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and Mineralogical Properties
of
Related Minnesota Prairie Soils

Harold F. Arneman, Aziz D. Khan,
and P. R. McMiller



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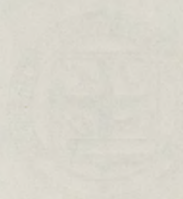
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Harold E. Johnson and H. H. Kline
and E. G. Millie



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Physical, Chemical, and Mineralogical Properties of Related Minnesota Prairie Soils

Harold F. Arneman, Aziz D. Khan, and P. R. McMiller¹

SOILS are the natural media for the growth of land plants. They are the result of living organisms and climate acting upon weathered geologic materials. The length of time that natural forces act upon this material has an important bearing on the characteristics of the soil. The drainage conditions in which a soil forms are equally important. Drainage is dependent upon surface relief, as well as the texture and composition of the parent material. The five factors of soil formation are (1) *climate*, (2) *biological activity*, (3) the *parent material*, (4) *relief*, and (5) *time*.

PURPOSE OF THE STUDY

This investigation was undertaken to determine the effect of slight differences in topography on the physical, mineralogical, and chemical characteristics of soils developed from similar parent materials. Three closely related prairie soils of south-central Minnesota were sampled. The samples were from the well-drained Clarion series, the moderately well-drained Nicollet series, and the poorly drained Webster series. The three soils have different morphological characteristics which permit them to be delineated on soil maps. The laboratory and field studies on these soils sought to determine how they differed in their characteristics.

CLARION-NICOLLET-WEBSTER SOIL ASSOCIATION

The Clarion-Nicollet-Webster soil association occupies slightly more than 13 percent of the land area of Minnesota. It occurs in a triangular shaped area in south central Minnesota approximately 200 miles wide along the Iowa-Minnesota boundary and about the same distance north to a

point in Stearns County Minnesota. The area extends south into Iowa, about as far as Des Moines, some 200 miles from the Minnesota state line (figure 1). Fully as important as the association's large size is its economic importance from an agricultural standpoint.

The soils of this area range from nearly level to strongly rolling. A large portion of the area lies nearly level which retards surface runoff and restricts internal drainage, at times interfering with working the land particularly in the early spring. Throughout the area are many small depressions that collect water from the surrounding higher land and some of these remain wet the greater part of the year.

The native vegetation which originally covered the area was tall deep-rooted native grasses with hardwood trees bordering many of the streams and fringing most of the lakes. As the roots of the native grasses decayed, the surface soils became abundantly enriched with organic matter; the amount being influenced to some extent by the slope of the land which affected the amount of water entering the soil and thus influencing the nature of the vegetative growth.

¹ Harold F. Arneman is Associate Professor of Soils. Aziz D. Khan, research assistant in the Department of Soils at the time of this study, is now with the Ministry of Agriculture, Republic of India. Much of the investigation reported on here was carried out in collaboration with the late P. R. McMiller (1887-1956), Professor Emeritus of Soils. The authors also wish to acknowledge with sincere appreciation the advice and assistance of John W. Gruner, Professor of Geology, University of Minnesota, in performing the mineralogical analysis reported in this bulletin.

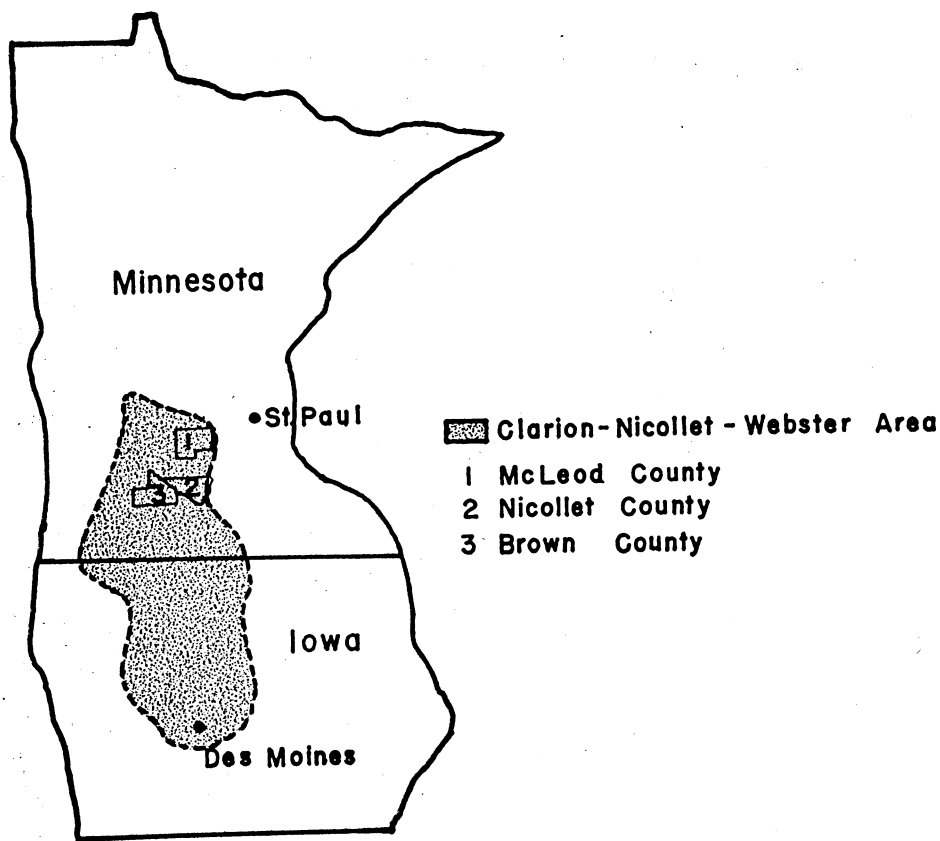


Fig. 1. Map of Minnesota and Iowa showing the approximate location of the Clarion-Nicollet-Webster Soil Association and the counties where the soil samples were collected.

The soils of this association developed from materials of glacial origin. Several ice sheets covered the area during the Pleistocene epoch. The most recent one, known as the Mankato lobe of the Wisconsin stage by Leighton (29)², is of principal concern in this study since it provided the parent materials from which the soils were formed.

The soils of the Clarion-Nicollet-Webster association developed under a temperate continental climate, characterized by long cold winters and fairly short warm sum-

mers. The mean annual temperature ranges from 40° F. in the north to 44° F. in the southern part of the area. The annual precipitation, which includes rain and melted snow, is fairly well distributed over the area and ranges from 26 inches in the western part to about 30 inches in the southeastern corner. Nearly three-fourths of this precipitation falls in the six-month frost-free period from April through September.

The three soils studied differ chiefly in drainage, the Clarion being well drained, the Nicollet moderately well drained, and the Webster poorly drained. Aside from drainage, the other factors of soil forma-

² Numbers in italic refer to Literature Cited, see page 35.

tion were essentially the same. This group of soils may be considered a catena according to the definition of Thorpe (51). The term catena was first used by Milne (37) but in a much broader sense than now used. According to Thorpe the term catena as commonly used in the United States refers to a group of soils differing from one another in relief or drainage. It

is a convenient method for classifying soils derived from similar parent material into geographic groups based chiefly on their drainage conditions.

The soils of the association have dark colored surface soils, with comparatively high contents of organic matter, and range in texture from medium to fine in both surface soil and subsoil.

Review of Literature

FEATURES OF THE BLACK PRAIRIE SOILS

Although agreeing in principle with much of Glinka's (10) system of soil classification, Marbut (33) recognized that differences in climate were wholly inadequate to account for many soil characteristics. In Europe and parts of Asia the temperature and the rainfall belts more or less coincide, but in the United States this does not always hold true. In central United States, temperatures increase from north to south whereas precipitation increases from west to east. Marbut also realized that the soils could not be adequately classified by geological means alone, so he chose to classify them on the characteristics of the soils themselves.

The one group of soils which would not fit into Glinka's classification prompted the recognition of an additional group known as the Black Prairie Soils (31). The soils of this group are unique in that they are confined almost entirely to the United States. They occur in areas where the climate is regarded as too humid for grasses but approach conditions more favorable to the growth of trees and favorable to the podzolic process of soil formation. These soils to a depth of about 2 feet are very similar to the Chernozem soils but they lack the zone of lime accumulations characteristic of the latter. Some European workers and Joffe (24) in the United States classify them as Degraded Chernozems, since there is a translocation of the sesquioxides, a compactness of the B horizon, and a poorly defined zone of

lime accumulation somewhere in the upper C horizon.

Marbut (32), however, took issue with this postulation advancing the following reasons for opposing it. The soils of the prairies are the normal product of the biological factor. The biological factor is regarded as the dominant factor in soil development in this group of soils. For this reason Marbut (31) proposed that until additional information proves to the contrary, the Black Prairie Soils should be treated as a distinct zonal group of soils.

SOIL WEATHERING AS INDICATED BY COMPOSITION OF COARSER MINERALS

Since the inorganic part of the soil is composed entirely of various minerals, it must be recognized that it is a very important part of the soil mass. Minerals differ widely in their resistance to chemical and physical destruction (18). This resistance depends upon many characteristics of the mineral, such as hardness, cleavage, coefficient of expansion, original cracks in the crystal, solubility under a given environment, and others.

Pettijohn (42) has calculated an order of persistency of soil forming minerals by comparing the minerals in sedimentary rocks of increasing geological age with those of recent sediments. He proposed the following resistance series: 1 zircon, 2 tourmaline, 3 monazite, 4 quartz, 5 garnet, 6 biotite, 7 apatite, 8 microcline, 9 ilmenite, 10 magnetite, 11 staurolite, 12 sya-

nite, 13 epidote, 14 hornblende, 15 andalusite, 16 topaz, 17 titanite, 18 zoisite, 19 augite, 20 sillimanite, 21 hypersthene, 22 diopside, 23 actinolite, and 24 olivine.

Other investigators list the stability series somewhat differently. Goldich (11) divides the minerals into three groups; (1) the least stable group which includes plagioclase, epidote, hornblende, titanite, and apatite, (2) the moderately stable group of magnetite, biotite, and orthoclase, and (3) the most stable group of zircon and quartz. Twenhofel (54) proposed another grouping. He listed chlorite, garnet, orthoclase, quartz, and zircon as stable minerals. The metastable to unstable minerals include augite, hornblende, ilmenite, magnetite, and plagioclase, and the unstable ones, apatite, and olivine.

The coarser minerals, larger than 0.05 mm. in diameter, are often divided into two groups on the basis of their specific gravity (18). The so-called light minerals are those with a density of less than about 2.85, whereas the heavy ones have a greater density. The light minerals include mainly quartz, calcite, feldspar, and muscovite. They generally make up about 98 percent of a mineral sediment. The heavy minerals, although comprising only about 2 percent of a soil sample, include a much greater variety of the mineral species and therefore are generally more helpful in characterizing a particular deposit than the light fraction. Most of the accessory minerals belong to the heavy group.

Some investigators divide the coarse minerals into three groups (20) based on their specific gravity. These are the orthoclase group, with specific gravities of 2.6 or less; the quartz group, with specific gravities of 2.6 to 2.85; and the ferrosilicate group, with specific gravities higher than 2.85. Hart (17) working with soils, used mineral analysis to study differences in the composition of parent materials. He found that soils could be grouped according to their mineral content, the grouping depending mainly on the origin of the parent material. Kruger (26), in studying the heavy minerals of sandy glacial materials of different ages and different drift sheets in Minnesota, found a wide varia-

tion and could not distinguish one glacial drift from another on the basis of heavy minerals alone.

To trace depositional differences in parent materials it seemed desirable to make an exact quantitative study of a limited number of the most resistant heavy minerals contained in the parent material. Marshall (35) working along this line with Missouri soils made three quantitative estimations as follows:

- (a) The sand fraction expressed as percentage of the whole soil;
- (b) The percentage of heavy minerals in the sand fraction;
- (c) The percentage of the most resistant minerals in the heavy mineral suite.

A discussion of the advantages and disadvantages of various techniques has been given by Grout (15). He found that a preliminary magnetic separation of the heavy minerals was useful in identification and saved time in counting. He also found that centrifuging with heavy liquids did not appreciably affect the quantities of heavy minerals recovered, neither did the evaluation of the centrifuged sample nor did the several types of special glassware used in the procedures have any effect. Grout further suggested that if only the ratio between two mineral species was desired time is saved and more accurate results are achieved by counting these two species only and combining all the other grains.

CLASSIFICATION AND IDENTIFICATION OF THE CLAY MINERALS

The term, clay, as stated by Twenhofel (53) carries with it three implications; (1) it is a plastic material with plastic properties, (2) it consists of particles of very fine size, and (3) it has an essential composition of crystalline mineral fragments that are predominantly hydrous aluminum silicates and occasionally hydrous magnesium silicates. The term clay implies nothing regarding its origin but is based on properties, texture, and composition, which are

obviously interrelated. For example, plasticity is the result of the constituent minerals and their grain size.

Although a great deal of chemical work has been done on clays, no definite crystal structures for the minerals could be given prior to 1931 for it was not known then whether clays were crystalline. With the development and improvement of techniques, workers in this field began to form definite opinions on the structure of the clays. Robinson and Holmes (45) in 1925 remarked that with a further development of X-ray techniques it might be possible to determine definitely whether complex mixtures such as soil colloids were crystalline, or if not, what constituted their composition.

Grim (13) working with clay minerals in 1942 classified them into three major and several minor groups. The major groups were known as the Kaolinite group, Montmorillonite group, and Illite group. Gruner (16) in 1932, suggested the structure of three isomeric members of the Kaolinite group as kaolinite, nacrite, and dickite, all of which have the ideal composition $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$. The distinction between them is attributed to different displacements of the silica layer relative to the aluminum layer in the lattice structure. Hofmann, Endell, and Wilm (21) made careful comparisons of two types of pyrophyllite. Both gave much the same X-ray pattern, but one strong line in the pattern on one type moved as the water content of the minerals varied, the other remained constant. The pyrophyllite structure that was influenced by water was called montmorillonite.

Grim, Bray, and Bradley (14) suggested the name illite as a group name rather than a specific mineral name for clay minerals that are similar to but not identical with white mica. The illites contain less potassium and more water than the white micas. They also differ in physical properties.

Credit is due Bragg (5) for much of the fundamental work on the structure of the silicate minerals. He states that the silicon oxygen bond is the strongest in all the structures and the silicon arrangement

may be considered the skeleton of a silicate structure. All silicon atoms in clay minerals are surrounded by four oxygen atoms, such a form being called the silicon tetrahedron. In clay minerals the oxygen atoms from one tetrahedron tie to the silicon of another tetrahedron to form a sheet-like structure called the silica sheet. The aluminum in the clay minerals form an octahedral structure with an aluminum atom in the center and an oxygen atom at each corner of the octahedron.

Marshall (34) has shown that replacement of one ion for another can take place in the crystal structure if both ions are approximately the same size. In this way Al^{+++} can replace Si^{++++} in the silica tetrahedral layer while Fe^{++} and Mg^{++} can replace Al^{+++} in the octahedral layer. If one ion is replaced by another of lower valence, there will be a negative charge left on the particle that must be satisfied by some other positive charge. This may account for some of the cation exchange properties of a colloid. In the years since the structural formulas for the various clay minerals were determined, much work has been done and reported in an attempt to use X-ray analysis in the study of soil colloids and pure minerals.

As early as 1887, LeChatelier (28) found that when clays are heated they lose water. He also observed that when a clay was compared with an inert material such as alundum the temperature of the clay would be lower than that of the inert material when water was driven off. This was the first attempt to determine the composition of a clay by differential thermal methods. It was not until many years after LeChatelier reported the results of his investigation that this kind of analysis was again used. Even now, perhaps, its importance in the study of clay minerals is not fully appreciated.

Norton (38) is of the opinion that thermal methods are particularly valuable in identifying clay minerals when they occur in either such a finely crystalline state that the petrographic method cannot be used or when they occur in mixtures in which the X-ray identification is difficult. Hendricks and Alexander (19) found thermal

analysis useful in determining mineralogical composition of clays, as well as of great value in interpreting the nature and occurrence of the cation exchange phenomena in soils. Shafer and Russell (49) regard this method useful as a quantitative measure for a number of clay minerals found in soils. In their paper they show several standard thermal curves for pure minerals and mineral mixtures. Page (40) pointed out that the standard curve for a montmorillonite clay in one area may have a different pattern from a montmorillonite clay in another. Inasmuch as there is no standard curve for montmorillonite on which all agree, it seems that a range of properties must be permitted within certain limits and accordingly an identification must be based on this rather than on that of a single standard.

CHEMICAL PROPERTIES OF PRAIRIE SOILS

Many soils can be characterized on the basis of their chemical properties. Rost (46) in his study of Minnesota prairie soils developed on different glacial drifts regarded them as degraded Chernozems. He noted that (a) carbonates had practically leached out of the solum, (b) the surface horizons were generally acid, (c) there was no pronounced translocation of sesquioxides, (d) there was a slight accumulation of Ca and Mg in the solum, (e) a high content of organic carbon in the top six inches which decreased gradually with depth, and (f) the content of nitrogen followed closely that of organic carbon. Alway *et al.* (1) found high organic matter and nitrogen contents in the surface soils of the Nebraska prairies gradually decreased with depth.

Rost *et al.* (47, 48) studied some other phases of chemical behavior of prairie soils and reported (a) that the soils were acid to slightly acid in the A and B horizons, (b) that the high total exchange

capacity decreased gradually from the surface downward, (c) that magnesium and calcium cations predominated on the exchange complex, and (d) that the exchangeable calcium decreased like the total exchange capacity but the magnesium ion remained more or less stationary.

Bailey (2) studied the hydrogen-ion concentration of Prairie soils in relation to other great soil groups and found that the Prairie soils are slightly more acid than Chernozems but considerably less acid than Gray-brown Podzolic soils and slightly less acid than Non-calcic Brown soils. Caldwell and Rost (8) in a study of some soils of southern Minnesota concluded that (a) a concentration of iron in the B₂ horizon of all the Prairie profiles examined indicated some fractionation of the soil minerals and offered distinct though limited evidence of podzolization, (b) the higher percentage of soluble silica in the clay fraction of the Black Prairies and Gray-brown Podzolic soils was interpreted to mean greater weathering in these soils than in the Chernozems. Their conclusions were that the characteristics of the Prairie soils were similar in some respects to those of both the Chernozems and the Gray-brown Podzolics. However, they were sufficiently distinct to warrant the separation of the Black Prairie soil as a distinct zonal great soil group.

Walker and Brown (57) made a statistical study of the carbon and nitrogen content of some Iowa prairie soils. Their results indicate that the Webster soils were generally higher in carbon and nitrogen than Clarion soils. Toogood (52) studied the surface twelve inches of Clarion and Webster soils from several localities and found Webster soils higher in organic matter, total nitrogen, available P₂O₅, total exchange capacity, pH, moisture equivalent, and lower in phosphate fixing capacity than Clarion soils. The two soils were similar in exchangeable potassium in the surface six inches, but in the second six inches the Webster was slightly higher.