Characteristics and genesis of gypsiferous soils of northwestern Iowa

Neil Frederick Walter
Iowa State University

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Characteristics and genesis of gypsiferous soils of northwestern Iowa

by

Neil Frederick Walter

A Thesis Submitted to the Graduate Faculty in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

Department: Agronomy
Major: Soil Morphology and Genesis

Signatures have been redacted for privacy

Iowa State University
Ames, Iowa

1980
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INTRODUCTION

Soil genesis includes many processes. They have been summarized by Simonson (1959) as being additions, removals, transfers, and transformations. The removal or leaching of salts originally present in parent materials is a very common process. As a general rule, the eastern portion of the United States has wet enough climates that removal of salts is common. In some instances, combinations of climate, parent material, and other factors have promoted soil development that results in soil environments that are undesirable for plant growth. As a general rule, the western portion of the United States has dry enough climates that removal of salts is not complete. In some instances, combinations of factors have promoted the addition or accumulation of salts in soils. Undesirable soil environments often result also.

The state of Iowa has been blessed with soil genetic factors that generally promote soil environments that are desirable for plant growth. Leaching of original salts has occurred to some degree in most soils. Yet the processes associated with severe leaching have not occurred. On the other hand, the accumulation of salts is minimal. Alkaline earth carbonates have accumulated in some soils. Accumulations of more soluble salts are extremely rare.

Inextensive gypsiferous soils have been recently observed in northwestern Iowa. The current study was initiated to further investigate the gypsiferous soils of northwestern Iowa. Specifically, the objectives of the study were to:
1. Determine the extent,
2. Determine the chemical and morphological characteristics, and
3. Determine the genesis of gypsiferous soils of northwestern Iowa,
   and to
4. Compare and contrast the gypsiferous soils of northwestern Iowa
to much more extensive areas of gypsiferous soils in southwestern Minnesota.
Gypsum as a Geologic Mineral

Calcium sulfate is a common mineral in the earth's crust. It is found in nature primarily as gypsum (CaSO$_4$·$2\text{H}_2\text{O}$) and anhydrite (CaSO$_4$). Gypsum crystallizes in the monoclinic system usually as tabular plates, elongate prisms, or needle-shaped (acicular) crystals (Mason and Berry, 1968). Tabular crystals sometimes grow together to form twins, giving a dovetail appearance. They also sometimes have curved surfaces rather than planes, giving the appearance of a double convex lens. This shape of crystal is called lenticular or lensoid.

Gypsum crystals exhibit good cleavage and are usually colorless. They become white, gray, or yellowish when massive. They have a hardness of 2 on the Mohs scale and a specific gravity of 2.32. Coarse crystals that are colorless and translucent are called selenite. Massive aggregate material with a parallel fibrous (acicular) structure is called satin spar. Fine-grained massive gypsum is commonly called alabaster. Gypsite is powdery gypsum commonly deposited near the soil surface by evaporation of gypsum-laden waters.

Anhydrite rarely forms crystals, but is usually massive or fibrous. It is colorless to bluish, violet, gray, or dark gray. Anhydrite is often found in extensive beds interstratified with gypsum, limestone, dolomite, and rock salt. It is believed to be the first stage of gypsum formation in some processes. The anhydrite later hydrates into gypsum due to water penetration. Anhydrite resembles rock gypsum but can be distinguished.
from it by the greater hardness of anhydrite (3.5 on the Mohs scale) and a higher specific gravity (2.98). See Appendix F, Slide 1 for a picture of rock gypsum.

Gypsum is a very important commercial mineral. It is used for plasters, wallboard, roof tile, in cements, and as a soil amendment. Gypsum can be heated to partially drive off the crystal water. Hemihydrate \((\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O})\) is plaster of Paris and is well-known for its solidifying properties when rehydrated. It is not frequently found in nature, only then on the surfaces of soil in hot, dry regions (Kovda, 1946).

Geologically, gypsum has several origins. They can be divided into two major processes: precipitation of already present \(\text{CaSO}_4\) from sea water, and chemical reactions within geologic materials to form \(\text{CaSO}_4\) (Wilder, 1902). Precipitation is probably the most prevalent mechanism of formation of geological deposits. As ancient seas evaporated, various salts reached their limits of solubility and precipitated. These deposits are called marine evaporites. Gypsum formed by this mechanism is normally interbedded with limestone, shales, sandstone, and rock salt. The clays and sands were suspended solids in the sea water. Currently, sea water is about 3.5% dissolved minerals. Of that, 77.8% is \(\text{NaCl}\), 10.9% is \(\text{MgCl}_2\), and 3.6% is \(\text{CaSO}_4\) (Wilder, 1902). When sea water evaporates, the concentration of the ionic constituents is increased. Their solubility limits are eventually reached. The most insoluble compounds precipitate first \((\text{CaCO}_3)\), next the sparingly soluble compounds \((\text{CaSO}_4)\), and as evaporation nears completion, the readily soluble salts \((\text{NaCl})\). Calcium sulfate is first deposited from sea water when 70-80% of the water is evaporated,
NaCl when > 90% is evaporated.

It can be readily seen that limestone should underlie most sedimentary gypsum deposits and that gypsum should underlie most rock salt deposits. Yet not all limestone deposits are overlain by gypsum nor are all gypsum deposits overlain by rock salt simply because the ancient seas may not have evaporated enough to precipitate the progressively more soluble salts. Gypsum deposits are more common worldwide than rock salt, but salt usually occurs in thicker beds. Conditions promoting 70-80% evaporation of sea water would be more frequently reached than those promoting > 90% evaporation. When > 90% evaporation did occur, the magnitude of NaCl in sea water did form thick beds. The dynamics of marine evaporite formation is a major topic in geochemistry. Any introductory geochemistry textbook offers a discussion of the subject. Krauskopf (1967) is a recommended text.

The second process of geologic gypsum formation is that of chemical reactions within geologic materials to form CaSO₄. A source of calcium and sulfur must be present. The most common source of sulfur is pyrite, FeS₂. Pyrite is another geologic mineral formed in marine evaporites under reducing conditions. The oxidation of pyrite is a well-known and discussed classic phenomenon of geochemistry. The sulfide is oxidized to sulfate in the presence of O₂ and is catalyzed by sulfur-oxidizing bacteria, i.e., Thiobacillus genus. A general equation is as follows:

\[
\text{FeS}_2 + \text{H}_2\text{O} + 7/2 \text{O}_2 \rightarrow \text{FeSO}_4 + \text{H}_2\text{SO}_4 \quad (\text{Eq. 1})
\]

One can see that an acidic product (H₂SO₄) is produced. If lime is present, another reaction takes place. The H₂SO₄ dissolves the CaCO₃ to
form CaSO₄.

\[
\text{FeSO}_4 + \text{H}_2\text{SO}_4 + 2\text{CaCO}_3 \rightarrow 2\text{CaSO}_4 + \text{FeCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \quad \text{(Eq. 2)}
\]

This reaction results in gypsum forming in place, or nearly so. The acidic waters may be carried some distance until calcareous materials are encountered. Anhydrite often may be the first mineral formed by this reaction. Gypsum may form later upon hydration. Iron does not stay in the carbonate form but usually goes to oxides.

Sulfuric acid may also come from sulfurous springs or volcanic materials and subsequently react with CaCO₃. These sources of sulfur are minor.

After gypsum has been formed geologically, it is often redistributed by fluviatile or aeolian action.

Gypsum Deposits in Iowa

The most notable gypsum deposits in Iowa are on the southeast side of the city of Fort Dodge, Webster County. The deposits cover an area of 25-30 square miles with a thickness of up to 10 ft. The Des Moines River valley runs through the area, thus allowing the gypsum to have been easily recognized by the early settlers. The gypsum deposits are covered by glacial drift < 100 ft thick. Crystals are rarely seen in the beds.

Keyes (1894) was the first to describe the Fort Dodge gypsum beds in detail. Dating of the beds is difficult since no fossils have been found in them. The beds evidently are of sedimentary origin since the gypsum does have dark, narrow bands interbedded within it (Appendix F, Slide 1). Keyes (1894) proposed that the beds were of Cretaceous
age and were deposited by a land-locked arm of the sea. There are no NaCl deposits overlying the gypsum, however. He proposed that the sea water may not have become concentrated enough to precipitate the NaCl, or that if NaCl was precipitated, it was later dissolved.

Wilder (1902) disputed the Cretaceous age by pointing out the red shales of Permian age which overlie the gypsum. These Permian "red beds" are found in the states to the west and south of Iowa as well as in Europe. They commonly contain gypsum. He felt that aridity was a necessary factor for large deposits of gypsum to accumulate and that the red color of the shales indicated a hot, dry climate. The covering of the red shales over the gypsum protected the beds from dissolution during the long weathering period from Permian times to Wisconsin drift deposition. Wilder (1902) agreed with Keyes' (1894) theories on why no NaCl is found above the gypsum. Yet he proposed a slightly different origin of the beds. He rejected the idea of a land-locked lake because the lake would have been phenomenally deep in order to precipitate the amount of gypsum present. He also rejected the idea of a lake fed by rivers because he concluded a 15 ft thick bed of gypsum with only 1% of sand and clay ruled out a lake fed by land streams. He proposed the idea of a partially land-locked lake intermittently open to the ocean along with some reactions between pyrite and limestone.

Wilder (1919) revised his theories further. The Fort Dodge gypsum deposits do not overlie limestone. They should, if the deposits are from sea water. He proposed the hypothesis that streams flowed over gypsum containing limestones, shales, and marls into a lake. The water
continuously evaporated leaving the gypsum. He still considered the age of the deposits as Permian, but put less emphasis on the idea of aridity.

Even at a much later date, Dorheim (1966) still could not conclude the age of the beds. At that time, there was some spore identification work being done. He believed it best to place the beds in the Upper Jurassic or Early Cretaceous periods.

Other gypsum deposits in Iowa are quite inaccessible. There are gypsum and anhydrite deposits in Mississippian and Devonian age deposits in the southeastern quadrant of the state. The area is roughly bounded by Hamilton Co. in central Iowa, Louisa Co. in eastern Iowa, and Taylor Co. in southern Iowa. The deposits are normally 500-1000 ft deep. The gypsum is in evaporite deposits with carbonate rock association. It is believed these deposits formed from the alteration of limestone by $\text{H}_2\text{SO}_4$ formed from the oxidation of pyrite. Anhydrite was first formed. Later some anhydrite was replaced by gypsum. Some anhydrite still interbeds the gypsum. Mines into these deposits have been operated at Centerville, Pella, and Sperry.

The early works on the gypsum resources in Iowa are quite interesting to read, particularly Wilder (1919). Those were exciting times for the growing mineral industry in Iowa. The proposed uses of gypsum were myriad.
Processes of Salt Accumulation in Soils

Introduction

The following discussion on salt accumulation in soils is in a general sense. Specific investigations are reviewed to illustrate a few specific processes. Numerous works with various regional and climatic differences will be given in later sections.

Soluble salts are one of the most dynamic of all soil constituents. Their concentration can be altered very rapidly. Processes associated with soluble salts can be more readily understood if the four processes given by Simonson (1959) which affect virtually all soil constituents are reviewed: additions, removals, transfers, and transformations.

Salts can be added to soils by several processes. Salts can be removed, primarily by water but also by aeolian action. Salts are transferred within the soil profile, some more easily than others. Salts can undergo transformations into other forms, thus altering the soil environment further. These four processes should be used as reference points around which the dynamics of soluble salts in soil are built.

Using these four processes, the soil can be investigated to determine its "salt balance." This term appears to have been first used by Kovda (1946). He defines it simply as the accounting for salts originally present in the soil, for salts lost, and for salts gained. The idea of a "balance" approach to studying a dynamic system is an increasingly popular model. Energy balance models are used to describe plant canopy systems. Moisture balance models are used to describe the accumulation and depletion of soil moisture in relation to climatic factors. Other
examples could be cited.

Soluble salts that occur in soils consist primarily of the cations of Na, Ca, and Mg and anions of Cl and SO₄. Minor amounts of K, HCO₃, CO₃, and NO₃ also occur (U.S. Salinity Lab Staff, 1954). The one property of these compounds that is most useful is their solubility in water. Knowing the solubility of salts is a prerequisite to investigating the salt balance of a soil system. Table 1 gives the solubility of common salts found in soils as well as calcite (CaCO₃) and dolomite (CaMg(CO₃)₂).

Table 1. Solubility of common soil constituents

<table>
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<th>Solubility in H₂O at 20°C</th>
<th>Classification</th>
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<tr>
<td></td>
<td>g/liter</td>
<td>moles/liter</td>
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<tr>
<td>CaCl₂</td>
<td>745</td>
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<td>NaCl</td>
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<td>KCl</td>
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<tr>
<td>MgSO₄</td>
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<tr>
<td>Na₂CO₃</td>
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</tr>
<tr>
<td>Na₂SO₄</td>
<td>124</td>
<td>0.9</td>
</tr>
<tr>
<td>K₂SO₄</td>
<td>112</td>
<td>0.6</td>
</tr>
<tr>
<td>CaSO₄</td>
<td>2.1</td>
<td>0.015</td>
</tr>
<tr>
<td>CaSO₄ · 2H₂O</td>
<td>2.5</td>
<td>0.015</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>0.01-0.05</td>
<td>1-5X10⁻⁴</td>
</tr>
<tr>
<td>CaMg(CO₃)₂</td>
<td>0.002-0.007</td>
<td>1-4X10⁻⁵</td>
</tr>
</tbody>
</table>

All data derived by the current author from Weast (1971) except for CaCO₃ and CaMg(CO₃)₂ which are derived from Krauskopf (1967).
Several notes should be given about Table 1. The data should be considered as approximate because some numbers are interpolations from given data. Kovda's (1946) Table 1, p. 86, Vol. I is quite different from the present author's Table 1. In nature, many of the salts will be hydrated. For example, MgSO₄ will probably occur as MgSO₄ • 7H₂O. Calculations by the author have shown that whether or not a salt is hydrated does not greatly affect its solubility when expressed in moles/liter. The solubility of only one hydrated salt, gypsum, is given because of its importance in the present study. The solubility of all carbonate salts is greatly affected by the partial pressure of CO₂ in the solution. The following relationships exist.

\[ \text{CO}_3^{2-} \rightleftharpoons \text{HCO}_3^- \rightleftharpoons \text{CO}_2 \]  

(Eq. 3)

This interaction explains why there is a range of solubilities given for calcite and dolomite. In soil systems, the CO₂ content of the soil water would vary with many environmental conditions. The solubility classifications given are by the author. These apparent divisions seem to be in common usage in the literature. They will be used for the remainder of the thesis.

The values given in Table 1 are in terms of salts dissolving in pure water. Solubilities are altered when salts dissolve in water containing other salts. The ionic composition of the solution determines whether the salt is more or less soluble than in pure water. The common ion effect can suppress solubility if the solution has a common ion with the dissolving salt. Solubility can be increased, especially for a sparingly soluble salt, if the solution contains well-dissociated, noncommon ions.
Solubility is increased probably by the increased polarity of the solution. Table 2 gives examples of the solubility of CaSO₄ in two different solutions. In one, the solubility is increased due to increased polarity of the water by NaCl. In the other, the solubility is decreased due to the common Ca ion.

Table 2. Solubility of CaSO₄ in two aqueous solutions of different ionic composition

<table>
<thead>
<tr>
<th>g/liter solution at 26° C</th>
<th>g/liter solution at 25° C</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>CaSO₄</td>
</tr>
<tr>
<td>0.00</td>
<td>2.12</td>
</tr>
<tr>
<td>91.15</td>
<td>6.66</td>
</tr>
<tr>
<td>143.99</td>
<td>7.18</td>
</tr>
<tr>
<td>148.34</td>
<td>7.16</td>
</tr>
<tr>
<td>176.50</td>
<td>7.12</td>
</tr>
<tr>
<td>228.76</td>
<td>6.79</td>
</tr>
<tr>
<td>264.17</td>
<td>6.50</td>
</tr>
<tr>
<td>320.49</td>
<td>5.72</td>
</tr>
<tr>
<td>280.30</td>
<td></td>
</tr>
<tr>
<td>367.85</td>
<td></td>
</tr>
</tbody>
</table>

*From Linke (1958).*

Accumulation of salts in soil: General

The origins of salts in soils will be discussed in a general way, but using the mineral gypsum as a specific example.

The original source and sometimes the direct source of all salts are the primary minerals in the earth's crust. Soil salts have their origin
in salt-containing parent material, seawater, airborne dust, salt-concentrating plants, salt-bearing surface or ground water, or in situ chemical reactions. Salt-bearing sedimentary deposits would give rise to salt-affected soils that formed in them. Specifically, gypsiferous parent materials are common in many parts of the world, primarily in arid and semiarid climates. Van Alphen and Romero (1971) discuss the extent of gypsiferous deposits in the North Africa-southern Europe-southwestern Asia region. Gypsum is often found mixed with marls, clays, silt, and sandstones.

The weathering of primary minerals consists of the gradual release of salts by the processes of hydrolysis, hydration, solution, oxidation, reduction, and carbonation (U.S. Salinity Lab Staff, 1954). Water containing CO₂ is a particularly active chemical weathering agent. Yet the weathering of primary minerals in situ is seldom of sufficient magnitude by itself to form a salt-affected soil. Salt-affected soils usually form in areas that receive salts from other locations.

The sea is a direct source of salts in soils of salt marshes along seacoasts. Periodic flooding replenishes the salt supply. Salts may also be moved inland by salt spray carried by winds. Salts may be carried by airborne dust particles. Wind may pick up salt-bearing soil particles in one area and deposit them in another. If subsequent rainfall is sufficient, the salts may move into the soil profile. A striking example of this airborne process is the White Sands of New Mexico. Water running over and through gypsum-bearing deposits carries gypsum to a closed depression in a valley. The water evaporates leaving sand-sized
gypsum particles. They are moved by the wind and deposited nearby. A dune field 1000 km² has developed (Dregne, 1976). Aeolian gypsum deposits also exist in southeastern Australia.

A minor but interesting method of salt accumulation is the concentrating of salts in the leaves of certain plants. Salts are removed from the soil and are concentrated in the stems and leaves. The leaves later fall from the plant, decompose, and release salts at the soil surface. The leaves may be blown to new areas as well.

Water is the primary carrier of salts from one location to another. All surface and ground water contains certain amounts of dissolved salts. The concentration and composition of the salt solution depends upon the soil and geologic material with which the water has been in contact. The idea of a salt balance must be examined to decipher the effect of salt-carrying waters upon soil. The areas of salt accumulation must be areas where the additions of salt are greater than removals. The most common areas are those with hot, dry climates. During the dry season of the year if not throughout the entire year, evapotranspiration exceeds runoff and percolation. Under these conditions, the major portion of the saline water brought into the soil profile evaporates, leaving the salts behind. In areas with more effective rainfall, the soluble salts originally present or formed later leach downward into the ground water.

Aridity is not a factor in salt accumulation in soils unless certain conditions of physiography cause the shallowness of a water table and the predominance of evaporation over outflow of soil water to ground water. "Accumulation" types of surfaces are necessary, i.e., closed depressions.
Closed depressions are common features in arid and semiarid regions due to lack of drainage net development. The depressions are usually not exceptionally large, but one in Iran is 150 X 500 km (Dregne, 1976). The major source of salts in these areas is a water table close to the surface. Water rises by capillarity from lower depths of the soil profile to shallower depths as evapotranspiration removes moisture. This phenomenon is called capillary rise, capillary draw, or the capillary fringe effect. It is a well-studied aspect of soil physics dealing with water movement in soils. Kovda (1946) states that an American investigator, Charles Lee, reported that the greatest depth from which ground water evaporates is 2.25 m. The present author did not find any other reference to Lee's work. Russian workers reported that about 2.7 m was the maximum depth from which ground water evaporates. A shallow water table would have a higher evaporation rate than a deeper one. Peck (1978) states that the critical depth of a water table has been defined empirically as that depth from which the maximum steady upward movement of water to the soil surface is 1 mm/day. The critical depth depends upon many factors, primarily soil properties. He said the range for most soils is 1-2 m, although some may be deeper.

Some salts enter depressions in surface runoff from upslope. Yet, it is believed that if there were no high water table or restricted drainage, few salts would evaporate near the soil surface (Dregne, 1976, and U.S. Salinity Lab Staff, 1954). Dregne (1976) uses this water table criterion to largely differentiate between two major types of salt-affected closed depressions: saline depressions and playas. Saline depressions
have a high enough water table to allow salts to evaporate near the soil surface. Playas are similar in physiography but are without a water table close enough to the surface to permit salt crusts to appear. Playas generally have medium- to fine-textured soils. Even though water may stand on playas for long periods after rains, there is sufficient permeability to allow salts to be leached from the surface soil. Saline depressions have lower permeability and salts accumulate in the soil surface. Gypsum is a common constituent. Dregne (1976) also states that carbonate deposited by capillary water evaporating from a shallow water table is a significant source of soil carbonates. The low permeability of a soil causes poor drainage by restricting the downward movement of water. Low permeability may be the result of a water-restrictive layer in the lower soil profile. The layer commonly contains a high percentage of clay or indurated CaCO₃ or silica. De Sigmond (1924) considered the presence of an impermeable layer essential for the formation of salt-affected soils in Hungary.

Microrelief is also an important factor in salt accumulation in closed depressions. Slight rises or microknolls on the depression floor tend to accumulate more salts than planar surfaces. The microknolls expose more soil surface to evaporation. They are then the loci of more rapid desiccation. With a shallow water table, capillary rise, evaporation, and accumulation of salts increase. Wadleigh and Firman (1948) showed this effect on a microscale using irrigated crop furrows. They found an extreme increase in salinity at the top of the seedbed ridge when compared to the middle of the furrow. This principle can be
expanded to a larger natural setting. A graphic representation of their results is most useful. An enlarged diagram of their results is found in "Diagnosis and Improvement of Saline and Alkali Soils," p. 42, Figure 14 (U.S. Salinity Lab Staff, 1954). The readily-soluble salts of NaCl and CaCl₂ were used in the study.

Kovda (1946) makes the general statement that there is more soluble salt accumulation on microrollunds than on planar surfaces. He says a difference of 10-25 cm in elevation over a distance of 20-50 m will make a marked difference in soil development. He gives data for two soil profiles in his Table 31, p. 76, Vol. I. One profile is on a level surface; the other is about 20-30 m away on a "slight elevation." The elevation is not quantified. Salt constituents were about 2-5 times higher in the soil found on the microrollund as on the level surface.

Accumulation of salts in soil: Specific

The decisive factor in explaining the differences in distribution of the various salts in soils is their solubility. As seen in Table 1, calcite is about ten times more soluble than dolomite, and gypsum is about 100 times more soluble than calcite. The readily-soluble salts are 40 to 450 times more soluble than gypsum. Of these readily-soluble salts, the chlorides, as a group, are more soluble than the sulfates.

Salt solubilities connected with the dynamics of ground water movement control the distribution of salt in soil profiles in nearly all cases (Kovda, 1946). When capillary solutions of ground water move towards the soil surface due to evaporative demand, pure water is constantly being removed, resulting in an increase in salt concentration in the remaining
solution. As each salt reaches its maximum solubility limit, it precipitates from the solution. Compounds of iron and silica would precipitate first, followed by dolomite and calcite. These compounds would be deepest in the soil profile. As water would continue to move upward, the solubility limit of gypsum would be reached next. Gypsum would form a zone of accumulation above the carbonates. The readily-soluble salts do not reach the point of saturation until they rise close to the soil surface, thus forming a third zone of salt accumulation. Only at near desiccation do some salts precipitate.

Hunt (1972) demonstrates this zonation of soluble salts due to evaporation on a geologic scale. When ancient seas evaporated from closed basins, definite rings of precipitated salts were often produced. Carbonates were the first salt to be precipitated as evaporation began. They formed a ring near the top edge of the basin. Next, the sparingly-soluble sulfates precipitated in a lower ring. The readily-soluble salts, the chlorides, were the last to be precipitated. They are located in the bottom of the basin. This concentric ring pattern of salt deposition is typical in Death Valley, Ca. and other areas of the western United States.

It should be pointed out that the three zones of salt accumulation described above in the soil profile are the ideal. In actuality, salts with a wide range of solubilities are often found distributed throughout the profile. The zones may be identified as regions of maximum accumulations of certain salts. Kovda (1946) states that the zones of maximum accumulation of gypsum and readily-soluble salts coincide when the water table is shallow (1-2 m or less). The maximum
concentration of gypsum and readily-soluble salts would be in the upper horizons. If the water table is deep (2.5-3.5 m), he says three separate zones are usually identifiable. Table 3 is a partial reproduction of his Table 39, p. 229, Vol. I. Profile No. 7 of Table 3 shows data for salt accumulation in a soil profile with a deep water table. Notice that there are three zones of maximum accumulation: readily-soluble salts at the surface, gypsum intermediate, and calcite deepest. Also note that there are amounts of all classes of salts throughout the whole profile. The zones are only maxima. It is quite rare to find a soil with 88% gypsum. Profile No. 40 of Table 3 shows data for a soil profile with a shallow water table. Notice that the zones of maximum accumulation of readily-soluble salts and gypsum coincide. Kovda (1946) presents three other sets of profile data similar to profile No. 7 and one other set of data similar to profile No. 40 showing the effect of the depth of the water table on the three zones. The data reproduced here present the case. It would be redundant to present the other data.

The process in which the readily-soluble salts accumulate in the surface horizons takes place only when evaporation and transpiration are at their peak, i.e., late spring, summer, and early autumn. The chloride salts (MgCl$_2$, NaCl, and CaCl$_2$) often precipitate near the soil surface during the dry daylight hours. An increase in humidity during the night redissolves these salts and makes them available once more for transport. In winter and early spring, moistening by rainwater dissolves the readily-soluble salts and flushes them down into the profile, possibly into ground water. Sodium sulfate is one of the last readily-soluble salts
Table 3. Zones of salt accumulation in soil profiles, deposited by evaporation from a water table

<table>
<thead>
<tr>
<th>Depth, cm</th>
<th>Readily-soluble salts, %</th>
<th>Gypsum %</th>
<th>Calcite %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Profile No. 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-2</td>
<td>3.5</td>
<td>23.6</td>
<td>5.1</td>
</tr>
<tr>
<td>2-12</td>
<td>7.9</td>
<td>22.8</td>
<td>4.5</td>
</tr>
<tr>
<td>12-23</td>
<td>4.7</td>
<td>26.4</td>
<td>3.7</td>
</tr>
<tr>
<td>23-35</td>
<td>3.8</td>
<td>40.9</td>
<td>2.3</td>
</tr>
<tr>
<td>35-46</td>
<td>2.5</td>
<td>88.0</td>
<td>Trace</td>
</tr>
<tr>
<td>46-57</td>
<td>2.3</td>
<td>84.9</td>
<td>Trace</td>
</tr>
<tr>
<td>60-70</td>
<td>1.8</td>
<td>86.5</td>
<td>2.0</td>
</tr>
<tr>
<td>95-115</td>
<td>3.7</td>
<td>18.7</td>
<td>13.0</td>
</tr>
<tr>
<td>115-130</td>
<td>3.4</td>
<td>14.6</td>
<td>13.0</td>
</tr>
<tr>
<td>135-155</td>
<td>3.4</td>
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<td>14.0</td>
</tr>
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<td>26.6</td>
<td>12.2</td>
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<tr>
<td></td>
<td>Profile No. 40</td>
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<td></td>
</tr>
<tr>
<td>0-5</td>
<td>5.4</td>
<td>21.1</td>
<td>12.3</td>
</tr>
<tr>
<td>5-18</td>
<td>2.2</td>
<td>20.4</td>
<td>15.7</td>
</tr>
<tr>
<td>18-35</td>
<td>2.1</td>
<td>9.3</td>
<td>22.2</td>
</tr>
<tr>
<td>35-67</td>
<td>1.8</td>
<td>6.3</td>
<td>27.6</td>
</tr>
<tr>
<td>67-100</td>
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<td>5.3</td>
<td>30.0</td>
</tr>
<tr>
<td>100-110</td>
<td>1.6</td>
<td>7.8</td>
<td>47.1</td>
</tr>
<tr>
<td>110-140</td>
<td>0.8</td>
<td>2.1</td>
<td>58.8</td>
</tr>
<tr>
<td>140-160</td>
<td>0.3</td>
<td>0.5</td>
<td>70.0</td>
</tr>
<tr>
<td>190-225</td>
<td>0.4</td>
<td>0.3</td>
<td>55.5</td>
</tr>
<tr>
<td>225-245</td>
<td>0.3</td>
<td>0.3</td>
<td>42.3</td>
</tr>
</tbody>
</table>

*From Kovda (1946).*
to be completely leached downward due to its relatively low solubility, especially under cold conditions. Gypsum as well as the carbonates become fixed almost permanently wherever they have precipitated. Very little of these salts returns to the ground water during the seasonal flushing. This seasonal cycle of alternate deposition and removal of salts is an important part of the salt balance of a soil. It will vary from place to place and year to year depending upon climatic conditions. It controls the ultimate concentration and composition of the salt profile. This will be discussed in more detail later. It is possible for the leaching during the wetter part of the year to effect a complete removal of any readily-soluble salts, leaving only the gypsum and carbonates. If the water table is shallow, the gypsum concentration would be at the surface with the carbonate concentration below it. If the water table is deep, the gypsum concentration would be within the middle to lower part of the profile. The surface horizons could be leached entirely. If the water table is deep, the readily-soluble salts may never reach the soil surface.

Iron and manganese compounds are of minor importance in the present study of soluble salts. One point will be mentioned however. Kovda (1946) states that iron often precipitates with manganese to form "shot-like" or large concretions. In the presence of CaCO₃, the Fe and Mn precipitate with it to form concretions 0.5-2.0 cm in size. The study of Fe and Mn precipitation is also discussed in most geochemistry texts.

The discussion so far has been concerned with ground water already containing the dissolved salts. Some salts can be formed in situ within
the soil profile by chemical reactions. Gypsum is the most common mineral that accumulates by this method. The soil material may contain sulfur compounds, usually pyrite (FeS₂), that oxidize to SO₄ ions in the presence of O₂. This reaction may be catalyzed by sulfur-oxidizing bacteria. This reaction has been given in Equation 1 previously. In the presence of CaCO₃, the SO₄ ions react with calcium ions to form CaSO₄ (Rozanov, 1951). See Equation 2. These reactions were discussed earlier under the section "Gypsum as a Geologic Mineral," in the realm of methods of geochemical gypsum formation in ancient times. This same process does occur on a smaller scale in soils today. It probably produces only small amounts of gypsum because the content of pyrite in most soils is low. It should be pointed out, however, that Equations 1 and 2 are highly important in the formation of gypsum in calcareous parent materials.

The gypsum is formed and may be carried by ground water to the present soil profile. Van Alphen and Romero (1971) state that gypsum can also be formed by Na₂SO₄ leaching from other soils and reacting with CaCO₃. Kovda (1946) gives reactions and discusses the process of ground water becoming mineralized as it flows through geologic materials.

Discussion has been given in which capillary water moves up toward the soil surface. What about soils in which water moves consistently downward? In climates with abundant rainfall, the soluble salts have been leached into the ground water. As a generality, this is the state of the soils in the eastern half of the United States. Quite acid conditions have developed in some cases. Yet in areas where rainfall is limited, the salts have not been removed. This is generally the case in the
western half of the United States. If it is assumed an initial soil containing carbonates, gypsum, and readily-soluble salts, then the three zones of salt accumulation would be in the opposite order from that discussed previously. The carbonate concentration would be highest at the surface or else fairly constant throughout the profile; the gypsum would be leached below the carbonate zone, and the readily-soluble salts would be leached deepest. Again, these phenomena are all explained by the solubilities of the various salts, i.e., how easily they move with leaching waters. Depending upon rainfall and soil permeability, it would be possible to have a soil with carbonates and gypsum, but with no readily-soluble salts, or a soil with only carbonates.

In concluding this section, the concept of a salt balance should be emphasized. The set of processes within a soil which affect salt accumulation and depletion is a never-ending, dynamic balance of additions, removals, transfers, and transformations. Many factors affect this balance. The direction and amount of water movement within a soil profile are the most important factors.

The processes of salt accumulation by translocation and deposition in a soil profile as well as in situ formation by chemical reactions are termed pedogenetic processes. Soils acquiring their salts by developing in originally saline parent materials do so by geogenetic processes (Van Alphen and Robért, 1971). Both pedogenetic and geogenetic means of salt accumulation have been presented here with the citation of only a few references. The author wishes to note that these same processes were given in textbooks and papers from all over the world. Repetitious
Calculation of soil age

The interaction of ground water and climate has been shown to be extremely important in the accumulation of salts in soils. Indeed, the influence of climate upon soil formation is important in all aspects of soil genesis. Climate is considered one of the five principal soil-forming factors. Buol et al. (1973) discuss the effect of climatic factors upon soil. It may be possible to approximate minimum soil age from knowing certain soil and climatic factors.

A few researchers have tried to correlate the amount of annual rainfall percolating through a soil to the removal of carbonates. Jenny (1941) correlated the depth of leaching of CaCO$_3$ to rainfall climatic factors on a transect from higher rainfall to lower rainfall in the Great Plains. He did not calculate any soil ages. Arkley (1963) also studied Great Plains soils, but used soils of a wide range of parent material ages: late-Wisconsin, Yarmouth, and Peorian. He assumed an original CaCO$_3$ content of each parent material. He then used the solubility of CaCO$_3$ and the rate of water movement in the soil calculated from climatic data to approximate the minimum soil age of a profile leached to a certain depth of CaCO$_3$. His calculated ages agreed well with the ages of the parent materials determined by other means.

Kovda (1946) is the only researcher known to the present author who attempts to calculate soil age from the amount of accumulation of salts, in this case gypsum. He uses three items as input: the annual rate of ground water evaporation per unit area, the dissolved gypsum content of
the ground water, and the total amount of gypsum in the soil profile per unit volume. The time it took to accumulate the gypsum can then be calculated. In one example, he assumed the annual rate of ground-water evaporation at 7,000 m$^3$/ha. The dissolved gypsum content of the ground water was 0.29 g/liter. Therefore each hectare (ha) of soil received about two metric tons of gypsum per year. The total amount of gypsum in a 135 cm layer of soil above the water table was 80-90 metric tons/ha. The approximate age of the salts in the soil would then be 40-45 years.

No example of the calculations was given, so the present author did the following.

Evaporation = 7,000 m$^3$/ha

1 m$^3$ = 1,000 liters

Therefore: $7,000 \text{ m}^3/\text{ha} \times 1,000 \text{ liters/m}^3 = 7 \times 10^6 \text{ liters/ha}$

Concentration of ground water = 0.29 g/liter

$7 \times 10^6 \text{ liters/ha} \times 0.29 \text{ g/liter} = 2 \times 10^7 \text{ g}$

$= 2 \times 10^7 \text{ kg}$

$= 2 \text{ metric tons}$

So: $80-90 \text{ metric tons/ha in soil}$

$= 40-50 \text{ years}$

2 metric tons accumulated/yr/ha

This is a short time in the realm of soil genesis. What percentage by weight is 80-90 metric tons/ha in a 135 cm layer of soil? The present author did the following calculations:

1 ha = $10^4$ m$^2$

135 cm = 1.35 m

Total volume of soil considered = $10^4$ m$^2 \times 1.35$ m = $1.35 \times 10^4$ m$^3$

or $1.35 \times 10^4$ m$^3 \times 10^6$ cm$^3$/m$^3 = 1.35 \times 10^{10}$ cm$^3$.

Assume a bulk density of 1.5 g/cm$^3$: 

1.35 \times 10^{10} \text{ cm}^3 \times 1.5 \text{ g/cm}^3 = 2 \times 10^{10} \text{ g} \\
= 2 \times 10^7 \text{ kg} \\
= 2 \times 10^4 \text{ metric tons, total weight}

Therefore: \frac{80-90 \text{ metric tons/ha gypsum}}{2 \times 10^4 \text{ metric tons/ha total soil}} \times 100 = 0.4\% \text{ gypsum}

This is not a high concentration of gypsum. An accumulation period of 40-45 years might be realistic. Kovda (1946) gave another example of a soil containing 6,000 metric tons/ha of gypsum in a 1.6 m layer. With an annual evaporation rate of 7,000 m$^3$/ha and a ground water gypsum concentration of 1.7 g/liter, the calculated age of the gypsum accumulation would span about 500 years. The current author calculated the gypsum content of this soil to be 25.0% by weight.

Such age calculations appear to be useful at first glance. However, there are several limitations and assumptions which should be discussed. Kovda (1946) does not discuss them. The current author will discuss these items later when his own data are presented.

Classification and Taxonomy of Salt-Affected Soils, Including Salt Transformations

Introduction

Salt-affected soils present a unique case in that they have been historically classified into categories pertaining to the type and amount of salt they contain as well as into regular taxonomic schemes. Therefore, the terms classification and taxonomy refer to two different ideas. Classification refers to arranging salt-affected soils into various categories according to the type and amount of salt contained, usually with a view toward crop growth. Few relationships to other soils are implied
Taxonomy refers to arranging salt-affected soils into a taxonomic scheme in relationship to other soils. Salt properties may be used in assigning taxonomic categories, but they may not.

Classification and taxonomy have been interwoven in historical development. It is easy at times to separate the terms and concepts used. At other times it is very difficult. The ensuing discussions may necessarily overlap at times.

There is an age-old controversy in the taxonomy of salt-affected soils whether to classify them according to their chemical constituents or according to their morphology. Certain transformations of salts usually result in a predictable morphology. If a soil is found with a certain morphology, the chemical constituents can likewise be predicted. Yet a problem arises when a certain morphological profile does not have the predicted chemical constituents. Which criteria should be used? It is somewhat difficult therefore to discuss taxonomy without considering the salt transformations as well. The current author chooses to discuss certain salt transformations in connection with taxonomic considerations. Otherwise duplicative discussions would be necessary.

The definitions of terms used to describe salt-affected soils have changed over the years. This fact plus the ever-evolving nature of soil taxonomy leads the current author to believe a brief review of the historical aspects of categorizing these soils would be in order. Only United States history will be given in detail. Other systems will be referred to briefly.
United States systems: Classification

E. W. Hilgard was the first researcher to make indepth studies of salt-affected soils in the western United States. He studied them from 1875-1916. The term "alkali" was applied to all such soils in those years. Hilgard introduced the distinctions of "white alkali" and "black alkali" soils (in Kelley, 1951). Basically, white alkali soils had whitish surfaces due to an accumulation of neutral salts. Black alkali soils had dark surfaces and were highly alkaline. The word alkali is of Arabic origin. Centuries ago, Arab tribesmen noted that the surface of certain soils looked like wood ashes. They designated these areas by the Arabic term for ashes. Cameron (1901) uses the terms white and black alkali and defines alkali soils as containing "an accumulation of water-soluble inorganic material sufficient in amount to have a deterrent effect upon vegetation." The term alkali did not imply any specific chemical constituent. He classifies salt-affected soils into four major groupings on the basis of the salt composition of soil and ground water found at four locations of the United States. The four classes were: Fresno type, Salt Lake type, Pecos type, and Billings type. The soil at each of these locations had a different suite of salt constituents and were believed to be typical of all salt-affected soils.

Workers in the 1930s considered that plants began to be adversely affected if the salt content of a soil exceeded 0.1%. After considerable experience with salt-affected soils, the U.S. Salinity Laboratory staff of Riverside, CA. proposed a classification in 1954 of four general categories (U.S. Salinity Lab Staff, 1954). The criteria for placement of a
soil were its content of soluble salts and exchangeable sodium. Soluble salt content was assessed by determining the electrical conductivity (EC) of the soil's saturation extract. The saturation extract is the solution removed from a soil paste just at saturation by vacuum filtration. The units are commonly expressed as millimhos/centimeter (mmhos/cm). The content of the exchangeable Na was assessed by determining the percentage of saturation of the cation exchange capacity with Na. The content is usually reported as Exchangeable Sodium Percentage (ESP).

In 1958, Bower et al. (1958) proposed slightly different names for the same four classes of soils. The classes and criteria are given in Table 4.

Table 4. Classes and criteria of salt-affected soils

<table>
<thead>
<tr>
<th>1954 class names</th>
<th>1958 class names</th>
<th>Electrical conductivity (EC) of saturation extract, mmhos/cm</th>
<th>Exchangeable sodium percentage (ESP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saline</td>
<td>Saline-nonsodic</td>
<td>≥ 4</td>
<td>&lt; 15</td>
</tr>
<tr>
<td>Saline-alkali</td>
<td>Saline-sodic</td>
<td>≥ 4</td>
<td>≥ 15</td>
</tr>
<tr>
<td>Nonsaline-alkali</td>
<td>Nonsaline-sodic</td>
<td>&lt; 4</td>
<td>≥ 15</td>
</tr>
<tr>
<td>Normal</td>
<td>Nonsaline-nonsodic</td>
<td>&lt; 4</td>
<td>&lt; 15</td>
</tr>
</tbody>
</table>

\(^a\)From U.S. Salinity Lab Staff (1954).

\(^b\)From Bower et al. (1958).
The general intent of the classification is to group soils according to plant responses. Because of differences among soils, plants, and environmental conditions, the EC value of 4 mmhos/cm and the ESP value of 15 should be considered as averages. In both the 1954 and 1958 classifications, a soil with excess soluble salts is termed saline. In the 1954 classification, a soil with excess Na is termed alkali. Remember that the original use of the term alkali when applied to soils meant salts as a whole. Yet by at least 1934, as will be seen from the following section on taxonomy, the term alkali was restricted to mean just sodium. Why this was done or how it got started is not clear. The alkali metals of the periodic chart include Na, but also include the common soil element potassium. Sodium is a much more common ion in soluble salts in soils than K.

The resulting confusion over the term alkali prompted the report of Bower et al. (1958). They suggested the use of the term alkali to be stopped due to its ambiguity of meaning. Instead, they substituted the word sodic. This action was a good one in the current author's opinion since "sodic" is a derivative of the root word "sodium". It is unfortunate that Buol et al. (1973) perpetuated the term alkali in their book by continuing to call the process of accumulating exchangeable Na "alkalization". In the remainder of this thesis, the 1958 names will be used in discussing salt-affected soils.

Saline-nonsodic soils have an EC of $\geq 4$ and an ESP of $< 15$. They contain an excess of soluble salts but not of exchangeable Na. The pH of a saturated paste is usually $< 8.5$. These soils would correspond to the
white alkali soils of Hilgard and the Solonchaks of the Russian taxonomic scheme discussed later. White crusts often form on their surfaces. In addition to readily-soluble salts, saline-nonsodic soils may contain large amounts of low solubility salts such as gypsum and Ca and Mg carbonates.

Saline-sodic soils have an EC of ≥ 4 and an ESP of ≥ 15. They contain excesses of both soluble salts and exchangeable Na. As long as excess soluble salts are present, the pH of a saturated paste is seldom > 8.5, and the particles remain flocculated. If excess salts are leached downward, the pH may increase to > 8.5, and the soil colloids may disperse and eluviate. These processes will be discussed under the following taxonomy section. Saline-sodic soils sometime contain gypsum.

Nonsaline-sodic soils have an EC of < 4 and an ESP of ≥ 15. The pH of a saturated paste is 8.5-10. They contain an excessive amount of exchangeable Na but not of soluble salts. These soils would correspond to the black alkali soils of Hilgard and the Solonetz and Solod soils of the Russian taxonomic scheme. Enough leaching has occurred to remove the soluble salts and begin to eluviate clay from the surface to the B horizon.

Nonsaline-nonsodic soils have an EC of < 4 and an ESP of < 15. They do not contain excessive amounts of either soluble salts or exchangeable Na and hence are termed "normal" soils.

Bower et al. (1958) include one more definition. They define a salt-affected soil as a soil that has been adversely modified for the growth of most crop plants by the presence or action of soluble salts. The
term includes soils that have an excess of soluble salts, an excess of exchangeable Na, or both. It is intended to be a general term encompassing all soils affected by salts and would include saline-nonsodic, saline-sodic, and nonsaline-sodic soils. The term may include some other soils as well, as will be seen in the discussion of the author's own results.

**United States systems: Taxonomy**

Kellogg (1934) presented the current ideas concerning taxonomic names at that time. He outlines four types of soils and presents their stages of development. His outline will be briefly presented, then discussed. Notice the interweaving of chemical and morphological criteria.

1. A normal soil has an exchange complex largely saturated with divalent cations. The coloids are flocculated, and the soil is nearly neutral in pH. 2. A Solonchak soil (saline soil) contains an excess of soluble salts. Often some divalent cations on the exchange complex have been replaced by Na. Yet the presence of the excess divalent cations keeps the soil colloids well-flocculated. The soil is not highly alkaline in reaction. The process of accumulating salts in soils is called salinization. 3. A Solonetz soil (alkali soil) has a high percentage of exchangeable Na and low amounts of soluble salts. As the drainage of a Solonchak improves, excess soluble salts are removed and the soil colloids become dispersed due to the high Na content. The soil exhibits a prismatic structure with hard aggregates. The soil reaction becomes highly alkaline. These processes are called solonization and may be said to consist of desalinization plus alkalization. 4. A Soloth (or Solod)
soil forms after the dispersed colloids of the Solonetz begin to move downward in the solum. The upper part of the solum becomes lower in pH, and a light-colored A2 horizon develops with platy structure. A dark, impermeable, columnar B2 horizon develops, sometimes called a "claypan". This process is called solodization.

The terms Solonchak, Solonetz, and Solod are taken directly from the Russian taxonomic scheme. All three words use the root word "sol" as their base, meaning salt in Russian (Kelley, 1951). Solonchack means "much salt" and would be similar to the white alkali soils of Hilgard. Solonetz means "little salt", referring to soils that at one time had a large concentration of Na, but are now fairly leached. Both Solonetz and Solod soils would be the black alkali soils of Hilgard.

Discussions of the genetic processes which effect salt-related morphological changes in soils are given by: U.S. Salinity Lab Staff (1954), Byers et al. (1938), and Vilenskii (1957). Salinization simply means "the process of becoming saline" and has no reference to any specific salt. Basically, the process of salinization is the one described earlier in the section "Accumulation of salts in soil: General." A high water table or restricted drainage leaves salts as water is evaporated. There is a net gain of salts over removals. Usually quite an excess of soluble salts accumulate. These soils normally appear light-colored due to the salt. This is the reason they are called white alkali. The term Solonchak applies to these soils and is sometimes preceded by a modifier if the accumulated salt is of a predominant type, i.e., gypsiferous Solonchak, calcium carbonate Solonchak. The modern classification of saline-nonsodic
would apply to these soils.

Alkalization (an outdated term) is the process by which significant quantities of exchangeable Na are imparted to the exchange complex. Calcium and magnesium are the principal cations in the solution of normal soils in dry regions. When excess soluble salts accumulate, Na may become the predominante cation in the soil solution. The ions are in a state of dynamic equilibrium between the exchange sites and the soil solution. Divalent cations such as Ca and Mg are more strongly adsorbed to the exchange sites than monovalent cations such as Na. At equivalent concentrations, the amounts of Ca and Mg ions adsorbed are several times that of Na ions. Generally half or more of the soluble cations must be Na before significant adsorption occurs.

How then does an exchange complex dominated by Na develop? As seen from Table 1, the solubility limits of Ca and Mg sulfates and carbonates are markedly lower than for the corresponding Na compounds. As the soil solution becomes concentrated through evapotranspiration, many of the Ca and Mg ions precipitate as compounds. The relative proportion of soluble Na ions therefore increases. Increased Na adsorption occurs. NaOH and Na₂CO₃ form eventually. Na₂CO₃ is formed from the reaction of NaOH with CO₂ from the air or from organic matter decomposition under anaerobic conditions. These compounds give rise to a high pH. Organic matter is also dissolved by these compounds and tends to concentrate at the soil surface as it moves upward with evaporating water. This dark residue gives rise to the name black alkali. The modern classification of saline-sodic would apply to these soils.
It should be pointed out that large amounts of NaOH and Na₂CO₃ will
not form as long as an excess of other soluble salts are still present.
A process of leaching (desalinization) must occur as well. The process
of desalination coupled with alkalization and the resulting effects upon
soil properties is called solonization, meaning "the forming of a Solo-
netz." A Solonetz soil exhibits a high pH and dark organic matter resi-
due in the surface horizons and soluble salts leached below the surface.
Confusion existed in 1938 as to the exact definition of Solonetz in both
American and Russian literature (Byers et al., 1938). Sometimes a chem-
ical definition was implied (high exchangeable Na content) and sometimes
a morphological definition was implied.

Dealkalization (an outdated term) is the process by which Na ions
are removed from the exchange complex. Under continued leaching, the ex-
changeable Na in the Solonetz soil begins to be removed. It hydrates and
begins to disperse clay. The clay illuviates into the B horizon. Dur-
ing this slow process, alternate wetting and drying of the profile occurs.
The dispersed clay fills the voids in the B horizon as it illuviates.
It is highly hydrated when moist, but shrinks markedly when dry. The
cyclic swelling of the B horizon produces severe pressure which destroys
previous structure and tends to orient the soil mass into vertical columns
or prisms. When the B horizon dries, the clay shrinks leaving fissures
between the columns. More clay moves into the fissures with the next
rain before the columns swell again. Eventually, the B horizon can be-
come a slowly permeable mass. Water movement is greatly restricted. The
surface horizon may be quite friable and neutral to slightly acid in
reaction. An eluviated A₂ develops. Sticky, dissolved organic matter often coats the tops and sides of the columns. It moves downward with the clay. The resulting soil is termed a Solod, and the process of dealkalization may be termed solodification, "the forming of a Solod."
The friable A horizon may be blown away leaving the impervious B horizon exposed. These areas are commonly called scab spots, clay spots, slick spots, clay pans, or buffalo wallows. The modern classification of non-saline-sodic would fit both Solonetz and Solod soils.

The processes just given seem to be the stages of development from a "normal" soil, to a Solonchak, to a Solonetz, and finally to a Solod. In each case, changing environmental conditions preclude certain steps. Of course, not all salt-affected soils go through the whole sequence of steps. At any stage of development, conditions may cause a soil to revert to a "normal" soil. Continued weathering of a Solod would eventually produce a "normal" (nonsaline-nonsodic) soil. Likewise one can find intergrades between each developmental stage. An often-noted stage is a Solodized-Solonetz, a Solonetz soil developing into a Solod. It would be a Solonetz soil developing a weak A₂ horizon, evidencing the initiation of clay movement.

One problem that did arise from the chemical definition of a Solonetz (high exchangeable Na) was that some Solonetz soils were found that had little exchangeable Na. Magnesium was found to be the dominant adsorbed cation. Whether the Mg ion is directly involved in solonization or is an ion that becomes dominant after solonization is not clear. Soil Taxonomy (Soil Survey Staff, 1975) states that Mg is the next ion in the
leaching sequence after Na is removed if chlorides are low and sulfates high. Riecken (1943) discusses the Mg weathering cycle in Solonetz soils. Byers et al. (1938) acknowledged the problem. Current taxonomic systems in use in the United States and Canada now use exchangeable Na plus Mg as a differentiating criterion.

The foregoing names of soil taxonomic classes and salt transformation processes are long out of date. Yet an understanding of them is necessary to understand many of the later cited specific research works.

Baldwin et al. (1938) report that the taxonomic system of C. F. Marbut in 1920 placed salt-affected soils as shown in Table 5. Pedocals

Table 5. Taxonomy of salt-affected soils in the 1920 system of C. F. Marbut

<table>
<thead>
<tr>
<th>Category VI</th>
<th>Pedalfers VI-1</th>
<th>Pedocals VI-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category III</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Salty soils</td>
<td>Salty soils</td>
<td></td>
</tr>
<tr>
<td>Alkali soils</td>
<td>Alkali soils</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

were soils having lime in all or part of the profile, roughly the soils in the western half of the United States. Pedalfers were soils leached of lime and containing iron and aluminum, roughly the soils of the eastern half of the United States. Category III was assumed to be "azonal or intrazonal soils." These soils were described as being very young in
development or showed soil characteristics dominated by some local factor of relief or parent material over the normal effects of climate and vegetation.

The system presented by Baldwin et al. (1938) placed salt-affected soils as shown in Table 6.

Table 6. Taxonomy of salt-affected soils in the 1938 system of Baldwin et al.

<table>
<thead>
<tr>
<th>Category VI</th>
<th>Category V</th>
<th>Category IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order</td>
<td>Suborder</td>
<td>Great Soil Groups</td>
</tr>
<tr>
<td>Intrazonal soils</td>
<td>Halomorphic (saline and alkali soils of imperfectly drained arid regions and littoral deposits)</td>
<td>Solonchak or saline soils Solonetz soils Soloth soils</td>
</tr>
</tbody>
</table>

The general characteristics of the Solonchak, Solonetz, and Soloth soils were given by Kellogg (1934) and discussed earlier. Intrazonal soils were defined as those showing characteristics dominated by some local factor of relief or parent material over the normal effects of climate and vegetation. The term "halomorphic" comes from the Greek roots for salt and form. The revisions of the 1938 system by Thorp and Smith (1949) did not change the categories for salt-affected soils.

The present taxonomic scheme in use in the United States, Soil Taxonomy, subdivides the former Solonchak, Solonetz, and Soloth soils into many more refined categories (Soil Survey Staff, 1975). By 1960 when
the Seventh Approximation was published, the term calcium carbonate Solonchak had been used as a great soil group in the 1938 system (McClelland et al., 1959). *Soil Taxonomy's Table 14 lists the approximate equivalents of the 1938 system (revised) in the present system. Calcium carbonate Solonchaks are mostly included in the Calciaquolls and partly in the Aquic Calciustolls. Solonchaks are mostly included in the Salorthids and partly in the Halaquepts. Solonetz soils are mostly included in the natric great groups of Alfisols, Aridisols, and Mollisols. Solorths are included partly in the Natraqualfs and in the natric subgroups of Cryoborolls, Duraquolls, Durixeralfs, and Haploxeralfs.

Van Alphen and Romero (1971) give a good review of how gypsiferous soils have been categorized since 1953 in the literature. Most of the categories were subgroups of some great soil groups. Many names were coined. The great groups used were: Solonchaks, Desert Soils, Rendzinas, Sierozems, Reddish-Brown soils, Lithosols, Regosols, and Alluvial soils. The name "gypsum Solonchak" was used for soils whose gypsum had formed by precipitation from evaporated shallow ground water.

Some diagnostic horizons used in classifying salt-affected soils in *Soil Taxonomy* are given here (Soil Survey Staff, 1975). Major concepts are given, not all of the criteria exceptions.

**Calcic horizon:** A calcic horizon is a horizon of accumulation of calcium carbonate or calcium and magnesium carbonate. In one form of the horizon, the zone of secondary carbonate enrichment must be $\geq 15$ cm thick, have a $\text{CaCO}_3$ equivalent $\geq 15\%$, and have a $\text{CaCO}_3$ equivalent at least 5% greater than the C horizon. In the other form of the
horizon, it is $\geq 15$ cm thick, has a $\text{CaCO}_3$ equivalent $\geq 15\%$, and contains $\geq 5\%$ by volume of identifiable secondary carbonates as pendants on pebbles, concretions, or as soft powdery forms. Air-dry fragments of a calcic horizon slake in water.

**Petrocalcic horizon:** A petrocalcic horizon is a calcic horizon that is continuous and indurated. Dry fragments do not slake in water. It cannot be penetrated by a spade or auger when dry, and is a barrier to roots.

**Gypsic horizon:** A gypsic horizon is a noncemented or weakly cemented horizon of enrichment with secondary sulfates that is $\geq 15$ cm thick has at least 5% more gypsum than the C horizon or underlying stratum, and in which the product of the thickness in centimeters and the percentage of gypsum is $\geq 150$. Dry fragments slake in water.

**Petrogypsic horizon:** A petrogypsic horizon is a gypsic horizon that is cemented strongly enough with gypsum that dry fragments do not slake in water and that roots cannot enter.

**Natric horizon:** A natric horizon is a special kind of argillic horizon that has, in addition to the properties of an argillic horizon, the following: 1. Either a. or b. (a) prisms or columns in some part that may or may not break into blocks, or (b) blocky structure and tongues of an eluvial horizon in which there are uncoated silt or sand grains extending $> 2.5$ cm into the horizon, and 2. Either a. or b. (a) a Sodium Adsorption Ratio (SAR) $\geq 13$ (or an Exchangeable Sodium Percentage (ESP) $\geq 15$) in some subhorizon within 40 cm of the upper boundary, or (b) more exchangeable Mg plus Na than Ca plus
exchangeable acidity in some subhorizon within 40 cm of the upper boundary if the SAR is $\geq 13$ (or ESP $\geq 15$) in some horizon within 2 m of the surface.

Salic horizon: A salic horizon is a horizon $\geq 15$ cm thick that contains a secondary enrichment of salts more soluble in cold water than gypsum (readily-soluble salts). It contains at least 2% salt, and the product of its thickness in centimeters and salt percentage by weight is $\geq 60$.

Gypsum content is not a major differentiating criterion in Soil Taxonomy. It is used at the great group level by name only in the Aridisol order, as Gypsiorthids. These are Aridisols with gypsic horizons but without argillic horizons. Even this category was a very recent idea, and the classification is considered provisional (Soil Survey Staff, 1975). It was intended primarily for non-United States use. Dregne (1976) says that Gypsiorthids are not very common because most accumulations of gypsum are not great enough to qualify as gypsic horizons.

Other diagnostic features predominate over the gypsum content. Many Aridisols containing gypsum would be Calciorthids. Generally, all soils containing gypsum will be calcareous, but not all calcareous soils contain gypsum.

The presence of gypsum is recognized also at the great group level in the Mollisols as well. The presence of a gypsic horizon is used as a diagnostic horizon as an alternate to a calcic horizon in the Calciaquolls, Calciborolls, Calciustolls, and Calcixerolls. The Calciaquoll, Calciustoll, and Calcixeroll great groups contain the concept of salts
being accumulated by evaporating ground water as one method of salt accumulation. However, the Calciaquolls are the only great group that embraces this process exclusively. The central concept of Calciaquoll genesis is the evaporation of shallow ground water. In humid regions, the setting of the soils is normally intermittent ponds in closed depressions left by recent glaciation.

To the current author's knowledge, the presence of gypsum is not recognized for any other soil order. It is not used at the great group level other than previously mentioned. It does not appear as a modifier at the suborder level. The amount of gypsum is a criterion for designating mineralogy classes at the family level. A soil is given a gypsic mineralogy class if more than 40% by weight is carbonates (expressed as $\text{CaCO}_3$) plus gypsum, and the gypsum is $> 35\%$ of the sum of carbonates and gypsum. The control section used for designating particle-size classes at the family level is also used for the mineralogy class. The whole soil, the particles $< 2 \text{ mm}$, or the particles $< 20 \text{ mm}$ may be used in designating the gypsic mineralogy class, whichever has the highest percentage of carbonates plus gypsum. The minimum amount of gypsum the control section must have to be in the gypsic mineralogy class is 14%, e.g.,

$\left(40\% \text{ CaCO}_3 + \text{gypsum}\right) \times 0.35 = 14\%$.

**Foreign systems**

Salt-affected soils are classified and placed in taxonomic schemes differently by many countries throughout the world. It is sometimes difficult to tell from the literature whether schemes proposed by foreign authors are for classification or for taxonomy. The age-old controversy
exists as to whether soils should be grouped taxonomically on their chemical properties, morphological properties, or both. Soil Taxonomy gives several correlations between its taxonomic system and some foreign systems (Soil Survey Staff, 1975). Its Table 16 correlates the current United States system with the current French system. Its Table 17 correlates the current United States system with the current Canadian system and cites appropriate references for further study of the Canadian system.

Its Table 18 correlates the current United States system with the current Soviet system and cites appropriate references for further study. Vilenskii (1957) gives the taxonomic criteria used to distinguish Solonchak, Solonetz, and Solod soils at that time as well as the processes of their genesis. He also gives some classifications of salt-affected soils based on their content and nature of soluble salts. Bazilevich and Pankova (1968) give a method of classifying salt-affected soils using three criteria: chemistry (type) of salinization, degree of salinity, and depth of the upper saline horizon. They proposed nine types of soil salinity according to cation-anion composition. A new method is proposed for estimating the degree of salinity according to the "total effect" of toxic ions. A method of computing toxic and nontoxic salts is also given.

In Australia, Northcotte and Skene (1972) set up six broad classes of salt-affected soils based on ionic constituents of the soil extracts, soil pH, and soil morphology. Their method of deciding where to "draw lines" is to be admired. They analyzed 1500 soil profiles, and then set
up their classes.

Effect of Salt-Affected Soils on Agronomic Crops

Excesses of soluble salts and exchangeable Na have important and usually detrimental effects upon plant growth. Agricultural production is limited in many parts of the world due to salt-affected soils. In the United States, the productivity of one-fourth of the 33 million acres under irrigation is reduced. Farming is completely prevented in other areas (Black, 1968). The effects of salts upon plants depend upon the soil texture, distribution of salt within the profile, composition of the salt, and species of plant. High contents of some ions, i.e., sodium, promote changes in the physical nature of the soil which harms plants.

The morphological changes evidenced in plants grown on salt-affected soils include the tip browning, curling, mottling, thickening, and chlorosis of leaves as well as changes in the internal vascular structure. Three theories have been advanced to account for the detrimental effects of soil salinity. Black (1968) discusses each in detail. The water availability theory states that the soluble salts increase the osmotic potential of the soil solution. Water is therefore less free to move from the soil into the roots. The availability of water to plants is decreased, and the plants suffer from a lack of water. This theory has been in existence the longest and is said to be accountable for the "physiological drought" of plants.

The osmotic inhibition theory states that plants are adversely affected by the excess of soluble salts taken up from salt-containing soil
water. This theory postulates that salts enter the plant and somehow interfere with its growth. The inhibition itself is not specified. The specific toxicity theory states that one or more specific ions exert a toxic effect on the plant. Many ions in high concentrations are toxic to plants.

Which theory or theories explain the salt-plant interactions best are not known. Possibly a combination of the three is at work on some species while other plant species are more affected by a singular mode. It is known that some species grown on salt-affected soils do assimilate a large amount of salt. It is also well-known that certain ions are toxic to plants, even in low concentrations. Boron is an example. A discussion of the effects of specific ions on plants is given by the U.S. Salinity Lab Staff (1954). Since gypsiferous soils are of primary concern in the present study, only the effects of Ca and $SO_4$ ions will be discussed. High concentrations of Ca affect some species more than others. It is sometimes difficult to tell if Ca or an associated anion is the cause of the injury. Sensitivity to $SO_4$ seems to be related to the tendency of high $SO_4$ concentrations limiting Ca uptake. Sodium and K are then taken up in increased quantities. The cationic balance within the plant becomes upset. It is very doubtful if harmful concentrations of Ca and $SO_4$ are ever reached in primarily gypsiferous soils due to the low solubility of gypsum.

The U.S. Salinity Lab Staff (1954) has given some relationships between soil characterization data and salt parameters. Various workers contributed to these relationships which represent averages over many
samples. The electrical conductivity of a saturation extract in mmhos/cm at 25° C is abbreviated EC. The saturation percentage, the percent water by weight in a soil at saturation, is abbreviated sat. %.

Percent salt in saturation extract = 0.064 X EC  

Percent salt in soil = \( \frac{\text{percent salt in saturation extract \times sat. } \%}{100} \)  

Osmotic pressure of saturation extract (atm.) = 0.36 X EC  

The Soil Survey Staff (1972) took the graphs given by the U.S. Salinity Lab Staff (1954) and developed other equations.

\[
\log \text{total salt in soil (ppm)} = 0.81 + 1.08 \log \text{EC} + \log \text{sat. } \%
\]  

\[
\text{total salt in soil (\%)} = \frac{\text{total salt in soil (ppm)}}{10,000}
\]  

It should be noted that Equation 7 as published in 1972 was erroneous. The general effects of various salt concentrations on plant growth are summarized in Table 7 (U.S. Salinity Lab Staff, 1954).

<table>
<thead>
<tr>
<th>0</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity effects</td>
<td>Yields to very sensitive</td>
<td>Yields of many crops reduced</td>
<td>Only tolerant crops yield satisfactorily</td>
<td>Only a very few tolerant crops yield satisfactorily</td>
</tr>
<tr>
<td>mostly negligible</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Plants are most sensitive to high salt concentrations during germination. Barren spots may show up on some soils. Yet one should use
caution to avoid confusion between effects of soil salinity and effects of low soil fertility. Plants that are stunted due to low fertility are usually yellowish green, whereas those stunted due to salinity are usually blue green. The bluish appearance is the result of a very heavy waxy coating on the surface of the leaves, and the darker color is due to an increased chlorophyll content. Plants may develop intense chlorosis on calcareous but nonsaline-nonsodic soils.

Since virtually all gypsiferous soils are calcareous, it is probable that the injurious effects of such soils on plants are due to fertility problems rather than salinity problems. The solubility of gypsum is so low that it is very doubtful any actual salt-plant interactions are important. Little has been published on the relationship between plant growth and gypsum content. Van Alphen and Romero (1971) summarize several experiments from various parts of the world and conclude that only when the gypsum content in the root zone is > 25% are lower yields to be expected. It appears that most of the studies were done under irrigation. Assuming water was not a limiting factor, the reduction in yields should be due to chemical effects. The accumulation of large amounts of gypsum necessarily reduces the amount of sand, silt, and clay in a given soil volume. There would be less inherent fertility reserve from which the plants could draw. Another problem of a physical nature is the induration of a gypsiferous layer (a petrogypsic horizon) within the root zone. The layer impedes root penetration, and therefore the plant has less soil volume from which to extract moisture and nutrients. Van Alphen and Romero (1971) concluded that as long as the gypsiferous layer
was not indurated, no difference in yield occurred if the layer is less than 30 cm thick. As for the effects of calcareous soils on yield, Pierre and Allaway (1939) stated that such soils in Iowa often have a complete crop failure while soils less than 100 ft away have corn yields of 50 bu/acre. Shrader (1953) estimated that highly calcareous soils in Iowa (now the Harps series) yielded 30% less than the associated noncalcareous Webster series.

How then do calcareous, gypsiferous soils affect plant nutrient availability and thus reduce yields? It can be assumed that the soil solution of gypsiferous layers is virtually saturated with gypsum. Consequently, low Mg/Ca and K/Ca ratios exist. Rarely do large quantities of readily-soluble Mg and K compounds exist in soils high in gypsum. Cations are taken up by the roots either through exchange reactions between plant roots and soil particles or from the soil solution itself. If the Mg/Ca and K/Ca ratios are very low in the soil solution, then a low uptake of Mg and K may result (Van Alphen and Romero, 1971).

There is evidence that calcareous soils are lower in exchangeable K than associated noncalcareous soils. Two studies done in Iowa show this fact. Pierre and Allaway (1939) and Stanford et al. (1941) both found that highly-calcareous soils contained much less exchangeable K than associated noncalcareous soils. Plant available phosphorus is also reduced in the presence of free Ca ions and CaCO$_3$. The phosphorus ions are precipitated as insoluble calcium phosphate forms (Black, 1968, and Tisdale and Nelson, 1966). Cole et al. (1953) reported that a monolayer of phosphate forms on CaCO$_3$ surfaces. Eik (1975) reported summary data on
surface soil samples analyzed by the Iowa State University Extension Soil Testing Laboratory. During the period 1968-1973, 70% of samples from a highly calcareous series (Harps) yielded low or very low available phosphorus results by the Bray I method. For the associated noncalcareous series (Webster), only 40% of the samples yielded low or very low.

Under alkaline conditions, the availability of iron to plants is also markedly reduced. The high pH promotes the precipitation of iron compounds as insoluble hydroxides (Tisdale and Nelson, 1966). Leaf chlorosis develops, especially in the younger leaves. Iron deficiency induced chlorosis is probably the most telltale sign of highly calcareous soils in the late-Wisconsin till plain of the upper Midwest.

Another micronutrient, zinc, is reduced in plant availability but by different means. Under alkaline conditions, zinc precipitates as insoluble carbonate, hydroxide, and phosphate forms (Tisdale and Nelson, 1966). Yet this action alone does not account for all of the problem. It has been shown that Ca and Mg carbonates adsorb Zn onto their surfaces. Zinc is most greatly adsorbed by magnesite, to an intermediate degree by dolomite, and least by calcite (Jurinak and Bauer, 1956). In the Mg bearing compounds, the Zn ion actually replaces the Mg ion in the crystal lattice structure. This substitution occurs because the ionic radii of Mg and Zn are similar, 0.78 Å and 0.83 Å respectively. The ionic radius of Ca is 1.06 Å. Dregne (1976) says that corn and beans are quite sensitive to low Zn levels.

One must be careful to accurately assess actual salinity effects from fertility effects. Sometime this is difficult to do. The U.S.
Salinity Lab Staff (1954) gives an extensive list on their page 67 of the tolerance of various crop plants to salt-affected soils. To compile the list, the staff used a field plot method of growing crops on nonsalt-affected soils and soils adjusted artificially to various salinity levels. Crop yields were related to electrical conductivity values of the saturation extract. Electrical conductivity values associated with a 50% decrease in crop yield were plotted. It should be pointed out that the table reflects a crop's relative salt tolerance under irrigation management practices. It does not reflect the inherent physiological ability of the crop to withstand salinity under any other conditions. Other discussions of soil salinity-plant growth interactions are given by Van Den Berg (1950), Kovda (1946), Hayward and Wadleigh (1949), Bernstein and Hayward (1958), Hayward and Bernstein (1958), and Bernstein (1962).

Effect of Gypsiferous Soils on Physical Structures

Salt-affected soils usually are more corrosive to metal than nonsalt-affected soils. Specifically, soils containing sulfates are also corrosive to concrete. Gypsiferous soils would be included. Free calcium oxide (CaO) in concrete reacts with sulfate to form ettringite (calcium aluminum sulfate). Etringite contains 31 molecules of crystal water (Van Alphen and Romero, 1971). Its formation leads to swelling and eventual disintegration of concrete. Concrete building foundations, irrigation structures, and drainage tile are commonly affected. If sulfates appear to be a problem, then sulfate-resistant concrete or some other building material should be used. Hobson (1968) suggests that if
concrete must still be used, then use dense compacted concrete, seal the soil-concrete interface with a water-impervious material, and try to maintain a hydraulic gradient from the concrete to the soil.

He also quotes the official U.S.D.A.-Soil Conservation Service guidelines for rating sulfate-containing soils. Less than 1,000 ppm water-soluble sulfates (expressed as $SO_4$) would be given a low rating for corrosivity of concrete. A moderate rating would be 1,000-7,000 ppm, and a high rating would be $> 7,000$ ppm. The current author calculates that a soil containing sulfates only in the form of gypsum would be given a moderate rating. The range of the moderate rating is $1,000$ ppm $SO_4$ (1.7 g/liter gypsum) to $7,000$ ppm $SO_4$ (12.2 g/liter gypsum). A saturated gypsum solution in pure water is about 30 meq/liter or 2.6 g/liter. In the presence of other salts, the solubility of gypsum may increase to 50 meq/liter or 4.3 g/liter. The solubility of gypsum is low enough by itself that it is not a great corrosivity hazard. If more soluble $SO_4$ forms are present ($MgSO_4$, $Na_2SO_4$), then the corrosivity hazard can increase greatly.

Gypsiferous soils also exhibit a unique form of erosion: pipe or tunnel erosion. Subsurface erosion occurs as the subsoil is dissolved by moving water and removed. The surface soil then collapses into the tunnels. Building foundations can be affected, but usually it is irrigation channels and structures that are damaged. Under irrigation, the subsidence rate is increased. Areas several meters square can drop several meters (Dregne, 1976). Soils must be high in soluble salt content before piping becomes a problem. Gypsiferous soils are normally the only soils with
the problem because no other soluble salt accumulates in such great quantities. The only control measures are to compact the soil periodically with heavy machinery and to grow deep rooted crops to stabilize the soil.

Unique Physical Characteristics of Gypsiferous Soils

Gypsiferous soils do have several unique physical properties that will be discussed. The subsurface tunnel erosion mentioned in the preceding section may be considered a unique physical property as well.

Moisture retention, and hence plant available water, varies widely among gypsiferous soils as well as between gypsiferous and nongypsiferous soils. Two factors are primarily responsible for the variation: the content of other mineral particles (sand, silt, and clay) in the soil other than gypsum, and the size of the gypsum crystals themselves. A high content of gypsum necessarily excludes a direct proportion of sand, silt, and clay. There are fewer fine particles for moisture retention. The size of the gypsum crystals varies greatly. Theoretically some could be in the clay-size range (< $2\mu$), but the smallest crystals are usually in the silt-size range (0.002-0.05 mm). Crystals are often in the sand-size range (0.05-2 mm) and occasionally are several mm in size. The size of the crystals is variable due to dynamic dissolution and regrowth. It is a well-known fact that plant-available water is almost completely a function of the particle-size fractions and organic matter content in the soil. Medium-textured soils have more plant-available water than very fine or coarse-textured soils. Salter and Williams (1965) studied the top two feet of 27 soils of different textural classes. The soils fell
into seven groups based on their plant-available water capacity (field capacity moisture percentage minus 15 bar moisture percentage):

1. silt loam
2. fine sandy loam, very fine sandy loam, loam
3. loamy sand, sandy loam, silty clay loam
4. clay, sandy clay loam
5. clay loam
6. sand/loamy sand
7. sand

Van Alphen and Romero (1971) present data that show what effect gypsum crystal size has on plant-available water capacity. A nongypsiferous surface layer had the same plant-available water capacity as a subsoil layer containing 80% gypsum by weight. Another profile had 13.2% by volume plant-available water for a horizon containing 1% gypsum and described as a sandy loam texture. A horizon below it contained 30.8% by volume plant-available water, had 54% gypsum by weight, and had a texture described as "gypsum powder". Gypsum can increase plant-available water capacity if its crystals are fine, but can reduce it if the crystals are large. Large crystals would act as sand grains. Each soil must be assessed on an individual basis.

As a general rule, the bulk density of gypsiferous soils is lower than that of nongypsiferous soils. The low bulk density is due to two factors. Gypsum has a lower particle density (2.3 g/cm³) than the normal mineral particles (2.65 g/cm³). Gypsiferous soils also have a high porosity due to voids between crystals. Lumps and crusts of gypsum are sometimes cemented and have a low porosity. A cemented layer can be very massive and may restrict root growth and water movement. Powdery gypsum layers are characterized by a low bulk density and a very friable to loose
consistence.

Van Alphen and Romero (1971) give bulk density data for four profiles from Syria. The data are not very useful because the degree of induration is not given. Since none is mentioned, none is assumed. For horizons containing 20-50% gypsum by weight, the bulk density ranged from 1.2 to 1.5 g/cm$^3$. This fact is not conclusive of any trend because other horizons containing 1-14% gypsum by weight had similar bulk densities. One horizon of 54% gypsum had a bulk density of 1.15 g/cm$^3$ and was described as "gypsum powder" in texture. Both Kellogg (1934) and Kovda (1946) described "puffy" Solonchaks. Even though no bulk density data were given, a low bulk density is implied in the name. Vilenskii (1957) defines a "puffy" Solonchak as one that has a loose layer under the surface which compresses underfoot and is loaded with small salt crystals. As salts accumulate by precipitation from evaporating ground water, a loose or "puffy" feature might be expected.

The hydraulic conductivity of gypsiferous soils is normally high. The soils are well-flocculated, and the bulk density is normally slightly lower than for nongypsiferous soils. If the soil is very friable, the hydraulic conductivity can be as high as 800 cm/day (13 inches/hr). If there is a cemented layer impeding water movement, then the rate can be almost nil, 5-10 cm/day (0.1 inches/hr) (Van Alphen and Romero, 1971). Gypsiferous soils are very erodible due to the low cohesive forces between gypsum particles.
Morphology of Gypsiferous Soils and Crystals

**Morphology of gypsum accumulations in soils**

The morphology of gypsiferous soils and crystals is exceedingly varied and is mainly determined by gypsum being fairly easily distributed within the soil profile. When water enters the profile, the crystals are affected to some degree. Addition of water by precipitation dissolves some gypsum. Loss of water by evapotranspiration precipitates it. Dissolved gypsum can move upward from a high water table. As gypsum moves within a profile, certain morphologies often result.

Some morphologies have been briefly mentioned in previous discussions in the thesis. A gypsic layer is simply a horizontal layer of gypsum enrichment in a profile. If it meets certain requirements, it is called a gypsic horizon (Soil Survey Staff, 1975). A petrogypsic horizon is a gypsic horizon that is cemented. It is restricted to arid climates, is rare in the United States, but is common in other parts of the world. A gypsic layer can have either a powdery or sandy appearance, depending upon the size of the crystals. Sizes $< 0.05$ mm would be silt or clay sized. Sizes $> 0.05$ mm to 2 mm would be sand sized. Vertical gypsum crusts also occur. They have a polygonal pattern and consist of two vertical plates of pure gypsum extending to a depth of up to one meter. The plates are separated by a thin layer of soil and are very resistant to disintegration (Van Alphen and Romero, 1971).

Gypsum may accumulate uniformly throughout the soil matrix. Where gravels or stones are present, it may accumulate on their undersides as pendants (Soil Survey Staff, 1975). Gypsum may be found as a pure white
powder in small pockets and channels. The channels and pockets are probably old root and insect holes. This form of gypsum is found primarily in the soil solum and is sometimes called gypsum mycelia, owing to its branched nature. The powder is sometimes called flour due to its fine size, less than about 0.05 mm. Gypsum is often found in the surface horizons as "puffy" farinaceous material (Kovda, 1946). Farinaceous (mealy) material implies a low bulk density and leads to the name "puffy" Solon-chak described previously. Sometimes the farinaceous gypsum is arranged in platy structure. Van Alphen and Romero (1971) give descriptions showing this. Kovda (1946) calls it "layered gypsum laminae sometimes growing together as swallowtails."

An interesting form of gypsum in soils is called rosettes, meaning crystals arranged in a circular or spheroidal manner around a center point. Authors describe them in various ways. Some call them nests. Kovda (1946) says that in deep soil horizons, gypsum accumulates as druses of various sizes, sometimes growing together as hollow spheres. Van Alphen and Romero (1971) called them gypsum rosettes. Rozanov (1951) describes "clusters of white, coarse-spongy gypsum" that appear to be the concept of a rosette. Rosettes tend to be found primarily below the solum.

A last form of gypsum is a porous, sponge-like form, with the word sponge-like not meaning fluffy but filled with voids as is a sponge. The present author is not sure what the form looks like. No sizes of crystals or voids are given. Kovda (1946) calls the form "porous accumulations with large holes." Rozanov (1951) describes a similar morphology as
"porous and sponge-like."

There is little information in the literature concerning the different morphologies of gypsum or the genetic processes responsible for their formation.

Morphology and genesis of gypsum crystals

As stated earlier, the forms of gypsum crystals are tabular plates, elongate prisms, acicular (needle shaped), and lenticular (lens shaped). Why do these different forms arise? Crystal growth occurs when a solution containing ion pairs reaches saturation. The ions begin to form a crystal from the solution by the process known as precipitation. Precipitation can be termed crystal growth in one sense. The ions form around a nucleus or seed crystal. The crystal begins to grow larger as ions come from solution and attach themselves to the edges of the crystal lattice. Various forms of crystals result depending upon the chemistry of the particular mineral. In the case of gypsum, Ca and SO_4^2- ions are involved. The chemical and physical environment in which crystals grow may affect the axes of growth and subsequently the final form of the crystal. Certain conditions may promote growth along one axis and hinder it on another. A study done by Edinger (1973) is an example of various solution conditions altering the final shape and size of gypsum crystals.

Very few works report the shape of gypsum crystals found in soil. Grigor'ev (1961) mentions the recrystallization of gypsum into larger crystals from smaller ones, but does not discuss forms or formation conditions. Tabular plates and elongate prisms seem to be the most common
forms of crystals mentioned in mineralogy texts as well as the forms most commonly found in soils. Evidently the conditions which produce crystal growth resulting in these forms are most common. The tabular form is sometimes composed of two crystals grown together to form twin crystals. Most texts call this "twinning", but it is described in various nontechnical ways. Mason and Berry (1968) call twinned gypsum crystals "swallowtail" twins, evidently due to their "V" shaped ends. Grigor'ev (1961) discusses some "hour glass" shaped crystals. Hanna and Stoops (1976) mentioned some "featherlike" crystals. The current author believes these shapes are probably twinned tabular plates. Grigor'ev says that the growth of hour glass shaped crystals is due to the inclusion of mud during growth. The latter authors believe the featherlike crystals are highly impure, and their appearance seems to be produced by crystal splitting due to the presence of small impurities.

Cody (1979) made a study of the formation of the lenticular habit. He reports that lenticular crystals are primarily found in Holocene sediments of three types: marginal marine sediments, inland saline lake sediments, and desert and saline soil environments. When they are found in arid regions, they grow in brackish to saline sodium chloride waters. He prepared a laboratory study to determine what factors must be present to promote the lenticular shape. Organic matter was found to be the major controlling factor. Without added organic matter from plants, crystals were usually smooth-faced elongate prisms. With added organic matter, pronounced lenticular morphology appeared. The crystals were often loosely cemented into a "nest" arrangement. The crystals
themselves were plate-like but with curved surfaces on the faces of the plate similar to a double convex lens. It is postulated that soluble organic matter inhibits crystal growth in an elongate manner by coating the exposed crystal surface. Ions from solution are prevented from attaching themselves. The crystal eventually grows thicker, resulting in a roughly lensoid shape.

Cody (1979) also found that the factors of water temperature, water salinity, and sediment type are not important in controlling the shape of crystal growth, but that pH was. If the growth medium was acidified to pH 1-2, then crystals were very elongated prisms (acicular) even in the presence of soluble plant organic matter. No conclusion was made as to whether low pH is the only controlling factor in producing acicular shapes. He also found that under very rapid evaporative conditions, prismatic crystals will predominate even in the presence of large amounts of soluble organic matter. Evidently the growth of lenticular shapes is slow. Shales and coal may often have acicular shaped crystals even though they are high in organic matter. The pyrite oxidation yielding the \( \text{SO}_4^2- \) ions also produces a very low pH. For lenticular shapes to form, slow evaporative conditions, the presence of soluble organic matter, and a pH that is not extremely acid are needed.

Hanna and Stoops (1976) reported finding lenticular crystals in some Egyptian soils. They studied seven profiles in northern Egypt near the outlet of the Nile River into the Mediterranean Sea. All soils formed in alluvium deposited by the Nile or the sea. The topography was very flat, all soils were poorly drained, and no profile had a water table at
> 100 cm. Lenticular gypsum crystals were found in the soils. Some formed dense layers of 0.1 mm sized crystals; some were found in voids. Both soil color and laboratory analyses showed the presence of organic matter. The authors did not discuss the genesis of the lenticular shapes. The three conditions proposed by Cody (1979) of pH, organic matter, and slow evaporative conditions were present at this study area.

He also found that slow evaporation produced larger crystals of all forms than rapid evaporation. The longer a solution is saturated, the more opportunity crystals have to grow.

**Salt-Affected Soils in Arid and Semiarid Regions**

Investigations about salt-affected soils in arid-semiarid and humid-subhumid regions will be discussed in the next two sections. Better climatic classifications than the terms used above are now available (Buol et al. 1973). Annual rainfall is only one of several factors that help to define climatic conditions. Yet the terms arid, semiarid, subhumid, and humid have been used for a long time. They still bring to mind a general concept of climate for most people. The terms are used here for this reason and not because they accurately define climate. Much of the literature, especially that of former years, uses these terms. Few modern climatology texts define these terms. An older text by Blair (1942) defines the terms as follows:

<table>
<thead>
<tr>
<th>Region</th>
<th>Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid</td>
<td>0-10 inches/year</td>
</tr>
<tr>
<td>Semiarid</td>
<td>10-20 &quot; &quot;</td>
</tr>
<tr>
<td>Subhumid</td>
<td>20-40 &quot; &quot;</td>
</tr>
<tr>
<td>Humid</td>
<td>40-80 &quot; &quot;</td>
</tr>
<tr>
<td>Very wet</td>
<td>&gt; 80 &quot; &quot;</td>
</tr>
</tbody>
</table>
In this section, studies will be presented which were done in areas with an average precipitation of about 20 inches/year or less. Soils of arid and semiarid regions have more extensive areas of salt accumulation than soils of wetter regions. Most of the investigations about salt-affected soils have been done in arid and semiarid regions. To present all of the works would be impractical. Many of the works would be inapplicable to the present study. A few selected papers are given to emphasize important principles or for later comparisons.

The problem of "magnesium Solonetz", or soils showing Solonetz morphology but without high contents of exchangeable Na, has been investigated primarily by Canadian workers. Ellis and Caldwell (1935) studied such soils on the glacial Lake Agassiz plain of Manitoba. The area had 18.5-20.5 inches/year average precipitation and a mean annual temperature of 35-37°F (1.6-2.7°C). Soils with good Solonetz morphology were found, but with none to trace amounts of exchangeable Na. The exchangeable Ca/Mg ratios were in the range of 1.55 to 1.00. There was evidently a lot of Mg on the exchange sites. They suggest that Mg clays can be highly hydrated and therefore move within the profile as high Na clays do. Riecken (1943) discusses the weathering cycle of Mg in Solonetz soils and concludes the high contents of exchangeable Mg develop after the normal Solonetz development. Which theory is correct is still in dispute.

The work of MacLean and Pawluk (1975) is only one example of many
studies made on Solonetzic soils of Canada. They studied soils near Vegreville, Alberta with climatic conditions of 410-450 mm/year average precipitation, 500-550 mm/year average potential evapotranspiration, and a mean annual temperature of 1°C. The bedrock of the area was soft, saline bentonitic shales and shaly sandstones. The area was covered by glacial and fluvioglacial drift. The till was typically clay loam texture with 1-3% CaCO₃ equivalent. The authors installed piezometers to monitor water flow and chemical constituents at depths of 3, 6, 12, and 24 inches below the water table. A transect was made from the top of a swell to a closed depression. They concluded there were more salts in the soils of the depression due to overland flow of saline water from the surrounding slopes and evaporation from a shallow water table. The maximum concentrations of soluble Na and Mg were above the maximum concentrations of carbonate and gypsum. They concluded this was evidence of a definite upward flow of water due to evapotranspiration.

Several studies have shown the extreme variability of salt content in soil throughout a year's cycle of climate. Jackson et al. (1956) did a study in South Australia under conditions of 18.4 inches/year average precipitation and 59°F mean annual temperature. Five soil profiles were studied which contained large amounts of readily-soluble salts, mostly NaCl. The investigation was conducted over a 12-month period. Soil and water salinity determinations were made every eight weeks. Soluble salts moved upward through the soil profile during the spring and summer and downward during the rainy season at the sites studied. When the summer water table was within four feet of the surface, large amounts of soluble
salts accumulated in the top inch of soil. One case showed an increase from 0.19% NaCl in the winter to 3.2% NaCl in the summer. The salinity of the ground water also increased during spring and summer. Ballantyne (1978) made a similar study in Saskatchewan but compared salt contents on a yearly basis. The yearly change was 0% for some profiles but up to 35% on others. Fluctuations in soluble salt content in ground water occurred below the depth of profile development in some soils. The ions having the greatest yearly net change were Ca, Mg, and Na.

"Saline seep" is the term given by some to areas of water outflow on the sides of hills in semiarid regions, particularly the northern Great Plains. This phenomenon is anomalous because excess water is not common in such regions. Doering and Sandoval (1976) reported that the saline seeps have greatly increased in number in recent years. One survey of a county in North Dakota showed 51% of the seeps had appeared since 1960. The authors list geologic, climatic, and cultural causes for the seeps. The seeps occur where highly permeable, nearly horizontal geologic strata are truncated on hillside surfaces. The water conducting strata may be sands and gravels or lignite. The strata are recharged from precipitation that infiltrates upslope land. The small grain-fallow cropping system currently in use in the northern Great Plains increases the opportunity for upslope water to percolate below the root zone of the soil profile. The infiltrated water becomes saline by passing through the geologic materials and then appears on a hillside. The authors said that the seeps of the northern Great Plains occur in regions having 14.5-17.5 inches/year average precipitation.
Ballantyne (1963) made a study of the saline seep areas of southeastern Saskatchewan. The seeps were found on undulating glacial till plains on the side of or near the base of slopes of 5-9%. They were small isolated areas and were called slick spots or scab spots. A recent study investigated the underlying strata of three dryland salinity sites in southern Saskatchewan (D. R. Cameron, et al., 1979. Strata underlying some dryland salinity sites. Agronomy Abstracts. Amer. Soc. Agron., Madison, Wi.). Holes up to 60 m deep were drilled to characterize the underlying stratigraphy. At one site, an inclined glacial ice thrust unit was found containing water under high artesian pressure. A permeable sandy deposit in the unit provided a hydraulic connection toward the surface. At another site, underground springs were encountered. They were believed to be contributing to seep development. At the third site, a more typical situation was found. Pebbly "glacial clay" was overlying a dense silty shale. Ground water tended to collect above the shale. Evidently for the formation of some saline seeps, the subsurface geology may also be an important factor.

Several studies have been made in the central and western portions of North Dakota. Kellogg's work (1934) has been cited earlier. Solonchak, Solonetz, and Solod development was discussed. His study area was in western North Dakota with 15 inches/year average precipitation and about 4°C mean annual temperature. Northwestern North Dakota is covered with glacial drift; southwestern North Dakota is residual material. The author described well the Solonchak and Solonetz soils of the area. No comments were given as to the origin of the salts or their makeup. The solodized
soils occurred in small irregular depressions dotting the landscape. Wind erosion had removed much of the A2 horizon leaving the top of the B2 horizon exposed. He described them with the words of Dokuchaev: "smallpox on the face of the steppe." Matzek (1955) studied the Chernozem and Solodized-Solonetz soils of north central North Dakota. He said the original till in which the soils formed contained 0.13-0.41% soluble salts. When the salts were leached from the top 15-36 inches, then Chernozem or Chestnut soils developed. If the salts were not leached, then Solonetz soils developed. He cites four local factors affecting the amount and distribution of soluble salts and carbonates: topography, permeability of soils and parent materials, salinity of parent material, and presence of a relatively high water table.

Mogen et al. (1959) also studied the soils of western North Dakota. Most of western North Dakota was covered by the then called Mankato glaciation which retreated some 12,000 radiocarbon years before present (rcybp). Some of the region was not covered by glaciation. Climatic conditions were: 14-17 inches/year average precipitation, 70-75% and 40-47% relative humidity at noon in January and July respectively, 35-47 inches/year average evaporation, 38-42°F mean annual temperature, and mean monthly temperatures of 2-14°F and 66-72°F for January and July, respectively. Generally, the soils studied were similar to those found by McClelland et al. (1959) in eastern North Dakota. This study will be discussed later. In western North Dakota, the soils severely affected by sodium (Solodized-Solonetz) were more common.

Several of the studies cited which were done in the northern Great
Plains have mentioned the presence of a bedrock of saline shales or till that was slightly saline. Extensive beds of shale underlie the glaciated regions of the upper Midwest and Great Plains and are also exposed on the modern surface in extensive areas of the nonglaciated region. The shale is called Pierre shale and is of Cretaceous age. Due to its marine origin, most shale should be expected to contain salt if it is not greatly weathered. Thorp et al. (1948) characterized the Pierre shale as containing Na and Mg sulfates, NaCl, and gypsum. Wilder (1919) said that shales of nearly every geological horizon in many worldwide localities contain individual crystals or rosettes of gypsum produced by the action of $SO_4$ from the oxidation of pyrite on CaCO$_3$. Many shales do contain pyrite. Glaciers that passed over the Pierre shale incorporated some of it into the drift. This is the source of most of the soluble salts and pyrite in the tills of the upper Midwest and Great Plains. The ultimate fate of the salts near the modern surface depends upon many factors.

The U.S. Geological Survey has done a many-faceted, ten-year hydrologic study on a prairie pothole area of central North Dakota. The following information is from the articles of Eisenlohr (1972) and Sloan (1972). A prairie pothole is defined as a water-holding depression of glacial origin that occurs north of the Missouri River on the plains of the United States and Canada. It is sometimes called a slough. The current author assumes the prairie potholes are similar to the closed depressions left by late-Wisconsin glaciation in the other areas of the United States, except that most depressions to the east of North Dakota have been drained for agricultural use. Most of the potholes studied
contained ponds that were fairly permanent, usually containing 2-5 ft of water. The study area was covered by late-Wisconsin glaciation and carbon-14 dated at < 13,000 rcybp. Average precipitation was 18 inches/year, and mean annual temperature was about 40° F. Open-pan evaporation was about 32 inches/year. The study showed by detailed investigation and supportive data that evaporation from the soil surface and transpiration by vegetation caused an increase in salinity in the soil surrounding the pothole. White salts are often found on the shoreline. Salts are brought to the surface by capillary rise of ground water and then left when evaporation occurs. It was found that a buildup of salts in a pothole was conditional upon its water balance, i.e., water inflow, seepage outflow, and evapotranspiration. More seepage outflow removes salts and results in less saline waters and soils. Less outflow results in a salt buildup, even of readily-soluble salts such as NaCl. Some ponds hold water intermittently. Salts are left in the center of the depression when the pond evaporates.

There is an abundant source of salts in the drift surrounding the potholes. The drift is derived from and differs little from the underlying bedrock. Gypsum and pyrite (FeS₂) are abundant in the Pierre shale and overlying Cretaceous and Tertiary rocks. Soluble constituents are leached from the till into the closed basins. The water level of the potholes was found not to be perched but was connected with the permanent water table of the topography. The origin of the water in the potholes is surficial. There are some fresh water potholes adjacent to saline ones. This anomaly can be explained by the relative altitudes of the
ponds. The pond water seeps out to a greater degree in higher elevation potholes than in lower ones. The electrical conductivity (EC) of the pond water was related to the altitude of the water surfaces. One pond at a relatively high elevation had an EC of 1.20 mmhos/cm. A pond with the surface water level about eight feet lower than the first pond had an EC of 42.5 mmhos/cm. It was also found that water flow in the slowly permeable tills was more vertical than horizontal due to vertical joints.

There are a number of springs in the area which feed some of the lakes and ponds. Sampling was done on the springs as well as their paired lakes. The samples were analyzed for various dissolved constituents, EC, and pH. Sloan's (1972) Table 7 gives the complete data. Table 8 of this thesis shows selected data for the springs that were calculated from his table.

The summary statistics of Table 8 are as follows:

**Na:** For all springs:
- $n = 12$, range $= 0.5-13.0$ meq/liter, $\bar{X} = 4.0$ meq/liter

Omitting highest two values:
- $n = 10$, range $= 0.5-6.7$ meq/liter, $\bar{X} = 2.3$ meq/liter

**SO$_4$**:
- For all springs:
  - $n = 12$, range $= 1.5-9.8$ meq/liter, $\bar{X} = 4.3$ meq/liter

**EC**:
- For all springs:
  - $n = 12$, range $= 0.624-2.38$ mmhos/cm, $\bar{X} = 1.10$ mmhos/cm

Table 9 gives selected data for some of the lakes. It should be apparent from Table 9 that the lakes invariably have higher concentrations of salts than the associated springs. The factor of concentration of the Na ion from a spring to its paired lake was calculated by the present author. This value ranges from 2 to 675.
Table 8. Chemical analyses of spring waters from Stutsman and Kidder Counties, North Dakota

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Na meq/liter</th>
<th>SO$_4$ meq/liter</th>
<th>EC mmhos/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unnamed Lake</td>
<td>0.6</td>
<td>1.9</td>
<td>0.624</td>
</tr>
<tr>
<td>East Chokecherry Lake</td>
<td>6.7</td>
<td>7.0</td>
<td>1.45</td>
</tr>
<tr>
<td>Tweedy Lake</td>
<td>1.0</td>
<td>1.7</td>
<td>0.846</td>
</tr>
<tr>
<td>Widgeon Lake</td>
<td>12.2</td>
<td>9.8</td>
<td>1.98</td>
</tr>
<tr>
<td>Crystal Springs (north)</td>
<td>0.5</td>
<td>1.6</td>
<td>0.656</td>
</tr>
<tr>
<td>Crystal Springs (south)</td>
<td>1.5</td>
<td>3.6</td>
<td>0.982</td>
</tr>
<tr>
<td>Alkaline Lake</td>
<td>3.1</td>
<td>4.3</td>
<td>1.08</td>
</tr>
<tr>
<td>Salt Alkaline Lake</td>
<td>13.0</td>
<td>9.8</td>
<td>2.38</td>
</tr>
<tr>
<td>Spring Lake</td>
<td>4.2</td>
<td>2.4</td>
<td>1.02</td>
</tr>
<tr>
<td>Stony Lake</td>
<td>1.3</td>
<td>1.5</td>
<td>0.628</td>
</tr>
<tr>
<td>Pass Lake</td>
<td>1.8</td>
<td>3.3</td>
<td>0.905</td>
</tr>
<tr>
<td>Mount Moriah</td>
<td>2.6</td>
<td>4.1</td>
<td>0.656</td>
</tr>
</tbody>
</table>

*Adapted from Sloan (1972).

The wide range of values for the lakes is probably due to the relative elevation of each on the landscape, as stated previously. The lakes with the least salinity are probably highest on the landscape. The lakes with the most salinity are probably lowest. The three lakes at Crystal Springs are in a toposequence and have seasonal spillover from one to the other. Paired springs were not available therefore for two of the lakes. Notice the increase in salinity from the top of the toposequence to its bottom.

Miller (1969) also did work in the same area. He studied the soil landscape of a slope about 450 ft long separating two ponds. The ponds
Table 9. Chemical analyses of lake waters from Stutsman and Kidder Counties, North Dakota

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Na meq/liter</th>
<th>SO₄ meq/liter</th>
<th>EC mmhos/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unnamed Lake</td>
<td>91.3 (152)</td>
<td>119.8</td>
<td>11.4</td>
</tr>
<tr>
<td>East Chokecherry Lake</td>
<td>4,522 (675)</td>
<td>4,708</td>
<td>111</td>
</tr>
<tr>
<td>Tweedy Lake</td>
<td>82.2 (82)</td>
<td>81.7</td>
<td>10.6</td>
</tr>
<tr>
<td>Widgeon Lake</td>
<td>27.7 (2)</td>
<td>31.3</td>
<td>4.48</td>
</tr>
<tr>
<td>Crystal Springs Lake</td>
<td>3.1 (6)</td>
<td>6.0</td>
<td>1.17</td>
</tr>
<tr>
<td>Crystal Springs: Middle Lake</td>
<td>37.0</td>
<td>45.6</td>
<td>5.47</td>
</tr>
<tr>
<td>Crystal Springs: Stink Lake</td>
<td>909</td>
<td>1,004</td>
<td>64.2</td>
</tr>
<tr>
<td>Alkaline Lake</td>
<td>196.5 (63)</td>
<td>239.6</td>
<td>20.3</td>
</tr>
<tr>
<td>Salt Alkaline Lake</td>
<td>197.4 (15)</td>
<td>372.9</td>
<td>25.9</td>
</tr>
<tr>
<td>Stony Lake</td>
<td>120.0 (92)</td>
<td>128.1</td>
<td>12.9</td>
</tr>
<tr>
<td>Pass Lake</td>
<td>143.5 (80)</td>
<td>182.3</td>
<td>14.9</td>
</tr>
</tbody>
</table>

Adapted from Sloan (1972).

Values in parentheses are factors that show the increased Na concentration of the lake water as compared to the associated spring water, i.e.,

\[
\frac{\text{Na meq/liter at lake}}{\text{Na meq/liter at associated spring}} \]

had water level differences of about 12 ft. Water definitely flowed from the upper pond, through the hillslope soil, to the lower pond. He found that during the water travel time, salinity gradually increased as the water flowed toward the lower pond due to evapotranspiration losses. The relative concentration of Na compared to Ca and Mg also increased. As water moved up in the profile by capillary draw, selective ion exchange with the soil colloids adsorbed more divalent cations than
monovalent cations. Water that reached capillary equilibrium during the night drained downward each day when equilibrium immediately above the water table was disrupted by evapotranspiration. The ground water became recharged with small amounts of water containing higher concentrations of Na. This whole process is another reason for the higher salinity normally found in the lower lakes. The assumed direction of flow of water within the profile was supported by the principles of Miller and Ratzalff (1965). These authors showed that the distribution of soluble Na and total soluble cations in a soil profile can give an indication of water movement direction. Sloan (1972) also found there is often a diurnal fluctuation of the water table of 1-2 inches due to draw down by evapotranspiration during the day and recharge at night.

The studies of Sloan (1972) and Eisenlohr (1972) are recommended for examination. They quantified principles that have long been assumed. The principles of salt accumulation they studied are applicable the world over.

A later study also examined the soils of the prairie pothole region of central North Dakota (R. J. Bigler, et al., 1979. Soils of semipermanent ponds and lakes of the Missouri Coteau in central North Dakota. Agronomy Abstracts. Amer. Soc. Agron., Madison, Wi.). The authors studied the soils from the edge to the middle of each of four closed depressions. Entisols were found on the edges and Typic and Cumulic Haplauquolls in the center. Water table fluctuation and oxidation-reduction potential were found to be highly negatively correlated, presumably influencing iron, gypsum, and sulfide in the soils. The sites appeared to
be affected by regional ground water movement because the EC of the soil extracts became much higher at lower elevations.

Salt-Affected Soils in Subhumid and Humid Regions, Excluding the Upper Midwest

This section will present studies on salt-affected soils in subhumid and humid regions, 20-80 inches/year average precipitation. Two limitations are made, however. Studies done on soils of the upper Midwest will be presented in a separate section later, due to their close affinity to the current study. The studies presented here were done in areas of 30 inches/year or more average precipitation. This is not an imposed limitation. No studies were found that have been done in 20-30 inches/year regions, outside the upper Midwest. It is somewhat unusual to find soluble salts in regions of > 30 inches/year average precipitation. All such findings were noted carefully. The studies presented are the totality of a fairly extensive search of the literature.

Cameron (1901) appears to be the first author to publish material concerning salt-affected soils in high rainfall areas. He only mentions them briefly. Salt-affected soils were found near College Park, Maryland. Ninety percent of the salts were nitrates; 50% was Ca(NO₃)₂. Similar soils were found near Cumberland, Maryland. Salt-affected soils near Starke, Bradford Co., Florida had crusts mainly of NaCl, but SO₄ and PO₄ were present in measurable quantities also. Similar soils were noted in Louisiana, Mississippi, and near Houston, Texas, and were found to contain mostly NaCl. Most of the sites were found after prolonged periods of dry weather. Salts evidently moved up from a water table below. The
current author wonders if some of these sites would have been called "salt licks" by the early pioneers.

Conner (1917) reported on some salt-affected soils in Indiana. He called them "black peat" soils, and NO$_3$ was responsible for the toxic conditions. During spring and summer, nitrification occurred and large amounts of NO$_3$ accumulated. The NO$_3$ was brought to the soil surface by evaporation and deposited. In very acid soils, water soluble Al salts were also found.

Ames and Schollenberger (1916) studied salt-affected soils in Ohio. At that time, such soils were only found in Brown and Clermont Cos. and the southern part of Highland Co. where soils formed in loess overlie Illinoian glacial deposits. The average precipitation was 30 inches/year. All soils were very poorly drained and contained many crayfish holes. The landowners said the "frost" of salts on the soil surfaces was most pronounced after a heavy rainfall. The authors then state: "This indicates that the subsoil water is strongly impregnated with salts, for when a connection is established between the saline subsoil water and the water evaporating from the surface, capillary rise of salts takes place followed by a crystallization at the surface." Sparse vegetation grows on the spots. Water from shallow wells in the area (8-12 ft deep) was high in Ca and Mg. Water from a shallow well about one mile from one site contained 3.59 g/liter total dissolved solids (3,590 ppm). Amounts of Ca, Mg, and SO$_4$ were determined and expressed as 1.65 g/liter of CaSO$_4$ • 2H$_2$O (or 19.2 meq/liter) and 3.76 g/liter of MgSO$_4$ • 7H$_2$O (or 30.5 meq/liter). These amounts are appreciable. No Al or Fe was found.
Calcium sulfide and calcium hyposulfite were reported in some artesian water at Ripley in Brown Co.

A water extract of one salt-affected soil was made by extracting 50 g of surface soil with 1 liter of water. Magnesium and Al sulfates were found to be the chief constituents. Only a trace of Ca was found. An adjacent soil that did not have a surface salt crust was also analyzed. It had much less soluble salts but appreciable quantities of \( \text{Al}_2(\text{SO}_4)_3 \) and was acid. Another locality was examined that had a surface salt crust. The soil profile was sampled in 1 ft intervals to a depth of 6 ft and was analyzed qualitatively. Calcium sulfate was found in all horizons except the 2-3 ft zone. Only the surface sample contained high amounts of \( \text{Al}_2(\text{SO}_4)_3 \). The water extract of the surface sample was strongly acid, the rest were neutral. No soluble Mg or Fe was found. Many iron concretions were found in soils in the area. The authors state that while salt-affected soils in arid regions normally contain \( \text{CO}_3, \text{SO}_4, \text{Cl}, \text{Na}, \text{K}, \text{Mg}, \) and Ca, these soils contained only Mg, Ca, and \( \text{SO}_4 \) with considerable amounts of Al in the surface layer. It was suggested that the oxidation of pyrites may be a contributing cause to the \( \text{SO}_4 \) accumulation.

Millar (1922) studied seven virgin and seven cultivated soils in Michigan. He did not describe the soils as to drainage or other properties. Soluble-salt contents were expressed in terms of the freezing point depression of water, and no analyses to determine ionic constituents were done. Less salts were found in the surface layers in spring and fall than during the summer. It was concluded that rainfall was
important in the distribution of salts within the profile.

It seems that investigations into salt-affected soils in the highly-agricultural Midwest were not pursued after about 1925. Although the above-mentioned articles are very old, no newer studies could be found. It is the belief of the current author that after initial investigations into such soils, research interests were turned to more pressing problems. The soils mentioned appear to be unusual, yet are very limited in extent and importance. It appears that most of the researchers cited so far were primarily interested in soil fertility rather than soil genesis studies.

Soils containing soluble salts have also been found in Mississippi. Hilgard (1860) first mentioned them in a reconnaissance report on the soils and geology of the state. He reported "gypseous prairies" of "heavy gray clay" in and around Rankin Co. along the Pearl River. Gypsum crystals were usually at depths of 3-4 ft but were sometimes located at depths of 15-18 inches. Recent indepth studies have been made of the area (D. E. Pettry, Dept. of Agronomy, Miss. State Univ., State College, Ms. Personal communication, 1979) and (D. E. Pettry et al., 1978. Geomorphic relationships and selected properties of Natraqualfs occurring on coastal plain terraces of Mississippi. Agronomy Abstracts. Amer. Soc. Agron., Madison, Wi.). At the time of the personal communication in the Spring of 1979, Dr. Pettry indicated that he had studied the gypsum-containing soils for four years and a publication would ensue. He confirmed Hilgard's report. The soils are high in Na, have salic horizons, and are classified as Natraqualfs. Two general regions of the soils occur. The
first has poorly-drained soils on broad flat terraces of streams on the coastal plain. The terraces are high, third and fourth order, and are remnants of relict conditions. The upper two feet of the soil profile contains 40-70% silt, and the subsoil (40-55 inches) contains coarse crystalline gypsum. The soils are very low in pH but have a base saturation > 35%. At "lower depths," the soil solution exceeds 15,000 ppm Na (or 652 meq/liter) and pH values exceed 12. Extractable Na comprises 10-70% of the cation exchange capacity. Analysis of the soil solution residue indicated Na$_2$CO$_3$ as a major constituent.

The other region is in Jasper Co. Very large masses of gypsum crystals are present, some weighing up to 20 lb. These soils are also high in Na content and base saturation. It is believed that truncation exposed the large masses of crystals. The formation of the gypsum in both regions is thought to be due to the weathering of Na and S containing feldspars and other minerals in the sediments. The soluble ions are brought into the soil profile by a high but fluctuating water table. The SO$_4$ ions formed by oxidation of the minerals combine with Ca in the soil profile to form gypsum. The latter region of gypsiferous soils has Ca laden montmorillonitic clays. There is also the possibility of some actual CaSO$_4$ coming up from deeply-buried marine evaporite beds. The high clay content of the soils prevents the dissolution of the gypsum even though the soils are poorly drained. The average rainfall is 48-60 inches/year, with some areas receiving 70 inches/year. It is quite unusual to find accumulations of soluble salts under such high rainfall conditions. Some hemihydrate (CaSO$_4$ · $\frac{1}{2}$H$_2$O) is present. It is very anomalous to find this
Dr. Pettry also stated that gypsum has been found in Florida under conditions of 75 inches/year average precipitation. Those sites are also old fluvial positions with Ca rich clays. A fluctuating water table brings up SO$_4$ ions to form gypsum. He said there are areas in the tropics high in Na salts with even higher annual precipitation. He concludes that excess salts in humid regions might not be as uncommon as some think.

Soils high in Na in Arkansas were studied by Horn et al. (1964). They reported there are medium-textured Solonetz soils covering about 600,000 acres in eastern Arkansas. Some are also found in northern Louisiana. The average precipitation was 48 inches/year and the mean annual temperature was 60-65°F. These soils developed in loess on uplands or loess-derived alluvium on floodplains. It is believed the loess is the source of Na and Mg containing minerals that weather. Two methods of salt accumulation occur. Salts may be left on the surface of soils when saline floodwaters cover floodplains, or salts may also move upward from shallow ground water. A combination of processes is probably at work. All soils were on 0-1% slopes. No gypsum was mentioned.

Solonetz soils have been studied in Illinois by Fehrenbacher et al. (1963) and Wilding et al. (1963). These were companion papers. Smith (1938) studied the same areas earlier but in a less-technical way. Solonetz soils occur on about 381,000 acres of nearly level uplands in south central Illinois and to a limited extent in western Illinois. Some also occur in south central Indiana. The average precipitation is 36-42 inches/year and the mean annual temperature is 54-57°F. The soils are
in irregular-shaped areas < 1 to > 100 acres in size and are intimately associated with rather strongly-developed planosolic soils. They are high in exchangeable Na and have columnar or prismatic structure in the B horizons. The soils are in areas having 2-8 ft of Peorian loess overlying a highly-developed paleosol formed in Illinoian till. The authors concluded that the source of the Na was the Na rich feldspars of the loess. The occurrence of these soils was correlated with areas overlying the highly-impermeable paleosols. The Na that was weathered out of the loess was not removed fast enough. Also some water appeared to be concentrating from surrounding pedons. Drying in the summer promoted exchangeable Na accumulation, clay movement, and the general process of Solonetz formation. No gypsum was mentioned in these soils. The concept as given by Kellogg (1934) of development of a normal soil to a Solonchak, to a Solonetz, to a Solodized-Solonetz cannot be applied to these soils. They were never Solonchaks. The classical sequence is more applicable to soils of arid and semiarid regions.

Another type of soil will be discussed that is common in subhumid and humid regions. Even though they are not salt-affected soils, they do have several similarities. These are the acid sulfate soils. Donner and Lynn (1977) give several basic principles of interest. Acid sulfate soils are found in coastal marsh areas near oceans. Their formation consists of two stages: a reduction phase in which sulfides (i.e., pyrite) accumulate and an oxidation phase in which acidity develops. The reduction phase needs sources of iron and sulfate (sea water and soil), a redox potential of about -400 mv, sulfate reducing bacteria (Desulfovibrio
genus), an energy source for the bacteria, and a mechanism to move the bicarbonate formed in the process. Pyrite (FeS$_2$) is formed. If the sediments are drained or aerated, the sulfide minerals being to oxidize by bacterial action forming the mineral jarosite and H$_2$SO$_4$. The pH becomes very low (3.0-3.5). If CaCO$_3$ is present in the sediments, the acidity is somewhat neutralized as the Ca and H$_2$SO$_4$ combine to form gypsum.

Acid sulfate soils are mentioned here due to their similarities in one way to some salt-affected soils. Of particular interest is the second or oxidation stage of their formation when FeS$_2$ oxidizes to SO$_4$. As discussed previously, this same process is at work in many salt-affected soils even though they are far removed from any sea coast. Sulfates form. If there are other mineral cations available, Na$_2$SO$_4$, CaSO$_4$, or MgSO$_4$ form. If not, H$_2$SO$_4$ persists and the pH becomes low. The reduction phase (the formation of pyrite) was done long ago in the reducing environments of ancient seas. The pyrite is now left in the various geologic materials to be oxidized and transformed. The present environmental conditions control the fate of the subsequent SO$_4$ ion.

One study concerning acid sulfate soils will be reviewed. It has long been a known fact that inland acid sulfate soils develop when pyrites but no mineral cations are present. One recent study gives such an example (C. D. Carson et al., 1979. Acidity and mineralogy of inland acid sulfate soils. Agronomy Abstracts. Amer. Soc. Agron., Madison, Wi.). The study was done in eastern Texas. It was found that pyrite bearing geologic formations gave rise to acid sulfate soils by the oxidation of the sulfides in the absence of CaCO$_3$. pH values were about 4. The
weathering of the sulfides gave rise to jarosite and iron oxides when it occurred near the soil surface.

The formation of \( \text{H}_2\text{SO}_4 \) from the oxidation of \( \text{FeS}_2 \) is responsible for the acid conditions produced from coal mine spoil banks. The pyrite in and around the coal seams oxidizes when exposed to the air.

Salt-Affected Soils of the Upper Midwest

This section will present studies on salt-affected soils in the upper Midwest. A separate section is reserved for such studies because of the close affinity of the geographical, climatic, and soil parameters to the current study. Most studies will fall into a subhumid climate classification, 20-40 inches/year average precipitation. A few may fall slightly below the 20 inches/year line.

Eastern North Dakota

McClelland et al. (1959) published a study of the soils of the eastern half of North Dakota as a companion paper to the one of Mogen et al. (1959) which covered the western half. The eastern half of North Dakota was covered by the then called Mankato glaciation which retreated about 12,000 rcybp. Friable calcareous loam till was left on the landscape surface, although some lacustrine sediments associated with glaciation are present also. Closed depressions are the dominant landscape feature. The eastern half of North Dakota has a range of 15-21 inches/year average precipitation and a mean annual temperature of 36-42°F. Mean open-pan evaporation is 28-35 inches/year. The authors studied six soil series located in a transect from a hillslope of > 10% slope to the center of
a closed depression. Descriptions were given for three profiles. The well-drained Barnes series was found on slopes of about 3-8%. Four of eleven Barnes profiles contained gypsum below 14 inches. It was stated that soluble salts are usually found in the C horizon or deeper in the Barnes series and that gypsum and a moderate amount of readily-soluble salts are found in the Cca or C horizons of calcium carbonate Solonchaks. Solonetz soils are in the center of the depressions and do contain considerable amounts of exchangeable Na. The authors say the till contains a lot of shale which is the source of highly-weatherable minerals. As discussed previously, the shale is probably Pierre shale that was incorporated in the till.

Much research has been done on the glacial Lake Agassiz area of eastern North Dakota and western Minnesota. About 12,000 rcybp, retreating glacial ice blocked meltwater draining to the north. A lake was formed that in different stages affected about 200,000 mi² of land, primarily in Canada. Not all of this area was covered with water at one time. The lake, called glacial Lake Agassiz, later drained and left a very level lake bottom topography in many areas. Eastern North Dakota, western Minnesota, and extreme northeastern South Dakota contain a total of about 22,000 mi² of this flat, lake bed topography (Mayer-Oakes, 1967). This area is currently drained by the Red River.

The first soils investigation into the glacial Lake Agassiz plain was apparently done by Dorsey (1906). He studied some soils near Grand Forks, North Dakota, an area with about 20 inches/year average precipitation. He found that there was enough rainfall to leach almost all
soluble salts to a depth of three ft although there were a few spots of significant amounts of salts at the soil surface. There were flowing artesian wells in the area containing 4,200 to 14,300 ppm of salts. Chloride was the most abundant ion; \( \text{SO}_4 \) was the second most abundant ion.

Several later studies were also done in the Grand Forks area. Sandoval and Shoesmith (1961) published a paper, but the reported data were expanded and more or less repeated in later papers. This 1961 paper will be cited, but not discussed. Sandoval et al. (1964b) studied soils in the same area as Sandoval and Shoesmith (1961). The area has about 20 inches/year average precipitation and an average monthly temperature of 4.4° and 70.7° F for January and July, respectively. The soils formed on the old lake plain of glacial Lake Agassiz. The lake sediments overlie till, and thin shale may underlie the drift or may be absent. The drift overlies the Dakota sandstone formation. Saline water is under artesian pressure in the sandstone and permeates the drift, reaching the surface. Soil salinity and wet conditions of the area are believed to be due to the artesian water. Specifically, the authors studied two soil areas. One was in an area of deep alluvium (13-15 ft over till) near the Red River with a slope of 2-3 ft/mile. The second area was in an area of thin alluvium over till. No thickness of materials was given, but the slope was 5-10 ft/mile. Fourteen soil sites were studied. Exchangeable Na percentage ranged from 3 to 34. All salt-affected sites had a fluctuating water table within 4-8 ft of the surface. The most saline areas had the shallowest water tables. The authors also had water wells to a depth of 12 ft at the study sites. Electrical conductivity (EC) of the
water ranged from 7.7 to 58.3 mmhos/cm. Total cations in the water ranged 116-756 meq/liter. Sodium ranged from 17-293 meq/liter and \( \text{SO}_4 \) ranged from 37-275 meq/liter. Ten flowing artesian wells were also sampled that were about 150 ft in depth, reaching into the Dakota sandstone. The EC of the waters ranged from 6.4 to 17.3 mmhos/cm, with an average of 7.5 mmhos/cm. The total salts ranged from 4,448 to 11,740 ppm. The average Na content of the ten wells was 67 meq/liter and the average \( \text{SO}_4 \) content was 31 meq/liter. These artesian waters were significantly saline.

Sandoval et al. (1964a) studied the same area as in the 1964b paper, yet the effects of microrelief on soil salinity were examined. Although the old lake plain is very flat, there is a gently undulating microrelief of microridges and microdepressions. The distance from ridgetop to ridgetop normally ranges from 75 to 500 ft, and the difference in elevation from the top of the ridge to the bottom of the depression is normally 1-2 ft. One specific microridge-microdepression system was studied. It had a distance of 200 ft from the top of the ridge to the middle of the depression and had a change in elevation of 1-1.5 ft. The authors found the greatest salinity in the soil formed on the microridge. The EC of the saturation extracts of a 72 inch profile ranged from 8.7 to 18.0 mmhos/cm. Sodium in the extracts ranged from 51 to 90 meq/liter. In the microdepression, the saturation extracts of an 84 inch profile gave an EC range of 0.9 to 3.1 mmhos/cm and a Na content of 2 to 5 meq/liter.

Benz et al. (1964) studied the same microridge-microdepression system. Piezometers were placed at depths of 20, 30, 40, and 60 ft. They
found the increase in salinity on the microridge carried down to 20 ft in the ground water. They also tested the piezometer pressure of flowing artesian wells in the area. The piezometric "surface" measured 870 ft in elevation. The well heads were about 847 ft in elevation, a net difference of 23 ft.

Western Minnesota

Rost (1936) reported that Solonetz soils occur in the Red River valley area of Minnesota but seem to be the most numerous in the southern part. The average precipitation in the region is about 22 inches/year. The soils occur as spots <16 ft to 65-85 ft in diameter. They may occur as isolated spots or be relatively numerous. The spots seem to lie on slopes of very slight depressions, so slight they are barely visible to the unaided eye. Most of the salt-affected soils are along the edge of the bed of glacial Lake Agassiz. The author theorizes that drainage probably developed first near the present day Red River, leaving the soils away from the river no mechanism for removal of salts. He studied six Solodized-Solonetz profiles which displayed well-developed morphology. An A2 horizon was present along with a dense columnar B horizon. Yet exchangeable Na was low in the soils; exchangeable Mg was high. All six profiles contained some gypsum. No explanation was given as to the reason for the high exchangeable Mg contents. Sherman et al. (1962) showed that a lot of the springs and artesian wells in the Red River valley area of Minnesota contain water high in Mg. This study will be discussed in detail later.

Another paper by Rost and Chang (1941) presented studies done in
Wilkin and Traverse Cos., Minnesota. These counties are near the North Dakota-South Dakota border and have an average precipitation of 20.3 inches/year, mean monthly temperatures of 9.7° and 71.8° F for January and July, respectively, and a mean annual temperature of 41.9° F. The authors studied five Solonchak soils in the Red River valley. Gypsum crystals were found in three profiles in the B and C horizons. The crystals were prominent, could be seen with the unaided eye, looked like medium sand grains, and could easily be mistaken as such. No theories were given as to the source of the salts. It was mentioned that the soils did have a high water table.

Rost and Maehl (1943) again studied solodized soils of the Red River valley. They found soils with soluble salts present in the B horizons located on slopes of very slight depressions. Soils with no soluble salts in the solum or in the entire profile were found in the depressions themselves.

Johnsgard (1971) found an interesting phenomenon in some soils of Clay Co., Mn. and Eddy and Richland Cos., N.D. Clay and Richland Cos. have touching corners and are located in the Fargo area. The soils there formed in the bed of glacial Lake Agassiz. Eddy Co. is about 50 miles west of Grand Forks, outside of the old lake bed. Its surficial deposits are outwash materials and end and ground moraines. The author found evidence of involution of soil profiles caused by the breakthrough of water under artesian pressure through a frozen zone of soil. The process was explained as follows. During the winter months, the soil freezes several feet deep. Artesian pressure gradually builds up below this frozen zone.
When spring comes, the soil begins to thaw from the surface downward. The layer of frozen soil becomes gradually thinner until a rupture point occurs, allowing the artesian water to flow upward through the break. Pictures were given showing the effects of the water flow on profile morphology. Reports from area farmers corroborated the theory of artesian flows. Depressions would mysteriously fill with water in the spring when no rainfall had occurred. Tractors would suddenly sink into wet ground when plowing. Sandoval et al. (1964b) also believed artesian water reached the soil surface by seepage.

Hole (1961) classified pedoturbation (soil mixing) into several specific categories. The above-mentioned phenomenon would be called aquapedoturbation and is defined as "soil mixing by water within the soil profile, such as by upwelling seepage waters." Other terms which may be of interest to the current study are faunal pedoturbation, which refers to the mixing of soil by animals, and crystal pedoturbation, which refers to "soil mixing by the growth and wasting of crystals in the soil."

**Eastern South Dakota**

Westin (1953) made a study of salt-affected soils in eastern South Dakota. His study area was Spink Co., in the James Basin. The climate was subhumid to semiarid with an average precipitation of 18 inches/year. Part of the county is in the bed of glacial Lake Dakota, and the rest is covered by till that at that time was identified as Mankato. Three-fourths of the soils formed in the lake bed and 1/3 to 1/2 of the soils formed in glacial till exhibited some degree of solonization. Less than 1/3 of the soils formed in outwash and alluvium were solodized. In the
glacial till area, closed depressions are the common landscape feature. Solonetz soils and Solodized-Solonetz soils were found on the level or slightly depressed areas. Solod soils were found in the lowest areas of the depressions. Solonchak soils were rare and were found in seep positions. He compared a Solonetz soil to a nonsaline-nonsodic Chernozem. The Solonetz was found in a basin and was alternately ponded and dry. The Chernozem was found on a sloping or convex position with no ponding. Below the B horizon of the Chernozem were carbonates and soluble salts. The "substrata" of the Chernozem was classified as saline-sodic. The author states that the parent materials were high in soluble salts and Na originally. The Solonetz profile had gypsum in it to within seven inches of the surface.

Other information on the salt-affected soils of eastern South Dakota was obtained by personal communication (M. J. Mausbach, U.S.D.A.-Soil Conservation Service, National Soil Survey Lab, Lincoln, Ne. Personal communication, 1978). Dr. Mausbach has worked as a soil survey party leader in McCook Co., South Dakota, which is about 20 miles west of Sioux Falls. He is also familiar with surrounding counties. The area was covered by the James lobe of late-Wisconsin glaciation. Closed depressions are the dominant landscape feature. The average precipitation is 21 inches/year and the mean annual temperature is 47° F. Gypsum is found in some of the soils, primarily those along the rims of closed depressions. As in Iowa, the rims of the depressions are often calcareous. No gypsum is found on the surface of these soils except possibly as a white crust after snow melt in the spring but before the first rain. The crystals are
normally found in the B and C horizons. In some of the well-drained soils on the convex rises, gypsum is found at depths of 3-6 ft. Usually the centers of the depressions are leached. Dr. Mausbach believes the B2t horizon of the soil in the center of the depression (Crossplain series, Typic Argiaquoll) perches the water table during wet periods of the year. A zone of saturation is created and evaporation of the capillary fringe leaves carbonates and gypsum in adjacent soils. The type location description for the Crossplain series states: "A perched water table is generally below 4 ft; but is within 1 ft of the surface in the spring."

The concentration of the gypsum in the profiles is always above the concentration of carbonates, indicating an upward movement of water.

Soils in this area may also have significant accumulations of Na. These soils are classified as Natraquolls and Natrustolls. The maximum accumulation of gypsum is either above or at the same depth as the carbonates, but the readily-soluble salts are always above the gypsum. Again, this arrangement indicates upward water movement. To the west of the McCook Co. area, the climate becomes drier and gypsum is mostly associated with the wetter soils.

The present author looked at the type location descriptions of several gypsum-containing series in eastern South Dakota. Fine or medium-sized nests of crystals were always mentioned whenever crystalline gypsum was present. The Soil Conservation Service (Soil Survey Staff, 1975) defines fine as < 5 mm and medium as 5-15 mm. Threads or flour gypsum were always in the upper part of the gypsum-containing layer.
There are few references to salt-affected soils in Iowa. It has been shown previously that prior to about 1940, some workers applied the term "alkali" to any salt-containing soil, not just to those containing large amounts of Na. Several Iowa Agricultural Experiment Station Bulletins prior to about 1930 did discuss the management of alkali soils. These were soils high in CaCO$_3$ that were found on the late-Wisconsin till plain of central and northern Iowa. Since the high CaCO$_3$ contents affected plant growth, several bulletins were published from a practical management standpoint. Most were nontechnical.

Stevenson and Brown (1915) said the soils high in CaCO$_3$ formed from evaporation of water around the edges of ponds and sloughs. They also said that CaCO$_3$ went to Ca(HCO$_3$)$_2$ upon CO$_2$ generation. Bancroft (1918) reported that there were quite evident salt crusts on the surface of newly-drained lands. They were removed in several years if good drainage was present. Calcium bicarbonate was found to be the primary soluble salt. Two sampling sites in Wright Co. showed no significant amounts of soluble Na or SO$_4$.

Stevenson et al. (1930) say that alkali soils are found as a ring around former ponded areas or depressions. They state: "A whitish deposit on the surface on the ground, giving it the appearance of having been lightly strewn with a fine white powder, is the first evidence of the injurious salt accumulation. . . . A high concentration of salts, which is characteristic of alkali spots, may be present for many years, but until drainage is established, the salts present remain in solution,
exerting their injurious effects on crops but showing no other evidence of their occurrence. They undoubtedly accumulate in the soil as deposits carried down from the adjacent uplands, by water flowing into the ponds and depressions. With the evaporation of the water, which is greater around the edges of the ponds, the salts gradually accumulate there until the concentration becomes very high." After drainage, "dry weather brings some to the surface with the water, which moves upward from the lower soil layers, and the deposit of whitish salts, referred to earlier, appears. . . ." The authors go on to state that large amounts of NO\textsubscript{3} and SO\textsubscript{4} are found in the soil water. Sodium salts usually occur in slightly larger amounts than in the "normal" soils adjacent to the alkali spots. There was never found a sufficient concentration of Na salts to singly account for crop injury. It was believed Ca and Mg bicarbonates and carbonates were the major salt constituents. The total concentration of all salts in solution was believed to be the cause of crop injury. Since this bulletin was written for farmers, no chemical data were reported.

Meldrum et al. (1941) still used the term "alkali spots" for the calcareous ring around depressions. A white crust on the surface of dry soils was also mentioned, although it was said to be more pronounced in some areas than in others. The authors did attribute the injury to crops to excess quantities of CaCO\textsubscript{3} and Ca(HCO\textsubscript{3})\textsubscript{2}, not to the total concentration of dissolved salts. This last statement appears best to the current author because of the severe fertility effects of high CaCO\textsubscript{3} contents. Fertility effects would probably far outweigh any salinity effects. The amount of readily-soluble salts was shown to be extremely small.
Bower and Pierre (1944) reported some soil properties for a fertility study of high lime soils. A "high lime Webster soil" (probably the current Harps series) from Webster Co. contained 30.9% CaCO₃ equivalent and had an exchangeable Na content of 0.30 meq/100 g by IN NH₄OAc extraction. A "normal" Webster soil (noncalcareous) from the Northern Iowa Experimental Association farm in Hancock Co. had 26.4, 7.0, and 0.54 meq/100 g of exchangeable Ca, Mg, and Na, respectively. It can be seen that the exchangeable Na contents of both soils are extremely low.

Outside of the late-Wisconsin glaciation region, little accumulation of carbonates or soluble salts occurs. Tyner (1940) used a Gosport soil sample in his paper on mechanical analysis of soils. It contained 0.3% CaSO₄. The Gosport series formed in acid shales of Pennsylvanian age exposed in southern Iowa. The sample itself contained no CaCO₃. Here is an example of an acid shale containing gypsum. Whether the gypsum was inherent in the shale or formed from weathering products is not known. The location of the sampling site was not given.

Some of the soils formed in Wisconsin loess in southern Iowa contain small amounts of exchangeable Na. The works of the Soil Survey Staff (1966, 1978) and Ulrich (1950) show that soil series such as Edina, Haig, Seymour, Appanoose, Kniffin, Rathbun, and Weller have maxima in the B and C horizons of 1-2 meq/100 g exchangeable Na. The highest amount detected was 2.4 meq/100 g in an Appanoose profile. This value would represent an ESP of 6.2. It is believed that the source of the Na in these soils is the minerals in the loess. Weathering has probably released Na faster than complete removals could occur. This genetic situation is not too
unusual. Soils very high in exchangeable Na are found about 100-150 miles east in Illinois (Fehrenbacher et al., 1963; Wilding et al., 1963).

The Napa series is an inextensive sodium-containing soil of the Missouri River bottomlands of western Iowa. Schafer (1952) presents the only known study of that series. The Napa series is associated with the Luton series, and both are dark, poorly-drained soils with clay texture. Napa soils occupy very shallow troughs on the eastern side of the bottomlands, protected from floods by natural levees. Table 10 gives data for a Napa profile, P-152, from Monona Co.

Table 10. Selected chemical properties of a Napa series profile, P-152

<table>
<thead>
<tr>
<th>Depth, inches</th>
<th>EC in mmhos/cm of sat. extract</th>
<th>Exchangeable Na, meq/100 g</th>
<th>ESP (^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-(\frac{1}{2})</td>
<td>1.5</td>
<td>1.64</td>
<td>7.9</td>
</tr>
<tr>
<td>(\frac{1}{2}-5)</td>
<td>1.5</td>
<td>2.83</td>
<td>11.2</td>
</tr>
<tr>
<td>5-9</td>
<td>2.6</td>
<td>7.52</td>
<td>20.8</td>
</tr>
<tr>
<td>9-14</td>
<td>4.2</td>
<td>9.12</td>
<td>25.5</td>
</tr>
<tr>
<td>14-20</td>
<td>5.7</td>
<td>8.29</td>
<td>26.9</td>
</tr>
<tr>
<td>20-28</td>
<td>4.5</td>
<td>8.50</td>
<td>29.0</td>
</tr>
</tbody>
</table>

\(^a\)From Schafer (1952).

\(^b\)Exchangeable sodium percentage.

An associated Luton profile had essentially nil amounts of sodium. No theories were given as to the origin of the salts.
Eastern Nebraska

The central and western parts of Nebraska have a dry enough climate that salt-affected soils are not too unusual. Eastern Nebraska however has enough rainfall that salt-affected soils are somewhat uncommon. The study of Lewis and Drew (1973) is the only one known that discusses such soils in this area. They studied an area in Lancaster Co., Nebraska. No climatic data were given. The topography of the area is maturely dissected uplands. A mantle of Peorian loess (Wisconsinian) thins progressively down the flanks of the interfluves gradually exposing the underlying reddish-brown Illinoian sediments and Kansan till. The landscape is similar to that of southwestern Iowa. The present author believes the term "reddish-brown Illinoian sediments" is a late-Sangamon paleosol. The authors speak of good structure in the sediments. Slick spots (high sodium soils) are found in two places on the landscape. The first is on sideslopes about 20-30 m below the crests of divides where the mantle of loess is 1-2 m thick over the slowly permeable Kansan till or Illinoian sediments. After periods of abundant rainfall, sideslope seepage is apparent due to the lateral subsurface flow of water from higher elevations. Slick spots develop in these seep areas.

Yet the paper was not concerned with those soils since their genesis appears evident. The second location of slick spots is at relatively high elevations, often only a few meters below the crest of the drainage divides. The Peorian loess is 2-5 m thick and seepage is not apparent after wet periods. Little water can come from upslope. The Sharpsburg series (Typic Argiudoll) and Wymore series (Aquic Arguidoll) are the soils
formed in the loess. The slick spots occur as circular areas 3-25 m in
diameter and are often located approximately along contour lines on the
landscape. The slick spots are slowly permeable, sticky when moist, and
hard when dry. Crop growth is poor. Farm machinery cannot be used in
these areas during wet periods. A slick spot profile had a maximum of
12.0 meq/100 g exchangeable Na along with abundant carbonate concretions.
An adjacent Sharpsburg profile had a maximum of 0.7 meq/100 g exchange-
able Na and carbonates were not present. The genesis of the slick spots
is believed to be related to the morphology of the material below the
loess and to climatic conditions. Borings indicated that concave, bench-
like depressions developed in the Kansan till or Illinoian sediments due
to erosional processes. The bench on the hillslope was first cut, then
covered by loess. During periods of high rainfall, a perched ephemeral
water table develops in the bench depression on the underlying till sur-
face. Capillary rise of ground water from the reservoir beneath the
slick spot contributes an accumulation of soluble salts in the soil pro-
file during periods of intense evapotranspiration. The Ca and Na weath-
ering products were released from minerals initially present in the
loess. It is believed the accumulation of soluble salts may be somewhat
of a relict feature from a past time of higher rainfall.

The current author wonders if such accumulations of salt might be
found in the same two landscape positions in southwestern Iowa. Data re-
ported by the Soil Survey Staff (1966) for two profiles each of the Adair
and Clarinda series showed all exchangeable Na values were \( \leq 0.4 \text{ meq/}
100 \text{ g} \).
Carbonate-Affected Soils

The carbonate minerals, specifically calcite and dolomite, are often present in gypsum-containing soils. They are commonly present in parent materials and may concentrate in soils due to the processes of salt accumulation discussed earlier. In the regions covered by late-Wisconsin glaciation, carbonates often accumulate around the edges of closed depressions due to water evaporation. The current author is especially interested in comparing the calcite/dolomite ratios of carbonate-enriched soils with the ratio of the unaltered parent material. Hopefully, the processes of carbonate accumulation (as well as other salts) can be better understood.

Calcite and dolomite are minerals that were deposited by ancient seas. Again, an introductory geochemistry text should be consulted for their original genesis. Donner and Lynn (1977) give a good overall discussion of the formation reactions and redistribution processes of both minerals in soils. Calcite and dolomite are extensive deposits the world over. The deposits have been slightly incorporated into surficial materials by the actions of wind, water, and glaciation. The solubilities of the minerals given in Table 1 show that calcite is more soluble in water than dolomite. By extension of this fact, calcite should dissolve more quickly and be more mobile in soils than dolomite. These assumptions have been borne out by research. Agronomic researchers, primarily in the first half of the twentieth century, repeatedly investigated the efficiency of liming materials for noncalcareous soils. Almost without exception, calcite was found to dissolve quicker than dolomite. Although
many studies have been done on this topic, only two will be cited here
(MacIntire and Shaw, 1925; Bear and Allen, 1932).

Literature pertaining to soils with carbonates will be briefly re-
viewed. Only studies done in areas of late-Wisconsin glaciation are in-
cluded here, due to their pertinence to the current study.

Redmond and McClelland (1959) investigated the genesis and morphol-
ogy of calcium carbonate Solonchak soils of eastern North Dakota. The
geology and climatic information on the region has been given previously
when discussing the paper of McClelland et al. (1959). The region was
covered by late-Wisconsin glaciation, and closed depressions are the com-
mon topographic feature. The carbonate-enriched soils occur in low re-
lief areas with inadequate surface drainage. They are usually on < 1%
slopes surrounding depressions or in the depressions themselves. They
are sometimes on slight rises on the landscape with less than 2 ft dif-
ference in elevation. A seasonally-high or permanently-high water table
exists, usually at depths of < 5 ft. The water table may be perched by
either a frozen soil layer 3-4 ft down that persists well into June or
by slowly permeable, fine-textured parent materials. The solum is more
permeable. Capillary rise of water brings carbonates and other salts up.
Evapotranspiration then leaves the salts at the soil surface. The same
process also occurs near the edges of ponds. Laboratory analysis showed
the most accumulation of carbonates near the surface, up to 35% CaCO₃
equivalent in some. The authors say the calcareous areas are becoming
larger and more calcareous. The growth of shallow-rooted crops such as
small grains tends to accumulate salts near the soil surface. The authors
also gave a method of estimating the theoretical rise in elevation of a soil due to carbonate accumulation:

\[
\frac{(a - b)}{100} \times C = \text{inches increase in elevation} \quad \text{(Eq. 9)}
\]

where:  
- \(a\) = weighted average carbonate percentage of a calcareous soil profile, to a depth of \(C\) inches,
- \(b\) = weighted average carbonate percentage of an adjacent soil profile, to a depth of \(C\) inches, and
- \(c\) = depth of profile considered, inches.

An example was given of a calcareous soil of 18.7% and an adjacent soil of 13.2% CaCO\(_3\) equivalent, both to a depth of 60 in.

\[
\frac{18.7 - 13.2}{100} \times 60 = 3.3 \text{ inches increase in elevation}
\]

The current author believes that if great differences in bulk density between the two soils exist, then the final answer should be multiplied by the factor:

\[
\frac{\text{bulk density of adjacent soil}}{\text{bulk density of calcareous soil}}
\]

The equation principle can be used for accumulations of salts of any kind, not just carbonates.

Sherman et al. (1962) studied the dolomitization of soils in the Red River valley of Minnesota. They studied soils in four counties in western Minnesota evidently as they were being mapped. Highly dolomitized soils were identified. More than 8,000 drillings were examined and several hundred samples were analyzed. It was found that the formation of large amounts of dolomite in soils was due to ground water high in Mg.

The area has many springs and artesian wells. The most dolomitized
soils were on slopes of minor depressions, indicating an upward movement of salts with evaporating water. Gypsum is present in some soils; MgSO₄ is very prevalent in some also. X-ray diffraction and differential thermal analysis gave no indication of the existence of magnesite (MgCO₃). Evidently dolomite is the only Mg containing carbonate mineral. Many soils had dolomite as ≥ 90% of the total carbonates. One soil reached 100%. The secondary origin of the dolomite is supported by the fact dolomitized areas cut across sedimentary bedding planes of different types of materials which are not dolomitized elsewhere. The conversion to dolomite must have occurred after deposition of the sediments.

Alway and Zetterberg (1935) studied the relative amounts of Ca and Mg carbonates in some Minnesota soils. The soils studied were scattered throughout the Des Moines lobe of the late-Wisconsin drift. None were from the bed of glacial Lake Agassiz. As a whole, the soils formed in the mentioned drift usually have all carbonates leached to a depth of 2-4 ft. Below, the CaCO₃ equivalent normally is 6-30% of the < 2 mm fraction. The authors collected 25 "composite" or "mixed together" samples of subsoil to analyze for calcite and dolomite. Most samples represented the uppermost section of the profile that effervesced with dilute HCl. Five of the sites had a lower horizon sampled as well. Of the 25 samples, 21 were from soils developed on till plains or clayey moraines. Of these 21, 19 were from the late-Wisconsin drift area; two were from the former Iowan drift area. Of these 21 samples, all were composites made of a number of individual sampling sites mixed into one "composite" sample. Nine samples were composites of 15 sampling sites: five sites about 10
yards apart in each of three fields a mile or more apart. Two samples were composites of five sampling sites in a single field. Ten samples were composites of ten sampling sites in a single field. The above accounts for 21 of the 25 composite samples. The final four samples were each from a single boring on a sandy outwash plain derived from late-Wisconsin drift. The samples were analyzed as follows: The < 2 mm portion was taken and then ground to pass a 100-mesh sieve. Five to ten grams of soil were dissolved in dilute HCl overnight. The mixture was treated with hot dilute HCl the next day. The authors were sure all carbonates had been dissolved. Calcium and magnesium were then determined on the extracts.

The results were expressed in terms of the mole ratio of CaCO$_3$/MgCO$_3$. The range of the 25 samples was 1.51 to 4.80, with a mean of 2.84. This mean value corresponds to a calcite/dolomite ratio on a weight basis of 1.00. In other words, there was an average of equal weights of calcite and dolomite in the samples. The study is not too useful from a soil genesis point of view. The authors were interested in the carbonate content of subsoils from an agronomic viewpoint. Hence, they chose soil profiles that were noncalcareous on the surface but with carbonate enrichment in the B and C horizons. They did not collect unweathered till samples for a comparison between parent materials and soils. No sampling of a profile was done on a horizon basis to show variations of calcite and dolomite with depth. Instead, many sampling sites were mixed into one composite sample. The authors did cite references which stated that the source of carbonates in the late-Wisconsin drift was the
limestone rocks of western Manitoba. Part of the carbonates was acquired from the limestone itself. Part was acquired from earlier drifts which had acquired their carbonates directly from the limestone. The carbonate composition of 31 limestones in Manitoba were given, and the values ranged from almost pure dolomite to almost pure calcite. Such data are interesting but are of little value. What is needed are the contents of the unweathered late-Wisconsin till in place. The carbonates influenced by soil development processes would not accurately reflect the contents of the original till. The calcite/dolomite ratios would be altered.

There are few if any works that have studied the carbonate composition of the late-Wisconsin till matrix (<2 mm) in Iowa. Works cited earlier under the section "Salt-Affected Soils of the Upper Midwest" have discussed to some degree the calcareous soils of Iowa. These works were from an agronomic point of view, and any morphologic or genetic concerns were secondary. Mendenhall (1967) studied what is now called the Harps series, a calcareous soil formed in the Des Moines lobe of late-Wisconsin glaciation. It is classified as a Typic Calciaquoll and was formed around the edges of closed depressions. Mendenhall (1967) did not differentiate the carbonate types; all values were reported as CaCO₃ equivalent. He does have four conclusions that are noteworthy: A. The highest CaCO₃ equivalent concentration was in the 0-35-inch zone. B. Below 35 inches, there was little variation in carbonate content. C. The highest concentration of carbonates occurred on slightly elevated rims of depressions. Soils at both higher and lower elevations had lower carbonate amounts in the 0-35-inch zone. D. Water movement evidently has influenced the
concentrating of carbonates.

Wenner et al. (1961) studied soils and parent materials of calcareous glacial till in Ohio. The area studied was covered by late-Wisconsin glaciation about 14,000-17,000 rcybp. The topography is nearly level to undulating. The calcareous till is loam, silt loam, or clay loam in texture with a CaCO$_3$ equivalent of 10-50%. Samples of the parent materials were collected at several depths below the point of initial effervescence in the soil profile. In all, 42 sites were studied, 10 well-drained, 17 moderately well-drained, and 15 imperfectly drained profiles. All soils had carbonates leached from their surfaces to a depth of 16-48 inches. Soils calcareous to the surface were not included. The results show that the CaCO$_3$ equivalent was lowest at the point of initial effervescence and increased with depth. Sometimes the values then decreased slightly, perhaps indicating a zone of carbonate accumulation. The results are as expected if the carbonates have been leached from the surface to lower depths. The mole ratios of Ca/Mg were calculated from extracts of soils in IN HCl. No laboratory procedure was given. Evidence showed greater Ca movement from the upper calcareous horizons, i.e., the Ca/Mg mole ratio increased with depth. This indicates Ca is more mobile than Mg in these parent materials. The authors concluded that about the first 30 inches of calcareous parent material under soil sola are altered in some way.

Steiger and Holowaychuk (1971) studied glacial till and lacustrine deposits in Ohio. They characterized nine parent material areas of western Ohio as to particle size, CaCO$_3$ equivalent content, and Ca/Mg mole ratios. Samples were collected from deep within the soil profile so as
to characterize the material from which at least part of the solum was derived. Since Wenner et al. (1961) had shown the upper 30 inches of calcareous material was somewhat altered, only samples > 20 inches below the depth of initial effervescence were studied. Sites in tills evidencing any stratification were also omitted. A total of 180 sites were examined. Laboratory analyses were run on the < 2 mm portion. Calcite and dolomite were determined by the method of Dreimanis (1962) after the < 2 mm portion was ground to < 200 mesh. Actual calcite and dolomite percentages were not reported as such but were: (a) lumped into total CaCO$_3$ equivalent values and (b) converted to Ca/Mg mole ratios. Wide ranges of particle size, CaCO$_3$ equivalent content, and Ca/Mg mole ratios were found. The nine parent material areas were characterized and compared in a very informative way. The general conclusion was that the glacial drift had appreciably higher Ca/Mg mole ratios than the underlying bedrock which is predominantly dolomite. It was previously thought that a large portion of the glacial drift had its origin only a few miles from the site of deposition. Yet this study showed that much of the drift came from nondolomitic areas to the north and northeast. Evidently in western Ohio, the till materials were transported a considerable distance before deposition.
LABORATORY METHODS

Soil Samples

Introduction

Soil cores about 1-3/4 inches in diameter were taken at the sampling sites with a hydraulic probe truck. The cores were wrapped in freezer paper and stored frozen for several months. The cores were then thawed, described, and sampled. Soil samples were air dried and placed in polyethylene-lined paper bags. All samples were hand ground to pass a 2mm sieve. Both an iron and a ceramic mortar and pestle were used in the grinding. Great care was taken to avoid grinding gravel, carbonate, or gypsum particles that were > 2mm. The samples were then stored in the air-dry condition until analyzed.

It is a common practice to determine the moisture content of air-dried samples by determining their weight loss upon drying at 105° C. The purpose of this is to be able to correct for the air-dried moisture content when expressing final results on an oven-dried weight basis. For gypsiferous soils, this procedure should not be done. Drying at 105° C drives off some if not all of the two crystal water molecules of the gypsum mineral. A nonvalid weight loss would result that would not truly represent the soil on a moisture-free basis. Instead, samples should be dried over a desiccant at room temperature until a constant weight is reached. No crystal water loss occurs. Nelson et al. (1978) found that samples of nongypsiferous soils and Volclay (montmorillonite) lost essentially the same amount of water when dried over silica gel (SiO₂) for
48 hours or heated at 105°C for 24 hours. It would have been very impractical to have dried all of the current study's samples in desiccators considering the time and desiccator space needed. Instead, six samples chosen to represent the range of particle sizes were dried to determine an average water content for the whole set. Several grams of each of the six samples were placed in a tared aluminum weighing pan (60 mm diameter, 15 mm depth) and dried in a silica gel containing desiccator until a constant weight was reached. The average moisture percentage of the six samples was determined to be 3.2%. Corrections for this amount of water in the air-dried samples were done in weighing out samples for subsequent analyses. To get the equivalent of 10.00 g soil on an oven-dried basis, 10.32 g of air-dried soil were weighed out.

Soils containing soluble salts require a slightly different approach in analysis than nonsalt-affected soils. Special problems are encountered. Because of this, the following laboratory methods may go into detail a little more than is common for most theses. Some procedures were modified by the author. The justification, development, and explanation of the procedures are given in the following sections.

**Particle size**

The percentage of > 2 mm gravel was determined by weighing the portion of the sample not passing a 2 mm sieve. Results are reported on a weight percentage basis.

**Normal (no treatment) method**  Three different procedures were used for determining the percentages of sand, silt, and clay. The first procedure described is the one normally used by the Iowa Soil Survey.
Laboratory. It was used for the analysis of some nongypsiferous geological samples. The other two methods are variations of this original procedure. The procedure is essentially that of Kilmer and Alexander (1949) with settling times taken from Tanner and Jackson (1947). Slight modifications have been made in the procedure. The detailed procedure as it was used in the current study is given by Walter et al. (1978). The steps of the procedure will not be repeated. Only a few comments will be given here that are not included by Walter et al. (1978). First, it is desirable to add only 50 ml of distilled water to the baby bottle before the addition of hydrogen peroxide. Second, 2 oz glass bottles can be used instead of 50 ml beakers for drying the particle-size fractions. The bottles do take longer to dry in the 105°C oven. They should be dried beyond visual dryness for at least two hours in an oven holding no water-containing samples. The bottles can be used seven to eight times without washing and retaring if the gross weight from one analysis is used for the tare weight of the next. Care should be taken not to have any particles fall into or out of the bottles between runs. The bottles should be washed after seven to eight runs.

The Calgon dispersing agent is of major importance in the particle-size analysis of soils. A more indepth discussion of it will ensue because its qualities largely influence the need of the other two modified particle-size analysis procedures. The use of sodium metaphosphate \((\text{NaPO}_3)\) for the dispersion of soils was first investigated by Tyner (1940). It was thought at that time that the compound was polymerized as \((\text{NaPO}_3)_6\), and hence was called sodium hexametaphosphate. Later work has
shown that the exact polymerization of the substance is erratic; therefore it is best to designate the substance as \((\text{NaPO}_3)^n\).

Originally, \(\text{NaPO}_3\) was made in individual labs. A pure solution of \(\text{NaPO}_3\) is slightly acidic. Tyner (1940) reports that under acidic conditions, sodium metaphosphate gradually converts to sodium orthophosphate \((\text{NaPO}_3 \rightarrow \text{Na}_3\text{PO}_4)\). The \(\text{Na}_3\text{PO}_4\) molecule is not as good a dispersant as \(\text{NaPO}_3\). It was found that a \(\text{NaPO}_3\) solution at pH 8-9 did not convert to \(\text{Na}_3\text{PO}_4\). The early users of \(\text{NaPO}_3\) added enough sodium carbonate \((\text{Na}_2\text{CO}_3)\) to bring the pH up to that level. Kilmer and Alexander (1949) recommended a solution of 36 g \(\text{NaPO}_3\) and 8 g \(\text{Na}_2\text{CO}_3\) per liter. The commercial product Calgon is \(\text{NaPO}_3\) buffered with a slight amount of \(\text{Na}_2\text{CO}_3\). It has long been used as a dispersant for soils. However, recent changes in the formula of Calgon have caused concern among some (Yaalon, 1976). The noncommercial Calgon also began to contain perfumes and coloring agents which made it unacceptable for laboratory use. Information received from the Calgon Corporation indicated that the note of Yaalon (1976) was not completely correct (Dorothy O'Conner, Calgon Corp., St. Louis, Mo., Personal communication, 1976). There are different Calgon formulas for different parts of the nation, probably depending upon water quality standards. Commercial-grade Calgon that had an analysis of about 90% \(\text{NaPO}_3\) and the other 10% composed of \(\text{Na}_2\text{CO}_3\) and \(\text{NaHCO}_3\) was purchased by the Iowa Soil Survey Laboratory.

The dispersive action of the Na ion is well-known. Most sodium salts will disperse soils to some degree. Yet the advantage of \(\text{NaPO}_3\) over other sodium-containing agents is the \(\text{PO}_3\) ion. The \(\text{PO}_3\) ion sequesters or
complexes divalent cations by forming soluble but highly undissociated calcium or magnesium metaphosphate. This process effectively removes the flocculation-promoting Ca ions from competing with Na on the exchange complex. In essence, two processes take place. Divalent cations are removed from activity as the highly hydrated Na becomes the dominant adsorbed cation. Sodium metaphosphate is noticeably more effective in promoting dispersion in calcareous soils than other Na compounds. When Tyner (1940) tested the use of NaPO₃, he did not use soils with a combination of high organic matter and high CaCO₃ contents. The soil with the highest amount of organic matter that was calcareous was a Houston black clay from Texas. Although no data were given, it is doubtful that the organic matter content was over 2-3%. Soils containing large amounts of both organic matter and CaCO₃ present special problems. The large amount of exchange sites for saturation with Na plus the large amounts of Ca often uses up the amount of added NaPO₃ solution as recommended by Tyner (1940), Day (1965), and Kilmer and Alexander (1949). Flocculation results and clay values are erroneous. The sample must then be rerun using an extra amount of NaPO₃. In his work at the Iowa Soil Survey Laboratory, the current author encountered this problem often. It seemed to be the worst in high-organic matter soils containing soft disseminated lime.

Since unnecessary time was being spent rerunning samples, the author decided it best to make the Calgon solution about 1.5 times as concentrated as that of Kilmer and Alexander (1949). The problem was solved efficiently. The Calgon solution used in all procedures mentioned in this thesis was made of 54 g commercial-grade Calgon plus 12 g Na₂CO₃.
per liter, dissolved in water. The added Na$_2$CO$_3$ is still necessary even at this concentration. A solution of 54 g Calgon/liter yields a pH of about 7.3. With the added Na$_2$CO$_3$, the pH is about 9.8. After five months, the pH is about 9.5.

**Hydrochloric acid treatment method**  The problem of dispersing gypsiferous soils becomes clearer. The water-soluble CaSO$_4$ dissociates into Ca and SO$_4$ ions. The large reserve of gypsum continues to supply Ca ions until all of the PO$_3$ ions are exhausted in forming calcium metaphosphate. The excess Ca ions in solution then inhibit any effective dispersion by the Na. Accurate particle-size analysis becomes impossible. Great amounts of added Calgon are ineffective because of the large reserve of gypsum. Also as more Calgon is added, more gypsum dissolves. The dissolved salts promote heavier weights of silt and clay aliquots. The results would be erroneous even if eventual dispersion could be accomplished.

A solution to the problem is to remove or render ineffective the gypsum. Tyner (1940) could not disperse a sample containing 3.3% CaSO$_4$ even with an added amount of NaPO$_3$ calculated to be equal the number of equivalents of the CaSO$_4$. He concluded that removal of gypsum by leaching or decantation before dispersion was the only possible way to analyze gypsiferous soils. Kilmer and Alexander (1949) reported that five washings of 150 ml of water are usually sufficient to remove the soluble salts in soils except those containing much coarse gypsum.

Some of the author's samples contained as much as 60% gypsum. It was concluded it was not pragmatically possible to dissolve the gypsum.
with water prior to dispersion. About 2.5 g/liter of gypsum dissolves at saturation. Assuming a 150 ml wash using a filter candle system, it would take about 16 washings of a 10 g soil sample to remove the gypsum. To reach saturation, a gypsum solution must be agitated for several hours. With only two filter candles available, the time involved was considered prohibitive. The author then investigated the solubility of gypsum in other solvents. Reference books indicated the maximum solubility was in dilute HCl. The data in Table 11 were calculated from Linke (1958).

Table 11. Solubility of gypsum in dilute HCl

<table>
<thead>
<tr>
<th>N HCl</th>
<th>Grams CaSO$_4$ • 2H$_2$O/liter solution at 25° C</th>
</tr>
</thead>
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<tr>
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<tr>
<td>0.3</td>
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<tr>
<td>1.6</td>
<td>20.9</td>
</tr>
<tr>
<td>1.2</td>
<td>22.0</td>
</tr>
</tbody>
</table>

*aCalculated from Linke (1958).

Experiments were run to see if the theoretical values held true and how long dissolution took. Gypsum crystals 0.5-2 mm in size were used in all experiments to ensure tests for dissolution time were adequate. Another problem encountered was the dissolution of calcite and dolomite by the HCl. Some of the HCl would be converted to CaCl$_2$. There would be less HCl left to dissolve gypsum. The CaCl$_2$ would also suppress the
dissolution of gypsum due to the common ion effect. A final procedure was developed as follows:

Weigh out 5 or 10 g of air-dried soil depending upon gypsum content into an 8 oz baby bottle. Add about 50 ml of 3N HCl and let stand for 30 minutes. Fill the baby bottle with a jet of distilled water. Decant the supernatant. Add 100 or 200 ml of 0.8 N HCl, again depending upon gypsum content. Stopper and shake for one hour on a reciprocating shaker. Decant the solution. Wash and decant a total of three times using 200 ml of water each time. Add 10 ml of Calgon solution and determine particle sizes as usual. The only other modification would be that the < 50µ coarse silt fraction must be pipetted. It cannot be determined by difference since much of the original whole soil has been dissolved.

The < 50µ coarse silt aliquot must be taken before the < 20µ and < 2µ aliquots. That is, it would not be accurate to stir the sample, take aliquots of the < 20µ and < 2µ size particles at the specified settling times, then restir the sample and pipette the < 50µ aliquot. Assuming a 25 ml pipette was used, this final distribution of < 50µ particles would be in a 950 ml volume, not the original 1000 ml volume since two 25 ml aliquots have already been taken. Also part of the < 20µ and < 2µ fractions which make up part of the total < 50µ fraction have been removed. The proper procedure would be to stir the sample and pipette the < 50µ, < 20µ, and < 2µ aliquots in that order.

The method developed by the author was later found to be similar to an Australian one by Piper (1942). That method also removed gypsum prior to particle-size analysis. After treatment in the usual way with
hydrogen peroxide ($H_2O_2$), the soil is transferred to a shaking cylinder and diluted to a volume of 650 ml with water. Next, 115 ml of 2N HCl are added. (This would calculate to be 0.3N HCl assuming no carbonates are present.) If the soil contains more than 10% CaCO$_3$, add an extra 2.5 ml of HCl for each percent present. Allow the carbon dioxide (CO$_2$) to escape, stopper, and shake for 8-16 hours. Filter the soil through a Buchner funnel using Whatman No. 50 filter paper. Wash the soil with six portions of 50 ml of 0.2N HCl, then with $H_2O$ until the filtrate is nearly neutral to litmus paper.

Even earlier, the International Society of Soil Science (1930) adopted a procedure that treated soils with $H_2O_2$, then with enough 1N HCl to leave 250 ml of 0.2N HCl. The soil was then stirred frequently for one hour and filtered through filter paper until the acid was removed. If soils contained $> 5\%$ CaCO$_3$, it was recommended to wash the soil once or twice with 0.2N HCl before the water wash. Robinson (1934) reported that the International procedure did not remove all gypsum in some soils, resulting in poor dispersion. He recommended that coarse gypsum be removed before the acid treatment by using 0.5N HCl and washing with ammonium acetate (NH$_4$OAc).

The treatment of soils with HCl was a standard method of removal of organic matter before the use of $H_2O_2$ was introduced. An advantage then is the omission of the $H_2O_2$ treatment for most soils. HCl is somewhat effective in removing organic matter bonding of soils. Winters and Harland (1930) treated soils by two methods: (1) 15-25% $H_2O_2$ followed by 0.1N HCl, or (2) 0.1N HCl alone. They found no difference in the
amount of < 2μ clay determined on several Illinois soils. The A1 horizons used were from the Putnam, Princeton, and Edina series. Although no organic matter contents were given, the series would probably contain appreciable amounts. Robinson (1934) stated that the International Society of Soil Science (1930) method using 0.2N HCl required H₂O₂ treatment only on soils containing > 1% organic carbon. In the current study, several soils high in organic matter content were analyzed by two methods: (1) digestion with H₂O₂ as in the regular particle size procedure, then HCl treatments as prescribed, or (2) the HCl treatments only. An increase in clay content was found when the H₂O₂ treatment was used only on soils containing more than about 4% organic carbon (6.9% organic matter). Evidently for soils containing < 4% organic carbon, the prescribed acid treatments destroy the organic matter bonding well. When particle size data are presented in later sections, those samples digested with H₂O₂ are identified. It was found that the H₂O₂ digestion medium should be pure water, not HCl. If HCl is added to the soils before the addition of H₂O₂ and boiling, much lower clay percentages result.

There are several serious disadvantages however to the treatment of soils with HCl. Iron, aluminum, and silica can be dissolved. Some clay particles may be destroyed. The author tested the method to assess its effects upon clay percentages. Noncalcareous soils containing no organic matter and formed in Wisconsin-age loess or glacial till were used. Filter candles were used for removing washes. The resultant clay percentages were very slightly lower than those determined without HCl treatment. Yet the differences in values were not statistically valid
considering the coefficient of variation of the methods used.

The HCl is a salt and must be completely removed before final dispersion. This washing process is time consuming. The use of filter candles was mentioned earlier. They are very slow to use unless one has a rack of many set up. The author also tried using a Buchner funnel with Whatman No. 42 filter paper as described by Franzmeier et al. (1977) for leaching. It proved to be even more inconvenient than filter candles.

The greatest disadvantage is probably the severe alteration of particle-size classes by the HCl in soils containing carbonates and/or gypsum. The distribution of sizes reported by the analysis is markedly different from the actual distribution of the soil as it exists in the field. Calcite and dolomite are dissolved. Much of the carbonates often exists as sand-sized particles (0.05-2 mm). If the carbonate particles are removed, the resultant values do not adequately reflect the textural properties of the soil. This problem is adequately discussed in papers cited by Kilmer and Alexander (1949). This same problem exists for soils containing gypsum. If a soil contains 60% gypsum, the particle-size distribution of the remaining 40% does not reflect the soil as it exists in the field. The author was well-aware of these problems when the analyses were done. The situation was one of either no particle-size data or particle-size data on the carbonate-free, gypsum-free fraction. It was decided that the latter alternative would be preferable.

Coupled with the problem of the dissolution of a major portion of the soil matrix is the problem of expressing the percentages of the remaining portion. The traditionally-accepted method is to report the
particle-size percentages on the basis of an oven dry, organic matter-
free, soluble salt-free weight. A soil sample is first digested with H₂O₂
to remove organic matter and then washed to remove soluble salts. The
remaining mineral portion is then oven dried. The fractions of sand,
silt, and clay are then reported as percentages of this remaining mineral
portion. United States methods use this procedure (Kilmer and Alexander,
1949; Day, 1965; Soil Survey Staff, 1972). It is interesting that only
one property of a soil, its particle-size fractionation, is reported on
this basis. Virtually all other properties are reported on the basis of
the whole soil. For example, common properties such as cation exchange
capacity, exchangeable ions, plant-available nutrients, and carbon con-
tents are almost always reported on the basis of the whole soil. Yet it
is interesting to note that the particle-size method adopted by the Inter-
national Society of Soil Science (1930) specifically stated, "all results
should be expressed as percentage of the fine earth (< 2mm) dried at 100-
110° C."

The author was interested as to how the United States convention of
expressing particle-size percentages was developed. He did not investi-
gate all early papers on the method. Communication with the USDA-Nation-
al Soil Survey Laboratory in Lincoln, Nebraska indicated simply that
particle-size results are expressed as they are due to time honored tra-
dition. It would seem to the author that two possible reasons may have
existed for originally reporting the values on an organic matter-free,
soluble salt-free basis. For soils containing hydrated salts such as
CaSO₄ · 2H₂O or MgSO₄ · 7H₂O, the drying of the soil at 105° C to report
on a whole soil basis would remove some of the crystal water. Also, by
determining the weight of particle sizes on just the organic matter-free,
soluble salt-free portion of the soil, one less determination needs to be
made. One size fraction can be determined by difference. Since the soil
had to be prepared in this manner and its subsequent oven-dried weight
determined as well, it probably became the practice to report the values
as percentages of this prepared sample.

The current author believes it is much better to report particle-
size fractions on the basis of the whole soil as it exists in the field.
Otherwise, values that appear misrepresentative often result. For exam-
ple, consider a soil containing 60% gypsum plus carbonates and 20% clay.
If the clay fraction were expressed on the basis of the remaining 40%
after the gypsum and carbonates were removed, it would be 50% clay. It
seems better to report the clay as 20% rather than 50%. Another example
of a similar situation is found on pages 562-563, Pedon 39, of *Soil Taxon-
omy* (Soil Survey Staff, 1975). Note that the 56-84 cm horizon contains
10% CaCO₃ equivalent and 68% gypsum. The clay fraction expressed as a
percentage of the nongypsiferous, noncarbonatic portion of the soil is
49.8%. The current author calculates the clay fraction would be 11.0%
if expressed on the basis of the whole soil. All particle-size data re-
ported in this thesis are on the basis of the whole soil.

**Barium chloride treatment method** The particle-size procedure
using HCl treatment has not been explained in great detail. The various
intricacies in developing laboratory methodology have not been discussed,
and for a reason. A much better method has since been discovered for
determining particle sizes of gypsiferous soils. The method is given by Hesse (1976) and does not involve dissolving the gypsum before analysis. The particle-size distribution including the gypsum crystals can be determined. It would give far more representative results. It is regrettable that the method was not discovered prior to the author's laboratory work. It was reported in a Netherlands journal, *Plant and Soil*. At the time of the author's work, the USDA-National Soil Survey Laboratory did not know of the method either.

The method proposed by Hesse (1976) is very ingenious. The soil is treated with a solution of barium chloride (BaCl₂). A coating or veneer of highly-insoluble barium sulfate (BaSO₄) forms around the gypsum particles. The gypsum is then rendered inactive, and the soil colloids can be dispersed with NaPO₃. A fairly accurate particle-size distribution of the whole soil can thus be determined. A few notes on the procedure given by Hesse should be mentioned. The BaSO₄ coating on the gypsum is somewhat unstable under acid conditions. A pure solution of BaCl₂ is slightly acidic, therefore the BaCl₂ solution is prepared with some triethanolamine (TEA) added to raise the pH. The BaSO₄ coating is also attacked gradually by the NaPO₃ dispersant solution. Hesse recommends that the NaPO₃ solution be in contact with the treated soil for 30 minutes. The soil is then poured into a malted milk mixer and stirred for two minutes. The soil is immediately sieved through a 0.05 mm sieve into a one-liter cylinder. Silt and clay are determined either by the regular hydrometer or pipette methods.

The present author did some limited work with this new method. A
fellow graduate student, Mr. Andrew Manu, desired to do some X-ray analysis on the clay fraction of some gypsiferous soils. The author worked with him in doing particle-size analysis by this method on some of the author's soil samples. Several modifications had to be made in the procedure. First, it was found that allowing the BaCl$_2$ treated soil to stand in contact with the dispersant solution for 30 minutes was too long. The NaPO$_3$ dissolved enough of the BaSO$_4$ veneer that CaSO$_4$ dissolved into the solution. No dispersion was effected. This happening occurred whether the NaPO$_3$ solution was made according to the concentration of Hesse or to the concentration of the Iowa Soil Survey Laboratory. It was found that no waiting time was best. Second, it was found that a larger amount of dispersant solution must be added than recommended by Hesse. The author finally decided upon 20 ml of solution prepared to the specifications of the Iowa Soil Survey Laboratory. Third, instead of mixing two minutes in a malted milk mixer, shaking slowly overnight in 8 oz baby bottles was tried. Various amounts of dispersant solution were added, yet no dispersion was effected. Evidently the long period of contact between the NaPO$_3$ and the soil dissolves some of the BaSO$_4$ coatings. Fourth, the particle-size fractions cannot be dried at 105° C because of crystal water loss from the gypsum. Experiments showed that the highest temperature at which no weight loss occurred from gypsum was 60-65° C. This value agrees with results found by other workers (Nijensohn, 1960; and Lagerwerff et al., 1965). The drying time takes several days when 2 oz glass bottles are used. For faster drying, a container such as a porcelain evaporating dish might be used. Excess water can be decanted
from the sand fraction container before placing in the oven. Experiments were also done to see if there was a difference in clay percentages determined on a nongypsiferous soil from clay aliquots dried at 60-65° C and 105° C. No difference was found. Evidently the same amount of water was driven off at 60-65° C as at 105° C.

The recommended procedure is as follows:

**Reagents:**

Barium chloride solution, 0.82N: Dissolve 100 g of BaCl₂ · 2H₂O in about 800 ml of water. Add 20 ml of triethanolamine and dilute to one liter. (The pH should be > 9.)

Dispersant solution: Dissolve 54 g commercial-grade Calgon and 12 g Na₂CO₃ per liter.

**Procedure:**

Weigh 10 g of air-dried soil into a 50 ml Pyrex culture tube (25 mm diameter X 150 mm length). Add 20 ml of BaCl₂ solution. Stopper and shake gently on a reciprocating shaker for one hour. Remove the stopper, wash off the stopper into the tube, and also wash down the sides of the tube. Centrifuge briefly until the particles are settled to the bottom of the tube. Decant and discard the supernatant liquid. Add about 40 ml of distilled water to the tube, and stir with a rubber-tipped stirring rod. Wash off the rod with distilled water into the tube. Centrifuge and decant the supernatant. Repeat the washing twice more. Add exactly 20 ml of dispersant solution and immediately wash the soil into the mixer cup. Bring the volume of solution in the cup to about 150-200 ml with water. Mix for two minutes and immediately sieve off the sand-sized
particles. Dilute the silt and clay-sized particles to one liter. A
set of samples can each be brought to this point before proceeding with
stirring and aliquoting. Dry all particle-size fractions at 60-65°C.

Hesse (1976) worked with soils having negligible amounts of organic
matter. He correctly assumes that most gypsiferous soils in the world
would be low in organic matter content. In the upper Midwest however,
some gypsiferous soils do contain appreciable amounts. If the BaCl₂
method were to be universally useful, it would be advantageous to incor-
porate organic matter destruction as well. The current author experi-
mented with using H₂O₂ as an oxidant. It proved to be unsatisfactory due
to its effervescence when reacting with manganese. Acetic acid is ine-
effective in complexing the manganese when carbonates are present. Since
nearly all gypsiferous soils are also calcareous, the manganese-induced
problem could not be overcome. The author then tried a weak solution of
sodium hypochlorite (NaOCl) as an oxidant. This chemical is available
commercially as "Clorox" brand bleach, which contains 5.25% NaOCl and
94.75% inert ingredients. Its pH is about 11 which would not promote an
acidic environment to dissolve BaSO₄. It worked very satisfactorily as
an oxidizing agent. It is noneffervescent and is quite efficient in ac-
tion. It is a salt and must be removed by washing before determining
particle sizes. Since the excess BaCl₂ must be removed by washing as
well, no extra procedural step is necessary. The advantage of using
H₂O₂ for most soils is that the washing step is unnecessary since H₂O₂
decomposes and evaporates upon heating. Sodium hypochlorite is a recog-
nized oxidizing agent for use with soils (Anderson, 1963; and
Lavkulich and Wiens, 1970).

The recommended procedure for soils containing appreciable amounts of organic matter is as follows:

Weigh 10 g of air-dried soil into a 50 ml Pyrex culture tube. Add 20 ml of BaCl₂ solution and 10 ml of Clorox. Stir with a rubber-tipped stirring rod. Let stand until gas evolution subsides (usually 5-15 minutes). Stopper and shake one hour. The rest of the procedure is the same as for soils not containing organic matter.

One such treatment of Clorox appeared to be sufficient for most soils. If necessary, additional treatments can be performed. After the one-hour shaking period, the soils can be centrifuged and the supernatant decanted. Ten milliliters of BaCl₂ can be readded plus 10-30 ml of Clorox. The samples can be heated in a sand or water bath if desired. The soils should be stirred immediately before being heated because a mass of soil left in the bottom of the tube can be forced upward as a piston when pressure increases beneath it. One drop of octyl alcohol will suppress any foaming that may occur. An hour of boiling can replace an hour of shaking.

The BaCl₂ treatment method of determining particle-size fractions of gypsiferous soils was not fully investigated to the author's satisfaction. Other priorities took precedence. There are several potential problems with the method that should be mentioned. First, there is the potential for crystal growth as the Ba coats the gypsum particles. Hesse's work found that there was no significant change in particle sizes from the natural state. If the BaSO₄ coated soil is
heated for a long period of time in the destruction of organic matter, crystal growth might result. Second, it appears that the more dispersant solution that is added, the more clay percentage that results. This is taking into account the added weight of the extra dispersant in calculations. The processes at work are not clear. Either more true clay is being dispersed or a small amount of gypsum is being stripped of its BaSO₄ coating and left to dissolve. Third, the harsh action of the malted milk mixer has long been known to possibly shatter some soil particles into smaller ones. This would probably be the case for a soft mineral such as gypsum. Yet as has been shown, overnight mixing in a reciprocating shaker is not feasible. Fourth, the treatments of this method do not give different results for nongypsiferous soils than do the treatments used in the regular particle-size procedure. The author did a brief examination using the standard sample used in the Iowa Soil Survey Laboratory. It is a noncalcareous, nongypsiferous soil formed in Wisconsin-age loess. The combined treatments of the addition of BaCl₂, centrifugation and washing, addition of NaOCl, and the two-minute dispersion in the malted milk mixer gave no difference in sand, coarse silt, fine silt, or clay percentages when compared to values determined by the regular particle-size procedure.

The BaCl₂ treatment method has its limitations. Still it is the best (and only) procedure available for particle-size analysis of a whole gypsiferous soil. It should be viewed as giving results somewhat less accurate than the methods available for nongypsiferous soils. Possibly the results should be reported only to the nearest whole percent.
Table 12 shows data determined on 12 samples by both methods. Little comparisons can be drawn from the table due to the different constituents that are analyzed by the two methods. It does appear that relatively little of the gypsum plus carbonates were in the clay-size fraction.

**Calcite and dolomite**

**Chittick apparatus method** Calcite and dolomite contents were determined using the Chittick apparatus following the procedure of Dreimanis (1962) with slight modifications. The general principle of the procedure is that calcite and dolomite dissolve at different rates in dilute HCl. The volume of CO₂ evolved at two different times is measured. The percentages of calcite and dolomite are calculated from empirical graphs relating the volumes of CO₂ that are evolved from known amounts of calcite and dolomite.

The procedure is as follows. All letters in parentheses refer to items in Figure 1.

Weigh out an exact 1.70 g sample of the < 2 mm soil portion into the reaction flask (B). Place a stirring bar in the flask and fit the flask snugly onto the stopper assembly (H). A slight water film on the stopper enhances a snug fit. Open the leveling stopcock (F) to the atmosphere, and adjust the leveling bulb (D) until the level of the displacement solution is at 20 ml above the 0 ml mark in the measuring burette (E). Close the leveling stopcock and lower the leveling bulb 2-3 cm. The level of the displacement solution should fall slightly and then
<table>
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<tr>
<th>County</th>
<th>State</th>
<th>Site</th>
<th>Depth, inches</th>
<th>Treat.</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
<th>Clay % &lt; 2μ</th>
<th>Gypsum %</th>
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a All particle-size data were determined by only one analysis.

b Treatments:
A. BaCl₂ treatment method. All surface samples treated with NaOCl.
   No soil constituents removed. Percentages expressed on the basis of the whole soil.
B. HCl treatment method. All surface samples treated with H₂O₂. Gypsum and carbonates
   removed before analysis. Percentages expressed on the basis of the original whole
   soil.

c Slight amount of gypsum present in soil, but undetectable by method used.
stabilize. If it continues to fall, there are air leaks in the system.

Fill the pipette (C) with 6\text{N} \text{HCl}. Begin to add \text{HCl} from the pipette into the reaction flask. Start a timer capable of showing seconds. Turn on the magnetic stirrer (A). Dispense exactly 20 ml of \text{HCl} into the flask. During the time the acid is being dispensed into the reaction flask, the level of the displacement solution in the leveling bulb must be kept at least 2-3 cm below the level of the fluid in the measuring burette. This prevents CO\textsubscript{2} from being forced back into the pipette containing HCl. Shortly before 30 seconds of reaction time have elapsed, level the displacement solution in the leveling bulb and measuring burette. At 30 seconds of reaction time, read the level of displacement solution in the measuring burette. Record the temperature from the thermometer (G) that is inserted into the reaction flask. Also record the barometric pressure.

Periodically lower the leveling bulb as CO\textsubscript{2} evolves to keep the level of displacement solution at least 2-3 cm lower than the level in the measuring burette. When CO\textsubscript{2} ceases to be evolved, record the volume of CO\textsubscript{2}, temperature, and barometric pressure. For samples low in dolomite content, CO\textsubscript{2} ceases to be evolved by 20 minutes of reaction time. For samples high in dolomite content, reaction time often exceeds 20 minutes. As a general rule, the author has found that if the difference in CO\textsubscript{2} evolved between 30 seconds and 20 minutes is > 15 ml, the reaction should be allowed to go to 30 minutes.

According to Dreimanis (1962), all of the calcite and 2-5\% of the dolomite present are dissolved by the 30-second reaction time reading.
CHITTICK APPARATUS
A. Magnetic stirrer
B. Reaction flask
C. Pipette
D. Leveling bulb
E. Measuring burette
F. Leveling stopcock
G. Thermometer
H. Stopper assembly

Figure 1. Diagram of the Chittick apparatus
When CO$_2$ evolution stops, 5-7% of the dolomite is still unreacted. At least 6-24 hours are required to dissolve all of the dolomite. Dreimanis' Figure 5 graph automatically accounts for this 5% of unreacted dolomite. The graph is quite reliable since it represents 75 analyses. This graph should be used in calculating results since it is incorrect to assume all carbonates have dissolved after CO$_2$ evolution stops. In following the calculation steps of Dreimanis (1962), steps A-F, page 525, the 2-5% of dolomite that dissolves within the first 30 seconds is also taken into account.

The correction factor table from the manual of the Association of Official Agricultural Chemists (AOAC) (1950) is used to correct all CO$_2$ volumes to a volume at a standard temperature and pressure. The table is far more accurate than is necessary, considering the overall accuracy of the Chittick apparatus. The current author made a study of the derivation and development of the table and concluded that there were several erroneous assumptions made in applying the table to the Dreimanis (1962) carbonate procedure. These assumptions crept in over the years as the procedure was adapted. Contact the author for a further discussion of the problem, if interested. The errors are important only if there is concern about the system from a physical chemistry standpoint. They are not important if the table is used to calculate the percentages of calcite and dolomite using the Dreimanis (1962) procedure. The AOAC correction factor table should be used simply because Dreimanis used it in developing his Figure 5 graph. If the graph is used, the table must also be used.
The current author tried to develop an equation that would generate the factors of the AOAC (1950) table. An exact equation is not possible without having other tables for other variables. An approximation equation was developed however that calculates factors of sufficient accuracy for most conditions of temperature and pressure encountered at the Iowa Soil Survey Laboratory.

Table factor = \( \frac{\text{mm Hg} - 27.68}{273 + t} \)  

(0.41753)  

(Eq. 10)

where: \( \text{mm Hg} \) = barometric pressure in mm of mercury (Hg)  
\( t \) = temperature inside reaction flask in \( ^\circ \text{C} \).

The equation is centered on the values of 25\( ^\circ \text{C} \) and 760 mm Hg.

Dreimanis' Figure 5 graph is too small to be used conveniently. It should be redrawn and enlarged. Since calculators are now common, regression equations can be easily developed that represent the two lines of his Figure 5. The following equations were calculated by Dr. R. E. Nelson, USDA-National Soil Survey Laboratory, Lincoln, Ne. Do all steps per Dreimanis (1962), steps A-F, page 525, then:

\( \% \text{ calcite} = F(0.232) \)  

(Eq. 11)

\( \% \text{ dolomite} = E(0.223) + 0.3 \).  

(Eq. 12)

All values are calculated on a weight percentage basis. The correlation coefficient between values picked off the graph and those calculated by these regression equations is 0.99998. Equations make the calculations of results faster and may avoid errors in reading values from graphs and tables.

Surface horizons of soils high in organic matter content are sometimes analyzed. The HCl together with manganese dioxide (MnO\(_2\)) present
in the soil can react to oxidize organic matter and thus release CO$_2$. An easily oxidizable ion such as ferrous iron ($\text{Fe}^{++}$) present in the HCl will prevent such reactions (Allison and Moodie, 1965). The 6N HCl is routinely prepared containing 0.15 M $\text{Fe}^{++}$.

Soils high in organic matter and carbonate contents often froth excessively upon addition of the HCl. The frothing can produce slightly erroneous results because it keeps some carbonates from contact with the HCl during the first 30 seconds of reaction time. One or two drops of octyl alcohol added to the sample effectively prevents frothing (Bundy and Bremner, 1972).

The heat from the electric motor of the magnetic stirrer will produce a slight increase in the second reading for CO$_2$ volume because of thermal expansion. The surface of the magnetic stirrer should be well-insulated. Also several blanks should be run of just 20 ml HCl to determine how much expansion occurs after 20-30 minutes of stirring. Subtract this correction (usually 1-2 ml) from the second CO$_2$ volume reading. An air-driven magnetic stirrer is ideal since it produces no heat.

Caution should be used in comparing calcite-dolomite data from one laboratory to another. One should first check the exact methods of the procedure and calculations. Some laboratories do not analyze the total < 2 mm portion, but a particular size fraction of it. The method used by the author analyzes the < 2 mm portion. Dreimanis (1962) analyzed only the fraction of the whole soil passing a 200 mesh sieve (< 0.074 mm). Should the sample be fine ground? The current author studied the question and found that fine grinding was not necessary but was desirable.
Several samples were analyzed using the whole < 2 mm portion. They were then ground in a mechanical grinder to try to pass a 200 mesh sieve. It was impossible to get the totality of the sample to pass the sieve. Even though the particles were ground fine enough, electrostatic forces held the particles together and prevented them from passing through the sieve. A 100 mesh sieve (0.149 mm openings) was then used. No consistent difference was found between the values from the < 2 mm samples and the < 2 mm samples ground < 0.149 mm. If fine grinding had given higher calcite values, then one would suspect the large calcite particles were not completely dissolving within 30 seconds.

The author also studied the reaction times of various sizes of calcite particles. Only the 1-2 mm size fraction approached not being completely dissolved at the end of 30 seconds. However, the amount of CO$_2$ evolved from a 1.70 g sample after 30 seconds was negligible. It is possible that less dolomite reacts in the first 30 seconds if the sample is not < 0.074 mm. It also may take longer for all of the dolomite to react. As long as the reaction is allowed to continue until CO$_2$ evolution stops, this should present no problem. There is a greater chance of sampling bias when using the whole < 2 mm portion. It is desirable to grind the sample somewhat finer for this reasons.

**Means of expressing carbonate data** The carbonate content of soils can be expressed in several ways. A common way is to express the total carbonate content assuming it was all CaCO$_3$, using the term CaCO$_3$ equivalent (eq.). This is the standard way of reporting data from methods incapable of differentiating carbonate types. The Chittick apparatus
has the capability of differentiating calcite and dolomite. Using the method of Dreimanis (1962), the results are expressed on a weight percentage basis. The following relationships were developed to enable comparison of data expressed in different ways.

\[ \text{CaCO}_3 \text{ eq } \% = \text{calcite } \% + (\text{dolomite } \% \times 1.086) \]  

(Eq. 13)

The equation is derived as follows:

- Molecular weight of calcite = 100.1 g
- Molecular weight of dolomite = 184.3 g
- Equivalent weight of calcite = 50.05 g
- Equivalent weight of dolomite = 46.08 g

\[
\frac{50.05 \text{ g}}{46.08 \text{ g}} = 1.086
\]

Therefore the weight of dolomite must be multiplied by a factor of 1.086 to be on an equivalent weight basis with calcite.

Percentages of inorganic carbon can also be calculated from calcite-dolomite data.

\[ \text{Inorganic carbon in calcite} = \text{calcite } \% \times 0.12 \]  

(Eq. 14)

\[ \text{Inorganic carbon in dolomite} = \text{dolomite } \% \times 0.13 \]  

(Eq. 15)

The equations are derived as follows:

- Molecular weight of carbon = 12.0 g
- The fraction of carbon in each molecule is:

\[
\text{Calcite:} \quad \frac{12.0 \text{ g}}{100.1 \text{ g}} = 0.12
\]

\[
\text{Dolomite:} \quad \frac{24.0 \text{ g}}{184.3 \text{ g}} = 0.13
\]

Some early researchers analyzed soils chemically in an attempt to determine carbonate types. Carbonates were dissolved in dilute HCl, and the extract was then analyzed for Ca and Mg. Usually no assumptions
were made as to the composition of the carbonate minerals. Data were reported simply as Ca/Mg mole ratios. After the Chittick apparatus was adapted for calcite-dolomite differentiation, researchers had two choices of reporting data. The apparatus as used by Dreimanis (1962) yields calcite-dolomite data on a weight percentage basis. Some researchers converted these values to Ca/Mg mole ratios. It is supposed this was done so that Ca/Mg mole ratios from the Chittick apparatus could be compared to Ca/Mg mole ratios determined by chemical methods. The author feels that if calcite and dolomite can be differentiated, the data should be reported as such. Ca/Mg mole ratios determined by chemical methods can be converted to calcite-dolomite weight percentages by assuming that all Ca and Mg came from the pure forms of CaCO$_3$ and CaMg(CO$_3$)$_2$. It is possible that some Ca and Mg from noncarbonatic minerals might be released upon treatment with dilute HCl.

With these thoughts in mind, some relationships were developed that may be helpful in understanding data reported in the literature.

(1) The Ca/Mg mole ratio of pure dolomite is 1.00.

\[
\frac{1 \text{ mole CaMg(CO}_3)_2}{1 \text{ mole Ca/1 mole Mg}} = 1.00
\]

(2) The Ca/Mg mole ratio of equal moles of calcite and dolomite is 2.00.

\[
\frac{2 \text{ moles Ca}}{1 \text{ mole Mg}} = 2.00
\]

(3) The Ca/Mg mole ratio of equal weights of calcite and dolomite is 2.85. It is derived as follows:

Molecular weight of calcite = 100.1
Molecular weight of dolomite = 184.3
(4) To convert Ca/Mg mole ratio data to calcite/dolomite weight (wt.) ratio data:

\[
\text{Calcite/dolomite wt. ratio} = (\text{Ca/Mg mole ratio} - 1) \times 0.543 \quad \text{(Eq. 16)}
\]

The equation is derived as follows:

Assume a Ca/Mg mole ratio of \( x \), which means

\[
\frac{x \text{ moles } \text{Ca}}{1 \text{ mole } \text{Mg}} . \quad \text{One mole of Ca would always be combined with one mole of Mg in dolomite, which would leave:}
\]

\[
\frac{x - 1 \text{ moles } \text{Ca}}{1 \text{ mole } \text{Ca} + 1 \text{ mole } \text{Mg}} = \frac{x - 1 \text{ moles } \text{calcite}}{1 \text{ mole } \text{dolomite}}
\]

\[
x - 1 \text{ moles } \text{calcite} \times \frac{100.1 \text{ g}}{\text{mole}} = 1 \text{ mole } \text{dolomite} \times \frac{184.3 \text{ g}}{\text{mole}}
\]

Combining:

\[
\frac{x - 1 \text{ moles } \text{calcite}}{1 \text{ mole } \text{dolomite}} \times \frac{100.1 \text{ g}}{184.3 \text{ g}} = (x - 1) \times 0.543
\]

(5) To convert calcite/dolomite weight ratio data to Ca/Mg mole ratio data:

\[
\text{Ca/Mg mole ratio} = \frac{\text{calcite/dolomite wt. ratio}}{0.543} + 1 \quad \text{(Eq. 17)}
\]

The equation is derived simply by rearranging Equation 16.
Gypsum

Acetone precipitation method Gypsum percentage was determined on all samples by the method of Bower and Huss (1948), which is also given as method 22b of the U.S. Salinity Lab Staff (1954) and method 6Fla of the Soil Survey Staff (1972). Slight modifications were made in the procedure to improve accuracy. The basic principles of the procedure involve precipitating gypsum from solution in a 1:1 acetone-water mixture, redissolving the precipitate in water, and determining electrical conductivity (EC) on the solution. A brief procedure is as follows:

Weigh 10 g of < 2 mm air-dried soil into an 8 oz baby bottle. Add 100 ml of distilled water, stopper, and shake in a reciprocating shaker for 1½ hours at a speed of about 240 cycles/minute. Take the bottle from the shaker and let it stand 5-10 minutes to allow particles to settle. Without shaking, carefully filter the solution through 90 mm diameter funnels equipped with 18.5 cm Whatman No. 40 filter paper. The first few milliters of filtrate are usually cloudy and should be collected in a waste beaker and discarded. The bulk of the filtrate should be collected in a 125 ml Erlenmeyer flask. Pipette a 5 ml aliquot into a 15 ml conical centrifuge tube. Add 5 ml of acetone, stopper, and mix. Let stand for about 10 minutes to allow the precipitate to form. Remove the stopper and wash it using acetone from a small wash bottle. Centrifuge for several minutes until the precipitate is massed in the bottom of the tube. Decant and discard the supernatant liquid. Carefully invert the tube in a rack and allow to drain for several minutes. Add 5 ml of acetone, stopper, and shake until the precipitate disintegrates. Wash the stopper,
and again centrifuge and decant as before. Invert and drain for several minutes. Place the tube upright and dry either overnight at room temperature or 15-18 minutes at 105° C. Cool and add exactly 10.00 ml of distilled water. Stopper and shake until all traces of the precipitate dissolve. Determine the EC of the solution with a conductivity meter and cell. Calculate the results by comparing to a standard curve prepared from determining EC on known concentrations of CaSO₄ expressed in meq/liter taken through all of the steps of the procedure.

CaSO₄ in soil meq/100 g =
meq/liter from std. curve \( \times \frac{\text{liter}}{1000 \text{ ml}} \times \frac{100 \text{ g}}{\text{g sample}} \times \frac{\text{ml} \ H_2O}{\text{in baby bottle}} \)

(\text{Eq. 18})

where it is assumed a 5 ml aliquot and a 10 ml final dilution were used both in preparing the standard curve and in analyzing the unknowns.

Gypsum % = CaSO₄ meq/100 g \( \times 0.08609 \)

(\text{Eq. 19})

where: 0.08609 = meq weight of gypsum.

The equations simplify to:

Gypsum % = \( \frac{\text{meq/liter from std. curve} \times \text{ml} \ H_2O \ \text{in baby bottle} \times 0.08609}{\text{grams sample} \ \times 10} \)

(\text{Eq. 20})

Results are on a weight percentage basis. A few notes on the procedure follow.

The amount of soil originally weighed out depends upon its gypsum content. Ten grams is not a fixed value, only a maximum. All of the gypsum present in the sample must dissolve in the volume of water used. For soils high in gypsum content (50-60%), a 0.50 g sample must be used.
For all samples requiring < 10 g, 200 ml of water should also be used. The original procedure of Bower and Huss (1948) prescribed a 1/2-hour shaking period. Only about 10 meq/liter of gypsum will dissolve in that period of time. If any values were > 10 meq/liter of gypsum, they would have to be rerun using a wider soil:water dilution ratio. One would suspect that there was still a reserve of undissolved gypsum in the soil. The author found that shaking for 1 1/2 hours dissolved about 20 meq/liter of gypsum. Only samples yielding concentrations > 20 meq/liter would need to be rerun at a wider ratio. By shaking for 1 1/2 hours, there is a higher probability of not having to rerun a sample. Indeed, one of the major disadvantages of the method is the necessity to rerun samples because of not knowing what soil:water dilution ratio is adequate.

To judge the gypsum content of a soil by visual observation takes experience. Profile descriptions should be consulted. Even though shaking for 1 1/2 hours instead of 1/2 hour takes up more time in the procedure, time is saved overall by not having to rerun as many samples.

The acetone can be dispensed from a burette, preferably an automatic filling burette. Any connectors in the apparatus should be of amber latex rubber. Acetone dissolves Tygon tubing. Black latex rubber contains sulfate. Even the rubber connections will dissolve slowly in acetone. The 10.00 ml of distilled water can be added from an automatic overflow pipette mounted on a stand. The water volume needs to be exact.

The precipitate should not stand in contact with the 1:1 acetone-water solution or with the pure acetone wash solution for much over an hour. The author found that evidently some gypsum redissolves in the
solution after a long period. After centrifuging, the supernatant should be decanted fairly quickly. After a period of time, the precipitate seems to loosen and some may be lost upon decantation.

Great care should be exercised not to jolt the tubes when inverting to drain. Some precipitate may be lost. When draining after the last acetone wash, do not leave inverted for over five minutes. Some dry precipitate particles may fall out.

A blank sample should be run by taking 100 ml of water through all the steps of the procedure. The first blank should be run using the same batches of distilled water, acetone, and filter paper as was used in determining the standard curve. Its final EC should be noted. There is no need to subtract the value of the blank from the standard curve values because the standard curve was determined using the same reagents and filter paper. Thereafter, a blank needs to be run only when a new batch of distilled water, acetone, or filter paper is begun. If a subsequent blank has a higher EC than the original blank, subtract only the difference in EC values from the EC values determined from soil samples.

Some extracts from soils high in organic matter content may be colored. The 1:1 acetone-water solution may cause a brown precipitate to form. Evidently the precipitate is sparingly soluble organic compounds, not gypsum.

The reasons for gypsum precipitating in a 1:1 acetone-water mixture was investigated. The mechanism is interesting since no new compound is formed as is normally the case in precipitation formation methods of analysis. The CaSO₄ only undergoes a change in physical form from dissolved
ions to flocculated molecules. In deciding upon the 1:1 acetone-water mixture, Bower and Huss (1948) did not know of any published works dealing with the topic (C. A. Bower, Univ. of Hawaii, Captain Cook, Hi. Personal communication, 1978). The specific solution was determined experimentally to give minimum solubility of $\text{CaSO}_4$ with appreciable solubility of other salts. The dissolution of any compound is dependent upon the intramolecular forces of a solid in relation to the hydration forces of the liquid. Since $\text{CaSO}_4$ is sparingly soluble, the net forces promoting solution evidently are not great. The addition of acid salts, neutral salts, or basic salts to a solution containing solid $\text{CaSO}_4$ always increases the solubility of the $\text{CaSO}_4$, as long as a common ion ($\text{Ca}^{++}$ or $\text{SO}_4^{2-}$) is not present. The salts, being strong dipoles, increase the polarity of the aqueous solution, and the solubility of $\text{CaSO}_4$ in increased. See Table 2 and Table 11 given earlier. Conversely, the addition of nonpolar compounds such as alcohols or sugars decrease the polarity of the solution, and the solubility of $\text{CaSO}_4$ is decreased. Data from Linke (1958) show that additions of methanol, ethanol, and $\text{n}$-propanol all decrease the solubility of $\text{CaSO}_4$. Similar reductions exist for all three alcohols. A 1:1 alcohol-water solution will dissolve about 0.003 g $\text{CaSO}_4$/100 g of saturated solution while pure water will dissolve about 0.2 g $\text{CaSO}_4$/100 g. No data were given for acetone. The mode of action is probably the same. Many salts have lower solubilities in nonaqueous solvents than in aqueous solvents. For the particular case of $\text{CaSO}_4$, it appears that the aqueous solubility is so low that a reduction in polarity due to acetone addition results in almost complete precipitation. The
more readily-soluble sulfates (Na, K, Mg, and H) are not precipitated.

Understanding the phenomenon of precipitation also allows another slight adjustment for economic benefit. The original procedure prescribed reagent-grade acetone. However, the primary difference between it and commercial-grade acetone is water content. Reagent-grade acetone is almost pure acetone while the commercial-grade contains about 2-3% water. Since the 1:1 acetone-water mixture is only approximate, the 2-3% water in the acetone should not make any difference in results. Experiments done by the author showed absolutely no difference in values using the two grades of acetone. The commercial grade is considerably cheaper than the reagent grade.

The author discovered two major errors in the procedure as stated by Bower and Huss (1948), U.S. Salinity Lab Staff (1954), and Soil Survey Staff (1972). The first one concerns the method of calculation. The ultimate step of the procedure is the determination of EC on a solution containing CaSO₄ and then calculating the CaSO₄ concentration from a standard curve. The papers cited above all construct their standard curves from data given by the National Research Council (1929), International Critical Tables. The data given are the concentrations of CaSO₄ in meq/liter and their corresponding EC values in mmhos/cm. These data are valid only when the conductivity meter and cell used are known to be exactly alike in response to the ones used in developing the table. As with all analytical instruments, responses may be similar but many conditions exist which prevent one instrument from responding exactly like another. Even if two instruments are standardized to a common benchmark
setting, it is no guarantee that the rest of the response curve will be identical. In the case of conductivity bridges, the standard reference solution is 0.01M KCl. It is quite unusual in the current author's opinion that one standard curve for all instruments has been published and used up to the present. It would seem extremely unlikely that one would publish a standard curve relating ionic concentrations of colored solutions to the absorbance readings of a spectrophotometer and then recommend the curve be used for all instruments.

The author discovered the problem when first calibrating his conductivity meter and cell. The response curve was far different from the National Research Council (1929) curve. Another observation is that the construction of conductivity meters has changed over the last 20 years, and the changes may also affect the response curve of each meter. Meters such as the one shown in Figure 26 of U.S.D.A. Handbook No. 60 (U.S. Salinity Lab Staff, 1954) have a continuously wound resistance coil that is adjusted until a null reading is reached. If the meter is set to a specific reference point, the rest of the response curve would probably be fairly consistent. In recent years, meters have been constructed that utilize a visual scale or digital readout. To enable all conductivity readings to be read on one scale, the meter contains a multiplier adjustment, i.e., X 1, X 10, X 100. Each adjustment setting routes the circuit through a different set of resistors. Each set may not be exactly constructed as to give a linear response in going from one multiplier adjustment to another. Setting the meter to a specific reference point at one adjustment setting in no way guarantees a proper response at other
settings. Each setting must be checked independently. The conductivity meter used had a multiplier adjustment and was also equipped with a variable resistor on each internal circuit board that could be adjusted manually. Standard conductivity solutions should be prepared for each adjustment range, and the circuit boards adjusted accordingly. A standard curve should still be run using the ionic species that is to be detected. The internal circuit boards of the meter used were far out of adjustment when first received. If the recommended procedure of using a published standard curve had been followed, highly erroneous results would have ensued.

The advent of desk-top programmable calculators has made it possible for most laboratories to omit the visual use of standard curve graphs in calculations. The standard curve relationship can be converted to a regression equation. By avoiding the visual use of a graph, the calculation process is faster, eye fatigue is reduced, and potential errors are avoided. A print-out of the calculations enables all data entries to be checked. The relationship between EC values and known ionic concentrations of CaSO₄ is not very well-represented by linear or logarithmic regression lines. A polynomial equation must be used. Most programmable calculators with statistics capabilities include such a program. Usually, such programs require equi-spaced EC data points. To obtain these, plot the standard curve on regular graph paper. Choose a set of equi-spaced EC values and determine their corresponding CaSO₄ concentrations. Develop the regression line from these data. For an example, the second-order polynomial regression equation developed for the National Research Council
(1929) data is:

$$\text{CaSO}_4 \text{ meq/liter} = -0.488 + 10.227 \text{ (EC)} + 1.742 \text{ (EC}^2\text{)}$$  
(Eq. 21)

The fit is excellent. The accuracy of third- and fourth-order equations was also tested. They provided almost no increase in accuracy.

The second major error discovered in the procedure was in the treatment of the CaSO₄ precipitate before determining EC. After the last acetone wash, the precipitate is dissolved in exactly 10.00 ml of water and EC is determined. The procedure as stated by Bower and Huss (1948), U.S. Salinity Lab Staff (1954), and Soil Survey Staff (1972) is to drain the precipitate by inverting the tube for several minutes, add the 10 ml of water, dissolve the precipitate, and determine EC. Low results were consistently obtained using this procedure. After several experiments to determine the problem, it was concluded that the acetone present in the mass of the precipitate does not allow the CaSO₄ to redissociate completely when it redissolves. Large amounts of acetone cause flocculation of Ca and SO₄ in pairs from solution. However, even the very small amount of acetone that is within the precipitate (normally ≤ ½ ml) evidently prevents complete dissociation of the CaSO₄ into Ca and SO₄ ions even when diluted with 10 ml of water. Even though the precipitate dissolves, complete dissociation is not guaranteed. The lack of complete dissociation subsequently lowers the EC of the solution since electrical conductance is dependent upon ions.

It was found that the precipitate must be completely dry before total and rapid dissociation occurs when redissolved. Drying overnight at room temperature, drying overnight at 105° C, and drying for 15-18 minutes at
105° C all gave the same results. One disadvantage to drying for more than about 20 minutes at 105° C is that the precipitate becomes slow to redissolve. The 10 ml of water must be added, the tubes stoppered and then shaken on a reciprocating shaker until all precipitate dissolves. If the precipitate dries overnight at room temperature or at 105° C for 15-18 minutes, the precipitate can be dissolved fairly quickly by hand shaking. When the precipitate is dry, it shrinks noticeably in volume, cracks often appear in the mass if it is large, and there is no acetone smell at the mouth of the tube. Drying at 105° C at this point probably converts the CaSO₄ • 2H₂O to CaSO₄ • \frac{1}{2}H₂O or CaSO₄. This is of no consequence. When dissolved in water, all forms are the same.

Another slight error caused by not drying the precipitate is the dilution error of the retained acetone on the 10.00 ml of added water. The volume of acetone retained depends upon the size of the precipitate but is usually ≤ 0.5 ml. The final dilution volume is a critical one that must be known in calculating results. The standard procedure of not drying the precipitate, adding 10.00 ml of water, and then using 10 ml in the calculations is erroneous. Experimental results obtained in this study show that assuming a 10.00 ml volume when actually a 10.5 ml volume is present results in values that are 5% low. Not drying the precipitate likewise yields results that are about an additional 15% low. Therefore, the method described may yield results up to 20% low due to this procedural step.

Two theoretical problems also exist with the method of Bower and Huss (1948). The first one is the possibility of the dissolution of CaCO₃
upon shaking and the subsequent combination of Ca$^{++}$ with free SO$_4^{2-}$ to form additional gypsum. It is unlikely that this phenomenon is of significance. Calcium carbonate is about 30-150 times less soluble than gypsum, depending upon the CO$_2$ content of the water. Since distilled water is low in CO$_2$ content, the actual values would be nearer the 150 end of the range. Also it is not likely that very much CaCO$_3$ dissolves upon shaking for 1½ hours. As has been shown, this treatment yields only about a 2/3 saturated gypsum solution. Since CaCO$_3$ is much more insoluble, it would be doubtful if 1½ hours of shaking would even produce a half-saturated solution. The massive amount of Ca$^{++}$ in solution from dissolved gypsum would further suppress CaCO$_3$ dissolution due to the common ion effect.

The second theoretical problem deals with exchange reactions occurring during the shaking period. Gypsum dissolves yielding a predominance of Ca$^{++}$ in the soil solution. The excess of Ca$^{++}$ may exchange with cations adsorbed on the exchange complex. Monovalent cations would be removed quicker than divalent cations. The resulting increase in Na, K, and Mg sulfates in the soil solution would not be detected by the acetone precipitation procedure since it is selective for CaSO$_4$. The net result would be an artificially low value for gypsum content in the soil. This phenomenon has been termed "exchange error" by Lagerwerff et al. (1965).

Could exchange error account for a significant error in the procedure? It was reported earlier that a maximum of about 20 meq/liter of gypsum dissolve in 1½ hours of shaking with water. Assume 200 ml of water were used to dissolve the gypsum.
\[ \frac{x \text{ meq}}{0.2 \text{ liter}} = \frac{20 \text{ meq}}{1.0 \text{ liter}} \]

\[ x = 4.00 \text{ meq of gypsum that will dissolve in 200 ml.} \]

Assume 5 g of soil contain this 4.00 meq of gypsum and that the soil has a cation exchange capacity (CEC) of 30 meq/100 g.

\[ \frac{y \text{ meq}}{5 \text{ g}} = \frac{30 \text{ meq}}{100 \text{ g}} \]

\[ y = 1.50 \text{ meq of CEC. Assume that one-half of the exchange sites are filled with ions other than Ca.} \]

\[ \frac{1.50 \text{ meq}}{2} = 0.75 \text{ meq of potential exchange sites.} \]

If during the 1\(\frac{1}{2}\) hours of shaking all of the non-Ca ions are exchanged for Ca from the dissolved gypsum, then the 4.00 meq of gypsum will be reduced by 0.75 meq.

\[ \frac{0.75 \text{ meq}}{4.00 \text{ meq}} \times 100 = 19\% \text{ error.} \]

The exchange error can be very important under certain circumstances. The magnitude of the error will depend upon at least three items: the CEC of the soil, the degree of saturation of the exchange complex with Ca, and the completeness of the cation exchange during the gypsum dissolution process. The error due to the CEC of the soil would decrease as gypsum content of the soil increased. As gypsum content increased, less soil would need to be weighed into the baby bottle. Less soil would give less total exchange sites. Also, as gypsum content of a soil increases, the CEC decreases. The gypsum that is present in a soil necessarily excludes a proportionate volume of sand, silt, and clay. Less exchange sites would be available. The degree of saturation of the exchange complex with Ca
would be variable. Most gypsiferous soils are calcareous. It would be
doubtful if a soil containing only gypsum would have an exchange complex
not dominated by Ca. The excess soluble salts must be leached from a
soil before an appreciable amount of exchangeable Na accumulates. It is
not known if 100% exchange occurs between the soil solution and the ex-
change sites during 1½ hours of shaking. The concentration of Ca⁺⁺ from
gypsum does not normally exceed 20 meq/liter during the shaking period.
It is not known if a concentration of 20 meq/liter of a divalent cation
would promote 100% exchange with the exchange sites in 1½ hours. Extract-
ing solutions in common use in soil analysis that depend upon 100% exchange
for their validity are: 1000 meq/liter KCl, 1000 meq/liter NaOAc, 1000
meq/liter NH₄OAc, and 500 meq/liter BaCl₂. One of these extractants is
in contact with the soil for about an hour. The rest are for several
hours or overnight. To accurately determine how much exchange can occur
during the gypsum dissolution process, a soil should be saturated with
one of several ions: Na, K, or Mg. It should then be shaken for 1½
hours in a 20 meq/liter CaSO₄ solution. The CaSO₄ solution should then
be analyzed for the foreign ions.

Lagerwerff et al. (1965) addressed the question of exchange error.
They compared four methods of determining gypsum. One method was rejected
due to its recovery of only 87% of gypsum added to several soils. It
contained an inherent erroneous assumption in its calculations. The other
two methods, Method I and Method III, gave 81% and 77% recovery, respec-
tively. However both methods utilized the National Research Council (1929)
standard curve. Method III was the method of Bower and Huss (1948)
without drying the precipitate. Lagerwerff et al. (1965) attributed the lack of 100% recovery to exchange error. The present author wonders if some of the error was due to the erroneous use of a standard curve and not drying the gypsum precipitate. The authors discovered the need to dry the precipitate but did not place emphasis on it. They concluded that not drying the precipitate caused an error of 2.8%, of which 0.5% was due to volume increase. The current study shows the error is much more severe.

The one method the authors suggested as being the most accurate for determining gypsum did not involve any EC. It did require analyzing saturation extracts for sulfate. The author did not collect enough quantity of soil to prepare saturation extracts for each sample. The method of Bower and Huss (1948) was used. After the errors in it were corrected, it may be a more accurate method than once believed. The exchange error problem would be most pronounced in noncalcareous soils having a high CEC and containing gypsum. In the case of the author's samples, the gypsum percentages which seem to be lower than the profile descriptions indicate are the uppermost one or two layers of a few profiles. These layers would probably have the greatest CEC of all layers in the profile.

Lagerwerff et al. (1965) made improvements in the method that should be mentioned. They calculated that gypsum was less soluble and other salts more soluble in a solution of 53% acetone, 13% glacial acetic acid, and 34% water than in 1:1 acetone-water. They also found that the mode of addition of the acetone mixture to the gypsum containing aliquot affects the density of the precipitate formed. Gently layering the acetone
mixture on top of the aliquot enables nucleation to proceed slowly. A dense precipitate forms that is less likely to contain entrapped salts. Running the acetone mixture directly into the aliquot with mixing enables nucleation to proceed rapidly. A loose precipitate forms that may contain entrapped salts.

Kovalenko (1972) and Sayegh et al. (1978) report other methods for determining gypsum in soils, but no great improvements seem to have been made.

**Weight loss method**

Most gypsum procedures are fairly time consuming. Nelson et al. (1978) developed a quick method for determining the approximate gypsum content of soils. The method is based on the principle of \( \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \) losing its two molecules of water upon heating at \( 105^\circ \text{C} \). The weight loss of a sample is correlated to gypsum content. A few of the author's samples were also analyzed by this method. A brief procedure is as follows:

Place about 8 g of < 2 mm air-dried soil into a tared aluminum weighing pan (60 mm diameter X 15 mm depth) and weigh to the nearest mg. Place the pan in a desiccator containing silica gel (\( \text{SiO}_2 \)). Dry the soil for a minimum of 48 hours. Weigh the pan with the soil immediately after removal from the desiccator. Dry the pan plus soil in an oven at \( 105^\circ \text{C} \) for 24 hours. Quickly transfer the pan to a desiccator, cool, and re-weigh. The calculations and their explanation are lengthy. See the cited reference.

The method requires little laboratory personnel time or facilities. The method is designed for field use as well. A desiccator can be
improvised from a mason fruit jar. In lieu of a 105°C oven, an infrared lamp, a gas burner, or an electric heating element can be used. The method is not capable of extreme accuracy. The authors recommended to report all values to the nearest whole percent and all values between 1-4% as < 4%.

The authors found that air-dried samples of nongypsiferous soils and montmorillonite lost essentially the same amount of water when dried over SiO₂ for 48 hours or at 105°C for 24 hours. Any weight loss upon heating should indicate the presence of gypsum. The theoretical weight loss of 2H₂O from gypsum is 20.9%. This weight loss factor is necessary for calculations. Yet it cannot be assumed that 20.9% of all gypsum is lost upon heating at 105°C for 24 hours. Reagent-grade CaSO₄ • 2H₂O should be dried in the specified manner and the weight loss determined. The actual weight loss should then be used in calculations. The drying oven should not contain any other samples containing water during the 24-hour period. If it does, the gypsum will only lose about 1½ molecules of water, a weight loss of 15.7%. The current author found that the weight loss of four samples of reagent-grade gypsum analyzed at three different times was 18.06, 18.26, 18.50, and 18.55%. Evidently about 1-3/4 molecules of water on the average were lost.

Several factors may affect the loss of crystal water upon heating. Already mentioned was the presence of water-containing samples in the drying oven. Some weight loss could occur from the destruction of organic matter. Silica gel is a fairly inefficient desiccant. It does not have great absorptive and adsorptive powers. It will vary in its drying
efficienty depending upon how long it has been since the SiO$_2$ has been rejuvenated (dried at 105° C to remove moisture). Any moisture not removed from the soil when dried over SiO$_2$ will appear to be gypsum weight loss when the soil is dried at 105° C. Anhydrous CaSO$_4$ is highly hygroscopic and is sometimes used as a desiccant. It is possible that it could reabsorb moisture from the SiO$_2$ after being dried at 105° C. Anhydrous CaSO$_4$ is a stronger desiccant than silica gel. Some hydrated minerals other than gypsum also lose crystal water upon heating at 105° C. The most common one encountered is MgSO$_4$ • 7H$_2$O. Experiments by the author found 5-6 molecules of water are lost upon heating at 105° C for 24 hours. Calculations show that 1% of MgSO$_4$ • 7H$_2$O would appear as about 2% of CaSO$_4$ • 2H$_2$O. If an appreciable amount of MgSO$_4$ • 7H$_2$O is present, the method can be highly inaccurate.

One disadvantage of the method is the small number of weighing pans that can fit into one desiccator. The author tried an adaptation for a desiccator to increase capacity. Three 5 ml beakers were placed equidistant from each other on the porcelain plate and against the walls of the desiccator. Another porcelain plate was laid upon the beakers. Likewise another three beakers and a plate were placed upon the second plate. The three-tiered arrangement can hold about three times as many pans. Upon repeated openings of the desiccator during weighings, the last pans to be weighed might have an opportunity to absorb an excessive amount of moisture from the air. However, a set of 16 pans consisting of 8 samples run in duplicate that were dispersed throughout the three tiers gave very consistent results. All weighing chambers of balances should contain two
50 ml beakers of desiccant to remove moisture. Several pans should be placed in the weighing chamber at one opening and then weighed as quickly as possible.

Several samples were analyzed by the weight loss method for comparison to the acetone precipitation method. Table 13 shows the data.

Table 13. Comparison of gypsum content of samples from Clay Co., Site 4, determined by two different methods

<table>
<thead>
<tr>
<th>Depth, inches</th>
<th>Gypsum (Weight loss method) %</th>
<th>Gypsum (Acetone precipitation method) %</th>
<th>Percentage error of weight loss method</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-3½</td>
<td>44.6, 44.6</td>
<td>35.2</td>
<td>+27</td>
</tr>
<tr>
<td>3½-7</td>
<td>36.7, 36.6</td>
<td>26.6</td>
<td>+38</td>
</tr>
<tr>
<td>7-11</td>
<td>64.5, 64.8</td>
<td>56.4</td>
<td>+15</td>
</tr>
<tr>
<td>11-18</td>
<td>53.0, 52.0</td>
<td>45.1</td>
<td>+16</td>
</tr>
<tr>
<td>18-25</td>
<td>53.6, 52.9</td>
<td>46.3</td>
<td>+15</td>
</tr>
<tr>
<td>25-31</td>
<td>9.6, 9.6</td>
<td>1.7</td>
<td>+465</td>
</tr>
<tr>
<td>31-37</td>
<td>11.2, 10.7</td>
<td>0.4</td>
<td>+2,650</td>
</tr>
<tr>
<td>Gypsum standard sample</td>
<td>62.2, 61.4</td>
<td>54.4±0.5</td>
<td>+14</td>
</tr>
</tbody>
</table>

Values determined by the weight loss method are duplicates in the same run. The samples were dried over SiO₂ for 96 hours. Values determined by the acetone precipitation method are singular values. Other characterization data for the Clay Co., Site 4 profile are given in Appendix B, Table 28. The value for the standard sample is the mean and standard deviation of 27 values each determined in a different run. The
standard sample was ground to pass a < 60 mesh sieve.

A wide discrepancy exists between the two methods. It is almost impossible that exchange error could account for almost any of the difference in six of the samples. For the 0-25 inch samples as well as the gypsum standard sample, only 0.50 g of soil was dissolved in 200 ml of water. Original analysis sheets for these six samples showed a maximum concentration of 16.4 meq/liter of gypsum were dissolved in the water.

\[
\frac{x \text{ meq}}{0.2 \text{ liter}} = \frac{16.4 \text{ meq}}{1.0 \text{ liter}}
\]

\[
x = 3.28 \text{ meq of gypsum that dissolved in 200 ml.}
\]

Assume a CEC of 20 meq/100 g.

\[
\frac{y \text{ meq}}{0.50 \text{ g sample}} = \frac{20 \text{ meq}}{100 \text{ g}}
\]

\[
y = 0.10 \text{ meq of CEC.}
\]

Even though the soils are high in gypsum content, assume 50% of the exchange sites are filled with non-Ca cations.

\[
\frac{0.10 \text{ meq}}{2} = 0.05 \text{ meq available for exchange.}
\]

Assume all non-Ca cations exchange for Ca ions from gypsum in solution.

The total of 3.28 meq of gypsum is reduced by 0.05 meq.

\[
\frac{0.05 \text{ meq}}{3.28 \text{ meq}} \times 100 = 1.5\% \text{ error.}
\]

It is evident that the error is not due to exchange phenomena, at least for those six samples. For the 25-31 and 31-37 inch samples, there was very little gypsum noted on the profile description. The values by the acetone precipitation method would appear much more accurate than the values by the weight loss method. The 25-31 and 31-37 inch horizons
appear to be a buried soil fairly high in organic matter content. The author wondered if the weight loss upon heating was due to organic matter decomposition. A profile was chosen that was fairly high in organic matter content but had no soluble salts or carbonates. It was analyzed for apparent gypsum content using the weight loss method. The results are given in Table 14.

During the weight loss method, the samples were dried over SiO₂ for 119 hours. Still they lost weight when dried at 105°C. The weight loss is calculated in terms of apparent gypsum percentage. The weight loss may be slightly correlated to organic matter content, but organic matter does not account for the majority of the weight loss. The apparent conclusion is that the soil is not being completely dried over SiO₂, even when left for much longer than the prescribed 48 hours. Evidently the SiO₂ must be recently rejuvenated to increase its absorptive efficiency. Even though the colored indicator in the silica gel is still a deep blue, the desiccant is not necessarily efficient. The problem was not investigated further. The presence of MgSO₄ · 7H₂O may have caused some of the discrepancies for the 0-25 inch samples of Clay Co., Site 4. It is very unlikely that any would be present in the 25-31 and 31-37 inch samples.

A standard sample containing a known amount of gypsum or a noncalcicccareous, nongypsiferous soil should be included in each run to check for abnormal weight losses upon heating at 105°C. A more efficient desiccant such as phosphorus pentoxide (P₂O₅) might be recommended. The weight loss method is valid only for approximate results. It may be useful in determining the soil: water ratio needed for complete dissolution of
<table>
<thead>
<tr>
<th>ISU sample No.</th>
<th>Depth, inches</th>
<th>Sand % 2-0.05 mm</th>
<th>Cs. Silt % 50-20 μ</th>
<th>Fl. Silt % 20-2 μ</th>
<th>Clay % &lt; 2 μ</th>
<th>pH</th>
<th>Total carbon %</th>
<th>Apparent gypsum %</th>
</tr>
</thead>
<tbody>
<tr>
<td>26186</td>
<td>0-7</td>
<td>24.3</td>
<td>28.0</td>
<td>19.4</td>
<td>28.3</td>
<td>6.1</td>
<td>2.35</td>
<td>4.4</td>
</tr>
<tr>
<td>87</td>
<td>7-12</td>
<td>21.5</td>
<td>18.0</td>
<td>38.5</td>
<td>30.0</td>
<td>5.5</td>
<td>1.65</td>
<td>4.3</td>
</tr>
<tr>
<td>88</td>
<td>12-16</td>
<td>20.7</td>
<td>18.7</td>
<td>30.1</td>
<td>30.5</td>
<td>5.4</td>
<td>0.82</td>
<td>4.0</td>
</tr>
<tr>
<td>89</td>
<td>16-20</td>
<td>25.9</td>
<td>18.0</td>
<td>25.8</td>
<td>30.3</td>
<td>5.1</td>
<td>0.32</td>
<td>3.8</td>
</tr>
<tr>
<td>90</td>
<td>20-25</td>
<td>34.4</td>
<td>10.7</td>
<td>20.9</td>
<td>34.0</td>
<td>5.0</td>
<td>0.21</td>
<td>3.6</td>
</tr>
</tbody>
</table>

a Particle size by regular method. Only organic matter removed.

b pH by 1:1 soil-water ratio.

c Total carbon by Leco high temperature combustion method.
gypsum in the more accurate chemical procedures.

Nelson et al. (1978) also include a section on correcting the properties of gypsiferous soils expressed on an oven-dried basis for the weight of crystal water lost upon heating.

**Total and organic carbon**

**High temperature combustion method**  Total carbon analysis by the Leco high-frequency induction furnace was attempted. The apparatus used was a model 521-300 induction furnace and a model 750-100 automatic carbon analyzer, both manufactured by the Laboratory Equipment Corp. (Leco), St. Joseph, Mi. The operation of the apparatus and a description of the method have been given by Tabatabai and Bremner (1970b). The basic principles of the procedure are that a sample of soil is heated to a molten state. All carbon present is converted to \( \text{CO}_2 \) and detected.

A brief procedure is as follows:

Weigh out a maximum of 0.260 g of air-dried soil into a specially-designed, carbon-free, ceramic crucible. Add approximately one gram each of tin, copper, and iron chips to serve as accelerators. Place the crucible in the induction furnace and initiate the cycle. The crucible contents will be heated to a molten state (above \( 1,650^\circ \text{C} \)). All carbon in the soil sample whether from organic or inorganic sources will be converted to \( \text{CO}_2 \). The gases evolved in combustion are swept away in an oxygen train, passing through a series of traps and catalysts to remove undesirable particles and gases. The final \( \text{O}_2-\text{CO}_2 \) mixture is collected in a cylinder maintained at a constant temperature, and the \( \text{CO}_2 \) content is determined by a thermistor-type thermal conductivity cell. The final
The conclusion of the author is that gypsiferous soils should not be analyzed by the Leco combustion method.

**Chemical oxidation method** Samples were analyzed for organic carbon content by the Iowa State University (ISU) Soil Testing Laboratory. The method used was essentially that of Mebius (1960) with slight modifications and is outlined specifically by Eik (1977). The basic principle of the procedure is that the organic carbon in soils is oxidized by
dichromate in the presence of $\text{H}_2\text{SO}_4$ and heat. The amount of dichromate that is reduced is determined and correlated to the amount of carbon initially present in the soil.

A brief procedure is as follows:

Weigh 0.20 g of soil ground < 80 mesh and place in a 125 ml Erlenmeyer flask fitted with a Standard Taper 24/40 glass joint. Add exactly 10.00 ml of 0.5N potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) solution and 15 ml of concentrated $\text{H}_2\text{SO}_4$. Swirl, place on a preheated individual hotplate, and connect the flask to a 40 cm reflux condenser. When boiling is reached, note the time and boil for 30 minutes. Raise the flask from the hotplate, place a piece of firebrick between each, and allow the flask to cool for about five minutes. Slowly pour 75 ml of distilled water through the top of the condenser into the flask. Remove the flasks, swirl, stopper, and allow to stand undisturbed overnight. The next day, the absorbance of the supernatant liquid is determined on a spectrophotometer set at 590 nanometers. Carefully withdraw enough supernatant to be placed in a cuvette. Determine organic carbon percentage by comparing to a standard curve. Results are reported as a weight percentage.

The actual Mebius method involves the determination of unreduced dichromate by titration with $\text{Fe}^{++}$ instead of spectrophotometrically. The method of Gupta et al. (1975) filters the soil-digestion solution mixture instead of allowing the soil particles to settle upon overnight standing. The ISU Soil Testing Laboratory found that the digestion solution oxidized some of the organic carbon in the fibers of the filter paper. The primary advantage of the Mebius method over the Walkley-Black method (Allison,
1965) is that heating the soil-digestion solution mixture reduces the variability of the percentage of organic carbon oxidized by the dichromate. Hutton and Simonson (1942) studied this problem of the Walkley-Black method and concluded, "The deviations in recovery of carbon are considered too large to permit the general use of the more rapid procedure for the study of carbon distribution in soil profiles."

**Total sulfur**

A few samples of glacial till material were analyzed for total sulfur content. The analysis was done by the research group of Dr. M. A. Tabatabai, Department of Agronomy, Iowa State University. The samples were first digested by the method of Tabatabai and Bremner (1970a) and then analyzed for sulfur by the method of Johnson and Nishita (1952). Since the procedures are lengthy and detailed and since the author has no experience with the latter method, only the citations will be given.

**Saturation extract**

The presence of soluble salts makes the chemical analysis of soils somewhat difficult. The salts dissolve in the extracting solutions and can greatly affect the results. The best estimate of the soluble salt content can be made from a water extract of the soil. The higher the moisture content of the soil, the easier the extract is to obtain, but the less representative it is to the soil solution to which plant roots are exposed. It is desirable to evaluate the properties of soils as near to their natural state as possible. The available water content of soils varies greatly depending upon texture. Plant-available water
is that water in the soil between field capacity (1/3 bar tension) and the permanent wilting percentage. Two different textured soils, one a sand and the other a clay, could have the same weight percentage of soluble salts. Yet the salt concentration of the soil solution when near the wilting percentage could be up to ten times as high for the sand as for the clay, due only to the moisture retention differences of the soils.

A satisfactory method for determining the soluble salt content of soils must take into account their variable water retention characteristics. It should also utilize an extract that closely represents the true soil solution. Extracts from soils at field capacity would be desirable but are difficult to obtain. The second best alternative would be the extract from a soil just at saturation. The extract from a saturated paste is commonly termed a saturation extract. A soil is stirred with a slow addition of water until the saturation point is reached. The saturation point is reasonably reproducible among different operators. The paste is vacuum filtered to remove as much of the water from the soil as possible. The special advantage of the saturation extract method is that the saturation percentage, the percentage of water when the soil is a saturated paste, is directly related to the available water capacity of a soil. Measurement of the salt concentration in the saturation extract thus gives a value which automatically takes into account the water-holding characteristics of the soil.

The water content of a soil at field capacity is about two times the content at the permanent wilting percentage. Measurements done at
the U.S. Salinity Laboratory indicate that over a considerable textural range, the water content at saturation is about four times that of the permanent wilting percentage. The soluble salt concentration in the saturation extract therefore is about one-half the concentration of the soil solution at field capacity and about one-fourth the concentration at the permanent wilting percentage.

Reeve and Doering (1965) extracted a set of soils at both the saturation percentage and at field capacity. Soluble salt data determined from the two extracts agreed well in respect to the foregoing relationships.

The procedure preferred by the author for preparing saturation extracts is given as method 62-1.3.2.1. of Bower and Wilcox (1965). Weigh several hundred grams of air-dried soil of known moisture content into a suitable mixing container that can be covered. Add known quantities of distilled water slowly and with constant stirring until a saturated condition is reached. Consolidate the mixture from time to time during mixing by tapping the container on the workbench. At saturation, the soil paste glistens as it reflects light, flows slightly when the container is tipped, and slides cleanly and freely off a spatula for all soils except those with high clay contents. After the mixing, cover the container and allow the sample to stand an hour or more. Recheck the criteria for saturation. If the paste has lost its glisten or has stiffened, add more water and mix. If free water has collected on the surface of the paste, add an additional quantity of dry soil. After it is certain saturation has been reached, allow the soil paste to sit
covered at least four hours. Transfer the paste to a Bucher funnel fitted with low ash, highly retentive filter paper. Apply vacuum and collect the filtrate in a test tube placed inside the suction flask. If the initial filtrate is turbid, refilter or discard it. Stop the filtration when air begins to pass through the filter.

Notes on the procedure from the author are as follows:

The soils prepared to a saturated condition were all very high in gypsum content (30-60%). The "flowing" aspect of the soil when the container is tipped is imperceptible. It is not a good criterion. When the soil did flow, it was beyond saturation.

Jarring of the container on the workbench collapses the air voids within the paste. The excess water, if any, will come to the surface of the paste. If "almost free water" appears on the surface immediately after jarring, the soil will definitely have free water on it in a few minutes. More soil should be added. During jarring, the paste should not consolidate into a mass with a level surface. The scars due to stirring should remain. If the scars flow together, the soil is too wet.

At saturation, the paste mass should be consistently dull in color when examined by stirring. No shiny surfaces within the mass should exist.

The paste slides cleanly and freely off a stainless steel spatula when pushed into the soil and removed vertically. The vertical position is important.

Use Whatman No. 42 filter paper for extraction. Press the soil into the Buchner funnel tightly. Voids will channel air through the paste.
If air is sucked through the paste before extraction is complete, press the soil again. Extraction is complete whenever dripping from the funnel essentially ceases. Normally this requires an hour or slightly less time. Sometimes the soil paste is packed tightly enough that no air will be sucked through the filter even when extraction is complete. As a general rule, about one-fourth of the water added to the soil will be recovered in the saturation extract.

Careful records should be kept of all quantities of soil and water. Assume 1 ml H₂O = 1 g H₂O. The saturation percentage can be calculated as follows:

Let \[ A = \frac{\text{total g of air-dried soil added} \times \text{air-dried moisture % of soil}}{100} \]

Saturation percentage = \[ \frac{\text{total g H₂O added + A}}{\text{total g air-dried soil added - A}} \times 100 \] (Eq. 22)

**Electrical conductivity**

The electrical conductivity of an electrolyte is proportional to the concentration of ions in solution. Electrical conductivity measurements have long been used to determine the concentration of dissolved salts in extracts of soils. The measurement is made by measuring the electrical resistance between parallel electrodes immersed in the solution. The units are reported as the reciprocal of electrical resistivity, electrical conductivity (EC), in mhos/cm. Most soil applications report values in millimhos/cm (mmhos/cm). The U.S. Salinity Laboratory has developed numerous relationships between the EC of solutions and their properties as well as the EC of soil extracts and their properties (U.S. Salinity Lab Staff, 1954). Some of these relationships have been given in
Equations 4-8 earlier in the thesis. The only other relationships that will be given are shown in Figure 4 of U.S. Salinity Lab Staff (1954) which relate EC values to total ionic concentrations of solutions in meq/liter. If the EC is $< 5$ mmhos/cm, then:

$$EC \text{ mmhos/cm } \times 10 \equiv \text{ total concentration meq/liter} \quad (\text{Eq. 23})$$

If the EC is $> 5$ mmhos/cm, then:

$$EC \text{ mmhos/cm } \times 12 \equiv \text{ total concentration meq/liter} \quad (\text{Eq. 24})$$

All electrical conductivity measurements determined in this thesis were done using a Model 10 meter and a Model 1100 cell manufactured by Markson Science Inc., Del Mar, Ca. The electrodes inside the cell are gold plated. This represents an improvement over the platinum electrodes used in cells for many years previously. Platinum electrodes require replatinizing periodically; gold ones do not. The cell also contains an automatic temperature sensor that converts all readings to a $25^\circ C$ basis. The sensor is accurate over a range of 0-100$^\circ C$. No extra charts, equations, or meter adjustments are needed for temperature compensation. The cell has a flow-through body design that requires a minimum amount of sample volume. It also allows easy rinsing with water and drying with acetone between readings. The meter and its potential problems have been described previously under the section on the acetone precipitation method for determining gypsum. Each multiplier scale range should be checked with a known conductivity standard for accuracy of response.

Cation exchange capacity

Cation exchange capacity (CEC) was determined using method 57-3 of Chapman (1965). The usual method of using 1N ammonium acetate ($\text{NH}_4\text{OAc}$
at pH 7.0 was not used due to the solubility of CaCO$_3$ and gypsum in the extractant. The solubility of both minerals is less in 1N sodium acetate (NaOAc) at pH 8.2. The basic principle of the procedure is that all soil exchange sites are first saturated with Na$^+$. The Na$^+$ is then replaced by NH$_4^+$ and the Na$^+$ concentration is determined in the resultant solution. A brief procedure is as follows:

Weigh 4.00-6.00 g of < 2 mm air-dried soil into a 50 ml round-bottom centrifuge tube. Add about 33 ml of 1N NaOAc at pH 8.2, stopper, and shake on a reciprocating shaker for five minutes. Remove and centrifuge until the supernatant liquid is clear. Decant and discard the supernatant. Repeat the extraction three more times. Be careful not to pour off any sediment adhering to the walls of the tube. After centrifugations, decantation, and readdition of the wash solution, shake the tube vigorously to dislodge the soil particles before placing the tube back on the shaker. Always use the same stopper for each tube each time.

Wash the sample in an identical manner with three 33 ml portions of 99% isopropanol. Also using the same procedure, replace the adsorbed Na with three 33 ml portions of 1N NH$_4$OAc at pH 7.0. Decant each wash into the same 100 ml volumetric flask. Dilute the solution to exactly 100 ml using 1N NH$_4$OAc. Determine the Na concentration in the solution.

The author used a Model 143 flame photometer manufactured by Instrumentation Laboratory, Inc., Boston, Ma. for determination of Na. Five milliliters of the extract were placed in a second 100 ml volumetric flask. Ten milliliters of 150 meq/liter lithium chloride (LiCl) solution were added in order to give a final concentration of 15 meq/liter of Li
required as an internal standard for the photometer. The flask was diluted to volume with \( \text{LN} \text{NH}_4\text{OAc} \). Standards containing known concentrations of sodium chloride (NaCl) in meq/liter plus 15 meq/liter Li, and prepared in \( \text{LN} \text{NH}_4\text{OAc} \) were also analyzed. A standard curve was drawn from those values. Calculations are as follows:

\[
\text{CEC meq/100 g} = \frac{\text{standard curve} \times 0.100 \text{ liter} \times 100 \text{ ml} \times 100 \text{ g}}{5 \text{ ml} \times \text{grams sample}} \tag{Eq. 25}
\]

where:
- 0.100 liter = original 100 ml dilution
- 100 ml = second 100 ml dilution
- 5 ml = aliquot taken for second dilution
- 100 g = to convert to a 100 g basis.

There have been several methods reported over the last 20 years that have attempted to improve on the CEC analysis of gypsiferous soils (Nijensohn, 1960; Yaalon et al., 1962; Garman and Hesse, 1975; Polemio and Rhoades, 1977; and Sayegh et al., 1978). Some methods involve removal of the gypsum before analysis or rendering it inactive due to BaCl\(_2\) treatment.

**Soluble, extractable, and exchangeable Na and K**

The determination of exchangeable cations in salt-affected soils presents special problems. Some of the soluble salts dissolve in the extracting solution and cause erroneous results. In nonsalt-affected soils, this problem is of no consequence. In salt-affected soils, separate determinations are made to assess the quantities of cations present in exchangeable and soluble forms. A completely satisfactory method has not been developed because there is a complex and shifting equilibrium among exchangeable salts, readily-soluble salts, and sparingly-soluble salts. A general understanding is that cations extracted in \( \text{LN} \text{NH}_4\text{OAc} \) are
soluble plus exchangeable forms. The soluble cations alone are determined from the saturation extract. The difference in these two values would be the exchangeable cations.

Soluble Na and K were determined from the saturation extracts. For the extracts analyzed, a dilution of 3 ml of saturation extract to 25 ml total volume was satisfactory for photometer determination. To a 25 ml volumetric flask, 3 ml of extract and 2.5 ml of 150 meq/liter LiCl solution were added, and then made to volume with 1N NH₄OAc. Sodium and potassium were determined in the same manner and with the same flame photometer as described under the CEC method. Calculations are as follows:

Soluble cation meq/100 g = cation meq/liter from \[
\frac{\text{H}_2\text{O}}{1 \text{ g soil}} \times \frac{\text{liter}}{1000 \text{ ml}} \times \frac{25 \text{ ml}}{3 \text{ ml}} \times 100 \text{ g}
\]

\text{(Eq. 26)}

where: \[
\frac{\text{ml H}_2\text{O}}{1 \text{ g soil}} = \text{saturation fraction or ''dilution ratio'' of the soil when wetted to saturation, i.e., saturation } \% \div 100
\]

\[
\frac{\text{liter}}{1000 \text{ ml}} = \text{conversion factor to convert ml to liter}
\]

25 ml = dilution volume
3 ml = aliquot volume diluted
100 g = to convert to a 100 g basis.

The equation can be simplified to:

Soluble cation meq/100 g = cation meq/liter from \[
\frac{\text{standard curve}}{1000 \times 3 \text{ ml}} \times \text{saturation } \% \times 25 \text{ ml}
\]

\text{(Eq. 27)}

The term extractable cations refers to those cations extracted with 1N NH₄OAc at pH 7.0. Extractable Na and K were determined by method 18.
The procedure is essentially that of the last \( \text{NH}_4\text{OAc} \) wash of the CEC procedure given earlier. Weigh 4.00-6.00 g of \(< 2 \text{ mm air-dried soil into a 50 ml round-bottom centrifuge tube. Add slightly less than 30 ml of } \text{IN NH}_4\text{OAc. Stopper and shake for five minutes on a reciprocating shaker. Centrifuge until the supernatant liquid is clear. Carefully decant the supernatant liquid into a 100 ml volumetric flask. Extract the soil two more times using the same procedure. Add 10 ml of 150 meq/liter LiCl solution to the flask and dilute to volume with } \text{NH}_4\text{OAc. See the CEC method for procedural notes and type of flame photometer used. Calculations are as follows:}

\[
\text{Extractable cation meq/100 g} = \text{from standard curve} \times 0.100 \text{ liter} \times \frac{100 \text{ g}}{\text{grams sample}}
\]  

(Eq. 28)

where: 0.100 liter = 100 ml dilution

100 g = to convert to a 100 g basis.

Exchangeable cations for salt-affected soils can then be calculated as follows:

\[
\text{Exchangeable cation meq/100 g} = (\text{extractable cation meq/100 g}) - (\text{soluble cation meq/100 g})
\]  

(Eq. 29)

Exchangeable Na was the cation desired to be quantified. Since exchangeable K could be determined on the same extracts with very little additional work, it was determined also.

Exchangeable Na was also determined on several nongypsiferous samples. The method just described for extractable cations using \( \text{IN NH}_4\text{OAc} \) was used.

Exchangeable sodium percentage (ESP) is a commonly-used term in studying salt-affected soils. It is the percentage of saturation of the exchange complex with Na and is calculated as follows:
\[
ESP = \frac{\text{exchangeable Na meq/100 g}}{\text{CEC meq/100 g}} \times 100 \quad \text{(Eq. 30)}
\]

**Soluble calcium and magnesium**

Soluble Ca and Mg were determined on saturation extracts using the procedure 62-3.2 of Bower and Wilcox (1965) with slight modifications. A brief procedure is as follows:

Pipette an exact 4 ml aliquot of saturation extract into a 30 ml beaker containing a small magnetic stirring bar. Dilute with distilled water to a volume of 15-20 ml. Start the magnetic stirrer. Add a pinch (about 5 mg) of dry sodium diethyldithiocarbamate. Add two drops of 4N NaOH and 20 drops of Calcon indicator. Titrate with standardized 0.02N ethylenediamine tetraacetate (EDTA) solution from a red to a stable, true blue color. Add one drop of concentrated HCl, one ml of the ammonium chloride (NH\(_4\)Cl)-ammonium hydroxide (NH\(_4\)OH) buffer, and two drops of Eriochrome Black T (EBT) indicator. Titrate with EDTA from a violet to a true, clear blue color. Calculations are as follows:

\[
\text{Ca meq/liter} = \frac{\text{ml of EDTA} \times \text{N meq/ml of EDTA for Ca}}{4 \text{ ml}} \times 1000 \quad \text{(Eq. 31)}
\]

where: \(\text{ml of EDTA}\) = the ml of EDTA used to reach the first endpoint
1000 = conversion factor from ml to liter
4 ml = aliquot taken.

\[
\text{Mg meq/liter} = \frac{\text{ml of EDTA} \times \text{N meq/ml of EDTA for Mg}}{4 \text{ ml}} \times 1000 \quad \text{(Eq. 32)}
\]

where: \(\text{ml of EDTA}\) = the ml of EDTA used between the first and second endpoints.

Several notes on the procedure not given in the cited method are as follows:
A 10 ml burette should be used for titrations. Blank solutions containing distilled water and the various reagents should be titrated to check for Ca and Mg contamination in the reagents. If present, the milliliters used to titrate a blank should be subtracted from all EDTA volumes for soil extracts. The endpoint colors of the blanks are also useful in determining endpoints for the unknowns.

The author found Calcon to be a much better indicator than murexide. Calcon is prepared by dissolving 20 mg/50 ml methanol. It could possibly be made more concentrated. Calcon coats the insoluble magnesium hydroxide (\(\text{Mg(OH)}_2\)) particles during the Ca titration and appears as red "snow flakes" in suspension. An excess of Calcon must be added to be available in solution. Too much Calcon however will interfere with the second endpoint. The Calcon endpoint is somewhat difficult to detect. Titrate the sample on a white sheet of paper under a light. Near the endpoint, add EDTA slowly at the rate of one drop every 5-15 seconds. As the endpoint is approached, the \(\text{Mg(OH)}_2\) particles will still be reddish but the solution matrix will be blue. Momentarily, the matrix solution gradually returns to a reddish tinge. Continue to add EDTA slowly between periods of waiting until the \(\text{Mg(OH)}_2\) particles remain blue, and the solution matrix is a true blue when looking through the beaker onto a white sheet of paper.

Triethanolamine can be used as the carrier of the EBT indicator. To help determine the EBT endpoint, the solution may have to be diluted with water again if it is too dark. At the endpoint, the color should be a clear blue with no tinge of purple when looking through the beaker onto
white paper. The EBT endpoint is much clearer than the Calcon endpoint.

Determining both Ca and Mg on the same aliquot saves the usually limited volume of saturation extract. A unique pipetting technique can also save extract volume. It is standard laboratory practice to rinse a pipette three times with a solution before the final aliquot is taken. Such a procedure would waste the extract. Instead, rinse the pipette well with water and then once with acetone. Blow out the pipette with a suction bulb and rinse again with acetone. Blow out the pipette several times until absolutely dry. The pipette is clean and dry, and the next aliquot can be pipetted immediately.

In calculations, it was implied that the EDTA would have a slightly different normality when standardized against Ca as when standardized against Mg. Although many assume that EDTA complexes divalent cations in equivalent amounts, this is not true in all cases. It is usual for EDTA to have a slightly lower normality for Ca than for Mg (R. E. Nelson, USDA-Soil Conservation Service, National Soil Survey Laboratory, Lincoln, Ne. Personal communication, 1978). The author has found this to be true in all of his work with EDTA. For example, the EDTA used in the just mentioned analysis had a normality 0.0010 meq/liter lower for Ca than for Mg, a decrease of about 5%.

The concentration of Ca and Mg in saturation extracts may be used in calculating a common expression of soluble ions in soils, the sodium adsorption ratio (SAR). It is a mathematical relationship between Na, Ca, and Mg concentrations. It is calculated as follows:
SAR = \frac{\text{Na}}{\sqrt{\frac{\text{Ca} + \text{Mg}}{2}}} \quad (\text{Eq. 33})

where: Na, Ca, and Mg represent the concentrations of the respective ions in meq/liter in the saturation extract.

The SAR is a unitless value. Recently, the U.S. Salinity Laboratory has revised its method of calculating SAR on soils having saturation extracts of \( \geq 20 \text{ mmhos/cm EC} \). See the footnote of page 28 of Soil Taxonomy (Soil Survey Staff, 1975). It is not believed that this change has been published elsewhere.

The SAR value can also be used to give an estimation of the exchangeable sodium percentage (ESP) of a soil. The U.S. Salinity Laboratory has developed a mathematical relationship between the two. See method 20b of U.S. Salinity Lab Staff (1954).

\[
\text{ESP} = \frac{100 (-0.0126 + 0.01475 \text{ SAR})}{1 + (-0.0126 + 0.01475 \text{ SAR})} \quad (\text{Eq. 34})
\]

pH

The determination of pH on salt-affected soils presents problems also. It is well-known that the pH of solutions measured by electrodes decreases as electrolyte concentration increases due to electrochemical effects (page 294 FF of Black, 1968). The pH values of salt-affected soils prepared in the usual 1:1 soil-water ratio would be erroneous. The pH values would be correlated to the amounts and kinds of soluble salts rather than hydrogen ion concentrations. In the case of highly gypsiferous soils, the values would merely reflect the pH of partially saturated gypsum solutions. For salt-affected soils, pH measurements must be done on saturated pastes. The problem of salts dissolving in excess water
is avoided. A saturated paste is prepared and allowed to stand for at least one hour. The electrodes are inserted into the paste and raised and lowered until a representative pH reading is obtained (method 21a, U.S. Salinity Lab Staff, 1954).

The pH of salt-affected soils is usually used to indicate Na content rather than just hydrogen ion content. The presence of appreciable amounts of Na in soils produces NaOH and Na₂CO₃ which are both highly alkaline. The U.S. Salinity Laboratory has made the following interpretations for pH readings of saturated soil pastes. (1) pH values ≥ 8.5 almost always indicate an ESP of ≥ 15 and the presence of alkaline earth carbonates. (2) The ESP of soils having pH values < 8.5 may or may not exceed 15. (3) Soils having pH values of < 7.5 almost always contain no alkaline earth carbonates.

For the current study, the preparation of saturated pastes for each sample solely for the purpose of determining pH would not be time efficient. Although high Na contents were not expected, it was desired to assess the soils for that possibility. The author used an unpublished, mimeographed method developed by the USDA-Soil Conservation Service, National Soil Survey Laboratory (R. E. Nelson, personal communication, 1979). It was entitled "Estimating Exchangeable Sodium, Gypsum, and Sodium Adsorption Ratio in Soils by pH Tests." The procedure is as follows:

Prior to the pH test, rub some soil between the thumb and forefinger. Discard the soil and then rub the fingers until free of the soil powder. This operation removes perspiration that may contain Na. Place a small
amount of < 2 mm soil into a well of a white porcelain spot plate. The sample should be about 0.5 cm in diameter. If the soil has not been ground to pass a 2 mm sieve, crush the sample between the fingers first. Add 10 drops of 40% ethanol solution from a dropper bottle and stir with a stirring rod. Add two drops of 0.02% phenol red indicator (La Motte Chemical Co., Baltimore, Md., Solution No. 2211-L). During the next two minutes, tilt the spot plate several times to help mix the soil and solution. After two minutes, read the pH of the supernatant solution by comparing its color to a color chip card for phenol red. If the pH is $\geq 7.8$, the SAR is $> 13$. If the pH is $< 7.8$, the SAR is $< 13$.

A few notes on the procedure are as follows:

Gypsum does not dissolve in the 40% ethanol solution. The presence of gypsum does not mask the presence of high Na contents. Soils high in dark organic matter may make color comparisons difficult. The color comparisons should be done in natural light if possible. The upper limit of phenol red is pH 8.4. If soils with pH values $> 8.4$ are expected, cresol red can be used (0.02%, La Motte Solution No. 2212-L). The procedure is very rapid.

Soils that have a pH value of $\leq 7.3$ do not contain alkaline earth carbonates. This finding agrees with the 1:1 soil-water electrode method. Yet it appears that soils containing large amounts of alkaline earth carbonates do not read as high by this colorimetric method as do such soils analyzed by the 1:1 soil-water electrode method. Soils that would be expected to read pH 7.6-7.9 by the electrode method only read pH 7.4-7.5 by this method. Possibly alkaline earth carbonates are also less soluble
in the 40% ethanol solution.

Water Samples

Introduction

Water samples were collected from various surface and ground waters. When samples were collected from wells through a series of pipes, the pipes were first flushed of stagnant water. All samples were placed in polyethylene bottles and stored 8-12 months at 3°C until analyzed.

Electrical conductivity

All electrical conductivity determinations were made directly on the water samples using the same apparatus as described under the section for soil samples.

Calcium sulfate and total sulfate

Calcium sulfate was determined on the water samples using the acetone precipitation method as described for gypsum analysis in soil samples. Pipette a 5 ml aliquot of sample directly into a 15 ml conical centrifuge tube. Add 5 ml of acetone and treat the precipitate exactly as for the gypsum procedure. After determining EC on the final solution, calculate results as follows:

\[
\text{CaSO}_4 \text{ meq/liter in water sample} = \text{CaSO}_4 \text{ meq/liter from standard curve} \\
\text{(Eq. 35)}
\]

assuming a 5 ml aliquot and a 10 ml final dilution were used both in preparing the standard curve and in analyzing the unknowns.

Total sulfate was determined on the samples using method 14b of U.S. Salinity Lab Staff (1954) with slight modifications. This method
is essentially the same as for determining CaSO₄ except that a small quantity of CaCl₂ is first added to the sample. All SO₄ that is not CaSO₄ will be converted to CaSO₄ and be precipitated by the acetone treatment. The author desired to test the accuracy of the method briefly although Bower and Huss (1948) found it to be satisfactory. Analyses were done on aliquots containing 10.0 meq/liter of CaSO₄ and varying concentrations of sodium sulfate (Na₂SO₄). One milliliter of 0.5N CaCl₂ was either added or not added to the tubes before addition of the acetone. If it was not added, the sulfate determined should equal the 10.0 meq/liter of CaSO₄. If it was added, the sulfate determined should equal the sum of the 10.0 meq/liter CaSO₄ and the added Na₂SO₄. The results are shown in Table 15.

At the lower concentrations of Na₂SO₄, both CaSO₄ and total SO₄ are determined fairly accurately. Where the proportion of Na₂SO₄ is 2-4 times that of CaSO₄ in the original aliquot, both determined values tend to be high. At these high concentrations with no CaCl₂ added, some Na₂SO₄ might be occluded in the CaSO₄ precipitate to make the final EC reading slightly high. When CaCl₂ is added, the large mass of precipitate that occurs might occlude some CaCl₂ or NaCl to make the final EC reading slightly high. Washing the precipitate an extra time with acetone and lowering the concentration of CaCl₂ to 0.25N did not improve results.

Sodium sulfate was chosen as the source of the added SO₄ in the trial because Na is a highly hydrated ion in solution. It was felt that NaSO₄ would cause more interference with the precipitation mechanism than
Table 15. Results of the accuracy of the CaCl₂-acetone precipitation method for calcium sulfate and total sulfate analysis

<table>
<thead>
<tr>
<th>CaSO₄ meq/liter</th>
<th>Na₂SO₄ meq/liter</th>
<th>1 ml 0.5N CaCl₂ added?</th>
<th>Determined SO₄ meq/literᵃ</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>0.0</td>
<td>No</td>
<td>10.0*</td>
</tr>
<tr>
<td>10.0</td>
<td>0.0</td>
<td>Yes</td>
<td>10.4</td>
</tr>
<tr>
<td>10.0</td>
<td>5.0</td>
<td>No</td>
<td>10.2</td>
</tr>
<tr>
<td>10.0</td>
<td>5.0</td>
<td>Yes</td>
<td>15.3</td>
</tr>
<tr>
<td>10.0</td>
<td>10.0</td>
<td>No</td>
<td>10.0</td>
</tr>
<tr>
<td>10.0</td>
<td>10.0</td>
<td>Yes</td>
<td>20.4</td>
</tr>
<tr>
<td>10.0</td>
<td>15.0</td>
<td>No</td>
<td>11.2*</td>
</tr>
<tr>
<td>10.0</td>
<td>15.0</td>
<td>Yes</td>
<td>25.0</td>
</tr>
<tr>
<td>10.0</td>
<td>20.0</td>
<td>No</td>
<td>11.5*</td>
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<tr>
<td>10.0</td>
<td>20.0</td>
<td>Yes</td>
<td>30.9</td>
</tr>
<tr>
<td>10.0</td>
<td>30.0</td>
<td>No</td>
<td>12.9</td>
</tr>
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<td>10.0</td>
<td>30.0</td>
<td>Yes</td>
<td>41.7</td>
</tr>
<tr>
<td>10.0</td>
<td>40.0</td>
<td>No</td>
<td>13.5</td>
</tr>
<tr>
<td>10.0</td>
<td>40.0</td>
<td>Yes</td>
<td>53.4*</td>
</tr>
</tbody>
</table>

ᵃValues in this column not marked with a * represent the mean of three analyses. Values marked with a * represent the mean of five analyses.

MgSO₄ or K₂SO₄. This appeared to be true. Instead of a typically white, curdy precipitate, the large amounts of added Na₂SO₄ caused a translucent gelatinous precipitate to form. It was difficult to centrifuge out. Also the large masses of gelatinous precipitate should not be dried directly in a 105°C oven. Spattering may occur. Instead they should dry at room temperature for several hours or overnight, and then at 105°C if necessary.
The 1 ml of 0.5N CaCl$_2$ contains 0.5 meq of Ca available for reaction with SO$_4$. The sample to be analyzed should not contain more than 0.5 meq of non-CaSO$_4$ sulfate. This would correspond to a 5 ml aliquot containing non-CaSO$_4$ sulfate at a concentration of 100 meq/liter.

Lagerwerff et al. (1965) suggested using calcium nitrate (Ca(NO$_3$)$_2$) instead of CaCl$_2$ as the source of free Ca. Nelson (1970) used Ca(NO$_3$)$_2$ as well as several other modifications to refine the procedure further.

**Sodium and potassium**

Sodium and potassium concentrations were determined on the water samples using the same basic procedure and instrument as given under the soil analysis section. Five milliliters of 150 meq/liter LiCl solution were added to a 50 ml volumetric flask. The solution was then made to volume with the water sample. Calculations are as follows:

\[
\text{Cation meq/liter} = \frac{\text{cation meq/liter from standard curve}}{45 \text{ ml}} \times 50 \text{ ml} \quad \text{(Eq. 36)}
\]

where:
- 50 ml = total dilution
- 45 ml = aliquot diluted.
SURFICIAL GEOLOGY AND PRESENT CLIMATE OF STUDY AREAS

Surficial Geology

Soil areas were studied in Webster, Clay, and Dickinson Counties in Iowa and Cottonwood and Redwood Counties in Minnesota. Figure 2 shows a soil association map of Iowa with the approximate study area locations noted. The study areas in Minnesota are about 50 miles north of Spirit Lake, Iowa. Their location is shown in Figure 3.

The soil association map of Iowa (Figure 2) can also be used to indicate surficial geology. Webster Co. is within the Clarion-Nicollet-Webster (CNW) soil association area. This region was covered by the Des Moines lobe of late-Wisconsin glaciation. The study area in Clay Co. is on the border between the Clarion-Nicollet-Webster and the Galva-Primghar-Sac (GPS) soil association areas. The GPS soil association area has a thin deposit of Wisconsin loess or loamy sediments overlying early-Wisconsin or pre-Wisconsin glacial drift. The crosshatched area of the GPS soil association area (Figure 2) is underlain by early-Wisconsin drift. The noncrosshatched area is underlain by pre-Wisconsin drift. The study area in Dickinson Co. is within the GPS soil association area and is underlain by early-Wisconsin drift. The study areas in Cottonwood and Redwood Counties, Minnesota are within the region also covered by the Des Moines lobe of late-Wisconsin glaciation. Figure 4 shows the locations of the late-Wisconsin glacial lobes and moraines of portions of Iowa, Minnesota, and South Dakota (Matsch et al., 1972).

Discussion of the surficial geology of southwestern Minnesota is
Figure 2. Soil association map of Iowa showing approximate study area locations. One inch equals 48 miles.
X = STUDY AREA LOCATIONS

B : Soils of Miss, River bottomland

III Gradational Boundary — Tentative Boundary — Abrupt Boundary

AGH: Adair-Grundy-Hair
ASE: Adair-Seymour-Edina
CKL: Clinton-Keswick-Lindley
CLC: Cresco-Louise-Clyde
CNW: Clarion-Nicollet-Webster
D: Downs
DT: Dinsdale-Tama
F: Fayette
FDS: Fayette-Dubuque-Stonyland
GPS: Galva-Primghar-Sac
GH: Grundy-Hair
KFC: Kenyon-Floyd-Clyde
LK: Lindley-Keswick-Weller
LOS: Lunan-Onawa-Solix
M: Marshall
MIH: Monona-Ida-Hamburg
Mo: Moody
OMT: Otley-Mahaska-Taintor
SSM: Shelby-Sharpsburg-Macksburg
TM: Toma-Muscattine
Figure 3. County map of southwestern Minnesota
Soil study area shown by "X". Isolines represent the content of Cretaceous Pierre shale, in percent, in the coarse sand fraction (1-2 mm) of New Ulm till
Figure 4. Late-Wisconsin glacial lobes and moraines of portions of Iowa, Minnesota, and South Dakota.
presented by Matsch (1972). The drift in southwestern Minnesota that was deposited by the advance and retreat of the Des Moines lobe is called New Ulm drift. This drift is believed to have had its source in the vicinity of the Winnipeg lowland. This area is a belt of Paleozoic sedimentary rocks, mostly fine-grained limestone and dolomites, that occurs in a zone as much as 140 miles wide and over 400 miles long. The area covers southern Manitoba and the northwestern corner of Minnesota. The New Ulm drift contains hard, brittle, noncalcareous, gray or greenish, siliceous shale. The most likely source for the shale is the Upper Cretaceous Pierre shale which covers an extensive area of eastern North and South Dakota and southern Minnesota.

The New Ulm drift is predominantly calcareous. New Ulm till is predominantly yellow to olive brown (oxidized) or dark gray (unoxidized). The till is predominantly a loam in texture. The New Ulm till is characterized by three major rock types in the coarse sand (1-2 mm) fraction: siliceous shale, carbonates (mostly fine-grained dolomite and limestone), and granitic rocks. The content of shale in the 1-2 mm size fraction is a unique property that varies with location. There is a regular decrease in shale content on either side of the topographic axis of the Minnesota River lowland. In other words, the shale content decreases in directions normal to the Minnesota River. See Figure 3 for a graphic representation of this phenomenon. The explanation of this occurrence assumes a depositional difference. It is believed the ice sheet crossed the Cretaceous shale area to the northwest and had a high, uniform content of shale. As the initially broad ice sheet became constricted within the Minnesota
River lowland, the physics of the glacier changed. Almost no erosion occurred on the axial part where the ice was the thickest. Along the thinner margins of the ice tongue, ice flowed outward toward the lowland margins. Erosion of the drift sheet was fairly active, and the shale load was "diluted" with shale-poor, underlying drift.

The New Ulm drift is known as Cary drift in Iowa. Its distribution in Iowa is shown in Figure 4. The Bemis moraine marks its southern, western, and eastern boundary. The glacier reached central Iowa by 14,000 rcybp (Ruhe, 1969). By 13,000 rcybp, the Des Moines lobe ice had melted back almost to the Minnesota border. During the next 1,000 years, most of the ice melted from southern Minnesota. Since the drift plain is relatively young geologically speaking, drainage nets are not yet well-developed. Outwash sands and gravels are present in the drift also, especially in end moraines. The New Ulm or Cary drift is known as the James (or James River) drift in eastern South Dakota.

The study areas in Webster Co., Ia. and Redwood and Cottonwood Counties, Mn. are located within the Cary (or New Ulm) drift region.

Matsch (1972) also describes what is termed an "extra-moranic", shale-bearing drift. It is a belt of loess-covered drift lying adjacent to and southwest of the Bemis moraine in southwestern Minnesota and northwestern Iowa. Lithologically, it is similar to New Ulm till within the boundary of the moraine. It has 15-20% of siliceous Cretaceous shale in the 1-2 mm size fraction, but tends to be slightly more silty than New Ulm till. This till is termed Tazewell in Iowa (Ruhe, 1969). Its lithology indicates it was derived from the same source area as New Ulm till.
Since the Bemis moraine overlies it, it is older than New Ulm (or Cary) till. Ruhe (1969) dated it at 20,000 rcybp, some 6,000 years older than Cary till. It has not been determined if this drift represents a regionally significant stage of the Des Moines lobe. Matsch (1972) considers the Tazewell till as "correlative with New Ulm till" and does consider it a part of New Ulm till, despite the age difference. Ruhe (1969) does not consider the Tazewell till part of the Cary (or New Ulm) till. There is a marked difference in drainage net development between the two drift areas in Iowa. The Tazewell drift area has well-developed open drainage with few closed depressions. See Figure 3.12 of Ruhe (1969). He also concludes that the drainage system must have been established on the Tazewell surface prior to deposition of the Cary drift. See Plate I of Ruhe (1969) for a pictorial representation of the surface geology of Iowa.

The study area in Clay Co. is situated on the boundary between the Cary and Tazewell drift areas. A pronounced terminal moraine is not present. The study area in Dickinson Co. is in the Tazewell drift area that is covered by loess or loamy sediments. The deposition of the loess ceased prior to 14,000 rcybp. The crosshatched area of the Galva-Primghar-Sac (GPS) soil association area in Figure 2 shows the area where loess or loamy sediments overlie Tazewell drift. The noncrosshatched area shows the area where loess overlies pre-Wisconsin drift.
Present Climate

Figure 5 shows a map of the mean annual temperatures (°F) of Iowa. Figure 6 shows a map of the mean annual precipitation (inches) of Iowa. Both figures are from Shaw and Waite (1964).

Figure 7 shows a map of the mean annual temperatures (°F) of southern Minnesota. Figure 8 shows a map of the mean annual precipitation (inches) of southern Minnesota. Both figures are from Wright (1972).

From these figures the climatic data for the study sites can be summarized. The data are presented in Table 16.

Table 16. Summary of selected climatic data for the study areas

<table>
<thead>
<tr>
<th>County</th>
<th>State</th>
<th>Mean annual temperature, °F</th>
<th>Mean annual precipitation, inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Webster</td>
<td>Iowa</td>
<td>48.5</td>
<td>30.0</td>
</tr>
<tr>
<td>Clay</td>
<td>Iowa</td>
<td>46.5</td>
<td>28.0</td>
</tr>
<tr>
<td>Dickinson</td>
<td>Iowa</td>
<td>46.0</td>
<td>27.0</td>
</tr>
<tr>
<td>Cottonwood-Redwood</td>
<td>Minnesota</td>
<td>46.0</td>
<td>25.0</td>
</tr>
</tbody>
</table>
Figure 5. Map of the mean annual temperatures (° F) of Iowa

One inch equals 58 miles.
Figure 6. Map of the mean annual precipitation (inches) of Iowa
One inch equals 88 miles

Figure 7. Map of the mean annual temperatures (°F) of southern Minnesota
One inch equals 116 miles.
Figure 8. Map of the mean annual precipitation (inches) of southern Minnesota

One inch equals 116 miles.
The legal locations will be given in locating the exact sampling sites. This location description includes the section, township, and range numbers as well as directional distances from specific points. The directions of north, south, east, and west will be abbreviated, N, S, E, and W, respectively. The terms section, township, and range will be abbreviated Sec., T, and R, respectively.

Dickinson County, Iowa

The study areas in Dickinson County are located in the southwestern portion of the county. They are within the area of Tazewell drift covered by a thin mantle of Wisconsin loess or loamy sediments. Figure 9 shows a map of Dickinson Co. with the study areas noted. Site 1 is near the "1" on the map and Sites 2 and 2A are near the "2" on the map. The wavy line which bisects the southwestern portion of the county is the approximate boundary between the Cary and Tazewell drift areas (W. N. Dankert, USDA-Soil Conservation Service, Spirit Lake, Iowa. Personal communication, 1978). The southwestern portion is the area of loess or loamy sediments overlying Tazewell drift. The remainder of the county to the north and east is the area covered by Cary drift. Some of the effects of the Cary glaciation, i.e., outwash sands and gravels, may extend into the area of loess or loamy sediments overlying Tazewell drift.

Site 1 is located 132 ft E and 72 ft N of the SW corner, SE%, Sec. 23, T98N, R38W. The site is located in a Lettri silty clay loam, 0-2% slopes,
Figure 9. Map of Dickinson County, Iowa, showing locations of study areas.

One-fourth inch equals one mile.
mapping unit. The Letri series consists of poorly-drained soils formed in less than 30 inches of loamy sediments over glacial till. A stone line or sandy erosional sediments up to four inches thick may be above the till surface. The Letri series is a member of the fine-loamy, mixed, mesic Typic Haplaquolls. The sampling site is in an area on about a 1% slope to the west. The soils slope generally in the other three directions. About 500 ft to the north is the base of a slope of 2-5%. A 1-2%, slightly concave slope rises to the east. About 500 ft to the south is the base of a slope of 2-5%. The sampling site is on a slight rise or microknoll. The dry soil surface is markedly lighter in color than the surrounding soil due to the presence of gypsum. The microknoll is about 30-40 ft in diameter and rises several inches higher than the surrounding soil. There is a sharp line of demarcation between the area with gypsum and the surrounding area.

Appendix F, Slide 2 shows a picture of the sampling site. A profile description of the soil at this site is included in Appendix A. Laboratory data for the soil are given in Appendix B, Table 23. The data and description indicate that almost all of the gypsum is in the upper part of the profile above the till. The gypsum content also abruptly decreases at a depth of 21-23 inches. There are dark subsurface horizons at depths of 21-23 and 23-25 inches. These will be discussed in a later section.

Site 2 is located 135 ft E and 160 ft N of the SW corner, NW^1, Sec. 25, T98N, R38W. The site is also located in a Letri mapping unit. The site is in a very broad, low saddle position. The area rises to the east at a < 1% slope for about one-half mile. Areas to the north and south also
have slopes of $< 1\%$ but rise to 2-4% at less than one-half mile. The drainage outlet of the area is to the west. Site 2 is located in a circular area, about 30 ft in diameter, that is much lighter in color than the surrounding area due to the presence of gypsum. The circular area of gypsiferous soil has an abrupt line of demarcation with the surrounding nongypsiferous area. The gypsiferous area is not on a microknoll. It has a planar surface consistent with the adjacent area. In sampling this site, the hydraulic probe was stopped repeatedly at a depth of 43 inches due to gravel. Several (6-7) similar gypsiferous "spots," also circular in nature, are upslope to the east-northeast of Site 2.

Site 2A is located 42 ft northwest of Site 2. It is located outside the gypsiferous area. This site was selected to demonstrate the extreme change in soil properties over a short distance.

Appendix F, Slide 3 shows a picture of the sampling sites. Profile descriptions of soils at both sites are included in Appendix A, and laboratory data are given in Appendix B, Table 24. The differences between the two profiles are striking. The profile that is present at Site 2A is not within the range of the Letri series. The upper layer of loamy sediments is 40 inches thick. Thirty inches of loamy sediments is the maximum thickness allowed within the range of the series. Carbonates are present at a depth of 42 inches. Typically, the carbonates are at depths of 16 to 30 inches. There is a two-inch erosional lag above the till at a depth of 40 to 42 inches. The profile at Site 2A contains no gypsum. The profile at Site 2 has lower amounts of sand, silt, and clay than the profile at Site 2A. This would be expected due to the large volume of
gypsum present. The gypsum content decreases abruptly at 18 inches. The 18-22 inch horizon is dark colored. The erosional lag begins at 22 inches, and the lower 13 inches of the profile are high in sand. In sampling, the probe could not penetrate below 43 inches, probably because of gravel overlying the till. If the gravel layer is thin at this site, the depth to the till in both profiles would be similar. The profile at Site 2 also contains slight amounts of carbonates to the soil surface. The organic carbon content decreases more rapidly than in the profile at Site 2A. The 30-36 and 36-43 inch horizons of the profile at Site 2 have a moist color of 10YR 5/8. Iron coatings on sand grains and iron concretions are also present.

Clay County, Iowa

The study area in Clay Co. is located in the north-central portion of the county near the border between the Cary and Tazewell drift areas. According to Fisher (1969), the study area is in the Ocheyedan-Webster-Guckeen-Marna soil association area. This area is considered to be within the Cary drift area. The Tazewell drift area is one-half mile to the north of the study area. Figure 10 is a map of Clay Co. with the location of study area noted by an "X". The wavy line which bisects the eastern portion of the county is the approximate boundary between the Cary and Tazewell drift areas. The region to the west of the line is the region of loess or loamy sediments overlying Tazewell drift. The region to the east of the line is the Cary drift region. Glacial outwash does extend into the Tazewell drift area. The boundary line shown in Figure
Figure 10. Map of Clay County, Iowa, showing location of study area

One-fourth inch equals one mile.
10 is an approximate boundary.

The study area is included on map sheet 21 of the Clay Co. soil survey report (Fisher, 1969). Sites 1-7 are included in a delineation mapped as Marna silty clay loam, calcareous variant, 0-2% slopes. The Marna series consists of poorly drained soils developed in clayey lacustrine sediments. It is commonly noncalcareous to a depth of 3-4 ft, but a variant mapped in Clay Co. is calcareous throughout the profile. The noncalcareous Marna is usually a silty clay texture, but the calcareous variant is usually a silty clay loam. The noncalcareous Marna is a member of the fine, montmorillonitic, mesic Typic Haplaquolls. The study sites are located within and adjacent to a small drainage way that is dry most of the year. The bottom of the drainage way does not appear to contain any gypsum. Within 100 ft to the south of the center of the drainage way are slight knolls or mounds which contain abundant gypsum and are noticeably lighter in color. The physiographic setting of the area is a flat lacustrine plain with low hills of glacial outwash sediments dotting the landscape. The flat plain extends to the north of the site area about one-fourth mile until it grades into a region of soils formed in loamy sediments and the underlying Tazewell drift. The plain extends to the south for almost a mile. To the east and west of the site area are low hills of 2-4% slope gradient at a distance of one-eighth mile.

Site 1 is located 815 ft N and 114 ft E of the SW corner, NW¼, Sec. 29, T97N, R36W. It is on a slight knoll about 100 ft south of the center of the small drainage way. The microknoll is about 150 ft in diameter and if 1-2 ft higher than the level lacustrine plain immediately adjacent to
the south. The microknoll also is 3-4 ft above the center of the drainage way. The gypsiferous soil on the microknoll shows evidence of abundant rodent burrowing. Site 2 is located in the center of the drainage way 100 ft north of Site 1. The hydraulic probe was stopped at a depth of 60 inches due to gravel. Figure 11 shows the arrangements of the sampling sites.

Profile descriptions of the soils at Sites 1 and 2 are included in Appendix A. Laboratory data are given in Appendix B, Tables 25 and 26 for Sites 1 and 2, respectively. The gypsum accumulation is in the upper part of the profile at Site 1. The gypsum content decreases abruptly at 68 inches. At the till contact at 80 inches, the gypsum content is very low. The upper 35 inches of the profile contain very little gravel. The 35-80 inch section appears to be stratified glacial sediments above the till. Enough sample was collected from each horizon of the profile at Site 1 to permit the analysis of saturation extracts. These data will be discussed in a later section.

The data and description for the profile at Site 2 indicate that no gypsum is present throughout the profile. The material in the upper 29 inches appears to be sediments. The till contact is at a depth of 24 inches.

Since it appeared that the mound of gypsum might have accumulated on top of a fairly level surface, further investigations were done. A transect was laid out over another gypsiferous microknoll immediately to the east of the Site 1 area. Five profiles were collected beginning in the middle of the drainage way and transecting the microknoll to the
Figure 11. Diagram showing the locations of Clay County, Sites 1-7
south. The last profile was collected beyond the microknoll on the flat lacustrine plain where no gypsum was evident. The sampling sites were spaced at intervals of 50 ft. Figure 11 shows the arrangement of the sampling sites. Appendix F, Slide 4 shows a picture of the transect sites. Site 3 is located 246 ft E and 815 ft N of the SW corner, NW<sub>1/4</sub>, Sec. 29, T97N, R36W, or 132 ft due east of Site 1. It is located in the center of the drainage way. In sampling, the hydraulic probe was stopped at 53 inches due to gravel. Site 4 is located 50 ft south of Site 3 on the northern edge of the microknoll. Its elevation is about 2 ft higher than Site 3 in the drainage way.

Site 5 is located 50 ft south of Site 4. It is on the crest of the microknoll. Its elevation is about 2 ft higher than Site 4, or about 4 ft higher than the center of the drainage way. Site 6 is located 50 ft south of Site 5 on the southern edge of the gypsiferous microknoll. Its elevation is about 1 ft lower than the crest of the microknoll. Site 7 is located 50 ft south of Site 6 on the nongypsiferous, Marna-like lacustrine plain. Its elevation is about 1 ft lower than Site 6, or about 2 ft lower than the crest of the microknoll.

Profile descriptions for the soils at Sites 3-7 are included in Appendix A. Laboratory data are given in Appendix B, Tables 27-31. The data and description for the profile at Site 3 indicate that this soil formed in alluvium and has organic matter extending deeply into the profile. The sediments are probably reworked glacial drift. No till was encountered to a depth of 52 inches. The profile at Site 4, on the edge of the microknoll, appears to have about 25 inches of gypsum accumulated
above the soil found at Site 3. The gypsum content decreases abruptly at 25 inches. The soil below 25 inches appears from the laboratory data to be similar to the soil exposed at Site 3. No till was encountered to a depth of 72 inches.

The profile at Site 5, located at the crest of the microknoll, has a deep accumulation of gypsum which decreases abruptly at 68 inches. No clear evidence of a buried surface is present. Till derived soil was reached at a depth of 68 inches and appears to be the B horizons of a buried soil. The profile at Site 6, located on the southern edge of the microknoll, has a gypsum accumulation also in the upper portion of the profile. The gypsum content decreases abruptly at 38 inches. The horizon at 38-44 inches appears to be a krotovina. The horizons beginning at 44 inches may be part of the buried surface present in the other profiles. Till was at 56 inches. The profile on Site 7, located outside the gypsisiferous area, contains essentially no gypsum in any part of the profile. The profile contains organic matter extending deeply into the profile. The upper 46 inches appear to be similar to the upper 32 inches of the profile at Site 3. A krotovina is at 46-54 inches. There appears to be stratified glacial sediments from 54 to 115 inches. Till was at a depth of 115 inches.

Combining the data and descriptions of the profiles at Sites 3-7 can give an indication of the material below the gypsisiferous mound. It appears that the dark soil exposed at Site 3 in the drainage way and at Site 7 in the level lacustrine plain underlies the mound. The area between Sites 3 and 7 was evidently also a dark soil at one time. It
probably sloped gently toward the drainage way. Subsequently, a large amount of gypsum has accumulated above the area. A diagram showing the cross section of Sites 3-7 is given as Figure 12. The till surface is uneven below the sites. It is possible that the till surface may have been dissected after deposition since the area was subjected to fluvial processes associated with the late-Wisconsin glaciation. The study site area appears to have been filled fairly level with glacial sediments. Some sediments nearer the till are coarse textured. The sediments near the present surface are fine textured and are the parent material for Marna and related soils. The gypsum appears to have accumulated after the glacial sediments were deposited and some soil development had occurred. The processes of gypsum accumulation will be discussed in a later section.

Site 8 is located 1134 ft E and 174 ft N of the SW corner, Sec. 29, T97N, R36W. It is located slightly more than one-half mile south-southeast of Sites 1-7. Site 8 is located in an area of Canisteo silty clay loam, gypsic variant, 0-2% slopes. It is shown on map sheet 21 of the Clay Co. soil survey report (Fisher, 1969). The Canisteo series consists of nearly level, poorly drained soils formed in glacial till or glacial sediments. The series is calcareous throughout the profile. In Clay Co., a variant of the Canisteo series was mapped that contained gypsum. The variant is small in extent, comprising only 144 acres. It is found to the northeast of the town of Spencer in the SW¼, Sec. 29 and the NW¼, Sec. 32, T97N, R36W and in Sec. 8, T96N, R36W. The gypsum in these delineations is not concentrated in clearly defined areas or microknolls.
Figure 12. Diagram showing the cross section of Clay County, Sites 3-7.
Instead it is fairly evenly distributed throughout soil areas of 50-100 acres. The 144 acres of the Canisteo, gypsic variant mapping unit in Clay County is composed of only two map delineations.

Site 8 is located on a nearly level lacustrine plain with low hills of glacial sediment dotting the landscape. Its specific setting is a nearly level surface between a Marna silty clay mapping unit slightly upslope to the west and a small drainage way to the east. The slope of the site is < 1%. The site appears to be in a very slightly concave position with a small rise along the north and east sides adjacent to the drainage way. The gypsiferous area may be described as a very slightly concave bench about 1/8 to 1/4 mile wide. The small rise is not a mound of gypsum accumulation. Any surface drainage of the area would be to the southeast.

Appendix F, Slide 5 shows a picture of the sampling site. A profile description is included in Appendix A. Laboratory data are given in Appendix B, Table 32. The data and description indicate that the soil developed in glacial sediments rather than till. Gravel is present in very small quantities. The gypsum accumulation is in the upper part of the profile and decreases abruptly at 56 inches. The reason the 38-43 inch horizon is lower in gypsum than adjacent horizons is the size of the crystals. Since they were segregated and often > 2 mm in size, they were not included in the < 2 mm portion. It should also be noted that other horizons may have more gypsum present than is actually determined for this same reason. Fine-textured sediments are at depths greater than 56 inches. These sediments are common in the area. Both Marna silty clay
and Guckeen clay loam, silty clay substratum soils are mapped in the area.

Webster County, Iowa

The study area in Webster Co. is located in the south-central portion of the county. It is within the Cary drift region of the late-Wisconsin glaciation. Figure 13 is a map of Webster Co. with the study area marked by an "X". Site 3 is located 1290 ft E and 845 ft N of the SW corner, Sec. 10, T87N, R29W. This location is also 12 ft W and 306 ft S of the clump of cottonwood trees on the SW edge of the most southerly 90° bend of Drainage Ditch No. 29 in the same section. The site is located in a Lanyon silty clay, 0-1% slopes, mapping unit. The Lanyon series consists of dark-colored, very poorly-drained soils that formed in clayey lacustrine sediments. The series is commonly silty clay in texture to a depth of 3-4 ft. Silty clay or silty clay loam textured sediments commonly are below that depth. The soils are on slopes of < 1%. The profile may be calcareous throughout or the surface layer may be noncalcareous. The Lanyon series is a member of the fine, montmorillonitic, mesic Typic Haplaquolls.

The study area is included on map sheet 62 of the Webster Co. soil survey report (Koppen, 1975). The surrounding area is extremely level. A slope gradient of less than 1% extends for about a mile or more in all directions. There are no major changes in relief for several miles in all directions. Site 3 appears to be in the central part of a very broad, shallow basin. An oblong delineation of Harps soils approximately
Figure 13. Map of Webster County, Iowa, showing location of study area

One inch equals 4.7 miles
3/4 mile long by 1/2 mile wide completely encompasses the Lanyon delineation. Site 3 does not appear to be on a microknoll.

Site 4 is located 95 ft north of Site 3 or 1290 ft E and 940 ft N of the SW corner, Sec. 10, T87N, R29W. It is noticeably more gravelly on the surface and lighter in color than the surrounding soils. It appears to be on a microknoll. Both Sites 3 and 4 are localized spots of gypsum accumulation. The spots are not as clearly defined as Sites 1 and 2 of Dickinson Co. or Sites 1 and 5 of Clay Co. There are numerous gypsiferous spots noted on the soil map within a one-half mile radius of Webster Co. Sites 3 and 4. All are located within Lanyon, Harps, or Canisteo mapping units.

Appendix F, Slide 6 shows a picture of the landscape surrounding Sites 3 and 4. Profile descriptions for the soils at both sites are included in Appendix A. Laboratory data are given in Appendix B, Tables 33 and 34. It is evident from the data and descriptions that both sites are somewhat coarser textured than allowed in the range of the Lanyon series. The profile at Site 4 contains appreciable amounts of gravel and noncalcareous sand. The gypsum content is greater in the upper part of the profile. However, the gypsum content does not decrease as abruptly as it did in the Clay and Dickinson Counties sites. The profiles at both Sites 3 and 4 have gypsum contents of several percent to depths of at least 6 ft. The laboratory data indicate gypsum is not present in the surface horizons of both profiles. The descriptions indicate the presence of very slight amounts. The data are probably low due to exchange error in the laboratory method. Refer to the section describing the
laboratory methodology for a discussion of the exchange error problem.

Cottonwood and Redwood Counties, Minnesota

Two new soil series, the Romnell and Jeffers series, were established in Cottonwood Co., Minnesota when it was being mapped in the mid-1970s. Both series contain gypsum. It was thought that a brief investigation of these soils would be beneficial since Cottonwood Co. has some climatic and parent material similarities with much of northwestern Iowa. The gypsum-containing soils of southwestern Minnesota are extensive enough to map as series. To date, extensive areas of gypsiferous soil have not been identified in Iowa. Only map spot symbols or variants of existing series have been used to designate gypsiferous areas.

The Romnell site is located 2,300 ft W and 30 ft S of the NE corner, Sec. 3, T108N, R38W in Cottonwood Co. This site is the official type location for the series. The Romnell series consists of deep, poorly-drained soils that formed in calcareous, loamy glacial till. They are found at the base of long, low (< 2%), slightly concave slopes on the late-Wisconsin drift plain. The depth to carbonates ranges from 30 to 55 inches. The texture is commonly clay loam in the solum and loam or clay loam in the C horizon. Gypsum occurs throughout the solum and the upper part of the C horizon. Contents are usually less than 5% but sub horizons in the lower A or upper B horizons contain as much as 15% gypsum in a few pedons. In its powder form, the gypsum coats faces of peds and fills root channels. It also consists of 1-5 mm crystals and 5-10 mm spheroidal nests of crystals. The Romnell series is a member of the
fine-loamy, mixed, mesic Cumulic Haplaquolls.

Appendix F, Slide 7 shows a picture of the Romnell site location. A profile description is included in Appendix A. Laboratory data are given in Appendix B, Table 35. The data indicate that this profile contains more clay in the 18-27 inch zone than is allowed in the range of the Romnell series. The upper 22 inches are noncalcareous. Gypsum is distributed fairly evenly throughout the profile but highest amounts are in the upper C horizon. The laboratory data show no gypsum in the upper two horizons, probably due to exchange error in the laboratory method.

The official type location of the Jeffers series is located 1,300 ft E and 660 ft N of the SW corner, Sec. 23, T107N, R37W. However, the author and the soil survey party based in Redwood Co. could not find the site at that location. Some of the members of the party had been to the official site before, and it was their conclusion that the listed location was erroneous. A site was then sampled that represented the site location for the Redwood Co. soil survey. It is located 1,340 ft N and 120 ft W of the SE corner, Sec. 36, T109N, R37W. The Jeffers series consists of deep, poorly-drained, calcareous soils that formed in loamy glacial till. They are on slightly convex slopes of < 2% on slight rises in poorly-drained areas or on the rims of depressions. The profile is calcareous throughout. The texture is commonly clay loam in the solum and loam or clay loam in the C horizon. Gypsum is present in the solum and has an average content of 2-5%. The C horizon lacks or has only a trace of gypsum. The form of the gypsum is either powder or larger crystals as in the Romnell series. The Jeffers series is a member of the
fine-loamy, mixed (calcareous), mesic Typic Haplaquolls. The site sampled is on a 2% slope to the southeast.

Also sampled was a Jeffers moderately well-drained (MWD) variant profile. During the course of the Cottonwood Co. survey, this variant was mapped separately. In the final correlation process, it was combined with the Jeffers series. The Jeffers MWD variant sampling site is located 1980 ft N and 100 ft W of the SE corner, Sec. 36, T109N, R37W or about 640 ft N and 20 ft E of the Jeffers site. The Jeffers MWD variant soils are found on the larger, more pronounced rises in the poorly-drained areas. The higher elevation of the rise allows slightly better drainage. The profile collected is on a 5% slope to the south. The gypsum accumulation is usually deep within the B horizon, commonly around 36 inches in depth. No crystals are usually visible on the dry soil surface.

Appendix F, Slide 8 shows a picture of the Jeffers and Jeffers MWD variant sampling sites. Profile descriptions for the soils at both sites are included in Appendix A. Laboratory data are given in Appendix B, Tables 36 and 37. The data and description for the Jeffers site indicate it to be outside the range for the series because of high contents of gypsum and the lack of mottles within 30 inches of the surface. The range in characteristics of the type description states that an average content of 2-5% is allowed. Yet laboratory data determined by the Minnesota Soil Survey Laboratory on seven Jeffers profiles indicated three had gypsum contents similar to those determined on the current profile. The determined gypsum percentage on the surface horizon may be low due to exchange error. The gypsum is in the upper part of the profile.
The data and description for the Jeffers MWD variant profile show it to be similar to the concept for the soil. No official ranges of characteristics exist since a series is not recognized. The concentration of the gypsum is between 32 and 53 inches depth. The very slight amounts of gypsum described in the upper 32 inches were not detected by the laboratory method probably due to exchange error.
DISCUSSION OF RESULTS AND INVESTIGATIONS

Source of Gypsum in the Study Sites

The characterization of the study sites has shown that the gypsum is sometimes present in very localized areas. Within a linear distance of several feet, the gypsum content changes abruptly. It appears that the gypsum accumulated above a former soil surface at one site. At other sites, the gypsum has a more uniform areal distribution.

There are several processes or set of processes that could promote such accumulations. The classic processes of salt accumulation in soils have been given previously in the section entitled "Accumulation of salts in soil: General." It is highly unlikely that accumulation of salt-containing dust would promote such localized concentrations. Sea water can also be rejected as a possible source since the study sites are far from the present-day ocean. It is also highly unlikely that salt-concentrating plants would promote the localized concentrations described. The content of gypsum in some sites is as much as 60% by weight. It is doubtful that plants would be responsible for such high concentrations. It would also be unlikely that in situ chemical reactions would be responsible for the totality of the accumulations.

It is not likely that the study sites represent soils that formed in parent materials containing an original high content of gypsum. In the sites where the gypsiferous soils formed in glacial till, it would be unlikely that a boulder of rock gypsum would be transported intact by the glacier for very long distances. Gypsum is a much softer mineral
than the limestones and granitic rocks found in the drift. If the gypsum was transported by the glacier, it would be expected that gypsiferous soils would be present on a more regional basis than the few very localized spots in northwestern Iowa. All of the sites in northwestern Iowa formed in or above materials that appear to be glacial sediments that had been reworked either by wind or water. It would be very unlikely that gypsum would concentrate in such localized spots in sediments deposited by fluvial or aeolian action. The gypsiferous soils of northwestern Iowa also contain calcite and dolomite while the surrounding soils are often noncalcareous. It is difficult to explain why certain areas of 100 ft or less in diameter would not be leached of carbonates and gypsum while the surrounding area is. Gypsum is a more soluble mineral than calcite, and it would be expected to have been removed before calcite.

The most likely source of gypsum in the study sites appears to be ground water containing dissolved gypsum. It appears that such water reaches the soil profile, evaporates, and precipitates the gypsum. This process is a common one throughout the world. Many instances of it have been cited in the literature. In terms of the salt balance concept, the gypsiferous areas are sites where the additions of gypsum are greater than the removals. The evaporation of ground water due to capillary rise from a high water table would explain the presence of calcareous, gypsiferous soils in an area leached of such salts. It would also explain how gypsum sometimes accumulates above a former soil surface. The continual precipitation of salts at or near the soil surface could eventually cover the surface. These accumulations may give rise to the microknoll shape
of some sites. The presence of a localized high water table could also explain why some gypsiferous soils are delineated so sharply on the landscape.

Some evidence does exist for the presence of a high water table containing dissolved gypsum at the study sites. All of the sites are located in poorly-drained areas. These areas would have had a high water table for some part of the year prior to artificial drainage by man. The sites are found in very low relief areas. The surrounding slopes are usually <2% for some distance. Ground water movement under the sites might be slow due to the lack of gradient. Hand probing showed a water table at a depth of about 1 ft at some sites while a short distance away, the water table was not found within 6 ft of the surface. The laboratory data show that the zone of maximum gypsum accumulation is above the zone of maximum carbonate accumulation in nine of the twelve gypsiferous profiles. This is evidence of dissolved salts being selectively precipitated as capillary rise and evapotranspiration occurs. Kovda's work (1946) discussed previously has shown that the least soluble salts (carbonates) will be precipitated first near the lower part of the profile. The more soluble salts (gypsum) will continue to move upward before being precipitated higher in the profile. Examples of profiles evidencing such arrangements are given in Table 3. In two of the twelve gypsiferous sites, the zones of maximum gypsum and carbonate accumulation approximately coincide. The morphologies of the segregations of gypsum crystals within the profiles probably indicate influence by water.

The ground water within the drift deposits of Iowa has been shown
to contain dissolved sulfates. Data from wells located in Iowa are given by Hendrixson (1912). Selected data are shown in Table 17. Included are data from wells that are explicitly noted to end in drift deposits and that have sulfate concentrations ≥ 2.0 meq/liter. A saturated solution of CaSO$_4$ contains about 30 meq/liter. It is evident from the data in Table 17 that areas of high-sulfate well water occur in both the Wisconsin and pre-Wisconsin drifts.

Water samples were collected in northwestern Iowa from both ground and surface sources near the study areas. The data are given in Table 18. Most of the ground water samples did contain an appreciable amount of sulfate.

Source of Gypsum Within the Glacial Drift

It is unlikely that water could be rising from deposits of gypsum underlying the drift. The drift deposits are normally 200 to 500 ft thick in northwestern Iowa. It would be highly unlikely that water from such depths would reach the surface. The gypsum bed at Fort Dodge is one of the few pre-Pleistocene outcrops in northwestern Iowa. It is possible that other gypsum beds were to the north of Iowa during preglacial times and were incorporated by the ice sheets into the drift. Yet there is no strong evidence of such an occurrence. Gypsum is very rarely found as a primary mineral within the drift deposits.

The most likely source of sulfates is the saline Pierre shale present in the drift. The research of Matsch (1972) that investigated the shale content of the New Ulm drift in southwestern Minnesota has been discussed
Table 17. Sulfate content of well waters from drift deposits in Iowa

<table>
<thead>
<tr>
<th>County</th>
<th>Town</th>
<th>Well depth, feet</th>
<th>$SO_4$ meq/liter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benton</td>
<td>Belle Plaine</td>
<td>193</td>
<td>37.8</td>
</tr>
<tr>
<td>Bremer</td>
<td>Fairbank</td>
<td>113</td>
<td>8.5</td>
</tr>
<tr>
<td>Buena Vista</td>
<td>Marathon</td>
<td>83</td>
<td>4.2</td>
</tr>
<tr>
<td>Clay</td>
<td>Bridgewater</td>
<td>250</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>Peterson</td>
<td>26</td>
<td>5.1</td>
</tr>
<tr>
<td>Dickinson</td>
<td>Lake Park</td>
<td>98</td>
<td>17.4</td>
</tr>
<tr>
<td></td>
<td>Spirit Lake</td>
<td>100</td>
<td>9.0</td>
</tr>
<tr>
<td>Greene</td>
<td>Jefferson</td>
<td>100</td>
<td>2.0</td>
</tr>
<tr>
<td>Hamilton</td>
<td>Duncombe</td>
<td>177</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Webster City</td>
<td>90-100</td>
<td>2.9</td>
</tr>
<tr>
<td>Humboldt</td>
<td>Livermore</td>
<td>135</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Rentwick</td>
<td>81</td>
<td>2.0</td>
</tr>
<tr>
<td>Kossoth</td>
<td>Luverne</td>
<td>35</td>
<td>2.9</td>
</tr>
<tr>
<td>Lucas</td>
<td>Woodburn</td>
<td>270</td>
<td>29.3</td>
</tr>
<tr>
<td>Mahaska</td>
<td>Stark</td>
<td>40</td>
<td>26.3</td>
</tr>
<tr>
<td>Marshall</td>
<td>State Center</td>
<td>161</td>
<td>26.1</td>
</tr>
<tr>
<td>Monona</td>
<td>Onawa</td>
<td>78</td>
<td>3.0</td>
</tr>
<tr>
<td>O'Brien</td>
<td>Hartley</td>
<td>205</td>
<td>31.7</td>
</tr>
<tr>
<td></td>
<td>Primghar</td>
<td>372</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>Sheldon</td>
<td>300</td>
<td>11.0</td>
</tr>
<tr>
<td>Plymouth</td>
<td>LeMars</td>
<td>70</td>
<td>2.6</td>
</tr>
<tr>
<td>Sac</td>
<td>Nemaha</td>
<td>400</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>Sac City</td>
<td>378</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>Schaller</td>
<td>432</td>
<td>20.3</td>
</tr>
<tr>
<td>Tama</td>
<td>Chelsea</td>
<td>100</td>
<td>40.1</td>
</tr>
<tr>
<td>Webster</td>
<td>Dayton</td>
<td>65-95</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>Dayton</td>
<td>92</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Harcourt</td>
<td>63</td>
<td>2.8</td>
</tr>
</tbody>
</table>

*Adapted from Hendrixson (1912).*
Table 18. Selected chemical data for water samples from northwestern Iowa

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Source</th>
<th>Geographic location</th>
<th>Legal location</th>
<th>CaSO₄</th>
<th>SO₄</th>
<th>Na</th>
<th>E.C. mmhos/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Drainage tile outlet.</td>
<td>Calhoun Co., at junction of creek with Highway 20.</td>
<td>SE½, Sec. 26, T88N, R32W.</td>
<td>4.7</td>
<td>5.0</td>
<td>1.0</td>
<td>1.10</td>
</tr>
<tr>
<td>2</td>
<td>Well, depth: 40-50 ft.</td>
<td>Webster Co., farmstead.</td>
<td>Western edge, NW¹, Sec. 10, T87N, R29W.</td>
<td>13.3</td>
<td>16.0</td>
<td>4.0</td>
<td>2.35</td>
</tr>
<tr>
<td>3</td>
<td>Well, depth: 25 ft.</td>
<td>Clay Co., farmstead.</td>
<td>Western edge, NW¹, Sec. 29, T97N, R36W.</td>
<td>9.8</td>
<td>10.5</td>
<td>0.7</td>
<td>1.10</td>
</tr>
<tr>
<td>3M</td>
<td>Unnamed slough.</td>
<td>Dickinson Co.</td>
<td>SW corner, Sec. 32, T100N, R37W.</td>
<td>9.4</td>
<td>10.9</td>
<td>0.6</td>
<td>1.40</td>
</tr>
<tr>
<td>4</td>
<td>Spirit Lake.</td>
<td>Dickinson Co., outlet of Spirit Lake into East Lake Okoboji.</td>
<td>Southern edge, Sec. 28, T100N, R36W.</td>
<td>0.4</td>
<td>1.2</td>
<td>0.4</td>
<td>0.420</td>
</tr>
<tr>
<td>5</td>
<td>Silver Lake.</td>
<td>Dickinson Co.</td>
<td>Sec. 28, T100N, R38W.</td>
<td>3.3</td>
<td>5.0</td>
<td>0.5</td>
<td>0.740</td>
</tr>
<tr>
<td>7</td>
<td>Gravel pit.</td>
<td>Dickinson Co., along County Road M27.</td>
<td>NW¹, Sec. 22, T98N, R38W.</td>
<td>0.8</td>
<td>2.8</td>
<td>0.3</td>
<td>0.420</td>
</tr>
<tr>
<td>8</td>
<td>Well, depth: 12-20 ft in floodplain of Stony Creek.</td>
<td>NE½, Sec. 21, T98N, R38W.</td>
<td>0.0</td>
<td>3.9</td>
<td>17.6</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Jemmerson Slough.</td>
<td>Dickinson Co.</td>
<td>Sec. 6, T99N, R36W.</td>
<td>2.4</td>
<td>5.0</td>
<td>0.5</td>
<td>0.685</td>
</tr>
<tr>
<td>Location</td>
<td>Description</td>
<td>Details</td>
<td>Samples</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>---------</td>
<td>---------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12M</td>
<td>Drainage tile outlet</td>
<td>Dickinson Co., west side of drainage way as it intersects road.</td>
<td>SW½, Sec. 19, T98N, R38W.</td>
<td>5.8 6.2 0.5 1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Well, depth: ?</td>
<td>Dickinson Co., farmstead</td>
<td>About 1000 ft. S of NW corner, Sec. 9, T99N, R38W.</td>
<td>8.0 9.2 1.0 1.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Seep</td>
<td>Dickinson Co.</td>
<td>1150 ft N and 760 ft W of SE corner, Sec. 6, T98N, R36W.</td>
<td>1.1 1.2 0.3 0.720</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Seep</td>
<td>Dickinson Co.</td>
<td>540 ft E and 1060 ft S of NW corner Sec. 4, T98N, R37W.</td>
<td>1.1 1.6 0.4 0.840</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Seep</td>
<td>Dickinson Co.</td>
<td>1050 ft N and 480 ft W of SE corner Sec. 10, T99N, R38W.</td>
<td>12.7 14.9 1.6 1.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Seep</td>
<td>Dickinson Co.</td>
<td>2400 ft N and 560 ft E of SW corner Sec. 32, T100N, R38W.</td>
<td>18.7 23.3 3.0 2.30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Sample No. 8 probably contaminated by barnyard upslope.*
previously. Some of the drift areas contain over 50% shale in the 1-2 mm size fraction. Figure 3 shows the shale contents for a portion of southwestern Minnesota. The shale content decreases on either side of the Minnesota River. Matsch (1972) theorizes that the configuration of the ice sheet changed as it flowed through the confines of the Minnesota River lowland. It would also be expected that the shale content would decrease with distance continuing south into Iowa. The drift would be getting farther from the source of the shale. The Algona moraine is fairly high in shale content (G. R. Hallberg, Iowa Geological Survey, Iowa City, Iowa. Personal communication, 1979). Figure 4 gives the location of the Algona moraine. Areas of the Cary drift in northwestern Iowa are also high in shale content. Shale contents usually decrease in a south or southeast direction for the remainder of the Cary drift region (G. R. Hallberg. Personal communication, 1979). Yet up to 30% shale is often found in the 1-2 mm size fraction near its borders. Dr. Hallberg states that the Pierre shale is a source of sulfates as well as pyrite (FeS₂). He has seen actual "pebbles" of gypsum in the matrix of Cary till that did not appear to be formed by secondary recrystallization. The "pebbles" may have been present in the original shale.

Thorp et al. (1948) characterized the Pierre shale as containing Na, Mg, and Ca sulfates and NaCl. Much of the late-Wisconsin glacial drift in North and South Dakota contains Pierre shale. Research works cited earlier, which discuss the salt-affected soils in these areas, attribute the source of soil salinity to the shale. The oxidation of pyrite is also an indirect but major source of sulfate. The oxidation of the
sulfur in pyrite to sulfate occurs in the presence of oxygen and is catalyzed by sulfur oxidizing bacteria. The equations for this reaction was given previously in Equation 1. If Ca is present and available for reaction, gypsum is formed (Equation 2). The Cary (or New Ulm) drift contains CaCO$_3$. Gypsum could be formed in those drifts when a source of sulfate was present. It has been suggested that the accumulation of gypsum at the study sites is probably linked to a high water table. The pyrite may be oxidized in the drift due to oxygen-laden ground water. It appears that geomorphic and climatic factors interact to promote localized high water tables, and thus concentrations of gypsum.

Some evidence exists for the possibility of oxidation of pyrite deep within drift deposits. Williams and Farvolden (1967) report that there is often a zone of oxidized colors along till joints within unoxidized portions of till. The permeability of the joints is considerably greater than the permeability of the pore space within the till matrix. Water moves preferentially through the joints. They found that water moving through till joints moves much farther before having its oxygen content depleted than water moving through the till matrix. Matsch (1972) found iron and manganese oxides along joints in till of Wisconsin age in Minnesota. The joints extended to depths greater than 50 ft. Sloan (1972) cites a paper which also reports joints extending to depths of 55 ft in some tills. Eisenlohr (1972) reports that water movement within the drift of certain areas of central North Dakota is more vertical than horizontal due to vertical joints. Gypsum crystals have been found packed within joints of pre-Wisconsin till in Sioux Co., Iowa (T. E.
Fenton, Dept. of Agronomy, Iowa State Univ., Ames, Iowa. Personal communication, 1978). The till was exposed in a road cut at the NE corner, Sec. 14, T97N, R48W. A zone of calcareous, oxidized till showed gypsum crystals in the joints. The zone began at a depth of 24.5 ft below the present surface and extended downward for 22.5 ft. A similar occurrence was found in Cherokee Co., Iowa (G. R. Hallberg, Iowa Geological Survey, Iowa City, Iowa. Personal communication, 1978). A 6 ft by 6 ft till joint filled with gypsum crystals was exposed. Dr. Hallberg suspected the filled joint was much larger than the exposed area. The gypsum was found in mottled, oxidized, calcareous till.

The pre-Wisconsin drifts have been characterized by Matsch (1972) as containing little if any shale. Yet there is evidence of gypsum within them. The formation of gypsum crystals within till joints may be due to two processes. Primary gypsum within the drift is dissolved in the ground water. Repeated wetting and drying promotes gypsum precipitation and crystal growth within the joints. The formation could also be due to the bringing of oxygen-laden water into the drift. Pyrites might be oxidized, and gypsum would be formed. Repeated wetting and drying of the joints would promote gypsum accumulation. If gypsum-containing joints are found in the pre-Wisconsin tills that generally lack shale, it would be expected that similar phenomena may occur in the shale-bearing late-Wisconsin tills.

It is common to find pyrite particles in the 0.05-2 mm size fraction of Wisconsin till samples in Iowa. Two samples from the present study showed an abundance of pyrite particles. They were: Dickinson Co.,
Site 2, 22-30 inch horizon, and Clay Co., Site 1, 68-80 inch horizon. At least for these two sites, there is direct evidence of a potential source of sulfate. It is possible that the study sites represent areas of abnormally high concentrations of shale within the drift. The gypsiferous areas in Iowa are highly localized. Work has not yet been completed on determining the shale content of the Cary drift on a regional basis. A piece of shale about 1 X ½ X ½ inch was found in the 42-50 inch horizon of Webster Co., Site 4. Noticeable amounts of shale were observed in the sand-size and gravel-size fractions in both Sites 3 and 4.

Several calcareous Cary and Tazewell till samples were also analyzed for total sulfur content. The data are presented in Table 19. Some of the samples were collected in Dickinson Co. near the study areas. Other samples were selected from ones collected by the Iowa Geological Survey. No organic matter was present in these samples. All sulfur detected was from inorganic sources. The data show that some sulfur is present. Few other conclusions can be made. The source of the sulfur is unknown, but pyrite is a possible source.

Correlative Calcite-Dolomite Data

The evaporation of ground water from the study sites should precipitate dissolved carbonates as well as gypsum. It is common to find soils on the late-Wisconsin drift plain that are carbonate enriched due to water evaporation. Evaporation around the edges of ponds within closed depressions is thought to have brought carbonates into the soil profile (Mendenhall, 1967). Carbonate enrichment of the gypsiferous soils
Table 19. Total sulfur data for calcareous Cary and Tazewell till samples

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>County</th>
<th>Till</th>
<th>Total S ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFW: 11</td>
<td>Dickinson</td>
<td>Cary</td>
<td>176</td>
</tr>
<tr>
<td>12</td>
<td>Dickinson</td>
<td>Tazewell</td>
<td>188</td>
</tr>
<tr>
<td>13</td>
<td>Dickinson</td>
<td>-- a</td>
<td>161</td>
</tr>
<tr>
<td>15</td>
<td>Calhoun</td>
<td>Cary</td>
<td>62</td>
</tr>
<tr>
<td>16</td>
<td>Dickinson</td>
<td>Cary</td>
<td>121</td>
</tr>
<tr>
<td>ISU: 20526</td>
<td>Dickinson</td>
<td>Cary</td>
<td>79</td>
</tr>
<tr>
<td>23337</td>
<td>Dickinson</td>
<td>Cary</td>
<td>33</td>
</tr>
<tr>
<td>23974</td>
<td>Dickinson</td>
<td>Cary</td>
<td>73</td>
</tr>
<tr>
<td>IGS: 32-78-1</td>
<td>Emmet</td>
<td>Cary</td>
<td>79</td>
</tr>
<tr>
<td>35-78-2</td>
<td>Franklin</td>
<td>Cary</td>
<td>59</td>
</tr>
<tr>
<td>55-78-1</td>
<td>Kossuth</td>
<td>Cary</td>
<td>54</td>
</tr>
<tr>
<td>74-78-1</td>
<td>Palo Alto</td>
<td>Cary</td>
<td>74</td>
</tr>
<tr>
<td>76-78-1</td>
<td>Pocahontas</td>
<td>Cary</td>
<td>66</td>
</tr>
</tbody>
</table>

Sample No. 13 is from the noncalcareous loamy sediments overlying Tazewell drift in the Letri mapping unit in Dickinson Co. collected upslope from Site 2.

would provide additional evidence that the process of evapotranspiration of ground water was the mechanism of gypsum accumulation. To this end, the calcite-dolomite contents of selected samples of calcareous Cary till in a reasonably unaltered state were determined so that the carbonate-enriched soils could be compared to the calcite-dolomite content of the till. Thirty-six calcareous Cary till samples were analyzed. Most of the samples were unoxidized; a few were oxidized or deoxidized. The samples had been collected by the Iowa Geological Survey from ten
counties within Iowa. Particle size had been determined by the Iowa Soil Survey Laboratory, and calcite-dolomite contents were determined by the author. The data are given in Appendix C, Table 38. Summary statistics on the data are given in Table 20. Samples showing evidence of particle sorting were omitted from analysis, i.e., samples from sand lenses. Almost all particle size data are within a range of 35-50% sand and 12-24% clay. The calcite-dolomite data are surprisingly consistent.

Table 20. Summary statistics on laboratory data for calcareous Cary till samples

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Calcite</th>
<th>Dolomite</th>
<th>Cal/Dol ratio</th>
<th>Sum Cal+Dol</th>
<th>Sand</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>range</td>
<td>1.4-6.4</td>
<td>9.0-14.4</td>
<td>0.14-0.50</td>
<td>10.4-19.8</td>
<td>32.9-51.6</td>
<td>9.15-24.8</td>
</tr>
<tr>
<td>mean</td>
<td>3.5</td>
<td>12.3</td>
<td>0.28</td>
<td>15.8</td>
<td>44.4</td>
<td>15.9</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>1.2</td>
<td>1.1</td>
<td>0.09</td>
<td>1.9</td>
<td>4.8</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*aAll range, mean, and std. dev. data given in percent, except Cal/Dol ratio which is unitless.

Calcite-dolomite data were also determined on several carbonate-enriched profiles whose accumulation of carbonates is believed to be due to the evaporation of water. All of the profiles selected are within or on the edges of closed depressions. The profiles are from soils formed in the Cary drift plain except for the Spicer profile. Profiles containing large amounts of snail shells were excluded. Samples were obtained from storage at the Iowa Soil Survey Laboratory. Three samples per profile
were analyzed, the surface sample, a sample from about 24 inches, and a sample from about 60 inches, so that these calcite-dolomite contents could be compared to the contents of the study sites. The depths of 24 and 60 inches are approximate due to the variation in sampling depths of the profiles. The data are given in Appendix D, Table 39.

The calcite-dolomite data do show a general trend. The calcite/dolomite ratio decreases with depth. The horizons at the surface and/or at about 24 inches are often enriched with calcite when compared to the average calcite data of Cary till. The average calcite content of the Cary till was 3.5%. Evapotranspiration has probably brought dissolved calcite into the profile. It is also evident that the calcite content of these same horizons is greater than the dolomite content. The explanation probably relates to the solubility of the two minerals. Calcite is more easily moved within the profile. Evaporating water brought calcite (actually Ca$^{++}$ and CO$_3^-\$) preferentially to near the soil surface where it was precipitated. The horizons at the 60 inches depth often contain calcite and dolomite in concentrations similar to the ranges found for the calcareous Cary till samples as shown in Table 20. The portion of the soil profile at about 60 inches appears to be less affected by the processes of dissolution and precipitation. The lower portion of the profile is more likely to have been formed in glacial till while the upper portion probably formed in somewhat reworked glacial sediments.

Wenner et al. (1961) studied soils that had been partially leached of carbonates from the surface downward. Water evidently moved in a predominantly downward direction. The authors found that the Ca/Mg ratio
of the soil carbonates increased with depth. Since the data in Appendix D, Table 39 show a consistent decrease in the calcite/dolomite ratio with depth, this lends support to the theory of upward water movement as the carrier of the carbonates.

Another interesting fact from Appendix D, Table 39 is the usually low dolomite content of the surface and 24 inch horizons. The average dolomite content of the calcareous Cary till samples was 12.3%. Yet almost all of the surface and 24 inch horizons are less than that figure. If the upper horizons represent layers of calcite enrichment, the calcite values should be greater than the 3.5% average. This is what is found experimentally. The dolomite values should be about the 12.3% average or possibly higher. It is unlikely that the surface horizons were leached of both calcite and dolomite before calcite reaccumulation started. These low-lying, poorly drained areas have been wet or ponded probably since the retreat of the ice sheet. It is unlikely that the soil would have been leached of carbonates before being recharged with them. It is also unlikely that the dolomite has been selectively weathered out during the calcite accumulation process. Dolomite is a less weatherable mineral than calcite. If dolomite was removed, greater quantities of calcite should have been removed. It would be difficult to explain why dolomite would be removed while calcite accumulated. The most probable answer relates to the parent material in which the soils formed. The upper part of the profiles formed in local alluvium derived from the drift materials upslope. Upslope, most of the upper soil horizons do not contain carbonates. The material which washed down onto the depressional
surface would be essentially devoid of calcite and dolomite. This material would be incorporated with or accumulated above the original depressional surface. The calcite and dolomite presently in these calcareous soils are probably due to the precipitation of Ca\(^{++}\), Mg\(^{++}\), and Co\(^{3+}\) from water. As stated earlier, the horizons at a depth of about 60 inches appear to be less affected by the hydrologic processes and more nearly reflect the calcite-dolomite contents of the calcareous Cary till.

References have been made to the movement of gypsum, calcite, and dolomite within ground water and their subsequent precipitation in soil profiles. It should be pointed out that actual molecules of these minerals do not move in solution. The molecules dissociate into their constituent ions when dissolution occurs, i.e., \(\text{CaSO}_4 \rightarrow \text{Ca}^{++} + \text{SO}_4^{2-}\). The constituent ions may form ion pairs in solution, however. The movement and precipitation of these minerals are dependent upon their solubility in water. As seen from Table 1, the molar solubilities of gypsum, calcite, and dolomite are approximately \(10^{-2}\), \(10^{-4}\), and \(10^{-5}\) moles/liter, respectively. Gypsum is about 100 times more soluble than calcite. Calcite is about ten times more soluble than dolomite. Precipitation of these minerals from solution is largely controlled by their solubilities. If a solution contains Ca\(^{++}\), Mg\(^{++}\), \(\text{CO}_3^{2-}\) and \(\text{SO}_4^{2-}\), dolomite \((\text{CaMg(CO}_3)_2\) should be precipitated when the concentrations of Ca\(^{++}\), Mg\(^{++}\), and \(\text{CO}_3^{2-}\) reach approximately \(10^{-5}\) moles/liter. Calcite \((\text{CaCO}_3)\) should be precipitated when the concentrations of Ca\(^{++}\) and \(\text{CO}_3^{2-}\) reach approximately \(10^{-4}\) moles/liter. The formation of the specific minerals of calcite and dolomite is dependent upon the concentration of \(\text{CO}_2\) in the water as well as
other factors. Their formation is often a complex geochemical process. Gypsum \((\text{CaSO}_4\cdot 2\text{H}_2\text{O})\) should be precipitated when the concentrations of \(\text{Ca}^{++}\) and \(\text{SO}_4^{\text{2-}}\) reach approximately \(10^{-2}\) moles/liter. Assuming an abundant supply of dissolved ions, about 100 moles of gypsum should be precipitated for every mole of calcite precipitated. One-tenth mole of dolomite should be precipitated for every mole of calcite precipitated.

The molar solubilities of minerals can also be expressed as their solubility product constant \((K_{\text{sp}})\). The \(K_{\text{sp}}\) values are calculated from knowing the molar solubilities of the minerals and their dissolved ionic forms. The \(K_{\text{sp}}\) values for gypsum, calcite, and dolomite are approximately \(10^{-4}\), \(10^{-8}\), and \(10^{-18}\), respectively. It appears from the \(K_{\text{sp}}\) values that dolomite is much less soluble than calcite. However, the large difference in \(K_{\text{sp}}\) values between the two is due to the equations used in calculating the values. A different equation is used for calculating the \(K_{\text{sp}}\) values for a molecule that yields two moles of dissolved ions for every mole of molecules \((\text{CaCO}_3 \rightarrow \text{Ca}^{++} + \text{CO}_3^{\text{2-}})\) than for a molecule that yields four moles of dissolved ions for every mole of molecules \((\text{CaMg(CO}_3)_2 \rightarrow \text{Ca}^{++} + \text{Mg}^{++} + 2\text{CO}_3^{\text{2-}})\). The molar solubilities of minerals are expressed independently of the minerals' dissolved ionic forms. Molar solubilities may be more useful than \(K_{\text{sp}}\) values for the comparison of solubilities of minerals that have different mole-ratio combinations.

The \(K_{\text{sp}}\) values can also be used to predict the occurrence of precipitation of gypsum, calcite, and dolomite from solution. When the \(K_{\text{sp}}\) for dolomite reaches approximately \(10^{-18}\), precipitation may result.
When the $K_{sp}$ for calcite reaches approximately $10^{-8}$, precipitation may result. When the $K_{sp}$ for gypsum reaches approximately $10^{-4}$, precipitation may result. The use of $K_{sp}$ values in predicting precipitation of minerals from solution is more accurate than the use of only molar solubilities. The $K_{sp}$ values take into consideration the multiple mole ratios needed for the formation of some minerals.

The comparison of calcite-dolomite data between the calcareous soils and the study sites is less applicable than expected. The problem is simply that the great mass of gypsum accumulated in most of the study sites obliterates the calcite-dolomite ratio relationships. The volume of gypsum necessarily excludes a proportionate amount of other soil constituents. The evaporating ground water probably contained greater amounts of dissolved gypsum than of dissolved calcite and dolomite. The gypsiferous soils do contain some calcite and dolomite in areas often surrounded by noncalcareous soils. This further supports the hypothesis of upward capillary water movement. Another factor supporting the same hypothesis is that the zone of maximum gypsum accumulation almost always occurs above the zone of maximum carbonate accumulation. This finding can probably be explained due to the $K_{sp}$ values of the minerals. Water moving upward in a profile due to the demand of evapotranspiration would become more concentrated with dissolved constituents also. The $K_{sp}$ for calcite and dolomite ($10^{-8}$ to $10^{-18}$) would be reached first. The $K_{sp}$ for gypsum ($10^{-4}$) would be reached next. If the water was moving upward, the calcite and dolomite would probably be precipitated below the zone of gypsum precipitation.
Although no ground water tables were monitored, it appears that the gypsum in the profile at Dickinson Co., Site 1 was deposited by ground water evaporation. The soil is calcareous throughout the profile. The surrounding soil is the Letri series, and carbonates are not present above a depth of 16 inches. The gypsiferous area is also clearly evident on the landscape and changes abruptly to the nongypsiferous area. The zone of maximum gypsum accumulation is above the zone of maximum carbonate accumulation. According to the work of Kovda (1946), the water table must have been fairly close to the surface to allow gypsum to concentrate in the upper part of the profile. If the water table had been deeper, the zone of maximum accumulation of gypsum would be in the middle or lower portions of the profile.

Water samples 7, 8, and 12M were collected within a two mile radius of Site 1. Sulfates were present, especially in the ground water samples. Site 1 is on a very slight slope. It appears that ground water may be rising to near the soil surface from the calcareous drift. Since the area is mantled with loamy sediments over firm Tazewell till, it is believed that precipitation usually percolates through the loamy sediments and flows on top of the till to lower elevations. This water could not be the source of the carbonates and sulfates since the loamy sediments are noncalcareous. Evidently the water containing the dissolved salts is coming from within the drift. It would seem that a "point source" of the upwelling water would be necessary to produce a gypsiferous area 30-40 ft in diameter. The low relief of the surrounding area would probably
promote slow rates of water movement to lower elevations.

It can also be seen from the laboratory data and profile description for the profile at Site 1 that the gypsum content decreases abruptly near the till contact. It will become apparent from the other sites also that gypsum seems to accumulate above a contact of different lithologic materials. An explanation appears to be that the different materials may affect the moisture relationships within the profile. Abrupt textural (porosity) differences within a profile often inhibit water in the upper layer from draining readily into the lower layer. This is especially true if the lower layer is markedly coarser textured than the upper layer. Day and Luthin (1953) and Taylor (1957) discuss this aspect of water movement in soils. The lithologic discontinuity may temporarily perch a receding water table or it may inhibit infiltrating water from flowing into the lower layer. The water in the upper layer may be left to evaporate if conditions are favorable. These processes may explain the sharp decline of gypsum contents at points of lithologic discontinuities. Bulk density differences may also be important.

There are dark bands high in organic matter at depths of 18, 21-23, and 23-25 inches. It is doubtful that the horizons were once at the soil surface and were later covered by the gypsum accumulation. There is a sharp decrease in organic carbon content between the 23-25 inch horizon and the first horizon formed in the till at 25-31 inches. The organic carbon values are 2.1 and 0.1%, respectively. If the 23-25 inch horizon was a former surface horizon, it would be expected that the organic carbon content would decrease gradually with depth. It would
also be highly unlikely to have a 30-40 ft area of soil with about 4 inches of A horizon overlying till while the surrounding area has about 2 ft of loamy material overlying the till. The dark horizons in the profile at Site 1 are best considered horizons with illuviated organic matter. The 9-21 inch horizon is very friable and permeable. It may be possible that organic matter and possibly mineral particles may eluviate through this loose layer. Evidence of organic matter movement exists on the gypsum crystals themselves. All crystals within the solum that are larger than about 0.25 mm in size are completely and evenly coated with a dark gray stain. This was verified by microscopic examination. The color of the crystals is usually 5Y 4/1 (moist) or 2.5Y 4/2 or 5/2 (dry). Appendix F, Slide 9 contains a picture of organic matter coated crystals. The profile description for the 11-25 inch horizon of the profile at Clay Co., Site 4 describes dark flows between the platy peds. These flows appear to be illuvial in nature. A similar situation exists in the 8-14, 14-18, and 18-33 inch horizons of the profile at Clay Co., Site 8.

The organic matter also seems to be distributed uniformly throughout the horizons containing massive amounts of gypsum. The laboratory data for Clay Co., Site 5 in Appendix B, Table 29 demonstrate such a relationship. The organic carbon contents between the depths of 14 and 41 inches are very uniform. The description indicates the contents may be similar even to a depth of 59 inches. It appears that the organic carbon in the profile has been fairly evenly distributed by some means. The values do not decrease with depth as rapidly as in most nongypsicferous soils that are not in alluvial positions.
Other evidence that may point to the movement of organic matter in suspension is that the dark bands occur above the lithologic discontinuity. As stated earlier, the discontinuity probably affects the water movement within the profile. The discontinuity may perch the water table when the lower material is not saturated with water. Such would be the case when precipitation is sufficient to percolate through the upper material to the discontinuity contact. The water would then probably flow laterally. This process may help explain some of the morphology of the dark bands. They are always horizontal and have very distinct, abrupt boundaries. Frequently, there are many small bands or strata layered in horizontal planes such as those described in the profile description for the 41-65 inch horizons of Clay Co., Site 5. Horizontal flow of water above the contact may be the cause of this horizontal orientation.

The dark bands are usually found above a layer containing an increased amount of calcite and dolomite. It could be possible that the presence of large amounts of carbonates promotes the precipitation of organic matter. Bartelli and Odell (1960a and b) studied some soils in Illinois that had a layer of clay and organic matter enriched material above coarse-textured calcareous drift. The authors theorized that percolating water did not flow readily into the lower, coarse-textured material. The clay and organic matter were deposited when the water evaporated. The enriched layer was called a "Beta B" horizon.

The cause of the soluble organic matter in the profiles at sites in the current study is not clear. There is no evidence of high Na contents. Iron and aluminum are the agents for the chelation and bonding of the
organic matter in the formation of spodic horizons. Since the profiles at the study sites are calcareous, it would not be expected that soluble Fe and Al would be present in large quantities. They would be insoluble at high pH levels. However, if the oxidation of pyrite releases Fe, small amounts of soluble Fe could move upward with the ground water.

Another anomaly of Dickinson Co., Site 1 is the platy structure found in the 9-21 inch horizon. Platy structure is normally associated with eluvial horizons stripped of weatherable minerals and enriched with resistant minerals. Soils formed under forest vegetation often have platy structure. There is no evidence of forest influence in the surrounding soils. Descriptions for profiles at Dickinson Co., Site 2; Clay Co., Sites 1, 4, 5, 6, and 8; and Cottonwood Co., Romnell site also have platy structure. Buol et al. (1973) state that platy structure may result from expansion and contraction normal to the soil surface. This expansion may be caused by freezing-thawing or wetting-drying cycles. They also state that movement of a seasonably perched water table may be involved. In soils formed under forest vegetation, a periodically perched water table may exist over a B horizon high in clay content. At the study sites, it appears that the fluctuating water table and evapotranspiration are the cause of the wetting-drying cycles. Platy structure is eventually formed due to the expansion and contraction associated with the cycle. Platy structure formation is further evidence of a fluctuating water table at the study sites.

The platy structure appears to form primarily in horizons that have large amounts of gypsum. This fact is probably due to the very friable
nature of these horizons. There is little silt and clay to fill the voids between the crystals. The crystals are relatively easy to reorient into a horizontal orientation. Platy structure is not a criterion for giving a horizon an A2 designation (Soil Survey Staff, 1975). The weathering of the horizon with the resultant increase in resistant minerals is the major criterion. The horizons showing platy structure in gypsiferous soils should not be designated with an A2. Gypsum is a very weatherable mineral.

Dickinson Co., Site 2 is very similar to Site 1. It appears that a localized high water table may be responsible for the accumulation of gypsum. The profile is calcareous throughout with the exception of the 18-22 inch horizon. The surrounding soils do not contain carbonates to a depth of about 3 ft. The gypsiferous soils are clearly evident on the landscape and change abruptly to nongypsiferous soils (Site 2A). The zone of maximum gypsum accumulation is above the zone of maximum carbonate accumulation. The water table evidently was fairly close to the surface since the gypsum is concentrated in the upper 18 inches of the profile.

Water samples 7, 8, and 12M were collected within a two-mile radius of Site 2. The gypsum in the profile decreases abruptly above a lithologic discontinuity. In this case, the lower material is probably erosional sands and gravels above the till surface. An abrupt dark band is above the sands and gravels at a depth of 18-22 inches. It appears to be an illuvial horizon similar to the ones in the profile at Dickinson Co., Site 1. Platy structure is found at a depth of 9-18 inches. The 30-36 and 36-43 inch horizons have the oxidized color of 10YR 5/8
with some 5Y 5/2 and 7.5YR 5/6 mottles. It is somewhat unusual to have material of this color at this depth in a poorly-drained soil. Iron oxides coat the sand grains and there also appears to be some segregations of cemented iron. Some of the iron may be derived from the oxidized pyrite.

The laboratory data show that the 22-30, 30-36, and 36-43 inch horizons are high in gravel content. The latter two horizons are also high in sand content. It is common to have up to 4 inches of sand and gravel above the till surface in the Letri series. It is unusual to find 21 inches of sand and gravel. In sampling, the hydraulic probe was prevented several times from penetrating deeper than 43 inches due to gravels. It is not known whether the till contact was imminent or whether the sand and gravel continued for some depth. It might be possible that there was a relationship between the presence of this thick layer of sand and gravel and a localized high water table. It might be possible that a sand and gravel lens within the drift was responsible as the "point source" of the water table. Three hand probings were made at equidistant locations that were on a 15 ft radius of Site 2. The sand and gravel lens above the till was 2, 5, and 12 inches thick. Similar probing was done at Site 2A, which is located in a nongypsiferous area 42 ft northwest of Site 2. The lens thickness was 0, 8, and 16 inches. Probing was then done at a site 75 ft north of Site 2A, still in the nongypsiferous area. Probing there and three times in a 15 ft radius indicated lens thicknesses of 0, 0, 0, and 1 inch. From these findings, it cannot be concluded that certain gypsiferous soils in the Letri delineation are over exceedingly
thick sand and gravel lenses while nongypsiferous soils are over normal thickness lenses.

Also investigated was another circular gypsiferous area upslope and to the east-northeast of Site 2. At that site, the soil was very moist to within 1-2 inches of the surface, and the water table was at 12 inches. Probing at 135 ft north of that site but in a nongypsiferous area indicated no water table within a depth of 58 inches. Another gypsiferous area was also investigated farther to the east. The soil was very moist to within 1-2 inches of the surface, and the water table was at 14 inches. Probing at 135 ft south of that site in a nongypsiferous area showed no water table within 58 inches. It is probably not common to find water table depths at about one foot at some locations and no water table within a depth of at least 6 ft at 135 ft away. The area is on a slope of < 1%. This finding is evidence of a shallow water table in some gypsiferous soils found in the Letri delineation. It appears that some water flows downslope confined within the Tazewell drift. The flow rate is probably slow due to the low slope gradient. At various points downslope, the water rises to near the surface of the loamy sediments. The water is possibly under local artesian pressure from upslope. The reason a high water table is found only in localized spots is not clear. A sand and gravel wedge within the drift may be the explanation but it is not evident.
Clay Co., Sites 1, 4, 5, and 6 will be discussed as a unit since they are located within the same study area. It appears that the gypsum accumulated at these sites due to precipitation from evaporating ground water. The profiles are calcareous throughout. The surrounding profiles are slightly calcareous also. The mapping unit is Marna silty clay loam, calcareous variant. The zone of maximum gypsum accumulation is above the zone of maximum carbonate accumulation in all profiles. The water table may have been shallow to allow the gypsum accumulation to form in the upper part of the profiles. In all profiles, the gypsum content decreases abruptly at a lithologic discontinuity. It should be noted that the 38-44 inch horizon of the profile at Site 6 appears to be a krotovina, not a lithologic discontinuity. Dark horizontal bands are at 43, 48, 59-63\(\frac{1}{2}\), and 63\(\frac{1}{2}\)-65 inches in the profile at Site 5. Platy structure is found in all of the profiles.

It has been shown in Figure 12 that the gypsum has accumulated above a former soil surface. The laboratory data for the profiles at Sites 3-7 show that the gypsum is concentrated on the well-defined microknoll. It is difficult to explain the hydrologic conditions that would have promoted such accumulation. The gypsiferous mounds are adjacent to the drainage way but on level terrain. There does not appear to be any obvious geomorphic reason why a localized high water table should appear at the sites. It is not likely that gypsum-laden water evaporated from the drainage way. Gypsum is not evident on both sides of the drainage way. Very localized mounds appear entirely on the southern side of the
drainage way. The data for Sites 2 and 3 show no gypsum contents in the profiles at the center of the drainage way. A possible explanation may be that ground water is moving downslope from the low hill to the west of Sites 1-7. The water rises to near the soil surface adjacent to the drainage way. Why only localized gypsum accumulations occur is not clear. It may be that the gypsum represents a relict feature of drier climates.

The profile descriptions of the soils at Sites 4, 5, and 6 note the abundant presence of krotovinas in some of the horizons containing abundant gypsum. There was abundant rodent burrowing at the sites. The larger krotovinas (4-5 cm) are probably caused by the rodents. The field had not been plowed in 7-8 years at the time of sampling. Other krotovinas are described that are about 1-5 mm in diameter and up to 30 mm long. The holes are filled with either dark surficial material or very fine gypsum crystals. These krotovinas do not appear to be root holes. The holes are the same size in diameter at several depths within the profile. Their orientation is not principally vertical, but random. Sometimes small filled pockets are found. It appears that insects, probably ants, formed the holes. Near the soil surface, slightly larger filled holes may indicate the activity of larger insects. Worm casts were also encountered. This abundance of biological activity was found only in the gypsiferous areas. It appears that insects and rodents may prefer these highly gypsiferous soils due to their friability.

Water sample No. 3 was collected from a 25 ft well less than one-fourth mile north of the study sites. It contained 10.5 meq/liter of total sulfate, of which 9.8 meq/liter were calcium sulfate. These data
will be used to calculate an approximate age of the gypsum accumulation. Kovda's work (1946) concerning the calculation of soil age has been discussed earlier in the section entitled "Calculation of soil age". He utilizes the current yearly rate of ground water evaporation, the dissolved gypsum content of the ground water, and the total amount of gypsum present in the soil profile. He does not mention several assumptions and limitations of the age calculation process.

Several assumptions must be made. It must be assumed that there was a constant concentration of dissolved gypsum in the ground water throughout the accumulation time period. A constant rate of ground water evaporation must also be assumed. It must be assumed that none of the gypsum deposited during the drier parts of the year was removed during the wetter parts of the year. Additions were complete; removals were negligible. The amount of gypsum brought in by ground water must be differentiated from any gypsum formed in-situ or originally present in the parent material. In most cases where it is evident that a high water table is present, it is assumed that gypsum from other sources is negligible.

There are also several limitations. Defining the phrase "rate of ground water evaporation" is complicated by several factors. Open-pan evaporation values would not be accurate due to the effects of plant canopies and surface soil desiccation on soil water evaporation. The water table would have to be consistently at the bare soil surface to approximate open-pan evaporation rates. Potential evapotranspiration rates are probably the most accurate. Yet if the water table fluctuates and the soil surface desiccates, potential evapotranspiration rates may be too
high. There is no way of knowing how consistently the soil was saturated. The method given calculates the age of the gypsum accumulation in the soil, not the age of the soil itself. A nongypsiferous soil might have existed for a time previous to the commencement of gypsum accumulation.

The age of the gypsum accumulation was calculated for the upper 68 inches of the profile at Clay Co., Site 5. The weighted average gypsum content is 50.9%. This content would correspond to $8.81 \times 10^3$ metric tons/ha. Water sample No. 3 contains 9.8 meq/liter of CaSO$_4$. Two rates of ground water evaporation were used. The first value was 23.1 inches/unit area/year. This value was determined by Shaw et al. (1958). It represents the average water use for meadow at 20 locations throughout Iowa over a three-year period. Soil profiles to a depth of 5 ft were studied. Water use represents evaporation, transpiration, runoff, and percolation. The data were determined during three abnormally dry years (R. H. Shaw, Dept. of Agronomy, Iowa State University, Ames, Iowa. Personal communication, 1979). Dr. Shaw stated that northwestern Iowa may have less than average water use due to lower rainfall. The presence of a high water table may increase water use. An evapotranspiration rate of 23.1 inches/year and a water concentration of 9.8 meq/liter of gypsum would leave 4.93 metric tons/ha/year in the soil. The age of the gypsum accumulation would be about 2,320 years.

A second "ground water evaporation rate" was taken from data given by Mather (1964). The value is $664 \text{ mm (26.1 inches)}$ /unit area/year of potential evapotranspiration calculated for Spencer, Iowa. Potential evapotranspiration was defined as "the quantity of water that would be
evaporated and transpired from a vegetation-covered area when the soil always contains an optimum of moisture." The evaporation of 664 mm of ground water per year would leave 5.58 metric tons/ha of gypsum in the soil. The age of the gypsum accumulation would be about 2,050 years. This latter figure may represent the more accurate age. Calculations were done similarly to those given in the section entitled "Calculation of soil age." A bulk density of 1.3 g/cm$^3$ was assumed.

The theoretical rise in elevation due to gypsum accumulation was also calculated for the upper 68 inches of the profile at Site 5. A bulk density of 1.3 g/cm$^3$ was assumed for the gypsiferous soil. The adjacent soil was assumed to have a bulk density of 1.5 g/cm$^3$ and to contain no gypsum. The equation for calculating rise in elevation has been given previously as Equation 9.

$$\frac{50.9\% - 0\%}{100} \times 68 \text{ inches} \times \frac{1.5 \text{ g/cm}^3}{1.3 \text{ g/cm}^3} = 40 \text{ inches rise}.$$  

It appears that approximately 40 inches of the upper 68 inches of the profile at Site 5 are due to the gypsum accumulation. This finding explains the mound or microknoll topography of Clay Co., Sites 1-7. It can also be assumed that accumulated gypsum may have given the microknoll shape to gypsiferous areas at other locations.

Detailed laboratory analyses were performed on the samples from the profile at Clay Co., Site 1. Enough soil was collected from each horizon to allow the preparation of a saturation extract. The exchangeable and soluble Na values are very low. The exchangeable Na values are equal to or lower than values determined for calcareous soils found in poorly-
drained areas of the Cary drift plain. Water sample No. 3, which was collected near the site, contained 0.7 meq/liter of Na. The highest contents of soluble Na and Mg in the saturation extracts were from the 16-20 inch horizon. It does not appear that the position within the profile of the maximum concentrations of soluble Na and Mg is of great significance. These ions would form more soluble sulfates than CaSO₄. The Na and Mg sulfates would move upward readily when evapotranspiration occurs and would move downward readily when flushing due to rainfall occurs. The salts may probably be present at any location within the profile depending upon the most recent hydrologic conditions.

It also appears that evaporating ground water precipitated gypsum within the profile of Clay Co., Site 8. The site is calcareous throughout the profile. The zone of maximum gypsum accumulation is above the zone of maximum carbonate accumulation. The gypsum content is evenly distributed to a depth of 56 inches. The gypsum content decreases abruptly at the lithologic discontinuity. Platy structure is in the 8-14, 14-18, 18-33, and 33-38 inch horizons. No dark bands are found in the profile but dark flows appear between the plates of the horizons with platy structure.

The gypsiferous soil from which the profile at Site 8 was taken occurs in a large area on a level to slightly concave swale. Very localized concentrations or mounds of gypsum are not evident. This fact would indicate the shallow water table may have been spread over a large area and not localized from a "point source". The ground water probably came from the gentle slope to the west. The physiographic nature of the
gypsiferous area probably allowed a high water table to remain longer than in the surrounding area. The farmer who farmed the field stated that the gypsiferous area was very slow to dry out after a rain.

Webster County, Iowa

The profiles at Webster Co., Sites 3 and 4 are calcareous throughout. In both profiles, the zone of maximum gypsum accumulation is not above the zone of maximum carbonate accumulation. No clearly defined zone of carbonate accumulation is evident. The gypsum is concentrated at depths of 2-3 ft in each profile. The upper 10 to 15 inches contain very little gypsum. These findings might indicate that the water table may not have been as high in these profiles as those profiles found in Clay and Dickinson Counties which contain abundant amounts of gypsum in the surface layers. The gypsum content in the profile at Site 3 does not cease abruptly at any depth. There is also no abrupt lithologic discontinuity within the profile. The gypsum content in the profile at Site 4 does not cease abruptly either. Finer textured horizons at 58-63 and 65-68 inches do show a decrease in gypsum content when compared to the adjacent horizons. The till is at 72 inches, but the change in texture from the overlying horizon is not pronounced. The calcite-dolomite data for the horizons formed in till are quite comparable to the data determined on the 36 calcareous Cary till samples.

The gravel and particle-size data for the profile at Site 4 show that the material is much coarser than the silty clay sediments that form the parent material of the Lanyon series. Since the site is on a slight
microknoll several inches higher than the surrounding surface, it may be possible that Site 4 represents a coarse-textured inclusion within a fine-textured mapping unit. The rise of the microknoll appears to be due to the actual parent material, not due to gypsum accumulation. The data for the profile at Site 3 show that it is more nearly within the textural range allowed for the Lanyon series. Site 3 is not on a microknoll. Both sites are near the center of a very large, low relief basin. It appears possible that ground water may flow slowly toward the center of the basin and rise to near the surface at various points near its center. It may be possible that the microknoll on which Site 4 is located was the loci of more rapid evaporation and hence more accumulation of gypsum. Kovda (1946), Sandoval et al. (1964a), and Benz et al. (1964) have shown that salts usually accumulate in greater quantities on microknolls than in microdepressions. There did not appear to be any gypsum in the lowest part of the basin near Sites 3 and 4.

No platy structure was observed in the profiles. There are no highly gypsiferous horizons near the surfaces. No dark bands were present in the profiles. There is some horizontal stratification 1-4 mm thick in the 36-44 inch horizon of the profile at Site 3 and the 23-33, 42-50, and 53-58 inch horizons of the profile at Site 4. These strata are not dark bands but bands of very small gypsum crystals. They are light in color (10YR 7/2 dry). They may represent the edge of a drying front of gypsum-laden water. Water sample No. 2 was collected from a 40-50 ft well about one-half mile to the north-northwest of Sites 3 and 4. The water contained 16.0 meq/liter of total sulfate, of which 13.3 meq/liter were
calcium sulfate.

Cottonwood and Redwood Counties, Minnesota

The laboratory data for the Romnell profile (Appendix B, Table 35) indicate that the upper 22 inches are noncalcareous. The gypsum content is also very low, even undetectable in the upper 18 inches by the method used. The zone of maximum gypsum accumulation is between a depth of 27 and 56 inches. The maximum gypsum content is 12.7% and is located in the 43-56 inch horizon. The zone of maximum gypsum accumulation is coincident with the zone of maximum carbonate accumulation. These findings indicate that the water table may have been deeper than for the sites in Iowa.

The gravel and particle-size data indicate that the upper 27 inches of the profile were probably formed in glacial sediments. The till surface appears to be at 27 inches, although the contact is not obvious. An abrupt lithologic discontinuity is not present. The gypsum content decreases at 56 inches. Weak platy structure is found in the 10-18 inch horizon. The platy structure is not well-expressed. No dark, horizontal bands are present. However, the profile description (Appendix A) shows a few horizontal strata 1-2 mm thick of very fine gypsum crystals in the 33-43 inch horizon. These crystals are light in color (10YR 8/1 dry, 7/2 moist). These strata appear to be similar to the ones found in the profile at Webster Co., Sites 3 and 4. They may represent the edge of a drying front of gypsum-laden water. No water samples were collected in Minnesota.

The laboratory data and profile description for the Jeffers profile indicate that the profile is calcareous throughout. Since the Jeffers
series is on the edges of shallow depressions, it is believed that evaporating water enriched the profile with carbonates. The evidence of a fairly shallow water table is stronger in the Jeffers site than in the Romnell site. The zone of maximum gypsum accumulation is above the zone of maximum carbonate accumulation. The gypsum is concentrated between 10 and 35 inches. There is probably more gypsum in the 14-20, 20-28, and 28-35 inch horizons than is shown by the laboratory analysis. Some of the crystals were > 2 mm in size and were included in the gravel fraction. Only a small amount of gypsum is present in the surface horizon. The gravel and particle-size data indicate the profile formed in fairly uniform parent material. No lithologic discontinuity is evident from either the data or the description. A decrease in gypsum content occurs at 35 inches, but it is not nearly as abrupt as in the soils with lithologic discontinuities in Iowa. No platy structure or horizontal bands were observed.

The laboratory data and profile description for the Jeffers MWD variant profile indicate that the profile is calcareous throughout. The zone of maximum carbonate accumulation is in the 16-23 inch horizon. The gypsum is concentrated in the 32-39, 39-46, and 46-53 inch horizons. The quantity of gypsum is not large. Finding the gypsum concentrated in the lower part of the profile may indicate a water table that was not exceptionally high. This would be expected in this moderately well-drained profile. Since the soils are higher in elevation on the low rises than the Jeffers series, the water table would be expected to be deeper. Comparison of the depths of the zone of gypsum accumulation in the Jeffers
and Jeffers MWD variant profiles may also support this hypothesis.

The gravel and particle-size data indicate that the profile formed in fairly uniform parent material. No lithologic discontinuity is evident. Platy structure or horizontal bands were not observed.

Besides the Romnell and Jeffers series, gypsum also appears in Cottonwood Co. as inclusions in other soils that have a lithologic discontinuity (R. E. Rolling, USDA-Soil Conservation Service, Red Lake, Minnesota, Personal communication, 1977). The Millington and Mayer series are two principal ones. Mr. Rolling was the party leader in charge of mapping Cottonwood Co. He stated that the discontinuity may be silty material over fine or coarse sand, silty material over glacial till, or silty clay material over fine or coarse sand. Gypsum has been observed as a 3-6 inch band of fine to coarse crystals associated with almost every type of lithologic discontinuity. His observations indicate the importance of a discontinuity in the formation of some gypsiferous soils.

In Redwood Co., the Romnell series occurs primarily south of the Cottonwood River. The Jeffers series occurs both to the north and south of the river (James Murray, USDA-Soil Conservation Service, Redwood Falls, Minnesota. Personal communication, 1977). It appears from Figure 3 that the Cottonwood River is approximately the isoline for contents of 30% shale in the 1-2 mm size fraction of the New Ulm till. To the north of the river are shale contents of 30 to > 50%. To the south, shale contents are 20-30%. The occurrence of the Romnell series may be correlated to the shale content of the till.
In conclusion, the major difference between the study sites in southwestern Minnesota and the sites in northwestern Iowa is the extent of the gypsiferous soils. The gypsiferous soils in Minnesota are continuous over enough areas to be mappable at the current scale of mapping. Two new series were established. In Iowa, the gypsiferous soils are far less extensive, sometimes occupying only a 30-40 ft circular area. It may be possible that conditions are optimum in southwestern Minnesota for shallow water tables bearing dissolved gypsum to remain for a portion of the year on broad areas of the landscape. Also present may be strong evaporative demand at the soil surface. The precipitation of gypsum within soil profiles may occur over fairly large landscape areas. The precipitated gypsum may not be removed by seasonal flushing during the wetter portion of the year. In northwestern Iowa, it may be that conditions are not optimum for broad-scale gypsum accumulation. Only areas with high water tables under specific geomorphic conditions seem to accumulate gypsum.

There are many areas in northwestern Iowa that have poorly-drained soils. It can also be assumed that most of the ground water contains CaSO₄. It may be that the evaporative demand is not great enough to evaporate large quantities of water and/or rainfall is sufficient enough to remove most gypsum during the wetter part of the year that might have precipitated during the drier part of the year.

Table 16 indicates that the study area in southwestern Minnesota has about 2-3 inches less mean annual precipitation than the study sites in Clay and Dickinson Counties, Iowa. The mean annual temperatures are essentially the same. It may be that this difference in annual
precipitation may be the primary cause of the different extents of gypsiferous soils. Less precipitation would not only increase evaporative demand on the water table but would also allow less gypsum to be redissolved and leached from profiles. Other factors such as differences in the salinity of the parent materials may be involved also.

Other Locations of Gypsiferous Soils

Other areas of gypsiferous soils were located by other workers or by the author. These soils were not sampled and examined extensively. Some were investigated visually with the aid of a hand probe. The locations of the areas will be given for the benefit of possible future investigators.

There are several highly localized gypsiferous areas upslope to the east-northeast of Dickinson Co., Site 2. Immediately across the road to the west of Site 2 are located other gypsiferous areas. These are located just north of the half section line on the eastern side of Sec. 26, T98N, R38W. Gypsum is evident on the north side of a small drainage way. Hand probing indicated gravel is present along the edges of the drainage way. This finding is common in this portion of Dickinson Co. Gypsum was evident along the drainage way as it traversed the section.

About a mile to the east-southeast of Site 2 are other gypsiferous areas. They are located at the southern quarter section line on the eastern edge of Sec. 25, T98N, R38W. The gypsiferous soils occur in a Letri mapping unit that is in a broad, low saddle position.
gradients are < 1% in all directions but do increase in slope within one-quarter mile to the north and south. The gypsiferous soils are located on a microknoll near the lowest elevation of the saddle. The microknoll appears to be formed from deposition of the parent material rather than from elevation of the site due to gypsum accumulation. Hand probing indicated the till surface was at 30 inches. A microdepression near the soils did contain some gypsum but the content appeared to be less than on the microknoll.

Soil maps indicated that virtually every poorly-drained soil in Sec. 23, 24, 25, and 26, T98N, R38W and Sec. 19 and 30, T98N, R37W in Dickinson Co. contained some areas of gypsum accumulation. The areas are too numerous to identify but are located in Letri, Spicer, Marcus, and Blue Earth mapping units.

Evidence of gypsum occurred on the western edge of the NW 1/4, Sec. 22, T98N, R38W along county road M27 in southwestern Dickinson Co. A recently dug drainage ditch along the roadside drained a gravel pit into Stony Creek. Very fine gypsum crystals (powder) were on the dry face of the ditch for its total length of about 200 yards. The gypsum was located at a depth of about 1-3 ft and appeared to have precipitated on the dry bank face. No gypsum was evident to the unaided eye on moist pieces of soil that were broken from the face. The soils in the area were mapped Talcot and Calco. Water sample No. 7 was taken from the gravel pit.

A gypsiferous area occurs immediately to the south of the above-mentioned area. The landscape slopes northward to the floodplain of Stony Creek. East of county road M27 was a gypsiferous area that was so wet that it had to be avoided by a farmer when plowing. It appears that the
area is a small concave bench position on the sideslope. Water sample No. 8 was collected near the site. The water well was located in the floodplain of Stony Creek. The data on the water sample appear to be spurious. A barnyard was located upslope from the well and may have contaminated the water.

Very fine gypsum crystals were on the dry bank face of Stony Creek in the SE¼, Sec. 27, T98N, R38W. The crystals appeared almost identical to the ones seen on the face of the drainage ditch noted previously. The drainage ditch is about 2 miles upstream from the present area. No gypsum could be seen with the unaided eye in soil obtained by hand probing into the creek bank. The soil was moist and black. It appears that gypsum-laden water probably migrated to the face of the dry bank. The soil at the creek bank has a gypsum content that is probably undetectable by laboratory methods.

It was common to observe gypsum crystals (powder) on the dry bank faces of streams and drainage ways in a portion of southwestern Dickinson Co. The 20 square mile area is approximately bounded by county roads M38 on the east, A34 on the north, M27 on the west, and A43 on the south. The area may extend beyond these boundaries.

A gypsiferous area is located in a Spicer mapping unit 600 ft N of the SW corner, NE¼, Sec. 9, T98N, R38W in southwestern Dickinson Co. One probing indicated an 8 inch sand lens beginning at about 30 inches. Another probing indicated a sand lens beginning at 32 inches and extending to at least 44 inches. The length of the probe prevented deeper investigation. The gypsum content ceased abruptly at the lithologic discontinuity.
Sometimes a dark horizontal band was also at the contact.

Another area is located 600 ft N and 800 ft W of the SE corner, Sec. 18, T98N, R38W. It is located in a Primghar mapping unit, but the soil is grading toward the Spicer series. The gypsiferous area was on a microknoll in a small swale. The swale was bounded by slight ridges on opposite sides. The distance between the two ridges was 300 ft. The decrease in elevation from the top of the ridges to the center of the swale was 2.5 ft. Very fine gypsum crystals were at the soil surface of the microknoll. A layer of abundant gypsum crystals was at a depth of 8-16 inches.

Gypsiferous areas also occur in a Marcus silty clay loam variant inclusion within a Marcus silty clay loam mapping unit in the SW¼, NW¼, Sec. 17, T98N, R37W in southwestern Dickinson Co. Gypsum is on the surface of microknolls within very slight depressional areas. Most of the pedons in this delineation (about 35 acres) are calcareous at a depth of 8-20 inches, and most have a layer of gypsum crystals in the upper B horizon (W. N. Dankert, USDA-Soil Conservation Service, Spirit Lake, Iowa. Personal communication, 1978). Evidently gypsum only occurs at the soil surface on the microknolls, although gypsum may occur lower in the profile throughout much of the delineation.

In southeastern Dickinson Co., gypsiferous areas occur in the western half of the NW¼, Sec. 18, T98N, R35W. These areas are within the Cary drift region. All previous sites in Dickinson Co. have been in the region of loess or loamy sediments over Tazewell drift. The areas are located in a Canisteo mapping unit with very low relief in all directions.
There are several small areas with gypsum at the soil surface and with abundant gypsum at a depth of 15 to 25 inches. In hand probing one gypsiferous area, no lithologic discontinuity was evident. About 50 ft away, 34 inches of sand was evident at a depth of 30 to 64 inches at two locations 10 ft apart. This area was nongypsiferous. The sand was saturated with water. Probing near this latter area indicated a sand layer was not present.

In northwestern Dickinson Co., gypsum occurred in the SW¼ of Sec. 3, T99N, R38W and the NW¼ of Sec. 10, T99N, R38W. This location is in a high relief area of the Cary drift region. The location is a drained lake or slough that is about 100 acres in size. Most of the bottom of the drained slough appears to be gypsiferous. The soils are calcareous with high contents of organic matter and are mapped Blue Earth mucky silt loam and Palms muck, calcareous variant. There are very fine crystals on the dry soil surface and greater concentrations of larger crystals commonly between depths of 20 and 45 inches. The occurrence of gypsum in this physiographic setting has not been mentioned before in the thesis. The other gypsiferous areas have occurred in low relief areas. It appears that gypsum may have been precipitated due to evaporation of the ponded water. Water sample No. 16 was collected near this area.

Large amounts of dissolved gypsum were evident in the water from two seep areas in Dickinson Co. Sample No. 22 was collected from a seep on a sideslope position along Dugout Creek (Table 18). There are a number of seeps along Dugout Creek (W. N. Dankert, USDA-Soil Conservation Service, Spirit Lake, Iowa. Personal communication, 1979). The seep had a very light sulfurous odor. Sample No. 23 was collected from the
top of a ridge adjacent to Silver Lake. It had very high quantities of dissolved gypsum. The seep had a very noticeable sulfurous odor. The water was slightly "milky" in appearance. This seep drains into Silver Lake. The sulfate content of Silver Lake (sample No. 5) is higher than the sulfate content of Spirit Lake (sample No. 4). The sulfurous odor at these seeps is probably due to hydrogen sulfide gas (H\textsubscript{2}S). Sulfate can be reduced to sulfide by bacteria under anaerobic conditions.

In Clay Co., the areas of the Canisteo, gypsic variant mapping unit are in the SW\textsubscript{4}, Sec. 29 and the NW\textsubscript{4}, Sec. 32, T97N, R36W and in Sec. 8, T96N, R36W. These areas are northeast of the town of Spencer. To the southwest of Spencer, near the town of Royal, gypsiferous areas occur in some Marcus mapping units. These areas were not delineated or located by a spot symbol on soil maps (R. G. Jones, USDA-Soil Conservation Service, Forest City, Iowa. Personal communication, 1979).

Some gypsiferous areas also occur in Calhoun Co. to the east of Rockwell City. One area is located 690 ft N and 275 ft W of the SE corner, SW\textsubscript{4}, Sec. 25, T88N, R32W. It is in a Harps loam mapping unit. Some very fine crystals were on the dry soil surface. Coarse crystals (1-2 mm) were in a layer at 30-38 inches. The crystals appeared to compose at least 50% of the volume of the soil matrix. The area is a microknoll about 100 by 50 ft in size. A short distance away, another area is located 275 ft N and 245 ft W of the SE corner, SW\textsubscript{4} of the same section. The area is also in a Harps delineation on a microknoll about 300 by 200 ft in size. The microknoll rises about 0.5-1 ft in elevation over a linear distance of about 300 ft. Hand probing at the latter area
indicated no evidence of a lithologic discontinuity. Probing a few feet away indicated a sand lens at least 28 inches thick. Sand occurred from a depth of 40 to 68 inches. The lower depth was the limit of the probe length. Water sample No. 1 was collected about one-half mile west of these areas.

Some gypsiferous areas also occur near Farnhamville in Calhoun Co. Some areas occur in the northern halves of the NW$_4$ and NE$_4$, Sec. 9, T86N, R31W. Some areas occur in the SE$_4$ of the same section and in the SW$_4$, Sec. 4, T86N, R31W. The areas occur in Canisteo and Webster mapping units. The topography is flat.

In Webster Co., other gypsum spot symbols are present on the soil maps for the NW$_4$, SW$_4$, Sec. 10, T87N, R30W and the SW$_4$, Sec. 21, T87N, R29W. The former area is in a Lanyon mapping unit that is surrounded by a Harps mapping unit. The latter area is in a Canisteo mapping unit.

Gypsum has been observed on the dry face of stream banks in southern Kossuth Co., although no gypsum has been observed in soils (R. G. Jones, USDA-Soil Conservation Service, Forest City, Iowa. Personal communication, 1979). Similar observations have occurred in Wright Co.

The previously mentioned areas in Calhoun, Webster, Kossuth and Wright Counties occurred in the Cary drift region. The following areas in O'Brien and Osceola Counties are in the region of loess or loamy sediments over Tazewell drift.

Gypsum crystals occur in a Marcus mapping unit in Sec. 15, T96N, R39W, in O'Brien Co. The crystals were at a depth of about 42 inches in some probings, but were absent in others.
Several gypsiferous areas occur in Osceola Co. One is located 0.4 miles E and 300 ft N of the SW corner, Sec. 21, T100N, R41W. This area was investigated in the mid-1960s when problems of deteriorating concrete drainage tile occurred. Gypsum also occurs to the south of this area in the northern part of Sec. 28. The setting of these areas is in the center of a low, broad saddle very similar to ones found in southwestern Dickinson Co. The areas are actually in a broad "trough", oriented in a northwest to southeast direction, with a slope of < 1%. The areas appear to be near the Cary-Tazewell border, but it is believed they are outside of the Bemis moraine. Gypsiferous areas also occur about a mile to the southeast in the southern edge of Sec. 28, T100N, R41W. These areas are in the same "trough" system.

Powdery gypsum crystals occurred on the dry face of an excavation near a farmstead located at the SW corner, Sec. 27, T100N, R41W. Similar crystals also occurred on the dry face of a road ditch in the SW corner, Sec. 34, T100N, R41W. It appears that very small amounts of gypsum are in some of the poorly-drained soils in central Osceola and southwestern Dickinson Counties. The amounts are too small to be seen when moist. Crystals are evident only upon drying.

The occurrence of gypsiferous areas in Iowa appears to be distributed within a region of northwestern Iowa. All gypsiferous areas are in poorly-drained areas, and virtually all of the areas with large amounts of gypsum accumulation are calcareous also. Investigations were made to check for the possibility of the occurrence of gypsum in poorly-drained, calcareous soils collected from a larger region of Iowa. Several
profiles were retrieved from the storage of the Iowa Soil Survey Laboratory and analyzed for gypsum content. All profiles were collected from the Gary drift region except for a Calco profile from Dickinson Co. and a Marcus profile from O'Brien Co. When feasible, three horizons per profile were analyzed: the surface horizon, a horizon at about 24 inches, and a horizon at about 60 inches. Only surface horizons were available for some profiles. The data are given in Appendix E, Table 40.

The occurrence of gypsum was infrequent. Gypsum was present in only three profiles that were collected from Dickinson Co. The Calco profile (30-76-39) was sampled from the southwestern portion of the county 314 ft N and 180 ft E of the SW corner, NW¼, Sec. 22, T98N, R38W. This location is in the floodplain of Stony Creek and is near the gravel pit drainage ditch that had powdery gypsum crystals on its dry banks. The Palms, calcareous variant profile (30-77-36) was sampled from the northwestern part of the county 50 ft W and 135 ft S of the NE corner, Sec. 5, T99N, R38W. This location is slightly over a mile from the previously mentioned large, gypsiferous slough bottom in Sec. 3. The other Palms, calcareous variant profile (30-78-21) was sampled from the extreme northwestern portion of the county 375 ft S and 95 ft W of the NE corner, Sec. 7, T100N, R38W.

It should be noted that the Palms profile from Hamilton Co. (40-77-3) was described as containing gypsum crystals in the 16-30 inch zone. Yet laboratory analysis indicated no detectable gypsum. Possibly the gypsum was in large enough crystals to have been included in the > 2 mm gravel fraction. The profile was sampled 850 ft S and 500 ft E of
the NW corner, NW 4/4, SE 1/4, Sec. 9, T89N, R26W.

Gypsum analysis was also performed on the carbonate-enriched profiles previously analyzed for calcite-dolomite contents. The data are given in Appendix D, Table 39. The only profile that contained gypsum was a Blue Earth profile from Pocahontas Co. It was sampled 2540 ft W and 2470 ft N of the SE corner, Sec. 16, T93N, R34W. The Blue Earth series formed in sediments in the bottoms of ponds and sloughs. It is calcareous throughout the profile.

In southwestern Minnesota, gypsiferous soils have been traced specifically into Murray, Lyon, Lincoln, and Nobles Counties (R. E. Rolling, USDA-Soil Conservation Service, Red Lake, Minnesota. Personal communication, 1977). Gypsiferous soils were traced to the extreme southwestern corner of Nobles Co. and also across the state line into Osceola Co., Iowa. Soil survey parties have indicated that gypsiferous soils occur in the region of Minnesota approximately bounded by the Minnesota River on the north and east and by South Dakota on the west (R. H. Rust, Dept. of Soil Science, Univ. of Minnesota, St. Paul, Minnesota. Personal communication, 1978). The Burr series has recently been proposed in Yellow Medicine Co., Minnesota. This series is similar to the Calco series except that it normally contains 5-20% gypsum in the control section. An extreme range of 30% gypsum is allowed.
Toward a Regional Model of Genesis

There are striking differences in the areal distribution of gypsiferous soils in northwestern Iowa and southwestern Minnesota. These differences have been discussed briefly. The question remains as to why these differences exist. It could be possible that the differences are due to the salinity of the parent materials. It may be that the gypsiferous soils are much more extensive in southwestern Minnesota because of a higher content of shale in the drift. Greater amounts of soluble salts would be released from the shale. Fairly extensive areas of salt-affected soils may result. In northwestern Iowa, the shale content may be lower. Lesser amounts of soluble salts would promote fewer extensive areas of salt-affected soils. All of the study sites in Minnesota and some of the sites in Iowa occur on the same late-Wisconsin drift plain. Other sites in Iowa occur on a different drift plain. Since the occurrence of gypsiferous soils transgresses different drift plains, it is less likely that parent material differences are the only cause of areal distribution differences.

Gypsum appears to occur in appreciable quantities in soils in the western portion of northern Iowa and southern Minnesota. Very fine crystals occurred on the dry faces of stream banks in north-central Iowa, but no gypsiferous soils were evident. Yet, carbonate-enriched soils occur to the edge of the Bemis moraine in north-central Iowa, about 90 miles east of Dickinson Co. West of northwestern Iowa, soils containing gypsum and carbonates appear to occur frequently. Works cited earlier have indicated that about 120 miles west of Dickinson Co., gypsum is commonly
present and readily-soluble salts (sodium compounds) may also become appreciable in depressional soils formed in late-Wisconsin drift in southeastern South Dakota. The question arose concerning the possibility of sodium salts being present in the depressional soils of Iowa. All of the water samples analyzed in the current study showed contents of sodium. Yet the pH values of the soil samples collected in the current study indicated high concentrations of sodium were not present. The highest pH value determined was 7.6. By the pH method used, this value would indicate a sodium adsorption ratio (SAR) of <13. Exchangeable and soluble sodium values were very low for the profile at Clay Co., Site 1. Data in the literature have not indicated high sodium concentrations in the carbonate-enriched soils of the Cary drift plain in Iowa. For additional investigation, several samples were analyzed for exchangeable sodium. Analysis was performed on samples previously analyzed for calcite-dolomite and/or gypsum contents. The data are given in Appendix D, Table 39 and Appendix E, Table 40. Very low values were present. Questions arose as to why gypsum does not occur in all carbonate-enriched soils, and why sodium compounds do not occur in all carbonate- and/or gypsum-enriched soils.

It appears that climatic conditions may be the primary reason for the different amounts and quantities of soluble salts in these soils. On a regional basis, differences in climate do exist. From Figures 5, 6, 7, and 8, it can be seen that the region from north-central Iowa to southeastern South Dakota has essentially the same mean annual temperature. Mean annual precipitation varies. The area near the eastern edge of the Bemis moraine in north-central Iowa has about 31 inches of mean annual
precipitation. The area near the western edge of the Bemis moraine in Clay and Dickinson Counties has 27-28 inches. Cottonwood and Redwood Counties in southwestern Minnesota have about 25 inches. Turner, McCook and Miner Counties in southeastern South Dakota have about 22-24 inches. These counties are about 20-40 miles west of Sioux Falls. Within 30-60 miles northwest of these counties, the mean annual precipitation is about 20 inches or less.

The carbonate-enriched soils in the eastern part of the region under consideration apparently contain little or no gypsum or sodium compounds. Soils on similar settings in the middle part of the region often contain carbonate, with gypsum present occasionally. Soils on similar settings immediately to the west and northwest of Sioux Falls, South Dakota often contain carbonate and gypsum, and sometimes appreciable amounts of sodium compounds. It appears that the region under consideration is a gradational or "buffer" zone between predominantly "leached" soils to predominantly "unleached" soils. In the former terms of C. F. Marbut, this region represents a gradational zone between the Pedalfers and the Pedocals.

It is important that accumulations of gypsum occur before accumulations of sodium compounds in the transect from the wetter climates to the drier climates. Sparingly-soluble gypsum is about 100 times more soluble than relatively insoluble CaCO$_3$. Readily-soluble Na$_2$SO$_4$ is about 50 times more soluble than gypsum. In the eastern portion of the region, the salt balance is such that only CaCO$_3$ apparently accumulates. Any other salts that are more soluble than CaCO$_3$ either are not precipitated or are
removed from the profile by seasonal leaching. In the middle portion of the region, the salt balance is such that some gypsum also accumulates. Evidently it is precipitated within the profile and is not removed by seasonal leaching. The readily-soluble salts are removed. In the western portion of the region, the salt balance is such that readily-soluble salts may accumulate also. Evidently they are precipitated within the profile and are not removed by seasonal leaching in some soils. The sequence of salts occurring in the transect from the eastern to the western portions of the region is expected. The solubilities of the salts promote similar sequences elsewhere in nature. The evaporation of a saline lake often leaves concentric rings of relatively insoluble, then sparingly-soluble, and then readily-soluble salts. Kovda (1946) states that a similar sequence often occurs in soil profiles with upward water movement due to evapotranspiration.

The climatic factors of mean annual temperature and precipitation are not completely adequate to describe the water balance of soils. Other climatic factors are also important, such as when the precipitation occurs, the amounts in which it occurs, wind speed, solar radiation, and other factors which affect evapotranspiration. Climatologists have developed equations which use such factors to model the water balance of soils. Mather (1964) gives soil water balance data for many locations within the United States. Data for locations which are in the region under discussion are given in Table 21. The data are the means of annual totals taken over many years. Potential evapotranspiration is the quantity of water that would be evaporated and transpired from a vegetation
Table 21. Soil water balance data for northwestern Iowa, southwestern Minnesota, and southeastern South Dakota

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<tr>
<td>Precipitation</td>
<td>648</td>
<td>641</td>
<td>683</td>
<td>577</td>
<td>725</td>
<td>696</td>
</tr>
<tr>
<td>Actual evapotranspiration</td>
<td>588</td>
<td>599</td>
<td>627</td>
<td>577</td>
<td>624</td>
<td>603</td>
</tr>
<tr>
<td>Water deficit</td>
<td>42</td>
<td>45</td>
<td>18</td>
<td>58</td>
<td>14</td>
<td>13</td>
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<tr>
<td>Water surplus</td>
<td>60</td>
<td>18</td>
<td>56</td>
<td>0</td>
<td>101</td>
<td>93</td>
</tr>
<tr>
<td>Town abbreviation</td>
<td>Potential evapotranspiration</td>
<td>Precipitation</td>
<td>Actual evapotranspiration</td>
<td>Water deficit</td>
<td>Water surplus</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------------------------</td>
<td>---------------</td>
<td>---------------------------</td>
<td>--------------</td>
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<td></td>
</tr>
<tr>
<td>South Dakota</td>
<td>South Dakota</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Armour</td>
<td>AR</td>
<td>665</td>
<td>583</td>
<td>583</td>
<td>0</td>
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<td>B</td>
<td>607</td>
<td>516</td>
<td>516</td>
<td>91</td>
<td></td>
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<tr>
<td>De Smet</td>
<td>D</td>
<td>613</td>
<td>560</td>
<td>560</td>
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<tr>
<td>Huron</td>
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<td>633</td>
<td>487</td>
<td>146</td>
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<tr>
<td>Mitchell</td>
<td>MI</td>
<td>647</td>
<td>598</td>
<td>49</td>
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<td>Sioux Falls</td>
<td>SF</td>
<td>664</td>
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<td>35</td>
<td>18</td>
<td></td>
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<td>Tyndall</td>
<td>TY</td>
<td>666</td>
<td>625</td>
<td>41</td>
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<tr>
<td>Water town</td>
<td>WA</td>
<td>589</td>
<td>541</td>
<td>48</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

\[a\] From Mather (1964).

\[b\] Letters below town names are abbreviations used in Figure 14.

\[c\] All data given in millimeters.
covered area when the soil always contains an optimum of moisture. Many climatic factors are used in the calculation of this value. Actual evapotranspiration is the calculated quantity of water that is evaporated under the actual climatic conditions of the location. Actual evapotranspiration will equal potential evapotranspiration as long as the precipitation is greater than the potential water needs of the plants, i.e., the soil does not become appreciably desiccated. Water surplus equals the excess precipitation which occurs when the soil moisture storage equals the water-holding capacity of the soil. Annual water surplus is calculated by subtracting actual evapotranspiration totals from precipitation totals. Water deficit is the difference between the potential and actual evapotranspiration values. The water deficit is the added amount of water that could have been evaporated if the soil was continually moist.

The data indicate the expected trend of more water surplus in the eastern portion of the region than in the western portion. The water surplus data were plotted on a regional map, and some relationships may be evident. The relationships are shown in Figure 14. Abbreviations used in Figure 14 are the towns given in Table 21. It appears that the value of about 100 mm mean annual water surplus may be the approximate boundary between the region of little or no gypsum accumulation and the region where gypsum may be accumulated. It also appears that the value of about 20 mm mean annual water surplus may be the approximate boundary between the region of possible gypsum accumulation and the region of common gypsum accumulation with the additional possibility of accumulation of
Figure 14. Map of northwestern Iowa, southwestern Minnesota, and southeastern South Dakota showing soil water balance relationships. Isolines represent mean annual water surplus, in millimeters. Town abbreviations given in Table 21. Map scale: 1 inch = 30 miles.
sodium compounds. The data presented in Figure 14 indicate the following
generalizations. The area of > 100 mm mean annual water surplus is lo-
cated in the extreme southeastern portion of the map. Probably CaCO₃ will
be the primary salt which will accumulate in certain soils. Gypsum might
be found sporadically. There are several gypsiferous areas within 20 miles
of Rockwell City. Northwestward, the area between 100 and 20 mm mean
annual water surplus may have CaCO₃ as well as gypsum accumulate in cer-
tain soils. The occurrence of gypsum is probably infrequent. Continu-
ing northwestward, the area of < 20 mm mean annual water surplus may have
CaCO₃, frequently gypsum, and sometimes sodium compounds accumulate in
certain soils. Some sodium-affected soils are known to occur in south-
eastern South Dakota. The isolines of Figure 14 should be considered
gradational boundaries. Their locations may be revised as further in-
formation becomes known.

The relationships between soil water balance data and actual water
movement in soils and the relationships between soil water movement and
salt accumulation are interrelated. It appears that two primary condi-
tions must be present for salt accumulation in soils to occur. There
must be ground water that contains the dissolved salts. There must also
be a water balance that will permit the processes of precipitation of
salts due to evapotranspiration to exceed the processes of dissolution
and leaching of the salts. Additions must exceed removals. The balance
between the processes of precipitation and leaching determine whether in-
soluble salts, sparingly-soluble salts, or readily-soluble salts will
accumulate. Many factors effect the water balance. Among the most
important ones are precipitation patterns and amounts, evapotranspiration patterns and amounts, and the geomorphic surface on which the soil occurs. Sloan (1972) has described ground water movements within poorly-drained depressional soils (Figure 15). Although his work was done in North Dakota, the principles may apply elsewhere also.

The relief of the depressions and the water table levels are greatly exaggerated for the illustration. Similar relationships may exist in broad, shallow depressions.

Figure 15A shows a diagram of the inflow of ground water into a depression. Drainage is not adequate to remove an appreciable portion of the inflowing water. Dissolved salts might concentrate within the depression if evapotranspiration occurred. Figure 15B shows a diagram of the outflow of water from a depression. Drainage is sufficient to remove most of the water that flows into the depression. Dissolved salts would be removed in drainage. Salts that might precipitate during some seasons of the year would probably be leached during other seasons.

Figure 15C shows a diagram of a combination of the inflow-outflow process, called through flow. Some water flows into the depression either superficially or by ground water. Subsurface drainage is sufficient to remove some of the inflowing water. Although the depression may be ponded, the pond water does not become stagnant. A constant "exchange" of water occurs. Salts may accumulate in some areas of the depression where inflow exceeds outflow. Salts may be removed in other areas where outflow equals or exceeds inflow.

The following discussion will attempt to relate these three types
Figure 15. Flow of ground water in closed depressions in relation to water table configuration

of hydrologic processes to depressions in the region extending from north-central Iowa to southeastern South Dakota. For the sake of comparison, uniform conditions except soil water balance data will be assumed for the whole region. A uniform parent material will be assumed. Ground water will be assumed to contain similar concentrations of dissolved Ca, Na, CO$_3$, SO$_4$, and other ions. The size and physiography of the depressions will be assumed to be similar. Only the soil water balance data will vary. Information from the literature on the soils of
this region will be used in the comparisons.

In the eastern part of the region, annual precipitation is the highest. Annual precipitation appreciably exceeds potential and actual evapotranspiration on a mean annual basis. Water flowing into depressions might not remain for an extended period of time. Additional precipitation and resultant ground water flow might create a through-flow situation for much of the depression (Figure 15C). Some water would be flowing in; other water would be flowing out. It would be doubtful that stagnant, saline ponds would form. The water would probably not be appreciably concentrated by evapotranspiration. Calcium carbonate might be the only salt precipitated. If the water ever became concentrated enough to precipitate gypsum or sodium compounds, those salts might be leached subsequently. Carbonate-enriched soils often occur around the edges or rims of depressions. Near the edges of the depression, evapotranspiration removes water not only from the pond surface but also from the adjacent soil due to the capillary rise of the water. The depression edge would be where most of the concentrating of the pond water might occur. Most salts would be precipitated there. The soils in the centers of the depressions might be less calcareous than those on the edges, or may even be noncalcareous to a depth of several feet. The centers of the depressions would probably be the last part of the depression to be desiccated and were probably desiccated less frequently than the depression edges. Also the centers of the depressions would probably be where most outflow occurred due to their lower relative elevation. Any salts which might have been precipitated there during some periods might be leached
by water outflow during other periods.

Moving westward in the region under consideration, mean annual precipitation becomes less. Precipitation may slightly exceed potential and actual evapotranspiration on a mean annual basis. The hydrology of the depressions may change slightly. The inflow and outflow of water into the depressions may occur at a slower rate. The water may have a longer opportunity to be affected by evapotranspiration. Enough concentrating may occur that gypsum may be precipitated around depression edges along with CaCO₃. The Jeffers soils probably represents an example of such an occurrence. It is doubtful that large quantities of readily-soluble sodium compounds would be precipitated and would remain in the soil profile. The soils in the centers of the depressions may be less calcareous than those on the edges.

In the western part of the region, precipitation equals actual evapotranspiration and is much less than potential evapotranspiration. Water flowing into depressions may be appreciably concentrated by evapotranspiration. Carbonates, gypsum, and sodium compounds may be precipitated. Water outflow may not be adequate to remove all of the precipitated salts. Water outflow would probably be reduced due to the lack of water volume. Much of the water in the depression may be left to evaporate. The most salts may accumulate around the edges of the depressions, but the trend may become less pronounced. In the far western edge of the region, the most saline portion of the depressions may be the centers. Surface and ground water flow may be sufficient to transport only the dissolved minerals to the lowest part of the depression. The water may then
There appears to be a general trend of salt location within the depressions from the wetter to the drier climates. In the wetter climates, carbonates appear to concentrate near the edges of the depressions. As the climate becomes progressively drier, carbonates may be present in much of the depression while gypsum and carbonates may concentrate near the depression edges. In still drier climates, gypsum may also occur throughout the depression while sodium may accumulate near the depression edges. In the driest climates, sodium may be concentrated near the centers of the depressions.

It should be stressed again that the preceding statements are generalities. Local variations in physiography and parent materials will affect the hydrologic relationships of the depressional systems. Some depressions may be different in salt content and location than surrounding ones. There are occurrences of sodium-affected soils in Illinois, Indiana, Arkansas, and Mississippi under conditions of much higher rainfall. Combinations of parent material, ground water flow, and physiography factors have caused these soils to form. Papers discussing these soils have been cited previously.

It is interesting that most of the gypsiferous soils in northwestern Iowa occur in areas of low relief. Climatic conditions in northwestern Iowa appear to be marginal for gypsum accumulation. The low relief areas might have slow ground water movement. Outflow may be less than in soils occurring in areas of high relief. The water within the soil profiles may be more likely to be affected by evapotranspiration. Gypsiferous
soils are often on microknolls within the poorly-drained areas. Evapo-
transpiration may be greater on the microknoll surface than on the sur-
rounding area. Gypsiferous soils also occur in areas of open drainage,
as was evident in Dickinson and Osceola Counties. These soils usually
occur on broad, low saddle positions. It is also interesting that slight
amounts of gypsum occur on the dry faces of stream banks and excavations
in these poorly-drained areas. A small amount of gypsum appears to be
present in the ground water. Under the right conditions, concentration
of gypsum may occur to form gypsiferous soils.

However, gypsum does occur in a few areas of high relief. Three
former lake beds in northwestern Dickinson Co. contained gypsum. There
are several reasons which may explain why gypsum accumulated in these
areas. It is probable that drainage was restricted in these depressions.
They became lakes. Inflow rates evidently exceeded outflow rates. It
appears that the depressions were wet a major portion of the time. Some
were not drained until a few years ago. The soils are usually mapped
as muck and mucky mineral soils. It appears that a water inflow situa-
tion may have been predominant. These three former lake beds are mapped
as calcareous mucks. Evidently the ponded water was sufficiently concen-
trated by evapotranspiration to cause carbonates to be precipitated.
At least in these three cases, evapotranspiration proceeded to the point
that gypsum was precipitated also. Outflow was insufficient to com-
pletely remove the gypsum. It is not known if high amounts of sodium
compounds are present. High amounts are not expected. Areas of muck
occur throughout the Des Moines lobe of late-Wisconsin glaciation.
If the muck is not calcareous, it is not likely that gypsum will be present. Noncalcareous mucks may have formed in depressions where through flow was sufficient to prevent precipitation of salts, even though the depression may have been ponded much of the time.

From the data in Table 21, it is evident that Cottonwood and Redwood Counties, Minnesota have less mean annual water surplus than do counties in northwestern Iowa. This fact may be one reason gypsiferous soils are more common in Minnesota than in Iowa. It also appears that some sulfate salts other than gypsum may be accumulating in some of the gypsiferous soils in southwestern Minnesota. Data determined by the Minnesota Soil Survey Laboratory on the saturation extracts of several Jeffers profiles from Cottonwood Co. indicate that the sulfate content often was 50-60 meq/liter and sometimes was 70 meq/liter. A saturated solution of gypsum in pure water contains about 30 meq/liter. In the presence of strong electrolytes, the solubility of gypsum may be up to 50 meq/liter. To have sulfate concentrations of 60-70 meq/liter, other cations beside Ca are probably present. The EC values of the saturation extracts were also as high as 5.00 mmhos/cm. These values are higher than the values determined on saturation extracts from the profile at Clay Co., Site 1 (Appendix B, Table 25).

The Cottonwood and Redwood Counties area of southwestern Minnesota also has nongypsiferous soils which reflect the effects of a drier climate. The Clarion and Nicollet soils are well and moderately-well to somewhat poorly-drained soils, respectively, that are mapped extensively on the Des Moines lobe of late-Wisconsin glaciation. These soils are
not mapped in Redwood Co. because soils occurring on equivalent settings contain calcic horizons. The soils that are mapped are classified as Udic Ustolls (James Murray, USDA-Soil Conservation Service, Redwood Falls, Minnesota. Personal communication, 1977). The Clarion and Nicollet soils, which are Udolls, are inclusions within these mapping units.

Saline lakes and saline soils are not common in Iowa. If past climatic conditions had been different, the possibility exists that saline lakes and saline soils may have formed. It would be interesting to compare Iowa with a region of similar parent materials and topography but with a drier climate. Such a comparison would be virtually impossible. A very general comparison will be made between the region of late-Wisconsin glaciation in northwestern Iowa and an area in central North Dakota. The work of Sloan (1972) was done in central North Dakota. That region was also covered by late-Wisconsin glaciation, and drainage nets are not well-developed. Undrained ponds and lakes are common. Climatic conditions consist of about 18 inches mean annual precipitation and 40°F mean annual temperature. Data given in Table 9 have demonstrated the salinity of some of the lakes in the region. Other workers have described the salt-affected soils of the region. Water quality data will be used as an approximate indicator of the chemical similarities of the parent materials. Data given in Table 8 were determined on spring waters from central North Dakota. Table 18 has given data for some ground water samples collected in northwestern Iowa. Samples No. 1, 2, 3, 12M, 16, 20, 21, 22, and 23 were used to compute average data for the ground water samples collected in northwestern Iowa. Table 22a gives the average values for
selected chemical properties of ground water samples from central North Dakota and northwestern Iowa.

Table 22a. Mean values of chemical properties for ground water samples from central North Dakota and northwestern Iowa

<table>
<thead>
<tr>
<th>Location</th>
<th>No. of samples</th>
<th>Na meq/liter</th>
<th>SO\textsubscript{4} meq/liter</th>
<th>EC mmhos/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central North Dakota</td>
<td>12</td>
<td>4.0(2.3)\textsuperscript{b}</td>
<td>4.3</td>
<td>1.10</td>
</tr>
<tr>
<td>Northwestern Iowa</td>
<td>9</td>
<td>1.4</td>
<td>9.8</td>
<td>1.40</td>
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</table>

\textsuperscript{a}Means calculated from Tables 8 and 18.

\textsuperscript{b}Mean Na content would be 2.3 meq/liter if two exceptionally high values are omitted.

The values are similar. The samples from North Dakota were collected entirely from springs. The samples from Iowa were collected from springs, wells, and drainage tile outlets. It may be possible that saline lakes and saline soils might have developed in certain portions of Iowa if drier climatic conditions had been present.

Bancroft (1918) and Stevenson et al. (1930) both mentioned white salt "crusts" on the dry surfaces of soils around the edges of recently-drained depressions in Iowa. Bancroft (1918) states that the "crusts" often disappear after several years of good drainage. It is not likely that these "crusts" might have represented large amounts of readily- and sparingly-soluble salts in carbonate-enriched soils prior to artificial drainage by man. The researchers studying the soils concluded that the white, powdery "crusts" were probably due to Ca and Mg bicarbonates.
If appreciable amounts of gypsum had been present in some soils at the time of artificial drainage, the gypsum may be detectable today. The removal of gypsum from soils would probably take a considerably longer time than has elapsed since artificial drainage. Since many of the poorly-drained areas of the upper Midwest are now artificially drained, the processes of salt accumulation may be reduced or have ceased in some instances. Some soils may be losing salt contents due to the increased outflow of ground water from poorly-drained areas.

Sandoval et al. (1964b) and Johnsgard (1971) have stated that artesian water from deep within underlying geologic materials may be the source of dissolved salts in much of the ground water in the Red River valley of North Dakota and Minnesota. It is unlikely that a similar situation exists in northwestern Iowa. It appears that almost all of the gypsiferous areas investigated can be explained by local hydrologic conditions. There is little or no evidence of water under regional artesian pressure reaching the land surface in northwestern Iowa, except by wells. Some artesian wells occur throughout the state. The artesian aquifers are much deeper in Iowa than in the Red River valley. Information given by Norton (1912) states that most of the artesian wells in Iowa at that time were at least 1,000 ft deep. Miller and Norton (1912) mentioned one "mineral spring" near Kalo in Webster Co. Meinzer (1912a) mentioned no artesian phenomena in Clay Co. Meinzer (1912b) also mentions no artesian phenomena in Dickinson Co. He does make the statement, "At some distance below the surface, the boulder clay is compact and impervious, but at certain horizons it includes sand and gravel that are charged with water
under pressure." He stated that it would be very unlikely to find any wells that would free-flow at the surface.

Taxonomic Considerations

Gypsiferous soils may present unique taxonomic problems. The profiles collected in southwestern Minnesota were collected from established soil series. The series taxonomy has been presented previously and will not be discussed further. The profiles collected in northwestern Iowa were collected from either gypsiferous inclusions within nongypsiferous mapping units or from a gypsiferous variant of an established series. All of the gypsiferous soils collected in northwestern Iowa would be classified as Aquolls at the suborder level. All profiles have mollic epipedons based strictly upon the moist color and thickness of the surface horizon. Soil Taxonomy (Soil Survey Staff, 1975) states that the color requirement for moist soil for a mollic epipedon is a Munsell color value and chroma both less than 3.5. Yet it should be noted that the color requirements may be expanded under some circumstances. If there is > 40% finely-divided lime, the color value should be 5 or less. This allowance is made because lime acts as a white pigment and lightens the usually dark color of organic matter. No statement is made whether such an allowance can be made for soils containing large quantities of gypsum. It is recommended that gypsum should be included in determining the 40% content of finely-divided, light-colored minerals. Gypsum is also a light-colored mineral. The purpose of the color requirement for mollic epipedons is to help select horizons that have ≥ 0.6% organic carbon.
content (1% organic matter content). Data given in Appendix B and profile descriptions given in Appendix A demonstrate that some horizons that have moist colors lighter than 3/3 also have $\geq 0.6\%$ organic carbon and $> 40\%$ gypsum plus carbonates. Apparently large amounts of gypsum lightens the color of soil containing $\geq 0.6\%$ organic carbon above a color value of 3.

The soils would be classified as Calciaquolls at the great group level. All have a calcic or gypsic horizon that has its upper boundary within 40 cm (16 inches) of the surface. Soil Taxonomy (Soil Survey Staff, 1975) makes the following statement about Calciaquolls: "Capillary rise of calcium-rich water followed by evapotranspiration have been important processes in their genesis." There are three subgroups of Calciaquolls: Typic, Aeric, and Petrocalcic. The gypsiferous soils collected in northwestern Iowa would be classified probably as Typic or Aeric Calciaquolls. The soils lack a petrocalcic horizon that has its upper boundary within one meter of the surface.

At the family level, determining particle-size classes presents a special problem. It is not known whether gypsum crystals should be included in determining the particle-size class. In the past, gypsum almost always has been removed from soil samples before performing particle-size analysis. The reporting of the particle-size data has been on a gypsum-free soil basis, not on a whole soil basis. The procedure of Hesse (1976) now allows the gypsum crystals to be included in the particle-size determination. A discussion of this procedure and the problems of expressing particle-size data are given in the section entitled
"LABORATORY METHODS: Particle size." It is recommended that gypsum crystals be included in determining the particle-size class at the family level. The class that was determined would more nearly represent the soil as it exists in its natural state. Insufficient particle-size data by the method of Hesse (1976) are available to determine particle-size classes for the soils studied. A control section of 25-100 cm (10-40 inches) would be used in determining particle-size classes for these soils.

The gypsiferous soils collected in northwestern Iowa would have a mesic soil temperature class at the family level. The determination of a mineralogy class also presents special concerns. A gypsic mineralogy class is assigned to soils having > 40% by weight of carbonates plus gypsum, with the gypsum being > 35% of the sum of carbonates plus gypsum. The same control section used in determining the particle-size classes is used in determining the mineralogy classes. A weighted average minimum of 14% gypsum must be present. Either the < 2 mm portion or the < 20 mm portion can be used in determining the gypsic mineralogy class, whichever has the highest percentage of carbonates plus gypsum. Three of ten gypsiferous soils collected in northwestern Iowa have a gypsic mineralogy class, based on data determined on the < 2 mm portion. Seven soils do not have a gypsic mineralogy class and would probably be assigned a mixed mineralogy class. Reaction classes are not used in families that have a gypsic mineralogy class. The gypsiferous soils would be classified as: gypsic or mixed, mesic Typic or Aeric Calciaquolls. Table 22b gives the taxonomic classes of all of the soils studied.
Table 22b. Taxonomic classes of the soils studied

<table>
<thead>
<tr>
<th>Profile location</th>
<th>Soil series</th>
<th>Taxonomic class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dickinson Co., Iowa</td>
<td>Inclusion within Letri</td>
<td>Aeric Calciaquoll&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Site 1</td>
<td>&quot;</td>
<td>Typic Calciaquoll</td>
</tr>
<tr>
<td>Site 2</td>
<td>&quot;</td>
<td>Cumulic Haplaquoll</td>
</tr>
<tr>
<td>Site 2A</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>Clay Co., Iowa</td>
<td>Inclusion within Marna, calcareous variant</td>
<td>Typic Calciaquoll</td>
</tr>
<tr>
<td>Site 1</td>
<td>&quot;</td>
<td>Cumulic Haplaquoll</td>
</tr>
<tr>
<td>Site 2</td>
<td>&quot;</td>
<td>Cumulic Haplaquoll</td>
</tr>
<tr>
<td>Site 3</td>
<td>&quot;</td>
<td>Typic Calciaquoll</td>
</tr>
<tr>
<td>Site 4</td>
<td>&quot;</td>
<td>Typic Calciaquoll&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Site 5</td>
<td>&quot;</td>
<td>Typic Calciaquoll&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>&quot;</td>
<td>Typic Calciaquoll&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Site 7</td>
<td>&quot;</td>
<td>Cumulic Haplaquoll</td>
</tr>
<tr>
<td>Site 8</td>
<td>Canisteo, gypsic variant</td>
<td>Typic Calciaquoll&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Webster Co., Iowa</td>
<td>Inclusion within Lanyon</td>
<td>Typic Calciaquoll</td>
</tr>
<tr>
<td>Site 3</td>
<td>&quot;</td>
<td>Typic Calciaquoll</td>
</tr>
<tr>
<td>Site 4</td>
<td>&quot;</td>
<td></td>
</tr>
<tr>
<td>Cottonwood Co., Minn.</td>
<td>Romnell Site</td>
<td>Romnell</td>
</tr>
<tr>
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<td></td>
<td>Cumulic Haplaquoll</td>
</tr>
<tr>
<td>Redwood Co., Minn.</td>
<td>Jeffers Site</td>
<td>Aeric Calciaquoll&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Jeffers MWD Variant</td>
<td>Inclusion within Jeffers</td>
</tr>
<tr>
<td></td>
<td>Site</td>
<td>Typic Calciustoll</td>
</tr>
</tbody>
</table>

<sup>a</sup>These soils lack mottles which are diagnostic for Aquolls. However, the soils are more similar to Aquolls than to any other suborder. Lack of mottling may be associated with high contents of gypsum.
The gypserous soils collected in northwestern Iowa contain an appreciable predominance of gypsum content over carbonate content. One differentiating criterion at the great group level of the Calciaquolls is that they must have a calcic or gypsic horizon that has its upper boundary within 40 cm of the surface. All ten of the gypserous soils have a gypsic horizon with its upper boundary within this depth. Only one soil has a calcic horizon with its upper boundary within this depth. There may be a better way to classify soils that have a gypsic horizon, but not a calcic horizon, with its upper boundary within 40 cm of the surface. Soil Taxonomy (Soil Survey Staff, 1975) makes the following statement in a discussion of the Typic Calciaquolls: "The best classification of the soils that have a gypsic but not a calcic horizon is still in question."

Since soils collected in the current study have a gypsic but not a calcic horizon within 40 cm of the surface, some taxonomic changes will be proposed. The taxonomic name of a soil should indicate some of the general properties of that soil. Soils classified as Calciaquolls may have concentrations of gypsum or carbonates or both. The properties of a soil with high contents of carbonates and low contents of gypsum are usually different from a soil with high contents of gypsum and low contents of carbonates. It would be advantageous to include the presence of high contents of gypsum as a differentiating criterion at the subgroup level of Calciaquolls. Relying on the designation of a gypsic mineralogy class is probably not sufficient to identify soils classified as Calciaquolls that have high contents of gypsum. A soil must have large quantities of gypsum over a considerable profile depth to have a gypsic
mineralogy class. Probably few soils would qualify.

It is proposed that a new subgroup, the Gypsic Calciaquolls, be established for soils classified as Calciaquolls that have a gypsic, but not a calcic horizon, that has its upper boundary within 40 cm of the surface. All other differentiating criteria for classifying as Typic Calciaquolls would remain the same. The term "gypsic" was chosen because all names at the subgroup level must end in "ic". The term "gypsic" appears to be the only logical name ending in "ic" that can be derived from the word "gypsum". A problem arises in that the term "gypsic" is the name of a mineralogy class at the family level. The use of the same term at both levels of the taxonomic scheme would be unacceptable. However, the mineralogy class names do not have to end in "ic". Table 12 of Soil Taxonomy (Soil Survey Staff, 1975) includes two mineralogy class names that end in "ous", e.g., micaceous and siliceous. Therefore, it is proposed that the term "gypsiferous" replace the term "gypsic" as a mineralogy class name.

Soils with much less gypsum than occurs in the soils collected in northwestern Iowa would classify as Gypsic Calciaquolls. A soil having a 10 inch horizon containing 6% gypsum would qualify if the upper boundary of the gypsic horizon, but not a calcic horizon, is within 40 cm of the surface.

Another problem exists with the gypsiferous soils collected in northwestern Iowa concerning their classification into the four broad categories of salt-affected soils proposed by Bower et al. (1958). These categories and the criteria for classification have been given previously in
Table 4. The soils would be nonsodic since their exchangeable sodium percentage (ESP) is < 15. The soils would also be nonsaline since the electrical conductivity (EC) of saturation extracts is probably < 4 mmhos/cm (Appendix B, Table 25). Nonsaline-nonsodic would be the term applied to the gypsiferous soils collected in northwestern Iowa. Nonsaline-nonsodic soils would be characterized as not containing an excess of soluble salts or of exchangeable Na. Yet the laboratory data indicate some horizons from soil profiles collected in the current study contain up to 60% gypsum.

It appears that soils containing up to 60% gypsum should be possibly designated "saline" to indicate the presence of large amounts of a salt. The reason such soils are not designated "saline" may be explained as follows. Equations 4 and 5 given previously state methods of calculating the approximate salt content of a soil using the EC of the saturation extract and the saturation percentage. As an example, calculations will be performed on data from the 8-16 inch horizon of the profile collected at Clay Co., Site 1 (Appendix B, Table 25).

Percent salt in saturation extract = 0.064 $\times$ 3.10 mmhos/cm = 0.20%
Percent salt in soil = $\frac{0.20\% \times 37.9\%}{100} = 0.08\%$

These equations predict a salt content of 0.08% while the data indicate a gypsum content of 56.4%. Apparently these equations predict the percentage of readily-soluble salts, not the percentage of sparingly-soluble salts such as gypsum. Even though a sample may contain large amounts of gypsum, the EC of the saturation extract remains low due to the low
solubility of gypsum. The criteria listed in Table 4 appear to be established according to the properties of readily-soluble salts also. A small amount of readily-soluble salt in a sample (0.1-0.2%) would give an EC value of a saturation extract of > 4 mmhos/cm. A large amount of gypsum would not give an EC value of > 4 mmhos/cm.

Since the gypsiferous soils collected in northwestern Iowa are technically classified as nonsaline-nonsodic and yet contain appreciable amounts of sparingly-soluble salt, the term that should be applied to them is unclear. Bower et al. (1958) included an additional definition of a salt-affected soil as a soil that has been adversely modified for the growth of most crop plants by the presence or action of soluble salts. This broad definition includes saline-sodic, saline-nonsodic, and nonsaline-sodic soils. By extension, it should also include soils obviously affected by the accumulation of sparingly-soluble salts. These soils have been modified for crop growth by the presence of salts. This is the reason the gypsiferous soils have been broadly termed "salt-affected" soils in this thesis.

Practical Considerations

The agronomic use and management of gypsiferous soils may or may not be different from the surrounding nongypsiferous soils. The size of the soil area and its content of gypsum may determine different management practices. The soil profiles collected in Dickinson, Clay, and Webster Counties contain high contents of gypsum. Maximum contents of 30-60% were common. The farmers in these counties stated almost without
exception that the gypsiferous soils produced lower crop yields than the
surrounding soils. All of the soils investigated were cropped to corn
or soybeans, except for the soils at Clay Co., Sites 1-7. These soils
were reverted to permanent pasture use due to their poor yields. One
farmer stated that the most obvious effects of the gypsiferous soils were
apparent in young soybean plants. The plants were stunted and chlorotic.
As the plants became older, the stunting and chlorosis appeared to be
less severe but were still noticeable at plant maturity. Another farmer
stated that prior to the availability of abundant fertilizer, gypsifer-
ous soils produced very low crop yields. With abundant fertilizer appli-
cation, the yields improved appreciably. Another farmer stated that soy-
beans grown on gypsiferous soils may die in a droughty year. In south-
western Minnesota, one farmer stated that crop yields were reduced on the
Jeffers soils. It would not appear that crop yield would be appreciably
reduced on the Romnell soils due to low gypsum contents of the soils.

Most of the adverse effects of gypsiferous soils on crop growth are
probably due to fertility effects rather than salinity effects. The
presence of carbonates may be more of the cause of fertility problems than
the presence of gypsum. The high pH levels of calcareous soils reduce the
plant availability of P and Fe (Tisdale and Nelson, 1966). The chlorosis
of soybean leaves may be due to a deficiency of iron. Potassium availa-
bility to plants is usually reduced on calcareous or gypsiferous soils.
Zinc deficiencies in plants may also result. All of these fertility re-
lationships have been discussed in the section entitled "Effects of Salt-
Affected Soils on Agronomic Crops." Most of the farmers indicated the
use of increased fertilizer application rates on gypsiferous soils. In southwestern Minnesota, the gypsiferous soil areas are large enough to be more easily managed separately. In northwestern Iowa, the soil areas are usually small enough to make separate management difficult. One farmer in Minnesota stated that toxic boron levels were reported on soil tests from some calcareous, gypsiferous soils. This statement should be verified.

The droughtiness of gypsiferous soils may be due primarily to physical effects rather than chemical effects. The dissolution of gypsum would induce little osmotic pressure differences in the soil solution. A saturated gypsum solution of 30 meq/liter would induce about a 1 atmosphere osmotic pressure deficit, according to Figures 4 and 6 of U.S. Salinity Lab Staff (1954). It appears that the presence of gypsum alone will not cause "physiological drought" effects on plants. If other more soluble salts were present, the effects might be different.

The accumulation of gypsum in soils necessarily excludes a proportionate volume of nongypsiferous material. There would be less sand, silt, and clay per unit volume of soil. Less silt and clay would probably affect fertility relationships. The presence of gypsum crystals in soils may affect the water-holding capacity of the soils also. If the crystals are predominantly sand-sized or larger, water-holding capacity may be reduced. If the crystals are silt- or clay-sized, water-holding capacity may be increased. The section entitled "Unique Physical Characteristics of Gypsiferous Soils" discusses these relationships. It appeared that most of the gypsum crystals observed in the gypsiferous soils that were
studied were sand-sized or larger. Water-holding capacity is probably reduced in the gypsiferous soils in comparison to the surrounding nongypsiferous soils. This is probably the reason why gypsiferous soils often appear droughty.

The only engineering aspect of gypsiferous soils that is of importance in the upper Midwest is the possible corrosion of concrete. Special blends of concrete should be used. Materials other than concrete are available for the manufacture of drainage tile. The section entitled "Effect of Gypsiferous Soils on Physical Structures" discusses further aspects of the subject. Some farmers reported that tractors "sink" deeply into the highly gypsiferous soils. The soils were described as having properties similar to "quicksand." Movement of the tractor caused it to sink more deeply. This phenomenon may be caused by the possible presence of a high water table and the very friable consistence of the soil.

The mapping of gypsiferous soils in southwestern Minnesota is possible. New series have been established. The gypsiferous soils in northwestern Iowa appear to be less extensive and often occur on small areas of the landscape. Most of the gypsiferous soils in northwestern Iowa cannot be delineated at the presently-used scale (4 inches = 1 mile). Identifying the soils is often difficult. The study sites in Clay, Dickinson, and Webster Counties were located originally by soil survey personnel. When the author investigated the sites, farmers would usually point out several gypsiferous soil areas nearby that were not noted on the soil maps. This finding is not a reflection upon the quality of mapping but on the difficulty of identifying the soil areas. As
has been indicated, many of the areas are circular areas less than 150 ft in diameter. The identification of such small-sized soil areas often depends upon chance discovery. Walking over or probing into the area is almost a necessity for discovery.

There are, however, a few means of predicting where gypsiferous soils would most likely occur. The soils are restricted to the northwestern portion of the state, and are normally in the region having < 100 mm mean annual water surplus. They occur only in areas of Wisconsin-age drift. The soils occur in poorly-drained areas. In addition, the poorly-drained areas are almost always in areas of low surrounding relief. Long, low slopes within the Cary drift region and low, broad saddle positions in the Tazewell drift region are commonly associated features. The gypsiferous soils often occur on microknolls within poorly-drained areas. If microknolls are observed on the landscape, they should be investigated. Crop cover may often camouflage small relief differences. Noticeably whitish or light-gray colored circular or oblong areas within poorly-drained areas should be investigated. These patterns can often be observed on aerial photographs. If circular, light-colored areas appear on photographs within normally dark-colored areas, gypsiferous soils may be indicated. In the Cary drift region, carbonate-enriched soils often appear as light-colored areas on aerial photographs. If photographic areas are observed that are light-colored and do not resemble the usual areal configuration of carbonate-enriched soils, gypsiferous soils may be indicated. Discolored (chlorotic) crop leaves observed in areas of normally-noncalcareous soils may indicate
gypsiferous soils also. Areas of drought-stressed crops within all poorly-drained areas may also indicate such soils.

The light color of gypsiferous soils that have gypsum present at the soil surface is less obvious under wet conditions. Color contrasts are greater under dry conditions. The dry soil surface of these soils is coated with a fine, white powder or "flour" of gypsum crystals. This powder can be described as appearing like "white mold" on the soil surface. A piece of surface soil that is examined closely will usually show the whitish salts on its upper surface. The whitish salts are most easily observed either in the spring after snow melt and before heavy spring rains or in the fall after a period of dry weather when crops are harvested. It appears that if powdery, white gypsum crystals appear on the dry soil surface, there will probably be an abundant accumulation of gypsum within 12 inches of the surface. Soils that have gypsum accumulations deep within the profile usually do not have gypsum on the soil surface. Special notice should be given to the dry faces of stream banks or excavations in poorly-drained areas. If a fine, white powder appears on the faces, gypsum is probably present in the ground water of the area. Gypsiferous soils are more likely to occur in that area. Calcareous soils formed in the bottoms of drained lakes should be examined for gypsum. Gypsum may occur in the calcareous lower horizons of muck soils that are noncalcareous at the surface.

There are several properties of soils that make the visual observation of gypsum difficult. A black, moist surface horizon will often mask the presence of gypsum. Gypsum is usually found in poorly-drained soils.
with gleyed lower horizons. Very fine gypsum crystals often blend into the gley color and are difficult to detect. Larger crystals that are distributed throughout the matrix of the solum are usually coated with the surrounding matrix material. The crystals blend into the soil matrix and are sometimes mistaken for medium, coarse, or very coarse sand grains. Pronounced segregations of large crystals are easily identified, however. Translucent to whitish sand grains may be mistaken for gypsum crystals. The sand grains should be checked for hardness. Gypsum crystals are softer than sand grains. Some particles of dolomite usually 0.25 to 2 mm in size are sometimes mistaken for gypsum also. The dolomite is whitish in color and does not effervesce readily with acid. Dolomite can be distinguished in two ways. The dolomite particles should be separated from the soil matrix. Acid should be added and a period of 5-10 seconds should elapse before close observation is made for effervescence. Gypsum that is white in color in soils is almost invariably composed of very fine, powdery crystals. Hard, white gypsum is not usually found in soils as 0.25 to 2.00 mm sized particles. Large gypsum crystals are either translucent or lightly coated with the surrounding matrix material. Since gypsum often occurs in carbonate-enriched soils, soft lime concretions may be confused with white, powdery gypsum. The two can be distinguished with the addition of acid.

To the present, only two gypsiferous soil areas have been identified in northwestern Iowa that are of sufficient size to warrant a separate mapping unit. The two areas, which totaled 144 acres in Clay Co., were mapped as Canisteo silty clay loam, gypsic variant. Most of the
other areas that have been identified are too small to delineate on soil maps at a scale of 1:15,840. Areas have been noted by spot symbols on the maps. Considering the climate of northwestern Iowa, it is not likely that many areas of gypsiferous soil will be identified that are of sufficient size to warrant separate mapping units. Osceola Co. is the only county not mapped that has a strong possibility of having gypsiferous soils. Some gypsiferous soils have been identified there already and have been mentioned previously. These soils will most likely occur in poorly-drained areas in the region of loess or loamy sediments over Tazewell drift.

Genesis of Specific Types of Gypsum Accumulations in Soils

Gypsum forms several different types of crystal habits. Gypsum crystals also segregate in soils into accumulations with various morphologies. The forms of gypsum crystals and their genesis have been discussed previously in the section entitled "Morphology and genesis of gypsum crystals." Only the forms of gypsum accumulations in soils have been given in the section entitled "Morphology of gypsum accumulations in soils." Although several authors mention the morphology of gypsum accumulations in soils, few authors discuss genetic aspects, i.e., why the gypsum accumulates in the form that it does. The following discussion will discuss the genesis of the various morphologies of gypsum accumulations in soils, with specific reference to the current study. The various morphologies probably result to a large degree due to the low solubility of gypsum. Gypsum is more easily dissolved and transported within the soil profile than most soil minerals. Gypsum's ease
of movement may be a major reason for the different forms of accumulations. Some forms appear to be produced primarily by physical processes, others by a combination of physical and chemical processes. To avoid confusion, the word "precipitation" will be used in this section to mean the deposition of dissolved salts from a solution. Atmospheric precipitation will be termed "rainfall", even though it is realized that rainfall is only one form of atmospheric precipitation.

Gypsum may accumulate throughout the matrix of a soil profile without obvious segregations. The processes of dissolution and precipitation are apparently fairly uniform throughout the profile. The gypsum content of a profile is usually low under these conditions.

Gypsum may accumulate in horizontal layers. If the layers meet certain criteria, they are called gypsic horizons (Soil Survey Staff, 1975). The crystals may be small and powdery (< 0.05 mm) or larger and sand-like in appearance (0.05 to several mm). The net addition-removal dynamics within the soil profile determine where a horizontal accumulation develops. Horizontal layers may accumulate by the repeated evaporation of water within that portion of the profile. The gypsum-laden water may come from either sources below the profile or from rainfall sources percolating through the upper portions of the profile. Rainfall may dissolve gypsum in the upper portions of the profile. Gypsum may be transported to lower depths. The causes of repeated desiccation of the soil profile to a certain depth may be due to several factors.

Evapotranspiration-demand patterns and rainfall patterns may be factors.
Porosity differences within the profile may cause temporary perching of water. A horizontal layer of gypsum may accumulate above a porosity-discontinuity. Sometimes thin horizontal strata 1-4 mm in thickness occur which contain fine, powdery gypsum crystals. These strata may represent a relatively recent deposition from an evaporated water source. The strata are believed to be recent because they are light in color (10YR 7/2 or 8/1 dry) and appear to be very pure. With time, these crystals may be incorporated into the soil matrix by expansion-contraction forces and other pedoturbation processes. The crystals may grow in size and may be coated with the surrounding matrix material.

A horizontal layer of gypsum may be cemented into a mass. A petrogypsic horizon is a gypsic horizon that is strongly cemented. The gypsum content of the layer is high, usually $>60\%$. This form of gypsum accumulation is restricted to arid climates and to parent materials that are rich in gypsum (Soil Survey Staff, 1975). The genesis of cemented horizontal layers may be due to the repeated precipitation of gypsum at a specific depth. Gypsum becomes the predominant mineral of the layer. The crystals may overlap and grow together, forming a cemented mass. Cemented horizontal layers may form from the downward movement of water added to the profile by rainfall. The volume of water added may not be sufficient to remove the gypsum below the profile. The water may be evaporated repeatedly at a specific depth. Since cemented horizontal layers of gypsum occur only in arid climates, it may be possible that gypsum is sometimes deposited on the soil surface in the form of wind-
blown dust. The genesis of gypsic and petrogypsic horizons may be similar to the genesis of calcic and petrocalcic horizons as given in Soil Taxonomy (Soil Survey Staff, 1975).

Vertical layers of cemented gypsum also occur. Their genesis is unclear. Van Alphen and Romero (1971) described the vertical layers as consisting of plates of almost pure gypsum extending to a depth of about one meter. The layers were also described as being arranged in a polygonal pattern. The vertical layers may be petrogypsic horizons oriented vertically rather than horizontally. Similar vertical gypsum accumulations have been described in some of the joints of pre-Wisconsin till in Iowa. The locations and genesis of these accumulations have been discussed in the section entitled "Source of the Gypsum Within the Glacial Drift." Gypsum-laden water may have evaporated repeatedly in the till joints. Appendix F, Slide 1 contains a picture of two pieces of cemented gypsum taken from till joints in Cherokee Co., Iowa. The gypsum plates are about 5-10 mm thick. Till joints in Sioux Co. that were filled with gypsum were described as being in a polygonal pattern. Why this pattern occurs is unknown except that the joints were formed with that configuration. It may be that the vertical layers occurring in soil profiles in arid climates are developed by the filling of fissures originally present in the parent material with gypsum.

Gypsum may occur as a fine, white powder on ped faces and in small channels and pockets. The channels are probably root holes and insect burrows. The pockets may be former insect chambers. The root channels
and insect burrows are often branched and continuous. Some authors call this form of gypsum "mycelia" due to its resemblance to fungal hyphae. Others call this form of gypsum "threads" or "veinlets". All of these terms are accurately descriptive of the appearance of this form of gypsum. The fine, white gypsum powder (< 0.05 mm) is sometimes called "flour". It is believed that this form of gypsum represents a relatively recent accumulation. Gypsum-laden water may have filled the voids formed by plant roots or insects. Desiccation of the soil due to evapotranspiration probably caused the precipitation of gypsum. This process may explain why the crystals are small and white. The crystals may be small because they were recently precipitated. They may have been precipitated rather rapidly since most root and insect holes occur in the upper and middle portions of the soil profile. The powder may be light in color (10YR 7/2 or 8/1, dry) because the crystals have not been mixed with the adjacent soil matrix by pedoturbation. The crystals have also not been coated with the surrounding soil material. Another indication that this form may represent a relatively-recent deposition is the continuous nature of the filled channels. The channels had not been broken up by pedoturbation prior to filling with gypsum. Short, broken segments of gypsum-filled channels sometimes occur. These may represent channels that are in the process of being incorporated into the soil matrix.

Gypsum may accumulate as farinaceous (mealy) material composed of an abundance of gypsum crystals in the upper part of the soil profile. The
gypsum accumulation is very friable and usually has a lower bulk density than nongypsiferous soil material. Soils with this type of gypsum accumulation have been called "puffy" Solonchaks in the past (Kellogg, 1934, and Kovda, 1946). The accumulation has probably resulted from repeated evaporation of gypsum-laden ground water near the soil surface. The repeated deposition probably promotes the farinaceous nature of the material. Many interstitial voids occur among the crystals. There is little weight from overlying horizons to compact the material. The farinaceous gypsum material is usually composed of crystals < 2 mm in size. The reason larger crystals do not occur may be due to the rate of desiccation of the upper part of the profile. Cody (1979) observed that slow evaporation of a gypsum-containing solution produced larger crystals than did rapid evaporation. The upper portion of the soil profile may desiccate more rapidly than the lower portion. Larger crystals usually occur in the lower portions of the profile.

The farinaceous gypsum material often has weak platy structure. The crystals are oriented in a horizontal pattern. Aggregation of the crystals into plates is usually weak. Buol et al. (1973) state that platy structure may result from expansion and contraction normal to the soil surface in freezing-thawing and wetting-drying cycles. A seasonally-high water table may be involved. The formation of platy structure in the farinaceous gypsum material may be associated with alternate wetting and drying by a fluctuating water table and evapotranspiration. Platy structure in gypsiferous soils appears to be more pronounced in horizons
high in gypsum content. The voids among the crystals may allow the crystals to be reoriented more easily into a horizontal orientation. All gypsiferous profiles collected in Clay and Dickinson Counties contain farinaceous gypsum accumulations with platy structure.

Most of the crystals in the farinaceous gypsum are prism shaped although some are lensoid shaped. Cody (1979) observed that fast evaporative conditions promoted the formation of prismatic shapes. Since the upper part of the soil profile may undergo relatively fast desiccation, prismatic shapes may predominate. Yet, lenticular crystals also occur in the above-mentioned profiles that have farinaceous gypsum material. Cody (1979) observed that three conditions are necessary for the formation of lenticular gypsum: the presence of soluble organic matter, fairly slow evaporative conditions, and a pH that is not highly acidic. The presence of soluble organic matter has been discussed in the section entitled "DISCUSSION OF RESULTS AND INVESTIGATIONS: Dickinson Co., Iowa.

Microscopic examination of some of the > 0.25 mm crystals in the sola of the gypsiferous profiles collected in Clay and Dickinson Counties indicated they were completely and evenly coated with dark gray stains. The color of the coatings was 5Y 4/1, moist and 2.5Y 4/2 or 5/2, dry. It appeared that virtually all crystals > 0.25 mm in diameter in the sola were coated. Those crystals between 0.05 and 0.25 mm in diameter may or may not be coated. The gypsum flour (< 0.05 mm crystals) in the channels was not coated since it was light in color (10YR 7/1, moist, 10YR 7/2 or 8/1, dry). The pH of the soils was neutral to mildly
alkaline. Both biconvex and plano-convex crystals were observed. Some crystals approached a spheroidal shape. Few lenticular crystals were > 2 mm in size. Appendix F, Slide 9 contains a picture of some lenticular crystals. No lenticular crystals were observed below the sola. The lack of organic material may be the limiting condition below the sola.

Rarely, some of the lenticular crystals are arranged in a small mass that appears to be very weakly cemented by organic material. The mass is usually not larger than 2.5 cm in diameter. Cody (1979) also observed a similar type of "nest" orientation when lenticular crystals formed around a piece of organic material. It is possible that the small masses of lenticular crystals observed in the study profiles have formed around a piece of organic material.

Gypsum may occur as large crystals of selenite arranged as a "rosette". A rosette is an arrangement of crystals in spheroidal fashion radiating outwardly from a central point. The crystals are usually elongated prisms of selenite up to 20 mm in length. This elongated shape has led some authors to call the spheroidal arrangement a "spiky rosette". Other authors call rosettes "nests of crystals". The selenite crystals are usually uncoated and translucent. Rosettes may range in size from about 1 cm up to 6 cm in diameter. They are easily recognized due to their size and crystal morphology. The central point of the rosette is often a void, although powdery lime or gypsum may occur in the void or be distributed among the large crystals. Rosettes occur almost entirely
in the lower portion of the soil profile, usually in the C horizon. Their genesis may be due to chemical and physical processes. The $\text{SO}_4^-$ that is produced from oxidation of sulfur in pyrite may react with $\text{CaCO}_3$ to form $\text{CaSO}_4$. Rosettes may have been formed by repeated additions of $\text{SO}_4^-$-containing water around a $\text{CaCO}_3$ concretion. Gypsum crystals may have formed around the concretion and radiated outwardly. Repeated additions of the water may have gradually dissolved the concretion to leave a void in the center of the rosette. The crystals which initially formed around the concretion may have acted as seed crystals for future growth. The presence of gypsum-saturated water under slow evaporative conditions may have allowed the crystals to grow large, up to 15-20 mm. Wilder (1919) states that shales in nearly every geological strata in many worldwide locations contain individual crystals or rosettes of selenite produced by the action of $\text{SO}_4^-$, produced from oxidation of pyrite, on $\text{CaCO}_3$.

There may be several reasons why rosettes normally occur in the C horizon but not in the solum. In the C horizon, little soluble organic matter may be present to coat the crystals. As stated earlier, organic coatings may impede crystal growth. Lenticular crystals may result. Slow evaporative conditions are required for large crystal growth. Evaporative conditions in the upper part of the profile may be too rapid to promote large crystal growth. Rosettes that might have formed in the solum may have been destroyed by pedoturbation processes that are probably more active in the solum than in the C horizon. In all of the profile descriptions examined by the author, smaller crystals were described in the upper part of the profile and the larger crystals and rosettes were
described in the lower part. This fact was true for descriptions of profiles collected in the upper Midwest, the Mid-East, and Russia. The principal reason for this finding may be due to the differences in evaporation rates within the profile. Descriptions of profiles collected at Clay Co. Sites 1 and 8 have examples of rosettes. Appendix F, Slide 9 contains a picture of a rosette.

Gypsum may occur as pendants coating the underside of pebbles. Gravity may allow free water to collect on the underside of pebbles. When the water evaporates, gypsum may be precipitated. Carbonate or gypsum pendants on the underside of pebbles may indicate illuviation of these minerals from overlying horizons (Rozanov, 1951).

Gypsum may occur as a porous accumulation resembling a sponge. This form of gypsum was not observed in the current study. Russian researchers appear to be the primary ones who discuss this form. Evidently it occurs in the lower portion of the profile. No sizes or clear descriptions of the gypsum were given. Rozanov (1951) stated that this type of accumulation results from the oxidation of sulfur-containing compounds within limestone. The $\text{SO}_4^-$ that is released reacts with $\text{CaCO}_3$ to form gypsum. He stated that this mode of genesis explained three observations. The lowest content of carbonate usually occurs in the same horizon with the highest content of gypsum. Some of the carbonate probably has been converted to gypsum. The peculiar porous structure of the material may be caused by the release of $\text{CO}_2$ during the reactions. The gypsum that is formed is usually coated with straw-colored or reddish-pink stains of ferric hydroxides. Evidently Fe may also be a reaction product.
CONCLUSION

The gypsiferous soils of northwestern Iowa are inextensive. They often occur in small areas on the landscape. Most gypsiferous soil areas are so small as to be unable to be delineated at the present scale of mapping. Spot symbols are used. The small areas are often difficult to identify and are easily overlooked. It is doubtful that extensive areas of gypsiferous soils will be identified in northwestern Iowa that will warrant the establishment of new series or variants of existing series.

Predicting the occurrence of gypsiferous soils is not precise. They occur only in the region of Cary drift or the region of loess or loamy sediments over Tazewell drift. The soils occur in poorly-drained areas primarily in the region having < 100 mm mean annual water surplus. Gypsiferous soils usually occur in areas of low relief. In the Cary drift region, the soils often occur near the centers of very broad, shallow basins. Gypsiferous soils may occur in areas of high relief but usually only in calcareous soils formed in the bottoms of former lakes and sloughs. In the region of the Tazewell drift, drainage nets are better developed. The soils usually occur near the centers of broad, low saddles. Gypsum is often most extensive on microknolls within poorly-drained areas.

It is believed that gypsum is precipitated within the soil profile due to the evaporation of gypsum-laden ground water. Although no water table measurements were made, other evidence indicates this process may
have been active. No evidence was observed of appreciable accumulations of readily-soluble salts. It is believed that shale within the drift may release soluble salts into the ground water. Oxidation of the sulfur in pyrite \((\text{FeS}_2)\) may release \(\text{SO}_4\). The \(\text{SO}_4\) may react with \(\text{CaCO}_3\) to form gypsum.

It appears that water rises to near the soil surface due to local hydrologic factors. Many gypsiferous soils had lithologic discontinuities. The gypsum usually occurs above the lithologic contact and usually decreases abruptly at the contact. It is theorized that the lithologic discontinuity may temporarily perch water. The upper portion of the profile may have been eventually desiccated, allowing the gypsum to precipitate.

The gypsiferous soils of northwestern Iowa had some unusual morphologies. Platy structure was observed. It is believed that expansion and contraction due to alternate wetting and drying may have caused the platy structure to form. Dark, horizontal bands were also observed within or immediately below horizons of appreciable gypsum accumulation. It is believed that the bands may represent illuviated surficial material high in organic matter content. The morphologies of the gypsum accumulations and segregations were varied.

The gypsiferous soils of southwestern Minnesota are more extensive in areal distribution. A drier climate is believed to be an important cause of more widespread gypsum accumulation. Parent material differences may also be involved.

The current study was designed as a generalized survey of the
gypsiferous soils. Recommendations can be made for future, more detailed studies. It would be desirable to make a detailed hydrologic study of several gypsiferous areas in northwestern Iowa. Piezometers could be used to monitor ground water flow and chemical composition. Benz et al. (1964), Fehrenbacher et al. (1963), Jackson et al. (1956), MacLean and Pawluk (1975) and Sandoval et al. (1964a) have presented studies which used piezometers to investigate ground water flow in saline areas. Detailed chemical analyses should be performed on the water samples. The samples should be collected throughout the year to determine if the concentration of dissolved constituents changes.

It would also be desirable to perform detailed core sampling to investigate the subsurface materials below small, circular gypsiferous areas. It could be determined if a sand and gravel lens within the drift might be a "point source" for a high water table. Sampling transects could also trace the extent of dark horizontal bands. Chemical analyses prescribed by the Soil Survey Staff (1975) might be performed on the dark bands to determine their similarity to spodic horizons.

It appears that northwestern Iowa is in a gradational zone between soils that do not contain salts more soluble than CaCO₃ and soils that often contain salts more soluble than CaCO₃. It would be interesting to study a series of depressions located on a transect from south-central Minnesota to southeastern South Dakota. Similar physiography and parent materials would be necessary. Profiles should be sampled from the edge to the center of each depression. The kinds, amounts, and locations of the salts both within each profile and within the depression
could be studied.

It would also be interesting to compare the soluble salts in soils occurring in a depression that is undrained to data determined on soils occurring in a depression that has been drained for many years.

In the laboratory, several experiments could be performed to better understand the genesis of certain forms of gypsum accumulations. Columns of soil could be constantly saturated from below with solutions containing various forms of dissolved sulfate. Evaporative demand could be placed at the surfaces of the columns. Evaporation of the water at the soil surface would cause precipitation of dissolved salts. One column could consist of a noncalcareous soil that was saturated with a CaSO₄ solution. After a period of time, the soil in the column could be removed and the gypsum crystal morphology and accumulation morphology could be examined. Another column could contain a noncalcareous soil that was interspersed with small pockets of CaCO₃. The saturating solution could be a very weak solution of H₂SO₄. After a period of time, the column could be examined to determine if gypsum rosettes formed around the CaCO₃. Another column could contain a soil devoid of organic matter but interspersed with small pockets of mucky soil. It could be determined if loosely-oriented lenticular crystals would form around the organic matter. Many experimental parameters could be altered in the studies, including soil pH, solution composition, and evaporation rate.
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APPENDIX A: PROFILE DESCRIPTIONS

Information and Conventions Used in Making the Descriptions

All sites except the Jeffers and Jeffers MWD variant sites were on slopes of \( \leq 1\% \) gradient. All sites were in poorly- or very poorly-drained areas, except for the Jeffers, moderately well-drained variant site. All sites were cropped to corn or soybeans except Clay Co., Sites 1-7. The area containing Clay Co., Sites 1-7 was in permanent pasture and had not been plowed in 7 to 8 years at the time of sampling. Plow layers were not distinguishable in some profiles. The section entitled "SITE CHARACTERIZATION" contains more information on the physiographic setting of the sampling sites and other information on surrounding soils. All profiles were collected and described by the author.

Munsell color notations are for moist soil unless otherwise noted. Description nomenclature was taken from Soil Survey Staff (1975). Descriptions were made from 1-3/4 inch soil cores. Topography of horizon boundaries was not given. The unusual morphology of some profiles caused difficulty in assigning horizon designations. Some designations are in question. Horizons containing \( > 40\% \) finely-divided carbonate plus gypsum were usually designated as "A3" if the color value and chroma were equal to or less than 5 and 3, respectively. The term "light" used as a textural modifier means that the textural estimate of the horizon is in the coarser portion of the class range. The term "heavy" used as a textural modifier means the textural estimate of the horizon is in the finer portion of the class range. The term "talcy" used as a textural modifier
refers to the smooth, talc-like feel that is imparted to soil by the presence of high contents of powdery gypsum. Textural estimates in the descriptions were determined on the whole soil. Laboratory textural determinations were made after gypsum and carbonates were removed from the soil. Differences in the two estimates result due to these facts.

Several assumptions were made in describing the morphology of gypsum accumulations. Gypsum "flour" is defined as very fine crystals < 0.05 mm in size. Flour accumulations are light-colored, e.g., 10YR 7/1 moist, 10YR 7/2 or 8/1 dry. "Pockets" are oblong or spheroidal voids filled with gypsum crystals. Pockets may have been insect dens. "Rosettes" are arrangements of selenite crystals in a spheroidal fashion radiating outwardly from a central point. Rosettes are usually 1-6 cm in diameter. The section entitled "Genesis of Specific Types of Gypsum Accumulations in Soils" gives further information on these forms of gypsum accumulations. The term "root hole" was used when it was evident that a cylindrical void was probably formed by a root. The term "channel" was used when it was suspected that insect burrowing may have formed some of the cylindrical voids also. In describing the size of root holes or channels, i.e., 2 X 10 mm, the first value represents the diameter of the channel, the second value represents its length. The characters "cs" were assigned to the horizon designations of all horizons containing > 1.0% gypsum.

All horizons described in the current study as noneffervescent would be neutral in reaction. All horizons described as having weak, strong, or violent effervescence would be mildly alkaline in reaction. The
characters "ca" were assigned to the horizon designations of all horizons containing \( \geq 18\% \) calcite plus dolomite. This value represents the mean plus the standard deviation of the calcite-dolomite sums determined on 36 calcareous Cary till samples (Table 20).

**Dickinson Co., Site 1**

Location: 132 ft E and 72 ft N of the SW corner, SE\( _{14} \), Sec. 23, T98N, R38W.

Setting: On about a 1\% west facing slope in a Letri silty clay loam, 0-2\% slopes, mapping unit.

Apcs, 0-9 inches: Black (2.5Y 2/1) light silty clay loam with few dark grayish-brown (2.5Y 3/2) mixings, weak fine and very fine subangular blocky structure, friable, few 0.1-0.5 mm gypsum crystals evident throughout matrix, strong effervescence, abrupt boundary.

B21cs, 9-21 inches: Very dark grayish-brown (2.5Y 3/2) talcy silt loam with few black (N 2/0) stains, weak very thin platy structure, very friable, majority of matrix is 0.25-1.0 mm gypsum crystals, common root holes 0.5 X 10-20 mm filled with gypsum flour, few horizontal strata 0.5 mm thick of gypsum flour, strong effervescence, abrupt boundary. Note: A 1 inch thick band of black (10YR 2/1) silty clay loam present at 18 inches. Was sampled with 21-33 inch horizon.

B22cs, 21-23 inches: Black (10YR 2/1) silty clay loam with few light olive-brown (2.5Y 5/4) mixings, weak very fine subangular blocky structure, friable, few root holes 1 X 10-20 mm filled with gypsum flour, few 0.1-0.25 mm gypsum crystals throughout matrix, weak effervescence, abrupt boundary.
B23, 23-25 inches: Black (N 2/0) silty clay loam with few light olive-brown (2.5Y 5/4) mixings, weak very fine subangular blocky structure, friable, few 0.1-0.25 mm gypsum crystals throughout matrix, strong effervescence, abrupt boundary.

II B3ca, 25-31 inches: Light olive-brown (2.5Y 5/6) clay loam, weak very fine subangular blocky structure, firm, no observable gypsum, few fine carbonate concretions, violent effervescence, gradual boundary.

II Cca, 31-60 inches: Identical to 25-31 inch horizon except has massive structure and common 20-40 mm olive-yellow (2.5Y 6/8) areas of carbonate enrichment. Small sand pocket at about 56 inches.

**Dickinson Co., Site 2**

**Location:** 135 ft E and 160 ft N of the SW corner, NW 1/4, Sec. 25, T98N, R38W.

**Setting:** On a < 1% west facing slope in a broad, low saddle. In a Letri silty clay loam, 0-2% slopes, mapping unit.

Apcs, 0-9 inches: Black (N 2/0) light silty clay loam with few dark-gray (5Y 4/1) mixings, weak very fine subangular blocky structure, friable, few 1 X 5-10 mm root holes filled with gypsum flour, common 0.05-0.25 mm gypsum crystals throughout matrix, weak effervescence, abrupt boundary.

A3cs, 9-18 inches: Dark-gray (5Y 4/1) taly silt loam with common black (5Y 2.5/1) flows and small krotovina fills, weak very thin platy structure, very friable, majority of matrix is 0.1-1.0 mm gypsum crystals, few horizontal strata 0.5 mm thick X 2.5 mm wide X 10 mm long of gypsum flour, common root holes as above, very weak effervescence, abrupt boundary.
B2gcs, 18-22 inches: Black (5Y 2.5/1) silty clay loam with few fine olive (5Y 5/3) mottles, weak very fine subangular blocky structure, friable, very few dark-gray (5Y 4/1) 3-5 mm pockets of gypsum crystals, no observable gypsum in matrix, noneffervescent, abrupt boundary.

II B3g, 22-30 inches: Olive-gray (5Y 4/2) gravelly loam with common fine olive (5Y 5/6) mottles and few very dark-gray (5Y 3/1) stains and small krotovina fills, weak very fine subangular blocky structure, friable, possibly very few 1-2 mm segregations of gypsum flour, few medium weakly cemented carbonate concretions with olive-yellow (2.5Y 6/6) interiors, few fine and medium soft carbonate concretions, weak effervescence, abrupt boundary.

II C1ir, 30-36 inches: Yellowish-brown (10YR 5/8) sand and gravel with common fine olive-gray (5Y 5/2) and few fine strong-brown (7.5YR 5/6) mottles, single grain, loose, no observable gypsum, iron coatings on sand grains, few fine iron concretions, few black (N 2/0) oxide coatings on pebbles, few fine soft carbonate concretions, weakly cemented concretions as above, strong effervescence, gradual boundary.

II C2ir, 36-43 inches: Identical to above horizon except for the presence of few fine olive-gray (5Y 5/2) and common fine strong-brown (7.5YR 5/6) mottles.

Dickinson Co., Site 2A

Location: 42 ft NW of Site 2.

Ap, 0-9 inches: Black (N 2/0) silty clay loam, cloddy parting to weak very fine subangular blocky structure, friable, no observable gypsum
throughout profile, no effervescence, abrupt boundary.

A12, 9-13 inches: Identical to above horizon except for weak fine prismatic parting to weak very fine and fine subangular blocky structure, very few dolomite concretions, and a clear boundary.

A13, 13-25 inches: Identical to 0-9 inch horizon except for weak medium prismatic parting to strong very fine and fine angular blocky structure, very few soft carbonate concretions, and a clear boundary.

A14, 25-33 inches: Identical to 0-9 inch horizon except for weak medium prismatic parting to moderate very fine subangular blocky structure, and a clear boundary.

A3, 33-40 inches: Black (5Y 2.5/1) silty clay loam with very few olive (5Y 5/3) mixings, weak medium prismatic parting to strong fine and very fine angular blocky structure, friable, no effervescence, abrupt boundary.

II Bl, 40-42 inches: Olive (5Y 5/3) sandy clay loam with common fine strong-brown (7.5YR 5/6) mottles, many dark-gray (5Y 4/1) mixings and few root fills, weak very fine subangular blocky structure, very friable, no effervescence, abrupt boundary.

II B2g, 42-48 inches: Olive-gray (5Y 5/2) clay loam with common fine strong-brown (7.5 YR 5/6) mottles and few dark-gray (5Y 4/1) root fills, weak medium prismatic parting to weak very fine subangular blocky structure, firm, few 15-20 mm soft carbonate concretions which appear to be dolomite, very weak effervescence, gradual boundary.

II C1g, 48-53 inches: Olive-gray (5Y 5/2) clay loam with few fine strong-brown (7.5 YR 5/6) mottles, massive, firm, carbonate concretions as above
plus few 3-5 mm dolomite concretions, strong effervescence, gradual boundary.

II C2g, 53-67 inches: Identical to above horizon except for many fine strong-brown (7.5YR 5/6) mottles.

**Clay Co., Site 1**

**Location:** 815 ft N and 114 ft E of the SW corner, NW\(\frac{1}{4}\), Sec. 29, T97N, R36W.

**Setting:** At center of a microknoll near a small drainage way on a level lacustrine plain. In a Marna silty clay loam, calcareous variant, 0-2% slopes, mapping unit.

**Apcs, 0-8 inches:** Black (10YR 2/1) silt loam with few fine gray (5Y 5/1) mixings, weak thin platy parting to weak fine granular structure, very friable, few root holes 0.5-1.0 mm diameter filled with gypsum flour, common 0.1-0.5 mm gypsum crystals throughout matrix, weak effervescence, abrupt boundary.

**A31cs, 8-16 inches:** Dark-gray (5Y 4/1) talcy silt loam with few black (10YR 2/1) mixings and small krotovina fills, weak thin platy parting to weak fine and very fine granular structure, very friable, common 1-2 mm pockets and root holes as above filled with gypsum flour, many 0.25-1.0 mm gypsum crystals throughout matrix, strong effervescence, gradual boundary.

**A32cs, 16-20 inches:** Identical to above horizon except for weak thin and very thin platy structure, few fine soft carbonate concretions, and violent effervescence.
A33cs, 20-30 inches: Identical to above horizon except no carbonate concretions, majority of matrix is 0.5-2 mm gypsum crystals.

B2gcs?, 30-35 inches: Gray (5Y 4/1) talcy silt loam with few fine dark yellowish-brown (10YR 4/6) mottles, talcy silt loam, very friable, same gypsum as in 20-30 inch horizon except 1-5 mm pockets occupy about 1/3 of matrix, few fine black (N 2/0) oxides, violent effervescence, abrupt boundary.

II B3gcs, 35-39 inches: Matrix is 1/2 light-gray (5Y 7/1) and 1/2 white (5Y 8/1) gravelly loam with few fine yellowish-brown (10YR 5/6) mottles, weak thin and very thin platy structure, very friable, many 0.25-1.0 mm gypsum crystals throughout matrix, 1-5 mm pockets of gypsum crystals occupy 1/2 of matrix, strong effervescence, abrupt boundary.

II C1cs, 39-42 inches: Matrix is 3/4 white (5Y 8/1) and 1/4 light-gray (5Y 7/1) sand and gravel, massive, loose, few 1-2 mm nests of 0.5-2 mm gypsum crystals, common 15-20 mm dolomite concretions, hard dolomite coatings 1 mm thick on some pebbles, weak effervescence, abrupt boundary.

II C2cs, 42-47 inches: Light yellowish-brown (10YR 6/4) sand and gravel with many fine yellowish-brown (10YR 5/6) and few fine dark-red (2.5YR 3/6) mottles, single grain loose, majority of matrix is 0.4-3 mm gypsum crystals, few fine black (N 2/0) oxides in a band at 43 inches, weak effervescence, clear boundary.

II C3cs, 47-53 inches: Pale-brown (10YR 6/3) sand and gravel with common fine yellowish-brown (10YR 5/6) mottles, single grain, loose, same gypsum as above, few dolomite coatings 5-10 mm thick on some pebbles, oxide band as above at 47 inches, strong effervescence, abrupt boundary.
II C4gca/c, 53-68 inches: Light olive-gray (5Y 6/2) light loam with common medium yellowish-brown (10YR 5/6) mottles, massive, firm, common 2-4 cm rosettes consisting of 1-2 mm X 2-8 mm gypsum crystals arranged around a void filled with 0.5 mm crystals, strong effervescence, clear boundary.

II C5gca/c, 68-80 inches: Olive-gray (5Y 5/2) gravelly sandy loam with common fine and medium yellowish-brown (10YR 5/6) mottles, massive, firm, few 1-3 mm pockets of 0.5-2 mm gypsum crystals, few 0.25-1 mm crystals throughout matrix, few fine black (N 2/0) oxides, strong effervescence, abrupt boundary.

III C6ca, 80-110 inches: Light olive-brown (2.5Y 5/4) heavy loam with common medium and coarse olive-gray (5Y 5/2) mottles, massive, firm, no observable gypsum, strong effervescence.

Clay Co., Site 2

Location: In center of small drainage way 100 ft N of Site 1.

A11, 0-12 inches: Black (N 2/0) silty clay loam, strong fine and medium granular structure, friable, no observable gypsum throughout profile, weak effervescence, clear boundary.

A12, 12-17 inches: Identical to above horizon except for few very dark-gray (5Y 3/1) mixings, weak fine subangular blocky structure, and clay loam texture.

A13, 17-21 inches: Identical to 12-17 inch horizon except for loam texture and more pebbles.

A3g, 21-29 inches: Matrix is 2/3 black (N 2/0) and 1/3 olive-gray (5Y 5/2) loam with few fine very dark-gray (10YR 3/1) mixings, weak fine and
very fine subangular blocky structure, friable, few fine dolomite concretions, weak effervescence, abrupt boundary.

II Bigca, 29-35 inches: Olive-gray (5Y 5/2) loam with common fine and medium yellowish-brown (10YR 5/6) mottles and few dark-gray (5Y 4/1) coatings on prism faces, weak medium prismatic parting to weak fine and very fine subangular blocky structure, friable, few medium and coarse carbonate concretions, few fine black (N 2/0) oxides, violent effervescence, gradual boundary.

II B2gca, 35-45 inches: Identical to above horizon except many fine and medium mottles and prisms part to moderate very fine angular blocky structure.

II B3gca, 45-52 inches: Identical to 29-35 inch horizon except weak fine and very fine subangular blocky structure, many fine and medium mottles, and no oxides or coatings.

II Cgca, 52-60 inches: Olive-gray (5Y 5/2) loam with many medium and coarse yellowish-brown (10YR 5/6) mottles, massive, friable, few fine black (N 2/0) oxides, strong effervescence.

Clay Co., Site 3

Location: In center of small drainage way 132 ft E of Site 1.

A1, 0-6 inches: Black (N 2/0) silty clay loam, moderate fine and very fine granular structure, friable, no observable gypsum throughout profile, weak effervescence, clear boundary.

A12, 6-19 inches: Identical to above horizon except for strong medium granular structure and few snail shell fragments.
A13, 19-27 inches: Identical to 0-6 inch horizon except for light clay loam texture, weak medium prismatic parting to weak fine subangular blocky texture, and few snail shell fragments.

II A14, 27-37 inches: Black (N 2/0) light clay loam, weak medium prismatic parting to moderate fine angular blocky structure, friable, few fine carbonate concretions, few snail shell fragments, weak effervescence, clear boundary.

II A15?, 37-52 inches: Identical to above horizon except for gravelly loam texture, very dark-gray (5Y 3/1) color, and prisms part to weak very fine and fine subangular blocky structure.

Clay Co., Site 4

Location: At edge of microknoll 50 ft S of Site 3.

A11cs, 0-3½ inches: Very dark-gray (10YR 3/1) talcy silt loam, weak thin platy parting to moderate fine and very fine granular structure, very friable, many 1-2 mm pockets and mixings of gypsum flour, strong effervescence, abrupt boundary.

A12cs, 3½-7 inches: Black (10YR 2/1) silt loam, moderate fine and medium granular structure, friable, few worm holes filled with gypsum flour, few 0.1-0.5 mm gypsum crystals throughout matrix, strong effervescence, abrupt boundary.

A31cs, 7-11 inches: Dark-gray (10YR 4/1) talcy silt loam, weak very thin platy structure, very friable, many 0.5-3 mm pockets of gypsum flour, many 0.5-1 mm strata of flour, strong effervescence, clear boundary.

A32cs, 11-25 inches: Dark-gray (10YR 4/1) talcy silt loam with few thin
discontinuous very dark-gray (10YR 3/1) flows between plates, black (10YR 2/1) fills in 5-10 mm krotovinas, weak very thin platy structure, very friable, common pockets and few strata of gypsum flour as above, majority of matrix is 0.05-0.25 mm gypsum crystals, violent effervescence, abrupt boundary.

II Al1bcs, 25-31 inches: Black (N 2/0) light clay loam, weak medium prismatic parting to weak very fine subangular blocky structure, friable, few 1 mm strata of gypsum flour, few 0.1-0.25 mm crystals throughout matrix, weak effervescence, abrupt boundary.

II A12b, 31-37 inches: Black (N 2/0) clay loam with few thin dark grayish-brown (2.5Y 4/2) coatings on prism faces, weak medium prismatic parting to moderate fine and very fine angular blocky structure, friable, few branched 1-2 mm channels filled with gypsum flour, very few snail shell fragments, noneffervescent, gradual boundary.

II A13b, 37-45 inches: Identical to above horizon except prisms part to weak very fine subangular blocky structure, gypsum only as very few 1-5 mm pockets of flour, and no snail shells.

II A14bcs, 45-57 inches: Black (N 2/0) light clay loam with few coatings as in 31-37 inch horizon, structure as above, friable, few pockets of gypsum as above, few gypsum flour coatings on prism faces, few branched 1-2 mm channels filled with flour, very few 5-20 mm carbonate concretions, noneffervescent, clear boundary.

II A15bg, 57-62 inches: Black (5Y 2.5/1) heavy loam with many fine and medium olive-gray (5Y 4/2 and 4/3) mottles, weak very fine subangular
blocky structure, friable, few pockets of gypsum flour and carbonate concretions as above, weak effervescence, abrupt boundary.

III A3bg, 62-68 inches: Identical to above horizon except gravelly loam texture and many carbonate concretions and pebbles.

III Cg, 68-72 inches: Mixed dark-gray (5Y 4/1) and olive (5Y 4/3) gravelly loam with few fine light olive-brown (2.5Y 5/6) mottles, massive, friable, no observable gypsum, few fine carbonate concretions, strong effervescence.

Clay Co., Site 5

Location: At center of microknoll 100 ft S of Site 3.

A1es, 0-8½ inches: Black (10YR 2/1) silt loam with dark gray (5Y 4/1) fills in small krotovinas, moderate fine and medium granular structure, very friable, common 0.1-0.5 mm gypsum crystals throughout matrix, strong effervescence, abrupt boundary.

A31cacs, 8½-14 inches: Dark-gray (5Y 4/1) talcy silt loam with common very dark-gray (10YR 3/1) worm casts and krotovina fills, weak very thin platy parting to weak very fine granular structure, very friable, common 0.5-1 mm pockets and 1 X 5-10 mm root holes filled with gypsum flour, majority of matrix is 0.1-0.5 mm crystals, violent effervescence, clear boundary.

A32cacs, 14-24 inches: Identical to above horizon except fewer worm casts and krotovina fills, few gray (5Y 6/1) krotovina fills, and weak very thin platy structure.

B21cacs, 24-33 inches: Mixed dark-gray (5Y 4/1) and very dark-gray
(5Y 3/1) talcy silt loam, weak very thin platy structure, very friable, many 1-2 X 10-20 mm channels filled with gypsum flour, majority of matrix is 0.1-0.5 mm crystals, violent effervescence, clear boundary.

B22cacs, 33-41 inches: Identical to above horizon except dark-gray (5Y 4/1) color with few thin very dark-gray (5Y 3/1) coats, gypsum filled channels are common, also few 5-10 mm pockets of gypsum flour.

B23cacs, 41-47 inches: Gray (5Y 5/1) talcy silt loam with few dark-gray (5Y 4/1) coats and krotovina fillings, weak very thin platy structure, very friable, 10 mm thick very dark-gray (5Y 3/1) band at 43 inches, majority of matrix is 0.1-0.5 mm gypsum crystals, very few 1-2 X 10-30 mm channels and 5-10 mm pockets filled with gypsum flour, violent effervescence, clear boundary.

B31cacs, 47-59 inches: Identical to above horizon except dark-gray (5Y 4/1) with no coats or fillings, band present at 48 inches similar to one at 43 inches, channels and pockets of gypsum flour are common, and massive.

B32cacs, 59-63½ inches: Gray (5Y 5/1) talcy loam with 1-2 mm very dark-gray (5Y 3/1) horizontal strata in ¼ of volume, massive, very friable, half of soil volume is 0.5-1 mm pockets and 1 X 5-10 mm channels filled with gypsum flour, few 3-5 mm pockets of 0.5-2 mm crystals, violent effervescence, abrupt boundary.

B33cs, 63½-65 inches. Very dark-gray (10YR 3/1) loam, massive, friable, many 0.5-1 X 10-20 mm channels filled with gypsum flour, many 3-5 X 10-30 mm channels filled with 0.5-1 mm crystals, weak effervescence, abrupt
boundary.

B34cs, 65-68 inches: Identical to above horizon except a dark-gray (5Y 4/1) sandy loam with strong effervescence.

II Blbgca, 68-73 inches: Gray (5Y 5/1) loam with common fine and medium yellowish-brown (10YR 5/6) mottles, weak very fine subangular blocky structure, massive, firm, no observable gypsum, few fine black (N 2/0) oxides, common root holes, strong effervescence, gradual boundary.

II B2bgca, 73-82 inches: Identical to above horizon except moderate very fine subangular blocky structure.

II B3bgca, 82-86 inches: Identical to 68-73 inch horizon.

Clay Co., Site 6

Location: At edge of microknoll 150 ft S of Site 3.

ApOc, 0-8 inches: Black (10YR 2/1) heavy silt loam with few gray (5Y 5/1) mixings, weak thin and medium platy parting to weak very fine angular blocky structure, friable, few 1 X 5-10 mm root holes filled with gypsum flour, few 0.1-0.25 mm crystals throughout matrix, strong effervescence, abrupt boundary.

A31cs, 8-12 inches: Very dark-gray (10YR 3/1) talcy silt loam with few dark-gray (10YR 4/1) mixings, weak thin and very thin platy structure, very friable, majority of matrix is 0.1-0.25 mm gypsum crystals, root holes as above, strong effervescence, clear boundary.

A32cs, 12-22 inches: Dark-gray (10YR 4/1) talcy silt loam with very dark-gray (10YR 3/1) coats on ped faces and black (10YR 2/1) small 3-4 mm krotovinas, weak thin and very thin platy structure, very friable,
majority of matrix is 0.1-0.25 mm gypsum crystals, few channels 1-2 x
10-15 mm filled with 0.1-0.25 mm crystals, violent effervescence, clear
boundary.

A33cs, 22-32 inches: Identical to above horizon except that channels
filled with gypsum are more abundant.

B2cs, 32-38 inches: Mixed dark-gray (10YR 4/1) and black (10YR 2/1) silt
loam due to krotovina, matrix has platy structure as above, krotovina has
weak very fine granular structure, friable, similar gypsum as in 12-22
inch horizon except filled channels are more abundant, strong efferves-
cence, clear boundary.

B3cs, 38-44 inches: Black (10YR 2/1) silty clay loam krotovina, few
dark-gray (10YR 4/1) channels of 0.1-0.25 mm crystals, weak subangular
blocky structure, friable, strong effervescence clear boundary.

II C1cs, 44-50 inches: Very dark-gray (5Y 3/1) loam, massive, friable,
no observable gypsum, strong effervescence, abrupt boundary.

II C2, 50-56 inches: Identical to above horizon except is olive-gray
(5Y 4/2) gravelly loam and contains few fine carbonate concretions.

III C4gca, 56-72 inches: Gray (5Y 5/1) light clay loam with many medium
and coarse yellowish-brown (10YR 5/6) and few medium strong-brown (7.5YR
4/6) mottles, massive, firm, few dark-gray (10YR 4/1) small krotovina
fills, strong effervescence, no observable gypsum.
Clay Co., Site 7

Location: Beyond edge of microknoll 200 ft S of Site 3.

A11, 0-15 inches: Black (10YR 2/1) silty clay loam, strong fine and medium granular structure, friable, very few 0.5 X 4 mm root holes filled with gypsum flour, very few snail shell fragments, weak effervescence, clear boundary.

A12, 15-20 inches: Black (N 2/0) silty clay loam, weak very fine subangular blocky structure, friable, no observable gypsum, noneffervescent, clear boundary.

A13, 20-26 inches: Identical to above horizon except few olive-gray (5Y 5/2) mixings, moderate fine granular structure, and weak effervescence.

A14, 26-30 inches: Identical to 15-20 inch horizon except clay loam texture, weak fine prismatic parting to strong very fine and fine angular blocky structure, and weak effervescence.

A15, 30-38 inches: Identical to 26-30 inch horizon except few 1-2 X 10-15 mm channels filled with gypsum flour and few 3-5 mm carbonate concretions.

B21, 38-46 inches: Olive-gray (5Y 4/2) light clay loam with common black (10YR 2/1) coatings on prism faces and in small krotovinas, weak medium prismatic parting to weak very fine subangular blocky structure, friable, no gypsum observed in remainder of profile, few 1-5 mm carbonate concretions, strong effervescence, clear boundary.

II B22, 46-54 inches: Mixed olive-gray (5Y 4/2) and black (N 2/0)
gravelly clay loam, krotovina present, very fine subangular blocky structure, friable, weak effervescence, clear boundary.

II B31g, 54-59 inches: Dark-gray (5Y 4/1) gravelly sandy loam with few fine yellowish-brown (10YR 5/6) mottles, common black (10YR 2/1) small krotovinas, massive, friable, strong effervescence, abrupt boundary.

II B32, 59-65 inches: Olive (5Y 5/3) gravelly sandy loam with common very dark-gray (10YR 3/1) small krotovinas, single grain, loose, few fine black (N 2/0) oxides, strong effervescence, clear boundary.

II C, 65-115 inches: Stratified sands and gravels predominantly olive-gray (5Y 5/2) and light olive-brown (2.5Y 5/4), strong effervescence.

III Og, 115-146 inches: Firm heavy loam till, predominantly olive-gray (5Y 4/2) and very dark gray (5Y 3/1) with few fine yellowish-red (5YR 4/6) mottles, strong effervescence.

Clay Co., Site 8

Location: 1134 ft E and 174 ft N of the SW corner, Sec. 29, T97N, R36W.

Setting: On a nearly level lacustrine plain in a Canisteo silty clay loam, gypsic variant, 0-2% slopes, mapping unit.

Apcs, 0-8 inches: Black (N 2/0) silty clay loam with few dark-gray (5Y 4/1) mixings, cloddy parting to weak very fine subangular blocky structure, friable, few 0.05-0.25 mm gypsum crystals throughout matrix, strong effervescence, abrupt boundary.

A31cs, 8-14 inches: Dark-gray (5Y 4/1) light silty clay loam with very dark-gray (10YR 3/1) material between plates, weak very thin and thin platy structure, very friable, common 0.5-1 X 10-20 mm root pores filled
with gypsum flour, large portion of matrix is 0.1-0.5 mm crystals, strong effervescence, gradual boundary.

A32cs, 14-18 inches: Identical to above horizon except very weak effervescence.

B21cs, 18-33 inches: Mixed very dark-gray (10YR 3/1) and dark-gray (5Y 4/1) silty clay loam, weak thick platy structure, very friable, majority of matrix is 1-5 mm gypsum crystals, common 1-2 X 10-20 mm channels filled with gypsum flour and 0.1-0.5 mm crystals, few fine carbonate concretions, weak effervescence, clear boundary.

B22cs, 33-38 inches: Identical to above horizon except fewer very dark-gray (10YR 3/1) colors, no filled channels, larger gypsum crystals in matrix, and strong effervescence.

B3cs, 38-43 inches: Olive (5Y 5/3) light silty clay loam with few dark-gray (5Y 4/1) mixings and flows, weak very fine subangular blocky structure, friable, common 10-15 mm rosettes of gypsum crystals 1-5 mm in length, violent effervescence, abrupt boundary.

C1cs, 43-46 inches: Olive (5Y 5/3) silt loam, massive, friable, few 1-2 mm X 10-15 mm channels filled with gypsum flour, many soft carbonate masses and seams, few fine black (N 2/0) oxides, violent effervescence, abrupt boundary.

C2gcs, 46-56 inches: Olive (5Y 5/3) light silty clay loam with common fine yellowish-brown (10YR 5/6) mottles, massive, friable, many networks of 1-2 mm channels filled with 0.1-0.5 mm crystals criss-crossing matrix in a random orientation, weak effervescence, gradual boundary.
II Cgca, 56-90 inches: Stratified silty clay and light silty clay loam sediments, predominantly olive (5Y 5/3) and olive-gray (5Y 5/2) with common fine and medium yellowish-brown (10YR 5/6) and few fine strong-brown (7.5 YR 4/6) mottles, no observable gypsum, few coarse soft carbonate concretions, strong effervescence.

Webster Co., Site 3

Location: 1290 ft E and 845 ft N of the SW corner, Sec. 10, T87N, R29W.

Setting: Near the center of a broad, shallow basin in a Lanyon silty clay, 0-1% slopes, mapping unit.

Ap, 0-9 inches: Black (10YR 2/1) silty clay loam, weak medium granular structure, friable, few 0.25-0.5 mm crystals throughout matrix, weak effervescence, abrupt boundary.

A3gca, 9-15 inches: Grayish-brown (2.5Y 5/2) silty clay loam with common fine yellowish-brown (10YR 5/6) mottles, some dark-gray (10YR 4/1) mixings, weak medium subangular blocky structure, friable, common 1-3 mm pockets and broken root pores filled with gypsum flour, strong effervescence, clear boundary.

B1gcs, 15-21 inches: Gray (10YR 5/1) silt loam with common medium yellowish-brown (10YR 5/6) mottles, weak fine granular structure, very friable, many 1 mm broken root pores filled with gypsum flour, common 1 mm crystals throughout matrix, violent effervescence, clear boundary.

B21gcs, 21-27 inches: Identical to above horizon except many medium mottles, moderate fine subangular blocky structure, and strong effervescence.
B22gcs, 27-36 inches: Identical to 21-27 inch horizon except common fine mottles.

B23gcaes, 36-44 inches: Gray (5Y 5/1) silt loam with common fine yellowish-brown (10YR 5/6) mottles, weak fine subangular blocky structure, very friable, many 5-10 mm pockets and few root holes filled with gypsum flour, many 3-4 mm horizontal strata of gypsum flour, strong effervescence, clear boundary.

B24gcaes, 44-48: Light gray (10YR 7/1) silt loam with common fine yellowish-brown (10YR 5/6) mottles, weak fine subangular blocky structure, very friable, common gypsum flour and up to 1 mm crystals throughout matrix, strong effervescence, clear boundary.

B3gcs, 48-64 inches: Identical to above horizon except matrix is gray (5Y 5/1) loam with few fine black (N 2/0) oxides, abrupt boundary.

Gcs, 64-67 inches: Olive-yellow (2.5Y 6/6) silt loam, massive, friable, few 0.1-0.25 gypsum crystals throughout matrix, strong effervescence.

Webster Co., Site 4

Location: On a microknoll 95 ft N of Site 3.

Ap, 0-10 inches: Black (10YR 2/1) loam, weak fine granular structure, friable, very few 0.1-0.25 mm gypsum crystals throughout matrix, violent effervescence, abrupt boundary.

B1gcaes, 10-15 inches: Grayish-brown (2.5Y 5/1) loam with few medium yellowish-brown (10YR 5/6) mottles, moderate fine granular structure, many 1 mm gypsum crystals throughout matrix, few snail shells, strong effervescence, clear boundary.
B21gcs, 15-23 inches: Dark grayish-brown (10YR 4/2) loam with few medium strong-brown (7.5YR 4/6) mottles, krotovina present, weak fine subangular blocky structure, very friable, few 0.5-1 mm channels filled with gypsum flour in lower part of horizon, few snail shells, strong effervescence, gradual boundary.

B22gcs, 23-33 inches: Gray (10YR 5/1) silt loam, weak fine subangular blocky structure, very friable, common 1-2 mm channels filled with gypsum flour, few 4-5 mm pockets of 0.5-1 mm gypsum crystals, few snail shells, strong effervescence, clear boundary.

B23gcs, 33-42 inches: Gray (10YR 6/1) loam with mottles and structure as above, friable, common 1-4 mm channels filled with 0.25-1 mm gypsum crystals, strong effervescence, clear boundary.

B3gcs, 42-50 inches: Gray (10YR 6/1) silt loam with common medium brownish-yellow (10YR 6/8) and yellowish-brown (10YR 5/6) mottles, weak fine granular structure, friable, common 1 mm horizontal strata of gypsum flour, strong effervescence, gradual boundary. Note: 1 X 0.5 X 0.5 inch piece of shale found in this horizon.

C1gcs, 50-53 inches: Mixed yellowish-brown (10YR 5/6) and gray (10YR 6/1) silt loam, massive, friable, few 2-3 mm pockets of 0.5 mm gypsum crystals, strong effervescence, clear boundary.

C2gcs, 53-58 inches: Matrix is 3/4 gray (10YR 6/1) and 1/4 yellowish-brown (10YR 5/6) loam, massive, friable, very few 1 mm horizontal strata of gypsum flour, few fine black (n 2/0) oxides, strong effervescence, abrupt boundary.
C3, 58-63 inches: Matrix is 3/4 brown (10YR 5/3) and 1/4 gray (10YR 6/1) silt loam with few fine red (2.5YR 4/6) and reddish-brown (2.5YR 5/4) mottles, massive, friable, no observable gypsum, strong effervescence, abrupt boundary.

All of the following horizons are massive and friable with strong effervescence and abrupt boundaries.

C4cs, 63-65 inches: Mixed gray (10YR 6/1) and yellowish-brown (10YR 5/4) sandy loam with few fine red (2.5YR 4/6) mottles, few 0.5-1 mm gypsum crystals throughout matrix.

C5, 65-68 inches: Brown (10YR 5/3) silt loam, very few 1 mm pockets of 0.1-0.25 mm gypsum crystals.

C6cs, 68-72 inches: Grayish-brown (10YR 5/2) sandy loam, common 1-2 mm pockets of 0.5 mm gypsum crystals, few 0.5 mm crystals throughout matrix.

II C7gcs, 72-76 inches: Grayish-brown (2.5YR 5/2) loam with few fine yellowish-brown (10YR 5/6) and red (2.5YR 4/6) mottles, common 0.25-0.5 mm gypsum crystals throughout matrix.

**Cottonwood Co., Romnell Site**

Location: 2,300 ft W and 30 ft S of NE corner, Sec. 3, T108N, R38W.

Setting: On a west-facing concave slope of about 1%

Ap, 0-10 inches: Black (N 2/0) clay loam, weak fine subangular blocky structure, friable, few 0.25-0.5 mm gypsum crystals throughout matrix, noneffervescent, abrupt boundary.

A3, 10-18 inches: Very dark-gray (N 3/0) silty clay loam, weak fine and
medium platy parting to weak fine subangular and angular blocky structure, friable, few 0.5-1 mm root holes filled with gypsum flour, noneffervescent, abrupt boundary.

B1, 18-22 inches: Very dark-gray (5Y 3/1) clay loam, moderate fine subangular blocky structure, friable, same gypsum as above but more common, noneffervescent, abrupt boundary.

B21g, 22-27 inches: Very dark-gray (5Y 3/1) clay loam with many coarse olive (5Y 4/3) mottles, weak coarse prismatic parting to moderate fine angular blocky structure, friable, few 0.5-1 mm root holes filled with gypsum flour, few 1-2 mm pockets of flour also, noneffervescent, abrupt boundary.

B22gcs, 27-33 inches: Olive-gray (5Y 4/2) clay loam with common fine yellowish-brown (10YR 5/6) mottles, moderate coarse prismatic parting to weak fine subangular blocky structure, friable, few 1-2 mm root holes filled with gypsum flour, few 1-2 mm gypsum crystals throughout matrix, weak effervescence, abrupt boundary.

B3gcs, 33-43 inches: Gray (5Y 5/1) clay loam with few fine yellowish-brown (10YR 5/6) mottles, moderate coarse prismatic parting to weak fine subangular blocky structure, friable, common 1-2 mm root holes filled with gypsum flour, common 1-5 mm pockets of 0.5-2 mm crystals, few 1-2 mm horizontal strata of gypsum flour, strong effervescence, abrupt boundary.

Clgcs, 43-56 inches: Gray (5Y 5/1) clay loam with few coarse olive-brown (2.5Y 4/6) and common medium light olive-brown (2.5Y 5/6) mottles, massive, friable, few 1-5 mm pockets of 0.5-1 mm gypsum crystals plus gypsum
flour, many 1-5 mm soft carbonate masses, violent effervescence, abrupt boundary.

C2g, 56-59 inches: Identical to above horizon but with less gypsum.

Redwood Co., Jeffers Site

Location: 1340 ft N and 120 ft W of the SE corner, Sec. 36, T109N, R37W.

Setting: On a south-facing slightly convex 2% slope.

Apcs, 0-10 inches: Black (N 2/0) clay loam, weak fine subangular blocky structure, friable, common 0.5-2 mm root holes filled with gypsum flour, few 0.25-0.5 mm crystals throughout matrix, strong effervescence, abrupt boundary.

A3cs, 10-14 inches: Very dark-gray (10YR 3/1) loam, weak fine subangular blocky structure, very friable, few 0.5-2 mm pockets and root holes filled with gypsum flour, many 0.5-5 mm crystals throughout matrix, strong effervescence, clear boundary.

Blcs, 14-20 inches: Very dark grayish-brown (2.5Y 3/2) loam, weak fine subangular blocky structure, very friable, many 0.5-5 mm gypsum crystals throughout matrix, violent effervescence, clear boundary.

B21gcs, 20-28 inches: Light olive-brown (2.5Y 5/4) loam with few dark grayish-brown (2.5Y 4/2) worm casts and ped coatings, weak fine and very fine granular structure, majority of matrix is 0.5-5 mm gypsum crystals, very friable to loose, violent effervescence, clear boundary.

B22gcs, 28-35 inches: Identical to above horizon except gypsum also occurs as 1-2 mm pockets of 0.1-0.25 mm crystals.
B3gcs, 35-41 inches: Light olive-brown (2.5Y 5/4) loam with many medium yellowish-brown (10YR 5/6) and few fine red (2.5YR 4/6) mottles, weak fine subangular blocky structure, friable, few 0.5-1 mm root holes filled with gypsum flour, no crystals in matrix, few 1-2 mm soft carbonate masses, strong effervescence, clear boundary.

Clg, 41-54 inches: Grayish-brown (2.5Y 5/2) loam with mottles as above, massive, friable, very few 0.5 mm root holes filled with flour, very few 1-4 mm pockets of 0.5-2 mm crystals, few 1-2 mm soft carbonate masses, strong effervescence, clear boundary.

C2g, 54-60 inches: Identical to above horizon except gypsum occurs as very few 0.5 mm pockets of flour and very few 0.5-2 mm crystals throughout matrix.

Redwood Co., Jeffers MWD Variant Site

Location: 1980 ft N and 100 ft W of the SE corner, Sec. 36, T109N, R37W.

Setting: On a south-facing slightly convex 5% slope.

Ap, 0-10 inches: Very dark-gray (10YR 3/1) light clay loam with few light olive-brown (2.5Y 5/4) mixings, weak fine subangular blocky structure, friable, few 0.25-0.5 mm gypsum crystals throughout matrix, weak effervescence, abrupt boundary.

B1, 10-16 inches: Light olive-brown (2.5Y 5/4) loam with common very dark grayish-brown (10YR 3/2) mixings and dark grayish-brown (2.5Y 4/2) worm casts, weak fine subangular blocky structure, friable, very few 0.25-0.5 mm gypsum crystals throughout matrix, violent effervescence, clear boundary.
B21ca, 16-23 inches: Identical to above horizon except no mixings, few worm casts, and does contain few fine soft carbonate concretions.

B22ca, 23-32 inches: Light olive-brown (2.5Y 5/4) loam with very few olive-gray (2.5Y 5/2) worm casts, weak fine subangular blocky structure, friable, very few 0.25-0.5 mm gypsum crystals throughout matrix, common fine and medium soft carbonate concretions, violent effervescence, clear boundary.

Clgcs, 32-39 inches: Matrix is 1/2 yellowish-brown (10YR 5/4) and 1/2 gray (5Y 5/1) loam with few fine brown (7.5YR 4/4) mottles, massive, friable, few 4-10 mm pockets of 0.5-2 mm gypsum crystals, very few 1-2 mm root holes filled with 0.5-1 mm crystals, many 0.5-1 mm crystals throughout matrix, few fine soft carbonate concretions, few fine black (N 2/0) oxides, strong effervescence, clear boundary.

C2gcs, 39-53 inches: Matrix is 1/2 yellowish-brown (10YR 5/6) and 1/2 grayish-brown (10YR 5/2) loam with few medium brown (7.5YR 4/4) mottles, massive, friable, channels 5 mm thick x 40-60 mm long x 10-20 mm wide filled with 0.1-0.5 mm gypsum crystals, few 5-10 mm pockets of 1-2 mm crystals, few 0.25-0.5 mm crystals throughout matrix, common medium and coarse soft carbonate concretions, few fine black (N 2/0) oxides on cleavage planes, violent effervescence, clear boundary.

C3, 53-60 inches: Yellowish-brown (10YR 5/6) loam with mottles and oxides as above, few 5-10 mm horizontal bands of olive-gray (5Y 5/2), massive, friable, no observable gypsum, strong effervescence.
APPENDIX B: LABORATORY DATA FOR PROFILES
COLLECTED AT STUDY SITES

Conventions and Abbreviations used in Reporting the Data

Gravel percentage was determined on the whole soil volume. All other analyses were determined on the < 2 mm portion. All sand, coarse silt, fine silt, and clay data were determined after carbonates and gypsum were removed from the samples. Results are reported on the basis of the original whole soil.

Gravel = > 2 mm         Clay = < 2μ
Coarse Silt = 50-20μ    Sand = 2-0.05 mm
Fine silt = 20-2μ

Samples marked with "#" were treated with hydrogen peroxide before particle-size analysis. All values marked with "*" indicate a rerun analysis was made to verify results. Some large gypsum crystals may have been included in the > 2 mm soil portion. Gypsum percentages determined may be lower than are actually present in the soil. Profile descriptions should be consulted for crystal sizes. pH values are not comparative to values that are determined by other pH methods. For interpretation of the values, see the section entitled "LABORATORY METHODS: pH." The sum of the percentages of sand, coarse silt, fine silt, clay, gypsum, calcite, dolomite, and organic matter (e.g., organic carbon % x 1.72) should equal approximately 100%. Horizons containing high contents of gypsum and organic carbon usually have sums that are below the theoretical 100% value. Gypsum percentages are probably low.

CEC = cation exchange capacity
SAR = sodium adsorption ratio
EC = electrical conductivity
ESP = exchangeable sodium percentage
Tr. = trace
O.C. = organic carbon
Cal = calcite
Dol = dolomite
Table 23. Laboratory data for Dickinson Co., Site 1

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<th>Clay</th>
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Table 24. Laboratory data for Dickinson Co., Sites 2 and 2A

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Table 27. Laboratory data for Clay Co., Site 3

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<th>Gypsum %</th>
<th>Calcite %</th>
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<th>Cal/Dol ratio</th>
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<th>pH</th>
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<th>Calcite</th>
<th>Dolo- mite</th>
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Table 29. Laboratory data for Clay Co., Site 5

| Depth in | Gravel % | Sand % | Coarse silt % | Fine silt % | Clay % | pH | Gypsum % | Calcite % | Dolomite % | Cal/Dol ratio | Cal+Dol Sum % | O.C. % |
|----------|----------|--------|---------------|-----------|--------|----|---------|----------|-----------|-------------|-------------|------------|------|
| 0-8½ Tr. | 11.5     | 10.4   | 4.6           | 20.2#     | 7.4    | 36.4| 3.6     | 1.7      | 2.12      | 5.3         | 3.3         |        |      |
| 8½-14 Tr.| 9.2      | 6.5    | 3.9           | 18.3*     | 7.4    | 55.5| 4.9     | 1.5      | 3.27      | 6.4         | 1.3         |        |      |
| 14-19    | 1        | 7.0    | 4.4           | 0.5       | 14.1   | 7.4 | 63.3    | 6.7      | 2.3       | 2.91        | 9.0         | 0.7      |      |
| 19-24    | 1        | 5.8    | 3.6           | 0.0       | 12.1   | 7.4 | 63.7    | 9.1      | 2.8*      | 3.25        | 11.9        | 0.4      |      |
| 24-33    | 1        | 9.2    | 6.3           | 2.4       | 16.9   | 7.4 | 58.7    | 3.6      | 0.0       | 1.80        | 5.6         | 0.5      |      |
| 33-41    | 5        | 15.4   | 3.8           | 0.1       | 14.4   | 7.4 | 56.4    | 4.5      | 2.8       | 1.61        | 7.3         | 0.4      |      |
| 41-47    | 1        | 15.6   | 3.3           | 0.7       | 13.9   | 7.5 | 53.7    | 8.0      | 2.7       | 2.96        | 10.7        |        |      |
| 47-53    | 1        | 14.3   | 3.5           | 1.3       | 14.8   | 7.4 | 56.4    | 5.3      | 3.7       | 1.43        | 9.0         |        |      |
| 53-59    | 4        | 19.4   | 3.2           | 1.2       | 15.2   | 7.4 | 51.5    | 3.0      | 3.1       | 0.97        | 6.1         |        |      |
| 59-63½   | 18       | 31.9   | 3.7           | 1.7       | 13.7   | 7.4 | 41.3    | 2.5      | 7.7       | 0.32        | 10.2        | 0.1      |      |
| 63½-65   | 3        | 30.9   | 8.3           | 12.3      | 24.1   | 7.5 | 23.3    | 0.5      | 2.6       | 0.19        | 3.1         | 0.4      |      |
| 65-68    | 41       | 42.6   | 5.6           | 4.8       | 18.2   | 7.4 | 15.0    | 2.9      | 12.0      | 0.24        | 14.9        | 0.1      |      |
| 68-73    | 10       | 22.9   | 10.0          | 15.1      | 25.3   | 7.5 | 0.2     | 10.1     | 15.6*     | 0.65        | 25.7        |        |      |
| 73-82    | 8        | 23.0   | 10.9          | 16.9      | 24.3   | 7.4 | 0.0     | 7.8      | 16.0      | 0.49        | 23.8        |        |      |
| 82-86    | 7        | 23.0   | 11.6          | 17.6      | 25.3   | 7.4 | 0.1     | 6.3      | 15.6      | 0.40        | 21.9        |        |      |
Table 30. Laboratory data for Clay Co., Site 6

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<th>pH</th>
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<th>Calcite</th>
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Table 31. Laboratory data for Clay Co., Site 7

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Table 37. Laboratory data for Redwood Co., Jeffers moderately well-drained variant site

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APPENDIX C: LABORATORY DATA FOR SELECTED CALCAREOUS CARY TILL SAMPLES

Conventions and Abbreviations Used in Reporting the Data

All analyses were performed on the < 2 mm portion. Carbonates were not removed before particle-size analysis. Sand = 2-0.062 mm.

Silt = 62-2µ Clay = < 2µ

Although the sand percentages are reported on a 2-0.062 mm basis, the following relationship exists:

Sand % (2-0.05 mm) = Sand % (2-0.062 mm) X 1.025

Cal = calcite
Dol = dolomite

ISU Lab No. = the sequential number assigned to the sample by the Iowa Soil Survey Laboratory.
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Conventions and Abbreviations Used in Reporting the Data

All analyses were performed on the < 2 mm portion. All depths are given in inches.

Cal = calcite

Dol = dolomite

ISU Lab No. = the sequential number assigned to the sample by the

Iowa Soil Survey Laboratory.
Table 39. Laboratory data for selected carbonate-enriched soils

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Conventions and Abbreviations Used in Reporting the Data

All analyses were determined on the < 2 mm portion. All depths are reported in inches. Values marked by "*" indicate a rerun analysis was made to verify results.

ISU Lab No. = the sequential number assigned to the sample by the Iowa Soil Survey Laboratory.
### Table 40. Laboratory data for selected poorly-drained soils

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APPENDIX F: PHOTOGRAPHIC SLIDES

Slide 1. Picture of rock gypsum and cemented crystals from till joints. Rock is from pit mine near Fort Dodge. Notice stratifications. Cemented crystals are from pre-Wisconsin till in Cherokee Co. Plates are 5-10 mm thick. One appears to be primarily tabular crystals, the other primarily acicular crystals.


Slide 3. Picture of Dickinson Co., Sites 2 and 2A. Facing east. Site 2 is marked by flag in light-colored soil area. Site 2A is marked by flag in dark-colored soil area to north of Site 2. Notice abrupt color change and circular nature of light-colored area. Other areas are to the east.


Slide 5. Picture of Clay Co., Site 8. Facing north. Sampling site is unmarked but is approximately 150 ft into field from immediate foreground.

Slide 6. Picture of Webster Co., Sites 3 and 4. Facing southeast. Sampling sites are unmarked but are approximately 200-300 ft south of row of trees in center of picture.
Sampling site is unmarked but is approximately 30 ft into field from center of road.

Slide 8. Picture of Redwood Co., Jeffers and Jeffers MWD variant sites. Facing north. Sampling sites are unmarked. Jeffers site is in immediate left foreground. Jeffers MWD variant site is on slight rise to north of Jeffers site.

Slide 9. At top of picture is soil material containing lenticular gypsum crystals. Lighter pieces are peds. Darker pieces are dark-coated crystals. From Redwood Co., Jeffers site, 14-20 inch horizon. Bottom left of picture is a portion of a rosette from Clay Co., Site 8, 38-42 inch horizon. This rosette is not well-pronounced. Notice crystals arranged around a central void. Bottom center of picture is a pendant of gypsum crystals on the underside of a pebble. Bottom right of picture is what appears to be a dolomite-coated iron concretion.