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TREE ROOT-SOIL INTERFACE.

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MICROMORPHOLOGY OF SOIL FABRIC AT
TREE ROOT-SOIL INTERFACE

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

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* * * * *

The Ohio State University

1967

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INTRODUCTION

Root channels and large pores or voids appear to be an important factor affecting the movement of water in soils, especially in forested soils. The interconnected channels formed by earthworms, burrowing animals and tree roots apparently provide effective routes for rapid downward flow of water. This water often appears as free water at some lower depth and changes to a lateral flow due to contact with a much less permeable soil layer (10).

Little information is available on the specific influence that tree roots have on soil porosity and other soil physical properties. Baver (9) writes:

There can be no doubt as to the beneficial effects of roots on soil porosity. The exact magnitude of these influences must await more reliable information.

Although numerous techniques and equipment have been developed in recent years, none seem to be satisfactory for making accurate measurements of soil porosity and pore size distribution of forested soils. These soils present special problems due to presence of numerous roots and channels, and also because often they are incoherent and have stony surface layers. Because of the very important effect of pore space distribution and continuity upon water movement and storage within soils, it is essential to obtain such measurements of these parameters with some degree of accuracy.

The objectives of this investigation were: 1) to observe the influence that tree roots have on some of the physical properties of soil material adjacent to them, 2) to obtain a better understanding of how tree roots influence water movement in forested soils, and 3) describe the organization of the soil at the root-soil interface by descriptions and photomicrographs. To accomplish these objectives it was necessary to develop a technique for collecting undisturbed soil samples with roots in place. By the use of soil thin sections, microscopic evaluation was made of the influence that tree roots have on contiguous soil. Studies were also made to determine the influence of soil type and root diameter on soil fabric as a function of proximity to root-soil interface. Investigations made on forested soils included chemical, physical, mineralogical, macro- and micro-morphological studies.

LITERATURE REVIEW

1. Root-soil relationships

Root channels and roots in forest soils of southeastern Ohio have been investigated by Gaiser (25) who reported on their size, development and distribution. He concluded that root channels contain materials relatively more permeable than the surrounding horizon and provide a pathway for water movement. He cautions against making estimates of physical and hydrologic characteristics of forested soils without giving due consideration to discontinuities in pores and channels caused by decay of tree roots.

Hursh and Hoover (36) mention that decay of roots each year creates relatively large continuous openings that serve as conducting channels for rapid movement of water through forest soil profile. They conclude also that there is little doubt that living and decayed root systems play an important role in development and morphology of soil profiles.

Wilde (103) writes:

The most important living constituent of forest soils is the root system of trees carrying beneficial mycorrhizal fungi which assist the trees in uptake of nutrients.

Voigt (98) studying the distribution of rainfall under forest stands observed that soil in vicinity of the root was wetter than surrounding soil and he surmised that the network of roots play a role in transporting water laterally and vertically. He suggests

that stemflow may be a principal point of entry of water into the soil and water flowing down the stem tended to follow the larger roots into the soil. Reynolds (73) using dyes to evaluate the pattern of rainwater percolation stated that water moved downward and lateral along the surface of large roots and entered the soil from the lower side of the root.

Discussing the effects of soil moisture tension on root growth, Gingrich and Russell (29) point out that as plant roots absorb water, soil moisture tension increases in immediate proximity of the roots giving rise to a moisture gradient toward the root that initiates moisture flow.

MacDougal (58) using a dendrographic level to measure a root of 4 cm thickness observed an increase in diameter beginning April 5, which continued for about a month with a total accretion of 1 mm in thickness. The daily variations show a gradual contraction beginning before midnight and continuing until daylight, then the contraction became more abrupt, and coincided with the contraction of the trunk. Shortly after midday, expansion began and continued until midnight.

Another reason for root volume changes according to Smith (87) is the development of cork cambium in the pericycle within the first 6-7 weeks of seasonal growth, thus causing the cortex to slough off. Sloughing off of cortex may result in decrease of root volume until secondary cortex forms. This phenomena is also suggested by Rogers and Head (74) as producing a volume change in roots.

A study of root-soil boundary using the electron microscope was conducted by Jenny, et al. (40) in order to acquire a better knowledge of the boundary conditions between the root and soil. Barley plants were grown in glass tubes containing bentonite clay and also in permutoxite sand. After a suitable period, all void spaces were perfused with a liquid resin monomer which hardened enough to allow sawing and grinding without disturbing the sample. Thin sections were cut and observed in the electron microscope. It was found that the root is surrounded by mucigel which fills the space between cell wall and mineral soil particles producing an intimate contact between the mucigel and the clay.

Effect of root growth and decay on the permeability of synthetic sandy loam soil was investigated by Barley (4). Corn was grown in Columns packed with non-aggregated sandy loam made from quartz sand and kaolin clay. The effects of root growth on pore-size distribution were studied microscopically on polished sections of "castolite"-impregnated columns. Pore space was calculated from the mass, and measured dimensions of the sandy loam columns. Polished sections were observed with 60 X magnification for measurement of pore intercepts on 0.9 mm transects adjacent to root channels and on transects more than 5 mm from the nearest root. These transects revealed that soil adjacent to root channels of 1 mm diameter was more compact than the soil several millimeters away. It was postulated that the volume increase of roots failed to cause a corresponding increase in volume of soil column, the large and consistent decrease noted in the permeability of columns

planted to corn could be attributed to a reduction of root-free pore space. Increase in permeability during root decay was considered to be due to freeing of the root channels for water movement. Dissection of columns infiltrated with Ponceau red solution showed no regular difference between flow velocity at root-soil boundaries and at points within soil. This suggests that roots were in close contact with their channel walls. Roots of 1 mm diameter usually formed straight channels, while finer roots of 0.1 mm diameter, also displaced soil grains but underwent some deflection, forming gently curved channels.

Growth or decay of grass roots according to Sedgely and Barley (5) had no effect on the apparent density of the soil cores. Their measurements of pore intercepts on line transects showed that the soil immediately adjacent to root channels was more compact than the soil 1.5 mm from any channel. Adjacent to roots there was a highly significant reduction in the number of pores per transect having a diameter less than but close to 100 μ and hence there were fewer pores within the diameter range likely to be most important in water conductivity at the low tensions used. They concluded that pore-size distribution changed but not total porosity. They suggest that at moderate porosities root expansion will be accommodated internally by local rearrangement of soil particles. Definite increases in porosity under grass in field experiments may be due to macro-organisms, which are usually more abundant in undisturbed grassland soils.

Part of decrease in conductivity caused by expansion of larger roots is attributed to production of hydrophobic substances by

rhizosphere organisms. The presence of any substance which increases the contact angle at liquid-air-soil interface reduces the radius of the widest pores and decreases water movement. In this study the decay of roots did not contribute to an increase in conductivity since vertical root channels left empty by decay were too wide to contain water at 30 cm tension.

Since most of the water movement following rain or irrigation occurs at low mean-moisture tensions, it is of more general interest to know the effect of root growth and decay on conductivity at low tensions. Barley and Sedgley (5) suggest that dead roots present in a soil may themselves conduct water if they persist after the tops of the plants have been removed. Little quantitative information is available about the effects of root growth and decay on pore-size distribution and other physical properties of the soil. More research emphasis has been on effects of root growth and decay on level of aggregation and aggregate stability.

Gill and Bolt (28) reviewed the classical studies of Pfeffer on root growth pressures expected by plants. Pfeffer's technique made it possible to observe root growth with various degrees of mechanical restraint. Gill and Miller (27) developed a method for study of the influence of mechanical restraint and aeration on growth of seedling roots. Microscopic examination of roots grown under mechanical restraint revealed distortion from their normal shape. They concluded that a root seedling imbedded in a finely granular material, such as

soil, must displace the solid framework of the soil before root expansion can occur and thus, there must be an increase in apparent volume of soil mass. One evidence for this is the lifting of sidewalks by growth of tree roots.

Wiersum (102), investigating the relationship of size and structure rigidity of pores to size penetration of roots, demonstrated that roots in a rigid system only penetrated a pore with diameter exceeding root diameter. Plasticity of young roots prevents their movement through short constricted zones or openings. Growing roots under field soil conditions would push particles aside to enlarge the pore opening.

Aubertin and Kardos (3) studied the effect of pore size and rigidity on root growth using a porous media. Maize roots did not grow through rigid porous systems having "pore neck" diameters smaller than 138μ , and reduced growth was observed with minimum size pores of 412μ . In non-rigid systems, roots grew equally well regardless of "pore neck" diameter. Phillips and Kirkham (70) pointed out that total quantity of primary and secondary roots decreased with increased pore rigidity.

McCaleb (57) described large root channels formed due to root decomposition in lower B horizons. These channels are filled with mixtures of materials which are largely composed of illuvial clay. Old root channels have linings of oriented clay originating in overlying horizons.

Soileau, et al. (33) prepared synthetic illite aggregates with synthetic iron-kaolinite coats. Microscopic observations indicated the

presence of partially orientated crystalline iron-kaolinite cutans around aggregates. Photomicrographs of wheat-root-aggregate associations, revealed intimate surface contact between the two with some penetration and disruption by the roots.

Buol and Hole (17) reported some characteristics of clay skins on peds of B horizon of a Gray-Brown podzolic soil. They observed that root channels in the B3 horizon were lined with clay-skin-like material.

Thorp, et al. (94) investigating genesis of Miami silt loam reported the presence of brown clay skins covering the surface of root holes in B22 horizon. Petrographic examination indicated preferred orientation of clay with c-axis of clay perpendicular to surface covered.

In order to facilitate the study and observation of root growth several techniques have been developed. Muzik and Whiteworth (64) describe the use of glass faced boxes to allow periodic observation of growing roots. Rogers and Head (81) describe their large and elaborate underground root observation laboratory allowing direct photographic observations of root growth. Fritts and Holowaychuk (24) reported root densities by horizons for three soils in Ohio. It was found that a much greater concentration of roots occurred in the A1 horizons associated with higher porosities and greater aeration.

Schuurman and Goedewaage (83) summarized methods used for the examination of root systems and roots. Under field experiments they describe the monolith investigation or pinboard method, auger method, and Weaver's method which consists of mapping a soil profile wall. They

also outline methods of examination of roots employing the use of containers in which plants are grown.

2. Soil-water relationships

Baver (8) pointed out that permeability of a soil profile for water is one of the most important factors to be considered in soil-water relationships. Nelson and Baver (65) state that a soil is a complex porous system which is made up of various sizes of pores and that wide variations exist between soils as to distribution and size of pores which in the surface layer may vary from one season to another. The disposition of infiltrated water is determined by the nature of the pore space. The water may be retained by smaller pores to be used in part by plants while some may pass through the soil. They found a close relationship between continuity of pore space and soil permeability.

An excellent review is presented by Russell (78) on soil porosity, size distribution and methods of evaluation. He discusses the use of apparent density plus moisture retention data to calculate total porosity. He also describes techniques for measurement of air filled voids by air pycnometers, such as those described by Kummer and Cooper (48) and Page (68).

Russell (78) discusses some of the limitations of suction method for interpretation of pore sizes. These data in height-of-capillary rise equation apply only to those pores in which an air-water interface

exists. Since the soil voids constitute a 3-dimensional network of cell-like cavities interconnected through narrow necks, water in a given pore will not be drained until applied tension exceeds that required to cause air-water interface to move through the largest necks connecting the large pore with the atmosphere. Starting with a saturated soil one will usually get isolated pores or "blocked pore effect," and therefore results in a shifting of effective pore size distribution toward a smaller size range. Because of this effect the suction method tends to underestimate volume percentage of larger size pores.

Bradfield and Jamieson (12) in evaluating the influence of roots on granulation indicated that colloidal materials have a strong effect on the stability of soil structure. The relationship between granule size and porosity can be variable. They point out that two soils having granules of similar size may differ in porosity because of packing effect. An orderly stacking of granules could produce a dense fabric like a brick wall, while random stacking may result in a more porous medium. Also soils having the same total pore space may vary widely in physical condition due to different pore size distribution. A relatively small amount of large pores will contribute a great deal to permeability of soil. This agrees with Hursh (35) who emphasizes the fact that one earthworm burrow through a block of heavy soil might contribute more to drainage than would the entire cross sectional area of pore space.

Studies of Yamamoto (106) indicate that forest soils have higher total pore space, field capacity, available water holding capacity and

greater volume of large size pores than adjacent cultivated or pastured soils. Investigations by Byrne and Kardos (19) support this conclusion and their data show that hardwood stands have a greater influence on these physical properties than pine stands. Influence of vegetative cover decreases with depth.

According to Lutz and Chandler (56) the usually high porosity of forest soils is in part due to their content of organic matter, galleries formed by soil animals and canals left after decay of roots. Old root canals extending into B and C horizons of heavy-textured soils provide an avenue for deeper penetration of new roots.

Total porosity has been divided into two divisions, capillary and non-capillary. These divisions are somewhat arbitrary according to Quirk and Panabokke (71) who suggest that pore size distribution be considered as a continuous function. Phenomena such as aeration and infiltration are closely associated with large pores in a soil.

Numerous methods have been employed to characterize the porosity and pore size distribution of soils. Methods involving tension have been employed by numerous workers (12,53,60,65,79) in order to relate porosity and pore size distribution to soil structure and permeability. The above methods use water as a wetting fluid thus there is the probability that clay-water interaction may modify the geometry of the pore space. Quirk and Panabokke (71) used non-polar liquids with the suction principle to obtain pore size distribution.

Air filled pore space in samples of any water content can be determined with air-space pycnometers (48,68,77,95,97) using Boyles' law

$P_1V_1 = P_2V_2$, with P and V the gas pressure and volume, respectively. This technique again may not measure the volume of entrapped and isolated air bodies surrounded by water and soil particles.

Microscopic evaluation of porosity and pore size distribution is another approach to characterizing the amount and geometry of soil pores (32, 72, 85, 93, 99). Swanson and Peterson (93) made a study of pore space patterns using soil thin sections. They measured volume-percentage pore space using a line intercept method to obtain the relative proportion of pore space to solid phase. They concluded that difference in pore spaces can be ascertained by measuring 50 to 100 microscopic fields. One of the advantages is that thin sections from oriented undisturbed samples show the natural soil structure and pore space patterns. On the other hand, microscopic methods of evaluating pore spaces have the disadvantages of not measuring very small capillary pores, and require large numbers of traverses and several slides to obtain a representative measurement of the soil.

Jamieson (39) attempted to relate percentage moisture by volume and pF relationship to pore size distribution. He postulated that two different types of processes cause shifts in the distribution of pore sizes in soils. One is related to the formation or the destruction of natural stable aggregates and the other to factors that effect changes in state of packing which is a dynamic process.

Harper (31) suggests a pore-space-clay ratio as an index of the physical character of the soil. Total pore space is less important than non-capillary pore space and/or stability of structure in

determining percolation. He concluded that fine-textured soils with low pore space-clay ratio have little non-capillary pore space and are less productive. He generalized that productive soils should have a pore space-clay ratio >1.5 . Ratios less than 1.0 are unfavorable for moisture absorption.

3. Micromorphology

The use of thin section microscopy by pedologists is a relatively new field. Kubiena's (47) classical writings on use of microscope to obtain information on soil morphology and soil dynamics led the way toward development of this area of soil science. Although not the first to prepare soil thin sections his book (47) brought to the attention of researchers in this country the usefulness and applications of this technique to micropedology. Thin sections can be used to observe soil constituents in their natural, undisturbed arrangement.

Brewer (14) (in Fabric and Mineral Analysis of Soils) presents in his book a comprehensive review and discussion on methods and application of micro-techniques. Most specimens of soils are too friable to be sectioned or polished without impregnation with some binding material. Impregnation procedure should be such as not to change the arrangement of soil fabric. When set the material should be hard and brittle, colorless, isotropic and have refractive index close to that of Canada balsam. The most commonly used impregnating media are polyester resins diluted with monomeric styrene (86, 63, 16, 21, 43, 45, 11). They harden after

addition of an organic oxidant catalyst. Cady (20) emphasizes that in order to use these materials the soil sample must be dry. For soils that change their structure radically upon drying, water-soluble materials, such as Cymel and Carbowax, have several advantages (49, 51, 59).

Kubiena (47) and Frei and Cline (23) have employed natural resins to impregnate samples. Selection of a lubricant and coolant for grinding present problems since water may cause dispersion and liquids, such as kerosene may dissolve the resin.

The use of soil thin sections for the study of soil microorganisms (1, 18, 42, 66) is a useful tool for soil microbiologists and provides further information on the dynamic aspect of soil.

Lund and Beals (55) used a short dehydration series combined with plastic embedding technique to study cotton roots in place. Thin sections did not show particle orientation at root-soil interface but did show some packing effect. Colored plastic was used to make pore identification easier.

Cady (20), discussing the applications of micromorphological observations, points out the strong emphasis and interest in arrangement of clay as an indication of genetic processes that have operated and the relation of clay to soil structure. Identification of clay films as to whether they are pressure oriented or translocated is very helpful to soil scientists in interpreting the genetic process involved. Observations and quantitative studies can be made on size, shape, spacing

and location of pores. The shape, arrangement and surface of grains give some indication of density and degree of weathering of a soil.

In conclusion Cady (20) writes:

The view of the soil in a thin section through a microscope approaches the view seen by the plant root and permits close, direct investigation of the physical and mineralogical environment of roots.

METHODS AND MATERIALS

Site selection and description of study area:

The soil profiles investigated in this study were sampled from two physiographic areas of Ohio. One soil profile was taken from a forested area located near Dover Dam in Tuscarawas County, Ohio. This site is an experimental area of the USDA Forest Service, Northeastern Forest Experiment Station for special hydrological studies. Physiographically it is within the Allegheny Plateau (50). The soil studied at this site (TU-6) is a Typic Hapludult in the coarse loamy, mixed, mesic family (90) and in this discussion is referred to as Clymer loam. Data obtained for this profile should complement other studies being conducted at the site and can probably be extrapolated to numerous other forested sites within Allegheny-Cumberland Plateau.

The second soil was taken from a forested area located in the northwest part of The Ohio State University farm. The soil at this site is a Miami silt loam, and it is classified as a Typic Hapludalf, fine, mixed mesic family. The latter site was selected for two primary reasons: 1) to make a comparison of influence that tree roots exert on soil fabric in a fine-textured soil as compared to one that is coarse loamy, and 2) to provide an easily accessible site for testing materials and methods to be used in the studies.

Hydrologic experimental area site: This site is approximately 110 miles northeast of Columbus, Ohio, and lies within the Allegheny Plateau. It is a highly dissected area with considerable relief. The main ridges tend to parallel the major streams and narrow spur ridges project out from these main ridges as interfluves between tributary stream branches.

The bedrock formation of the area is part of the Allegheny division of Pennsylvanian geologic age. Formations at sample site consist of interbedded sandstones, siltstones, clay shale with occasional thin coal measures (50). Most of the surficial materials in which the soils have developed, however, consist of mixed colluvium derived from substrate bedrock of the ridges.

Native vegetation of the area was mixed hardwoods. Present vegetation at the study site consists of oak, hickory and beech with white oak as the dominant species.

The climate of the area is humid and temperate (57) with moderately cold winters and warm humid summers. The average frost-free season is about 151 days. The mean annual precipitation is approximately 39 inches with about 55% occurring during the growing season.

The soil profile selected from this area is only one of a number examined in two trenches excavated up and down the upper three-fourths of a south facing slope. The upper slope had a gradient of 28% and decreased to 23% at mid-slope producing a slightly concave profile.

Five soils were described and sampled along the two trenches. Near the crest of the ridge a coarse-textured DeKalb sandy loam (TU-5) profile was observed. The soil profiles at mid-slope and lower one-third of the slope were classified as Clymer loam (TU-6), (TU-7), (TU-8). The soil at one other site (TU-9) has a fragipan and was classified as a variant of the DeKalb series. Profile (TU-6) was selected to represent this study area because of the relatively large extent of similar soils within the hydrologic experimental area.

Clymer loam Profile (TU-6)

The site where this profile was sampled occurs at lower edge of the upper third of a south-facing slope. The slope has a gradient of 23% at the site. Present vegetation is primarily white oak and beech.

The profile was moist at the time of description and sampling and colors were read for moist conditions. The profile was described using criteria as defined by Soil Survey Manual (79) and 7th Approximation (90). It is coarse loamy in the control section instead of fine loamy and hence is actually a taxadjunct of the Clymer series.

- 01 2 to 0 inches, leaf litter and twigs from oak, beech and hickory.
- A1 0 to 2 inches, black (10YR 2/1) loam; moderate, medium crumb structure; friable; roots abundant; 15 to 20 percent coarse skeleton of sandstone fragments; lower boundary clear, wavy.
- A2 2 to 7 inches, yellowish brown (10YR 5/6) loam with grayish brown (10YR 5/2) ped surfaces; weak, fine and medium sub-angular blocky structure; friable; roots abundant; 15 to 20 percent coarse skeleton of sandstone fragments; lower boundary clear, wavy.

- A3** 7 to 12 inches, yellowish brown (10YR 5/4 5/6) loam containing considerable silt; weak, fine and medium sub-angular blocky structure; friable; 15 to 20 percent coarse skeleton of sandstone fragments; lower boundary clear, smooth.
- Bl_t** 12 to 17 inches, yellowish brown (10YR 5/6) loam with yellowish brown (10YR 5/4) ped surfaces; weak to moderate, fine and medium subangular blocky structure; friable; roots plentiful; very patchy thin clay films; lower boundary clear, wavy.
- B21_t** 17 to 22 inches, yellowish brown (10YR 5/6) loam with yellowish brown (10YR 5/4) on about 40 percent of the ped surfaces; weak to moderate, medium subangular blocky structure; moderately firm, slightly sticky and slightly plastic; roots plentiful but decreasing in size with depth; thin patchy clay films; about 40 percent coarse skeleton of pebble to large channer size sandstone fragments, fragments horizontally oriented; lower boundary clear, wavy.
- IIB22_t** 22 to 28 inches, strong brown (7.5 YR 5/6) heavy sandy loam, moderate to weak, medium subangular blocky structure; friable; few fine roots; thin patchy, brown (7.5YR 4/4 5/4) clay films; about 25 percent coarse skeleton of sandstone fragments; lower boundary abrupt, smooth.
- IIB3** 28 to 38 inches, brownish yellow (10YR 6/6) sand crudely banded with brown (7.5YR 4/4 5/4) loamy coarse sand; bands are up to about 2 inches thick and are diffuse and irregular but somewhat horizontally oriented; few to common black Fe-Mn stains in banded material; single grain in sand and moderate coarse subangular blocky structure in loamy coarse sand; clay film bridging in banded material; few roots; lower boundary gradual, wavy.
- IIC1** 38 to 48 inches, yellowish brown (10YR 5/6) sand with banded mottling of brown (7.5 YR 5/4) and brownish yellow (10YR 6/6); massive or single grained with weak coarse subangular blocky structure in banded material; very few roots; sparse patches of clay film bridging; lower boundary abrupt, smooth.
- IIC2** 48 to 50 inches, yellowish brown (10YR 5/6) to brownish yellow (10YR 6/6) and strong brown (7.5YR 5/6) loam with many (20%) yellowish red and common (10%) light olive gray (5Y 6/2) mottles; weak, medium angular blocky structure; thin patchy clay films on surfaces of partings in upper inch; lower boundary clear smooth.

IIIC3 50 to 56 inches+, altered clayey shale. Light olive gray (5Y 6/2) with distinct few strong brown (7.5Y 5/6) and common light olive brown (2.5Y 5/4) mottles; massive; firm in place but can be dug easily with a spade.

Ohio State University Site: The site is located on the Ohio State University campus farm west of Olentangy River. The area is gently to moderately sloping and lies within a broad high lime till plain of Wisconsin Age (30). Near the site the drainage ways trend eastward to empty into the Olentangy River. There is some shallow dissection of the till plain along these drainages.

The till in the area is strongly calcareous, medium textured and compact. It is about 60 feet thick and is underlain by rocks of Devonian age (92).

The climate of the area is humid and temperate with warm summers and moderately cold winters (57). Average mean annual precipitation is 37.14 inches as recorded at O.S.U. weather station from 1921-1946. The average mean annual temperature for the same period was 53.2° F. A relatively long growing season of approximately 185 days can be expected with the average date of last spring killing frost occurring about May 8.

Miami silt loam Profile (FR-7)

This profile was sampled at a site near crest of a gentle sloping knoll with a 2% gradient sloping to the north. Present vegetation is maple, ash, and beech trees.

At the time of sampling the profile was moist in the solum but was wet in the upper C horizon. Samples of the latter were collected at a later date when the water table had subsided. The calcareous C horizon contains numerous cobbles and stones, dominantly limestone and dolomite.

- 01 $\frac{1}{2}$ to 0 inch, litter of leaves and twigs from mixed hardwoods.
- A1 0 to 3 inches, very dark gray (10YR 3/1) silt loam; moderate, medium and fine granular structure; friable when moist, non-sticky and non-plastic when wet; roots abundant; lower boundary abrupt and smooth.
- A2 3 to 8 inches, brown (10YR 4/3) silt loam; weak, fine and medium subangular blocky structure; friable when moist, non-sticky and non-plastic when wet; roots abundant; lower boundary gradual.
- A3 8 to 11 inches, yellowish brown (10YR 5/4) to brown (10YR 4/3) silt loam; weak, medium subangular blocky structure; friable to slightly firm when moist, non-sticky and non-plastic when wet; roots abundant; lower boundary gradual.
- B1 11 to 15 inches, yellowish brown (10YR 5/4) clay loam with dark yellowish brown (10YR 4/4) ped surfaces; moderate, medium subangular blocky structure firm when moist, sticky when wet; roots plentiful but decreasing in volume; lower boundary clear smooth.
- B21t 15 to 19 inches, dark yellowish brown (10YR 4/4) clay with yellowish brown (10YR 5/4) ped surfaces, moderate, medium and coarse subangular blocky structure; firm when moist, sticky and plastic when wet; few small roots; thin, patchy clay films; lower boundary gradual wavy.
- B22t 19 to 26 inches, dark yellowish brown (10YR 4/4) clay loam with brown (10YR 4/3) ped surfaces; moderate to strong, medium subangular blocky structure; very firm when moist and hard when dry, very sticky and plastic when wet; few small roots; continuous moderately thick clay films; coarse fragments about 5 percent by volume; lower boundary clear smooth.
- C1 26 to 30 inches, light olive brown (2.5Y 5/4) and dark yellowish brown (10YR 5/4) fine loam; weak, coarse subangular blocky structure; firm when moist and sticky when

- C1 wet; slight increase in roots; gravel to cobble size
 contd. coarse fragments about 30 percent by volume; lower
 boundary abrupt and irregular; calcareous.
- C2 30 to 48 inches, mottled pale olive (5Y 6/3), brown (10YR
 4/3) and yellowish brown (10YR 5/6) loam till; firm in
 place, sticky when wet; pebble and cobbles are numerous;
 calcareous.
- C3 48 to 66 inches, yellowish brown (10YR 5/4) loam till with
 olive gray (5Y5/2) mottling; firm and compact in place;
 dolomite and limestone cobbles, 20 percent by volume;
 calcareous. Sampled 60-65 inches.

Sampling techniques:

1. Bulk samples. The profiles were sampled by horizon for routine analysis. The Clymer soil was sampled from a 24-inch trench excavated to a depth of 5 feet. A pit was excavated approximately 3 feet wide and 48 inches deep to sample the Miami profile. An "orchard" auger was used to obtain bulk samples from the C3 horizon. One gallon of soil was collected from each horizon. Samples were allowed to air dry and then were sieved and the fine earth fraction, ($< 2\text{mm}$), was stored in quart size cartons.
2. Undisturbed samples: Natural clods, ranging in size from 100 to 200 cc were collected for bulk density and thin section analysis. These clods were obtained from horizons below the A2 by gently prying them from the pit face with a pen-knife. Triplicate clods were collected from respective horizons for bulk density determinations and were suspended from a thin wire and immersed in a saran mixture. Saran coated clods were allowed to dry, then labeled, wrapped in

aluminum foil for protection, and placed in pint cartons for transportation to the laboratory.

Two clods were taken for thin section analysis from each horizon below the A2, maintaining the orientation at all times. After wrapping the oriented clods with saran wrap a vertical arrow mark was made on the saran wrap to designate the orientations. The clods were then wrapped in aluminum foil and placed in pint cartons to avoid disturbance during handling and transportation.

Natural clods could not be obtained by the above method from the more fragile A1 and A2 horizons because of numerous roots. These horizons were sampled for bulk density and thin section analysis by freezing in situ.

A freezing technique was developed for obtaining relatively undisturbed soil samples. The following procedures were used to freeze soil blocks in situ:

After carefully removing the surficial horizon consisting of undecomposed loose leaves and organic debris, small holes were made in the soil block by removing cores with a No. 8 cork borer. The resulting holes were spaced approximately 10-15 cm apart, depending on the soil texture and moisture content and extended to a depth of 8-10 cm. Small quantities (approximately 75-100 ml) of liquid nitrogen were applied to each hole from a Dewar container by means of a funnel to direct the flow. Subsequent applications were repeated for each hole three to five times at about two-minute intervals. Freezing proceeded

radially from the bottom of the holes, thus allowing the lower area of the block to freeze faster. Liquid nitrogen was then applied to the surface of the soil block. To facilitate this an insulated retainer was used to reduce spattering and to concentrate the liquid nitrogen to the area being sampled. In this case the retainer was made by cutting away the bottom and top of a (10x16x24 cm) metal can and insulating the sides with styrofoam (4 cm thick). The sharp edge of the can was gently pressed downward into the soil surface to surround the block to be sampled and thus enclose the surface area containing the holes previously treated with liquid nitrogen. Liquid nitrogen was then applied until frosting appeared on the soil surface, indicating the block was adequately frozen and rigid enough to be excavated without deformation or breaking.

The frozen block was isolated from the surrounding soil by use of spade and/or other hand tools, 3-5 minutes after the last application of nitrogen, and then removed. Special care was given to roots and stones lying in part within the frozen block and in the adjacent soil. All roots were carefully cut with pruning shears close to the relatively abrupt frozen-unfrozen interface. This method was found to be the most efficient for cutting the roots without disturbing the frozen sample. Stones frozen into the soil block were left in place whenever possible.

Once the soil block had been removed from the soil profile, it was placed on a sheet of polyethylene film and trimmed to the desired size and shape by removing the unfrozen or partially frozen adhering

soil. Additional liquid nitrogen was applied to the surface of any area that was not completely and thoroughly frozen. The sample was wrapped for protection and placed in an insulated container for transportation to the laboratory. At the laboratory the wrapped samples were stored in a freezer prior to initiation of measurements or other investigations. After cutting the desired number of small blocks, the remainder of the initial block was returned to the freezer for further storage in case subsequent studies were to be made. A more comprehensive discussion of this and other techniques are included in the text on page 39.

Physical measurements:

1. Mechanical analysis: Mechanical analysis was determined by a modified sedimentation-pipette method of Steele and Bradfield (91) using sodium hexametaphosphate as the dispersing agent. Particle size classes and textural classes are according to U.S. Dept. of Agr. Classification System (89). Silt and clay were subdivided into fine and coarse subfractions. Coarse skeletal material was determined by weighing the entire sample, and then weighing again after the >2 mm material was removed by rolling and sieving.
2. Bulk density: The method used for bulk density measurements involved measuring the weight and volume of a natural soil clod coated with Dow Saran Resin F-120. The method used is a modification of a technique used by Brasher, et al. (13). The saran solution was prepared by adding one part Dow Saran Resin F-120 to six

parts methyl ethyl ketone. Clods which were coherent enough to allow sampling without use of freezing in situ were coated with one coat in the field and allowed to air dry in the laboratory. The less coherent, A1 and A2 horizons that contained numerous roots were frozen in the field with use of liquid nitrogen. These larger blocks were brought to the laboratory and maintained in frozen state until they were cut into suitable size blocks and coated with saran. The frozen coated clods were then allowed to air dry to constant weight. After reaching air dryness, the clods were weighed, then dipped into saran solution five additional times at 20-minute intervals to waterproof the clods. After the saran was dried, the clods were weighed in air and in water.

The weight and volume measurements of the clod were corrected for weight and volume of saran applied. Since density of the saran (1.3 g/cc) and the number of coats are known, the volume of saran can be calculated.

Bulk density determinations were obtained for air dry and 1/3 atmosphere moisture content. To accomplish this the saran on one end of the clod or block was sawed off in order to expose a portion of the soil. The exposed area was seated on a water tension table to wet up at 0 cm tension. Moisture retention at sixty centimeter tension was measured and the clods allowed to wet up again. Clods after reaching equilibrium, usually in 3-4 days, were seated in a pressure cooker at 5 pounds pressure (1/3 atmosphere) for desorption over a period of two days allowing the clods to attain

equilibrium at this pressure. Upon removal from pressure cooker, they were immediately weighed in air, again dipped in saran until waterproofed, and then weighed in air and in water as soon as the saran coatings had dried. Both calculated bulk densities (air dry and 1/3 atmosphere) were corrected for coarse skeleton greater than 5 percent.

3. Moisture retention: Saran coated natural clods were saturated and moisture retention was measured after equilibrating on a tension table at 60 cm tension. The clods were again saturated and seated in a pressure cooker with ceramic porous plates to determine 1/3 atmosphere moisture content.
4. Particle density: A direct method described by Blake (10) was used to determine particle density of samples from each horizon. Following completion of measurements of natural clods for bulk density and moisture retention the saran was cut or peeled away and the clod crushed to pass through a 2 mm sieve. Roots sieved out were ground with a Wiley mill and mixed with the mineral soil.

A pycnometer (specific gravity flask) was used to determine particle density as outlined by Blake (10). Entrapped air was removed by use of an aspirator attached to a vacuum dessicator.

5. Total porosity: Total porosity of the soil was calculated by use of the following formula for estimation of percent pore space:

$$\% \text{ pore space} = 100 - \frac{\text{bulk density (air dry)}}{\text{particle density}} \times 100.$$

6. Non-capillary porosity: Non-capillary porosity was determined by subtracting the volume percentage moisture content at 60 cm tension from total porosity value calculated.
7. Maximum potential extensibility: An estimate of the maximum soil extensibility was calculated from natural clod bulk density measurements (61). The change in thickness of fabric volume per unit of thickness was obtained by subtracting from unity the cube root of bulk density measured at 1/3 atmosphere moisture divided by bulk density measured on air dry clod.

$$\text{MPE} = 1 - \sqrt[3]{\frac{D_b \text{ moist}}{D_b \text{ dry}}}$$

The change in thickness per unit thickness of dry soil is referred to as the coefficient of maximum potential movement or extensibility. The formula above is a close approximation to coefficient of linear extensibility described by Soil Survey Staff (90).

Chemical Methods:

1. pH determinations: A 10-gram soil sample was mixed with 10 ml of distilled water and the pH was read with a Beckman model G pH meter.
2. Exchangeable hydrogen: The method of Peech, et al. (69) was used to determine exchangeable hydrogen. A 10-gram soil sample was leached with barium chloride-triethanolamine solution buffered at pH 8.2.

The soil was then leached with a 0.5N BaCl_2 solution and the leachate was titrated with standard HCl using bromcresol green and methyl red as indicators and titrating to a violet end point.

3. Exchangeable calcium and magnesium: Exchangeable calcium and magnesium were extracted by neutral 1N NH_4OAc solution and determined by the EDTA method of Barrows and Simpson (6) with the calcium and magnesium being run separately.
4. Exchangeable potassium: An aliquot of the NH_4OAc used for extracting calcium and magnesium was analyzed for potassium using Coleman Jr. Spectrophotometer at a wavelength of 770 m μ .
5. Organic carbon determination: Organic carbon was determined by a dry combustion method. A one-gram soil sample and approximately 0.25 gram of MnO_2 were placed in an alundum ignition boat and heated to between 900° C and 950° C for 10 minutes with O_2 passing through the chamber. Carbon was collected as CO_2 and weighed in an ascarite filled absorption bulb according to Salter (81) as later modified by Winters and Smith (109).
6. Calcium carbonate equivalent and calcium and dolomite ratio: Determinations were made by a method developed by Dreimanis (22) employing the Chittick Apparatus. The separation of calcite and dolomite is dependent upon the reaction rate with HCl. A 20-ml aliquot of 6N HCl was added to a flask containing 1-3 grams of soil. The volume of CO_2 evolved after 30 seconds was measured and recorded.

A second measurement of CO₂ evolved was made after all CO₂ reaction ceased, usually 30-45 minutes. The percent calcite was calculated from CO₂ evolved in the first 30 seconds and percent dolomite from the quantity of CO₂ evolved after the 30-second measurement. Calcium carbonate equivalent was calculated from the summation of calcite and dolomite values.

7. Free iron oxide determination: Free iron oxide was determined by a method described by Kilmer (46). The iron was reduced by shaking samples overnight with sodium dithionite. Ten drops of barium diphenylamine sulfonate was used as an indicator and the solution was titrated with potassium dichromate to a violet blue end point.

Clay mineralogy - X-ray techniques

1. Separation of the clay fraction: The clay fraction was separated from the bulk samples utilizing the automated fractionator developed by Rutledge, et al. (80) after dispersion with sodium carbonate as discussed by Jackson (37). The Al horizons were also pretreated to remove organic matter. Organic matter removal was accomplished by digestion with hydrogen peroxide on a hotplate. After fractionation the clays were flocculated with an excess of NaCl and stored in a 30% methanol solution.
2. Sample preparation: Approximately 50 ml of the clay-methanol suspension was placed in 100-ml centrifuge tube. The clay was saturated with Mg by washing it three times with 1N MgCl₂. Excess salts

were removed by washing with water and water-methanol mixtures until decantate yields a negative chloride test. Three oriented specimens of each clay suspension were prepared by plating out a thin layer of clay on a porous ceramic plate using a water aspirator to apply a vacuum to the ceramic plate. After plating, approximately 5 ml of 10% ethylene glycol solution was added to the surface of clay being prepared for glycolation treatment. The glycolated sample was then placed in a dessicator in the presence of free ethylene glycol for 24 hours prior to disposing of excess glycol in an oven at 40°C for 24 hours before irradiation. The other two specimens were allowed to air dry for 36 hours. After air drying, one of the specimens was irradiated, heated to 400° C for two hours and then irradiated again after cooling to 100-200° C. The other air dry specimen was heated to 550° C and irradiated upon cooling.

3. X-ray equipment and operating conditions: X-ray diffractograms were obtained with a proportional counter using a Norelco electronic circuit panel model 12206 and a Bristol Dynamaster Dual-Range strip-chart recorder. Each specimen was X-rayed from 2° two theta to 40° two theta. The following machine conditions and settings were used:

Radiation: Iron K Alpha

Filter: Manganese

Potential: 40 kv

Current: 8 ma

Goniometer scan speed: 2 degrees 2 theta per minute

Strip-chart drive speed: 30 inches per hour
Signal input selector: gas flow
Function selector: continuous counting
Plot: linear
Receiving slit width: .006 inches
Divergence slit: 1 degree
Pulse height analyzer: baseline 11 volts, window 5.5 volts
Proportional counter: 1700 volts
Time constant: 1 second
Counting rate: 200 counts per second

Micromorphology - Thin Section Techniques

1. Impregnation of samples: A modification of a procedure reported by Smeck (36) was used for impregnation. Pretreatment was necessary for samples collected by freezing with liquid nitrogen in situ before they were impregnated. To obtain proper impregnation and curing of castolite-styrene mixture the samples must be dry. Samples were sawed from larger frozen blocks using a diamond saw in a cold-room (-10° C) to maintain the system at a low temperature. The cut samples were then placed in tapered drinking glasses, maintaining orientation at all times and not allowing sample to thaw at any time. The frozen samples were lyophilized for 48 hours in a Virtis-freeze dryer at a vacuum of approximately 150 microns. A check sample following lyophilization was heat treated at 105° C for 12 hours and weighings before and after heat treatment indicated no further loss of water.

The samples were impregnated with a mixture of 40% castolite and 60% styrene solution by placing them in a dessicator evacuated to 5-6 mm of mercury. In order to facilitate hardening of the plastic, 8-10 drops of methyl ethyl ketone peroxide were added per 100 ml of solution. The samples were allowed to remain under a vacuum for one hour, removed and allowed to gel at room temperature. After samples had gelled at room temperature (usually 5-6 days) they were placed in an oven at 50° C and allowed to cure for 2-3 days or until completely hardened.

2. Preparation of thin sections: The technique employed by Miller (63) and Smeck (53) was used to cut, mount, and grind thin sections except for certain modifications of the mounting process. Prior to bonding the section to a glass slide, it was cleaned with kerosene, and placed in a vacuum oven for 4-6 hours at 40° C to dry the surface. The polished, and dried, surface of the section was bonded to a glass slide using an epoxy resin of comparable optical properties as Lakeside 70 cement. The resin offers advantages over the latter, in not requiring heat treatment for mounting and in its very high bonding strength.

One vertical and one horizontal slide was prepared from all horizons and numerous additional slides were cut from A2 and B22t horizons of both soils. The location of roots in the impregnated block dictated the selection of areas from which thin sections were cut. Appropriate orientation of the specimen on the slide was maintained throughout slide preparation.

Thin sections were ground to a thickness of approximately 30 μ using optical properties of quartz grains as a measure of section thickness. After grinding and polishing, the surface was cleaned and a cover glass was cemented to section with Canada balsam mixed with xylene.

3. Thin section analysis techniques: Thin sections were analyzed with a petrographic microscope equipped with polaroid and 35 mm camera attachments. The fabric of each horizon was described using terminology proposed by Brewer (14) and Kubiena (47). Quantitative observations were made using a calibrated mechanical stage and a calibrated micrometer scale in one of the oculars.

Packing density index:- Determinations were made in soil material immediately adjacent to the tree roots. Methods used for packing density measurements are similar to those developed by Kahn (44) and modified by McCracken and Weed (62). In the investigations reported, packing density is expressed as relative length of traverses of thin sections occupied by grains ($>20 \mu$), voids, oriented clay and s-matrix (14) and is reported as a percentage of the total intercept distance observed. At least 10 traverses were made for each root-soil boundary observed. The percent of each component was recorded at different distance intervals of the traverse away from soil-root interface. Packing index measurements of B22t horizon of both soils included observations of 6 roots in the 4mm and 6 roots in the 6-7mm diameter size range. A total of 24 root-soil boundaries were measured for packing index in the B22t horizons and 8 for A2

horizons for each soil. Oriented clay was identified by birefringence, extinction and its occurrence as separate bodies with distinct boundaries.

Grain orientations: Measurements were made to determine the percent of elongate mineral grains with a minimal length of ($>30\ \mu$) and oriented (within 30°) parallel to root surface. Measurements were made along concentric lines that circumscribed the root. In each measurement interval, all grains were classified either as oriented or non-oriented with reference to the root-soil interface. These measurements were made at intervals of 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1.0, and 2.0 mm away from the root-soil interface. Preliminary studies indicated no root influence on orientation of grains at distances beyond 2 mm from the root for the root sizes studied. Also problems were encountered in measuring beyond 2 mm range because root-soil interface reference could not be maintained in the same microscopic field beyond this distance.

Microscopic pore space measurements: Volume-percentage of pores ($>50\mu$) were measured using a microscopic linear intercept technique developed by Rosiwal (75). The sum of the pore intercepts were divided by the sum of the total transect lengths to give a close approximation to its percentage by volume. This micrometric method of quantitatively measuring porosity expressed as volume had been questioned at first. Lincoln and Reitz (54), however, have worked out a geometrical proof supporting the method. Later,

Anderson and Binnie (2) applied a statistical proof and concluded that volumetric ratios can be estimated by measuring lengths of line segments. Likewise, Swanson and Peterson (93) found micrometric measurements of porosity to be comparable to tension methods. Holmes (33) states that with sufficient number of transects, the volume-percentage pore space can be estimated with a relatively high degree of accuracy by this procedure.

The measurements of only those pores with diameters ($>50 \mu$) were measured in order to allow an arbitrary comparison to volume of pores drained by 60 cm tension. Although realizing soils do not necessarily conform to the capillary-tube model, it was considered justifiable to apply the capillary-rise equation to estimate the pore diameter size that 60 cm height-of-liquid rise would drain. Distribution of pores was recorded for diameter size intervals ranging from 0.05 to 4.0 mm. Non-capillary porosity ($>50\mu$) was recorded as volume-percentage and also the frequency of different size ranges of pores larger than this limit were determined.

RESULTS AND DISCUSSION

Discussion of sampling and impregnating techniques.

1. Obtaining undisturbed soil samples:

The use of hand tools or core samplers for obtaining relatively undisturbed samples presents problems in forested soils having an abundance of roots, or in soils that have stones or are non-coherent.

The nature of this study necessitated the development of a technique for obtaining relatively large blocks of undisturbed soil containing roots. To be able to investigate the soil-root boundary and surrounding environment it was necessary to avoid any alteration of the spatial arrangement of the roots or soil matrix. Several methods discussed below had been investigated before the techniques used were adopted.

Freezing technique and impregnation
with castolite-styrene mixtures: A detailed description of the technique and materials used is presented in Materials and Methods Section.

This freezing technique was utilized to obtain undisturbed soil samples from forested soils having a wide range of textures. It was found that sandy or other less coherent soils can usually be frozen to a depth of 5 to 8 cm with direct surface application of liquid nitrogen without boring holes. With medium or finer textured soils it was necessary to bore holes at intervals to allow

rapid penetration to greater depths and subsequently quicker freezing. Caution must be exercised, however, to avoid disturbing the block. By using a No. 8 cork borer and applying only a small amount of pressure to avoid continued force when the borer is obstructed by roots or rock fragments was found to be effective.

The rate of penetration and intensity of freezing by liquid nitrogen was investigated in a silt loam soil. As the data in table 1 show, the freezing of soil penetrated 7 cm from the point of application within 10 minutes. The freezing was also intense, reaching temperatures below -35°C . in 8 minutes within 3 cm of the point of contact. A sharp freezing temperature differential ranging from lower than -35°C to 0°C was established over the 7 cm zone within 10 minutes, and apparently did not change appreciably after this time interval.

The behavior of soil in a wet state was not investigated. It is anticipated that soils in this state may undergo some disruption or other disturbance upon freezing, due to increased volume of the resultant ice.

2. Impregnating techniques

Castolite.- soil thin sections containing roots in situ were made from segments of soil selected from the interior of the frozen block, some distance from the periphery or from the holes made by the cork borer. Samples were maintained in a frozen state and cut into blocks approximately (4 x 4 x 5 cm) with a diamond saw while main-

TABLE 1. TEMPERATURE READINGS IN SOIL BLOCK DURING AND FOLLOWING LIQUID NITROGEN APPLICATION AT SURFACE. PROBES WERE INSERTED IN AN OPEN VERTICAL FACE AT DEPTH INTERVALS INDICATED

Elec- trode	Depth Inter- val cm.	Time intervals (minutes)									
		0	1	3	4-5a	6a	8	10	14	16	20
		°C	°C	°C	°C	°C					
1	1	20	-20	^b	—	—	—	—	—	—	-20
2	3	20	15	1	-11	-28	—	—	—	-27	-16
3	5	20	18	15	9	3	-5	-15	-18	-16	-10
4	7	20	19.5	15.5	11	8	6	-0	-1	-1	-1
5	9	20	19.5	18	17	15	14	12	8	7	5
6	12	20	19.5	18	18	17	16	15	14	14	13

^aLiquid nitrogen applied to surface at this time. Time intervals began after taking 0 readings and then first application of liquid nitrogen was added.

^bA Tri-R electronic thermometer was used to measure temperatures; missing data are due to temperatures dropping lower than the -35°C , lower unit of calibration.

taining the original orientation. A Castolite-styrene solution was used to impregnate lyophilized samples in vacuo as described in the Methods and Materials Section. The lyophilizing process reduced the moisture content sufficiently to facilitate excellent impregnation. These samples showed no apparent evidence of alteration in the spatial arrangement of soil matrix.

An undesirable feature of this impregnating technique is root dehydration resulting in some shrinkage. The root volume change is believed to occur in two different steps of the procedure. Small shrinkage was observed following the lyophilizing step. Some of this might be eliminated if a lower vacuum could be attained with the freeze-drying unit. The second phase of treatment causing some shrinkage can be related to impregnating material. Polyester resins diluted with a styrene monomer show a volume decrease on conversion from liquid to a cured solid state.^{1/}

Treatment effect caused an increase in the space between root and soil (Figs. 8, 17, and 18), and hence quantitative measurements of these voids were not attempted.

Water soluble resin "Cymel 405": A water soluble melamine resin manufactured by American Cyanamid Company, called "Cymel 405" was used in an attempt to impregnate blocks of unfrozen soil in situ. The resin in powder form was mixed in warm water at a ratio of 40 parts resin to 60 parts water. The catalyst used consisted of a mixture of one part benzoic acid to three parts alcohol. The amount

¹I. H. Updegaff, Resins Research Department, American Cyanamide.

of dilution and type of catalyst was suggested by personal communication from Klaus Flach.^{2/}

The behavior of this resin was evaluated in the following manner: A series of treatments were initiated to establish the proper amount of catalyst to be used with the resin. Paper drinking cups each containing 100 ml. of the diluted Cymel resin were treated with the following volumes of catalyst: 0, 0.5, 1, 2, and 4 ml. Daily observations of treatments showed that samples receiving 2 and 4 ml of catalyst became very hard the second day, and also were brittle, and showed numerous cracks and visible evidence of decrease in volume. The treatment receiving no catalyst was reasonably hard after seven days. From this study it was concluded that 0.5 of catalyst per 100 ml of diluted resin would be the preferred treatment to explore. This treatment required 3 days to harden, but visible results of polymerization were evident in the first 24 hours. Reimpregnation was attempted in the laboratory in a vacuum dessicator, but no noticeable improvement on quality of impregnated sample was observed.

The Cymel resin was taken to the field in an effort to impregnate a soil block containing undisturbed root segments. In the first effort to impregnate soil in situ the resin and catalyst were applied to the surface of A1 horizon of Miami silt loam. An open end metal retainer was pressed into the soil to confine the liquid to the surface block within the retainer's walls. A head of 3-5 cm of liquid

^{2/} Klaus W. Flach, Soil Survey Laboratory, Riverside, California.

was maintained for 12 hours. After 5 days, the sample hardened and proved too brittle for cutting thin sections. A second attempt was made by exposing a vertical face of a 10x10x10 cm soil block, taking precaution not to disturb roots growing through the block. The resin mixture was applied as a liquid column in direct contact with the one exposed vertical face of the block in order to facilitate faster saturation of the soil block. Additional liquid was added at intervals in order to maintain a liquid level near the surface of the block. The block was then excavated in 5 days. The sample hardened within the first 1½ cm. of exposed soil face in contact with the liquid and along larger channels throughout the block. The large pores were not completely filled with resin and the hardened section of the block left much to be desired because it fractured easily with sawing or grinding operations.

Water soluble resin "Catalin 9399": This water soluble melamine resin by Catalin Corporation, New York, was tested in laboratory and found to behave similarly to "Cymel 405" in its application to obtaining undisturbed soil samples. This resin comes in a liquid form but the viscosity is too high for adequate impregnation without dilution.

"Carbowax 6000": Polyethylene glycol, usually referred to as "Carbowax" has been used for soil impregnation by numerous researchers (49, 51, 59). MacKenzie and Dawson (59) and Langston and Lee (51) described the applicability of Carbowax to impregnate wet organic soils. The soil moisture is replaced with high molecular weight polyethylene glycol compound (Carbowax 6000) with no observable volume change.

Moist samples were impregnated in laboratory by immersion in liquid "Carbowax 6000" at 65° C for 4 days. Several thin section slides were made of B22 horizon of Miami soil with no noticeable evidence of shrinkage. However, cutting and grinding sections of a coarser textured Clymer soil presented serious problems in that sand grains would pluck out of the relatively soft carbowax. Cutting and grinding of soil block produced enough heat to cause softening of Carbowax (M.P. 65° C). Smearing of the surface of block and possible reorientation of particles made the Carbowax impregnated samples unsuitable for observations.

Carbowax was used in the field to impregnate soil blocks in situ. An infra-red heater was used as a heat source to maintain the temperature of soil block above the 65° C melting point of this material. Aluminum foil served as reflectors and also to direct the heat to soil block being sampled. It was possible to collect a 15 x 15 x 8 cm block of soil. Carbowax crystals were applied to surface of the block and along the side that was partially exposed, care being taken not to disturb roots that were present. The crystals were melted by the space-heater which permitted the liquid Carbowax to penetrate the block slowly. Additional Carbowax crystals were added as the liquid infiltrated the block. Heat was applied for 6 hours and then removed, two hours later the block was excavated. The center of the block was not permeated by Carbowax treatment but the sides and surface were penetrated to an average thickness of one inch, making the block relatively stable and easy to remove and transport. The block was

rigid enough to allow sawing into smaller blocks. Sawing Carbowax treated samples with a diamond saw using kerosene as a coolant presented a problem, because the kerosene wetted the entire block and thus induced softening and crumbling. Dry sawing of samples met with better success even though the friction of the saw melted some Carbowax and left a smear on surface of blocks. It was possible, however, to remove this smear with emery cloth. Blocks containing roots, upon sawing and grinding, showed evidence of disturbance around the root area. Apparently the strength of Carbowax is not great enough to allow grinding and polishing of mineral grains and roots to the desired thickness of about 30 μ . Although not a serious problem, the Carbowax exhibits slight anisotropic optical properties.

The Carbowax fulfills certain desired requirements for impregnation in the field as it shows less evidence of shrinkage than other materials. However, the low melting point and low strength of the cured material limits its use for making thin sections of soils with numerous sand-size grains.

Chemical grout "AM-9": Another material, manufactured by American Cyanamid is called "AM-9" chemical grout, and was tested for possible use in collecting undisturbed samples from loose (incoherent) soil materials. Upon mixing with water this material has a low viscosity and hardens quickly when a starter or catalyst is added. It forms a gel that is somewhat stable. It has been used effectively for sampling and stabilizing sandy materials. The material, however, shows a rapid

volume decrease upon exposure to air. It seems potentially useful for obtaining samples if a method could be developed to remove the AM-9 gel and reimpregnate the sample with a material of greater strength and hardness.

Of the several techniques and materials tried, freezing of soil in situ by liquid nitrogen and later impregnating cut blocks of the soil with Castolite was judged to be the most satisfactory for conducting the investigations. As pointed out earlier some problems were encountered in the use of this procedure.

Although not specifically investigated, one might expect some disruption or volume change when the soil is frozen under these conditions. Freezing of soil blocks while at very low moisture levels, approaching the wilting point, may produce samples that are very fragile.

This freezing technique allows bulk density measurements, moisture retention and micromorphological studies to be made on very loose and incoherent materials, or soils such as those of the surface layers of forested soils that have abundant roots. Heretofore, these were difficult to obtain. Qualitative evidence indicated that better saran coating of the (friable soils) sample without excessive penetration of the liquid was obtained while the sample was in the frozen state. In addition there was little or no danger of the samples crumbling or disintegrating while being coated. It is anticipated that this method should also prove to be useful for obtaining undisturbed samples of organic soils. It may also facilitate the collection

of unconsolidated material, such as strip mine spoil banks and land fills, without further disturbance during sampling.

The freezing technique is not recommended for soils with a moisture content greater than field capacity. Poor freezing penetration was observed under excessive moisture conditions and may be due to resultant ice forming a physical barrier to penetration of liquid nitrogen. A similar experience is reported in studies by U.S. Army Engineer Waterways Experiment Station (96), which showed that smaller samples were obtained with a liquid nitrogen soil-moisture sampler when there was excessive moisture.

Properties of Soils Used in Investigation

1. Physical properties.- Particle-size distribution - The mechanical analyses data are given in Tables 2 and 3. As the data indicate the sand fraction of Clymer loam (TU-6) profile is relatively uniform in upper 22 inches of profile, i.e., down to the lower part of B21t horizon. Coarse and medium sand are predominant in this fraction. Below this depth there is a marked increase in sand with a content of 69.2% in IIB22t horizon and 84.5% and 93.0% in IIB3 and IIC1. Coarse and medium sand predominate in the sand fraction of the IIB22t horizon and are likewise predominant in the IIB3 and IIC1. The IIC1 horizon is underlain at a depth of 48 inches by partially weathered clayey shale, containing considerably less sand and more silt.

TABLE 2. MECHANICAL ANALYSIS OF CLYMER LOAM (TU-6)

Hori- zon	Depth in.	Particle Size Distribution (percent)														Textural class
		>2mm	Sand (mm)						Silt (μ)				Clay (μ)			
			Very coarse	Coarse	me- dium	Fine	Very fine	Total	Very fine	Fine	Coarse	Total	Fine	Coarse	Total	
			1-2	.5-1	.25-.5	.1- .25	.05-.1	.05-2	2-5	2-20	20-50	2-50	<.2	.2-2	<.2	
A1	0-2	9.3	1.3	12.5	15.4	10.5	3.2	42.9	9.9	37.8	9.3	47.1	1.6	8.4	10.0	Loam
A2	2-7	20.0	1.7	15.3	15.6	11.6	2.9	47.1	8.6	32.4	10.3	42.7	1.9	8.3	10.2	Loam
A3	7-12	6.5	1.9	13.9	13.8	9.9	2.1	41.5	9.1	36.1	11.4	47.5	2.0	8.9	10.9	Loam
B1	12-17	2.1	2.8	16.3	13.7	9.4	2.4	44.6	8.5	32.3	9.9	42.2	2.8	10.4	13.2	Loam
B21t	17-22	6.6	1.8	15.8	14.2	10.1	2.4	44.3	7.8	29.8	9.1	38.9	4.7	12.1	16.8	Loam
IIB22t	22-28	31.7	0.8	23.8	27.6	14.0	3.0	69.2	4.2	12.5	3.0	15.5	5.4	9.9	15.3	Sandy loam
IIB3	28-38	38.9	0.6	27.9	36.1	16.4	3.5	84.5	2.6	5.9	1.7	7.6	2.7	5.2	7.9	Loamy c. sand
IIC1	38-48	21.7	1.8	58.8	22.4	7.4	2.6	93.0	2.0	N.D.	N.D.	2.4	1.5	3.1	4.6	C. sand
IIIC2	48-50	9.0	4.1	17.2	6.6	10.8	10.8	49.5	9.0	23.0	11.1	34.1	3.9	12.5	16.4	Loam
IIIC3	50-56	26.0	3.1	2.9	1.5	2.7	10.4	20.6	10.3	36.3	20.2	56.5	6.0	16.9	22.9	Silt loam

The A and upper B horizons of the Clymer profile are fairly uniform in silt content, the values ranging from 38.9% to 47.5%. There is an abrupt change in this fraction at 22 inches, i.e., the top of IIB22t horizon. Silt content drops to 15.5%, 7.6% and 2.4% in the IIB22t, IIB3 and IIC1 horizons, respectively. Silt content increases abruptly to 34.1% and 56.5% below 48 inches in the IIIC2 and IIIC3 horizons.

Clay content is uniform in the A horizons, averaging approximately 10.5%, but increases to 16.8% and 15.3% in B21t and IIB22t horizons. Lowest clay content (4.6%) was observed in the coarse sand IIC1 horizon but increased in the partially-weathered shaley IIIC3 horizon to a content of 22.9%. In the portion of the profile above the shaley substrate the fine ($<0.2 \mu$) clay increases from the surface downward and IIB22t with a content of 5.4% has the highest percentage. This represents a 3-fold increase over that found in the A horizons. This fraction drops to 1.5% in the IIC1 horizon. The relatively higher content of fine clay, 3.9 and 6.0 percent in the IIIC2 and IIIC3 horizons is attributed to the fact that this material has been derived from shale.

A lithologic discontinuity seems evident at a depth of 22 inches. The presence of a discontinuity is based on a marked change in sand and silt content in the Clymer (TU-6) and in other profiles observed in the same area. The relatively high silt content in the upper 22 inches suggests that this fraction may be of loessial origin.

Horizontal fragment orientation was observed along the trench in the lower B which might be attributed to slope (23%) movement of colluvium. The high sand content of II materials may be due to slope movement rather than weathering of sandstone fragments or lenses. The sharp break between horizons IIC1 and IIIC2 is an indication of very little vertical mixing.

Clay mineralogy indicates a mixed mineralogy for upper part of profile with a kaolinitic mineralogy in the coarser textured II material. It is postulated that the variability of clay mineralogy in the profile is probably due to the lower material inheriting its kaolinite from the sandstone and shale parent rock. Chemical data show an increase in pH and base saturation below 22 inches, which is inconsistent with the possible theory that kaolinite is the end product of a high degree of weathering in this zone. Coarse sand layers are prevalent in the lower solum IIB3 and IIC1 of most profiles of this area. This sand layer is present over the substratum practically throughout the slope and constitute the lower portion of the colluvium. The coarse sand layer overlying a less permeable shale layer is the zone of subsurface water build-up and provides an avenue for lateral or downslope movement of subsurface water as described by Whipkey (1961). Although a lithological discontinuity adds to the complexity of investigating the genesis, there is strong evidence of the presence of an argillic horizon. Marked increase of fine clay going from eluvial to illuvial horizons and a B/A total clay ratio of approximately 1.6 add support.

Field descriptions described thin patchy clay films and thin sections reveal oriented clay films, verifying the presence of translocated clay along conducting voids.

The amount of coarse skeleton (>2 mm) material in the Clymer soil consists of 9.3% in A1 horizon, increasing to 20% in A2. A minimum of 2.1% coarse skeleton was observed in B1 horizon. A maximum of 38.9% was measured in the IIB3 and the high sandstone content may be attributed to slope movement.

Compared to the Clymer soil the Miami profile is considerably finer, especially in the B horizons. The sand content is relatively uniform in the A and B horizons ranging from 20.4% to 24.2% in fine and very fine sand constituting over a half of this fraction. There is a marked progressive increase in sand in the C horizons, ranging from 37.4% in the C1 to 44.0% in the C3.

The silt fraction of Miami decreases gradually with depth from 56.5% in the A1 to a minimum of 36.2% in the B21t horizon. There is a sharp change in silt content between the B1 and B21t horizon at approximately 15-inch depth with a drop in values from 48.5% to 36.2%. This decrease in silt at the B1-B21t boundary is an indication of the presence of a thin loess mantle. The prevalence of such thin deposits in West-Central Ohio has been postulated by Wilding (104). The very fine (2-5 μ) silt makes up about one-fifth of the total silt fraction in the silty overlay and decreases with depth.

The clay content increases from 22.1% in the A1 horizon to a maximum of 42.8% in the B21t and drops to a minimum of 15.1% in the

TABLE 3. MECHANICAL ANALYSIS OF MIAMI SILT LOAM (FR-7)

Hori- zon	Depth inches	Particle Size Distribution (percent)												Tex- tural class	
		Sand (mm)						Silt (μ)				Clay (μ)			
		Very Coarse	Coarse	Medium	Fine	Very fine	Total	Very fine	Fine	Coarse	Total	Fine	Coarse		Total
		1-2	.5-1	.25-.5	.1-.25	.05-.1	.05-2	2-5	2-20	20-50	2-50	<.2	.2-2		<.2
A1	0-3	1.9	3.4	2.8	7.3	6.0	21.4	10.2	36.3	20.4	56.5	7.1	15.0	22.1	Silt loam
A2	3-8	2.3	3.5	3.3	8.2	6.9	24.2	12.1	39.2	13.4	52.6	4.6	18.6	23.2	Silt loam
A3	8-11	2.2	3.6	3.3	8.0	6.4	23.5	12.4	39.7	13.6	53.3	5.7	17.5	23.2	Silt loam
B1	11-15	2.5	3.5	2.9	7.2	6.0	22.1	10.8	35.2	13.3	48.5	11.0	18.4	29.4	Clay loam
B21t	15-19	3.5	3.5	2.5	6.1	5.4	21.0	8.4	24.8	11.4	36.2	21.9	20.9	42.8	Clay
B22t	19-26	2.7	3.5	2.6	6.3	5.3	20.4	9.7	29.2	11.4	40.6	18.8	20.2	39.0	Clay loam
C1	26-30	6.9	7.6	4.5	9.6	8.8	37.4	8.4	29.2	13.6	42.8	6.8	13.0	19.8	Loam
C2	30-44	7.8	7.9	4.4	9.7	8.6	38.4	8.3	29.0	13.3	42.3	6.5	12.8	19.3	Loam
C3	60-65	5.9	6.9	5.5	13.5	12.2	44.0	6.8	25.6	15.3	40.9	5.2	9.9	15.1	Loam

C3 horizon, thus, producing a pronounced clay bulge. On the basis of this characteristic and on the prevalence of clay films the B21t and B22t easily qualify as argillic horizons according to criteria set forth by the Soil Survey Staff (90). Expressed on a ratio basis, clay content of the illuvial horizons B21t and B22t to that of eluvial horizons, A1 and A2 are 1.8 and exceeds considerably the 1.2 ratio sometimes used as a criteria. The fine ($<0.2\mu$) clay increases 3 to 4 fold from the A horizons to B2 horizons. The clay bulge can be related to translocation of clay from overlying horizons and the possible sedentary accumulation and some synthesis of clay in the B2 horizons.

Bulk density: Bulk density measurements of clod samples from most of the horizons of the two soils were made at controlled moisture levels of 1/3 atmosphere moisture content and at air-dry conditions. The freezing technique was used to collect undisturbed clods from non-coherent, A1 and A2 horizons. It was not possible to measure the A1 horizon of Clymer soil for 1/3 atmosphere because the clods did not equilibrate properly during saturation and thus gave erratic data.

In the Miami soil the bulk densities range from 1.22 (air-dry) in A1 horizon to 1.86 in C1 horizon. In both soils the low values in the A1 horizons are attributed to the presence of numerous small roots and high organic matter content. In contrast the dense, slowly permeable till has a bulk density of 1.86. The influence of moisture content of soil on its bulk density is very marked in the Miami soil especially in the B22t horizon where values of 1.52 and 1.74 for 1/3

atmosphere and air dry moisture contents respectively were obtained. Coefficient of maximum potential extensibility was 0.045 in this horizon indicating relatively large volume changes of soil fabric with changes in moisture content. Small tree roots in this horizon in spite of the high bulk density were observed to follow along natural ped surfaces or channels. Comparable bulk density values obtained at 1/3 atmosphere versus air-dry moisture content for the Clymer profile show a maximum difference of only 0.004. As the data in Table 4 show, the bulk density values for the Clymer soil range from 0.98 air dry measurement in A1 horizon to 1.79 in IIB22t horizon and 1.70 in the IIC1 horizon. Using the values for air-dry vs. 1/3 atmosphere bulk densities, very low values were obtained for maximum potential extensibility. Even in the IIB22t horizon the maximum potential extensibility was 0.006 inch per inch, indicating very small volume changes of soil fabric with changes in moisture content.

Non-capillary porosity: In the Clymer soil the non-capillary porosity decreased from the surface 21.3% to 9.9% in the IIB22t horizon (See Table 5, page 80). In the coarser horizons, beginning with IIB3, the non-capillary porosity increased up to a value of 23.5% in the IIC1. In contrast the Miami has a lower non-capillary porosity of 19.3% in A1 horizon decreasing to 7.7% in the C1 horizon. An estimate of non-capillary as measured by a micrometric method compared closely to this method using bulk density, and particle density values

TABLE 4. PERCENT MOISTURE RETENTION BY VOLUME, BULK DENSITIES, AND COEFFICIENT OF MAXIMUM POTENTIAL EXTENSIBILITY FOR CLYMER AND MIAMI SOILS

Horizon	Depth inches	% moisture by volume		Bulk density		Coefficient of maximum poten- tial extensi- bility
		60 cm.	1/3 atm.	1/3 atm.	Air dry	
<u>Clymer loam (TU-6)</u>						
A1	0-2	24.0	--	--	0.98	--
A2	2-7	31.1	28.9	1.49	1.53	0.010
A3	7-12	25.7	23.5	1.55	1.56	0.002
B1	12-17	24.5	22.1	1.62	1.64	0.003
B21t	17-22	24.9	23.0	1.70	1.73	0.006
IIB22t	22-28	23.1	19.9	1.76	1.79	0.006
IIB3	28-38	16.7	14.2	1.73	1.75	0.004
IIC1	38-48	12.6	11.0	1.69	1.70	0.002
<u>Miami silt loam (FR-7)</u>						
A1	0-3	33.4	---	1.12	1.22	0.028
A2	3-8	29.5	27.8	1.48	1.53	0.010
A3	8-11	28.7	27.0	1.56	1.61	0.011
B1	11-15	28.0	25.6	1.62	1.64	0.017
B21t	15-19	27.7	25.8	1.56	1.73	0.034
B22t	19-26	28.7	27.7	1.52	1.74	0.045
C1	26-30	24.9	21.9	1.80	1.86	0.013

to calculate total porosity and then subtracting the 60 cm tension moisture content to obtain an estimate of non-capillary porosity. The difference in the A1 horizons may be attributed to the clods not becoming completely saturated and also the probability of entrapped air or "blocked pore" effect causing a lower estimate of the large pores.

Particle density: The particle density in the Clymer soil ranged from 2.66 to 2.68 g/cc in all horizons except the A1 where an extremely low value of 1.79 g/cc was obtained (Table 5, see page 81).

Particle density range in the Miami soil was from 2.58 g/cc in A1 horizon to 2.77 g/cc in B22t horizon. The particle density differences between the two soils parallels the difference observed in particle density of parent material. Coarse skeleton from the Miami profile ranged from 2.65 to 2.70 g/cc. In contrast these measurements made on weathered sandstone fragments from Clymer profile range from 2.45 to 2.65 g/cc.

2. Clay Mineralogy

Each crystalline substance has its own characteristic atomic structure which diffracts X-rays in a characteristic pattern. Hence, clay minerals can be characterized by their unique "c"-axis or "d"-spacing.

Qualitative analysis of oriented clay mineral specimens were determined by the orders of the "d" spacing of basal reflections. Jackson (37) described how the "d" spacing is influenced by cation

saturation, kind of interlayer liquid sorbed on clay surfaces and on the liquid medium from which the colloids are dried. This may affect the degree of orientation because the drying of polar liquids have been observed to have a compression effect on clay particles.

The characteristic "d" spacing has been determined for most clay minerals for both normal specimen preparation and those receiving treatments, such as saturations with Mg cations, ethylene glycolation, and heat treatments. Spacings listed by Brown (15) were used primarily for qualitative identification of clay mineral in this study.

Clay mineral species were identified by their characteristic d-spacing resulting from specimen treatments used in this study. Illite is indicated by a $10\text{\AA}$ "d" spacing and chlorite by a $14\text{\AA}$ "d" spacing which does not expand upon glycolation nor collapse when heated to 400°C . Kaolinite is identified qualitatively by presence of $7.2\text{\AA}$ and $3.6\text{\AA}$ "d" spacing which are destroyed upon heating to 550°C . Decomposition of kaolinite at 550°C is due to loss of its hydroxyl ions in octahedral positions. The peaks ($7.2\text{\AA}$ and $3.6\text{\AA}$) coincide with second and fourth order peaks, respectively, of vermiculite and chlorite, but can be differentiated since chlorite low in iron is stable at 550°C while vermiculite collapses to $10\text{\AA}$ at 400°C . However, some iron-rich chlorites, particularly those of poor crystallinity and small particle size dehydrate at lower temperature (15). The use of $3.5 \pm \text{\AA}$ peak of air dry treatments may be helpful in some cases to identify the presence of chlorite even though the peak nearly

coincides with the 002 kaolinite basal spacing of $3.57\text{\AA}$. The chlorite peak in some cases can be observed on the shoulder or as a doublet with the kaolinite. Montmorillonite can be differentiated from other clays by its $14\text{-}15\text{\AA}$ d-spacing for air dry treatment that expands to $17\text{-}18\text{\AA}$ upon glycolation and then collapses to $10\text{\AA}$ upon heating to 400°C . Vermiculite is differentiated from montmorillonite and chlorite by the $14.7\text{\AA}$ spacing of air dry vermiculite, which does not expand upon glycolation as does montmorillonite. Vermiculite collapses to $10\text{\AA}$ when heated to 400°C while chlorite remains stable at this temperature.

Clay size quartz is also identified in the X-ray diffractogram, having a (100) peak at $4.26\text{\AA}$ and the (101) peak at $3.34\text{\AA}$.

Diffractograms obtained for the clay fraction of the Clymer profile indicate a mixed clay mineralogy. The $10\text{\AA}$ peaks, indicative of illite, show up only as traces in A1 (Fig. 1) and A2 (Fig. 36) horizons, increase slightly in the B1 horizon and show substantial quantities of illite in the B21t (Fig. 37) and IIB22t horizons. Strong intensity illite peaks were observed in IIB3 (Fig. 39) and IIIC3 horizons.

Strong $7.2\text{\AA}$ peaks indicating presence of kaolinite occur in the A1 horizon with a marked decrease in A2 horizon. The B21t (Fig. 37) horizon has the greatest amount of kaolinite, excluding layers below the first lithologic break. In the IIB3 (Fig. 38) horizon, kaolinite is the dominant mineral representing an estimated 50% total clay fraction. Kaolinite decreases in IIIC3 horizon while the intensity of

Figure 1. X-ray diffractograms of Mg saturated clay specimens from A1 horizon of Clymer loam (TU-6).

illite peaks increase relative to IIB3 horizon. Expansion of $14.6\text{\AA}$ peaks to approximately $16\text{\AA}$ in the IIB22t horizon indicates a trace of montmorillonite that is probably interlayered with a $14\text{\AA}$ non-expanding component. Interlayer polyhydroxy aluminum in A1 and A2 horizons is suggested by the distinct peaks occurring at $12.7\text{\AA}$.

The decrease in kaolinite from A1 to A2 horizon is paralleled by an increase in quartz with A2 horizon.

Vermiculite may occur as interstratified montmorillonite-vermiculite or as a vermiculite with a low layer charge which may show swelling characteristics with glycol similar to high-charge montmorillonites (15).

Traces of chlorite in the IIB22t horizon are indicated by presence of a peak at $13.87\text{\AA}$ after heat treatment to 550°C . Brown (15) describes how heat treatment may enhance the chlorite 001 peak by modifying the brucite layers through dehydration while the talc layer is largely unchanged. The resulting 001 reflected intensities are increased at the expense of decreased intensities in 002, 003, and 004 reflections.

The X-ray diffractograms of the Miami silt loam profile FR-7 indicate the presence of kaolinite, vermiculite, illite, and montmorillonite in all horizons and traces of chlorite in the C-horizon (See Figs. 2, 39, 40, and 41).

Illite is the dominant clay mineral in the C horizons and relatively abundant in B22t and A1 horizon. Kaolinite occurs in

Figure 2. X-ray diffractograms of Mg saturated clay specimens from Al horizon of Miami silt loam (FR-7).

small quantities throughout the profile with greatest amounts in Al (Fig. 2) and C horizons. Upon glycolation, all horizons exhibit $14\text{\AA}$ components that are partially or completely expandable. This is supported by relatively large maximum potential extensibility values measured for Miami soil. The montmorillonite present is difficult to distinguish from a montmorillonite-vermiculite interlayer or a montmorillonite=hydroxy aluminum interlayer without additional diagnostic treatments. Some discrete vermiculite is present in all horizons.

The Miami silt loam profile shows a mixed clay mineralogy derived from an illitic parent material. Holowaychuk (34) has described the Miami parent material as illitic. Studies on genesis of a Miami silt loam by Thorp, et al. (94) suggest a mixed mineralogy for the sola. They suggested a possible weathering sequence of illite weathering to vermiculite which in turn may be transformed to montmorillonite. This weathering sequence compares to that proposed for a podzol soil by Ross and Mortland (76). Clay mineralogy of Miami soil for this study differs from that reported by Thorp, et al. by a lack of appreciable increase of montmorillonite in illuvial horizons.

There is a strong possibility that X-ray analysis of $<0.2\ \mu$ size fraction would demonstrate greater differences in montmorillonite content of illuvial versus eluvial horizons. Smeck (86) and Gersper (26) found that montmorillonite was generally concentrated in the fine clay fraction. Small quantities of montmorillonite in this size fraction exhibit sharper peaks because they are not masked by dilution with entire clay fraction.

Further fractionation of the clay and quantitative analysis were not made in this investigation since the study was not oriented toward establishing clay gains and losses or to making a thorough study of the genesis of soil. Major emphasis was placed on a qualitative clay analysis in order to better interpret root-soil relationships.

3. Micromorphology - Thin Section Analysis

The physical organization of the soil fabric in its undisturbed state was investigated by preparing thin sections of each horizon and examining the sections under a petrographic microscope. This allows one to supplement and extend the macro-morphological studies of the soil described in the field. Observations made with thin sections provide much additional information about the morphology of the soil. Valuable information can be obtained that would contribute to a better understanding of the origin of parent material, as well as porosity, clay translocation, particle orientation, and structure.

The descriptions of the micromorphology for Clymer and Miami soils are presented in sequence from surface by horizons. Terminology used in this section was taken primarily from Brewer (14).

Clymer TU-6

Horizon

A1 This horizon is characterized by its very porous open type of structure (Fig. 8). Voids $> 50 \mu$ diameter make up

26% of the volume. There are numerous aggregates of 3-4 mm size class which appear to be cemented by organic substances. Organic matter in general is in a well decomposed stage as evidenced by presence of remaining residues from decomposed roots or other plant material.

In some microscopic fields as much as 60% of the area consisted of fecal pellets stained with organic residue. Aggregates or agglomerated fecal pellets were observed in close proximity to decomposing roots. Fungal hyphae were common in this horizon, often entwining the aggregates.

There appears to be a random distribution pattern of grains with respect to voids and channels. The fabric is aseptic (no plasma separations). The random and loose packing of the aggregates account for the relatively high porosity of this horizon.

A2 This horizon is less porous having approximately 11% pores $> 50 \mu$. The denser fabric is characterized by some vesicular pores, and by lower porosity estimations obtained in horizontal thin sections as compared to vertical. It is expected that this feature is associated with platy structure. This horizon is a somewhat bleached zone dominated by sand size particles with some staining from decomposing organic matter (Fig. 9) and tonguing of A1 horizon above into this horizon.

Fig. 3.-Photomicrograph of Miami A1 horizon showing sponge-like fabric and excreta from mites, 35X,uncrossed nicol.

Fig. 4.- Photomicrograph of Miami A2 horizon showing aseptic fabric and perthite grain. 35X,crossed-nicol.

Fig. 5.- Photomicrograph of Miami B1 horizon showing conducting void and sub-cutanically oriented clay. 35X,crossed-nicol.

Fig. 6.- Photomicrograph of Miami B22t horizon showing conducting channels with thick ferriargillans. 35X,crossed-nicol.

Fig. 7.- Photomicrograph of Miami C1 horizon showing dense fabric and argillan surrounding walls of conducting void. 35X, crossed nicol.

Fig. 8.- Photomicrograph of Clymer A1 horizon showing porous fabric, organic matter and transverse cut of tree root. 35X, crossed-nicol.

Fig. 9.- Photomicrograph of Clymer A2 horizon showing random orientation of mineral grain and presence of decomposed organic matter. 35X, crossed-nicol.

Fig.10.- Photomicrograph of Clymer IIB22t horizon showing skelsepic fabric and clay coating and bridging at mineral grains. 35X, crossed nicol.

Fig. 11.- Photomicrograph of Clymer IIB3t showing abundance of sand size grains bridged by argillan high in iron oxide. 35X, crossed-nicol.

Fig. 12.- Photomicrograph of Clymer A1 horizon showing fecal pellets and loose packing of mineral grains. 35X, crossed nicol.

Fig. 13.- Photomicrograph of Miami A2 horizon showing radical cut root with void and matrix material. 35X, crossed nicol.

Fig. 14.- Photomicrograph of Clymer A2 horizon showing large void formed by decomposed root with bark intact. 35X, crossed-nicol.

Fig. 15.- Photomicrograph of Miami B22t horizon showing new roots growing in old channels with only remnants of bark remaining. 35X, crossed-nicol.

Fig. 16.- Photomicrograph of Miami B22t horizon showing tubular channel containing decomposed remnants of old root and channel walls lined with oriented clay. 35X, crossed-nicol.

Fig. 17.- Photomicrograph of Clymer IIB22t horizon showing transverse cut of root, oriented grains, root-soil space of 100 μ . 35X, crossed-nicol.

Fig. 18.- Photomicrograph of Miami B22t horizon showing soil-root interface, and oriented clay. 35X, crossed-nicol.

Fig. 19.- Photomicrograph of Miami B22t horizon showing soil-root interface, oriented clay, and increase in voids at 0.9 mm from root. 35X, crossed-nicol.

Fig. 20.- Photomicrograph of Miami B22t horizon showing ferriargillans around lithorelict and lining walls of void. 35X, crossed-nicol.

The fabric is aseptic with only occasional flecks of oriented clay. Some of the feldspar grains show evidence of etching or corrosion due to weathering.

Few round Fe-Mn concretions were observed. Large open channels were observed where the shell or rind (Fig. 12) of a root was intact and there was no evidence of collapse or filling of the channel created by decomposition of an old root.

A3 This horizon is similar to the A2 horizon except for less evidence of grain weathering, and less material of biological origin. This horizon has an aseptic fabric with lower porosity. Flecks of clay were observed within matrix but there was no evidence of oriented clay along channels. Few ellipsoidal Fe-Mn concretions with concentric ring-like structures were observed. Decomposed organic matter was observed in macrovoids and along the walls of voids.

B1 Few small voids are lined with oriented clay as thick as 0.03 mm but larger conducting channels show no evidence of the presence of oriented clay. Oriented clay has formed ring-like outlines of old voids that are now filled with matrix material. Clay flecks occur throughout the matrix. No evidence of striated, pressure oriented clay was observed in this horizon. The channels are interconnected forming excellent routes for rapid water movement. Few small Fe-Mn

concretions were observed. The fabric is basically aseptic except for occasional plasma separations around small conducting voids.

B21t Channels are commonly lined with ferriargillans, and some of the smaller size pores are almost completely filled with oriented clay. This horizon has a skel-insepic fabric (part of the plasma occurs as isolated patches and also surfaces of grain are coated with plasma). Sand grains are coated with oriented clay. Some of the channels or pores do not contain oriented clay particularly those larger than 0.5-1.0 mm in size.

Sub-cutanic clay within the ped seemed to outline the boundary of former conducting voids which are now filled with matrix material.

Large pores ($> 50 \mu$) make up 10% of section area. Many of the micropores are constructed by the packing effect of sand size grains forming interstitial pores as classified by Johnson, et al. (41), or as simple packing voids as defined by Brewer (14).

IIB22t Moderately thick ferriargillans occur along conducting voids. A few complex reddish-yellow clay flows were observed that exhibit a wavy extinction line. Some areas show a close packing of sand grains with numerous grain to grain bridges.

Grains are more commonly bridged by oriented clay that coats the grains and orient themselves parallel to grain surfaces.

The fabric is generally skelsepic (Fig.10) with some insepic areas. Some of the larger channels are not lined with oriented clay. There appears to be a higher percentage of silt-size particles along the walls of these channels suggesting possible movement or sorting of soil material. Lack of clay films on these larger channels is attributed to rapid movement of water through these larger openings thus the velocity of the water may tend to strip any clay that is present on the walls or prevent the accretion of clay to walls while in a dispersed state.

IIB3 The horizon is dominated by sand-size fractions that are relatively close packed. The fabric is primarily skelsepic (Fig.11) with many of the grains bridged by oriented clay. Some thick (0.5 mm) reddish-brown or reddish-yellow ferriar-gillans are present, and faces of lithorelicts are coated by oriented clay. The majority of the pores are interstitial. They are irregular in shape and bounded by angular surfaces of adjacent grains. According to Brewer (14) they would be classified as simple packing voids. A high percentage of total clay content is oriented in this horizon. The thick clay flows observed along channels indicate translocation of clay from overlying horizons.

IIIC2 This horizon has a dense matrix fabric with few pores. Few small circular pores are lined and almost plugged with oriented clay. Common shale fragments are present which show a striated clay pattern. Some of these shale chips have a thin band or coating of oriented clay on their surfaces. The fabric is variable, with lattisepic areas but is more commonly insepic.

Small crevices or cracks in shales and other lithorelicts contain thin bands of yellow oriented clay along their walls. This horizon shows evidence that weathering is still active at this depth and that some of the clay described above has formed in situ.

Miami FR-7

A1 The fabric is generally asepic (no plasma separations) and characterized by aggregates grading from 0.5-4.0 mm in size. Roots are numerous and represent varying stages of decomposition ranging from no cellular structure remaining to completely intact roots. The larger macrovoids contain numerous fecal pellets that are dark brown and ellipsoidal in shape. Voids make up 22% of the volume. The aggregates are bound together by organic substances and form an open type structure similar to that which Kubiena (47) described as sponge-like. Few lithorelicts of shale chips and pebbles

from parent material were observed in this horizon.

Excreta from mites were observed within the central core of a decomposing root (Fig. 3). These excreta were spherical and the same color as the surrounding partially-decomposed organic material which supplied the source of material for the mites to ingest. Remnants of tubular pores were present that were partially collapsed and filled with silt, sand, organic material and the scattered fecal pellets.

A2

The fabric of this horizon is relatively denser with pores making up about 11% of the volume (Fig. 4). A greater volume of pore space was observed on vertical thin sections and suggest some degree of platiness of structure. A few vesicular pores and a few large channels or voids were observed.

The fabric is asepic with occasional flecks of oriented clay distributed throughout the matrix in a random pattern. Hornblende and feldspar grains in general show marks of weathering although some fresh grains were observed within the matrix. Coarse silt and sand grains tend to orient themselves so their long axis is parallel to root surfaces.

The fabric takes on a bleached color relative to horizons above and below, except for flecks of clay and organic stains interspersed with the matrix. Shale chips were noted frequently and exhibited a striated clay orientation. Few rounded to oblong Fe-Mn concretions were present. Also present was a large (300 μ diameter) sclerotia outlined with a thick dark brown wall. No evidence of oriented clay was observed along pores or channel walls. Numerous channels contain remnants of plant material indicative of decomposed roots.

B1 This horizon has oriented clay lining the walls of small pores ranging from 0.03 to 0.15 mm thick. Thin yellow to yellowish-red clay films occur along channels. Some grains are coated with oriented clay. Clay along channels is discontinuous with only patches of clay skin remaining (Fig. 5). There is strong evidence that destructive forces have been active in these channels and that at least some of the clay has been stripped. Thorp, et al. (94) suggested that both accumulation of clay and also degradation or stripping has occurred in similar horizons. Ferrimanganiferous nodules were observed. Pores make up approximately 10% of the volume.

Evidence of faunal activity decreased sharply from A1 and A2 horizons. Single fecal pellets were observed in

channels containing the shells of decomposing roots and suggests that the fauna are using channels previously established by roots.

B21t The fabric is generally insepic characterized by moderately thick yellowish-red clay flows lining the smaller pores. Ferriargillans are common in channels and pores. Large channels (> 0.5 mm) often do not have clay films along their walls but exhibit subcutanic clay, oriented parallel to channel walls. There seems to be enough disturbance or destructive forces along the walls of larger channels to prevent the accumulation of dispersed clay. Field observations indicate that roots tend to follow the channels formed along ped surfaces.

B22t Strongly oriented, reddish-yellow ferriargillans are prevalent in this horizon (Fig. 6). They exhibit high birefringence and range from .05- to 0.4 mm thick. The strongly oriented clay along conducting voids indicates that such sites are zones of accumulation of translocated clay. Some oriented clay occurs as coating around isolated sand grain or shale chips. Sand and silt grains are oriented with reference to surface of roots. Oriented clay is present, subcutanic to the soil-root interface but not as cutanic clay films along the channel wall (Fig. 16). Oriented clay occurs at intervals of 0.1 mm and greater away from soil-root inter-

face but is generally oriented with reference to the root surface. The roots seem to occupy voids that are connected to larger channels forming a dendritic pattern. Dessication cracks may account for the origin of the complex systems of channels.

The fabric is variable with some areas exhibiting a lattisepic fabric and others a complex plasma fabric. Areas of thick reddish-yellow ferriargillans are associated with complex interconnecting system of channels. The plasma between voids appears as fine particles heavily stained with iron.

Channel type voids seem to account for much of the pore space of $>50 \mu$ diameter. The size of these channels may vary considerably with different moisture levels.

C1 This horizon is quite dense with a volume-percentage of 7% for voids (Fig. 7). Calcite and/or dolomite are present in appreciable quantities as observed by their distinctly high birefringence. Oriented clay appears as flecks throughout the fabric and as parallel striation along surfaces of shale chips. Few small pores are lined with moderately oriented clay. A root was observed growing inside of channel that had been occupied by a larger root with only the outline of the bark remaining. Material of silt size

and smaller had almost filled the area not occupied by the live root.

There is some evidence of translocated clay in this horizon and a few clay films are present in certain zones even though the horizon is calcareous (Fig. 7). The percentage of oriented clay in this horizon would be very small in comparison to B horizons described previously.

4. Volume-Percentage Pore Space

It is generally accepted that characterizations of the soil pore system are important in a study of the movement and storage of soil water and air (9, 65, 78, 56). Vomocil (100) states that for these objectives the most useful information about the pore system of a soil profile is the pore-size distribution or the volume occupied by larger pores.

The application of volume-percentage pore space measurements to soil water movement requires that the characteristics of the entire profile be considered. In freely draining soils or where air is not entrapped, the amount of water percolating through a soil is controlled by the permeability of the least permeable layer.

Because of the tremendous influence non-capillary size pores have on the permeability of a soil, it would be helpful to consider some of the factors contributing to non-capillary porosity. In a review made by Baver (7) it is concluded that non-capillary porosity of a soil may be the result of coarse texture, loose granular structure, cracks produced by shrinkage, or biological channels. Tree roots are likely to have made a major contribution to the latter in the soils studied. All of these factors appear to be important in the Miami soil, whereas in Clymer the texture and biological channels are likely to be more important. Maximum potential extensibility data shown in Table 4 indicate a shrinkage potential of 0.045 inches per inch for the Miami B22t, suggesting that cracks produced by shrinkage may be an important factor in the Miami soil.

Total porosity values, shown in Table 5, were determined by calculations using measured values for specific gravity of particles and the volume-weight (bulk density-air dry). Non-capillary porosity values shown in this table were obtained by subtracting the volume percentage of water retained at 60 cm of tension from the calculated total porosity.

TABLE 5. PARTICLE DENSITY AND POROSITY DATA FOR CLYMER LOAM
AND MIAMI SILT LOAM PROFILES

Horizon	Depth inches	Particle density g/cc	Percent ^a pore space (calculated)	Percent non- ^b capillary pore space
<u>Clymer loam (TU-6)</u>				
A1	0-2	1.79	45.3	21.3
A2	2-7	2.66	42.5	11.4
A3	7-12	2.67	41.6	15.9
B1	12-17	2.68	38.8	14.3
B21t	17-22	2.66	35.0	10.1
B22t	22-28	2.67	33.0	9.9
IIB3	28-38	2.67	34.5	17.8
IIC1	38.48	2.66	36.1	23.7
<u>Miami silt loam (FR-7)</u>				
A1	0-3	2.58	52.7	19.3
A2	3-8	2.70	43.3	13.8
A3	8-11	2.68	39.9	11.2
B1	11-15	2.75	40.4	12.4
B21t	15-19	2.77	37.5	9.8
B22t	19-26	2.77	37.2	8.5
C1	26-30	2.76	32.6	7.7

^aCalculated percent pore space = $100 - \frac{\text{bulk density (air dry)}}{\text{particle density}} \times 100$

^bPercent non-capillary pore space = (% pore space calculated) -
(% moisture by volume at 60 cm tension)

In the discussion the lower limit of effective pore size is considered to be approximately 50 μ . This is approximately equivalent to pore openings calculated for tension of 60 cm water column. Non-capillary porosity measurements obtained by methods used commonly are helpful in evaluating the permeability of a soil, but these however, do not provide information on nature, orientation, size distribution or the configuration of pores of this magnitude.

Micrometric measurements were made on thin section slides for >50 μ pores in the A1, A2 and B22 horizons for both of the two soils. This method of determining porosity provided qualitative as well as quantitative data on the size frequency of pores of this size and larger. It avoids the errors introduced by "blocked pore" effect in tension studies that produce an under-estimate of larger pores (78,93). In the studies cited the non-capillary porosity measurements obtained by volume-weight and moisture retention agreed closely with the values derived microscopically by soil thin sections. The greatest difference occurs in the A1 horizons, the micrometric method giving a higher pore volume percentage. The distribution of pores of the A1 horizons included numerous pores of large size, some greater than 1.0 mm diameter. Studies by Swanson and Peterson (93) using both methods showed similar differences. As described above, the tension method may under-estimate the volume of larger pores.

TABLE 6. MICROMETRIC ESTIMATIONS OF VOLUME-PERCENTAGE OF NON-CAPILLARY PORES FOR SELECTED HORIZONS OF CLYMER PROFILE (TU-6). PORE SIZE DISTRIBUTION, FREQUENCY, MEAN DEVIATION AND RANGE OF MEANS ARE GIVEN.

Horizon & depth	No. of slides observed	0.05-0.1		0.1-0.2		0.2-0.5		0.5-1.0		1.0-2.0		2.0-4.0		All Pores .05-4 mm %
		mm N ^b	%	mm N	%	mm N	%	mm N	%	mm N	%	mm N	%	
A1 0-2"	(4) Mean	52.2	2.8	49.2	5.8	34.8	8.5	9.2	5.4	2.4	3.4	0.2	0.5	26.4
	Mean dev. ^a		0.6		0.8		1.8		1.1		1.5		0.7	3.0
	Range		2.1-		4.1-		6.3-		3.2-		1.8-		0-	22.6-
			3.6		6.5		11.8		6.6		5.7		2.0	32.1
A2	(4) Mean	32.7	1.5	29.7	2.9	16.7	3.7	4.0	2.1	1.7	2.0	0	0	12.2
	Mean dev.		0.3		0.7		1.3		1.9		1.7			
	Range		1.1-		1.6-		2.6-		1.0-		0.7-			5.3-
			1.9		3.7		6.3		5.7		4.2			20.9
A3	(2) Mean	21.0	1.2	21.0	2.5	8.0	1.9	2.0	1.4	1.0	1.3	0.5	1.0	9.2
	Mean dev.		0.1		0.5		0.5		0.3		1.3		1.0	1.3
	Range		1.0-		2.0-		1.8-		1.1-		0-		0-	7.9-
			1.3		2.9		1.9		1.7		2.7		2.0	10.5
B22t	(6) Mean	29.0	1.2	23.8	2.2	10.8	2.3	3.3	2.0	1.1	1.2	0.2	0.2	9.2
	Mean dev.		0.5		0.5		0.6		1.0		0.8		0.5	
	Range		0.2-		0.6-		1.0-		0.7-		0-		0-	6.4-
			2.3		3.7		3.6		4.1		3.2		1.4	11.6

^a Mean deviation.

^bN - The average number of pores measured per slide in respective size classes.

TABLE 7. MICROMETRIC ESTIMATION OF VOLUME-PERCENTAGE OF NON-CAPILLARY PORES FOR SELECTED HORIZONS OF MIAMI PROFILE (FR-7). PORE SIZE DISTRIBUTION, FREQUENCY, MEAN DEVIATION AND RANGE OF MEANS ARE GIVEN.

Horizon & depth	No. of slides observed	0.05-0.1		0.1-0.2		0.2-0.5		0.5-1.0		1.0-2.0		2.0-4.0		All pores .05-4 mm
		mm N ^b	%	mm N	%	mm N	%	mm N	%	mm N	%	N	%	
A1	(4) Mean	18.2	0.9	22.5	2.5	19.2	4.5	7.2	3.8	3.2	3.9	4.3	6.6	22.5
	Mean dev. ^a		0.3		0.3		0.9		1.0		2.2		3.4	6.3
	Range		0.5-		2.2-		2.6-		2.8-		1.0		6.5-	11.7-
			1.3		2.9		5.6		5.5		8.2		12.5	28.3
A2	(5) Mean	28.8	1.4	22.2	2.3	17.0	3.8	4.8	2.5	2.3	2.1	0.5	0.9	13.0
	Mean dev.		0.1		0.3		1.2		0.6		1.2		0.9	1.1
	Range		1.3-		1.9-		2.1-		1.8-		1.0-		1.7-	10.8-
			1.6		2.8		5.3		4.1		4.7		2.1	14.8
B1	(5) Mean	29.8	1.7	21.8	2.5	17.4	4.4	3.5	1.9	1.3	1.3	1.0	0.3	11.5
	Mean dev.		0.2		0.2		0.9		0.7		0.4		0.5	1.5
	Range		1.5-		1.9-		3.2-		1.1-		0.8-			
			2.1		2.9		5.9		3.1		2.2		0-1.7	9.1- 14.4
B22	(8) Mean	25.4	2.1	15.9	2.8	8.6	3.1	1.7	1.2	.1	0.1	0	0	9.3
	Mean dev.		0.5		0.8		1.4		0.5		0.1			2.6
	Range		1.2-		1.3-		0.7-		0.8-		0-			4.0-
			2.9		4.2		5.7		2.7		1.0			13.5
C	(2) Mean	16.0	0.8	10.0	1.2	5.5	1.4	0.5	0.3	0	0	0	0	3.6
	Mean dev.		0		0.1		0.7		0.3					0.4
	Range		0.8-		1.1-		0.7-		0-					3.2-
			0.3		1.3		2.0		0.6					4.1

^aMean deviation

^bN - The average number of pores measured per slide in respective size classes.

The Clymer soil shows a decrease of non-capillary pores (Table 6) with depth down to 22 inches where the lithologic discontinuity occurs. The change in material to one with a much higher content of coarse and medium sand size, produces a marked increase in non-capillary porosity. The IIB3 horizon of Clymer with 17.8% non-capillary porosity (Table 5) is a good illustration for the influence of high sand content on this property.

The distribution of pores in IIB22t horizon of Clymer (Fig. 21) shows a maximum volume-percentage in 0.2 to 0.5 mm range. The Miami B22t shows also a maximum percentage in this range; however, there is a strong shift of volume-percentage pores to smaller diameter classes <1.0 mm. The distribution of pores in the A2 horizon of both soils are very similar (Figures 21 and 23) and approximates a normal distribution about 0.2-0.5 mm class.

In the Miami soil the volume-percentage of non-capillary pores decreased with depth and the distribution shifts toward the smaller diameter class ranges. The extreme differences are pointed out in Table 7, where the A1 horizon has 6.6 percent pores in the 2 to 4 mm size range as compared to 0 percent pores of this size range for the C horizon. The highest volume-percentage pore space in the Miami soil occurs in A1 horizon and within the 2 to 4 mm diameter class range. The shift of pore size distribution to large pores in this horizon may be related to loose packing of the large 1 to 4 mm size range aggregates and to earthworm activity. Field observations and

Figure 21. Distribution of volume-percentage $>50 \mu$ diameter size determined micrometrically for A1, A2, and B22 horizons of Clymer and Miami soils.

Figure 22. Summation plot of volume-percentage pores $> 50 \mu$ as determined by micrometric methods, for different pore diameter class ranges. Clymer and Miami Al horizons.

Figure 23. Summation plot of volume-percentage pores $>50 \mu$ determined by micrometric methods, for different pore diameter classes. Clymer and Miami A2 horizons.

Figure 24. Summation plot of volume-percentage pores $>50 \mu$ as determined by micrometric methods for different pore diameter classes. Clymer and Miami B22t horizons.

microscopic examination of thin sections provide evidence of considerable earthworm casts and channels in this horizon. In contrast, these channels and casts were less evident in the A1 horizon of the more acid Clymer soil. This horizon in the latter soil had a greater volume of pores in the 0.1-0.5 mm diameter range. Pores occurring within the 0.1 to 0.2 mm size range may be due to simple packing voids formed by the medium and coarse sand since the sand content of the Clymer is twofold greater than that of the Miami A1. The loose packing of the aggregates in the Clymer is probably the source for the pores in 0.2 to 0.5 mm size range.

Comparing the size of pores to frequency it is shown that the Miami A1 horizon has an average of 22 pores per slide observed in 0.1 to 0.2 mm class range, constituting a volume of 2.5%. In comparison, an average of three pores per slide in the 1.0 to 2.0 mm range constitutes 3.9% of the non-capillary pore space. It can readily be seen why a few large pores may make greater contributions to soil permeability than do the more numerous smaller pores.

Figure 25 shows the percent non-capillary porosity for several horizons of both soils as measured by micrometric and modified tension methods. An average of 116 mm in distance and 129 microscopic fields per slide were transected micrometrically. These revealed considerable range in values per slide for the larger pores (Tables 6 and 7), hence the validity of data from probably less than four slides leave some doubt as to whether the sample size is sufficient to be

Figure 25. Percent volume of pores $>50 \mu$ in diameter for different depths in Miami and Clymer profiles, comparing measurements obtained by micrometric to that calculated from bulk density, particle density, and 60 cm tension moisture content.

representative of the horizon. In the modified tension method the aeration porosity data reported in Table 5 were obtained by subtracting the moisture content by volume at 60 cm tension from the total porosity calculated from bulk density and particle density values. The plot of these data as shown in Figure 25 indicate good agreement between the two procedures as far as measurement of total aeration porosity is concerned. As stated previously, however, the modified tension method does not provide information on the size distribution of these pore spaces.

C. Micromorphologic Investigation of Soil Fabric
At Tree Root-Soil Interface

A series of detailed microscopic examinations were made of the soil fabric within 4 mm radius of the root-soil boundary to determine what influence tree roots may have on the physical organization of the adjacent soil. Pedological features quantitatively measured include the distribution and content of grains in size, voids, s-matrix material, and oriented clay. Other features evaluated include lithorelicts, Fe-Mn nodules, organic matter and decaying roots. Where possible these features are expressed as percent of the microscopic field they occupy. The percentage of each were determined by making linear transects at various distance intervals away from the soil-root interface. Because of the limited field of a microscope it was necessary to select root sizes that would not exceed the size of the field. For this reason

roots of 4 mm and 6 to 7 mm were chosen. S-matrix material listed as one of the pedological features above is described by Brewer (14) as the material within the simplest (primary) ped, or composing apedal soil materials, in which the pedological features occur. It consists of the plasma, skeleton grains, and voids that do not occur in pedological features other than plasma separations. In this study s-matrix includes all material not included in measurements of grains ($> 20 \mu$), voids ($> 20 \mu$), and oriented clay.

Percentage means of selected pedological features, such as grains, voids, s-matrix and oriented clay were statistically compared as a function of proximity to soil-root interface, root diameter size and soil type. Analysis of variance tables for these summarizations are presented in Appendix B. A summary of significant "F" values are shown in tables 8 and 9.

Another study was made where concentric transects encircled or circumscribed the soil-root boundary at several distance intervals. Elongate grains with a minimal length greater than 30μ were classified as oriented or unoriented in reference to the root surface. Oriented grains were defined as grains with an elongate axis oriented within 30° of direction parallel to the root surface.

TABLE 8. SUMMARY OF SIGNIFICANT "F" VALUES FROM ANALYSIS OF VARIANCE COMPUTATIONS OF MEAN PERCENTAGES FOR SELECTED SOIL FABRIC COMPONENTS. CLYMER AND MIAMI B22t HORIZONS.

	% grains >20 μ	% Voids >20 μ	% s-matrix	% oriented clay	% elongate grains oriented parallel to roots
Soil	**	-	**	**	-
Root diameter	*	**	**	-	*
Distance	**	*	**	**	**
Soil x root diameter	-	-	-	*	-
Soil x distance	**	-	**	-	-
Root diameter x distance	-	-	-	-	-
Soil x root dia. x distance	-	-	-	-	-

* = .05 level

** = .01 level

TABLE 9. SUMMARY OF SIGNIFICANT "F" VALUES FROM ANALYSIS OF VARIANCE COMPUTATION OF MEAN PERCENTAGES FOR SELECTED SOIL FABRIC COMPONENTS. CLYMER AND MIAMI A2 HORIZONS.

	% grains >20 μ	% voids	% s-matrix	% elongate grains oriented parallel to roots
Soil	-	*	-	-
Distance	-	-	*	**
Soil x distance	-	-	-	-

* = 0.05 level

** = 0.01 level

1. Elongate ($>30 \mu$) grains oriented parallel to root surface: The data from this study suggest strong grain orientation adjacent to the root. Analysis of variance (Tables 23 and 28) indicates a highly significant difference between means for distance intervals away from root-soil interface (Figure 26). The degree of grain orientation with distance from the interface is not significantly different between Clymer and Miami soils. Figure 27 illustrates significant effect (0.05 level) that different root diameters have on grain orientation. It suggests that greater orientation is obtained with larger roots primarily in the 0.4 to 2.0 mm radial interval with little difference immediately adjacent to the root. Duncan's Multiple Range Test was used to determine significant differences between means for both soils at .01 confidence level. The Miami B22t horizon shows a significant decrease in root influence on grain orientation to occur between the 0.4 to 0.6 mm distance interval. In the Clymer a similar decrease in root influence was noted at 0.3 to 0.4 mm distance interval in the Clymer soil. In the A2 horizon significant decreases in particle orientation extend from 0.4 to 0.6 mm radial distance from the root with no significant difference noted between the two soils.

In summary there is a progressive decrease in oriented grains ($>30 \mu$) with increase in radial distance from the root for both soils in both eluvial A2 horizons and illuvial B2 horizons. It would seem plausible that this orientation effect is related primarily to:

TABLE 10. MEANS FOR PERCENT OF ELONGATE GRAINS ($> 30 \mu$)
ORIENTED WITHIN 30° OF PARALLEL TO ROOT SURFACE.
CLYMER AND MIAMI A2 HORIZONS.

Distance from soil-root interface mm.	Clymer loam (TU-6)	Miami silt loam (FR-7)	Mean
0	66.32	66.85	66.58
0.1	56.05	52.55	54.30
0.2	53.37	51.70	52.53
0.3	47.22	43.52	45.37
0.4	41.82	42.05	41.92
0.6	36.90	38.42	37.66
0.8	38.45	38.30	38.37
1.0	34.20	35.80	35.00
2.0	34.57	32.65	33.61
	Soil mean <u>45.43</u>	Soil mean <u>44.64</u>	

TABLE 11. MEANS FOR PERCENT OF ELONGATE GRAINS ($> 30\mu$) ORIENTED WITHIN 30° OF PARALLEL TO ROOT SURFACE. CLYMER AND MIAMI B22t HORIZONS.

Distance from soil-root interface mm.	Clymer loam TU-6			Miami silt loam (FR-7)			Distance means
	(A) 4mm root diameter	(B) 6-7 mm root diameter	Means (A+B)	(A) 4 mm root diameter	(B) 6-7 mm root diameter	Means (A+B)	
0.0	72.53	71.51	72.02	67.85	69.93	68.89	70.45
0.1	65.61	65.08	65.35	63.26	63.88	63.57	64.46
0.2	56.28	55.38	55.83	56.76	56.58	56.67	56.25
0.3	47.63	50.33	48.98	50.30	52.96	51.63	40.30
0.4	39.98	44.66	42.35	47.73	45.187	46.45	44.39
0.6	38.65	42.65	40.65	40.73	40.65	40.69	40.67
0.8	38.26	40.61	39.44	39.10	38.56	38.83	39.13
1.0	34.31	38.85	36.58	36.38	36.63	36.50	36.54
2.0	34.76	35.61	35.19	31.75	35.15	33.45	34.42
	Soil mean		48.48		Soil mean		48.52

Figure 26. Percent elongate grains $> 30 \mu$ oriented parallel to root surface in relation to distance intervals from soil-root interface with root sizes averaged together. Clymer and Miami A2 horizons. (DMR-Means with same lower case letters are not significant at .01 level.)

Figure 27. Percent elongate grains $>30 \mu$ oriented parallel to root surface in relation to distance intervals from soil-root interface with root sizes 4 mm and 6-7 mm averaged together. Clymer and Miami B22t horizons. (DMR- means with same lower case letters are not significant at .01 level.)

Figure 28. Percent elongate grains $>30\ \mu$ oriented parallel to root surface in relation to distance intervals from soil-root interface with means for both soils averaged together for 4 mm and 6-7 mm diameter roots. Clymer and Miami B22t horizons.

TABLE 12. MEANS FOR THE PERCENT OF GRAINS $> 20 \mu$ AS MEASURED
ALONG LINEAR TRANSECTS. CLYMER AND MIAMI A2
HORIZONS.

Distance from soil-root interface mm.	Clymer loam (TU-6)	Miami silt loam (FR-7)	Mean
0-0.2	16.07*	16.52	16.30
0.2-0.4	22.20	17.77	19.98
0.4-0.6	22.85	22.05	22.45
0.6-1.0	22.65	25.52	24.08
1.0-2.0	26.07	17.10	21.58
2.0-4.0	25.20	18.80	22.00
	Soil mean <u>22.50</u>	Soil mean <u>19.62</u>	

*Each mean is the average of measured percentage of four
thin section slides with 8-10 transects made per slide.

TABLE 13. MEANS OF PERCENT GRAINS ($> 20 \mu$) AS MEASURED ALONG LINEAR TRANSECTS.
CLYMER AND MIAMI B22t HORIZONS.

Distance from soil-root interface mm.	Clymer loam TU-6		Means (A+B)	Miami silt loam (FR-7)		Means (A+B)	Distance means
	(A) 4 mm root diameter	(B) 6 mm root diameter		(A) 4 mm root diameter	(B) 6 mm root diameter		
0-0.2	23.08	23.18	23.13	14.21	11.36	12.79	17.96
0.2-0.4	30.16	23.83	27.00	15.85	13.80	14.82	20.91
0.4-0.6	35.75	31.68	33.71	15.61	12.38	14.00	23.85
0.6-1.0	33.73	35.65	34.69	20.61	14.06	17.34	26.01
1.0-2.0	38.91	36.80	37.85	14.68	10.78	12.73	25.29
2.0-4.0	39.26	38.25	38.75	14.05	12.23	13.14	25.95
	Soil mean	<u>32.52</u>		Soil mean	<u>14.39</u>

Figure 29. Percent grains $> 20 \mu$ size in relation to distance interval from soil-root interface with root diameter sizes averaged together for each soil. Clymer and Miami B22t horizons. (DMR- Means with same lower case letters are not significant at .01 level.)

pressure from the root, due to initial root elongation; normal diameter enlargement associated with root growth; and seasonal and/or daily expansion and contraction with change in turgor pressure of root cells. In addition some pressure may possibly result from wind action against the tree which could produce stress on larger roots serving as an anchor.

2. Distribution and content of grains ($>20\ \mu$): Measurement of the relative proportion of thin section area comprised of grains ($>20\mu$) shows a progressive increase (Tables 12 and 13) with distance away from soil-root interface. Highly significant differences between soils would be expected because Clymer contains an appreciably higher sand content than Miami as shown by mechanical analyses data (Tables 2 and 3). There is a highly significant interaction between soil and distance from root-soil boundary, and thus means for Clymer and Miami soils are plotted separately in Figure 29. The Clymer soil suggests a significant increase in percentage ($>20\ \mu$) grains with distance from the soil-root interface. This relationship did not hold (at the .05 or .01 level) for the Miami soil though a similar trend was noted. In Clymer, the increasing percentage of ($>20\ \mu$) grains beyond 0.4 mm of the root-soil interface was not significant at .01 level. Differences between root diameters did not significantly influence (at the .05 level) the percentage of grains observed throughout radial intervals. The percentage of grains in A2 horizons showed no significant difference between soils for different distance intervals.

The Clymer soil contains a high content of sand size grains which present a solid surface for pressure to be exerted against. When the root expands the influence of the pressure exerted extends through a greater distance interval because of the relatively close packing of the skeleton grains. Thus, movement or rearrangement of a grain near soil-root interface will exert influence on adjacent grains initiating a chain reaction.

Some of the variability in the Miami soil for estimation of ($> 20 \mu$) grain percentages may be due in part to their paucity in the total soil as compared to the s-matrix. This would result in much lower sampling population. The plot for Miami soil (Fig. 29) of distance vs. percent grains suggests a possible sorting effect with a slight accumulation of larger grains in 0.6 to 1.0 mm interval even though data are not significant statistically. This would require further study to determine whether such a postulation is valid. The progressive increase in Clymer soil from root to 4 mm distance suggests that pressures from root enlargement is translocated beyond the 4 mm interval studied.

3. Oriented clay:- The percentage oriented clay was measured by linear transect at distance intervals from root-soil interface. Highly significant differences were found between soils, with Miami having twice as much total oriented clay. There is a decrease in oriented clay with distance from the root in both soils, though it is not significant for Miami and not progressive for either soil (Fig. 30). An increase in clay content occurs in the 0.4 to 0.6 mm interval for both soils which coincides with the zone of higher percentage pores. The distance interval of 0-0.2 mm from soil-root interface contains the highest percent oriented clay but not in the form of argillans coating the channel walls as might be anticipated. A part of this oriented clay occurs subcutanically and represents the outlines of older conducting voids that have been partially filled. However, more frequently the clay occurs as zones with striated birefringence indicative of pressure-orientation (14). The pores that occur in 0.4 to 0.6 range usually are lined with oriented clay suggesting illuvial accumulation.

Clay orientation was not measured for A2 horizons, since they contained only occasional flecks of clay interspersed within the matrix.

TABLE 14. MEANS OF PERCENT ORIENTED CLAY AS MEASURED ALONG LINEAR TRANSECTS.
CLYMER AND MIAMI B22t HORIZONS.

Distance from soil-root interface mm.	Clymer loam (TU-6)			Miami silt loam (FR-7)			Distance means
	(A) 4 mm root diameter	(B) 6 mm root diameter	Means (A+B)	(A) 4 mm root diameter	(B) 6 mm Root diameter	Means (A+B)	
0-0.2	2.80	1.60	2.20	4.70	5.71	5.70	3.95
0.2-0.4	1.45	0.98	1.21	3.55	5.23	4.39	2.80
0.4-0.6	2.70	1.20	1.95	3.90	5.30	4.60	3.27
0.6-1.0	1.45	0.75	1.10	3.63	3.53	3.58	2.34
1.0-2.0	1.28	0.65	0.96	3.63	2.60	3.11	2.04
2.0-4.0	1.33	0.63	0.98	2.95	2.15	2.55	1.76
	Soil mean <u>1.40</u>			Soil mean <u>3.99</u>			

*Means of percent in columns (A) and (B) represent the mean percentage that was measured for 6 thin section slides with 8-10 transects being made per slide.

Figure 30. Percent oriented clay in relation to distance intervals from soil-root interface with means of both root diameter sizes averaged together for each soil. Clymer and Miami B22t horizons. (DMR- Means with same lower case letters are not significant at .01 level.)

In order to have clay movement from horizon to horizon in a soil, something must initiate the clay movement and something must stop it, according to Soil Survey Staff (90). It is assumed that the clay is carried by water and must be in a dispersed state and that wetting of a dry soil leads to disruption of the fabric and to dispersion of clay. A halting of percolation water by capillary withdrawal favors the orientation of clays on ped faces and walls of pores. There are several possible explanations for the lack of argillans along the wall of soil-root interface. First, the chemical and biological environment in proximity to the root probably favors the flocculation of clay, because of a higher concentration of cations. Secondly, the physical pressure and tension exerted by expansion and contraction of the root would disrupt the clay flows along the channel wall and also disrupt peds thus leaving new planes of weakness that may show up as streaks of illuvial or pressure oriented clay. The area adjacent to the root is a zone of increased physical forces and chemical and biological activity. Argillans do not seem to form along root channels containing active roots due to destruction forces exceeding the rate of illuviation.

TABLE 15. MEANS OF VALUES IN PERCENT OF s-MATRIX MATERIAL
AS MEASURED ALONG LINEAR TRANSECTS. CLYMER AND
MIAMI A2 HORIZONS

Distance from soil-root interface mm.	Clymer loam (TU-6)	Miami silt loam (FR-7)	Mean
0-0.2	75.20	71.32	73.26
0.2-0.4	67.27	70.60	68.93
0.4-0.6	68.47	62.32	65.40
0.6-1.0	61.62	63.62	62.62
1.0-2.0	60.27	67.07	63.67
2.0-4.0	61.22	65.57	63.40
Soil mean	<u>65.67</u>	Soil mean	<u>66.75</u>

TABLE 16. MEANS OF VALUES IN PERCENT OF S-MATRIX AS MEASURED ALONG LINEAR TRANSECTS.
CLYMER AND MIAMI B22t HORIZONS

Distance from soil-root interface mm.	Clymer loam TU-6		Means (A+B)	Miami silt loam (FR-7)		Means (A+B)	Distance means
	(A) 4 mm root diameter	(B) 6 mm root diameter		(A) 4 mm root diameter	(B) 6 mm root diameter		
0-0.2	66.45	67.70	67.07	70.18	72.03	71.10	69.09
0.2-0.4	56.71	62.93	59.82	65.51	70.06	67.79	63.80
0.4-0.6	45.46	57.13	51.30	63.80	70.06	66.93	59.11
0.6-1.0	51.51	56.71	54.11	60.80	67.71	64.25	69.18
1.0-2.0	41.85	50.15	46.00	66.01	66.16	66.09	56.04
2.0-4.0	44.63	49.71	47.17	67.81	71.68	69.75	58.46
	Soil mean	<u>54.24</u>		Soil mean	<u>67.65</u>

Figure 31. Percent s-matrix material in relation to distance intervals from soil-root interface. Clymer and Miami A2 horizons. (DMR- Means with same lower case letters are not significant at .01 level.)

Figure 32. Percent s-matrix material in relation to distance intervals from root-soil interface with means from both root diameter sizes of 4 mm and 6-7 mm averaged together. Clymer and Miami B22t horizons. (DMR- Means with same lower case letters are not significant at .01 level.)

Figure 33. Percent s-matrix in relation to distance intervals from soil-root interface with the means of both soils averaged together for 4 mm and 6-7 mm diameter roots. Clymer and Miami B22t horizons.

4. S-matrix: Analysis of variance for data from the B22t horizon of both soils (Tables 15 and 16), shows a highly significant difference in the mean percentage s-matrix between Miami and Clymer with means of 67.6% and 54.2%, respectively. Larger roots (6 mm diameter) had significantly greater mean percentages of s-matrix associated with them than with smaller roots (4 mm diameter) - 63.5 versus 58.4%, respectively.

The percentage s-matrix decreases with distance from root-soil interface, although not significantly for the Miami soil (Fig. 32). In the Clymer soil the decrease in s-matrix beyond 0.4 mm was not significantly different at 0.01 confidence level.

The A2 horizons exhibited little differentiation in s-matrix between soils but were highly significant for distance intervals. Combined means for both soils indicated no significant difference in means beyond the 0.6 mm distance interval.

It seems reasonable to postulate that due to a higher percentage of s-matrix, and oriented clay immediately adjacent to the root, the cation exchange and water-holding capacities would be enhanced.

5. Voids: The data for the means of percent boids ($>20\ \mu$) are given in Tables 18 and 19. These data suggest a decrease in voids adjacent to the root. Analysis of variance, Table 23, indicates an increase that is significantly different for percent voids with distance intervals away from the root-soil interface. However, this increase is not progressive. A peak (Fig. 34) occurs for both Clymer and Miami soils at a distance interval of 0.4 to 0.6 mm and the high percent void area occurring in this interval was examined for the amount of variance about the means. Examination of data from 12 Clymer slides used in the study and which included both root sizes gave a mean value of 11.2% when root sizes were averaged together. The large mean deviation of 6.7% obtained is largely accounted for by two slides that gave values of 33.4 and 23.2% pores in the 0.4 to 0.6 mm distance interval. A large part of the variability between observations may be due to the fact that the interval observed is small and the percent voids represents about one-tenth of the fabric measured. There is little doubt on the basis of the quantitative data and the qualitative observations that the percent pore space near the root soil boundary is lower than in areas farther away.

Tables 19 and 20 present data showing the distribution of different pore diameter ranges at intervals away from the root-soil interface. In the 0 to 0.2 distance interval the majority of pore space is in smaller 20-50 μ diameter grouping. There is a reversal of this relationship beyond 0.5 to 1.0 mm distance away from root in

TABLE 17. MEANS FOR THE PERCENT OF VOIDS ($>20 \mu$) AS
MEASURED ALONG LINEAR TRANSECTS.
CLYMER AND MIAMI A2 HORIZONS.

Distance from soil-root interface mm.	Clymer loam (TU-6)	Miami silt loam (FR-7)	Mean
0-0.2	5.50	2.97	4.23
0.2-0.4	8.00	4.47	6.23
0.4-0.6	5.37	5.82	5.60
0.6-1.0	10.70	3.95	7.32
1.0-2.0	10.90	7.50	9.20
2.0-4.0	10.65	10.12	10.40
Soil mean	8.52	Soil mean	5.80

TABLE 18. MEANS OF PERCENT VOIDS ($>20\ \mu$) AS MEASURED ALONG LINEAR TRANSECTS.
CLYMER AND MIAMI B22t HORIZONS.

Distance from soil-root interface mm.	Clymer loam TU-6			Miami silt loam (FR-7)			Distance means
	(A) 4 mm root diameter	(B) 6 mm root diameter	Means (A+B)	(A) 4 mm root diameter	(B) 6 mm root diameter	Means (A+B)	
0-0.2	5.73	4.20	4.96	5.01	6.98	6.00	5.48
0.2-0.4	11.00	7.43	9.21	9.75	8.85	9.30	9.25
0.4-0.6	14.51	8.03	11.27	13.98	11.16	12.57	11.92
0.6-1.0	8.28	4.91	6.60	10.91	11.10	11.00	8.80
1.0-2.0	12.58	5.35	8.96	13.51	9.31	11.41	10.19
2.0-4.0	11.63	5.86	8.75	11.51	7.75	9.63	9.19
	Soil Mean	<u>8.29</u>		Soil Mean	9.98

Figure 34. Percent voids $> 20 \mu$ in relation to distance intervals from soil root interface with the means of both root size classes averaged together for each soil. Clymer and Miami B22t horizons. (DMR- Means with same lower case letters are not significant at .01 level.)

TABLE 19. VOLUME-PERCENTAGE OF PORES MEASURED BY LINEAR TRANSECTS AND THEIR SIZE RANGE DISTRIBUTION
RELATIVE TO DISTANCE INTERVALS FROM SOIL-ROOT INTERFACE. CLYMER AND MIAMI B22t HORIZONS.

Distance from soil- root inter- face (mm)	Clymer loam (TU-6)					Miami silt loam (FR-7)				
	Pore diameter size ranges (μ)				Total (A+B+C)	Pore diameter size ranges (μ)				Total (A+B+C)
	(A)	(B)	(C)			(A)	(B)	(C)		
	20-50	50-100	100-200	>200		20-50	50-100	100-200	>200	
0-0.2	3.4	0.9	0.6	0.0	1.5	5.1	0.9	0.0	0.0	0.9
0.2-0.4	2.4	2.1	4.7	0.0	6.8	6.0	1.8	1.5	0.0	3.3
0.4-0.6	2.1	2.2	6.8	0.0	9.1	6.4	3.3	2.8	0.0	6.1
0.6-1.0	1.6	1.3	1.7	2.0	5.0	4.2	3.4	3.4	0.0	6.8
1.0-2.0	4.2	1.8	1.5	1.4	4.7	2.6	4.0	3.2	1.6	8.8
2.0-4.0	1.0	1.4	2.0	4.3	7.7	2.2	3.4	2.8	1.2	7.4

TABLE 20. VOLUME PERCENTAGE OF PORES MEASURED BY LINEAR TRANSECTS AND THEIR SIZE RANGE DISTRIBUTION RELATIVE TO DISTANCE FROM SOIL-ROOT INTERFACE. CLYMER AND MIAMI A2 HORIZONS.

Distance from soil- root interface (mm)	Clymer loam (TU-6)					Miami Silt loam (FR-7)				
	Pore diameter size ranges(μ)				Total (A+B+C)	Pore diameter size ranges (μ)				Total (A+B+C)
	(A)	(B)	(C)	(A)		(B)	(C)			
	20-50	50-100	100-200	>200		20-50	50-100	100-200	>200	
0-0.2	4.3	1.2	0.0	0.0	1.2	2.4	0.5	0.0	0.0	0.5
0.2-0.4	5.3	1.2	1.5	0.0	2.7	3.8	0.6	0.0	0.0	0.6
0.4-0.6	2.6	2.7	0.0	0.0	2.7	2.2	3.6	0.0	0.0	3.6
0.6-1.0	4.4	2.5	0.9	2.9	6.3	1.5	1.5	0.6	0.0	2.4
1.0-2.0	2.9	2.1	3.6	2.3	8.0	1.9	2.9	1.4	1.3	5.6
2.0-4.0	2.0	5.3	2.4	0.9	8.6	1.3	3.3	3.0	2.8	8.8

Figure 35. Distribution of volume-percentage pores $> 20 \mu$ as determined by micrometric methods and related to distance intervals from soil-root interface. Clymer and Miami B22 horizons.

Miami soil. In the Clymer soil the non-capillary percentage increases markedly at 0.2-0.4 distance interval.

Although high variability exists in data for relative percentage of $> 100 \mu$ pores there seems to be strong support to indicate a compaction effect around the root with a shift of pore size distribution toward the smaller capillary size pores (Figure 35). Variability of observations about the mean was much lower in the Clymer 0 to 0.2 mm distance interval and about 70% of the measured pore space is in the 20-50 μ diameter range to give a volume-percentage of 3.4%. This required a high frequency of pores of this size to give this volume. In the 0.4 to 0.6 mm distance, approximately 75% of the volume-percentage voids greater than 20 μ occurred as 100-200 μ pores. A relatively small number were required to account for the 6.8% volume occurring in this size class. Statistically, a greater variation might be expected in areas containing large size pores.

SUMMARY AND CONCLUSIONS

Root channels and the larger pores appear to have a strong influence on the rapid downward movement of water observed in forested soils. The quantity of aeration porosity and the pore size distribution are important factors in evaluating the permeability of a soil profile. Current techniques and equipment available are not adequate, however, for making accurate porosity measurements in forested soils, since these contain numerous roots and channels of varying sizes and often are stony and incoherent.

Little information is available on what specific influence tree roots have on the soil fabric at the tree root-soil interface. The objectives of this study were directed to an evaluation of what influences tree roots have on the physical properties and spatial arrangement of adjacent soil materials. Such information would contribute to a better understanding of the role tree roots play in water movement in forested soils and the physical habitat as a factor in root-soil environment.

Two soil profiles were selected that differ considerably in mechanical composition. One of the soils, Profile TU-6 and referred to as Clymer loam, is a Typic Hapludult in the coarse loamy, mixed, mesic family and was described and sampled at a site located on an experimental area of Northeastern Forest Experimental Station, USDA, Forest Service, near Dover Dam in Tuscarawas County, Ohio. The other soil, Miami silt loam profile (FR-7) a Typic Hapludalf, fine, mixed

mesic family, was taken at a site on the northwest side of The Ohio State University Farm. The two soils represent a strong contrast in type of parent material, topography, and subsoil texture.

Field descriptions and chemical, physical and mineralogical measurements were made on samples from all horizons in order to better characterize and contrast the soil properties of the two profiles used in the study.

To investigate the micromorphology of the soil fabric in the vicinity of root-soil interface, it was necessary to develop a technique for obtaining relatively undisturbed soil samples with roots in place. A comparison was made of several materials and techniques for taking of undisturbed samples. The freezing of blocks in situ technique was selected as a suitable method for this study. The frozen blocks were lyophilized, then impregnated with Castolite-Styrene mixture under vacuum and soil thin section slides prepared for various observations under a petrographic microscope.

Volume-percentage pore space was determined micrometrically by a linear transect technique. The volume-percentage and distribution in selected horizons from Clymer and Miami soils were determined by this technique. These data were compared with porosity data obtained from particle density, bulk density, and 60 cm tension data.

A study of the soil fabric in vicinity of root-soil interface was made by estimating the percentage of different micromorphological features such as grains $>20 \mu$ size, voids $>20 \mu$, s-matrix material, oriented clay, and the percent of elongate grains oriented within

30° of parallel to the root surface in the A2 and B22t horizons both soils. Measurements were made at distance intervals of 0 to 0.2, 0.2 to 0.4, 0.4 to 0.6, 0.6 to 1.0, 1.0 to 2.0, and 2.0 to 4.0 mm away from root-soil interface of two sizes of roots, 4 mm and 6 to 7 mm in diameter. Data were statistically evaluated by analysis of variance.

1. Bulk densities in Miami soil range from a low of 1.22 g/cc in A1 horizon to progressively higher values with depth reaching 1.86 g/cc in the C horizon. Even wider differences were observed in Clymer soil which had a very low 0.98 g/cc value for the loosely packed A1 horizon with a relatively high organic matter content and increased to a high of 1.76 g/cc in the sandy IIB22t horizon.
2. Moisture content had a strong influence on bulk density measurements in the finer textured soils. This was well illustrated by B22t horizon of Miami with values of 1.52 to 1.74 g/cc representing bulk density at 1/3 atmosphere and air dry moisture content respectively.
3. Calculations of coefficient of maximum potential movement by swelling, i.e., extensibility indicate a very low change, 0.006 of fabric volume thickness for Clymer IIB22t horizon as compared to a much higher value of 0.045 in B22t of Miami soil.
4. Some tree roots were observed in the clayey B22t horizon of Miami having high bulk density, 1.74 g/cc at 1/3 atmosphere, however, these roots as observed in the field tended to follow structural cracks or channels.
5. Thin section analysis revealed a random and loose packing of aggregates in A1 horizons, with earth worm casts, fecal pellets, and fungal

hyphae that entwined and sometimes penetrated soil aggregates. These features have a strong positive influence on aggregate stability and mixing of the layer.

6. A mixed clay mineralogy, that included kaolinite, illite, vermiculite, montmorillonite and interstratified montmorillonite-vermiculite, was observed for Clymer profile in the upper part of the profile with a change to kaolinitic mineralogy in the sandier subsoil.
7. A mixed clay mineralogy was observed for Miami soil that revealed the presence of kaolinite, vermiculite, illite, and montmorillonite with interlayering of montmorillonite and vermiculite. The underlying till is primarily illitic.
8. Of the several techniques and materials tried, freezing of soil in situ by liquid nitrogen and later impregnating cut blocks of soil with Castolite-Styrene mixture was judged to be the most satisfactory for this investigation. Spatial arrangement of soil fabric and roots appeared to be unaltered by this technique.
9. The use of liquid nitrogen to freeze soil blocks in situ, was used successfully to obtain undisturbed samples of horizons having a high number of roots, stones, and incoherent materials. These soil blocks with undisturbed roots in place were used successfully for preparation of soil thin sections.
10. The freezing technique was also employed to collect undisturbed clods for bulk density and moisture retention movements. This allowed sampling of non-coherent layers having an abundance of roots that heretofore were impossible to sample by mechanical samplers or natural clod methods.

Qualitative evidence indicated a better saran coating of the porous samples without excessive penetration of liquid due to the sample being in a frozen state. There was also less danger of crumbling or disintegration of samples while applying the saran coating.

11. Micrometric measurements of $> 50 \mu$, non-capillary pores, gave values that compared closely to non-capillary porosity measurements obtained by calculations using volume-weight and moisture retention data. The greatest difference occurred in A1 horizon where micrometric estimations of pores gave a higher percentage.
12. In the Miami soil the volume-percentage of non-capillary pores decreased with depth and the pore size distribution shifted toward the smaller diameter size range. This is illustrated by Miami soil where A1 horizon had 6.6% pores in 2 to 4 mm size range, compared to 0% pores in this size range in the denser C horizon.
13. The distribution of pores in Miami B22t showed a shift of volume-percentage pores to smaller diameter classes < 1.0 mm with the greatest volume percentage occurring in the 0.2-0.5 mm class. The coarse textured Clymer IIB22t showed a more equal distribution of volume-percentage over pore size ranges of 0.05 to 4 mm diameter was found in the Miami soils.
14. A few large pores often may contribute more to permeability of these soils than the remaining pore system. Data illustrating this reveal that an average of 22 pores measured per slide in 0.1 to 0.2 mm class range constitute a volume of 2.5% as compared to average of three pores per slide in 1.0 to 2.0 mm diameter range with a volume of 3.9%. Hence a small number of large pores should have a greater

influence on soil permeability than numerous capillary and smaller class ranges of non-capillary.

15. Elongate grains, $>30 \mu$ diameter, are strongly oriented with reference to the root surface. This influence is strong in the section 0 to 0.5 mm distance from the soil-root interface. The orientation of the grains so their long axis is nearly parallel to root surface may be the result of physical pressure from the root during elongation and normal diameter enlargement. Highly significant differences were observed for B22t and A2 horizons between means of values of percentage of oriented grains and distance from the root-soil interface.
16. The soil fabric in close proximity to root-soil interface for B22t horizon of both soils has a higher percentage of oriented clay than was found at intervals farther away from the root. The oriented clay that occurs subcutanically within s-matrix appears to be due to effect of pressure and tension exerted by the root and normal wetting and drying.
17. The percent s-matrix material was significantly higher near root-soil boundary for Clymer soil, but decreased with distance.
18. The percentage of pore space was less for both soils near the root-soil interface. This is associated with a large increase in the number and volume percentage of small (20-50 μ) pores close to the root.
19. A comparison of 4 mm and 6 to 7 mm root diameter sizes suggest that the 6 to 7 mm roots have a greater influence on soil fabric near the root, as expressed by a decrease in voids, and distribution and content of grains $> 20 \mu$, and an increase in s-matrix and oriented grains parallel to root surface.

In summary, within the 0-0.4 mm distance interval of root-soil interface there is a relative decrease in grains $> 20 \mu$ and voids as contrasted to an increase in s-matrix material, oriented clay, and percent elongate grains oriented parallel to root surface. These features imply that the matrix contains more fine-size materials, less porosity ($> 20 \mu$), and also there is a shift in pore-size distribution to 20-50 μ and smaller diameter ranges.

The physical pressure or tension exerted by roots and to a lesser degree from wetting and drying of soil probably caused the large grains to be reoriented parallel to the root and a disruption of existing large pores with rearrangement of particles. Skeleton grains present a solid surface for the pressure to be exerted against.

The data obtained for the several micromorphological features: relative content of mineral grains, content of oriented clay, s-matrix and distribution of voids according to size and relative abundance all indicate that the soil material immediately adjacent to the root is finer textured and less permeable to water and air. In addition Miller (63) reported that oriented clay deposits at sites next to roots have a higher content of organic material than was found in clay farther away from such sites. It can be inferred from these observations that the soil fabric immediately adjacent to the root would have higher cation exchange capacity and moisture retention properties. It can also be surmised that this relatively thin layer of soil would reduce the movement of soil water or air to or away from the root. These observations and inferences suggest that these properties of the soil contiguous to a root may differ appreciably

from such properties of the soil farther away from the root. It is apparent that at least in the case of forest soils, indiscriminate sampling of soil for evaluation of properties that would contribute to a better understanding of the physical habitat of a root may be questioned.

APPENDIX A

Chemical Properties for Clymer and Miami Profiles

TABLE 21. pH, ORGANIC CARBON, FREE IRON OXIDES AND EXCHANGEABLE CATIONS OF
CLYMER LOAM VARIANT (TU-6)

Horizon	Depth inches	pH 1:1 (H ₂ O)	Organic Carbon %	Exchangeable cations M.e./100g				CEC m.e./ 100 g.	Total Bases m.e./100 g.	Base Satura- tion-%	% Free Fe ₂ O ₃
				H	Ca	Mg	K				
A1	0-2	4.1	9.0	25.0	1.6	0.7	0.56	27.9	2.9	10	1.4
A2	2-7	4.2	1.6	9.4	0.1	0.1	0.15	9.7	0.3	4	1.5
A3	7-12	4.3	0.4	5.2	0.0	0.0	0.10	5.3	0.1	2	1.5
B1	12-17	4.3	0.3	5.4	0.0	0.1	0.13	5.6	0.2	4	2.0
B21t	17-22	4.4	0.2	7.6	0.2	0.2	0.15	8.1	0.5	7	2.2
B22t	22-28	4.4	0.2	6.7	0.0	0.5	0.18	7.4	0.7	9	1.8
IIB3	28-38	4.7	0.2	3.2	0.3	0.4	0.13	4.0	0.8	21	0.9
IIC1	38-48	4.9	0.2	2.0	0.1	0.3	0.08	2.5	0.5	19	1.0
IIIC2	48-50	4.8	0.2	6.5	0.3	1.0	0.08	7.9	1.4	18	3.4
IIIC3	50-56	4.7	0.1	10.6	0.1	2.4	0.20	13.3	2.7	20	2.9

TABLE 22. PH, ORGANIC CARBON, CaCO_3 EQUIVALENT, EXCHANGEABLE CATION AND FREE IRON OXIDE OF
MIAMI SILT LOAM (FR-7)

Horizon	Depth inches	pH 1:1 (H_2O)	Organic Carbon %	CaCO_3 Equiv. %	Exchangeable cations m.e./100g.				CEC m.e./100g.	Total Bases m.e./100g.	Base Saturated %	% Free Fe_2O_3
					H	Ca	Mg	K				
A1	0-3	6.5	4.4		5.5	17.8	2.4	0.79	26.5	21.0	79	2.4
A2	3-8	5.1	1.4		9.6	4.1	1.3	0.31	15.3	5.7	37	2.8
A3	8-11	5.1	1.1		9.4	4.4	1.3	0.20	15.3	5.9	39	2.5
B1	11-15	5.7	1.0		6.9	7.5	2.6	0.26	17.3	10.4	60	3.3
B21t	15-19	6.4	0.9		5.7	13.0	5.3	0.38	24.4	18.7	77	4.5
B22t	19-26	6.4	0.9		6.3	11.6	5.1	0.36	23.4	17.1	73	4.3
C1	26-30	7.8		33.4								2.5
C2	30-44	7.9		34.9								2.4
C3	60-65	8.0		24.6								

APPENDIX B

Analysis of Variance Tables

TABLE 23. ANALYSIS OF VARIANCE FOR PERCENT ELONGATE GRAINS
 ($> 30 \mu$) ORIENTED PARALLEL TO ROOT SURFACE.
 CLYMER AND MIAMI B22t HORIZONS.

Sources	d.f.	SS	MS	F
Total	215	34,893.85	--	--
Soil (A)	1	0.07	0.07	0.00
Root diameter (B)	1	83.12	83.12	5.17*
Distance (C)	8	31,443.55	3,930.44	244.81**
Soil x Root Dia. (AB)	1	20.16	20.16	1.25
Soil x distance (AC)	8	247.09	30.88	1.92
Root dia. x distance (BC)	8	59.75	7.46	0.46
Soil x Root dia. x distance (ABC)	8	150.24	18.78	1.16
Error	180	2,889.84	16.05	--

TABLE 24. ANALYSIS OF VARIANCE FOR PERCENT GRAINS ($> 20 \mu$)
 DIAMETER MEASURED ALONG LINEAR TRANSECTS.
 CLYMER AND MIAMI B22t HORIZONS.

Sources	d.f.	SS	MS	F
Total	143	19,994.85	--	--
Soil (A)	1	12,171.60	12,171.60	299.23**
Root diameter (B)	1	254.66	254.66	6.26*
Distance (C)	5	1,269.13	253.82	6.24**
Soil x Root dia. (AB)	1	19.72	19.72	0.48
Soil x distance (AC)	5	1,222.97	244.59	6.01**
Root dia. x distance (BC)	5	40.57	8.11	0.19
Soil x Root dia. x distance (ABC)	5	135.14	27.02	0.66
Error	120	4,881.03	40.67	--

TABLE 25. ANALYSIS OF VARIANCE FOR PERCENT VOIDS ($> 20 \mu$) as
AS MEASURED ALONG LINEAR TRANSECTS. CLYMER AND
MIAMI B22t HORIZONS

Sources	d.f.	SS	MS	F
Total	143	5,471.33	--	--
Soil (A)	1	103.19	103.19	2.97
Root diameter (B)	1	351.25	351.25	10.11**
Distance (C)	5	536.71	107.34	3.09*
Soil x Root diameter (AB)	1	84.79	84.79	2.44
Soil x distance (AC)	5	70.69	14.13	0.40
Root dia. x distance (BC)	5	156.30	31.26	0.90
Soil x Root dia. x distance (ABC)	5	3.12	0.62	0.02
Error	120	4,165.27	34.71	--

TABLE 26. ANALYSIS OF VARIANCE FOR PERCENT s-MATRIX
MATERIAL AS MEASURED ALONG LINEAR TRANSECTS.
CLYMER AND MIAMI B22t HORIZONS

Sources	d.f.	SS	MS	F
Total	143	18,322.15	--	--
Soil (A)	1	6,470.86	6,470.86	122.48**
Root diameter (B)	1	939.93	939.93	17.79**
Distance (C)	5	2,667.90	533.58	10.10**
Soil x root dia. (AB)	1	49.82	49.82	0.94
Soil x distance (AC)	5	1,570.91	314.18	5.94**
Root dia. x distance (BC)	5	178.24	35.64	0.67
Soil x root dia. x distance (ABC)	5	104.90	20.98	0.39
Error	120	6,339.57	52.82	--

TABLE 27. ANALYSIS OF VARIANCE FOR PERCENT ORIENTED CLAY
AS MEASURED ALONG LINEAR TRANSECTS.
CLYMER AND MIAMI B22t HORIZONS.

Sources	d.f.	SS	MS	F
Total	143	586.61	--	--
Soil (A)	1	241.28	241.28	134.69**
Root diameter (B)	1	4.06	4.06	2.27
Distance (C)	5	80.33	16.06	8.96**
Soil x root dia. (AB)	1	10.13	10.13	5.65*
Soil x distance (AC)	5	14.64	2.92	1.63
Root dia. x distance (BC)	5	8.77	1.75	0.97
Soil x root dia. x distance (ABC)	5	12.43	2.48	1.38
Error	120	214.95	1.79	--

TABLE 28. ANALYSIS OF VARIANCE FOR PERCENT ELONGATE GRAINS
 ($>30 \mu$) ORIENTED PARALLEL TO ROOT SURFACE.
 CLYMER AND MIAMI A2 HORIZONS.

Sources	d.f.	SS	MS	F
Total	71	8,316.99	--	--
Soil (A)	1	11.20	11.20	0.90
Distance (C)	8	7,570.47	946.30	76.13**
Soil X distance (AC)	8	64.14	8.01	0.64
Error	54	671.17	12.42	--

TABLE 29. ANALYSIS OF VARIANCE FOR PERCENT GRAINS ($>20 \mu$)
 DIAMETER AS MEASURED ALONG LINEAR TRANSECTS.
 CLYMER AND MIAMI A2 HORIZONS.

Sources	d.f.	SS	MS	F
Total	47	1,604.36	--	--
Soil (A)	1	99.47	99.47	3.52
Distance (C)	5	288.53	57.70	2.04
Soil x distance (AC)	5	200.92	40.18	1.42
Error	36	1,015.42	28.20	--

TABLE 30. ANALYSIS OF VARIANCE FOR PERCENT VOIDS ($> 20 \mu$)
AS MEASURED ALONG LINEAR TRANSECTS. CLYMER AND
MIAMI A2 HORIZONS.

Sources	d.f.	SS	MS	F
Total	47	1,049.04	--	--
Soil (A)	1	88.56	88.56	4.66*
Distance (C)	5	212.09	42.41	2.23
Soil x distance (AC)	5	64.29	12.85	0.67
Error	36	684.09	19.00	--

TABLE 31. ANALYSIS OF VARIANCE FOR PERCENT s-MATRIX MATERIAL
AS MEASURED ALONG LINEAR TRANSECTS. CLYMER AND
MIAMI A2 HORIZONS.

Sources	d.f.	SS	MS	F
Total	47	2,203.94	--	--
Soil (A)	1	13.86	13.86	0.39
Distance (C)	5	680.05	136.01	3.89**
Soil X distance (AC)	5	252.24	50.44	1.44
Error	36	1,257.77	34.93	--

APPENDIX C**Selected X-Ray Diffractograms**

Figure 36. X-ray diffractograms of Mg saturated clay specimens from A2 horizon of Clymer loam (TU-6).

Figure 37. X-ray diffractograms of Mg saturated clay specimens from B2lt horizon of Clymer loam (TU-6).

Figure 38. X-ray diffractograms of Mg saturated clay specimens from IIB3 horizon of Clymer loam (TU-6).

Figure 39. X-ray diffractograms of Mg saturated clay specimens from A2 horizon of Miami silt loam (FR-7).

Figure 40. X-ray diffractograms of Mg saturated clay specimens from B22t horizon of Miami silt loam (FR-7).

Figure 41. X-ray diffractograms of Mg saturated clay specimens from C1 horizon of Miami silt loam (FR-7).

Root-Soil Moisture Relationship

An effort was made to measure the influence of moisture tension on root-soil volume. The question of interest is whether or not a void or space exists between the soil material and root surface at different levels of moisture; and if so, does this space become larger during seasonally dry periods? This study attempted to make quantitative measurements of root diameters that might be associated with changes in moisture stress. The measurement of root diameters and soil-root interface diameters for soil blocks receiving different moisture stresses were made under laboratory conditions. Keeping in mind that the results cannot be directly applied to existing field conditions, but should provide information on some of the dynamics involved.

Smaller blocks (6 x 6 x 1½ cm) were cut with a diamond saw in a cold room (-10° C) from frozen soil blocks containing roots. Frozen blocks were coated with Dow Saran Resin F-120. Prior to coating with Saran resin, the exposed root sector was covered by taping an inverted small plastic planchet over it. The purpose of covering the root section and adjacent soil material was to prevent the saran from covering the root or permeating space adjacent to the root. After the saran had dried, the planchet and tape were carefully removed exposing the root section and surrounding soil material. The blocks with exposed root sections were seated on a tension table and allowed to equilibrate with water at 0 cm tension for two days. Then a tension of 60 cm was applied overnight. The blocks were then measured using a traveling microscope calibrated to read to one micron. Traverses at right angles to each other were made across the root diameter and soil-

root interface. The measured traverse was marked on the root to facilitate making subsequent measurement on the same part of the root after it was equilibrated at a lower level of moisture content.

After recording the above measurements the blocks were equilibrated in a pressure membrane at pressure equivalent to 15 atmospheres for 48 hours and making diameter measurement immediately following removal.

Next the blocks were placed in a dessicator containing a 30% by weight mixture of sulfuric acid and water. This mixture gives a relative humidity of 75% corresponding to a pF of 5.6 and $\approx$ 400 atmospheres (9). The blocks were allowed to equilibrate in the dessicator with sulfuric acid-water mixture for one week and then diameter measurements were again recorded.

The use of saran to coat the block alleviated the problems previously experienced where radial cracks developed outward from root upon thawing and also in case of the Clymer soil, it was too fragile to be handled without some support. The most serious limitation of the technique employed was the inability to distinguish the soil-root boundary. In some instances the cork or bark layer separated from the rest of root and in other cases it seemed to curl slightly, causing a large change in diameter measurements. Although the data collected were quite erratic, there seemed to be a trend suggesting a decrease in root diameter with increased moisture stress. Spaces or voids were observed between root surface and soil material after 15 atmosphere treatment and particularly after equilibrating with sulfuric acid-water mixture. Measurements were also recorded on length and width of

blocks after being subjected to the above treatments. A linear decrease of 1.6% was observed for Clymer horizons going from 15 atmosphere to 400 atmosphere treatments. For the same treatment the Miami B22 showed a lineal decrease of 14.1%.

Although data collected were adjudged to be inconsistent, there appears to be forces moving toward the root, contraction, as the surface of block loses moisture and also an outward force away from root in immediate vicinity of root upon removal of moisture by high tensions. Hence, the void area may be greater during period of high moisture stress in the field than under laboratory conditions where all sides of the block are open. Thin sections observed of fine textured Miami suggest that dessication cracks may occur at intervals of 0.5 to 1.0 mm away from the soil-root interface. This could be attributed to finer materials and smaller size pores capable of retaining more water than adjacent soil fabric.

This part of the study was undertaken in latter part of the overall investigation and, therefore, time became a limiting factor. Although the data taken were erratic, it is felt that this basic study has merit and by refining the techniques it would provide useful information.

Two ways of improving the technique would be to use a dye or stain root to provide a sharper boundary between soil material and root. Another improvement would be the use of a portable traveling microscope set up to measure samples without having to move them from tension table or pressure membrane.

Table 32. ROOT AND SOIL-ROOT INTERFACE DIAMETER MEASUREMENT FOLLOWING TREATMENT OF
ROOT AND SOIL WITH DIFFERENT MOISTURE TENSIONS. MIAMI A2 and B22t HORIZONS
AND CLYMER IIB22t HORIZON

Sample	60 cm Tension		15 Atmospheres Tension		H ₂ SO ₄ + H ₂ O $\approx$ 400 Atm.	
	Root dia. mm	Soil-root Interface dia. mm	Root dia. mm	Soil-root Interface dia. mm	Root dia. mm	Soil-root interface dia. mm
1) Miami B22	6.442	7.214	5.339	7.269	----	----
	6.516	6.616	5.758	6.704	----	----
2) Miami B22	4.193	4.823	6.076	6.343	5.886	6.257
	6.046	6.395	5.971	6.367	5.979	6.338
3) Miami B22	5.004	5.004	----	----	5.198	5.384
	5.163	5.618	5.174	5.491	5.275	5.484
4) Miami A2	6.374	6.374	6.243	----	6.644	7.153
	6.475	7.060	7.044	7.541	6.745	7.580
5) Clymer B22	25.378	25.622	25.640	26.019	25.610	26.092
	21.904	23.387	21.843	22.130	21.598	22.576
6) Clymer B22	26.117	26.811	27.104	26.550	24.983	26.781
	25.064	25.271	25.142	25.460	24.227	26.114

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