0.28	2.09	2.55	5.48	0.40	1.53	0.00	4.11	6.04
Ck1	60- 80	8.6	0.48	1.17	0.28	2.09	3.45	6.99	0.40	2.21	0.29	6.02	8.92
Ck2	80-100	8.4	2.06	3.69	0.46	7.73	22.20	34.08	0.50	27.78	0.09	3.82	32.19
Ck3	100-125	8.5	1.60	3.09	0.48	5.59	16.45	25.61	0.50	20.57	0.00	3.73	24.80
Ck4	125-150	8.5	1.40	2.61	0.48	4.99	13.32	21.40	0.50	16.63	0.00	3.82	20.95
Underlying glacial drift													
	c 200-240	8.3	1.54	1.43	0.66	12.97	11.51	26.57	0.69	18.46	0.00	2.20	21.35
	c 280-320	8.3	1.45	1.17	0.64	11.98	10.28	24.07	0.40	15.30	0.00	2.48	18.18
	c 360-400	8.2	2.10	1.35	0.92	19.96	15.62	37.85	0.30	32.38	0.00	2.68	35.36
	c 480-520	8.3	1.05	1.00	1.02	7.98	6.58	16.58	0.69	11.46	0.48	3.44	16.07
	c 560-600	8.3	1.35	1.13	0.92	11.48	8.22	21.75	0.40	15.20	0.09	3.44	19.13
	b 640-680	8.3	2.55	1.74	1.71	29.94	16.45	49.84	0.40	40.85	0.00	2.68	43.93

b = Dark gray till; c = Stratified material.

b,c Samples obtained by deep drilling.

TABLE 18 . Chemical analysis of the saturation extract of Profile 3, Site 1 (Gleyed Dark Gray Luvisol).

				Soluble Cations meq/L					Soluble Anions meq/L				
Horizon	Depth cm	pH	EC_e mS/cm	Na	K	Ca	Mg	Total	Cl	SO_4	CO_3	HCO_3	Total
Ap	0- 20	7.4	0.57	0.23	1.18	4.04	1.40	6.85	0.40	0.31	0.00	0.96	1.67
Ahe	20- 28	7.2	0.28	0.22	0.59	2.24	0.68	3.73	0.30	0.71	0.00	1.53	2.54
Aegj	28- 43	7.2	0.35	0.33	0.82	3.79	0.99	5.93	0.30	0.20	0.00	1.24	1.74
Bt1	43- 63	7.1	0.23	0.27	0.48	1.45	0.78	2.98	0.50	0.20	0.00	0.86	1.56
Bt2	63- 83	7.1	0.19	0.23	0.38	1.05	0.60	2.26	0.40	0.54	0.00	0.86	1.80
Bt3	83- 93	7.8	0.23	0.27	0.41	1.35	0.71	2.74	0.40	0.2	0.00	0.96	1.56
Btj4	93-115	8.1	0.24	0.28	0.38	1.55	0.82	3.03	0.40	0.1	0.00	1.34	1.84
BC1	115-135	8.5	0.39	0.35	0.43	3.09	1.48	5.35	0.40	1.16	0.48	2.87	4.91
BC2	135-155	8.5	0.34	0.28	0.33	2.79	1.23	4.63	0.50	0.82	0.29	2.48	4.09
Ckg1	155-180	8.5	0.35	0.35	0.28	3.39	1.48	5.50	0.59	1.16	0.00	3.54	5.29
Ckg2	180-240	8.5	0.40	0.48	0.23	3.39	1.31	5.41	0.50	1.02	0.09	2.96	4.57
Ckg3	240-260	8.5	0.38	0.48	0.22	3.24	1.31	5.25	0.59	1.09	0.48	2.29	4.45

TABLE 19 . Chemical analysis of the saturation extract of Profile 6, Site 1 (Rego Black).

				Soluble Cations meq/L					Soluble Anions meq/L				
Horizon	Depth cm	pH	EC_e mS/cm	Na	K	Ca	Mg	Total	Cl	SO_4	CO_3	HCO_3	Total
Ah	0- 8	8.2	1.07	0.36	1.69	7.68	7.81	17.54	0.79	7.34	0.95	12.14	21.23
Ahk1	8- 28	8.3	1.44	1.69	0.77	8.08	14.80	25.25	0.40	1.29	1.43	12.81	15.93
Ahk2	28- 48	8.4	1.10	1.69	0.61	6.34	9.46	18.10	0.50	8.19	0.86	10.52	20.07
AC	48- 64	8.6	0.67	0.74	0.69	4.99	4.52	10.94	0.40	3.74	0.76	4.97	9.87
Ccag	64- 90	8.6	0.57	0.48	0.79	4.69	3.04	9.00	0.40	4.18	0.38	4.49	9.45
Underlying glacial drift													
	a 240-270			0.36	0.51	2.85	1.23	4.95	0.40	0.61	0.00	2.68	3.69
	a 270-300			0.40	0.48	2.54	1.23	4.65	0.59	0.61	0.00	2.89	4.09

a = Brown till samples obtained by deep drilling.

TABLE 20. Chemical analysis of the saturation extract of Profile 1, Site 2 (Humic Luvic Gleysol).

				Soluble Cations meq/L					Soluble Anions meq/L				
Horizon	Depth cm	pH	EC_e mS/cm	Na	K	Ca	Mg	Total	Cl	SO_4	CO_3	HCO_3	Total
Ahe	0- 14	7.6	0.78	0.52	1.12	7.08	3.03	11.76	0.51	2.48	0.0	5.68	8.67
Aeg	14- 26	7.4	0.43	0.69	0.36	3.04	1.73	5.82	0.25	0.24	0.0	1.28	1.77
AB	26- 34	7.8	0.39	0.39	0.41	2.69	1.40	4.89	0.17	0.41	0.0	0.96	1.54
Btg1	34- 54	8.1	0.41	0.43	0.46	2.89	1.48	5.26	0.17	1.22	0.0	0.96	2.35
Btg2	54- 72	8.4	0.53	0.43	0.51	3.94	1.97	6.85	0.17	2.52	0.0	2.48	5.17
BC	72- 92	8.5	0.52	0.52	0.43	4.34	1.81	7.10	0.17	1.84	0.0	2.24	4.25
Ckg1	92-132	8.4	0.52	0.43	0.36	4.34	1.64	6.77	0.25	0.85	0.0	2.80	3.96
Underlying glacial drift													
	a 132-292	8.4	0.68	0.96	0.84	5.19	2.71	9.7	0.42	2.21	0.0	3.36	5.99
	b 292-348	8.4	2.06	0.83	0.56	4.69	3.04	9.12	0.34	1.33	0.0	2.88	4.55
	b 400-500	8.4	2.06	1.35	1.05	8.98	6.58	17.96	0.69	9.89	0.0	4.11	14.69

a = Brown till; b = Dark gray till.

a,b Samples obtained by deep drilling.

TABLE 21. Chemical analysis of the saturation extract of Profile 2, Site 2 (Gleyed Black, Saline phase).

				Soluble Cations meq/L					Soluble Anions meq/L				
Horizon	Depth cm	pH	EC_e mS/cm	Na	K	Ca	Mg	Total	Cl	SO_4	CO_3	HCO_3	Total
Apks	0- 6	8.5	5.20	12.61	1.43	21.46	60.85	96.35	0.68	88.43	0.40	6.16	95.67
Aps	6- 15	8.2	7.10	15.65	1.23	26.45	95.39	138.72	0.42	141.12	0.00	5.84	147.38
Ahs	15- 30	7.9	6.50	14.35	1.07	24.4	86.35	126.17	0.59	128.52	0.00	3.92	133.03
Bmks	30- 48	7.9	5.40	14.35	0.64	21.96	66.61	103.36	1.10	97.51	0.00	3.28	101.89
Ckgjs1	48- 58	8.0	3.70	9.56	0.51	11.98	39.47	61.52	0.25	57.76	0.00	3.60	61.61
Ckgjs2	58- 88	8.2	2.36	6.96	0.36	6.24	22.20	35.76	0.42	33.83	0.00	2.96	37.21
Ckgjs3	88-100	8.1	2.20	7.83	0.33	6.84	16.86	31.86	0.69	17.78	0.00	3.52	21.99
<u>Underlying glacial drift</u>													
	a 100-120	7.7	2.24	2.58	0.42	11.23	17.27	31.50	1.10	9.30	0.00	4.60	15.00
	a 120-145	7.8	1.24	1.81	0.34	6.29	7.56	16.00	1.00	2.90	0.00	8.00	11.90
	a 145-170	7.9	1.26	1.85	0.41	2.94	8.14	13.34	1.50	1.30	0.00	4.30	7.10
	a 170-200	7.9	1.44	1.95	0.46	6.99	8.30	17.70	4.80	3.10	0.00	4.70	12.60
	a 250-300	8.0	1.08	1.56	0.41	4.64	5.67	12.28	4.70	1.60	0.00	3.80	10.10
	b 360-385	7.7	2.89	2.09	0.75	24.8	18.67	46.31	0.90	39.70	0.00	2.50	43.10
	b 385-405	7.7	2.87	1.94	0.80	23.70	19.08	45.52	0.90	39.80	0.00	3.40	44.10

a = Brown till; b = Dark gray till.

a,b Samples obtained by deep drilling.

TABLE 22. Chemical analysis of the saturation extract of Profile 3, Site 2 (Rego Humic Gleysol).

Horizon	Depth cm	pH	EC_e mS/cm	Soluble Cations meq/L					Soluble Anions meq/L				
				Na	K	Ca	Mg	Total	Cl	SO_4	CO_3	HCO_3	Total
Ah1	0- 5	7.7	1.26	0.69	2.38	11.98	4.77	19.82	0.51	2.62	0.00	8.00	11.13
Ah2	5- 25	8.0	1.36	0.87	7.16	14.47	4.85	27.35	0.34	11.83	0.00	10.24	22.41
Ahk	25- 50	8.2	1.08	1.04	0.20	10.98	3.70	15.92	0.25	11.63	0.00	3.52	15.40
AC	50- 77	8.3	0.70	0.96	0.18	6.24	2.14	9.52	0.09	6.22	0.00	2.64	8.95
Ckg1	77- 90	8.4	0.41	0.78	0.51	3.24	1.15	5.68	0.09	1.90	0.00	2.24	4.23
Ckg2	90-105	8.4	0.47	0.91	0.36	3.59	1.40	6.26	0.25	3.20	0.00	2.64	6.09
<u>Underlying glacial drift</u>													
	a 125-200	8.5	0.43	0.69	0.46	3.64	1.84	6.63	0.40	0.99	0.00	3.73	5.12
	b 300-350	8.5	0.59	0.91	0.61	3.89	1.56	6.97	0.50	0.44	0.00	4.85	5.79

a = Brown till; b = Dark gray till.

a,b Samples obtained by deep drilling.

APPENDIX E

(Mg CO_3 content in calcite and ratio of calcite: dolomite in soil concretions and pebbles at Sites 1 and 2)

TABLE 23 . Mol % $MgCO_3$ in calcite and ratio of calcite:dolomite in soil concretions and pebbles at Site 1 using X-ray diffractograms.

	X-Ray Diffractograms Determination			Planimeter Determination		
Horizon designation and depth (cm)	d_{211} (104) Å	$*\blacktriangle d_{211}$ (104) Å using standard calcite	Mol. % $MgCO_3$ in calcite	Area under calcite peak (cm^2)	Area under dolomite peak (cm^2)	$\frac{\text{Area under calcite}}{\text{calcite + dolo.}}$
Prof. 1 26- 40 Cks1 (c)	3.0278	0.0129	2.4	17.52	3.11	0.85
26- 40 (p)	3.0278	0.0129	2.4	7.02	49.25	0.13
40- 50 Ccas (c)	3.0244	0.0163	3.3	18.31	3.38	0.84
40- 50 (p)	3.0270	0.0137	2.5	1.87	44.64	0.04
50- 60 Ckgs2 (c)	3.0227	0.0180	4.1	16.86	1.42	0.92
50- 60 (p)	--	--	-	--	3.64	0.00
150-180 Ckg7 (c)	3.0338	0.0069	0.4	6.67	5.69	0.54
150-180 (p)	--	--	-	--	56.55	0.00
a 240-280 (c)	3.0329	0.0078	0.6	3.82	6.36	0.38
a 240-280 (p)	3.0381	0.0024	0.0	33.52	1.60	0.95
a 320-360 (c)	3.0329	0.0078	0.6	4.09	6.76	0.38
a 320-360 (p)	--	--	-	--	67.08	0.00
b 400-440 (c)	3.0329	0.0078	0.6	6.43	3.91	0.62
b 400-440 (p)	3.0347	0.0060	0.4	18.18	23.34	0.44
b 520-560 (c)	3.0364	0.0043	0.0	3.94	5.60	0.41
b 520-560 (p)	--	--	-	--	44.23	0.00
Prof. 2 60- 80 Ck1 (c)	3.0295	0.0112	1.8	7.97	7.70	0.51
60- 80 (p)	3.0347	0.0060	0.4	43.75	--	1.00
80-100 Ck2 (c)	3.0295	0.0112	1.8	12.95	1.87	0.87
80-100 (p)	--	--	-	--	39.65	0.00
c160-200 (c)	3.0312	0.0095	1.2	4.89	5.33	0.48
c160-200 (p)	3.0381	0.0026	0.0	3.23	31.74	0.09
c320-360 (c)	3.0338	0.0069	0.4	3.08	6.13	0.33
c320-360 (p)	3.0381	0.0026	0.0	29.88	--	1.00
c400-440 (c)	3.0355	0.0052	0.0	5.78	2.80	0.67
c400-440 (p)	--	--	-	--	--	--
b600-640 (c)	3.0381	0.0026	0.0	19.42	--	1.00
b600-640 (p)	3.0398	0.0060	0.0	2.67	1.13	0.70
Prof. 3 155-180 Ckg1 (c)	3.0355	0.0052	0.0	3.33	3.42	0.49
155-180 (p)	--	--	-	--	--	--
a225-238 (c)	3.0329	0.0078	0.5	3.56	3.24	0.52
a225-238 (p)	3.0390	0.0017	0.0	--	--	--
a262-275 (c)	3.0329	0.0078	0.5	6.49	4.00	0.62
a262-275 (p)	3.0364	0.0043	0.0	--	--	--
Prof. 6 64- 90 Ck1 (c)	3.0278	0.0129	2.4	--	--	--
64- 90 (p)	3.0372	0.0035	0.0			
a270-300 (c)	3.0347	0.0060	0.1			
a270-300 (p)	3.0381		0.0			

$\blacktriangle d_{211}$ (104) Å = see method and material.
(c) = concretion; (p) = pebble
$* d_{211}$ (104) Å of standard calcite = 3.0407.
a = Brown till; b = Dark gray till; c = Stratified material.
Samples a,b,c were obtained by deep drilling.

TABLE 24 . Mol % $MgCO_3$ in calcite and ratio of calcite:dolomite in soil concretions and pebbles at Site 2 using X-ray diffractograms.

Horizon designation and depth (cm)	X-Ray Diffractograms Determination			Planimeter Determination		
	d_{211} (104) Å	*Δ d_{211} (104) Å using standard calcite	Mol. % $MgCO_3$ in calcite	Area under calcite peak (cm^2)	Area under dolomite peak (cm^2)	$\frac{\text{Area under calcite}}{\text{calcite + dolo.}}$
Prof. 1 120-136 Ckgl (c)	3.0329	0.0078	0.6	17.29	5.56	0.76
120-136 (p)	3.0381	0.0026	0.0			
a221-235 (c)	3.0347	0.0060	0.1	5.66	10.10	0.36
a221-235 (p)	3.0355	0.0052	0.0			
b458-499 (c)	3.0338	0.0069	0.4	3.38	6.07	0.36
b458-499 (p)	3.0390	0.0017	0.0			
Prof. 2 48- 58 Ckgjsl (c)	3.0210	0.0197	4.4	6.22	--	1.00
48- 58 (p)	--	--	-	--	--	--
100-120 (c)	3.0270	0.0137	2.6	11.73	3.94	0.75
100-120 (p)	3.0355	0.0052	0.0	40.67	1.07	0.97
a170-200 (c)	3.0304	0.0103	1.4	11.73	6.09	0.66
a170-200 (p)	3.0290	0.0117	1.6	37.91	--	1.00
a260-300 (c)	3.0312	0.0095	1.2	4.26	7.20	0.37
a260-300 (p)	3.0364	0.0043	0.0	11.11	55.13	0.17
b360-385 (c)	3.0295	0.0112	1.2	4.76	9.16	0.34
b360-385 (p)	--	--	-	--	35.18	0.00
b385-405 (c)	3.0312	0.0095	1.2	4.10	11.20	0.27
b385-405 (p)	3.0364	0.0043	0.0	40.85	2.62	0.94
Prof. 3 a154-196 (c)	3.0338	0.0069	0.4	4.04	7.69	0.34
154-196 (p)	3.0325	0.0082	0.5			
235-265 (c)	3.0355	0.0052	0.0	4.44	6.09	0.42
235-265 (p)	--	--	-			
463-487 (c)	3.0317	0.0090	0.7	4.49	7.78	0.37
463-487 (p)	3.0338	0.0069	0.4	--	--	--
Well 12 a 80-120 (c)	3.0321	0.0086	1.0	7.64	9.07	0.46
a 80-120 (p)	3.0364	0.0043	0.0	--	--	--
a320-360 (c)	3.0338	0.0069	0.4	4.76	9.42	0.33
a320-360 (p)	3.0338	0.0069	0.4	--	--	--
b552-592 (c)	3.0338	0.0069	0.4	5.96	5.20	0.53
b552-592 (p)	--	--	-	--	--	--
Well 13 a 40- 80 (c)	3.0304	0.0103	1.4	8.04	6.09	0.57
a 40- 80 (p)	--	--	-	--	46.40	0.0
a120-160 (c)	3.0321	0.0086	1.0	5.02	5.24	0.49
a120-160 (p)	3.0390	0.0017	0.0	22.23	30.89	0.42
a240-280 (c)	3.0347	0.0060	0.1	4.44	6.25	0.41
a240-280 (p)	3.0355	0.0052	0.0	48.77	1.88	0.96
b440-480 (c)	3.0347	0.0060	0.2	7.20	7.82	0.48
b440-480 (p)	3.0364	0.0043	0.0	46.42	--	1.00

Δ d_{211} (104) Å = See method and material.

(c) = concretion; (p) = pebble

*d_{211} (104) Å of standard calcite = 3.0407.

a = Brown till; b = Dark gray till.

Samples a,b were obtained by deep drilling.

APPENDIX F

(Micromorphological characterization of
representative profile horizons at
Sites 1 and 2)

Micromorphological Characterization

Profile 1, Site 1 (Rego Black, saline phase)

7 to 11 cm Apks

The soil mass shows spongy structure with porous rough fragments. The void pattern is characterized by the presence of craze planes (C)*, interconected irregular orthovughs (O), and dendroid channels (R).

The coarse material is dominated over the fine and the $c/f_{20\mu m}$** related distribution is single space porphyric.

The coarse material includes rounded to sub-angular, mostly fine to very fine sand grains of quartz (VF), quartzite (R), plagioclase (O), microcline (R), hypersthene (R), biotite (VR), alterite (O), opaque minerals, siliceous rock fragments, and silt size calcite (R).

The dark brownish fine mass consists of clay and organo-ferric compound materials giving rise to humi-mull granic plasmic fabric.

Organic matter is mostly in the fine mass with strongly humified plant remains (F) and considerably humified plant remains (VR).

<u>Pedological features</u>: as sand and coarse silt size granotubles (R), orthic iron nodules, organoneoferrans,

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*(VR) = very rare; (R) = rare; (O) = occasionally; (C) = common; (F) = frequent; (VF) = very frequent.

**$c/f_{20\mu m}$ = coarse to fine material with 20 m size limit.

embedded grain organan and lithorelicts (R).

17 to 21 cm AC

The soil mass shows irregular jointed structure with compact rough fragments. The void pattern is characterized by the presence of craze planes (F) and irregular vughs (C) and channels (O).

The coarse material is dominant over the fine and the $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular, mostly fine to very fine sand grains of quartz (VF), dolomite and alterite (O), quartzite; microcline; tormaline; opaque minerals; siliceous and ferruginous rock fragments (R), garnet; orthoclase and plagioclase; biotite and brown hornblends (VR).

The dark brownish fine mass consists of clay, organoferric compound material and pellitic to aleuritic calcite with some clusters of salt accumulation probably of sulfates (O) giving rise to skelsepic-crystic plasmic fabric.

Organic matter is mostly in the fine mass with strongly humified plant remains (F).

Pedological features: mostly grain organo calci-argillans (C), calcite crystal chamber; calcitans and neocalcitans; orthic ironnodules (R), lithorelicts (VR).

30 to 35 cm Ccas

The soil mass shows porous structure with compact rough fragments. The void pattern is characterized by the presence of irregular ortho vughs (F), craze planes (O), channels (R), chambers and vesicles (VR).

The coarse material is dominant over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular, mostly fine to very fine sand size grains of quartz (VF), calcareous rock fragment (C), quartzite, alterite and calcite (O), dolomite; opaque minerals and silicious rock fragment (R), hypersthene and biotite (VR).

The brownish fine mass consists of clay, organoferric compound material and *pellitic to aleuritic calcite with some clusters of salt accumulation probably sulfates (R) giving rise to skelsepic crystic plasmic ferric.

Organic matter is mostly in pedological features with strongly humified plant remains (C).

Pedological features: mostly as orthic calcite nodules (C), organo ferric nodules (O), orthic iron nodules; carbonates iron nodules; calcite intercalary crystals; inherted iron nodules and ferrigenous concretions (R).

62-67 cm Ck_4

The soil mass shows irregular jointed-porous structure with compact rough fragments (F). The void pattern is characterized by the presence of vughs (F), skew planes (C) and vesicles (R).

The coarse material is dominated over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

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*Most of pellitic to aleuritic calcite is present as clusters marking the separation of plasmic material.

The coarse material includes rounded to subangular, mostly fine to very fine sand size grains of quartz (VF), limestone fragment (C), opaque minerals (O), plagioclase; garnet and alterite (R), microcline (VR).

The brownish fine mass consists of clay, ferruginous compounds and pellitic to aleuritic calcite giving rise to crystic plasmic fabric.

Organic matter is present as strongly humified material mixed occasionally with iron compounds(R).

Pedological features: mostly as calcite nodules (C), single and compound orthic iron nodules; inherted iron nodules; ferrans and neo-ferrans and calcite isotubles (O), calcite crystal chamber and ferruginous concretions (R).

Note: Accumulation of iron compounds in different forms is a prominent feature.

125 to 130 cm Ck5*

The soil mass shows irregular jointed structure with compact rough fragments of different sizes. The void pattern characterize by the presence of ortho skew planes (C), vughs (O), and vesicles (R).

The coarse material is dominant over the fine material and $c/f_{20\ m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular, mostly fine to very fine sand size grains of quartz (VF),

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*The other Ck's horizons are described but because of their similarity to the one above, therefore, it was decided not to present them here.

quartzite, limestone, and siliceous rock fragments and opaque minerals (O), alterite, orthoclase and green hornblende (R), biotite and garnet (VR).

The brownish fine mass consists of clay, ferruginous compounds and micro or creptocrystaline calcite giving rise to vo-skelmasepic plasmic fabric.

Organic matter is mostly strongly humified and clustered (VR).

Pedological features: as orthic iron nodules (C), inherted iron and calcite nodules and neoferrans (O), calcite intercalary crystals (R).

Profile 2, Site 1 (Orthic Black)

10 to 15 cm Ap

The soil mass shows spongy structure trending occasionally to irregular jointed with rough porous fragments. The void pattern characterized by the presence of craze planes (C) and irregular vughs (O).

The coarse material is dominated over the fine material and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular mostly fine to very fine sand size grains of quartz (VF), alterite; quartzite, limestone and siliceous rock fragments (O), plagioclase, orthoclase and microcline; green hornblende; garnet and brown hornblende (R).

The dark brownish-very dark brown fine mass consists of clay, organic compounds giving rise to humi-mullgranic plasmic fabric.

Organic matter presents mostly in the fine mass as considerably humified plant remains (O) and strongly humified plant remains (F).

Pedological features: as sand and coarse silt size inherted from nodules (C), ferruginous lithorelicts (O) and fungal hypha (R).

Note: Plagioclase, orthoclase, and microcline and more and bigger in size comparing with the same horizon for Profile 1.

20 to 24 cm Ahe

The soil mass shows irregular jointed trending occasionally to spongy structure with rough compact fragments. The void pattern characterize by the presence of craze planes (F) and irregular ortho vughs (C).

The coarse material is dominant over the fine material and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular mostly fine to very fine sand size grains of quartz (VF), quartzite; alterite and opaque minerals (O), microcline and garnet (R), green hornblende; biotite; amphibole and calcite (R).

The brown-dark brown fine mass consists of clay and organic compounds giving rise to mull-granic plasmic ferric.

Organic matter present mostly in the fine mass as strongly humified plant remains (C).

Pedological features: as inherted iron nodules and ferruginous lithorelicts (O) and fungal hypha (R).

35 to 45 cm Bt

The soil mass shows irregular jointed structure with compact smooth fragments. The void pattern characterize by the presence of craze planes (F) and ortho vughs (C).

The coarse material is dominated over the fine material and $c/f_{20\mu m}$ related distribution as single space porphyric.

The coarse material includes rounded to subangular, mostly fine to very fine sand size grains of quartz (F), opaque (C), quartzite and alterite (O), plagioclase; microcline; orthoclase and dolomite (R), augite; amphibole; biotite and calcite (VR).

The light brown fine mass consists mainly of clay and some ferruginous or organoferric compounds giving rise to skel-vo-mas-lattisepic plasmic ferric.

Organic matter present as strongly humified plant remains showing some clustering effect (O).

Pedological features: as orthic and inherted iron nodules and weakly oriented ferriargillans (C), lithorelicts mostly ferruginous (O) and fungal hypha (VR).

115 to 125 cm Ck3

The soil mass shows irregular jointed structure with compact rough and occasionally smooth fragments. The voids pattern characterize by the presence of skew and craze planes (C), irregular ortho vughs (C) and vesicles (O).

The coarse material is dominated over the fine and the $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse materials include rounded to subangular, mostly fine to very fine sand grain size of quartz (F), limestone fragments (C), plagioclase; ferruginous alterite and opaque minerals (O), green hornblends; biotite; microcline and orthoclase; dolomite and siliceous rock fragments (R), amphibole and augite (VR).

The light brown-brownish fine mass consists of clay, ferruginous compounds, pellitic and aleuritic calcite and few organic compounds giving rise with the coarse material to Vo-skelsepic crystic plasmic fabric.

Organic matter present as strongly humified clusters of plant remains (O).

Pedological features: as fine size (20 to 100 m) of inherted iron and calcite nodules; medium orthic iron nodules (O), ferrans and neoferrans; calcite intercalary crystals; orthic calcite isotubles, compound pedological features* and ferruginous concretions (R).

Profile 3, Site 1 (Gleyed Dark Gray Luvisols)

22 to 28 cm Ahe

The soil mass shows irregular jointed structure with some plate-like trend and compact smooth fragments. The void pattern characterized by the presence of craze planes (C) and irregular vughs (O).

The coarse material is dominant over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

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*This feature composed of ferrans and neoferrans and calcite crystalleria as crystal sheet in planner voide.

The coarse material includes rounded to subangular, mostly fine to very fine sand grains size of quartz (VF), plagioclase; opaque minerals; alterite; siliceous and limestone rock fragments (O), microcline and orthoclase; biotite; green hornblende, dolomite (R), brown hornblende and augite (VR).

The brown fine mass consists of clay, organic compounds masked mostly by the clay, ferric compounds and microcrystalline calcite giving rise to vo-skelsepic crystic plasmic fabric.

Organic matter is mostly strongly humified plant remains masked by fine material with some clustered units within these materials (O).

Pedological features: as calcite nodules and lithorelicts (O), neocalcitans and fungal hypha (R).

37 to 42 cm Aeg

The soil mass shows cracked structure with banded trend decreasing with depth, meanwhile the dense soil mass is partially fragmented to smooth compact fragments. The void pattern characterize by the presence of irregular jointed planes (O) and irregular ortho vughs (C).

The coarse material is dominant over the fine and the $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular, mostly 20 to 50 μm grain size of quartz (VF), *quartzite (C), orthoclase and microcline; alterite and opaque minerals (O),

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*Quartzite present also as coarse to very coarse sand size grains.

plagioclase; needle shape calcite with 100 m in length (R)

The brownish fine mass consists of clay, organic compounds giving rise to silasepic with some weak development of vo-skelsepic plasmic fabric.

Organic matter is mostly present as strongly humified plant remains showing a sort of plate-like pattern (C) and small pellets (R).

Pedological features: as orthic iron nodules (F) with different stages of formation, moreover compound units are present (R), weakly to moderately developed organic striotubles (C) and calcitic fungal hypha (R).

45 to 59 cm Btl

The soil mass shows regular jointed structure with compact smooth fragments. The void pattern characterize by the presence of medium dendroide channels (C), craze planes (O) and ortho irregular vughs and chambers (O).

The fine material is dominant over the coarse material and the c/f$_{20\mu m}$ related distribution is double space porphyric with some open porphyric trend.

The coarse material includes rounded to subangular, mostly fine to very fine sand grain size of quartz (F), quartzite and microcline (O), orthoclase; plagioclase hornblende and siliceous rock fragments (R), hypersthen; garnet and alterite (R).

The dark brown fine mass consists of clay, organo-ferric and organic compounds giving rise with the coarse material to skel-vo-lattisepic plasmic fabric.

Organic matter is present as strongly humified within the fine materials.

Pedological features: as ferriargillans and neoferriargillans (C), organoargillans; orthic iron nodules and inherted simple and compound iron nodules (O), ferrans; neoferran and papules (R).

70-74 cm Bt2

The soil mass shows regular jointed structure with compact smooth fragments. The void pattern characterize by the presence of dendritic channels (F), chambers (O) and ortho regular vughs (C).

The coarse material is dominated over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular, mostly fine to very fine sand size grains of quartz (F), quartzite fragments >2 mm in diameter (C), hornblende (O), orthoclase; alterite and opaque minerals (R), plagioclase; biotite and garnet (VR).

The brown to dark brown fine mass consists of clay, organic compounds and calcitic material (R), giving rise to skelvo-lattisepic plasmic fabric.

Organic matter is mostly present as strongly humified plant remains organized as clusters of pellets, less humified fibers, and masked within tne plasmic material.

Pedological features: as mostly void ferriargillans (C), fine orthic iron nodules, organo-argillans and inherted iron nodules which occasionally of compound character (O), grain ferriargillans (R).

125 to 130 cm BC1

The soil mass shows irregular jointed structure with smooth compact fragments. The void pattern characterize by the presence of dendritic channels and ortho irregular vughs (C) and craze planes (O).

The coarse material is dominant over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular, mostly fine to very fine sand size grains of quartz (F), quartzite; opaque minerals; plagioclase and alterite (O), needle shape calcite (> 100 μ m in diameter); orthoclase; hornblende and biotite and siliceous rock fragments (R), hypersthene (VR). Meanwhile, coarse to very coarse calcite and dolomite grains are found.

The brownish material of fine mass consists of caly, pellitic and alleuritic calcite (O) and ferric compound (R) giving rise with the coarse material to vo-skel-lattisepic crystic plasmic ferric.

Organic matter present as strongly humified plant remains and fine* pellets (O).

Pedological features: as void ferriargillans (F), grain ferriargillans, ferrans; calcite intercalary crystals and calcitic nodules and dendritic isotubles (O), calcitic fungal hypha and orthic iron nodules (R).

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* fine = 20 to 100 μm in size.

Profile 6, Site 1 (Rego Black)

4 to 7 cm Ah

The soil mass shows spongy-irregular jointed structure with porous rough crumbs. The void pattern characterize by the presence of irregular ortho rough vughs (F) and craze planes (C).

The coarse material is dominated over the fine $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes mostly subangular medium and coarse silt size grains of quartz (F), opaque minerals and needle shape calcite; siliceous and ferrugenous rock fragments (R).

The dark brown fine mass consists of caly and organic compounds, giving rise to humi-mullgranic plasmic fabric.

Organic matter present as strongly decomposed plant remains masked by the fine material accompanied by pellets (F) and considerably decomposed plant tissues (fibrous) (O).

Pedological features: as inherted iron nodules (O), fungal hypha (VR).

30 to 34 cm Ahk2

The soil mass shows cracked structure with smooth compact fragments. The void pattern is characterized by the presence of craze planes and irregular ortho vughs (C), ortho jointed planes and branchoide channels (O) and vesicles (R).

The coarse material is dominated over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular, mostly coarse silt and fine sand size grains of quartz (VF), limestone fragments, and *siliceous rock fragments (C), quartzite; plagioclase and alterite (O), hornblende and orthoclase (R).

The brownish fine mass consists of clay and organic compound which masked by fine material; cutinic material and alluritic to pellitic calcite giving rise to skel-vosepic plasmic fabric.

Organic matter present mostly as strongly humified plant remains within cutinic material (O) and calcitic inherted nodules (R).

70 to 74 cm Ccag

The soil mass shows irregular jointed-fragmented structure with rough compact fragments. The void pattern is characterized by the presence of irregular craze planes and irregular ortho vughs (F).

The coarse material is closely dominated over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes mostly rounded to subangular, fine to very fine sand grain size of quartz (F), quartzite; hornblende; alterite; opaque, siliceous rock fragments and dolomite (O), hypersthene (R); biotite (VR) and >2 mm size

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* These fragments are present also as very coarse sand and bigger size.

of limestone fragments occasionally ferruginous (C).

The light brown fine mass consists of clay, ferric compounds and allurtic to pellitic calcite giving rise with the coarse material to vo-insepic crystic plasmic fabric.

Organic matter is present as strongly humified clustered materials with pellets (O).

<u>Pedological features</u>: as fine iron nodules (∿30μm) (F), calcite nodules (mostly of inherted types) (C), calcite intercalary crystals; ferrans and neoferrans (O), calcitic fungal hypha and medium inherted iron nodules (o.2 mm) (R).

<u>105 to 110 cm Ck1</u>

The soil mass shows irregular jointed structure with rough compact fragments. The void pattern characterize by the presence of irregular craze planes (F) and irregular ortho vughs (C).

The coarse material is dominated over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular, fine to very fine sand size grains of quartz (F), quartzite; calcite; limestone fragments; opaque minerals and siliceous rock fragments (O), *hypersthene; *orthoclase and *microcline; plagioclase and alterite (R).

The light brown fine mass consists of clay, alluritic and pellitic calcite; ferric and organic compound giving rise to skel-vo-insepic crystic plasmic fabric.

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*These minerals are present also as coarse sand size.

Organic matter is strongly humified within the fine material occasionally occurring as diffuse patches (O).

Pedological features: as inherted calcite nodules (F), fine orthic calcite nodules; calcite intercalary crystals and orthic iron nodules (C), neoferrans (O), inherted iron nodules and calcitic simple isotubles (R).

Profile 1, Site 2 (Humic Luvic Gleysols)

25 to 29 cm Aeg

The soil mass shows irregular jointed structure with smooth compact fragments. The void pattern characterized by the presence of meso-macro ortho craze planes (F) and irregular vughs (O).

The coarse material is dominated over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular, fine sand and medium to coarse silt size grains of quartz (F), quartzite (O), hornblende; hypersthene; calcitic rock fragments; opaque minerals; laterite; dolomite and plagioclase (R).

The grey-light brownish fine mass consists of clay, ferric compounds giving rise to silasepic and occasionally skel-vosepic plasmic fabric.

Organic matter is mostly lightly-considerably humified plant remains present in the fine material as tissues (O) and cutinic material (R).

Pedological features: is as orthic iron nodules (O) and organoferrans (R).

26 to 32 cm AB

The soil mass shows irregular jointed-weak fragmented structure with smooth compact fragments. The void pattern characterized by the presence of micro-meso joint and craze planes (F) and irregular meso vughs (R).

The coarse material is dominated over the fine and $c/f_{20\mu m}$ related distribution is double space porphyric.

The coarse material includes rounded to subangular, coarse silt and fine to very fine sand size grains of quartz (VF), quartzite, alterite (O), calcite; dolomite and calcitic rock fragments (R), orthoclase, hypersthene and opaque minerals (VR).

The brown-dark brown fine mass consists of clay, ferric compounds giving rise with the coarse material for argi-silasepic with weak development of skel-vosepic plasmic fabric.

Organic matter is mostly considerably-strongly humified plant remains occur in the fine and cutinic material and occasionally as clusters within the voids (R).

Pedological features: as orthic iron nodules (F), neoorganans (O) and organoferrans; weak ferriargillans; calcitic fungal hypha (R).

50 to 56 cm Btgl

The soil mass shows irregular jointed structure with smooth compact fragments. The void pattern characterize by the presence of micro-meso craze planes (VF), irregular vughs (F).

The coarse material is dominated over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular grains, of fine to very fine sand size grains of quartz (VF), quartzite, opaque and alterite (O), hornblende; hypersthene; orthoclase and plagioclase (R).

The dark brown fine mass consists of clay, ferric compounds giving rise for lattisepic to vo-skelsepic plasmic fabric.

Organic matter is mostly as strongly humified plant remains within the fine material (VR).

Pedological features: as inherted iron nodules and weakly to moderately developed ferriargillans (F), orthic iron nodules (O), neoferrans and ferrans (R).

68 to 76 cm Btg2

The soil mass shows irregular jointed structure with compact smooth fragments, the voids pattern characterize by the presence of micro-meso skew and craze plane (F), anastomosing channels (O) and irregular meta vughs (F).

The fine material is dominated over the coarse and the $c/f_{20\mu m}$ related distribution is double space porphyric.

The coarse material includes rounded to subangular grains of fine to very fine sand size grains of quartz (VF), quartzite; hornblendes; hypersthene and opaque minerals (O), orthoclase; plagioclase; ferruginous rock fragments and alterite (R), garnet (VR).

The dark brownish fine mass consists of clay and ferric compounds giving rise to skel-vosepic and ominosepic plasmic fabric.

Organic matter is mostly as strongly humified plant remains within the fine material (VR).

Pedological features: as meta skew planes and vughs ferriargillans (F), embedded grain ferriargillans, anastomosing channels ferriargillans, secondary and tertiary peds ferriargillans; orthic and inherted iron nodules (O).

88 to 94 cm BC

The soil mass shows weak irregular jointed structure with compact smooth fragments. The voids pattern characterize by the presence of micro-meso skew and craze planes and irregular vughs (F), anastomosing channels (O).

The fine material is dominated over the coarse material and $c/f_{20\mu m}$ related distribution is double space porphyric and occasionally single space porphyric.

The coarse material includes rounded to subangular, fine to very fine sand size grains of quartz (VF), quartzite (F), dolomite, opaque minerals and ferruginous rock fragments (O), hypersthene; green hornblende; orthoclase and alterite (R), brown hornblende (VR).

The light brown-brown fine mass consists mainly of clay and ferric compounds giving rise to skel-vosepic to weak insepic plasmic fabric.

Organic matter present as strongly humified plant remains masked by fine material (R).

Pedological features: inherted iron nodules (F), orthic iron clay papules; weakly planes and channels ferriargillans (O), ped ferriargillans (R).

130 to 134 cm Ckgl

The soil mass shows irregular jointed structure with smooth compact fragments. The voids pattern characterize by the presence of ortho skew and craze planes (F) and irregular vughs (O).

The coarse material is dominated over the fine and $c/f_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular fine to very fine sand size grains of quartz (VF), quartzite; alterite; calcitic and dolomitic rock fragments, alterite and opaque minerals (O), microcline and orthoclase; plagioclase and hypersthene (R), green hornblends (VR).

The brown-dark brown fine mass consists of clay, ferric compounds and pellitic to alluritic calcite (F) giving rise to lati-skel-vosepic plasmic fabric.

Organic matter is present as strongly humified plant remains masked with the fine material (VR).

Pedological features: as orthic iron nodules (F), moderately developed calcitans and calcite nodules (O), inherted iron nodules; calcitic pedodes; clay papules; ferrans and calcitic shells (R).

Profile 2, Site 2 (Gleyed Black, saline phase)

10 to 14 cm Aps

The soil mass shows irregular jointed-weak spongy structure with rough porous fragments. The voids pattern characterize by the presence of micro-meso ortho craze planes (F), irregular vughs (C) and single channels (R).

The coarse material is dominated over the fine and c/f$_{20\mu m}$ related distribution is single space porphyric.

The coarse material includes rounded to subangular, fine to very fine sand size grains of quartz (VF), quartzite (C), green and brown hornblende and opaque minerals (O), plagioclase and calcite (R), alterite (VR).

The dark brownish fine mass consists of clay and organic ferric compounds giving rise to humi mull-granic plasmic fabric.

Organic matter is mostly present in the fine material as considerably-strongly humified (F) and slightly humified (R).

Pedological features: as orthic iron nodules (O), litho and pedorelict (R) and fungal hypha (VR).

22 to 26 cm Ahs

The soil mass shows irregular jointed-weak spongy structure with rough porous fragments. The voids pattern characterize by the presence of micro-meso craze planes (F), irregular vughs (O) and single and dendroid channels (R).

The fine material is dominated over the coarse and c/f$_{20\mu m}$ related distribution is double space porphyric.

The coarse material includes rounded to subangular, fine to very fine sand grain size of quartz (F), quartzite, hypersthene, needle shape calcite; brown and green hornblende and opaque minerals (O), microcline; plagioclase and alterite (R).

The brownish fine mass consists of clay, organic material (C) and ferric compounds (R) giving rise to lattisepic with weak skelsepic-crystic plasmic fabric.

Organic matter is strongly humified plant remains masked within fine material (C) with occasionally occurred as clusters, considerably humified in channels (O) or as plant tissues fragment (R).

Pedological features: is present as inherted iron nodules (O), ferriargillans, orthic iron nodules; calcitans and neocalcitans (R).

36 to 40 cm Bmks

The soil mass shows irregular jointed to weak porous structure with compact rough fragments. The voids pattern characterized by the presence of micro-meso meta craze and skew planes (F), irregular vughs (C) and single channels (O).

The fine material is dominated over the coarse and $c/f_{20\mu m}$ related distribution is double space porphyric.

The coarse material includes rounded to subangular, fine to very fine sand size grains of quartz (VF), quartzite and opaque minerals (C), microcline; hornblende and laterite (O), orthoclase; hypersthene and plagioclase (R).

The brown-dark brown fine mass consists of clay, organo-ferric compounds and pelletic to alluritic calcite giving rise to weak vo-skelsepic plasmic fabric.

Organic matter is strongly humified plant remains, mostly masked within the fine material and occasionally occur as clusters.

Pedological features: is as orthic iron nodules (C) and weak ferriargillans (O).

92 to 96 cm Ckg3

The soil mass shows irregular jointed to porous structure with rough compact fragments and crumbs. The voids pattern characterized by the presence of ortho, micro-meso skew and craze planes; irregular vughs and chambers (C).

The fine material is dominated over the coarse and $c/f_{20\mu m}$ related distribution is double space porphyric.

The coarse material includes rounded to subangular, fine to very fine sand size grains of quartz (F), calcite and dolomite (C), quartzite, hornblende, alterite and opaque (O), hypersthene (R).

The brown fine mass consists of clay, ferric compound and pellitic to alluritic calcite giving rise with the coarse material to skel-vosepic to weak crystic plasmic fabric.

The organic matter is strongly humified within the fine material (R).

Pedological features: is orthic and meta iron nodules (F), neocalcitan (C), calcitans and calcitic and dolomitic lithorelicts (O).

APPENDIX G

(Glossary of micromorphological terms)

GLOSSARY

Argillans. Cutans composed essentially of clay-minerals. They may be composed of pure clay minerals (e.g.: Palygorskans) or of clay minerals complexated with organic matter or iron oxihydrates (respectively organoargillans and ferriargillans).

Argi-silasepic plasmic fabric. See plasmic fabric.

Banded structure (fabric). Refers to a platy type of fabric in which the skeletal fraction is distributed relatively uniformly throughout each plate, but in which the plasma is composed primarily of clays, sesquioxides and humic substances is concentrated in bands at the top or within each plate.

Calcitans (Calcans). See soluans.

Carbonated iron nodules. See nodules.

c/f Related distribution. (c/f stands for coarse versus finer material.) It expresses the distribution of individual particles in relation to finer material and associated voids not included in the particles.

Chambers. Meta voids (smooth wall voids) differing from vughs and vesicles in that they are interconnected through channels and usually have a characteristic shape.

Channels. Voids, larger than those resulting from normal packing, and with a tubular form. Their branching pattern can be single, dendroid, anastomosing or trellsed.

Concretions. Are glaebules with a generally concentric fabric about a centre which may be a point, a line or a plane.

Cracked structure. See soil structure.

Craze planes. See planes.

Crystallaria. Single crystals, or arrangements of crystals of relatively pure fraction of the plasma that do not enclose the S-matrix of the soil material but form cohexive masses; their morphology (especially shape and internal fabric) is consistent with their formation and present occurrence in original voids in the enclosing soil material.

Crystic plasmic fabric. See plasmic fabric.

Crystal chamber. Crystallaria formed in vughs, vesicles and chambers. Generally, a crystallization from the walls inwards may be observed by the preservation of a central void.

Crystal sheet. Planar shaped crystallaria formed in planes.

Cutan. A modification of the texture, structure, or fabric at natural surfaces in soil materials due to concentration of particular soil constituents or in situ modification of the plasma.

Dendroid channels. See channels.

Double-space porphyric related distribution. Related distribution of coarse particles in a dense fine mass with the distance between the coarser grains being one to two times their diameters.

Embedded grain organan. See organan.

Ferrans. A cutan composed of a concentration of iron oxides.

Ferrigenous concretion. See concretions.

Ferriargillans. See argillans.

Grain organo-Calciargillans. See argillans.

Granotubules. See pedotubules.

Glaebules. A glaebule is a three-dimensional unit, within the soil matrix, and usually approximately prolate to equant in shape; their morphology (especially size, shape and/or internal fabric) is incompatible with their present occurrence of being within a single void in the present soil material. They are recognized as units either because of a greater concentration of some constituent such as carbonates, iron oxides, and/or a difference in fabric compared with the enclosing soil material, or because they have a distinct boundary with the enclosing soil material.

Humi-mull granic plasmic fabric. See plasmic fabric.

Intercalary crystals. Crystallaria that consist of single large crystals or crystal groups of a few large crystals present in the soil material and apparently not associated to voids of equivalent size or shape to that of the crystallaria as a whole; the crystals are euhedral to subeuhedral, having at least some well developed crystal faces.

Isotubules. See pedotubules.

Jointed structure. See soil structure.

Lati-skel-vosepic plasmic fabric. See plasmic fabric.

Lithorelicts. Features derived from the parent rock and usually recognized by their rock structure and fabric.

Mull granic plasmic fabric. See plasmic fabric.

Neoferrans. A sub-cutan composed of a concentration of iron oxides.

Neo calcitans (Neo calcan). A sub-cutan composed of a concentration of carbonates.

Nodules. An glaebules having an undifferentiated internal fabric, which may be, however, a recognizable soil or rock fabric. They could be orthic (formed in situ) or inherited.

Ominosepic plasmic fabric. See plasmic fabric.

Organan. A cutan composed of a concentration of organic matter.

Organo argillans. See argillans.

Organo ferric nodules. See nodules.

Organo neoferrans. See neoferrans.

Orthic iron nodules. See nodules.

Orthic pedological features. See pedological feature.

Ortho vughs. Vughs whose walls appear to result from the normal random packing of plasma and skeleton grains.

Papules. Clayey glaebules with a continuous or lamellar fabric and sharp external boundaries.

Pedodes. Glaebules with a hollow interior, often with a drusy lining of crystals; there may be associated veins or an outside layer of chalcedonic silica; they are usually spheroidal and discrete.

Pedological features. Recognizable units within a soil material which are distinguishable from the enclosing material for any reason such as origin, differences in concentration of some fraction of the plasma, or differences in arrangement of the constituents (fabric). These units can be orthic (formed in situ) or inherited.

Pedotubules. A pedological feature consisting of soil material (skeleton grains or skeleton grains plus plasma, as distinct from concentrations of fractions of the plasma) and having a tubular external form, either single tubes or branching systems of tubes; the external boundaries are relatively sharp. They can be classified as:

Granotubules. The basic fabric is essentially of granular type (essentially skeleton grains).

Aggrotubules. Recognizable aggregates of plasma and skeleton occur without directional arrangement with regard to the external form.

Isotubules. Have essentially a porphyroskelic basic fabric, without directional arrangement with regard to the external form.

Striotubules. Have a porphyroskelic basic fabric with a semi-ellipsoidal directional arrangement with the walls of the pedotubule approximately tangential to the semi-ellipsoid. They may be weakly, moderately, or strongly developed. Cleavage striotubules and segmental striotubules are the result of an ellipsoidal parting of the tublic material.

Pellitic to aleuritic crystals. Microcrystalline crystals with a shape of pellet-like.

Pellets (Fecal Pellets). Is defined as rounded to oval shape faunal excreta, however, bodies with the morphological characteristics of fecal pellets occur in what appear to be the remnants of tunnels or burrows, and these are properly neither pedotubules nor glaebules. In addition, aggrotubules may consist of these pellets.

Planes. Voids that are planar according to ratios of their principal axes. They may be subdivided into:

Joint planes. Planar voids that transverse the soil material in some fairly regular pattern such as parallel or subparallel sets.

Skew planes. Planar voids that traverse the soil material in an irregular manner.

Craze planes. Essentially irregular planar voids which occur as an intricate network.

Plasma. Is that part of a soil material that is capable of being moved or having been moved, reorganized and/or concentrated by soil forming processes.

Plasmic fabric. The arrangement of the plasma grains and the voids between them, in the S-matrix without reference to the skeleton grains or larger interapedal voids. It could be classified to:

Argillasepic fabric. Plasma is composed dominantly of anisotropic clay minerals and exhibits a flecked orientation pattern with recognizable domains.

Silasepic fabric. The high proportion of silt size grains makes the domains difficult to recognize.

Sepic Plasmic fabrics. Plasma separations with a striated extinction pattern are present. They can be subdivided into:

Insepic fabric. Isolated patches of plasma separations (with striated orientation) occur within a plasma of dominantly flecked extinction pattern.

Mosepic fabric. Numerous and relatively large patches of plasma separations with striated extinction pattern adjoin each other virtually and have no preferred orientation with regard to each other.

Vosepic fabric. Plasma separations with striated orientation occur subcutanically to the surface of skeleton grains or relatively hard pedological features.

Masepic fabric. Plasma separations with striated extinction pattern occurring in elongated zones that are associated neither with walls of voids nor with surfaces of skeleton grains. More sets of subparallel zones may form bimasepic, trimasepic, etc. fabrics.

Lattisepic fabric. Plasma separation with striated extinction pattern occurring as two sets of acicular and prolate domains in lattice-like pattern.

Crystic plasmic fabrics. Optical recognizable birefringent (or isotropic) crystals build up the plasma and are responsible for its birefringence.

Compound fabrics can occur (e.g. skel-vo-insepic plasmic fabric). This means several fabric elements are present; in these the weaker elements are named first (skel in the example) and the stronger elements last (insepic in the example). Sepic fabrics can also be compounded with other types such as crystic. Brewer and Pawluk (1975) introduced the term Granic fabric which consisted of unaccommodated, typically loosely packed, discrete units without coatings on, or bridges between units. Granic fabric could be classified to: Orthogranic (loosely packed mineral grains and/or rock nodules); Phytogranic (loosely packed, dark usually isotropic, moder-like organic units); Mullgranic (loosely packed mull like units consisting of plasma plus skeleton grains with the birefringence of the plasma masked by finely disseminated, porbably colloidal organic matter); Matrigranic (loosely packed units composed of normal soil material, that is plasma plus skeleton grains, not uncommonly with included pedological features, but not mull-like material. These granic fabrics can be compounded with each other.

Silasepic plasmic fabric. See plasmic fabric.

Single space porphyric related distribution. Related distribution of coarse particles in a dense fine mass with the distance between the coarser grains is less than one time of their diameters.

Skeleton grains. Are individual, relatively stable grains that are not readily translocated, concentrated or reorganized by soil forming processes. They include mineral grains and resistant siliceous and organic bodies larger than colloidal size.

Skew planes. See planes.

Skelsepic-crystic plasmic fabric. See plasmic fabric.

Skel-vo-insepic crystic plasmic fabric. See plasmic fabric.

Skel-vo-maslattisepic plasmic fabric. See plasmic fabric.

Skel-vo-lattisepic plasmic fabric. See plasmic fabric.

Skel-vosepic plasmic fabric. See plasmic fabric.

S-matrix. The material within the simplest (primary) peds, or comprising apedal soil materials, in which the pedological features occur.

Soil structure. The physical constitution of a soil material as expressed by the size, shape and arrangement of the solid particles and voids, including both the primary particles to form compound particles and the compound particles themselves; fabric is the element of structure which deals with arrangement.

Soluans. Cutans composed of more or less soluble crystalline salts such as gypsum (gypsans), calcite (calcitans) or halite (halans).

Spongy structure. See soil structure.

Striotubules. See pedotubules.

Vesicles. Voids differ from vughs principally in that their walls consist of smooth, simple curves.

Vo-insepic crystic plasmic fabric. See plasmic fabric.

Vo-skelsepic plasmic fabric. See plasmic fabric.

Vo-skelsepic crystic plasmic fabric. See plasmic fabric.

Vo-skel-masepic plasmic fabric. See plasmic fabric.

Vughs. Relatively large voids, usually irregular and not normally interconnected with other voids of comparable size. Their wall appear morphologically to be due to unaltered, normal, random packing of plasma and skeleton grains.

APPENDIX H

(Water table levels for the period 1979-1982)

TABLE 25. Water table levels for the period 1979-1982.

Well no.	1979								1980												1981							1982
	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Mar.	Apr.	May	June	July	July	Aug.	Sep.	Oct.	Nov.	Dec.	Apr.	May	June	July	Sep.	Oct.	Dec.	Feb.
1	6	53	122	178	D	238	254	284	297	316	27	79	125	158	173	196	213	212	216	208	29	118	133	169	248	275	269	292
2	145	105	127	202	268	303	D	D	D	D	312	273	207	208	140	125	152	150	177	148	234	-	161	201	269	242	240	238
3	f	f	7	158	197	225	228	237	242	D	15	51	120	154	156	168	165	153	164	168	135	95	106	156	D	D	D	D
4	f	f	32	140	187	228	234	231	D	ff	6	14	109	149	157	171	178	176	169	171	27	72	87	150	D	D	D	D
5	f	f	f	83	88	158	163	183	ff	ff	f	f	41	97	67	63	130	133	140	144	+23	2	21	121	D	172	182	D
6	f	f	112	137	157	210	-	-	-	-	f	111	148	163	114	142	149	157	177	188	12	109	122	159	216	226	237	D
7	f	95	165	241	D	260	D	D	D	D	209	259	393	390	391	389	391	395	400	409	201	300	324	370	119	162	179	248
8	D	D	D	D	D	D	D	430	463	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	352	320	404
9	D	160	154	261	D	250	D	D	D	D	353	359	319	269	258	206	273	267	250	250	361	349	302	166	119	120	161	305
10	65	81	120	160	145	158	144	159	D	D	98	112	155	184	176	183	D	192	177	189	209	150	144	199	153	161	172	291
11	+	+	+	+	+	+	506	403	436	D	406	412	423	439	446	451	438	426	413	419	450	467	458	451	452	461	457	465
12	+	+	+	+	+	+	424	372	405	430	437	456	457	448	430	424	416	408	401	407	449	-	450	438	412	423	447	479
13	+	+	+	+	+	+	508	276	309	350	364	358	267	260	262	255	209	208	255	250	327	141	223	232	282	275	268	348
14	+	+	+	+	+	+	239	239	255	ff	24	40	103	153	157	171	188	191	191	192	88	-	92	164	274	287	269	-
15	+	+	+	+	+	+	+	+	+	+	+	203	182	204	218	222	183	185	199	213	258	-	163	209	290	266	254	336

f = flooded.
D = dry.
- = no. reading.
ff = frozen.
\+ = not constructed.
+23 = height of water table above ground.

APPENDIX I

(Chemical analysis of ground water for Wells 1 to 15
for nine months in 1979 and 1980)

TABLE 26. Chemical analysis of ground water for Wells 1 to 15 for July 1979.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Well 14	Well 15
Date sampled		July 19/79							July 19/79						
pH															
EC_w mS/cm		1.60							2.30						
Ca^{++} meq/L		5.30							7.50						
Mg^{++} meq/L		13.70							27.50						
Na^{++} meq/L		2.80							2.20						
K^{+} meq/L		0.20							0.40						
T. CAT. meq/L		22.00							37.60						
SO_4^{--} meq/L		20.10							25.40						
Cl^{-} meq/L		1.90							2.90						
CO_3^{--} meq/L															
HCO_3^{-} meq/L		NIL							11.20						
T. ANS. meq/L		22.00							39.50						

TABLE 27. Chemical analysis of ground water for Wells 1 to 15 for September 1979.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Well 14	Well 15
Date sampled		Sep. 12/79	Sep. 12/79	Sep. 12/79		Sep. 12/79				Sep. 12/79					
pH		8.36	7.25	7.33		7.42				8.04					
EC_w mS/cm		1.70	1.00	0.96		0.36				1.12					
Ca^{++} meq/L		5.74	7.23	6.64		2.04				4.99					
Mg^{++} meq/L		12.33	5.34	4.36		0.82				4.52					
Na^{++} meq/L		2.19	0.54	0.53		0.10				0.49					
K^{+} meq/L		0.20	0.25	0.04		0.26				0.40					
T. CAT. meq/L		20.46	13.36	11.57		3.22				10.40					
SO_4^{--} meq/L		17.70	5.20	2.62		1.29				3.06					
Cl^{-} meq/L		0.34	0.34	0.34		0.17				0.34					
CO_3^{--} meq/L		0.08	0.00	0.48		0.00				0.48					
HCO_3^{-} meq/L		3.04	7.36	9.04		2.00				8.24					
T. ANS. meq/L		21.16	12.90	12.48		3.46				12.12					

TABLE 28. Chemical analysis of ground water for Wells 1 to 15 for April 1980.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Well 14	Well 15
Date sampled	April 21/80	April 21/80	April 21/80	April 21/80			April 21/80	DRY	April 21/80	April 21/80	April 21/80	April 21/80	April 21/80	April 21/80	
pH	8.03	7.69	8.06	8.10			7.87		7.74	8.26	8.15	8.38	7.67	8.28	
EC_w mS/cm	0.45	1.90	0.40	0.50			0.52		3.30	0.72	1.32	1.03	2.60	0.36	
Ca^{++} meq/ L	2.99	13.47	2.04	3.14			3.59		20.46	2.59	10.48	7.00	18.96	2.29	
Mg^{++} meq/L	1.56	10.69	1.48	1.81			1.73		24.67	2.96	4.85	3.04	14.80	1.15	
Na^{+} meq/ L	0.17	1.06	0.16	0.17			0.14		1.33	0.19	0.30	0.22	1.87	0.14	
K^{+} meq/L	0.14	0.52	0.33	0.15			0.14		0.59	0.31	0.22	0.28	0.36	0.24	
T. CAT. meq/L	4.86	26.01	4.01	5.27			5.60		47.05	6.05	15.85	10.54	35.99	3.82	
SO_4^{--} meq/L	1.56	25.02	1.33	1.19			2.35		49.13	1.87	14.42	6.73	36.07	1.43	
Cl^{-} meq/L	0.25	0.42	0.17	0.17			0.25		0.68	0.17	0.17	0.25	0.25	0.17	
CO_3^{--} meq/L	0.24	0.24	0.08	0.32			0.16		0.24	0.40	0.00	0.32	0.00	0.08	
HCO_3^{-} meq/L	3.52	2.64	2.32	3.04			2.64		2.96	3.84	2.16	4.20	2.64	2.96	
T. ANS. meq/L	5.57	28.32	3.90	4.72			5.40		53.01	6.28	16.75	11.50	38.96	4.64	

TABLE 29. Chemical analysis of ground water for Wells 1 to 15 for May 1980.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Well 14	Well 15
Date sampled	May 7/80	May 7/80	May 7/80	May 7/80		May 7/80	May 7/80	DRY	May 7/80	May 7/80	May 7/80	May 7/80	May 7/80	May 7/80	May 7/80
pH	8.39	7.91	8.46	8.50		8.11	7.76		8.03	8.32	7.90	8.31	7.48	8.17	8.11
EC_w mS/cm	0.50	2.70	0.55	0.63		0.45	0.61		3.37	0.80	2.02	1.04	2.97	0.75	0.65
Ca^{++} meq/L	3.39	19.96	3.14	3.44		3.14	4.24		28.94	1.70	20.95	3.39	29.44	2.39	3.19
Mg^{++} meq/L	1.81	15.62	2.22	2.38		1.48	2.22		24.67	3.37	8.06	4.03	18.91	2.55	3.54
Na^+ meq/L	0.16	1.52	0.24	0.24		0.25	0.06		1.39	0.17	0.52	0.96	2.17	0.24	0.24
K^+ meq/L	0.09	0.31	0.24	0.11		0.16	0.12		0.54	0.31	0.25	0.28	0.38	0.17	0.14
T. CAT. meq/L	5.45	37.41	5.84	6.17		5.03	6.64		55.54	5.55	29.78	8.66	50.90	5.35	7.11
SO_4^{--} meq/L	2.41	36.35	2.28	2.04		1.73	3.06		46.92	2.28	24.51	6.63	41.92	3.43	2.58
Cl^- meq/L	0.85	0.34	0.25	0.17		0.17	0.17		0.68	0.17	0.17	0.17	0.42	0.17	0.25
CO_3^{--} meq/L	0.24	0.08	0.16	0.24		0.00	0.00		0.00	0.08	0.00	0.00	0.00	0.00	0.00
HCO_3^- meq/L	4.24	3.36	3.28	4.00		3.92	2.80		2.32	3.84	3.24	2.24	4.16	3.04	4.72
T. ANS. meq/L	7.74	0.13	5.97	6.45		5.82	6.03		49.92	6.37	27.92	9.04	46.50	6.64	7.55

TABLE 30. Chemical analysis of ground water for Wells 1 to 15 for June 1980.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Well 14	Well 15
Date sampled	June 12/80	June 12/80	June 12/80	June 12/80	June 12/80	June 12/80	June 12/80	DRY	June 12/80	June 12/80	June 12/80	June 12/80	June 12/80	June 12/80	June 12/80
pH	8.42	7.88	8.00	8.59	8.40	8.12	7.60		7.90	7.42	7.90	8.08	8.00	8.26	8.45
EC_w mS/cm	0.58	2.65	0.93	0.62	0.48	0.39	0.54		3.22	0.95	2.25	0.98	3.10	0.65	0.71
Ca^{++} meq/L	1.65	23.45	5.64	4.49	3.44	3.14	3.89		29.44	6.99	31.19	3.64	32.68	2.94	1.90
Mg^{++} meq/L	2.38	18.09	3.86	2.47	1.15	1.15	2.14		26.31	4.03	11.51	6.58	23.85	2.47	3.54
Na^+ meq/L	0.39	1.91	0.53	0.35	0.17	0.26	0.10		1.56	0.48	0.95	0.87	3.09	0.39	0.39
K^+ meq/L	0.11	0.31	0.17	0.06	0.54	0.10	0.10		0.13	0.33	0.36	0.21	0.46	0.23	0.18
T. CAT. meq/L	4.53	43.76	10.20	7.37	5.30	4.65	6.23		57.44	11.83	44.01	11.30	60.08	6.03	6.01
SO_4^{--} meq/L	1.63	38.11	5.95	2.52	1.39	1.05	3.06		50.59	3.64	34.71	5.24	49.40	2.96	2.96
Cl^- meq/L	0.17	0.17	0.17	0.17	0.17	0.00	0.09		0.51	0.17	0.09	0.17	0.42	0.17	0.09
CO_3^{--} meq/L	0.08	0.00	0.48	0.24	0.00	0.00	0.16		0.00	0.00	0.00	0.24	0.00	0.00	0.00
HCO_3^- meq/L	3.2	1.68	5.04	4.16	3.44	3.40	3.44		1.84	8.88	1.52	7.36	2.16	2.48	3.44
T. ANS. meq/L	5.08	39.96	11.64	8.09	5.00	4.45	6.75		52.94	12.69	36.32	13.01	51.98	5.61	6.49

TABLE 31. Chemical analysis of ground water for Wells 1 to 15 for July 1980.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Well 14	Well 15
Date sampled	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80	July 8/80
pH	8.19	7.98	8.25	8.56	8.58	8.34	8.04	8.29	8.06	7.41	7.80	8.21	8.08	8.33	8.51
EC_w mS/cm	0.58	2.12	0.77	0.60	0.46	0.30	0.44	1.50	3.08	0.87	2.10	0.84	3.08	0.42	0.42
Ca^{++} meq/L	4.74	20.45	4.74	3.89	5.99	2.54	3.44	14.97	29.94	6.99	30.69	4.10	27.94	3.29	1.75
Mg^{++} meq/L	2.30	17.27	3.86	2.63	1.48	1.49	1.56	10.69	25.49	3.86	10.69	3.06	26.31	2.30	3.62
Na^{+} meq/L	0.16	1.87	0.52	0.27	0.43	0.12	0.17	0.87	1.48	0.28	0.74	0.61	3.39	0.39	0.32
K^{+} meq/L	0.11	0.28	0.18	0.05	0.43	0.10	0.15	0.75	0.51	0.33	0.31	0.24	0.41	0.21	0.18
T. CAT. meq/L	7.31	39.87	9.30	6.84	8.33	4.25	5.32	27.28	57.42	11.46	42.43	8.01	58.05	6.19	5.87
SO_4^{--} meq/L	3.43	34.78	5.30	2.65	3.77	1.73	2.69	22.27	48.89	1.22	32.88	4.12	51.71	2.86	1.50
Cl^{-} meq/L	0.25	0.17	0.34	0.17	0.17	0.17	0.17	0.17	0.51	0.17	0.17	0.17	0.51	0.17	0.17
CO_3^{--} meq/L	0.32	0.00	0.08	0.16	0.32	0.00	0.00	0.16	0.16	0.56	0.40	0.40	0.33	0.00	0.16
HCO_3^{-} meq/L	4.00	3.00	3.44	4.32	4.88	3.28	3.84	3.20	2.64	7.52	4.56	4.50	4.24	2.80	4.08
T. ANS. meq/L	8.00	37.95	9.16	7.30	9.14	5.18	6.70	25.80	52.20	9.47	38.01	9.19	56.79	5.83	5.91

TABLE 32. Chemical analysis of ground water for Wells 1 to 15 for September 1980.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Well 14	Well 15
Date sampled	Sep. 30/80	Sep. 30/80	Sep. 30/80	Sep. 30/80	Sep. 30/80	Sep. 30/80	Sep. 30/80	DRY	Sep. 30/80	Sep. 30/80	Sep. 30/80	Sep. 30/80	Sep. 30/80	Sep. 30/80	Sep. 30/80
pH	8.54	7.80	8.50	8.17	8.51	7.83	7.46		7.95	8.10	7.85	7.92	7.83	8.19	8.25
EC_w mS/cm	0.37	2.35	0.65	0.50	0.45	0.41	0.51		2.95	0.90	2.30	0.90	3.30	0.57	0.64
Ca^{++} meq/L	1.65	17.21	3.94	4.29	2.89	3.69	4.14		20.96	8.48	24.45	3.49	23.45	4.44	3.94
Mg^{++} meq/L	2.88	19.74	3.86	2.55	1.48	1.48	2.05		27.96	4.60	14.80	7.73	32.89	2.55	3.95
Na^{+} meq/L	0.28	1.70	0.36	0.29	0.22	0.08	0.12		1.43	0.26	0.76	0.56	4.09	0.20	0.29
K^{+} meq/L	0.18	0.25	0.14	0.41	0.32	0.12	0.10		0.38	0.35	0.28	0.19	0.37	0.14	0.14
T. CAT. meq/L	4.99	38.90	8.30	7.54	6.91	6.37	6.41		50.73	13.69	40.29	11.97	60.80	7.33	8.32
SO_4^{--} meq/L	1.29	34.85	4.73	2.69	1.33	2.07	3.47		50.49	8.81	35.33	8.02	57.90	0.99	1.77
Cl^{-} meq/L	0.50	0.50	0.59	0.20	0.30	0.30	0.20		0.89	0.40	0.40	0.59	0.69	0.20	0.30
CO_3^{--} meq/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.57	0.10	0.19	0.00	0.00	0.29
HCO_3^{-} meq/L	4.01	6.50	3.82	4.21	5.82	4.97	3.44		3.63	6.04	5.93	5.18	5.83	5.45	7.93
T. ANS. meq/L	5.80	41.85	9.14	7.10	7.45	7.34	7.11		55.01	15.82	41.76	13.98	64.42	6.64	10.29

TABLE 33. Chemical analysis of ground water for Wells 1 to 15 for November 1980.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Well 14	Well 15
Date sampled	Nov. 5/80	Nov. 5/80	Nov. 5/80	Nov. 5/80	Nov. 5/80	Nov. 5/80	Nov. 5/80	DRY	Nov. 5/80	Nov. 5/80	Nov. 5/80	Nov. 5/80	Nov. 5/80	Nov. 5/80	Nov. 5/80
pH	7.05	7.56	7.25	7.54	7.10	7.42	7.05		7.55	7.19	7.21	7.50	7.46	missing	7.24
EC_w mS/cm	0.68	2.28	0.79	0.54	0.47	0.42	0.58		2.72	0.88	2.22	1.08	3.22		0.63
Ca^{++} meq/L	4.99	14.47	5.49	3.49	3.19	2.54	4.04		19.96	3.10	29.44	4.24	30.94		3.64
Mg^{++} meq/L	3.45	18.91	3.86	2.55	1.71	1.56	2.22		25.49	5.01	11.51	7.89	27.96		4.70
Na^+ meq/L	0.37	2.22	0.48	0.36	0.15	0.19	0.15		1.22	0.52	1.13	1.17	1.17		0.37
K^+ meq/L	0.09	0.33	0.15	0.05	0.33	0.49	0.12		0.41	0.43	0.38	0.28	0.48		0.17
T. CAT meq/L	8.90	35.93	9.98	6.45	5.38	4.78	6.53		47.08	9.06	42.46	13.58	60.55		8.88
$SO_4^{=}$ meq/L	3.77	31.82	6.19	2.14	1.67	1.73	3.64		44.13	3.09	33.35	8.77	53.55		2.86
Cl^- meq/L	0.25	0.34	0.25	0.25	0.17	0.17	0.08		0.51	0.25	0.34	0.25	0.76		0.25
$CO_3^{=}$ meq/L	--	--	--	--	--	--	--		--	--	--	--	--		--
HCO_3^- meq/L	6.40	6.56	5.28	4.40	4.72	4.00	4.00		5.92	7.48	5.28	6.72	4.96		6.40
T. ANS. meq/L	10.42	38.72	11.72	6.79	6.56	5.90	7.72		50.56	10.82	38.97	15.74	55.27		9.51

APPENDIX J

(Monthly temperature and precipitation during
1979-1981 for Hamiota)

TABLE 34. Monthly temperature and precipitation during 1979-1981 for Hamiota (adapted from Atmo. Env. 1975).

Temp. °C & prec. mm		1979												1980											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Temp.	MN.	-22.4	-21.6	- 9.5		7.3	15.8	M	16.2	11.6	M	- 5.2	-11.7	-19.4		M	7.8	14.8	15.8	18.9	15.4	11.0	3.9		-15.4
	MAX.	-16.9	-16.4	- 3.6		13.1	22.6	M	23.8	18.0	M	- 0.3	- 6.8	-14.2		M	16.6	23.2	22.7	25.6	20.9	16.4	9.0		-11.1
	MIN.	-27.9	-26.7	-15.3		1.4	8.9	M	8.6	5.2	M	-10.0	-16.5	-24.6		M	- 1.1	6.4	8.9	12.2	9.8	5.6	- 1.2		-19.7
Prec.	P	0.0	17.8	30.5	61.8	52.5	15.9	52.5	14.2	38.1	1.5		2.5	8.0	28.0	M	0.0	34.0	62.4	93.6	114.0	48.8	14.2	1.2	M
	R/P	0.0	0.0	0.0	12.3	52.5	15.9	52.5	14.2	38.1	1.5		T	0.0	T	0.0	0.0	34.0	62.4	93.6	114.0	48.8	13.0	0.3	0.0
	S/N	0.0	17.8	30.5	49.5	0.0	0.0	0.0	0.0	0.0	0.0		2.5	8.0	28.0	M	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.9	M

Temp. °C & prec. mm		1981											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Temp.	MN.	-13.1	- 9.5							11.9			
	MAX.	- 7.8	- 4.4							18.8			
	MIN.	-18.4	-14.6							4.9			
Prec.	P		M	7.0	21.0	29.8	79.3	49.0	130.0	47.0	46.0	8.0	6.0
	R/P		0.0	7.0	21.0	29.8	79.3	49.0	130.0	47.0	39.0	1.0	T
	S/N		M	T	T	0.0	0.0	0.0	0.0	0.0	7.0	7.0	6.0

Temp. = Temperature; Prec. = Precipitation; MN. = Mean; MAX. = Maximum; MIN. = Minimum; P = Total precipitation; R/P = Rainfall; S/N = Snowfall

APPENDIX K

(Soil and air temperature within the period
1978-1981 along the studied
transects at Sites 1 and 2)

TABLE 35. Soil and air temperature data with time for two locations near Wells 7 and 8, Site 1 within the period 1978-1981.

Well 7										Well 8									
			Soil Temperature °C										Soil Temperature °C						
			Depth (cm)										Depth (cm)						
Date	Time of day	Air temp. °C	2.5	5	10	20	50	100	150	Date	Time of day	Air temp. °C	2.5	5	10	20	50	100	150
2-11-78	13.00	18.9	14.4	10.6	7.8	7.2	8.3	10.6	11.1	2-11-78	13.15	18.3	13.3	10.6	8.3	6.1	7.8	9.4	10.6
21-12-78	14.35	-4.4	-2.8	-2.8	-1.7	-1.7	-0.6	1.7	2.8	21-12-78	14.30	-4.4	-3.9	-3.9	-3.3	-2.8	-1.1	1.7	3.3
14- 6-79	13.40	26.1	23.9	22.8	21.7	19.4	16.1	11.1	8.9	24- 5-79	9.30	14.4	13.3	10.6	8.9	8.3	3.9	-0.6	-0.6
19- 7-79	13.30	33.0	23.2	28.4	23.5	19.5	17.2	14.1	11.7	19- 7-79	13.30	33.0	34.2	32.0	28.7	23.6	15.3	10.2	8.5
23- 8-79	12.00	17.8	17.8	17.8	17.2	17.2	16.7	14.4	13.3	23- 8-79	11.30	16.1	17.8	17.8	17.8	18.3	17.2	13.3	11.1
12- 9-79	15.00	14.4	13.9	13.3	13.3	13.9	13.3	12.2	14.4	12- 9-79	15.00	13.9	14.4	13.3	12.8	12.8	13.3	11.7	11.1
5-12-79	10.30	-1.0	-2.8	-2.2	-2.2	-1.1	0.0	2.8	4.4	5-12-79	10.40	-1.0	-1.1	-1.1	-1.1	-1.1	0.0	2.2	3.9
22- 1-80	10.10	-13.3	-9.4	-8.9	-7.8	-5.6	-3.3	-0.6	+1.7	22- 1-80	10.15	-11.7	-6.7	-7.2	-6.7	-7.2	-5.6	-1.1	0.0
18- 3-80	9.58	-11.7	-10.0	-9.4	-9.4	-8.9	-7.2	-5.6	-3.9	18- 3-80	10.05	-10.0	-10.0	-10.0	-10.0	-10.0	-8.9	-5.6	-3.3
21- 4-80	15.30	31.7	23.3	20.6	16.7	13.9	6.1	2.2	2.2	21- 4-80	15.35	33.3	11.1	11.1	11.7	11.7	7.2	1.7	1.7
13- 6-80	8.00	20.0	20.0	19.4	19.4	18.9	16.1	11.1	8.9	13- 6-80	8.00	20.0	20.0	20.0	20.0	20.6	19.4	11.1	8.3
9- 7-80	8.00	24.0	19.0	19.0	19.0	19.0	14.0	11.0	9.0	9- 7-80	8.30	24.0	21.0	20.0	19.0	18.0	16.0	12.0	9.0
1-10-80	9.20	11.1	9.4	8.9	10.0	10.6	10.6	11.1	10.8	1-10-80	9.20	10.6	11.1	10.0	10.6	11.1	11.7	11.1	11.1
2-12-80	9.35	-21.0	--	--	--	--	0.0	2.8	5.6	2-12-80	9.40	-21.0	-12.8	-11.8	-9.4	-5.6	0.6	5.6	6.1
15- 4-81	15.40	21.9	--	--	--	--	2.7	1.6	1.6	15- 4-81	15.50	21.9	18.1	14.8	9.2	3.8	0.9	0.5	0.9
15- 7-81	9.00		18.5	18.5	18.3	18.7	16.8	13.4	10.7	15- 7-81	9.00		19.8	19.6	19.5	19.8	18.6	14.6	11.4
10- 9-81	14.46		26.8	25.7	20.9	17.0	16.7	15.7	15.2	10- 9-81	14.36		30.5	27.4	23.6	19.9	18.5	16.3	15.1
28-10-81	9.15		2.8	2.8	2.8	2.8	5.6	8.3	10.0	28-10-81	9.15		2.2	1.7	1.1	1.7	3.3	7.2	8.3
10-12-81	13.15		--	--	--	--	1.0	3.0	4.4	10-12-81			5.5	5.2	4.3	2.9	0.0	2.4	3.9

TABLE 36. Soil and air temperature data with time for two locations near Wells 9 and 10, Site 1 within the period 1978-1981.

Well 9

Date	Time of day	Air temp. °C	Soil Temperature °C						
			Depth (cm)						
			2.5	5	10	20	50	100	150
2-11-78	13.30	18.3	11.1	8.9	7.2	5.0	6.7	8.9	10.0
21-12-78	14.25	- 4.4	- 3.9	- 3.3	- 3.3	- 3.3	- 1.7	1.7	2.8
24- 5-79	9.30	14.4	11.1	9.4	8.3	7.8	3.9	0.0	0.0
14- 6-79	13.40	26.1	21.7	21.7	21.7	19.4	14.4	7.2	3.9
19- 7-79	13.00	33.0	32.2	29.0	25.0	20.8	17.2	13.4	10.5
23- 8-79	11.15	16.1	18.3	18.9	18.9	19.4	18.3	15.0	12.8
12- 9-79	14.30	14.4	13.3	13.3	13.3	12.8	13.9	13.3	12.2
5-12-79	10.45	- 1.0	- 2.2	- 1.7	- 1.7	- 1.1	0.0	2.2	4.4
22- 1-80	10.25	-13.3	- 9.4	- 9.4	- 8.3	- 6.7	- 4.4	- 1.1	0.6
18- 3-80	10.10	-10.0	-10.6	-10.0	-10.0	- 8.9	- 7.8	- 5.6	- 3.9
21- 4-80	15.40	32.2	30.6	27.8	22.2	13.3	6.1	1.7	1.7
13- 6-80	8.00	20.0	20.0	20.0	20.0	20.6	17.8	12.2	8.9
9- 7-80	9.00	24.0	20.0	20.0	19.0	19.0	15.0	12.0	9.0
1-10-80	9.20	11.1	9.4	8.9	10.6	11.1	11.1	10.6	10.6
2-12-80	9.47	-21.0	--	--	--	--	0.0	2.8	4.4
15- 4-81	15.55	25.3	--	--	--	--	0.4	- 0.2	0.8
22- 7-81	4.0		37.5	32.7	25.9	22.90	19.80	16.4	14.3
10- 9-81	3.26		29.3	26.6	22.6	19.3	17.6	16.0	14.3
28-10-81	8.45	6.7	2.2	2.2	2.2	2.8	6.1	8.3	10.6
10-12-81	13.20						0.5	2.6	3.8

Well 10

Date	Time of day	Air temp. °C	Soil Temperature °C						
			Depth (cm)						
			2.5	5	10	20	50	100	150
2-11-78	13.45	18.3	13.3	8.3	6.7	6.1	7.8	8.9	8.9
24- 5-79	9.30	14.4	7.8	5.6	4.4	2.8	1.1	1.1	1.7
14- 6-79	13.40	26.1	17.8	14.4	14.4	13.3	10.6	8.3	7.8
19- 7-79	13.00	20.0	19.3	16.1	15.2	13.1	10.9	8.9	7.5
23- 8-79	11.00	15.6	14.4	13.9	13.9	13.9	12.2	10.6	9.4
12- 9-79	14.00	13.9	13.9	12.8	12.8	12.8	11.7	11.1	10.6
5-12-79	10.55	- 1.0	- 0.6	- 0.6	- 0.6	0.0	2.2	3.9	5.6
22- 1-80	10.35	-12.8	- 2.2	- 1.1	- 1.1	- 6.1	0.0	2.2	2.8
18- 3-80	10.27	-10.0	- 3.9	- 3.3	- 3.9	- 3.3	- 2.8	- 1.1	0.0
21- 4-80	15.50	27.8	18.9	11.1	9.4	5.0	3.3	4.4	5.0
13- 6-80	8.00	20.0	14.4	13.9	13.3	13.3	10.6	8.3	7.2
9- 7-80	9.00	24.0	14.0	14.0	13.0	13.0	10.0	9.0	7.0
1-10-80	9.20	7.8	8.3	10.0	10.6	10.6	10.0	10.0	10.0
2-12-80	9.58	-21.0	- 8.9	- 5.6	- 3.9	- 0.6	2.2	4.4	6.1
15- 4-81	16.00	25.3	8.4	3.6	2.6	0.8	0.9	1.7	2.5
15- 7-81	9.00		16.3	15.6	15.5	14.3	11.7	8.3	7.4
10- 9-81	13.50		18.0	15.9	15.2	14.9	14.0	12.5	11.0
28-10-81	8.45	6.7	3.9	5.0	5.6	6.7	8.3	9.4	10.6
10-12-81	13.20		2.6	1.5	1.2	0.1	1.6	3.4	4.3

TABLE 37. Soil and air temperature data with time for two locations near Wells 1 and 3, Site 2 within the period 1978-1981.

Well 1									
			Soil Temperature °C						
			Depth (cm)						
Date	Time of day	Air temp. °C	2.5	5	10	20	50	100	150
2-11-78	10.00	16.7	6.4	3.9	2.2	4.7	6.0	8.2	8.8
21-12-78	13.40	- 6.7	- 4.4	- 3.9	- 3.3	- 1.7	0.6	2.2	2.8
24- 5-79	11.30	15.0	14.4	12.2	8.9	7.8	6.1	3.9	2.8
14- 6-79	15.40	21.7	17.2	18.9	17.2	15.6	11.7	8.3	7.2
19- 7-79	15.00	30.0	26.6	24.6	20.4	15.6	13.6	11.8	8.6
23- 8-79	14.00	22.8	23.9	21.7	17.8	15.6	13.9	13.3	11.7
12- 9-79	16.00	13.3	13.9	13.9	12.8	11.7	11.1	11.1	10.6
19-10-79	9.00	0.0	- 1.7	- 1.1	0.6	3.9	6.1	6.1	6.7
5-12-79	11.20	- 1.0	- 2.2	- 2.2	- 2.2	- 1.1	1.1	2.8	4.4
22- 1-80	11.30	-12.2	- 5.0	- 5.0	- 4.4	- 4.4	- 3.9	- 1.7	1.1
18- 3-80	10.50	- 9.4	- 7.2	- 7.2	- 6.7	- 5.6	- 3.9	- 2.8	- 1.7
21- 4-80	16.00	28.9	18.9	17.2	13.9	8.9	4.4	2.2	1.7
13- 6-80	16.00	19.4	16.7	16.1	15.6	14.4	11.7	7.8	8.9
8- 7-80	8.30	24.0	12.0	12.0	11.0	10.0	9.0	5.0	7.0
1-10-80	8.45	4.4	7.8	8.3	9.4	10.6	10.6	10.0	11.1
2-12-80	10.15	-21.0	-11.1	-10.0	- 7.2	- 1.7	2.8	5.6	5.0
15- 4-81	14.00	23.0	4.3	1.6	1.3	1.2	1.2	2.1	
14- 7-81	14.00		19.4	18.9	18.1	16.8	13.2	9.6	11.0
10- 9-81	15.30		22.3	20.5	17.7	14.6	14.0	11.2	12.6
28-10-81	11.30	10.6	1.7	1.7	1.7	2.8	5.0	8.3	7.2
10-12-81	13.20		2.5	2.8	2.3	1.2	0.8	4.5	3.1

Well 3									
			Soil Temperature °C						
			Depth (cm)						
Date	Time of day	Air temp. °C	2.5	5	10	20	50	100	150
2-11-78	11.00	17.2	4.4	4.4	3.9	5.0	7.8	8.9	8.9
19- 7-79	15.00	26.0	19.3	18.2	16.6	14.6	12.7	10.5	9.1
23- 8-79	14.30	18.9	16.7	16.7	16.1	16.1	14.4	13.3	12.2
12- 2-79	16.00	11.1	10.6	10.6	10.6	10.6	11.1	10.6	9.4
19-10-79	9.00	0.0	- 0.6	0.6	1.7	3.9	5.6	6.1	6.1
5-12-79	11.30	- 1.0	- 2.2	- 2.2	- 2.2	- 1.1	1.1	2.8	2.8
22- 1-80	11.40	-13.9	- 3.3	- 3.3	- 3.3	- 2.8	- 1.1	0.0	+ 1.7
18- 3-80	11.16	- 6.7	- 3.9	- 3.9	- 3.9	- 3.3	- 2.2	- 1.1	0.0
21- 4-80	16.10	26.7	16.1	13.9	11.1	6.1	2.8	2.8	3.9
13- 6-80	9.00	19.4	15.0	14.4	13.9	13.3	10.6	8.3	6.7
8- 7-80	9.00	22.0	12.0	12.0	12.0	13.0	11.0	8.0	7.0
1-10-80	8.45	4.4	7.8	8.3	8.9	10.0	8.9	8.9	8.9
2-12-80	10.15	-21.0	-10.0	- 8.9	- 6.1	- 1.1	2.8	4.4	5.6
15- 4-81	14.20	23.6	1.6	1.7	1.6	1.2	1.3	2.1	3.2
14- 7-81	14.00		16.9	16.5	15.8	14.5	11.7	9.6	8.6
10- 9-81	15.42		17.7	16.7	14.8	13.3	12.0	11.0	9.8
28-10-81	11.30		- 5.6	- 5.6	1.67	2.2	5.0	6.1	7.8
10-12-81	13.20		2.9	4.3	2.5	0.4	1.9	3.3	4.6