CLAY MINERAL COMPOSITION OF VERTISOLS OF NORTH-CENTRAL ARIZONA

by

Ezzeddin Taib Rahoma

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APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

David M. Hendricks
DAVID M. HENDRICKS
Associate Professor of Soils, Water
and Engineering

Sept. 6, 1974
Date

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ABSTRACT

Two pedons representative of the Springerville soil series were studied to determine their clay mineral properties. Particle size analysis showed a high percentage of clay content. In some horizons the clay content is as high as 50%. Quantitative analysis of clay minerals showed that the per cent montmorillonite ranges from 30 to 43% in the fine clay (< 0.2μ) fraction, and from 0.5 to 30% in the coarse clay (2-0.2μ) fraction, while in the fine silt (5-2μ) the percentage ranges from 12 to 18%. The per cent vermiculite ranges from 7 to 16% in the fine clay fraction, 3 to 6% in the coarse fraction, and from 4 to 8% in the fine silt fraction. X-ray diffraction data showed the dominance of montmorillonite with the presence of vermiculite, mica, kaolinite, and the possible presence of chlorite. Elemental analysis data showed a great similarity among the horizons. The silica-alumina, silica-iron, and silica-sesquioxide ratios were high indicating that limited leaching conditions prevailed in the system. The uniformity among the pedons of Springerville soils is mainly due to the same soil forming processes acting on the area.

INTRODUCTION

Vertisols represent important and dynamic soils in materials weathered from basalt flows, cinders, and related volcanic material in various parts of central Arizona (see Figure 1). These soils have a peculiar habit of vertical churning, and on partial drying form wide deep cracks due to shrinkage caused by montmorillonite clays. These cracks, often 4 to 6 inches wide at the surface, may extend to a depth of 3 to 4 feet. Soil material from the surface as a result of wind, water, and animal activity often falls into the cracks. During wet seasons the montmorillonite clays expand and the surface cracks close.

Considerable research has been done on Vertisols because of their characteristic habit, and their importance to agricultural use in some areas as productive soils for some crops. Vertisols in Arizona are used primarily for range (Johnson, Cady, and James, 1962).

Vertisols in the north-central part of Arizona consist primarily of the Springerville series. Two pedons representative of the Springerville series were sampled for mineralogical and chemical analysis from western Yavapai County.

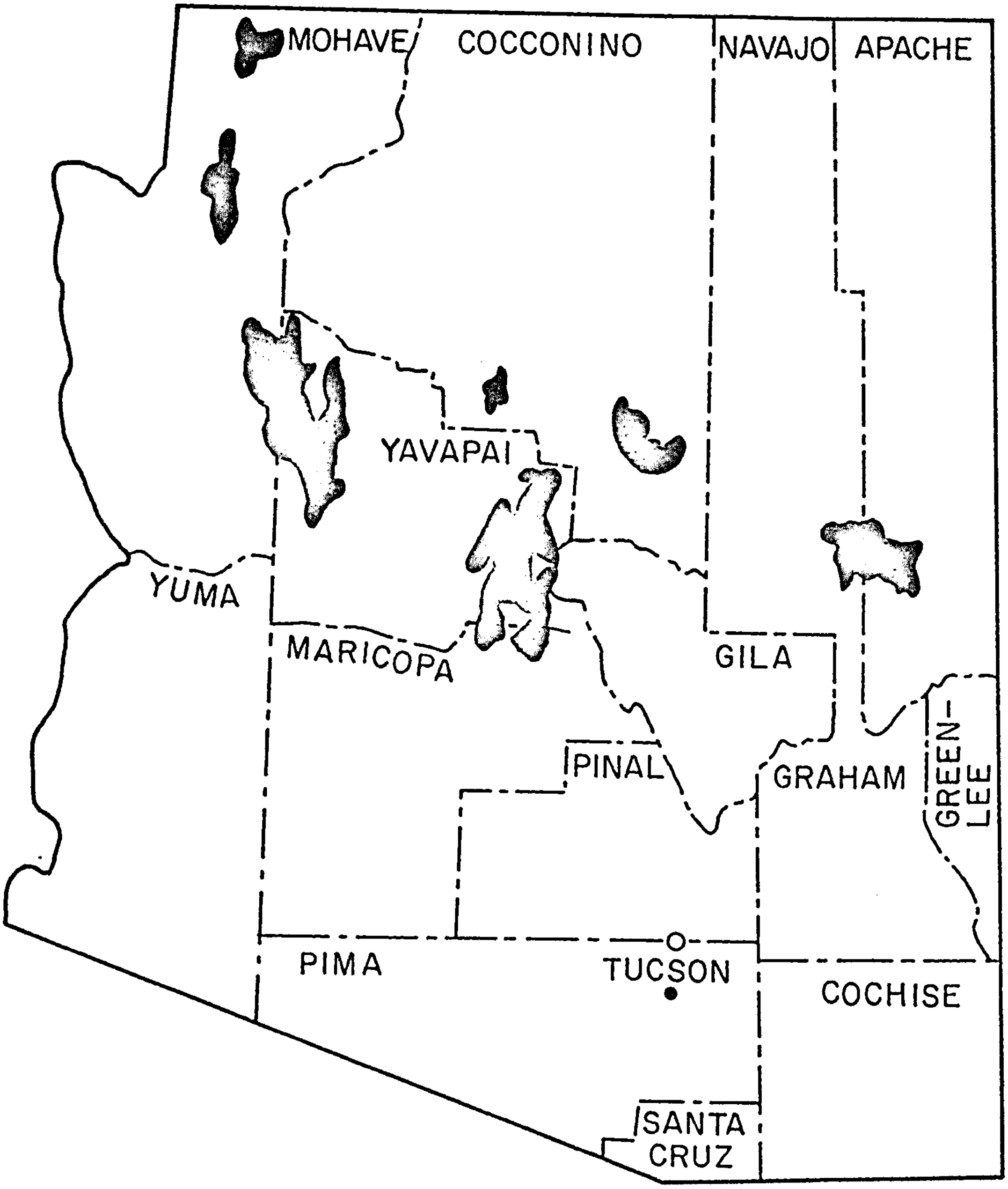


Figure 1. Map of Arizona showing the distribution of Vertisols.

The major objective of this study is to determine the basic nature of the clays of the two pedons of the Springerville series in order to make a contribution toward a greater understanding of the intrinsic properties of the Springerville and related soils.

REVIEW OF LITERATURE

Nature of Vertisols

Vertisols are characterized by a high clay content, consisting dominantly of an expanding type of clay, formation of wide cracks on the surface, high C.E.C., and are generally dark in color. The differences in some chemical, physical, or mineralogical properties among Vertisols are due to the differences in the soil forming factors that are acting on these soils, intensity of weathering, and type and amount of clay present. All studies of Vertisols have shown that a great similarity in their physical and mineralogical properties exist, although some differences in their chemical composition have been observed.

Dudal and Branao (1965) reported that Vertisols contain high clay percentages, are plastic and sticky when wet, and mostly dark in color with low chromas. Lack of horizon development in Vertisols is mainly due to the action of soil forming processes associated with shrinking and swelling. "Gilgai" formation is one of the characteristics of Vertisol soils accompanined by a vertical churning as a result of the contraction and the expansion of the soil. As a result of all these mechanisms together the soil is gradually overturned to some depth. The sliding of one mass of soil on another caused by the pressures exerted by expansion produces another important feature of Vertisols called "slickenslides." Mineralogically montmorillonite and expandable mixed layer clays were reported as the main constituents of Vertisols in most areas (Dudal and Branao, 1965).

Mohr, Vanbaren, and Vanschuylenborgh (1972) stated that the most conspicuous characteristics of most Vertisols is their shrinking and swelling capacity upon wetting and drying. The cracks that are formed as a result of shrinking are hexagonal in shape with a prismatic macro-structure. The color of these Vertisols of tropical regions is generally dark to very dark which is not due to the high content of organic matter as noted by Mohr et al. (1972). The dark color mainly reflects the presence of carbon that is not oxidizable with H_2O_2 in the clay fractions. One of the typical features of Vertisols is the presence of nodules or concretions of lime in some or all of the horizons (Mohr et aL, 1972). This is also typical in the two pedons of the Springerville Vertisols considered in this thesis.

The surface horizon structure of most Vertisols is very fine to medium granular which develops from a brittle surface crust which forms at the surface immediately after the rainy seasons.

Ahmed and James (1969) reported that parent materials under different moisture regimes have a strong influence on the development and formation of Vertisols. Caribbean Vertisols have two types of parent material related to the moisture regime prevailing in the area. In a very wide range of rainfall regimes the soils developed on marl and limestone or chalk, while similar soils developed on marl, calcareous sandstone, and indurated limestone under an annual rainfall of 120 cm or less.

Kunze, Oakes, and Bloodworth (1963) described in their study of the Grumusols of the coastal plain of Texas that the A1 horizon in the Beaumont clay has a thickness of 12 to 20 inches with a dark gray color. The structure of the Ac horizons are weak to moderate coarse blocky to very weak, the structure being influenced by the type of vegetation. The pH of the A horizons varies from 5.0 to 8.0 and is strongly acidic or neutral in the parent material.

Springerville soils are deep soils on well drained uplands (Williams and Anderson, 1967). These soils characteristically have a high percentage of stones (30-50 per cent), mainly basaltic in composition. They have dark grayish-brown to reddish-brown surface horizons. The underlying horizons are brown or reddish-brown. Due to the strong tendency of shrinking and swelling and much heaving the horizons are difficult to distinguish.

The Vertisols of central Arizona are on well-drained areas and are mainly grayish brown through brown to reddish brown in color (Johnson et al., 1962). They have a high clay content increasing with depth. The common features of Vertisols such as churning, slickenslides, and turning over of the soil materials are present. Johnson et al. (1962) stated that Arizona Vertisols have a stronger chroma and are better aerated than some other kinds of common Vertisols. They listed some of the important characteristics of Arizona Vertisols as:

1. Montmorillonite clay.
2. High base saturation with Ca and Mg.
3. High shrinkage ratio; cracks and slickenslides.
4. Moist and dry seasons.
5. Lack of textural horizons.
6. Presence of free calcium carbonates.
7. Evidence of churning.

MORPHOLOGY AND CLASSIFICATION OF SPRINGERVILLE SOILS

Springerville soils together with other Vertisols are unique in their characteristics and show great similarities in their physical, chemical, and mineralogical properties. They often have coarse fragments consisting of gravel, cobbles, or stones. These coarse fragments are often concentrated on the soil surface but may be present within the soil in amounts up to 40 per cent by volume. Depth to bedrock ranges from 30 to 70 inches (Soil Conservation Service, 1971). During the dry seasons in Arizona (in June and in October) the Vertisols have cracks 1 inch or more wide and 20 to 36 inches deep. In most years these cracks remain open for a total of more than 90 days, but not throughout the year. Most of the horizons have a per cent base saturation of 80 to 100. The color of both A and C horizons is mainly of 7.5 YR hue, but may range from 10YR through 5YR, values are 3 through 5 dry and 2 through 4 moist, and chromas are 2 or 3. The texture of the profile is generally uniform ranging from silty clay to clay.

The two pedons selected for this study are composed of dark brown heavy clay which upon wetting and drying form wide cracks on the soil surfaces. The soils are moderately alkaline (pH 8.0) with no apparent salt accumulation. Clay content is high with a moderately slow to very slow permeability. These soils are well drained with deep subsurface horizons (50-60 inches deep). Basalt rock is the main compound of the parent material. Near the surface the color is dark brown with an increase in the value and chroma with depth.

Vertisols in north-central Arizona include two series: the very fine (> 60% clay) and black-colored McNary series which is of limited extent and the brown-colored Springerville series (Buol, 1964). The names are taken from the towns of McNary and Springerville, Arizona. The Springerville series is classified as a member of a fine, montmorillonitic mesic family of Typic Chromusterts (U.S.D.A., 1967).

Usterts were defined in the 7th approximation classification (U.S.D.A., 1960) as follows: "They are the Vertisols that have chromas of more than 1.5 throughout the upper 30 cm (12 inches) and that lack distinct or prominent mottling within the surface 75 cm (30 inches). The hues are often redder than 10YR."

The soil taxonomy (U.S.D.A., 1974) lists the main characteristics of the Usterts as follows:

1. Cracks that open and close more than once in most years.
2. Mean annual soil temperature of 22°C or more.
3. Mean summer and mean winter soil temperatures at a depth of 50 cm that differ by > 5°C.

Springerville soils are classified according to the U.S.D.A. (1974) as follows: Order--Vertisol; Suborder--Ustert ; Great Group--Chromustert; Sub-Group--Typic Chromusterts.

The Springerville was formerly classified in the Grumusol Great soil group (Johnson et al., 1962).

Vertisol Minerology

As a result of many studies done on Vertisols, montmorillonite and "mixed layer" clays have been reported to be an important constituent of the clay fraction (Dudal and Branao, 1965). Vermiculite, illite, kaolinite, and quartz are other constituents present in different amounts. The physical and chemical environments determine the degree of weathering and the type of clay mineral formed.

Rich and Kunze (1964) listed some factors favoring the formation of montmorillonite as follows:

1. High Si:Al ratio.
2. Relative abundance of Mg, Fe, Ca, Na, and K.
3. Lower concentration of H ions.
4. Parent material rich in Mg, Fe, and Ca such as mafic rocks and volcanic ash of intermediate composition.
5. Weathering evironment and efficiency of drainage.

Grim (1968) concluded that the favorable conditions for the formation of kaolinite type of minerals are low temperatures and acid conditions, while in alkaline conditions mica will tend to form in the presence of K. If Mg instead of K is present montmorillonite will form.

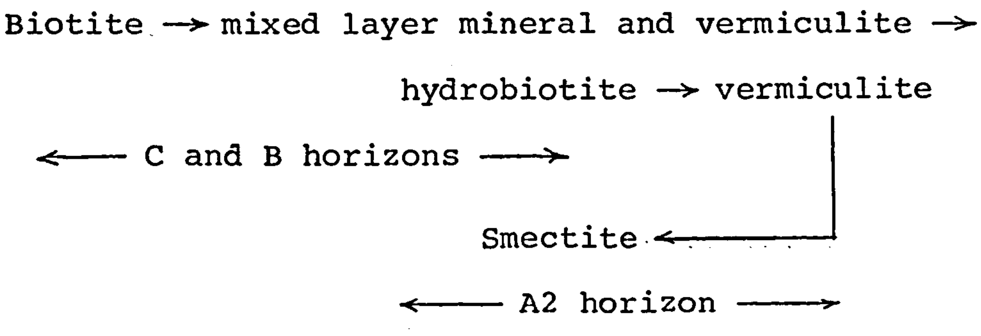
Mica may weather through several stages of alteration and under certain conditions form montmorillonite. Fields and Swindale (1954) listed the important stages in the weathering of mica in soils as follows:

1. Mica. Unweathered mica (muscovite and biotite) with basal spacing of 10 Å.
2. Illite. Still 10 Å as first order basal spacing except hydroxyl has increased and K decreased with an increase in exchange capacity.
3. Vermiculite. The above micaceous minerals are essentially non-expanding. The remainder are expanding, with basal spacings greater than 10 Å.

The weathering sequence in the formation of montmorillonite and vermiculite as weathering products of mica as described by Fields and Swindale (1954) is as follows:

$$\text{mica} \xrightarrow{H^+} \text{illite} \xrightarrow{H^+} \text{vermiculite} \xrightarrow{Ca^{++}} \text{montmorillonite}$$

Data of some samples of podzolic soil reported by Kapoor (1972) indicated that the breakdown of biotite during the early stages of weathering results in the formation of some vermiculite and mixed-layer mineral. As the interlayer regions increased, the build up of mixed layer mineral increased with an alternation of 10 Å biotite and 14 Å vermiculite units to form hydrobiotite. At the late stages of weathering vermiculite and montmorillonite tend to form. The sequence of this weathering as discussed by Kapoor (1972) is as follows:



Ojanuga (1973) concluded that in a humid tropical climate, mica weathers to form kaolinite under acid (pH 4.9-5.2) conditions. Under these conditions weathering of mica is considered as a stage in biotite weathering especially when the parent material is granitic rock.

METHODS AND MATERIALS

The Soils and Their Environment

The importance of the five soil forming factors have been recognized for about one hundred years. More recently Jenny (1941) has extended the concept of soil forming factors and given them a rigorous mathematical treatment. The interaction of the particular nature of the soil forming factors climate, organisms (mainly vegetation), parent material, topography, and time associated with the Vertisols of northern Arizona have resulted in the formation of their properties.

Climate

The mean annual soil temperatures in the Springerville ranges from 47° to 59°F. The mean annual precipitation ranges primarily from 12 to 16 inches although Springerville soils are reported to occur in rainfall areas of more than 20 inches. Johnson (1962) described the climatic conditions in the northern part of Arizona, including where the Springerville soils are found, to be characterized by thunderstorms accompanied by precipitation in July, August, and September. In December, January, and February gentle rain prevails. Springerville soils become almost completely dry in May, June, and July. In the area where the two pedons are sampled the rainfall ranges from 14 to 16 inches and the mean annual soil temperature is estimated to be about 52°F.

Vegetation

The vegetation associated with the Springerville soils, especially in the warmer drier part, is primarily grass type vegetation including muhly, tabosa, sideoats grama, squirreltail, blue grama, three-awns, cliff rose, and some annuals. Juniper, piñon pine, cacti, and ceanothus are also common. At the sites of both Springerville pedons sampled for this study the vegetation is quite similar to those listed for the Springerville soils in general. Vertisols in Arizona are used mainly as grazing areas or serve as important watersheds during a certain period of the year.

Parent Material

The Vertisols in the north-central part of Arizona are formed on weathered or partially weathered basalt, volcanic cinders, and bombs. Johnson et al. (1962) considered the parent material of the Springerville soils to be derived from volcanic cinders and weathered basalt. The amounts of mica in the parent material are very low as compared to other Vertisols. The depths to the bedrock in both pedons used in this study ranged from 30 to 70 inches. The underlying R horizons in both soils are composed mainly of basalt. Lime coatings of varying thickness on the rock surfaces are common at a depth of 60 inches or more. At both sites the soils contain 30 to 40% rock fragments over 3 inches in diameter.

Topography

The Springerville soils are on upland plains or mesas at elevations of 4200 to 7500 feet. The slopes are dominantly 1 to 5 per cent although in a few areas they range up to 10 per cent. The soil shows slight gilgai micro relief. The Springerville cobbly clay pedon occurs on a gently sloping basalt plain with 4 per cent slope and general convex shape. The other pedon is on a gently sloping basalt hill of a convex complex relief with approximately 7 per cent slope. The Springerville cobbly clay sampled occurs at an elevation of 5800 feet and the Springerville gravelly clay is found at 6100 feet.

Time

Rode (1961) considered time as being less important in soil formation than other factors because it is not a source of energy or matter. Nevertheless, soil features tend to become more pronounced with time. Yaalon (1971) considers the age of features characteristic of Vertisols such as gilgai, slickenslides, and mottles to be more than approximately 10^3 years. The basalts associated with the Springerville soils are considered to be late Tertiary (Jagger and

Palache, 1905). The basalt mesas and plateaus where the Springerville soils are found are quite stable surfaces and the Springerville soils can be considered as old soils even though they lack morphological development.

Pedon Descriptions of the Two Springerville Soils

Springerville Cobbly Clay

Location: SE 1/4 Sec. 14; T21N, R28W, Yavapai County, Arizona.

A1. 0-2" Dark brown (10YR4/3) cobbly clay, dark brown (10YR3/3) moist; strong fine granular structure; loose, friable, sticky and plastic; few very fine and fine roots; many interstitial pores; non-effervescent; moderately alkaline (pH 8.0); clear smooth boundary.

C1. 2-36" Dark brown (7.5YR2/4) clay, dark brown (7.5YR3/2) moist; parallelpiped structure; hard, firm, very sticky and plastic; abundant medium and coarse and few fine roots; very few fine tubular pores; many fine and medium slickenslides and pressure faces; slightly effervescent; moderately alkaline (pH 8.0); clear wavy boundary.

C2ca. 36-50" Yellowish-red (5YR4/6) gravelly clay (20% gravels) yellowish-red (5YR4/6) moist; with many medium and coarse distinct pinkish-white

(5YR8/2) and reddish-yellow (7.5YR7/6) $CaCO_3$ mottles, reddish-yellow (5YR6/8) moist; firm, sticky and plastic; few fine roots; many fine tubular pores; slightly effervescent; moderately alkaline (pH 8.0); gradual wavy boundary.

C3ca. 50-58" White (5YR8/1) and reddish-yellow (5YR6/8) basalt rock with lime material in fractures; pinkish-white (5YR8/2) and reddish-brown (5YR4/3) moist; slightly effervescent; moderately alkaline (pH 8.0); abrupt wavy boundary.

R. 58-60"+ Gray (2.5Y5/0) basalt bedrock, very dark gray (2.5Y3/0) moist; with white (7.5YR8/0) and reddish-yellow (7.5YR6/8) lime coatins on surface.

Springerville Gravelly Clay

Location: SW 1/4, Sec. 36, T12N, R1E, Yavapai County, Arizona.

A1. 0-2" Brown (7.5YR4/2) gravelly clay, dark brown (7.5YR3/2) when moist; weak fine granular structure; loose, friable, sticky and plastic; plentiful very fine roots; common micro and very fine interstitial pores; 25% gravel" slightly effervescent; moderately alkaline (pH 8.2); abrupt smooth boundary.

C1. 2-8" Brown (7.5YR4/2) clay, dark brown (7.5YR3/2) when moist; massive; hard, firm, sticky and plastic; abundant very fine roots; common micro and very fine interstitial pores; more than 5% gravel; common pressure faces; slightly effervescent; moderately alkaline (pH 8.2); clear smooth boundary.

C2. 8-46" Brown (7.5YR4/2) clay, dark brown (7.5YR3/2) when moist; massive; very firm, sticky and plastic; few very fine roots; common very fine and fine interstitial pores; many medium slickenslides; slightly effervescent; moderately alkaline (pH 8.2); abrupt smooth boundary.

C3ca. 46-67" Mottled white (7.5YR8/1) and brown (7.5YR5/2) very gravelly clay loam which is composed of basalt, gravel, ash, and cinders, mottled white (10YR8/1) and brown (7.5YR5/4) when moist; massive; hard, firm, sticky and slightly plastic; many very fine interstitial pores; 55% fine gravel; violently effervescent; moderately alkaline (pH 8.4); abrupt wavy boundary.

R. 67-75" Dark Gray (7.5YR4/0) lime-coated basalt bedrock.

Removal of Carbonates, Organic Matter, and Particle Size Separation

Several treatments using sodium acetate buffered at pH 5.0 were used to remove carbonates (Grossman and Millet, 1961). Organic matter was removed by oxidation with hydrogen peroxide (Jackson, 1956). The silt plus clay (< 50μ) fractions were separated from the sand and fine gravel by wet sieving through a 300 mesh sieve. The coarse silt (50-20μ), medium silt (20-5μ), fine silt (5-2μ), and clay (< 2μ) separates were fractionated by sedimentation and decantation (Jackson, 1956). The appropriate sedimentation times were chosen for each separation to satisfy Stokes law. The fine clay (< 0.2μ) was separated from the coarse clay (2-0.2μ) by repeated centrifugation and decantation (Jackson, 1956).

Total Elemental Analysis

The determination of Ti, Fe, Mg, Ca, K, and Na followed the hydrofluoric-perchloric acid dehydration-dissolution method of Riley (1958). Ti was determined spectrophotometrically using tiron (Rigg and Wagenbauer, 1961). Fe, Mg, Ca, K, and Na were determined by atomic absorption using a Perkin Elmer model 303 spectrophotometer. Strontium chloride and perchloride acid were used to minimize possible interferences in the determination of Ca and Mg (Dickson and Johnson, 1966). SiO_2 was determined by the molybdenum blue method (Shapiro and Brannock, 1956) and Al_2O_3 was determined spectrophotometrically using chrome azurol S for color development (Hendricks, 1974). SiO_2 and Al_2O_3 were determined following sodium hydroxide fusion.

Quantitative Determination of Clay Minerals

The methods used to gain a quantitative estimate of the different clay minerals are essentially those described by Alexiades and Jackson (1965). Vermiculite was determined on the basis of the part of the cation exchange capacity measured by Ca replaced by Mg which is blocked by K fixation on oven-drying at 110°C and subsequently not exchanged by NH_4. The cation exchange capacity measured by the nonfixed K replaced in 1N NH_4Cl was used to give a measure of the montmorillonite content after making a correction for the exchange capacities of other clay minerals. Total K was used to provide a measure of the mica present. Amorphous material was determined on the basis of the quantity of SiO_2 and Al_2O_3 removed by selective dissolution by a 2.5 minute treatment with boiling 0.5N NaOH. The SiO_2 and Al_2O_3 were determined spectrophotometrically by the molybdenum blue (Shapiro and Brannock, 1956) and chrome azurol S (Hendricks, 1974) methods, respectively.

X-Ray Diffraction Analysis

A Norelco X-ray diffractometer system was used for the X-ray analysis of the fine silt (5-2μ), coarse clay (2-0.2μ), and fine clay (<0.2μ) separates. Cu Kα radiation was used while Cu Kβ radiation was removed and background and scatter radiation was reduced with a curved graphite monochrometer and pulse height discrimination.

Samples were mounted on glass petrographic slides using the paste method described by Theisen and Harward (1962). The following treatments were made prior to X-ray diffraction scans:

1. Mg--saturated and equilibrated at 54 per cent relative humidity.
2. Mg--saturated and solvated with glycerol.
3. Mg--saturated and solvated with ethylene glycol.
4. K--saturation and heated to 105°C.
5. K--saturation and heated to 300°C for three hours.
6. K--saturation and heated to 500°C for three hours.

Details concerning the above treatments are described by the Western Regional Technical Committee, W-87 (1970).

RESULTS AND DISCUSSION

Particle Size Distribution

The total clay fraction (< 2μ) in the two pedons of Springerville soils is about 50% of the fine earth. The fine clay (< 0.2μ) increases with depth from 21.6% at depths of 0 to 2" in the Springerville cobbly clay to 25.5% at depths of 2 to 36" and then decreases again. In the Springerville gravelly clay the fine clay (< 0.2μ) increases from 24.8% at depths of 0 to 2" to 26.8% at depths of 2 to 8" and then decreases to 11.0% at depths of 46 to 67". The particle size distribution of the two pedons is shown in Tables 1 and 2.

X-Ray Diffraction Analysis

The fine clay, coarse clay, and fine silt from all horizons of the Springerville cobbly clay and Springerville gravelly clay were analyzed by X-ray diffraction. The diffractograms of the A1 and C1 horizons from each pedon are shown in Figures 2 through 25. Diffractograms of the fine silt, coarse clay, and fine clay of the other horizons are on file in the Department of Soils, Water, and Engineering, The University of Arizona.

Estimates of the relative amounts of the different clay minerals present in the three size fractions of all horizons in the two soils as interpreted from the X-ray

Table 1. Particle size analysis of Springerville cobbly clay.

Horizon	Depth inches	% sand 2-0.05 mm	% very coarse silt 50-20 μ	% coarse silt 20-10 μ	% medium silt 10-5 μ	% fine silt 5-2 μ	% coarse clay 2-0.2 μ	% fine clay <0.2 μ
A1	0-2"	1.9	39.9	5.6	10.3	9.3	11.6	21.6
C1	2-36"	0.8	30.3	10.9	6.1	5.6	20.8	25.5
C2Ca	36-50"	23.8	29.5	9.6	2.1	2.0	15.1	17.9
C3Ca	50-58"	24.3	34.6	10.5	4.3	1.6	9.9	14.7

Table 2. Particle size analysis of Springerville gravelly clay.

Horizon	Depth inches	% sand 2-0.05 mm	% very coarse silt 50-20 μ	% coarse silt 20-10 μ	% medium silt 10-5 μ	% fine silt 5-2 μ	% coarse clay 2-0.2 μ	% fine clay <0.2 μ
A1	0-2"	8.0	33.6	5.5	9.5	4.4	14.7	24.8
C1	2-8"	0.5	31.4	10.8	6.4	1.8	22.4	26.8
C2	8-46"	4.5	33.9	11.2	2.3	1.5	19.9	26.7
C3Ca	46-67"	48.2	18.1	5.7	5.7	4.2	7.2	11.0

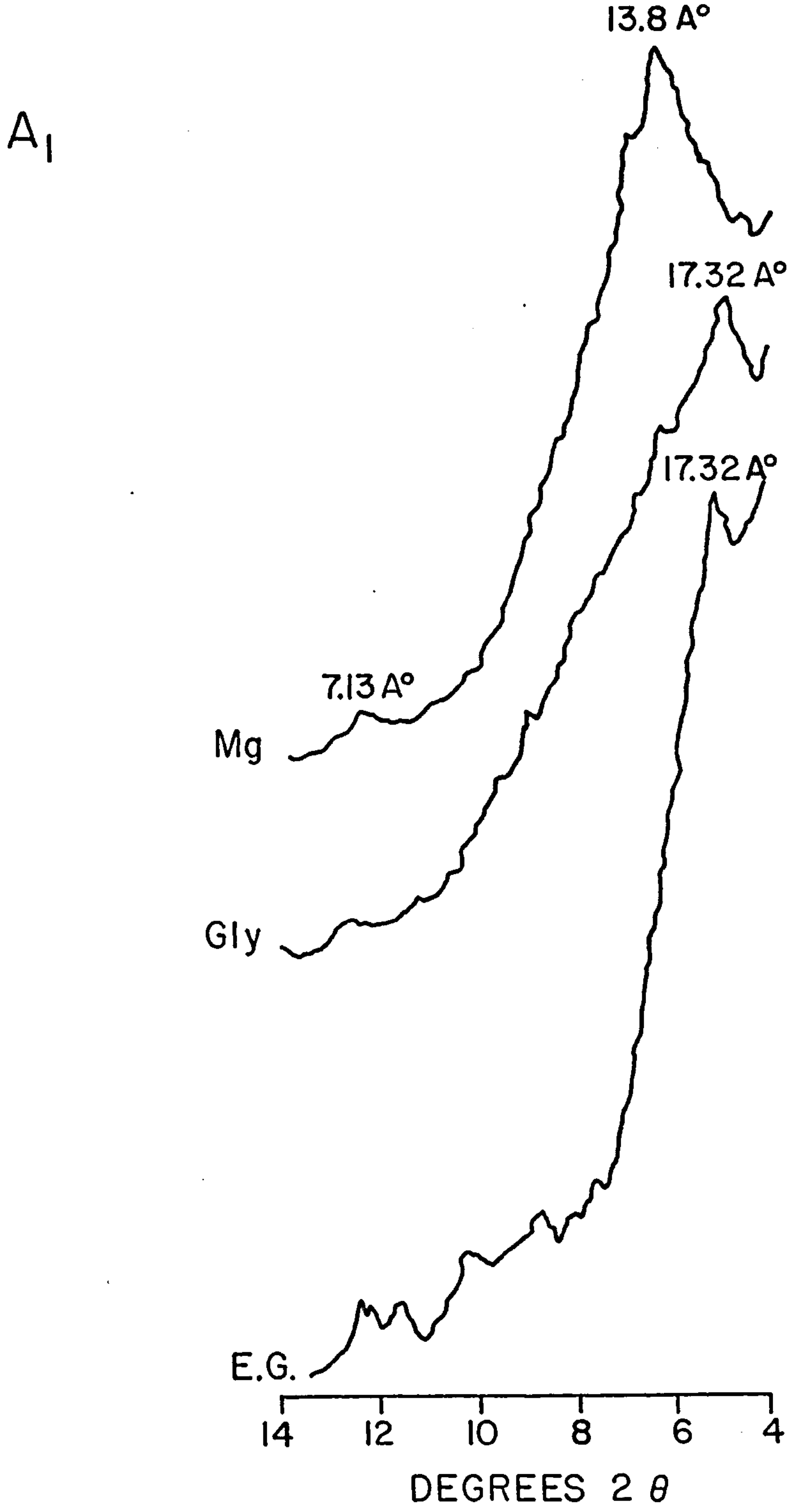


Figure 2. Diffractograms of Springerville cobbly clay, Al horizon (0-2"), fine clay, Mg-saturated and solvated with glycerol and ethylene glycerol.

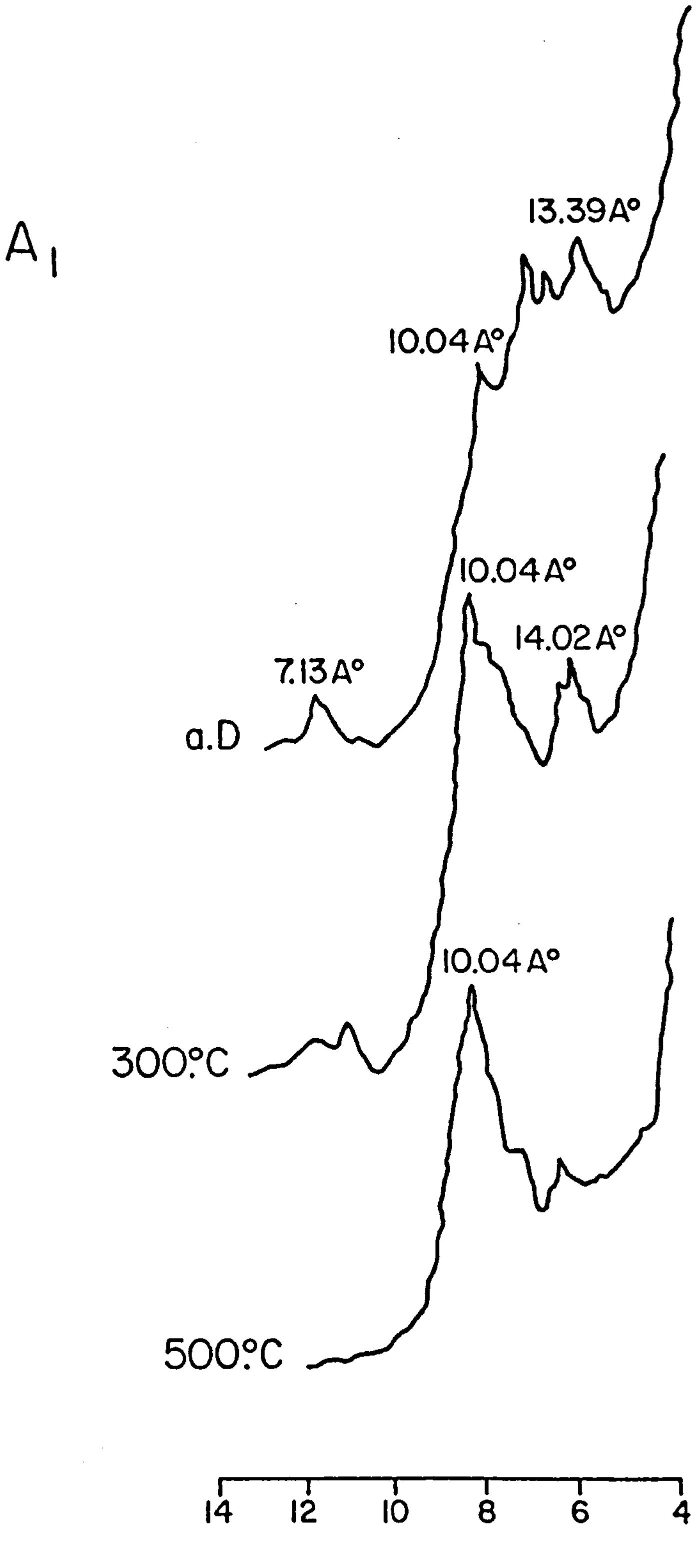


Figure 3. Diffractograms of Springerville cobbly clay, A1 horizon (0-2"), fine clay, K-saturated and heated to 300° and 500°C.

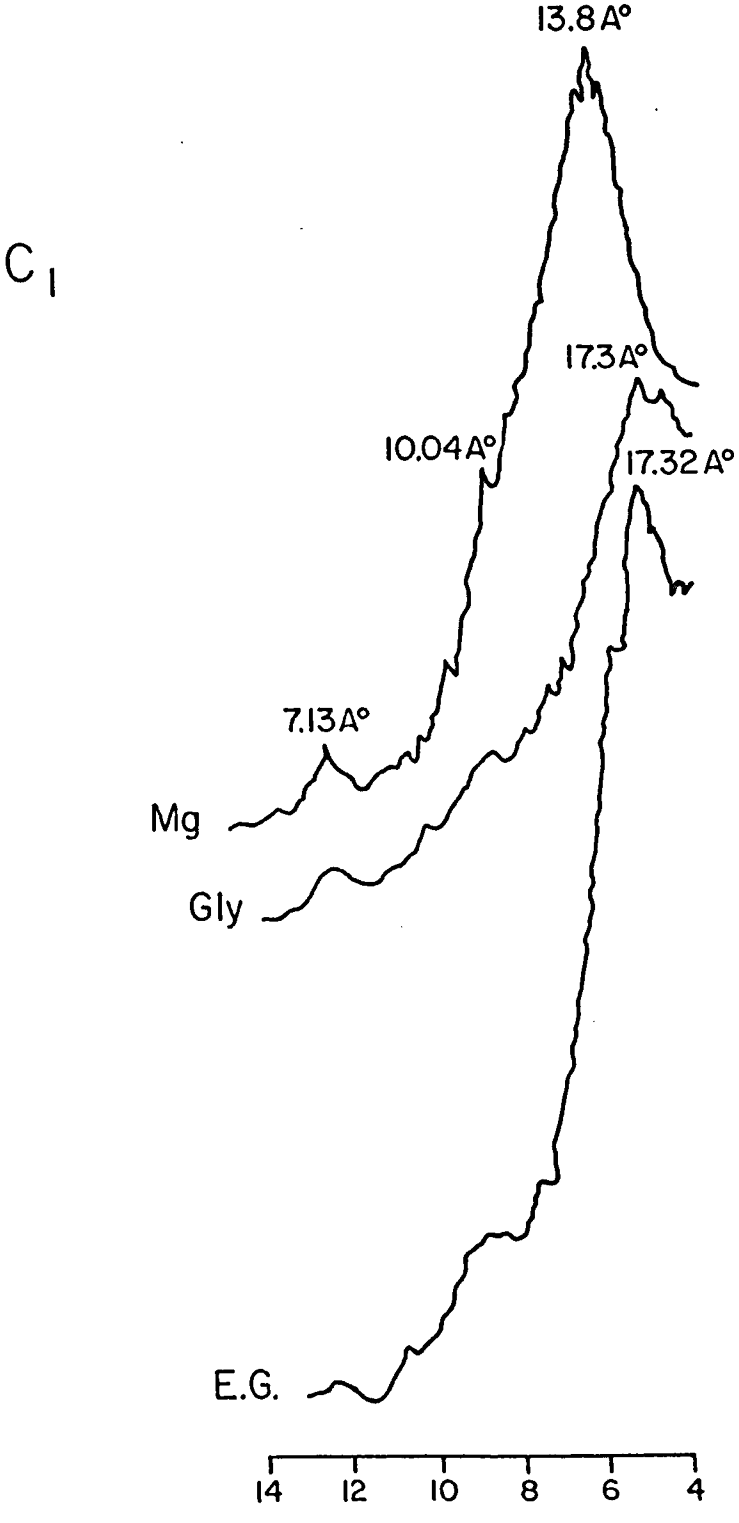


Figure 4. Diffractograms of Springerville cobbly clay, C1 horizon (2-36"), fine clay, Mg-saturated and solvated with glycerol and ethylene glycol.

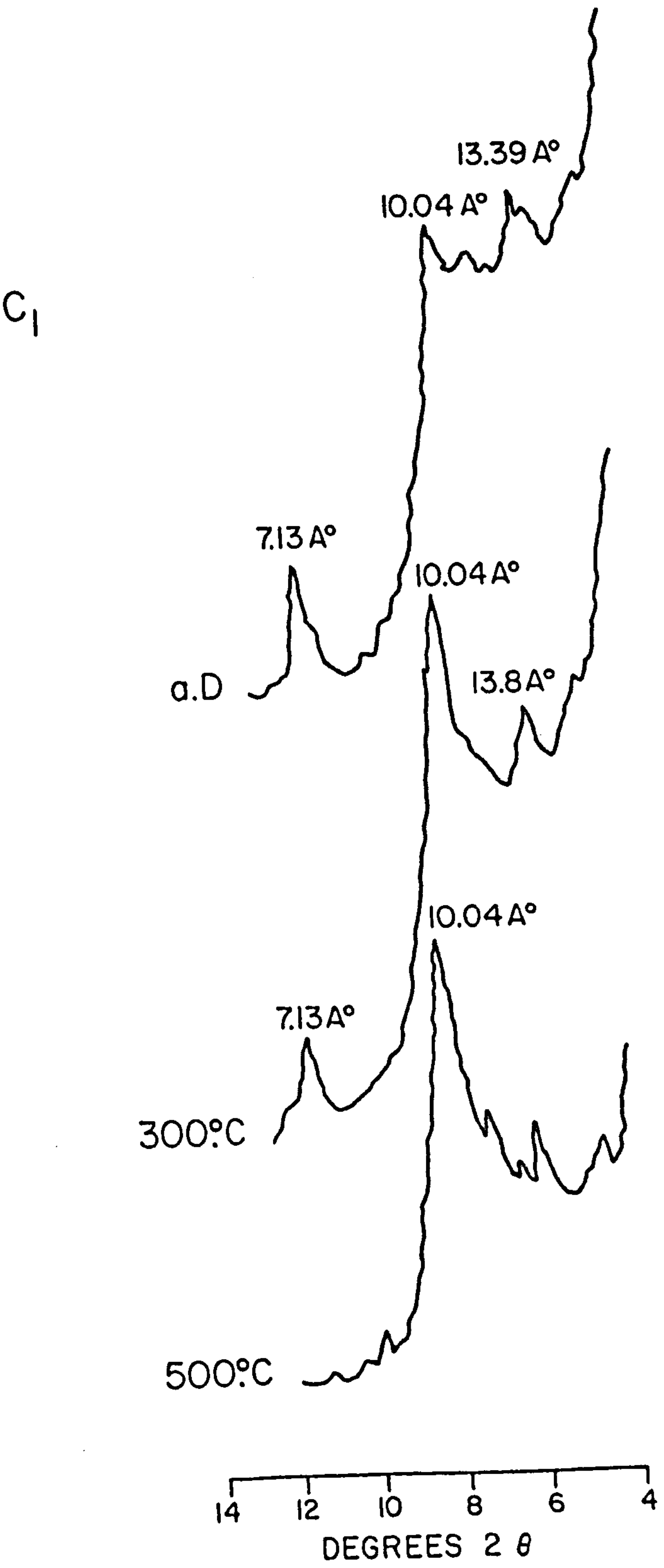


Figure 5. Diffractograms of Springerville cobbly clay, C1 horizon (2-36"), fine clay, K-saturated and heated to 300° and 500°C.

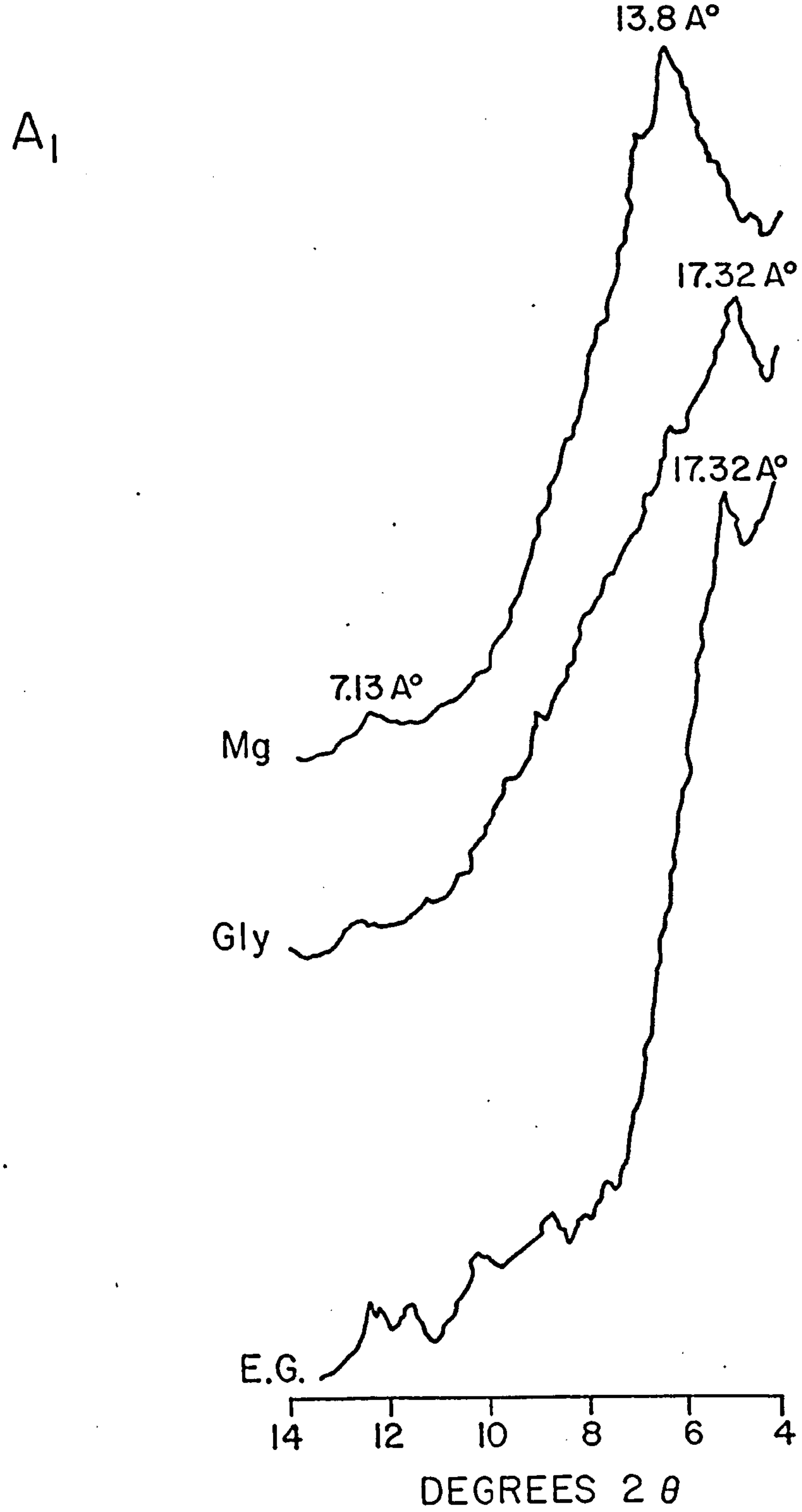


Figure 6. Diffractograms of Springerville gravelly clay, Al horizon (0-2"), fine clay, Mg-saturated and solvated with glycerol and ethylene glycol.

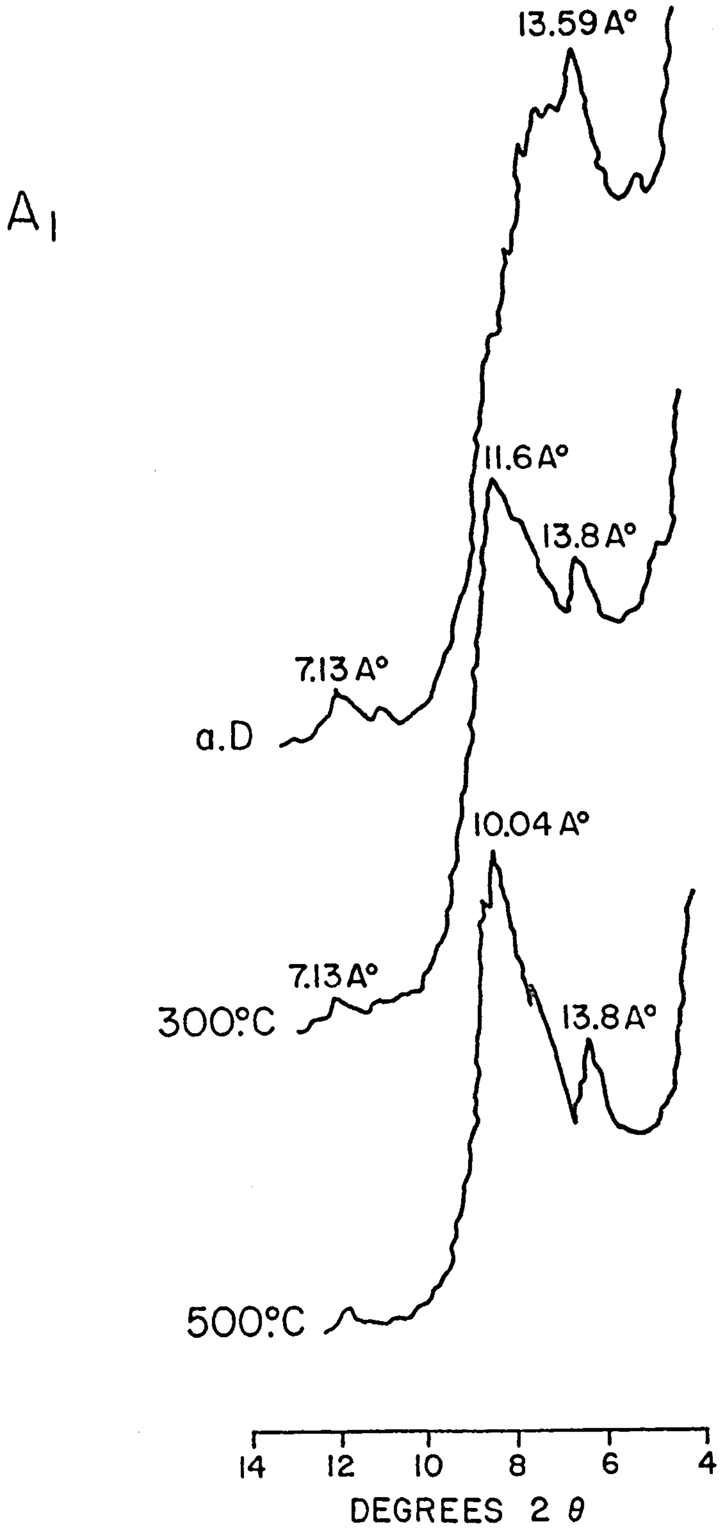


Figure 7. Diffractograms of Springerville gravelly clay, A1 horizon (0-2"), fine clay, K-saturated and heated to 300° and 500°C.

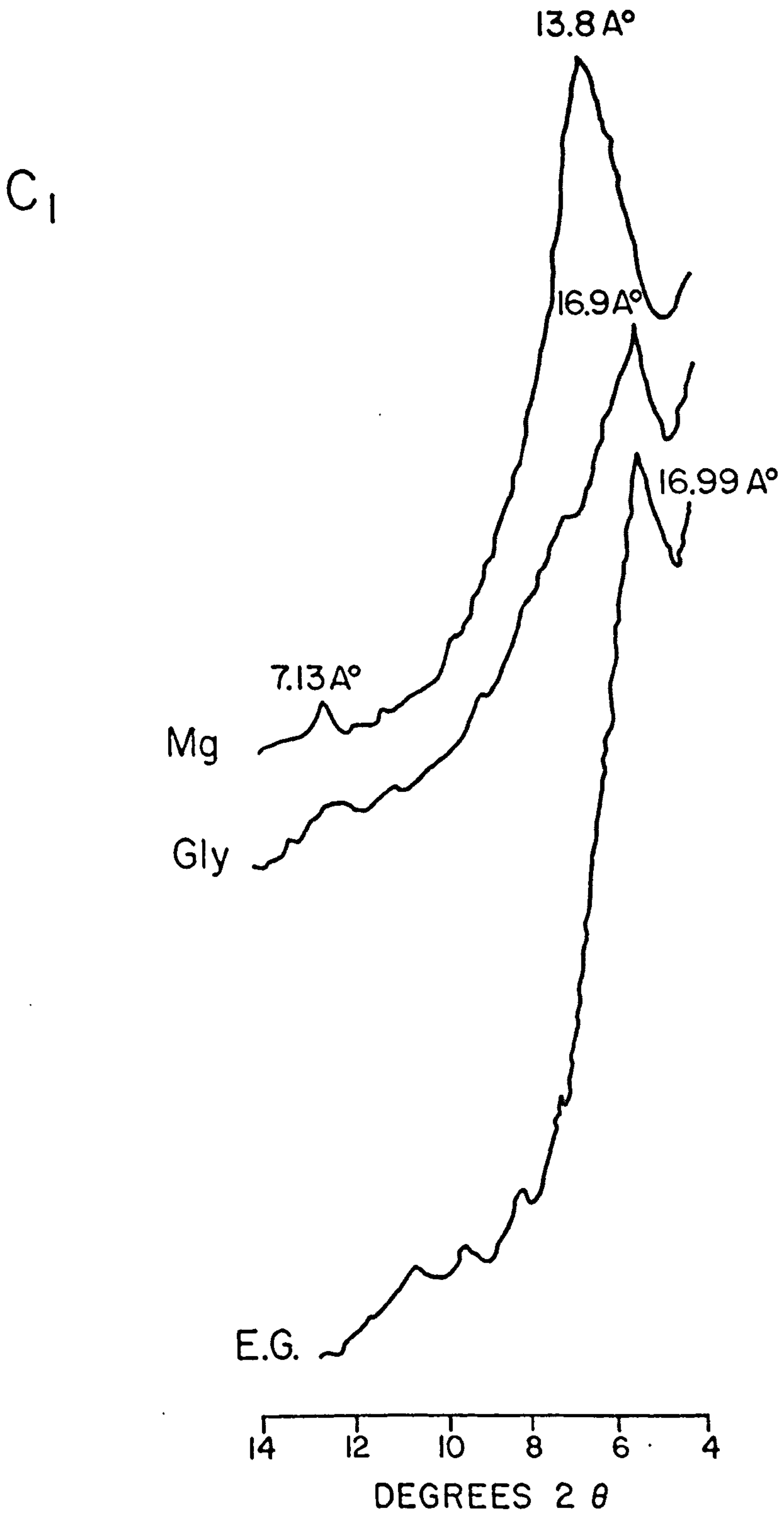


Figure 8. Diffractograms of Springerville gravelly clay, C1 horizon (2-8"), fine clay, Mg-saturated and solvated with glycerol and ethylene glycol.

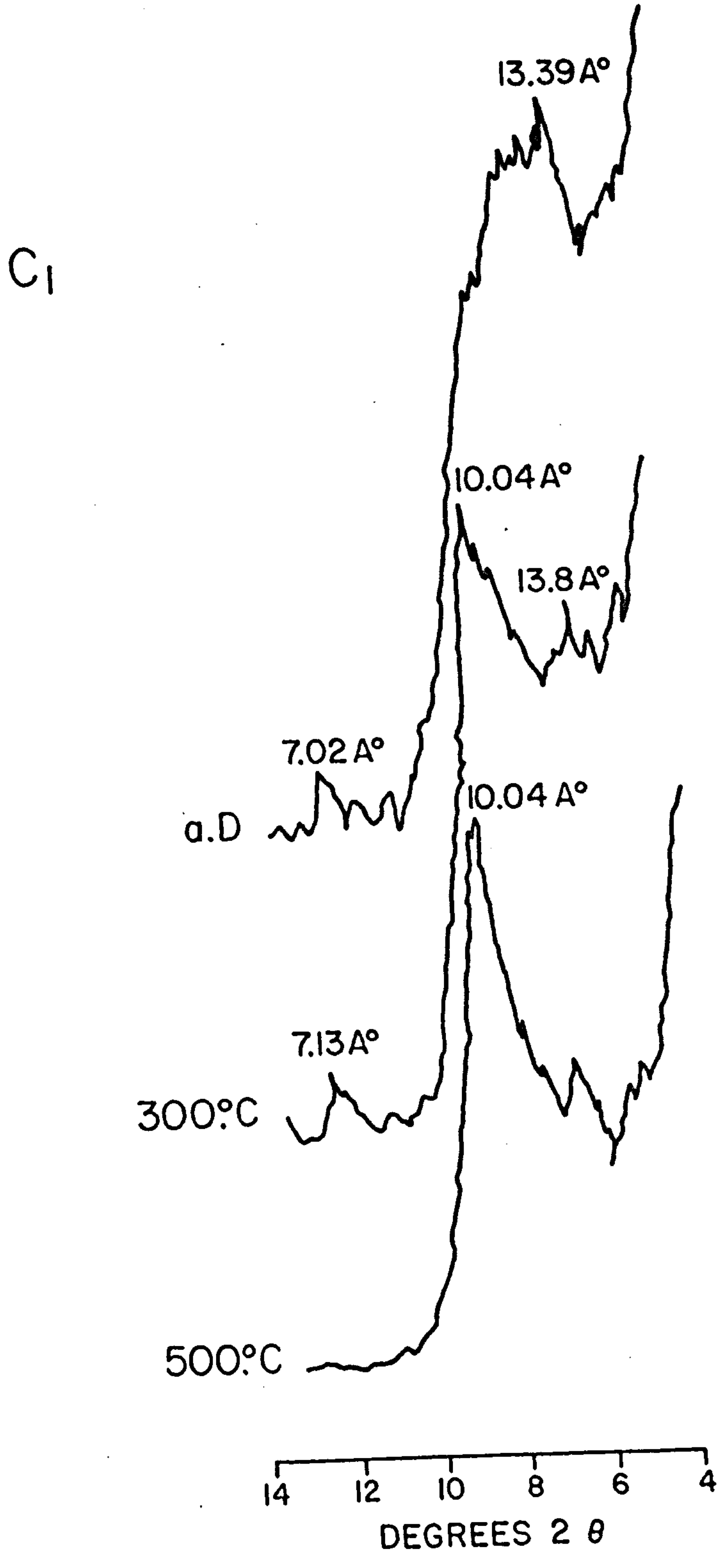


Figure 9. Diffractograms of Springerville gravelly clay, C1 horizon (2-8"), fine clay, K-saturated and heated to 300° and 500°C.

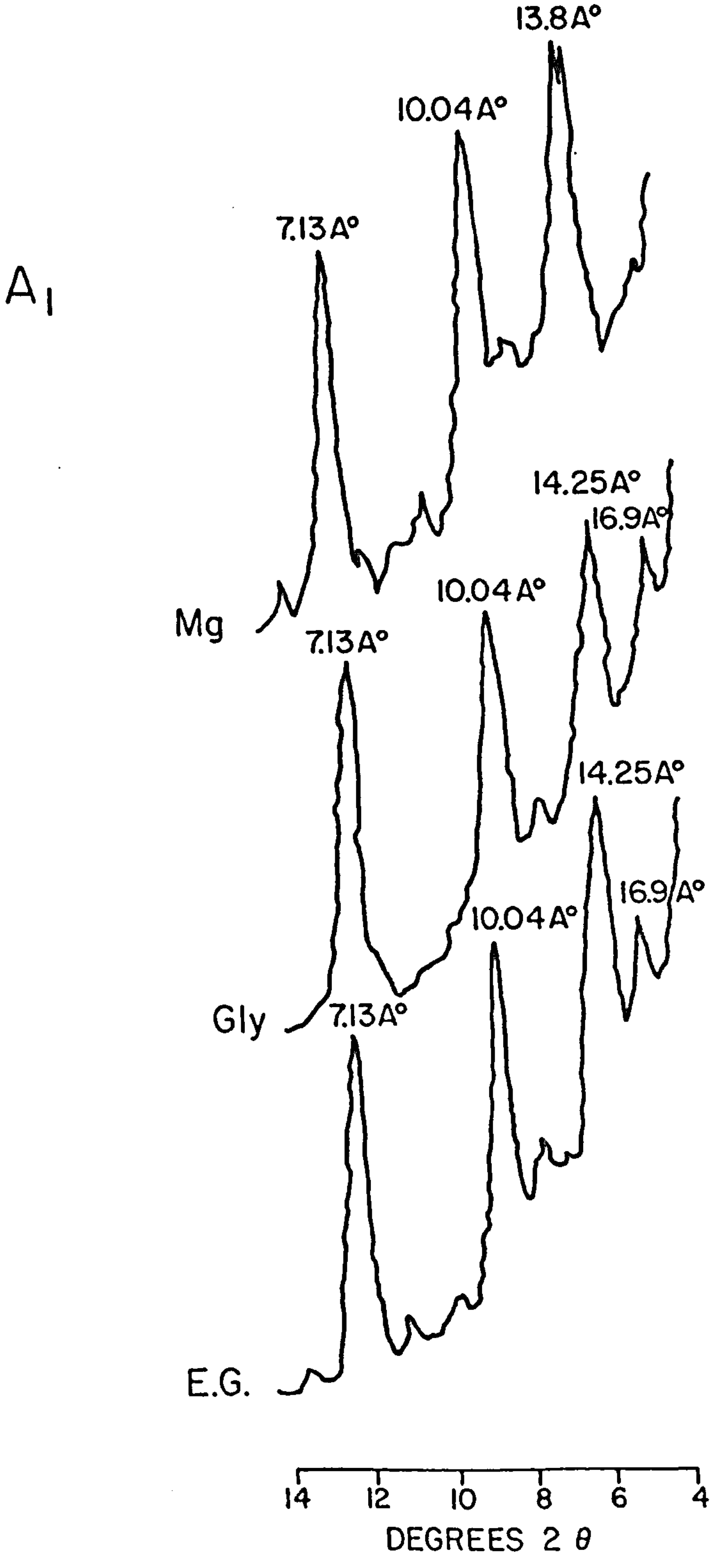


Figure 10. Diffractograms of Springerville cobbly clay, Al horizon (0-2"), coarse clay, Mg-saturated and solvated with glycerol and ethylene glycol.

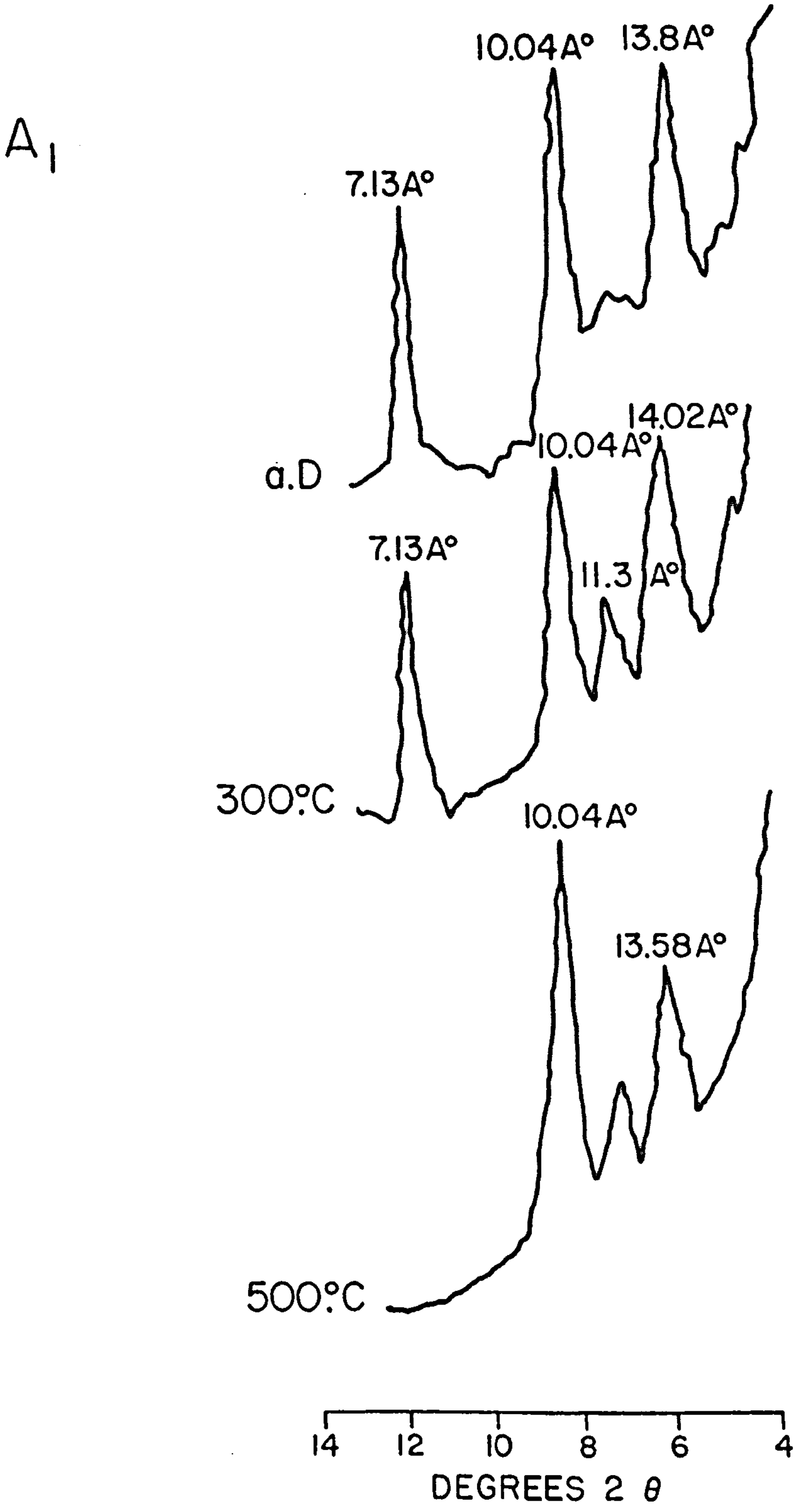


Figure 11. Diffractograms of Springerville cobbly clay, Al horizon (0-2"), coarse clay, K-saturated and heated to 300° and 500°C.

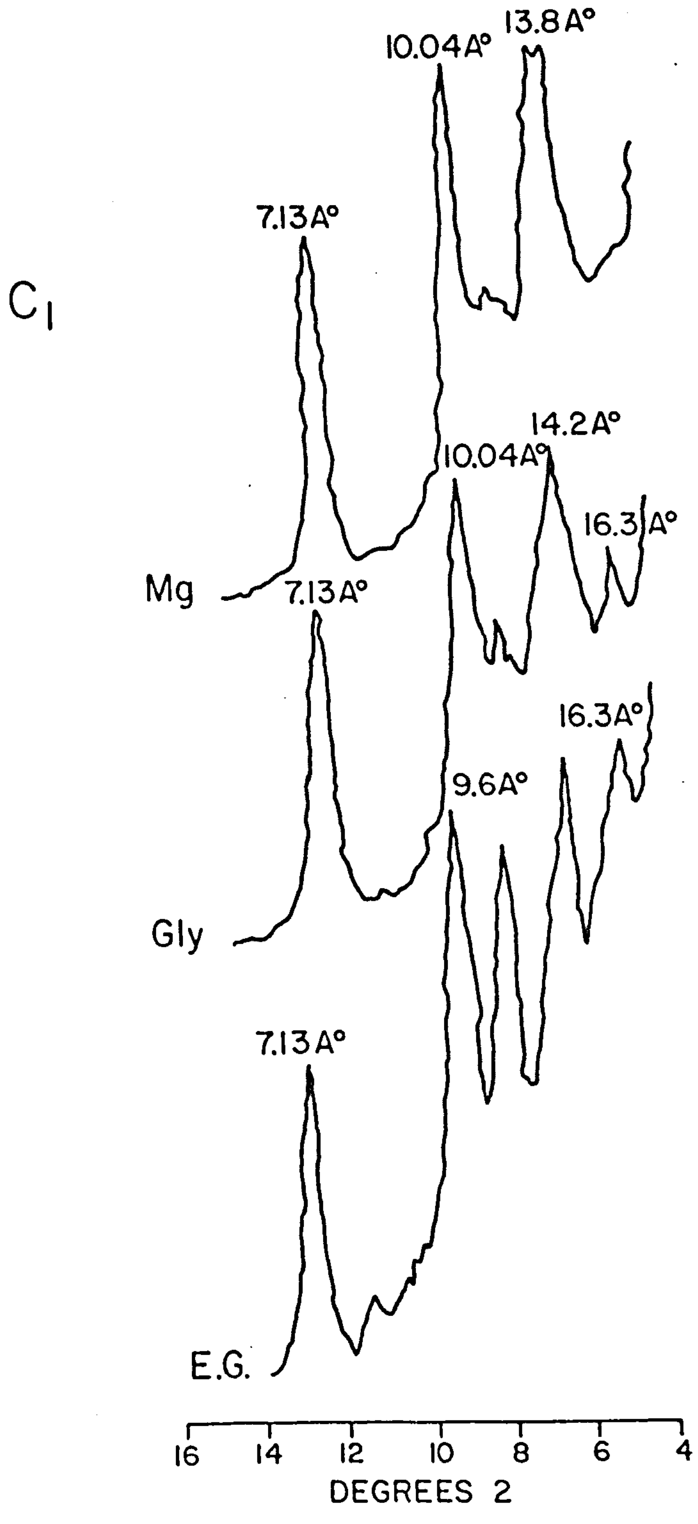


Figure 12. Diffractograms of Springerville cobbly clay, C1 horizon (2-36"), coarse clay, Mg-saturated and solvated with glycerol and ethylene glycol.

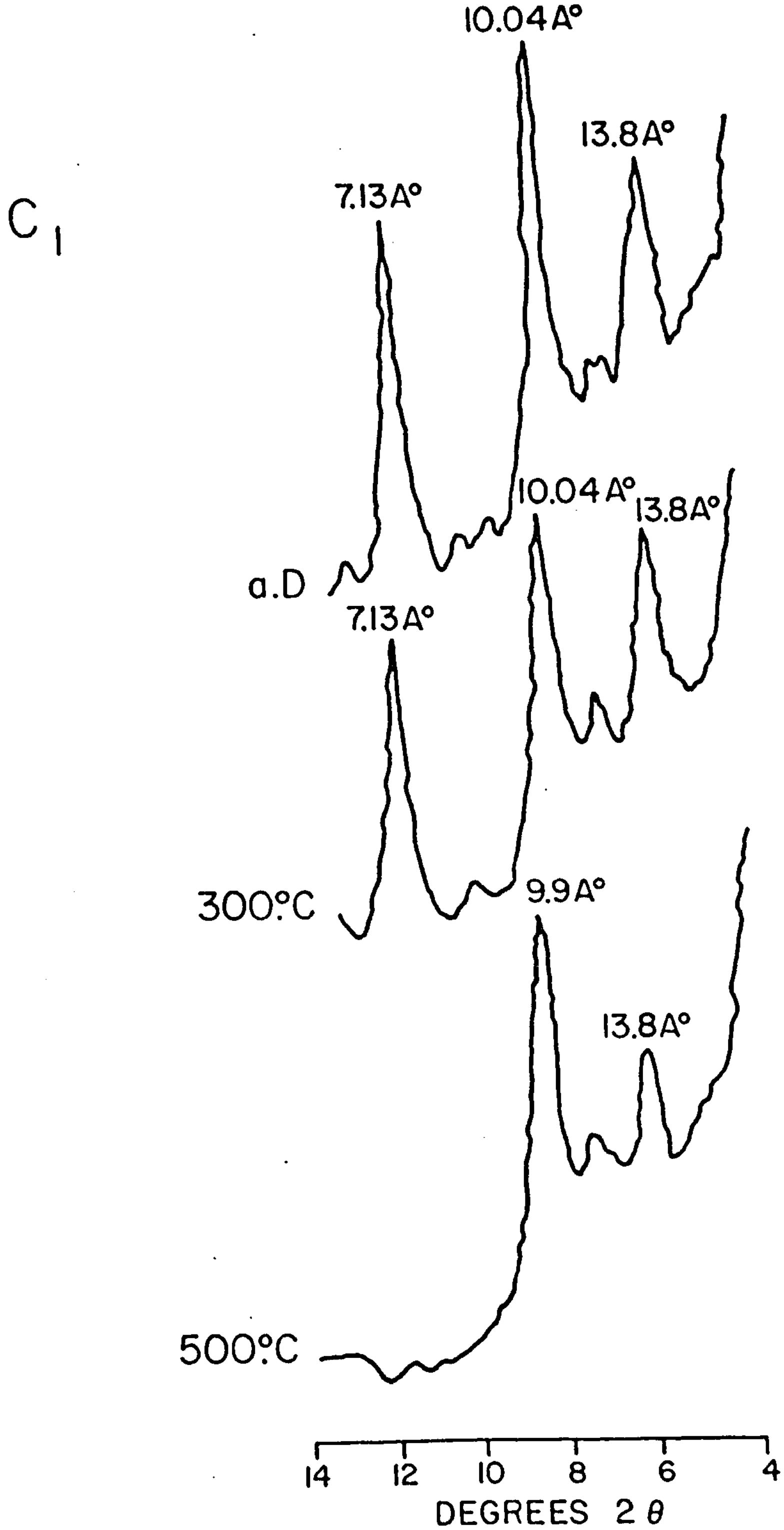


Figure 13. Diffractograms of Springerville cobbly clay, Cl horizon (2-36"), coarse clay, K-saturated and heated to 300° and 500°C.

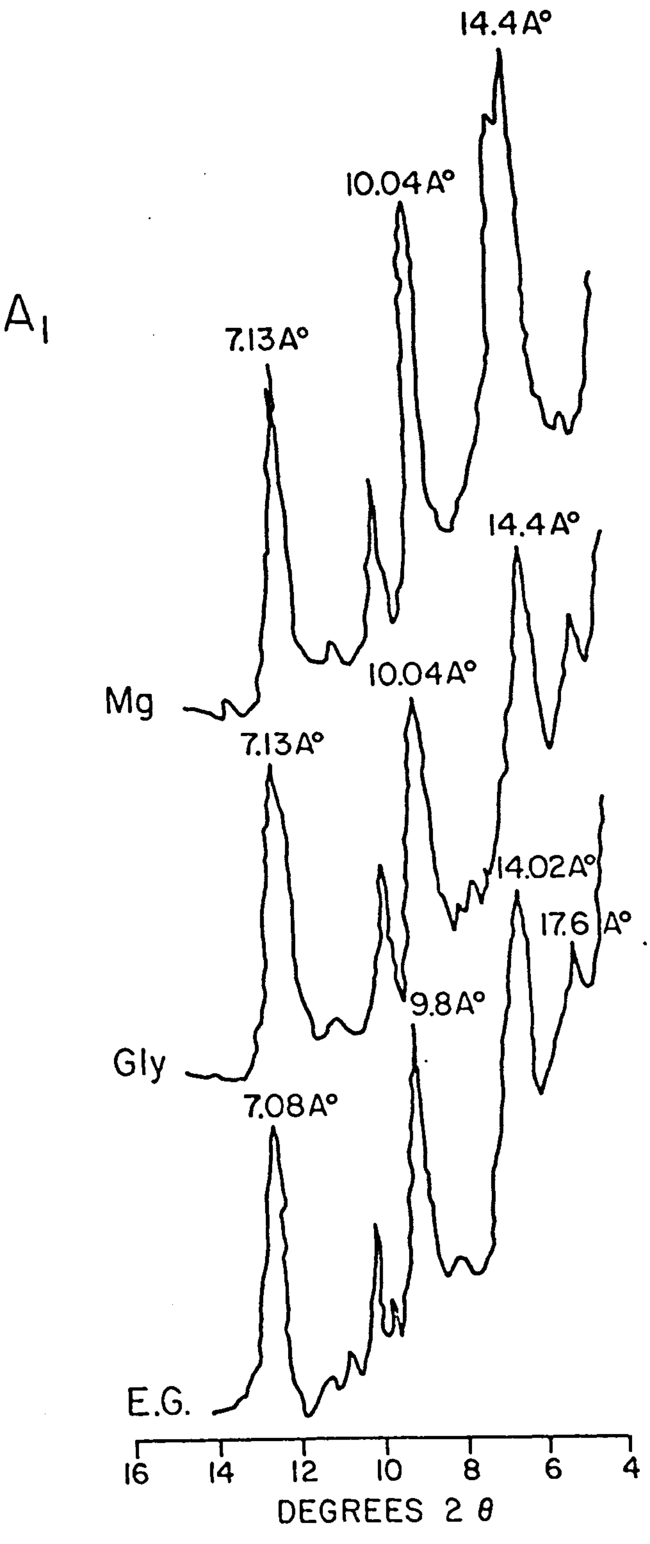


Figure 14. Diffractograms of Springerville gravelly clay, A1 horizon (0-2"), coarse clay, Mg-saturated and solvated with glycerol and ethylene glycol.

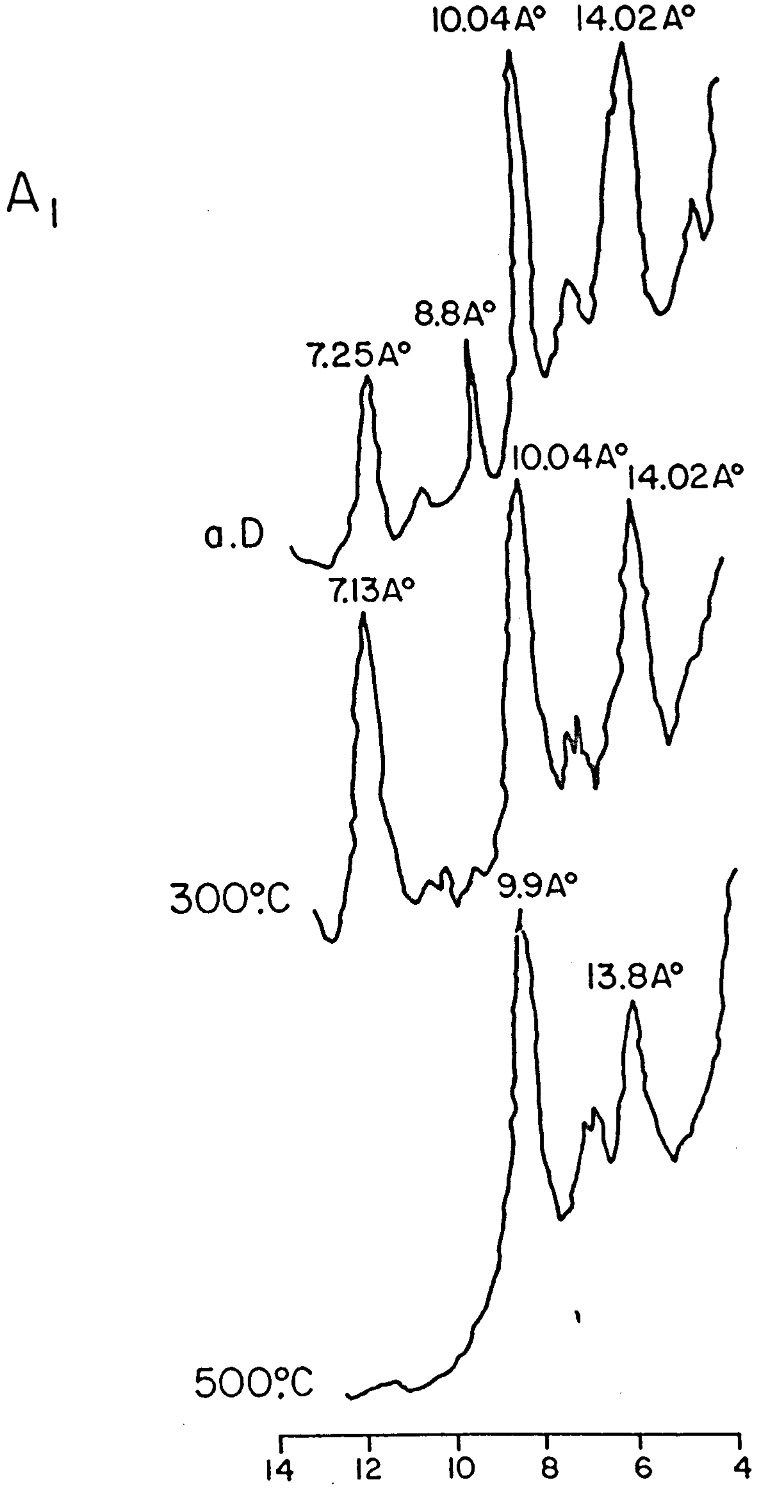


Figure 15. Diffractograms of Springerville gravelly clay, A1 horizon (0-2"), coarse clay, K-saturated and heated to 300° and 500°C.

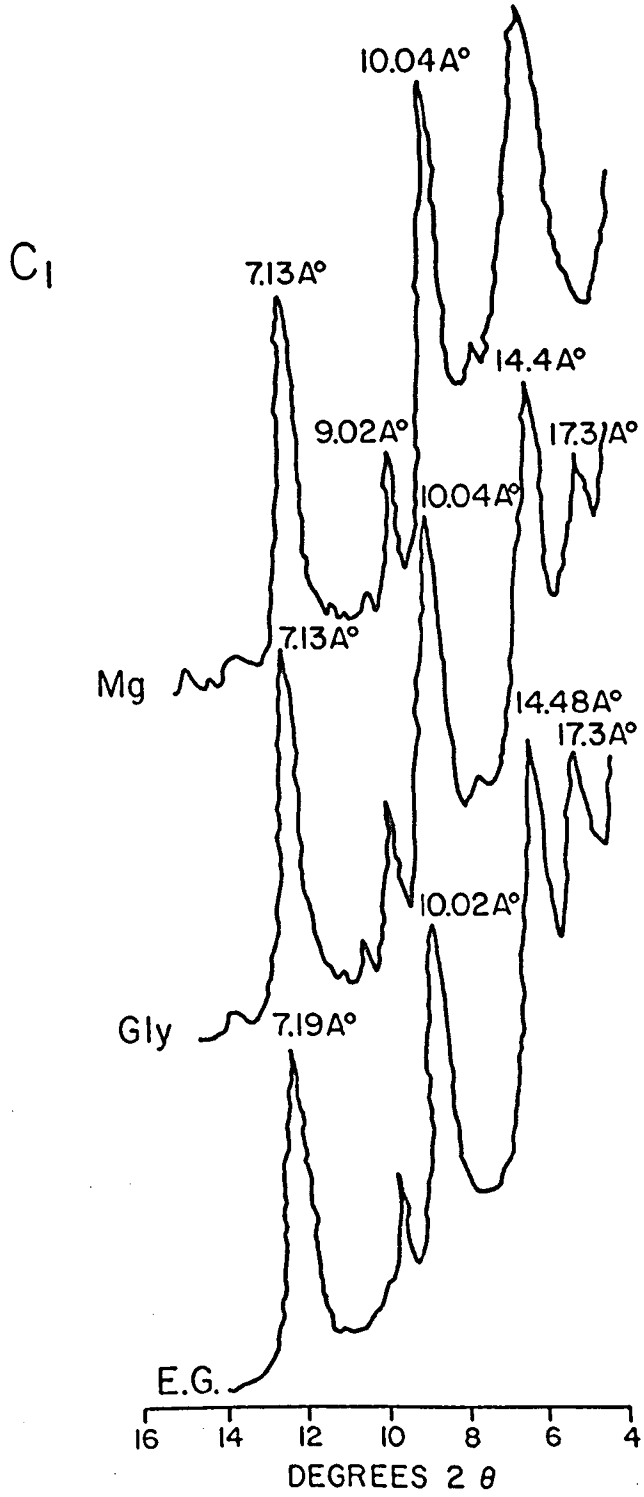


Figure 16. Diffractograms of Springerville gravelly clay, Cl horizon (2-8"), coarse clay, Mg-saturated and solvated with glycerol and ethylene glycol.

Figure 17. Diffractograms of Springerville gravelly clay, C1 horizon (2-8"), coarse clay, K-saturated and heated to 300° and 500°C.

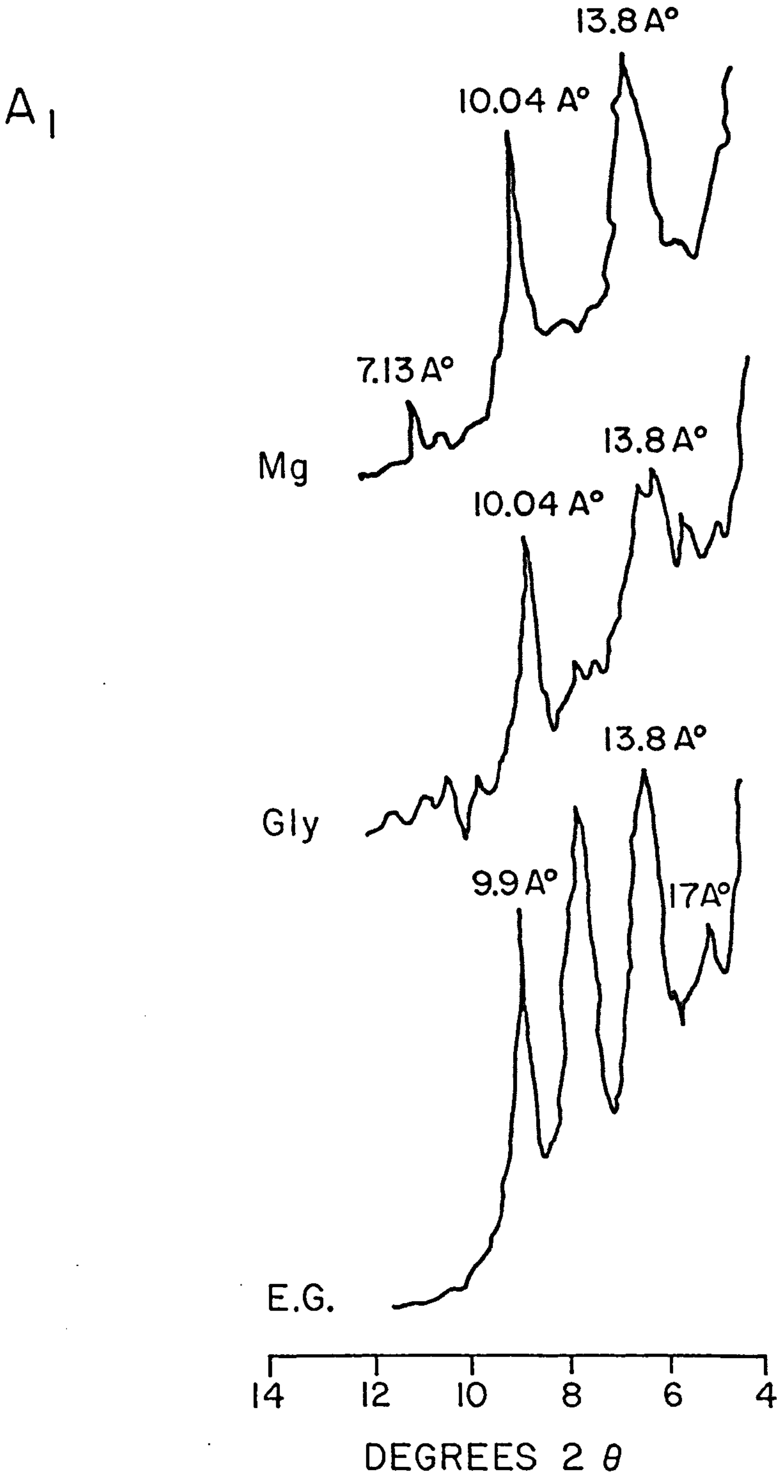


Figure 18. Diffractograms of Springerville cobbly clay, A1 horizon (0-2"), fine silt, Mg-saturated and solvated with glycerol and ethylene glycol.

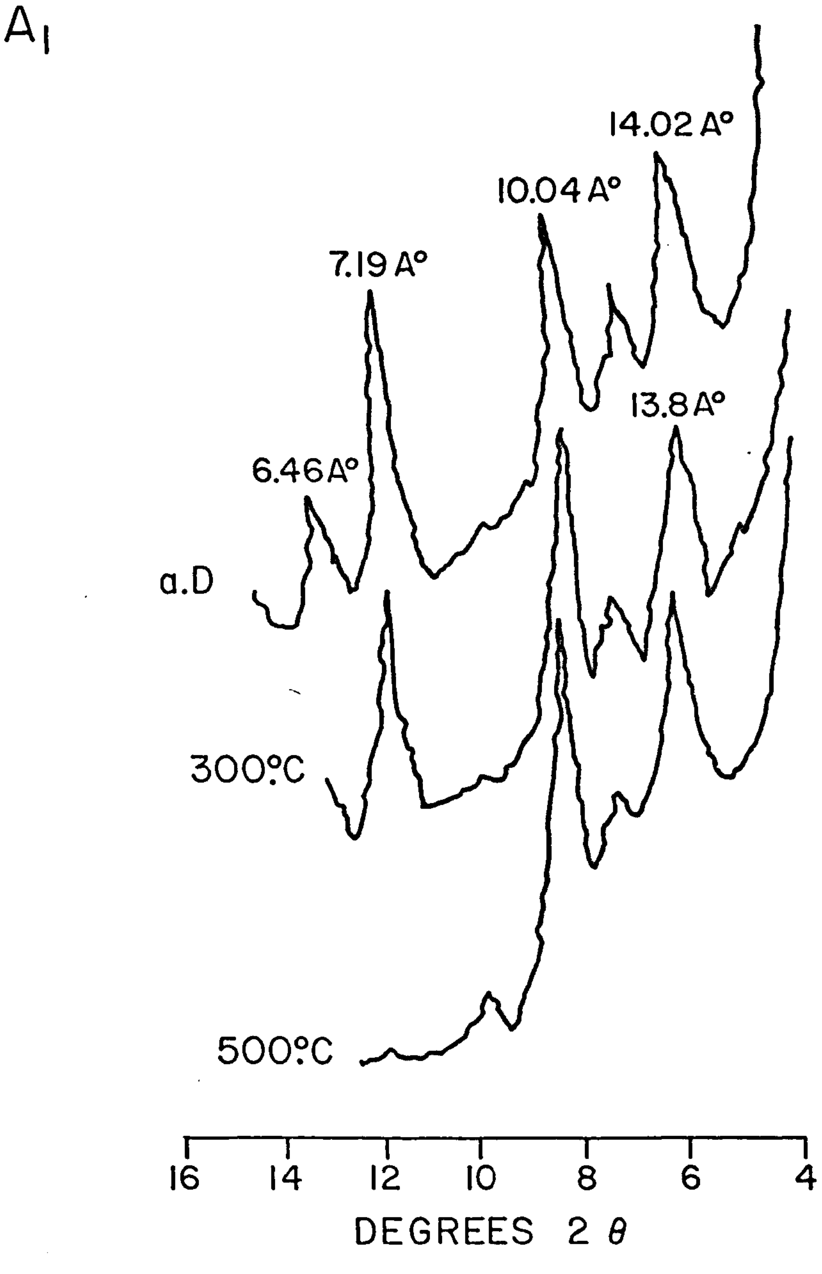


Figure 19. Diffractograms of Springerville cobbly clay, Al horizon (0-2"), fine silt, K-saturated and heated to 300° and 500°C.

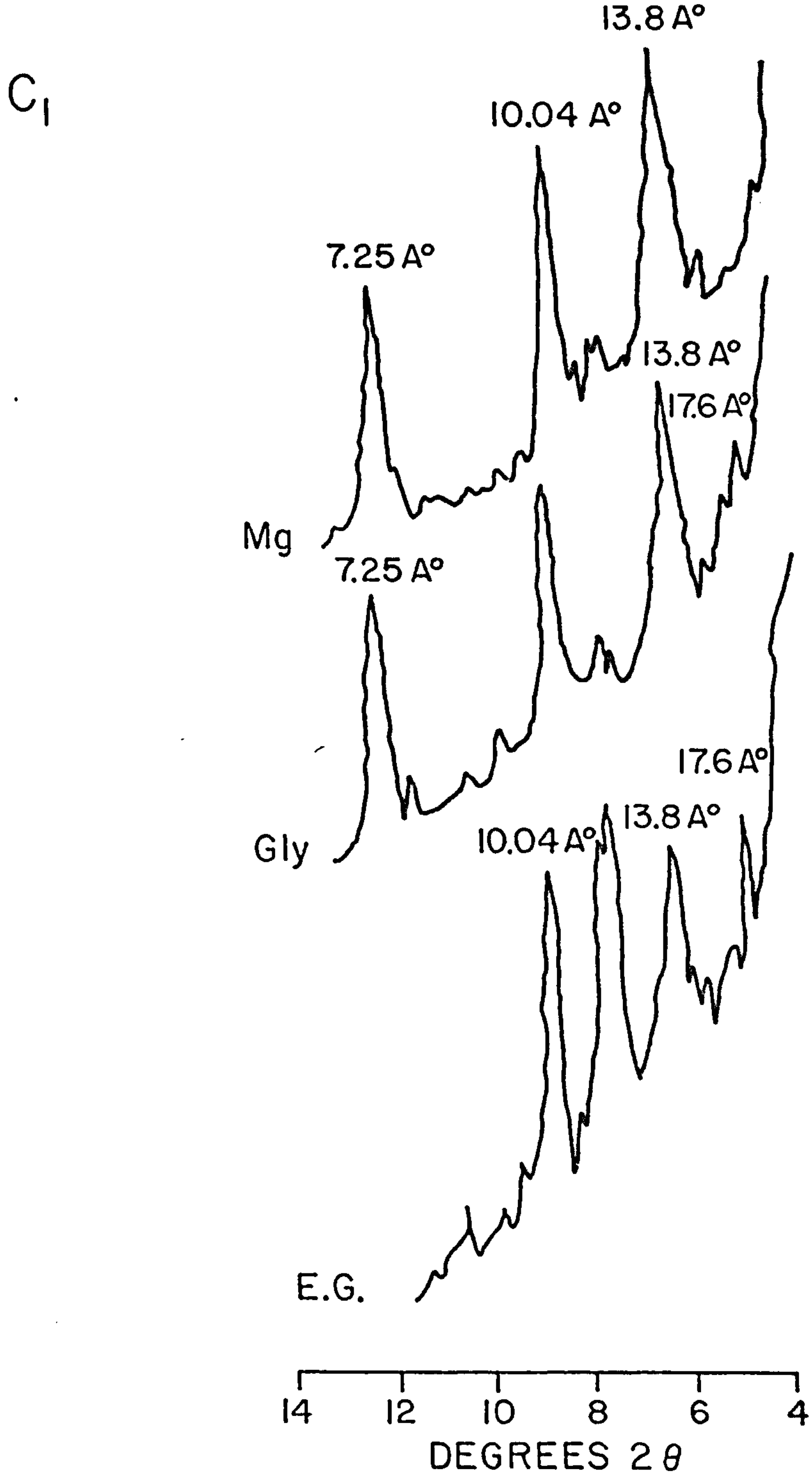


Figure 20. Diffractograms of Springerville cobbly clay, Cl horizon (2-36"), fine silt, Mg-saturated and solvated with glycerol and ethylene glycol.

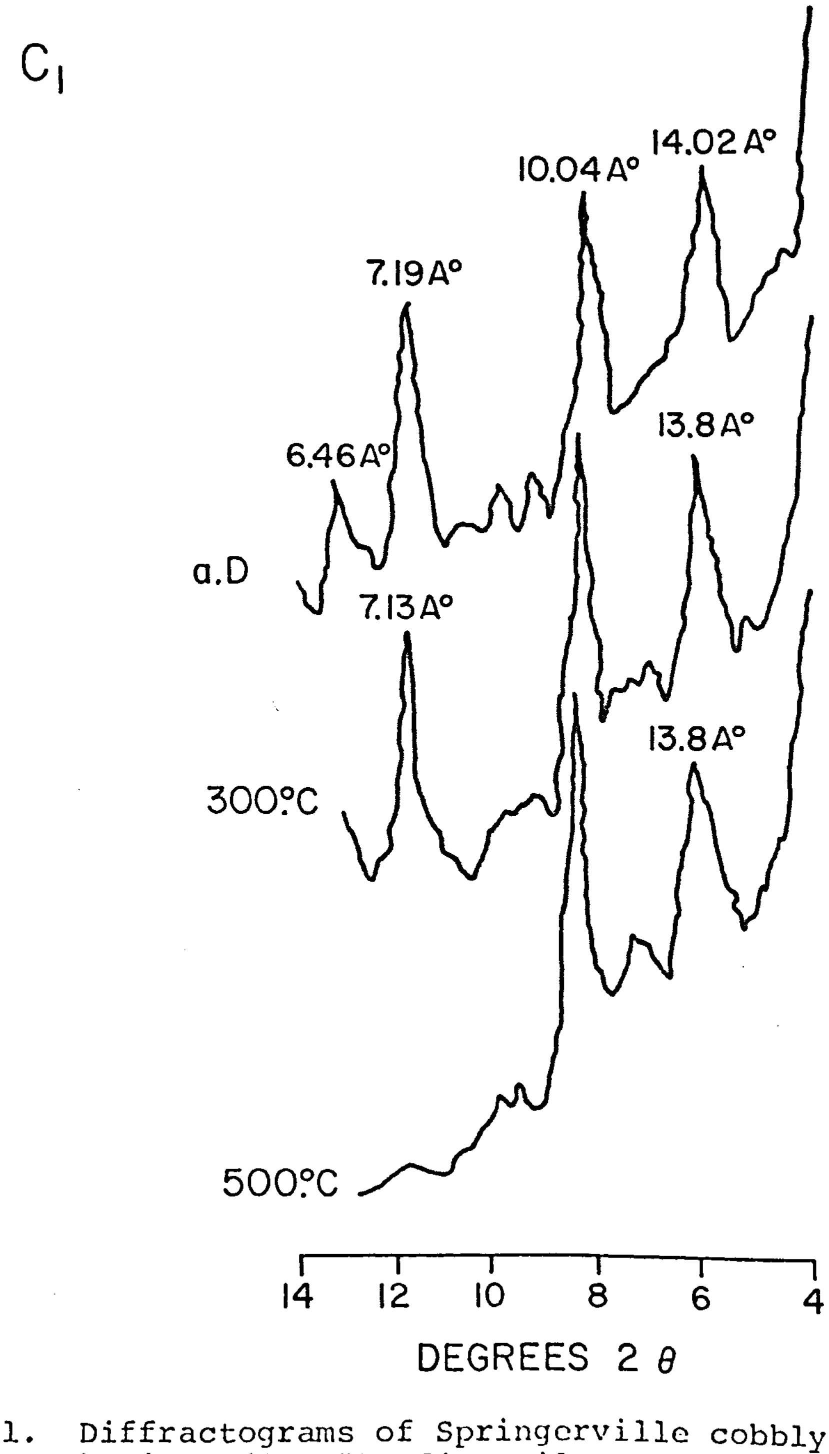


Figure 21. Diffractograms of Springerville cobbly clay, C1 horizon (2-36"), fine silt, K-saturated and heated to 300° and 500°C.

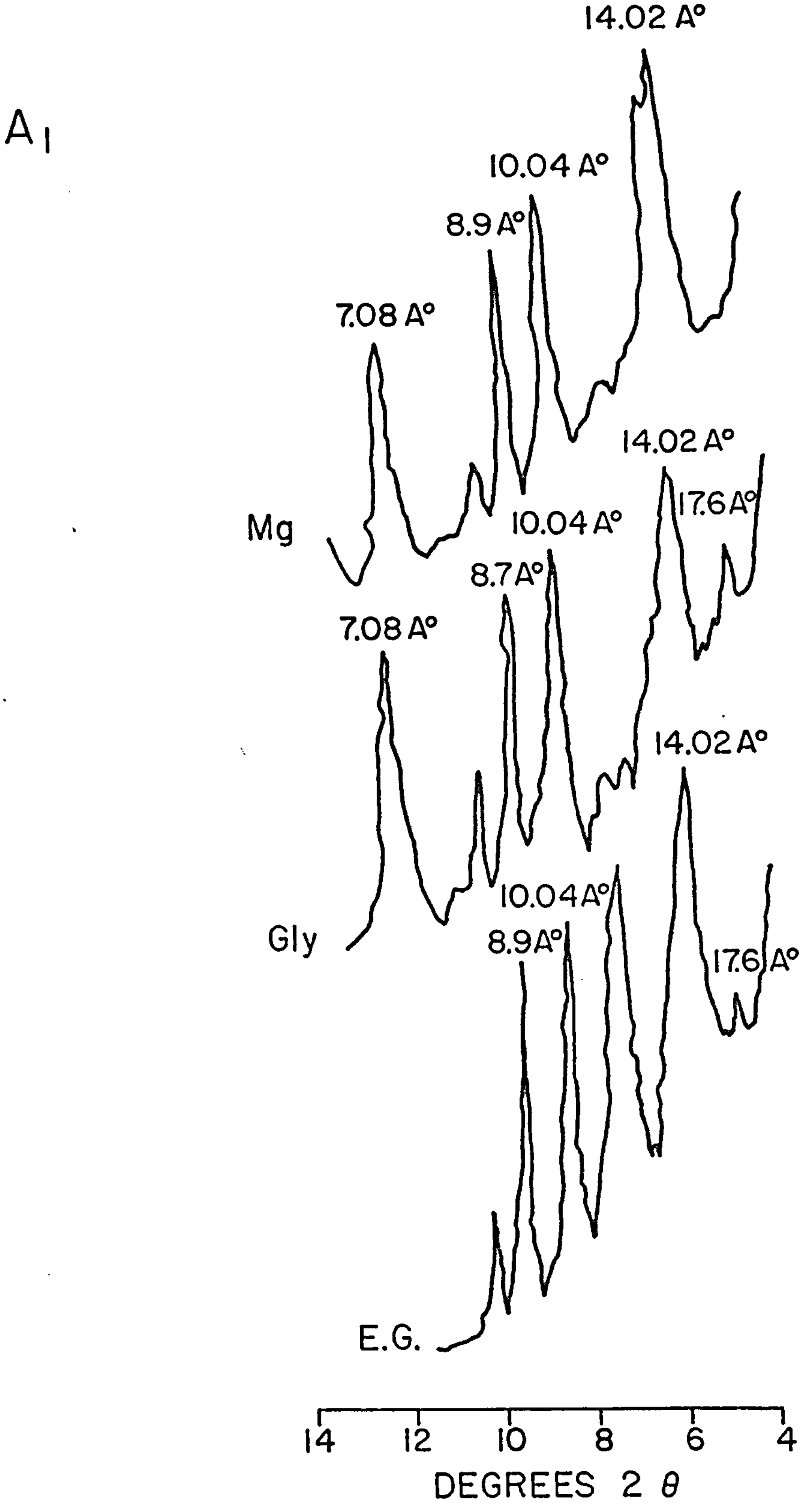


Figure 22. Diffractograms of Springerville gravelly clay, A1 horizon (0-2"), fine silt, Mg-saturated and solvated with glycerol and ethylene glycol.

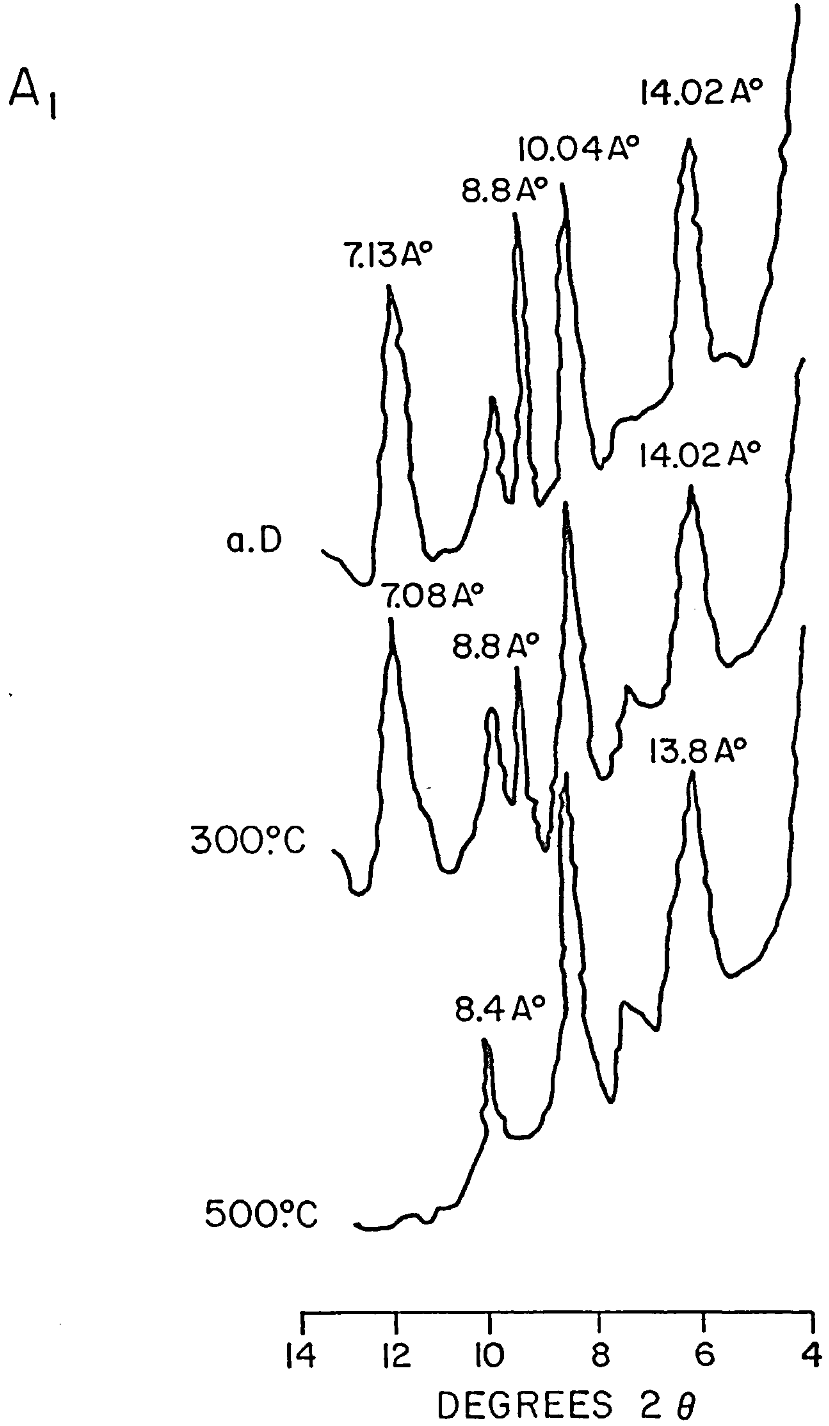


Figure 23. Diffractograms of Springerville gravelly clay, A1 horizon (0-2"), fine silt, K-saturated and heated to 300° and 500°C.

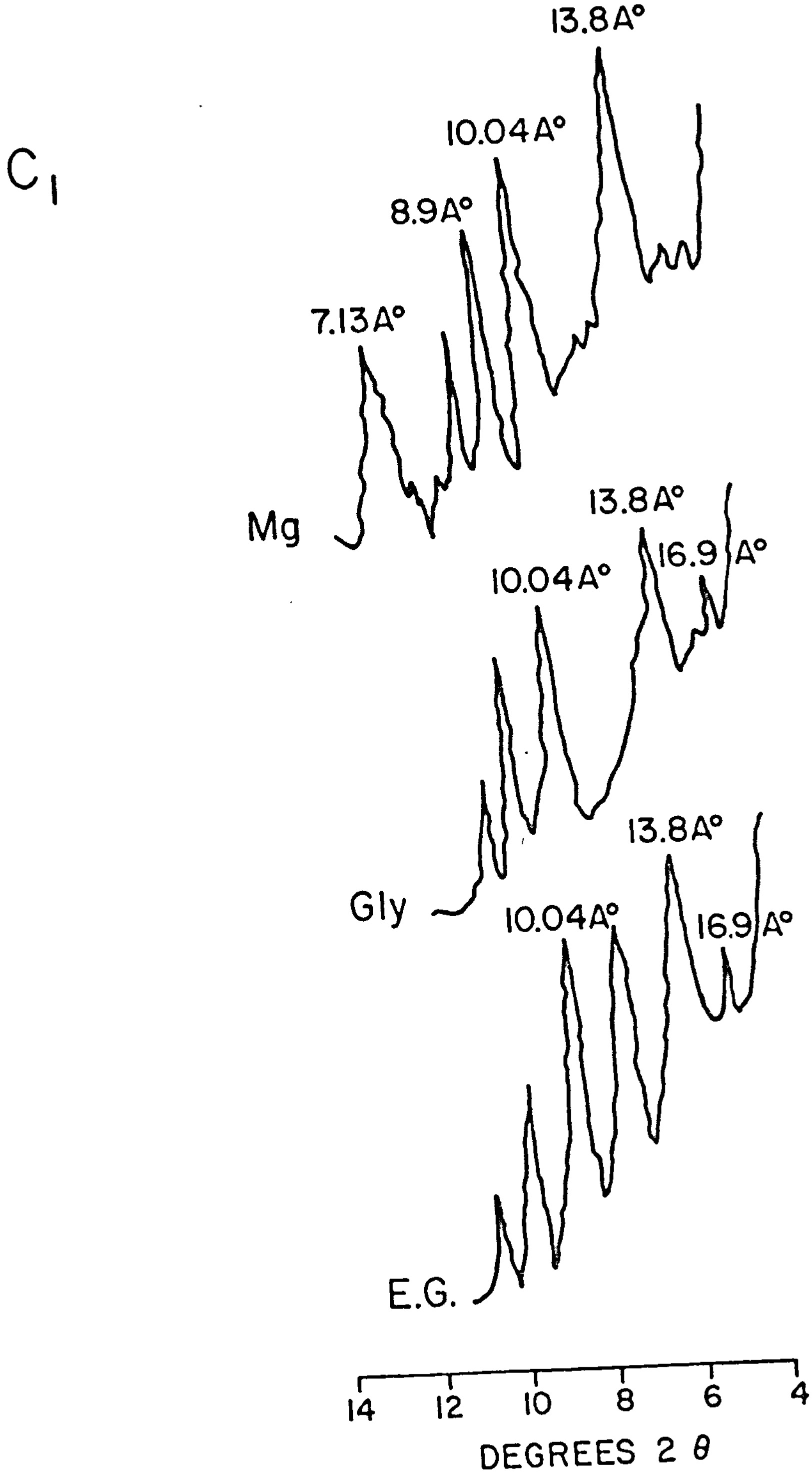


Figure 24. Diffractograms of Springerville gravelly clay, C1 horizon (2-8"), fine silt, Mg-saturated and solvated with glycerol and ethylene glycol.

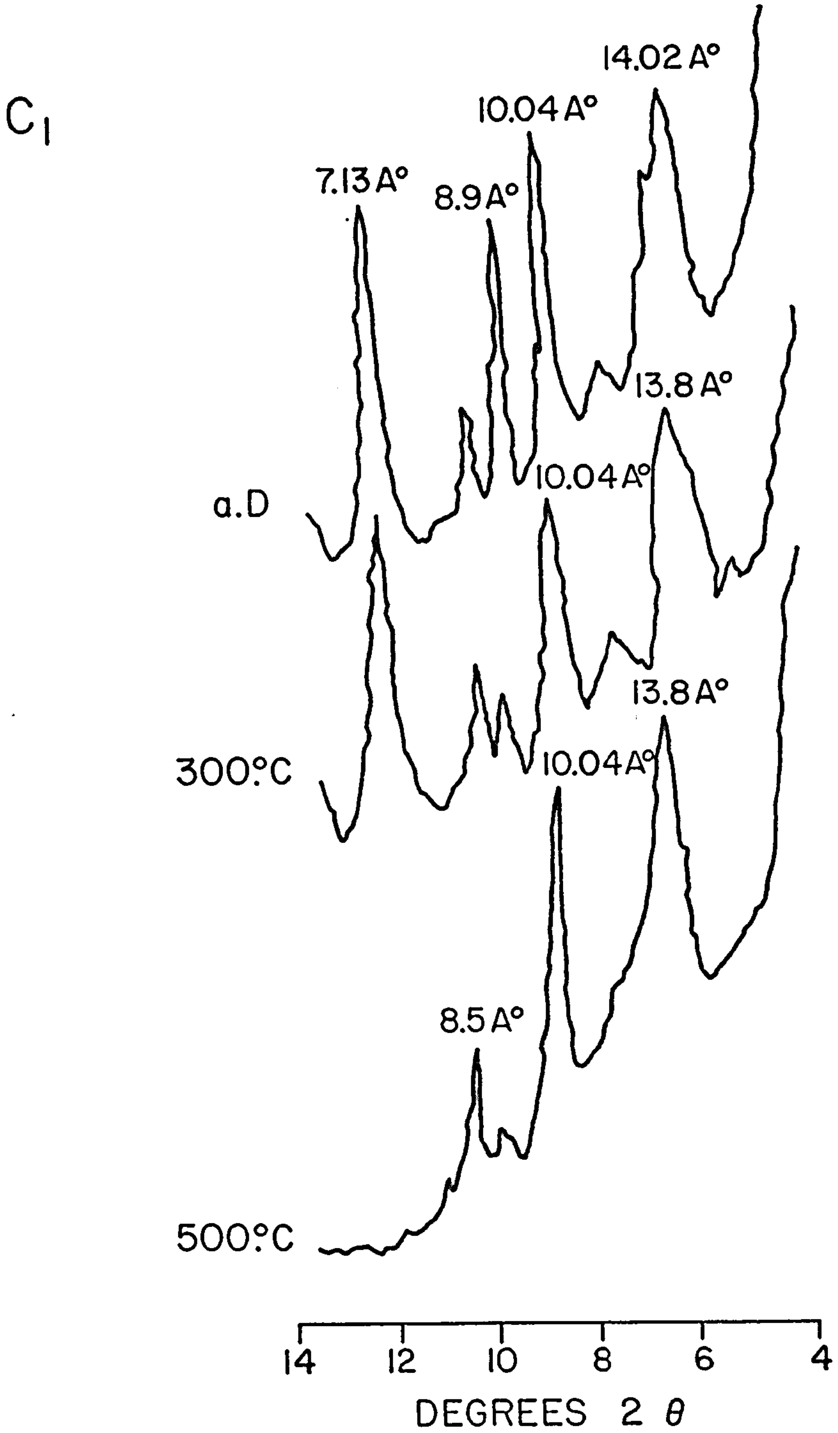


Figure 25. Diffractograms of Springerville gravelly clay, Cl horizon (2-8"), fine silt, K-saturated and heated to 300° and 500°C.

diffraction analyses are presented in Tables 3 and 4. Montmorillonite is the dominant clay mineral present in the fine clay fractions. The appearance of a 16.7-17.7 Å peak in the fine clay samples saturated with Mg solvated both with glycerol and ethylene glycol is due to the presence of montmorillonite as shown in Figures 2 through 9. The 16.2 Å line of the K-saturated sample collapsed to 10.04 Å after heating to 300°C providing further evidence for the presence of montmorillonite. The presence of vermiculite in small amounts in the fine clay is indicated by a slight increase in the intensity of 10.04 Å reflection in K-saturation (Figures 2 through 9). Small amounts of mica (illite) and kaolinite are also present as revealed by the presence in the X-ray tracing of the Mg-saturated samples of 10 Å and 7.1 Å peaks, respectively. The latter peak disappeared following the 500°C heat treatment.

The diffractograms of the coarse clay fractions also show the presence of montmorillonite, although in smaller amounts, as indicated by the appearance of a peak between 16.7 and 17.7 Å of the solvated samples (Figures 10 through 17). The persistence of 14.2 Å in samples saturated with K and heated to 500°C for two hours confirms the presence of chlorite. The 10 Å and 7.1 Å are present in the coarse clay fractions as a result of the presence of mica (illite) and kaolinite, respectively.

Table 3. Estimated relative amounts of each clay mineral in Springerville cobbly clay based on X-ray diffraction data.

Horizon	Depth	Kaolinite	Mica	Montmorillonite	Vermiculite	Chlorite
Fine clay (<0.2 μ):						
A1	0-2"	2[a]	2	4	2	1
C1	2-36"	1	1	3	1	-
C2Ca	36-50"	2	1	3	2	1
C3Ca	50-58"	2	1	2	2	2
Coarse clay (2-0.2 μ):						
A1	0-2"	2	3	3	2	2
C1	2-36"	2	3	2	3	2
C2Ca	36-50"	3	4	2	2	2
C3Ca	50-58"	2	3	3	3	3
Fine silt (5-2 μ):						
A1	0-2"	2	3	2	3	3
C1	2-36"	2	3	3	4	3
C2Ca	36-50"	3	4	2	3	3
C3Ca	50-58"	3	4	3	3	3

[a] Amounts of each clay mineral present: -, looked for but not detected; 1, trace; 2, small; 3, moderate; 4, abundant; 5, dominant.

Table 4. Estimated relative amounts of each clay mineral in Springerville gravelly clay based on X-ray diffraction data.

Horizon	Depth	Kaolinite	Mica	Montmorillonite	Vermiculite	Chlorite
Fine clay (<0.2 μ):						
A1	0-2"	1[a]	-	4	-	1
C1	2-8"	1	-	4	-	1
C2	8-46"	1	-	3	1	1
C3Ca	46-67"	1	2	3	2	1
Coarse clay (2-0.2 μ):						
A1	0-2"	2	3	4	2	2
C1	2-8"	3	3	4	3	3
C2	8-46"	3	4	3	3	3
C3Ca	46-67"	2	3	3	2	2
Fine silt (5-2 μ):						
A1	0-2"	3	3	4	3	3
C1	2-8"	2	3	3	2	3
C2	8-46"	3	4	2	3	3
C3Ca	46-67"	3	4	3	3	3

[a] Amounts of each clay mineral present: -, looked for but not detected; 1, trace; 2, small; 3, moderate; 4, abundant; 5, dominant.

The fine silt fractions contain montmorillonite, mica (illite), kaolinite, chlorite, and feldspars. The presence of the 8.8 Å to 9.0 Å peak is probably due to a random instratification of some sort (Figures 18 through 25). The presence of feldspars in the fine silt is suggested by the 6.4 Å peak, and the presence of 3.73 and 3.1 Å lines in diffractograms extended to 30° 2θ.

As shown by the estimated amounts of the clay minerals (Tables 3 and 4), montmorillonite decreases with an increase in particle size. In the fine clay fractions montmorillonite is present as the dominant clay mineral, while in the coarse clay and fine silt montmorillonite is estimated to be abundant in small amounts. Mica, kaolinite, and vermiculite are present in very small amounts in the fine clay fractions compared to those present in the coarse clay and fine silt. Chlorite is not detected in the fine clay fraction, but does occur in the coarse clay and fine silt in small to moderate amounts.

Elemental Analysis

The results of the elemental analysis for fine silt, coarse clay, and fine clay fractions of the two pedons are shown in Tables 5 and 6. The silica-alumina, silica-iron, and silica-sesquioxide ratios are shown in Table 7. The results show high silica-alumina, silica-iron, and silica sesquioxide ratios indicating limited conditions of

Table 5. Elemental composition of Springerville cobbly clay.

Horizons	Separate	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	Total %
A1	<0.2 μ	47.1	25.7	4.7	1.0	0.3	2.7	0.2	0.8	82.6
C1		47.1	26.1	4.8	1.3	0.3	3.1	0.1	0.5	83.3
C2Ca		45.9	26.6	5.6	1.5	0.3	3.0	0.3	0.8	83.8
C3Ca		48.7	25.9	5.3	1.9	0.3	3.0	0.1	0.8	85.7
A1	2-0.2 μ	48.7	26.1	4.4	1.9	0.3	3.0	1.0	1.0	86.0
C1		52.4	25.9	4.8	2.1	0.3	3.0	1.0	1.3	90.7
C2Ca		53.5	25.6	4.4	1.4	0.4	3.0	0.5	0.6	89.3
C3Ca		47.3	22.2	4.7	1.9	0.3	3.0	0.4	0.5	80.1
A1	5-2 μ	49.2	21.2	5.5	2.7	0.2	3.0	0.5	1.0	82.9
C1		50.1	18.6	5.7	2.3	0.3	3.0	0.6	1.2	81.8
C2Ca		48.9	21.2	4.6	2.7	0.7	3.0	0.5	1.0	82.5
C3Ca		48.2	23.9	4.6	1.7	0.6	3.0	0.7	1.2	83.6

Table 6. Elemental composition of Springerville gravelly clay.

Horizons	Separate	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	Total %
A1	<0.2 μ	44.9	19.9	5.6	1.9	0.2	3.2	0.1	0.6	76.5
C1		46.9	20.8	4.7	2.4	0.4	2.8	0.3	0.9	79.1
C2		48.2	21.4	5.2	1.8	0.4	3.2	0.4	1.0	81.5
C3Ca		47.1	20.7	4.8	1.7	0.5	3.2	0.3	0.8	79.1
A1	2-0.2 μ	48.2	25.5	4.5	1.0	0.3	2.7	0.4	0.5	83.0
C1		48.3	24.9	4.8	1.5	0.7	2.7	0.1	0.9	83.9
C2		51.4	25.8	4.4	1.5	0.7	2.6	0.1	0.8	87.3
C3Ca		49.1	24.7	4.8	1.7	0.4	2.7	0.2	0.7	84.4
A1	5-2 μ	48.9	24.9	4.8	2.5	0.4	2.8	1.4	1.2	86.8
C1		51.4	24.7	4.6	1.0	0.4	2.9	1.4	1.2	87.5
C2		54.6	25.8	4.8	2.7	0.6	2.9	1.5	1.2	94.0
C3Ca		50.8	25.2	4.7	2.5	0.6	2.9	0.4	0.5	87.6

Table 7. Silica-alumina, silica-iron, and silica-sesquioxide molar ratios of Springerville soil clays of fine clay samples.

Horizons	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	$SiO_2/Al_2O_3 + Fe_2O_3$
A1	3.12	26.89	2.76
C1	3.05	26.89	2.74
C2Ca	3.26	24.36	2.88
C3Ca	3.24	25.35	2.84
A1	3.84	22.02	3.27
C1	4.05	25.21	3.43
C2	4.00	25.00	3.31
C3Ca	3.90	26.89	3.37

leaching in the system from which clay minerals form (Keller, 1968). The pH of all horizons is about 8.0 at which the solubility of Al_2O_3 decreases to a minimum and the solubility of SiO_2 is reduced to only a small amount (Keller, 1968).

Parent material rich in Ca, Mg, and Fe are considered to be essential conditions for the formation of montmorillonite clays (Ross and Hendricks, 1945).

K is present in relatively small amounts and is considered to be the main cation held in mica layers. Marshall (1964) reported that most of the clays having a variable c-axis spacing contain up to 1% of monoexchangeable K_2O, which indicates the presence of a small proportion of mica units mixed with montmorillonite. Although basalt, the parent rock for these soils, does not contain mica, small aelian additions of mica have undoubtedly been made.

Al, Fe, and Mg are present in appreciable amounts. These ions are the most common occupants of octahedral sites in montmorillonite. In vermiculite, on the other hand, K is replaced by hydrated exchangeable Mg and there is an isomorphous substitution of Al for Si in the tetrahedral layers.

The elemental composition of the clays of the Springerville pedons shows a great uniformity which indicates that these soils formed from very similar parent materials; were subjected to similar weathering and under the same soil forming processes. One important factor which contributes to the uniformity of the distribution of the major elements in the horizons of Vertisol soils in general is the mechanism of self-turning or self-swallowing. The silica-alumina, silica-iron, and silica-sesquioxide ratios are high as shown in Table 7, indicating a limited leaching condition in the area.

Quantitative Determination of Clay Minerals

Vermiculite was determined on the basis of the part of the cation exchange capacity measured by Ca replaced by Mg and montmorillonite was determined by the cation exchange capacity measured by the non-fixed K. The per cent montmorillonite and vermiculite as determined by this method are shown in Tables 8 and 9.

The montmorillonite content of the fine clay fraction by this method is considerably lower than would be expected based on the X-ray diffraction data described above. This may have been caused, at least in part, by a partial loss of sample during the procedure.

The percentages of montmorillonite in the fine clay fractions range between 29 and 43%. The per cent vermiculite in these fractions ranges from 7 to 16%. In the coarse clay fractions montmorillonite ranges from 2 or less to 30% while the per cent vermiculite is from 3 to 6%. The per cent montmorillonite in the fine silt fraction ranges from 9 to 18% and the per cent vermiculite in the same fraction ranges from 4 to 8%. The amorphous material (Tables 10 and 11) is

Table 8. Per cent montmorillonite, vermiculite, and mica for selected samples of Springerville cobbly clay.

Horizons	Size of fraction	% Montmorillonite	% Vermiculite	% Mica
A1	<0.2 μ	30	15	7.6
C1		31	14	5.4
C2Ca		38	7	7.6
C3Ca		*	*	7.6
A1	2-0.2 μ	2	3	10.6
C1		2	3	13.4
C2Ca		17	6	6.0
C3Ca		30	4	5.1
A1	5-2 μ	*	*	9.8
C1		12	8	12.5
C2Ca		15	5	10.3
C3Ca		*	*	12.2

*Not determined.

Table 9. Per cent montmorillonite, vermiculite, and mica for selected samples of Springerville gravelly clay.

Horizons	Size of fraction	% Montmorillonite	% Vermiculite	% Mica
A1	<0.2 μ	39	13	5.7
C1		34	16	9.3
C2		37	15	9.8
C3Ca		43	13	8.0
A1	2-0.2 μ	0.5	6	5.1
C1		*	4	9.2
C2		*	4	8.3
C3Ca		6	4	7.3
A1	5-2 μ	18	4	12.2
C1		10	4	11.9
C2		*	*	12.2
C3Ca		*	*	4.8

*Not determined.

Table 10. Amorphous material as determined by 0.5 N NaOH selective dissolution analysis of Springerville cobbly clay.

Depth	Horizon	Separate	% SiO_2	% Al_2O_3	Amor.	SiO_2/Al_2O_3 molar ratio
0-2"	A1	<0.2 μ	5.6	2.4	8.8	4.0
		2-0.2 μ	1.8	0.6	3.3	4.6
		5-2 μ	*	*	*	*
2-36"	C1	<0.2 μ	5.6	2.4	8.8	4.0
		2-0.2 μ	1.3	0.5	2.0	4.4
		5-2 μ	*	*	*	*
36-50"	C2Ca	<0.2 μ	5.2	2.8	8.8	3.7
		2-0.2 μ	1.6	0.8	2.6	3.2
		5-2 μ	*	*	*	*
50-58"	C3Ca	<0.2 μ	1.9	0.7	2.8	5.1
		2-0.2 μ	2.8	1.0	4.2	5.1
		5-2 μ	*	*	*	*

*Not determined.

Table 11. Amorphous material as determined by a 0.5 N NaOH selective dissolution analysis of Springerville gravelly clay.

Depth	Horizon	Separate	% SiO_2	% Al_2O_3	Amor.	SiO_2/Al_2O_3 molar ratio
0-2"	A1	<0.2 μ	5.3	2.2	8.3	4.1
		2-0.2 μ	2.1	0.6	3.0	5.8
		5-2 μ	3.1	2.1	5.7	2.5
2-8"	C1	<0.2 μ	5.5	2.1	8.4	4.4
		2-0.2 μ	1.9	0.6	2.7	5.8
		5-2 μ	3.4	1.8	5.7	3.2
8-46"	C2	<0.2 μ	4.7	1.9	7.3	4.2
		2-0.2 μ	1.9	0.6	2.7	5.2
		5-2 μ	*	*	*	*
46-67"	C3Ca	<0.2 μ	4.6	2.1	7.4	3.7
		2-0.2 μ	1.9	0.6	2.7	5.0
		5-2 μ	2.8	1.3	4.5	3.8

*Not determined.

based on the quantity of SiO_2 plus Al_2O_3 dissolved by the selective dissolution method divided by 0.9 as recommended by Alexiades and Jackson (1965). The amorphous material has a SiO_2/Al_2O_3 molar ratio greater than 3 suggesting that it may be montmorillonite in nature. Thus in calculating the montmorillonite content the cation exchange capacity due to amorphous material was subtracted.

Mica determinations are based on the K content of mineral fractions. Tables 8 and 9 show the percentages of mica in each fraction. The fine silt fraction has the highest mica content indicating its low stability in the finer fractions.

SUMMARY AND CONCLUSIONS

Quantitative analysis of clay minerals supported by the X-ray analysis of the two pedons of the Springerville soils shows the dominance of the montmorillonite type of clay minerals. Fine clay, coarse clay, and fine silt samples show the presence of vermiculite, mica, kaolinite, and possible presence of some chlorites. Elemental analyses of the fine clay ($< 0.2\mu$), coarse clay ($2-0.2\mu$), and fine silt ($5-2\mu$) show a great uniformity among the horizons of the two pedons. Silica-alumina, silica-iron, and silica-sesquioxide ratios are high confirming that limited leaching conditions prevail in the systems. The per cent montmorillonite ranges from 2 to 43% and the per cent vermiculite ranges from 3 to 16%.

From this study it is concluded that the mineralogical properties of the Springerville soils, Typic Chromusterts, are homogeneous with depth. Soil forming processes are the most important factor that contribute to the similarity of horizons among the two pedons of the Springerville soils. Chemical elements are well distributed within the horizons of the two pedons as a result of "self-turning" mechanisms. It is further concluded that basalt, the parent material under the prevailing climatic conditions, favors the formation of montmorillonite. Montmorillonite by virtue of its expanding-contracting properties contributes to the high shrink-swell characteristic of the Springerville soils which in turn results in the "self-churning" action which contributes to the uniform vertical distribution of clay minerals.

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