MORPHOLOGY AND GENESIS OF SOME SOILS CONTAINING FRAGIPANS IN NORTHERN MICHIGAN

By

Nicolaos John Yassoglou

AN ABSTRACT

Submitted to the School of Graduate Studies of Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

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Nicolaos John Yassoglou

ABSTRACT

The morphology and genesis of three soil profiles representative of the McBride, Isabella and Nester series were investigated. These three series constitute a lithosequence of well drained, bisequal podzols of North Michigan formed on calcareous sandy loam, sandy clay loam, and clay loam till, respectively.

Soils of the above lithosequence frequently contain fragipans, horizons, which are reversibly indurated when dry and friable or firm when wet.

Fragipans are formed in the eluvial zone of the lower sequum. They have high bulk densities, and low water permeabilities. They restrict the root growth of plants.

Chemical, physical, mineralogical and microscopical determinations showed that the necessary conditions for the induration of the fragipan were the close packing of the sand and coarse silt grains and an "optimum" clay content. The clay of the fragipan consists mainly of non-expanding minerals (illite, chlorite, kaolinite). It forms solid bridges holding together the sand grains. Free alumina may also have a cementing role, as it shows a small increase in the fragipan.

The important properties of the fragipan have been developed genetically. The close packing of the grains, the loss of the non-expanding clay and the rearrangement of the matrix substances result in a significant reduction of the volume of the fragipan and in the formation of vertical cracks in this part of the profile.

Results of X-ray, D.T.A., specific surface and total K analyses showed that illite and interstratified clays are being drastically

weathered near the surface of the soil. Discrete minerals of montmorillonite and vermiculite are being formed there.

The primary minerals which showed significant weathering are: calcite, hornblende, olivine and epidote.

The weathering of both the clay and primary minerals decreases with increasing depth from the surface.

Films of anisotropic (well oriented) clay have been seen in the thin sections of all the horizons of the lower sequa except the C horizon. The number and the thickness of the films, however, increase with depth and reach a maximum in the B_t horizon.

The Podzol sequa are characterized by a high state of physical, biological, and chemical activity, while the Gray-Brown Podzolic sequa are characterized by high physical activity. The chemical and biological activities in the latter sequa seem to be lower than in the podzol sequa.

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IN MEMORY OF

SOPHIA CHLOROU

whose will enabled two generations
of Greek foresters to pursue their
advanced studies in foreign countries

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INTRODUCTION

Things can be classified according to their properties either empirically on the basis of observations and experience, or scientifically on the basis of laws which explain and predict when, where, how and why these properties develop.

Soil classification has as its aim the development of schemes, which will enable us to estimate the suitability and potential of each soil for specific purposes, such as Agriculture, Forestry, Engineering etc. This suitability or potential, however, depends on the properties of the soil.

Soil genesis tries to develop and formulate laws, which will enable us to estimate or predict the properties of each soil, when the magnitude of each of the soil forming factors, as proposed by Jenny (31) is known.

Each soil genesis problem, therefore, is designed to answer specific questions and contribute to the formulation of the laws of soil classification.

The present investigation has as its purpose to study the properties and genesis of the soils of Northern Michigan having fragipans in relation to the existing magnitudes of the soil forming factors in this area.

Fragipans are soil horizons, which are reversibly indurated when they are dry and slightly cohesive or firm but fragile when they are moist. They decrease the water permeability of the soil and cause serious deformations in the root system of the plants. When exposed by soil erosion they are difficult to plow. When strongly developed they seem to reduce the physiological depth of the soil.

It is important to pedology, agriculture and forestry to know how these soils are formed, what causes the induration of the fragipans and how they could be destroyed in order to develop better physical conditions for the growth of plants.

To answer these questions, the changes which have occurred in the profiles, since zero time of soil formation, have been evaluated by detailed field, chemical, physical, mineralogical and microscopical studies.

REVIEW OF LITERATURE

A. General views on Podzols

A great number of works on podzols have been published, since Sprengel (1837) described what we know now as podzol soils.

Joffe, in his Pedology, after reviewing the classical works and hypotheses concerning the genesis, the morphology and the chemical properties of the podzols of the world, and citing two typical podzol profiles on the coastal plain of New Jersey, makes the following general statement:

"In general, the process of podzolization results in the depletion of the alkali and alkaline earth bases from the A_1 and more so from the A_2 horizon. The reason for the difference is due to the higher organic matter content of the A_1 horizon and hence a higher cation adsorption capacity. On parent material rich in bases, the return of these through the vegetation contributes to the differential distribution of the bases in the profile. The type of vegetation, whether rich or poor in bases, may also be a factor.

"With the depletion of bases, the sesquioxides and the clay particles enter into circulation, move downwards and accumulate in the profile to form the B horizon and give its characteristics. The absorptive power of the clay causes the retention of some alkaline earth bases which in turn enhance the precipitation of the sesquioxides."

Marbut (40) included the podzols in his Pedalfers. According to him, a typical podzol profile consists of a relatively thick layer of only partially decomposed organic debris, underlain by a gray layer of mineral soil. This layer ranges in thickness from a mere film up to more than one foot. The gray layer is underlaid by the ortstein or orterde, which is heavier in texture than the gray layer and it is brown, dark brown or coffee brown in color. The color is stronger at the top of this layer and its texture is also finer. Sometimes it is cemented into a hardpan which is hardest near the top. The ortstein is underlaid by the parent material, but there is a gradation from one into the other. Chemically the gray (A) horizon has a relatively low amount of iron and alumina and often of alkalies and alkaline earths, and a high percentage of silica. The ortstein (B) horizon contains a relatively high percentage of alumina, iron oxide and organic matter, and a lower percentage of silica. The A horizon is lower in iron, alumina, alkalies and alkaline earths than the parent material and higher in silica.

Marbut pointed out that previous investigations indicated that iron and alumina were carried down from the A horizon in colloidal form along with colloidal organic matter and deposited in the B horizon. The precipitation of the colloids in the B horizon resulted mainly from colloidal reactions controlled by the composition of the solution and the concentration of the colloidal suspension. Some of the iron is removed entirely from the soil through drain water.

Soils which have developed under the influence of a relatively weak podzolization are, according to Marbut, podzolic soils but not true podzols. These soils have coarser textured A horizons and finer textured B horizons which differ from the ortstein of the true podzols in having no higher organic matter than the A horizon and not being indurated as a rule.

B. Podzols of Michigan

McCool, Veatch and Spurway (45) have given the following general description of a podzolizolized soil from the northern part of Michigan:

1. Thin humus soil.
2. Gray podzolized horizon (3-24 inch).
3. Brown horizon (dark coffee brown to light leather color and dull yellow): thickness 4 in. to 4 feet; horizon of acid concentration.
4. Horizon showing iron oxide coloration; highest clay content: gradation to substratum.
5. Substratum.

Veatch (59) separated the Podzol region of Michigan soils from the Gray-Brown Podzolic region by a line which follows the approximate southern limit of the native white pine and beech vegetation. He also established a transitional zone between the Podzol region of the northern part of Michigan and the Gray-Brown Podzolic region of the southern part of the state.

Veatch and Millar (60) recognized in Michigan the so called bisequa profiles, which consist of more than one zone of eluviation and more than one zone of illuviation.

Gardner and Whiteside (21) studied bisequa profiles of the Podzol-Gray Brown Podzolic transition area. Their studies showed that these profiles consist of a Podzol upper sequum underlain by the A_2

and B_2 or sequum, of a Gray-Brown Podzolic profile. In the sandier soils the Podzol sequum is much more strongly developed than the Gray-Brown Podzolic sequum, while in the finer soils the reverse is true. The authors concluded that all horizons are genetic and are the result of either simultaneous development or of the development of a younger Podzol profile in the A_2 horizon of an older Gray-Brown Podzolic soil.

Cann and Whiteside (12) investigated the genesis of a Podzol Gray-Brown Podzolic intergrade soil profile. They found that loss in weight and gain in volume takes place largely in the Podzol sequum of the profile and a marked increase of organic material in the Podzol B and a slight increase of organic matter and considerable clay in the Gray Brown Podzolic B. Both horizons, therefore, are illuvial but the principal constituent accumulated is organic matter in the Podzol B and silicate clay in the Gray-Brown Podzolic B. The authors concluded that the development of the bisequum is a result of simultaneous processes involving the movement of different constituents and their deposition in different parts of the solum.

Veatch (61), in his book "Soils and Land of Michigan", gives the following description of the most complete profile in Michigan possible under the natural environment:

"1. Surface horizon of organic accumulation including the material commonly designated humus.

2. Maximum eluviation: usually light grayish, or bleached, incoherent or friable.

3. Horizon of secondary illuviation; commonly brown or yellow; colloidal matter mostly organic and iron oxides;

higher aluminum silicate content than in No. 2 but less than in No. 5.

4. Lower lixiviated or blanched horizon; yellowish becoming a lighter shade with depth and in extreme development, glei-like, gray mottled, or containing concretions and partial cementation by iron oxides.

5. Alferric horizon; maximum content of clay and maximum coloring from ferric oxides.

6. Transitional horizon of weathering between solum and unaltered parent material, slight accumulation of carbonates.

7. Unweathered parent material."

Veatch states, however, that not all the profiles in Michigan follow the above pattern. He describes variations of Podzols as the Gray Podzol which is the "normal" Podzol soil, the Brown Podzol which develops an orterde brown horizon but its eluvial gray surface horizon is very weak or absent, and the Gray Podzol clays (developed on clay materials) in which orterde horizon is very weak or absent.

Mateiski and Turk (43) studied the heavy minerals of some Michigan Podzol profiles. They concluded that the brown B horizon of some Podzol profiles is the result of the decomposition of a relatively high original content of opaque and ferromagnesian minerals. The least resistant mineral was found to be the dark green hornblende. The authors considered organic matter as an effective weathering agent in the B horizons.

Bailey, Whiteside and Erickson (2) studied the role of glacial materials as a factor in the morphology and genesis of 23 soil series of Michigan. They found that the sola increase in thickness except when the parent rock contained more than 12% acid soluble materials. The percentage of increase in clay contents relative to that in the parent rocks is small except in the very sandy materials, where most of the clay might be pedogenetic in origin.

McKenzie (46) studied the redox potentials in the different horizons of the Kalkaska-Saugatuck-Roscommon soil catena in Michigan. He found that in the well drained Kalkaska, the A horizon had the lowest oxidation potential of all the horizons, while the Bir and C horizons had the highest oxidation potential in the profile. He also isolated from the Bir microorganisms able to oxidize ferrous iron.

C. Soils with fragipan horizons

Carlisle (14) has summarized in his Ph.D. thesis several publications regarding reversibly indurated soil horizons. These investigations need not be rementioned in the present literature review. Carlisle studied the Mardin and Volusia soil series of New York. Mardin is a moderately well drained series classified as Podzol. Volusia is a poorly drained Low-Humic Gley soil series. Both series belong to the Bath-Mardin-Freemond-Volusia-Chippewa soil catena, and they have been developed on silty glacial till. The upper solum of Mardin shows a typical podzol sequum to a depth of 15 inches. Underlying the podzol B horizon is a lighter colored and coarser textured horizon 3-6 inches thick, which Carlisle names an A'_2 horizon. The color of this horizon is light yellowish brown ($2.5Y^6/_4$ - $5Y^6/_3$) with yellowish brown mottles. It has a coarse silt loam or very fine sandy loam texture and a weakly to moderately developed fine and medium platy structure, and sometimes a very weak medium blocky structure. The A'_2 horizon is friable to slightly firm and brittle when dry. The pH ranges from 5.0 to 5.5. Carlisle assumes that this horizon is a genetic one, because of its constant thickness and constant depth from the surface of the soil within a given kind of profile. He also bases his assumption on the fact that this horizon is always located in the same position relative to other horizons of the profile.

Below the A'_2 is the fragipan or B' horizon, which is about three feet thick, very firm, dense and slowly permeable to water. This horizon is compacted and has an olive brown color. It is very firm when moist and hard to extremely hard when dry. The pan is divided into very large prisms (6"-3' across) by vertical gray streaks 1/4 - 1 1/2 inches wide and 50-60 inches long. On a horizontal plane the streaks form a polygonal pattern. These streaks are filled with gray silt loam.

The imperfectly and poorly drained Volusia soils have an A_1 horizon 3-4 inches thick underlain by A'_2 and B' horizons similar to those in Mardin but more strongly gleyed.

Carlisle advances the hypothesis that the above soils were formed from a compact, slowly permeable and calcareous ground moraine. By means of physical weathering, an increase of the water permeability resulted in the development of an eluvial A'_2 horizon through lateral water movement, and in the deposition of silty materials in the cracks formed during dry weather. Continued deposition resulted in the high bulk density and low permeability of the pan. The character of the profile above the pan is a result of the water conditions produced by the interaction of the pan and topography. Degradation of the pan in Mardin soils is due to accelerated loss of clay from parts of the pan exposed to acid solution moving downwards from the Podzol horizons.

Carlisle, Knox and Grossman (16) described fragipans as dense, brittle subsoil horizons that appear to be indurated when dry but not indurated when moist. They consider them as genetic horizons found below an A-B horizon sequences (seoua) characteristic of Podzols, Brown Podzolic soils or Acid Brown Earths, and as components of Low-Humic Gley soils. They are found in materials of various textures but their characteristics vary with their texture. The authors state that fine sandy loam or silt loam fragipans are thicker, firmer and harder when dry than the coarser textured pans. Loamy sand and sandy loam fragipans have a weak, thick platy or weak, subangular blocky structure tending toward a massive condition. Fine sandy loam and silt loam fragipans have a very coarse prismatic structure outlined by vertical planes of grayish silty material, that form polygonal pattern on a horizontal plane. Clay loam and silty clay loam fragipans are similar to the ones of intermediate texture.

Brewer (8), in his Report of Overseas visit, describes Non-calcic Brown soils in California in the United States and in the vicinity of Madrid, Spain. These soils have a well developed A_2 horizon which is structureless, very hard and brittle when dry and friable when moist. The author states that the hardness of this horizon is associated with the distribution of particles of silt and very fine sand which form white, bleached coatings on the coarser grains. These coatings are seen through a (10X) hand lens. Brewer points out that the Non-calic Brown soils of California and Spain are morphologically similar to strongly differentiated soils formed on granites, granodiorites and rocks of similar composition, in the Southern Tablelands of New South Wales, Australia.

Winters and Simonson (67) describe the fragipan as a horizon in the profile that is slowly permeable, compact or dense, hard when dry and moderately friable to friable when moist. Silt loam is cited as the predominant textural class. They also state that very fine sandy loam, silty clay loam and clay loam are common textures of fragipans. Change of consistence with change in moisture content is a striking feature of fragipans. They suggest that the slaking of lumps from fragipans, when placed in water after air drying, is an evidence that the layers are not cemented by silica, even though they occur in regions where release of large amounts of colloidal silica can be expected. If the cementing agent were the silica gel, drying would destroy its cementing power. The silica gel would not regain its cementing properties unless it were dissolved and reprecipitated, which would not occur as the soil was rewetted.

Knox (36) studied four fragipan horizons from Orange County, N. Y. Microscopical examination showed that sand grains are partially coated and bonded together with yellowish brown bridges of fine material. These bridges consist of crystals of fine silt and coarse clay held together by a finer crystalline matrix. Optical and X-ray diffraction examinations revealed that the fine-grained material which holds the sand and silt particles together was illite. Stability and synthesis experiments designed to study the role of possible bonding materials as hydrous iron and aluminum oxides, colloidal silica, and clay showed that illite was responsible for a major part of the strength of typical fragipans, and that both illite and colloidal silica are involved in the strength of an extreme pan. Knox assumes that the effectiveness of illite as binding material in the fragipan is due to high bulk density, lack of effective structure, and special distribution of clay.

Grossman and M. G. Cline (23) studied twenty-four fragipan horizons of New York State. The texture of these horizons fell into two groups: (1) sandy loams and coarse loams, and (2) medium to fine silt loams. The authors tried to determine the relationships between rigidity and particle size distribution. Fragments of fragipan were shaped by hand into rough cylinders approximately 40 mm. long and 25 mm. in diameter. These cylinders were dried for 48 hours at a temperature of 42° C. After drying, the cylinders were encased from both ends in plaster of paris and they were crushed by slow application of an axial stress. The maximum stress withstood per unit of cross-sectional area was found to be highly correlated with per cent of total clay. The data did not justify any special role of the ultra-fine clay as a bonding agent. Grossman and Cline concluded that clay was the principle bonding agent, that very fine sand and silt may be equally effective as a matrix within which such clay bonds occur, and that clay can also be responsible for weakness of the pan due to the development of structure, depending upon its amount and distribution.

Anderson and White (1) studied three highly weathered soils of southern Indiana having fragipan horizons. These horizons are found immediately below the main part of the B horizon or the zone of maximum clay accumulation. In addition to the fragipan profiles, a fourth profile which did not have a fragipan, but was formed from similar parent material, was studied for comparison. Results showed a higher pH value for the profile which did not have a fragipan. The authors reached three conclusions regarding the fragipans of the moderately well drained Hosmer silt loam soil: (a) The clay of these horizons is lower in montmorillonite compared to a similar soil profile without a fragipan. (b) Only a small amount of the montmorillonite of these horizons is capable of expansion under normal conditions. (c) They consist of soil particles which are weakly cemented by iron oxides.

Grossman et al (24) found in the Hosmer series of Illinois that fragipan and bisequal nature increase with decreasing loess thickness and with latitude from north to south. The horizon they name as fragipan is located below the ($B^1{}_2$) horizon of maximum clay illuviation and it has an intermediate microstructure between the rich in clay films microstructure of $B^1{}_2$ and the unaltered microstructure of the C_1 horizon.

Fitzpatrick (19) suggests that indurated layers of certain Scottish and Norwegian soils have been formed by permafrost. He lists several macroscopic characteristics of these horizons as occurrence, topography, drainage, structure, thickness, depth, compaction and induration, which are very similar to the characteristics of the fragipans described by American authors and found in soils of Michigan during this investigation.

Fitzpatrick suggests that structural features of the indurated layer were produced under periglacial conditions existing in previous times, and through the following mechanism:

"At first summer thawing would take place to a considerable depth. Succeeding tundra conditions with the accompanying vegetation and litter would provide insulation which would cause a steady reduction of the depth of thawing. The reduction in depth of thawing would take place slowly, allowing the gradual but steady rise in the permafrost table. This gradual upward movement of the permafrost table would produce a marked development of alternating laminae of clear ice and the soil which would account for the well developed laminar structure of the indurated layer, especially at its upper surface. The presence of continuous vegetative cover would tend to cause the depth of thawing to be fairly uniform in any locality."

This suggestion is based on examinations of the permanently frozen subsoils of Spitzbergen, which revealed a macrostructure similar to the one of the indurated layer of the Scottish soils. The structure of the permafrost layer, which contained bands of clear ice, was preserved after a gradual thawing. Fitzpatrick was able to produce vesicular pores by freezing a mass of soil puddled with tap water and with ice cold water saturated with carbon dioxide. The presence of the CO_2 in the water increased the number and the size of the pores.

FIELD STUDIES

Field studies have been made mainly on soils in Osceola County, Michigan. A few soils of neighboring Lake County have also been studied during this investigation. The field studies were completed during three summer periods of detailed soil surveying, in 1956, 1957 and 1958.

I. General environment

Osceola County is located in the northern part of Lower Peninsula, and falls entirely within the Podzol Region of Michigan.

(1) Climate. The climate of Michigan is significantly influenced by the presence of the Great Lakes. In the interior counties the climate alternates between continental and semimarine, depending on the direction and the force of the wind. When there is little or no wind, the continental climate prevails, but strong winds from the Lakes transform the climate into semimarine. Narrow belts along the shores of the Great Lakes have marine climates. Soils studied in this investigation are subjected to the continental-semimarine type of climate. Precipitation in Michigan is fairly well distributed through the year. The relative humidity is high in the winter and moderate in the summer. The number of cloudy days is about equal to the number of the clear days, but clear days are more frequent during the summer months.

Following are some meteorological data from Reed City, Osceola County, taken from the Yearbook of Agriculture, 1941, p. 914-924.

Temperature			Average Precipitation in inches	
January average	18.7° F		Winter	4.44
July average	69.2° F		Spring	7.41
Maximum	102° F		Summer	9.45
Minimum	-42° F		Fall	8.43
			Annual	29.73

Length of Growing Season 125 days.

(2) Geology. Michigan was entirely covered by ice sheets during recent glacial periods and, therefore, the surface forms are largely the result of the type and thickness of the glacial deposits.

Osceola County is located in the Northern Highland of the South Peninsula. The altitude above the sea level ranges from about 1200 feet to 1400 feet. The physiography of the biggest part of Osceola and of the sites studied in Lake County are morainic. A relatively small area consists of glacial and outwash channels.

(3) Vegetation. The predominant woodland vegetation of the area at present consists of northern hardwoods, including the following species: Sugar maple (Acer saccharum, Marsh), Elm (Ulmus americana, L.), Basswood (Tilia americana, L.), Beech (Fagus grandifolia, Ehrh.), Hemlock (Tsuga canadensis, L.), Aspen (Populus tremuloides, Michx.), and scattered White pine (Pinus strobus, L.)

The present composition and distribution of the vegetation has resulted from the extensive lumbering and subsequent burning during the last quarter of the 19th century. The original vegetation before the lumbering was, according to Veatch (59), of a hardwood-conifer type, consisting of the hardwoods mentioned above, plus Red pine (Pinus resinosa, Ait) and White pine (Pinus strobus, L.). The pines used to form pure or mixed with hardwoods stands.

Opinions concerning the climax vegetation are divided into two groups. One considers pine-hemlock and the other considers hemlock-deciduous forest as a climax. The latter group considers pine on sandy soils as an edaphic climax or post climax.

Potzger (54) states that pollen profiles indicate that pine is a post climax and Tsuga-broadleaved genera are the climax. Pollen profiles, according to Potzger, also show that, since the last glaciation, climatic fluctuations from central Indiana to the Upper Peninsula of Michigan were not sufficient to cause great changes in the forest cover. He assumes that Picea glauca constituted a belt between the ice front and the deciduous forest to the south in the interior of Indiana. When Pinus crowded in, Picea started being replaced by deciduous species associated with Tsuga and subsequently Pinus started to decline.

II. Soils

The object of this investigation was to study the morphology and genesis of certain soils in Northern Michigan containing fragipan horizons.

Fragipans have been defined in the U. S. as compact soil horizons, rich in sand and silt, and which are hard and brittle when dry but loose or firm when wet. They have a platy structure and discontinuous vesicular pores in their upper part, and a massive structure in the lower part. Their upper boundary is sharply defined, while the lower boundary is usually diffuse. They have relatively light colors. Their common characteristic is the reversible induration, which differentiates them from other non-reversible pans.

Guy Smith gives the following definition of fragipan in the 5th Approximation:

"A fragipan is a loamy subsurface horizon, usually underlying a B, very low in organic matter, with high bulk density relative to the solum above, seemingly cemented when dry, having hard or very hard consistence, but when moist moderate or weak brittleness (tendency for a ped to rupture suddenly rather than undergoing deformation as increasing pressure is applied). It is mottled, slowly or very slowly permeable to water, and usually has occasional or frequent bleached cracks forming polygons. Fragipans are usually found with abrupt or clear upper horizon boundaries at from 15 to 40 inches below the original surface, vary from a few inches to several feet in thickness and have gradual or diffuse lower boundaries. They are nearly free of roots except for the bleached cracks. Clay skins are scarce to common both in the polygonal cracks and in the interiors of the peds."

It has been repeatedly observed in the field that soils of Northern Michigan, which have fragipan horizons, belong to the lithosequences of soils formed from glacial drifts of loamy sand, sandy loam, sandy clay loam, clay loam, and sandy clay textures. The most pronounced fragipans, however, are found in profiles developed on sandy loam or sandy clay loam parent materials. In the case of sandy clay loam and finer textured parent materials, the fragipans are more strongly developed in deeply leached profiles (limy horizons below 40 inches from the surface). The weakest fragipans are found on clay loam parent material. Loam parent materials were not common and silt loams were absent in the area studied and these textures were not studied, although it is evident in other parts of Michigan that fragipans form in loam and silt loam materials, too.

Fragipan horizons were recognized in well drained soils as well as in imperfectly drained soils. The imperfectly drained soils were not dry enough to reveal the extreme hardness of their pan, but the physical properties of the pan were conspicuous. Most of the fragipans are found in soils with bisequa profiles which are the zonal profiles in this area. In the case of the finest members of the lithosequence, the upper Podzol sequum is very weakly developed, while clearly developed Podzol upper sequa are found on loamy sand and sandy loam parent materials. Soils formed on sandy loam and finer parent materials do not develop orstein in the area studied, but they do form orterde or Bhir horizon, of which the color ranges from the moderate orange yellow to the dark reddish brown. The light colored Bhir forms on heavy members of the lithosequence. The eluvial gray A2 horizon is almost always present, but its thickness is quite variable, ranging usually from one inch up to five or six inches.

As a general rule, the fragipan horizon develops in the second eluvial zone of the profile, just below the Podzol B horizon. In most of the soils it is a continuous horizon, but in sand and loamy sand profiles having multiple textural bands, the fragipan develops in the finer textured bands below the second eluvial zone, while the coarser layers between the bands do not show any cementation.

In the case of well developed fragipans, the cemented zone can be divided into three individual layers: upper, middle, and lower.

The upper layer constitutes a transitional layer between the Podzol Bhir and the fragipan. Its upper boundary is rather diffuse but its lower boundary is sharply defined. Both boundaries are irregular. It is coarse, platy and vesicular in structure and weakly cemented, while the Bhir usually has a weak crumb structure and it is not cemented. Some organic matter and sesquioxides precipitate in this layer, producing a darker color than that of the layer below. The roots are fairly well distributed in this layer. It seems that this layer was originally similar to the horizon below, and that it has been affected by processes responsible for the development of the upper Podzol sequum. Its thickness usually ranges between one and two inches.

The middle horizon has a distinct platy and vesicular structure, and it is much denser and harder than the overlying transitional layer. Its texture usually is coarser than the Bhir and the immediately underlying horizon. There is no macroscopical evidence of any kind of illuviation. The usual colors of this layer are: (moist) 10 YR $^5/_2$, 10 YR $^6/_1$, 10 YR $^6/_2$, 10 YR $^7/_2$, and 10 YR $^7/_3$. This horizon contains a few blocks richer in clay than the rest of the horizon. These finer textured blocks have a reddish brown color in contrast to the grayish color of the bulk of the horizon. The color of the blocks depends on the amount of clay present, which varies with the degree of eluviation of each one of them. The most common colors observed are 10 YR $^5/_4$, 5 YR $^5/_3$, 5 YR $^4/_3$, and 7.5 YR $^4/_4$. The size of the blocks is quite variable, but they generally are less than one inch in their longest dimension. Depending on the degree of eluviation of the clay, some of the blocks are considerably harder and others much softer than the rest of the horizon. Usually the grayer their color, the harder they are. The blocks are more abundant and relatively softer in soils developed on the finer textured materials in the lithosequence, but the hardest of them have been found in soils formed from loamy sand parent materials. As mentioned above, the upper boundary is sharp and irregular as the Podzol sequum extends as tongues into the fragipan. The depth to the upper boundary varies in most cases from 10-22 inches. The deepest pans are usually found in the coarser textured members of the lithosequence. In many cases a sheath of silty material has been found around the pebbles in these profiles. Similar formations have been found by Fitzpatrick (19) in permafrost horizons. The thickness of this layer ranges from 5 to 12 inches. The highest thickness is found on coarser soils. Root branching is rare in this layer, but a few tap roots go through it. Tap roots of alfalfa have been observed which apparently had difficulties in penetrating the pan, for they take a zigzag course following cracks. The degree of cementation of this layer varies in different places, and it seems to depend on the amount of clay present.

The lower layer of the pan is also very dense but considerably harder and a little richer in clay than the middle layer. Its structure is massive, but sometimes when pressed it breaks into coarse platy or subangular and angular blocky fragments. The vesicular discontinuous pores are considerably less abundant in this part of the pan. Its upper boundary is clear and irregular. The lower boundary is also clear in most cases but sometimes it is gradual, and generally is very irregular, with many tongues extending into the underlying illuvial zone. The thickness of this layer varies considerably even in the same soil, mainly because of the tongues and the irregularity of the lower boundary; it usually ranges between 5 and 15 inches. Finer textured blocks are more abundant in this layer than in the middle one, but they usually are softer than the bulk of the layer, except in loamy sand soils, in which they may be harder. Due to the higher clay content, the color of the lower layer is a little more pinkish than the color of the middle layer. Common colors are: (moist) 10 YR 5/2 and 7.5 6/2. There is no root branching in this horizon either, and tap roots have zigzag shapes.

In many soils and especially in those formed on sandy clay loams and clay loams, a transitional layer is developed between the pan and the second zone of illuviation. This transitional layer is illuvial and resembles the underlying B_t horizon, for the most part, but in certain places and especially on the edges of the structural units, it is grayish in color, shows eluviation and generally its properties in these places are similar to the properties of the pan. It has a medium, subangular blocky structure.

Most of the fragipan profiles studied have several wedge-like cracks extending from the top of the pan down to the transitional illuvial horizon. Silt and clay have been deposited by percolating water in these cracks. In certain parts of the cracks, silty clay or clay balls form by deposition. The cracks contain, also, plant roots and soil materials falling down from the Podzol sequum under the influence of gravity. In pits dug 5-6 feet wide, the cracks have not been found to form regular polygonal pattern on a horizontal surface, as described by Carlisle (14) in soils of New York, and by other workers. The cracks, due to their vertical orientation, contribute to the internal drainage of the soil, which otherwise would have been imperfect, because of the low water permeability of the fragipan. Besides the vertical cracks, horizontal plane-like cracks have been found in the pan of many soils. These cracks contribute to the platiness of the structure of the pan. They are 0.5 - 2 mm. wide, while the vertical ones can be as wide as 2 or 3 inches. The cracks have a white color and, when examined under the binocular microscope, are found to be filled with silt.

The pan of the imperfectly drained soils has similar physical properties to those of the well drained soils, but it is mottled, and being wet for longer periods, reveals its hardness for shorter periods during the year than the pans in the well drained soils.

The fragipan of Michigan soils is compact, has a high bulk density, exhibits a reversible induration, and generally is similar in its macroscopical characteristics to those described elsewhere in the U. S. and abroad, as cited in the literature review. The relatively high bulk density of many soils of Michigan is not limited only to the fragipan, but it extends down to the transitional illuvial horizon and even to the Bt horizon. The bulk density of the soil below the fragipan decreases with depth.

Below the transitional horizon is the second illuvial horizon or Bt, which is the horizon richest in clay. It usually has a brown or reddish brown color. There are numerous and conspicuous clay coatings along the root channels and on the surfaces of structural units. The structure is usually medium subangular blocky but sometimes it is angular blocky. There is a fair root branching in this horizon. Root branching and clay coatings are also found in the overlying transitional illuvial horizon. The thickness of the Bt ranges between 12 and 25 inches. Coarse soils have usually thicker Bt horizons. There is no evidence of cementation in this horizon, except a slight one in the case of loamy sand and some sandy loam materials. Common moist colors of the Bt are 5 YR 4/4, 5 YR 4/3, 5 YR 3/4, and 7.5 YR 4/4.

The Bt horizon is underlaid by the parent material or C horizon which is a calcareous gritty glacial drift. Due to the presence of lime and to the relatively low amount of iron associated with the clay, the C horizon has lighter color than the Bt. Common colors are: (moist) 5 YR 6/3, 7.5 YR 6/4, 7.5 YR 5/4, 5 YR 5/3, 5 YR 3/4. There are no clay coatings in the C horizon except in a thin layer immediately below the Bt. The C horizon is generally not so compact, as the overlying layers and roots show a fair amount of branching.

These fragipan profiles are usually moderately acid from the surface down to the lower boundary of the Bt horizon.

Since fragipans are found in Michigan mostly in the lithosequences of soil formed in loamy sand to clay loam primary materials, and since well drained members of the catenas which fall within the above lithosequences, frequently form well developed fragipans, which are apparently cemented for longer periods annually than imperfectly drained fragipans, it was decided to select representatives of these for the present investigation. Three well drained Podzol profiles of the above lithosequence, having well expressed fragipans were selected for study.

The profiles selected for this study belong to the following soil series:

(1) McBride formed in sandy loam parent material

(2) Isabella formed in sandy clay loam to sandy clay parent

material

(3) Nester formed on clay loam to silty clay loam parent material

Following are descriptions of the three profiles which have been subjected to detailed field and laboratory studies:

I. McBride sandy loam

Location:	NW 1/4, SE 1/4, Section 23, T 20 N, R 11 W, Lake County, 100 feet east of the road across from the farmhouse.
Vegetation:	Sugar maple, 40 years old stand
Drainage:	well drained
Slope:	8% East
Physiography:	Rolling glacial moraine

Horizon	Depth	Description
A^0	0-1"	Leaf litter and partially decomposed organic material. It contains many fibrous roots.
A_1	1-3"	Dark grayish yellowish brown (10 YR 3/2 moist); coarse, sandy loam; rich in well decomposed and intermixed organic material, heavily matted with fibrous roots; moderate, medium, crumb; friable; pH. 5.4; boundary abrupt.
A2	3-5"	Light brownish gray - grayish yellowish brown (10 YR 5/1 moist); loamy sand; the number of fibrous roots is smaller than in A_0, A_1; numerous channels, root and worm holes, and different passages are filled with dark materials from A_0 and A_1; weak, medium,

Color names used are ISCC-NBS names.

subangular blocky, friable; pH 5.2; boundary abrupt.

Bhir 5-17" Moderate yellowish brown (10 YR 4/4 moist); loamy sand; rich in roots of various sizes; weak, medium, subangular blocky; friable; pH 5.3; boundary clear.

Bm (trans.) 17-19" Moderate yellowish brown (10 YR 5/4 moist); loamy sand; few roots; vesicular, moderate, thick, platy and medium, subangular blocky; friable when wet, weakly cemented when dry; contains small lumps which resemble the horizon below; pH 5.6; boundary clear, irregular.

A_{2m} 19-24" Light yellowish brown (10 YR 7/4 moist); loamy sand; fibrous roots are practically absent, a very few tap roots go through this horizon without branching; vesicular, strong, very thick, platy; indurated when dry, friable when wet; a few worm holes are filled with materials from overlying horizons; wedge-shaped vertical cracks contain silt and clay deposits; 0.5 - 2.0 mm. wide horizontal plane-like cracks filled with silt; compact; pH 5.8; boundary clear, irregular.

A_{3m} 24-35" Light grayish brown (7.5 YR 6/2 moist) for its greatest part, but contains moderate brown (5 YR 4/3 moist) lumps, which are finer in texture than the rest of the horizon and increase in number and size with depth, sandy loam; massive but when pressed, it breaks into strong, very thick, platy and medium, subangular blocky fragments; indurated when dry, friable when wet; vertical and horizontal cracks same as in the overlying horizon; root distribution also same as above; very compact; (this is the hardest of all the horizons of the profile); pH 5.6; boundary clear and irregular.

Bt	35-53"	Moderate brown (5 YR 3/4 moist); coarse, sandy clay loam; strong, medium, angular blocky; when moist is very firm, somewhat compact; rich in clay coatings but not indurated; roots are abundant; pH 5.2; boundary clear and wavy.
C	+ 53"	Light grayish reddish brown - light brown (5 YR 5/3 moist); sandy loam; moderate, medium, subangular blocky; no clay coatings; moist, firm but not compact; roots fairly abundant; pH 7.8; calcareous.

II. Isabella sandy loam

Location:	SW 1/4, NE 1/4, NW 1/4, Section 31, T 19 N, R 9 W, Osceola County, Michigan.
Vegetation:	Sugar maple, elm, beech, and white pine
Drainage:	Well drained
Slope:	16% West
Physiography:	Glacial moraine.

Horizon	Depth	Description
Ao	0-1"	Leaf litter and partially decomposed organic material.
A1	1-3"	Dark grayish yellowish brown (10 YR 2/1 moist); sandy loam; weak, medium, crumb; friable; rich in

fibrous roots and well decomposed and intermixed organic matter; pH 4.7; boundary abrupt.

A_2 3-5" Light grayish yellowish brown (10 YR 6/2 moist); coarse, sandy loam; weak, fine, crumb; moist, friable; fewer roots than in A_1; it contains root holes and other large pores filled with dark material from the A_1; pH 4.7; boundary abrupt.

Bhir 5-11" Moderate brown (5 YR 3/3, 4/3 moist); sandy loam; weak, fine, subangular blocky; moist, friable; roots of various sizes are abundant; pH 4.6; boundary clear and irregular.

B_m (trans.) 11-13" Grayish yellowish brown to moderate yellowish brown (10 YR 5/3, 4/3 moist) loamy sand; vesicular, moderate, thick, platy and medium, angular blocky; weakly cemented, moderately compacted; few roots; pH 4.6; boundary sharp and irregular.

A_{2m} 13-21" Light brownish gray - light grayish yellowish brown (10 YR 6/1 moist); with finer textured moderate yellowish brown (10 YR 5/4 moist) lumps; loamy sand; vesicular, strong, medium platy; indurated when it is dry and friable when moist, strongly compacted; wedge-like and vertical cracks and old root holes contain silt and clay deposits and materials that have fallen down from upper horizons; root distribution very sparse; pH 4.9; boundary abrupt.

A_{3m} 21-34" Light grayish brown (7.5 YR 6/2 moist) with finer textured light brown (5 YR 5/3 moist) lumps; sandy loam; massive, but when pressed, it breaks into moderate, medium, subangular blocky fragments; indurated when dry, (the hardest horizon in the profile), strongly compacted; cracks and root holes same as in the horizon above; pH 5.0; boundary diffuse and irregular.

A & B 34-42" Moderate brown (7.5 YR 4/4 moist), sandy clay loam for the most part; sandy clay loam, but small portions are yellowish gray (10 YR 7/1 moist) and have loamy sand texture; weak, medium, subangular blocky; moist firm, moderately compact, the vertical cracks stop in this horizon and contain grayish sandy materials along with silt and clay deposits; there are numerous clay coatings along the root holes and other channels; fine fibrous roots are abundant; pH 4.8; boundary abrupt and irregular.

Bt* 42-55" Moderate brown (7.5 YR 4/4 moist); sandy clay loam; weak, medium blocky; moist, very firm, not compact; rich in moderate brown (5 YR 4/3 moist) clay coatings along the root holes and planes of weakness; roots are abundant; pH 5.3; boundary clear and wavy.

C + 56 Light brown (7.5 5/4 moist); sandy clay loam; weak,

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* Between the B_t and C horizons have been found 1-3 inches thick pockets of silty materials which have no genetic relations with the horizons, but they are geologic depositions frequent in the glacial deposits.

medium, subangular blocky; firm but not compact; no clay coatings; few roots; pH 7.9, calcareous.

III. Nester sandy loam

Location: SW 1/4, SW 1/4, SE 1/4, Section 36, T 19 N, R 10 W, Osceola County, Michigan.

Vegetation: Sugar maple, aspen, birch, ash, basswood and few firs.

Drainage: Well drained

Slope: 2% East

Physiography: Moraine

Horizon	Depth	Description
A_0	0-1"	Leaf litter and partially decomposed organic matter; abundant fibrous roots; boundary abrupt and wavy.
A_1	1-5"	Dark grayish yellowish brown (10 YR $^2/_2$ moist); sandy loam; moderate, medium, crumb; moist, friable; rich in well decomposed and intermixed organic matter; matted with fibrous and larger roots; pH 5.4; boundary abrupt and smooth.
A_2/Bhir	5-9"	Grayish yellowish brown (10 YR $^5/_2$ moist), but in certain spots a weak moderate yellowish brown (10 YR $^4/_4$ moist) orterde has developed; sandy loam; moderate, medium, platy and subangular blocky; friable, roots of various sizes are abundant; root and worm holes are filled with materials from the A_1; pH 5.2; boundary abrupt and irregular. The A_2 and Bhir are not developed well enough to be distinguished as

individual horizons.

A2m 9-16" Grayish yellowish brown (10 YR 5/2 moist) with finer textured moderate brown (7.5 YR 4/4 moist) lumps 1/4 - 6" in diameter; sandy loam; vesicular, moderate, thick, platy, with some vertical cracks and horizontal planes of weakness; cemented when dry, friable when moist; (When dry, it is the hardest horizon in the profile.) very few unbranched roots penetrate this horizon; silt and clay deposits are present in the cracks and there are a few clay coatings along root channels; pH 5.4; boundary clear and irregular.

A & B 16-27" Moderate brown (7.5 YR 4/4 moist) for the most part and grayish yellowish brown (10 YR 5/2 moist) in some eluvial spots; clay loam, in the illuvial parts and sandy loam in the eluvial parts; moderate, medium, subangular blocky; dry cemented or moist extremely firm; moderately compact; the vertical cracks end in this horizon and contain sand silt and clay deposits; there is a fair root branching; clay coatings are abundant along the root channels; pH 5.0; boundary clear and irregular.

Bt 27-48" Moderate brown (5 YR 4/4 moist); clay; strong, medium, subangular blocky; moist very firm, moderately compact; roots are abundant; numerous clay coatings along the root channels and on the surfaces of the structural units; pH 5.0; boundary clear and wavy.

C	48-65"	Moderate brown (5 YR 4/3 moist); clay loam to sandy clay loam containing fine gravels of decomposing limestone; moderate, medium, subangular blocky; moist very firm; roots are fairly abundant; few clay coatings in its upper part; pH 7.6; boundary abrupt and wavy.
D	+ 65"	Moderate brown (7.5 YR 4/4 moist) calcareous; coarse sandy loam; not compact.

Remarks:

The morphology of the described and other similar profiles suggests that podzolization has disintegrated the upper part of the fragipan.

The presence of the finer textured lumps in the fragipan and the existence of a transitional eluvial-illuvial layer just below the fragipan, show that the pan had been in the past richer in clay, and that at least some of its properties and features are previously developed genetical B_t horizons. The finer lumps can be considered as relics of the parent material.

The dependence of the hardness of the pan and of its finer textured lumps on the clay content suggests that clay plays a certain role as a binding agent.

The transitional eluvial-illuvial horizon of the McBride soil was not well defined and, therefore, in sampling, it was split between the lower horizon of the pan and the underlying second illuvial horizon. The symbol Bhir used here does not imply outstanding accumulation of iron and organic matter causing cementation as stated in the Soil Survey Manual.

METHODS OF ANALYSIS

Studies of the physical, chemical and mineralogical properties of each horizon were conducted in the laboratory to determine the kind and amount of changes in the course of soil genesis of the three selected profiles.

Six undisturbed core samples and a three to four pound bag sample were taken from each of the horizons described in the previous chapter. The bag samples were parts of a bigger and thoroughly mixed sample, representative of each horizon.

Methods followed in the laboratory determinations are:

I. DETERMINATION OF PHYSICAL PROPERTIES

1. Water permeability, pore size distribution, and bulk density were determined on six replicate core samples from each horizon, according to Uhland and O'Neal (58) methods.

Water permeability was determined by applying 100 cc. of distilled water on top of the water saturated cores, and recording the time which elapsed until water on top of the core was completely drained. In the case of cores with slow permeability, the volume of water passed through the core in two hours was estimated by measuring the volume of the water which remained on the top of the core at that time and substructing it from 100 ml. No constant head of water was used.

Pore size distribution. Water saturated cores were weighed and placed on 60 cm. tension tables. After constant weight was obtained, the samples were oven dried at 105° C. until a new constant weight was reached. The weight losses in grams on the tension table and in the oven divided by the volume of the cores (347 ml.) represent the per cent non-capillary and capillary porosity respectively.

Bulk density was determined by dividing the oven dry weight of the soil sample by the volume of the core.

2. Hardness. Grossman and Cline (23) measured hardness of fragipans by recording the crushing pressure applied on dry and roughly cylindrical artificially molded cylinders of soil materials. They expressed their results in terms of a crushing number which was related to the force applied and the size (cross section) of the cylinders.

Since crushing values are scientifically sound only when geometrically perfect bodies are being tested, it was felt that this method could not be successfully used in the present study, because it is extremely difficult to prepare geometrically perfect soil samples without destroying their natural structure. The problem is still more difficult in the case of fragipan horizons because of their brittleness and their numerous planes of weakness. It was decided, therefore, to use the relative resistance of the undisturbed cores of soil to the vertical penetration of a 90° metallic cone as a measure of the soil hardness.

A disadvantage of this method is adherence on the soil-metal interface which may modify the results especially in fine textured soils. Factors influencing the magnitude of the adherence are: texture, structure, type of clay minerals present, organic matter, and water content. In the case of the profiles studied, however, the differences in hardness of the tested horizons were so great that the influence of adherence could be disregarded.

Another problem in measuring hardness was the proper water content of the samples at the time of measurement. Fragipans have been defined as horizons indurated when dry but not indurated when moist. It has been observed, however, that deeper and finer horizons, not having the appearance and the properties of fragipan, exhibit an extreme hardness when they are air dried. It has also been observed, both in the field and in the laboratory, that moist fragipans partially maintain their hardness if their water content is below field capacity, while other horizons become either friable or plastic.

The water content at one atmosphere tension was found to be satisfactory for these measurements.

The two hardest core samples from each of the tested horizons were water saturated and placed in pressure cookers, where they were subjected to one atmosphere pressure until their water content had reached equilibrium (constant weight). The force required to push the cone for 1.5 cm. into the undisturbed soil of the core was measured by means of an unconfined compression apparatus. The very hard cores of the A_{3m} horizons were tested by means of a Tinius Olsen hydraulic press. Three measurements were made on each base of the cores. The average Cone Penetration Resistance for each horizon was calculated by using the formula suggested by Capper and Cassie (13):

$$CPR = \frac{(\sqrt{W_2} - \sqrt{W_1})^2}{\pi (P_2 - P_1)^2}$$

where CPR = cone penetration resistance

W_1 = weight of the cone in Kgms.

W_2 = applied load in Kgms.

P_1 = penetration in cm. due to the weight of the cone

P_2 = final penetration due to the load applied plus the weight of the cone (1.5 cm.)

3. Mechanical Analyses: The bulk samples were crushed lightly with a wooden rolling pin to avoid fracturing primary particles, and the material passing through a 2 mm. screen was used in studies of the properties of the bulk samples. 25 gms. of moderately fine textured soil samples and 50 gms. of sandy soil samples were used. Organic matter was destroyed by overnight digestion with 200 ml. of 10% H_2O_2, followed by digestion with 50 ml. of 30% H_2O_2 on a 90° C. hot plate until reaction ceased and the excess of H_2O_2 was evaporated. Samples of A_1 horizons rich in organic matter were repeatedly digested with 10% and 30% H_2O_2 until they were not reactive with H_2O_2.

Carbonates and exchangeable Ca^{++} ions were removed by washing the samples with 300 cc. of 1% HCl solution in Buchner funnels. The calcareous samples of the C horizons were repeatedly titrated with 1% HCl until a constant pH of 3.5 - 4.0 was obtained. The chlorides were then removed by washing with distilled water until $AgNO_3$ produced no white precipitate with the leachates. The samples were then titrated to pH 8.5 with 0.1 NaOH and were shaken overnight. After shaking, the sand was separated from the silt and clay by sieving through a 300 mesh sieve. The sands were oven dried and then separated into coarse, medium, fine, and very fine fractions by mechanical shaking for 15 minutes in a nest of sieves, and finally these separates were weighed. A 1000 ml. water suspension was made from the less than 50μ fraction and the amounts of 50-20, 20-5, 5-2 and less than 2 micron soil separates were determined by the pipette method as described by Kilmer and Alexander (35). Corrections for the NaOH added in each sample were made.

The results of the mechanical analyses were calculated on an oven dry, organic matter free and carbonate free and H saturated basis.

4. Hygroscopic water. 10 gms. of air dry soil were weighed, oven dried for four hours and weighed again. The loss in weight expressed as a per cent of the oven dry weight of the soil represents the per cent of hygroscopic water.

II. CHEMICAL ANALYSES

The samples were crushed by a wooden rolling pin and passed through a 1 mm. sieve.

1. Organic Carbon. The dry combustion method of the carbon train was followed as described by Piper (51). 1-3 gms. of oven dry soil were mixed with 0.25 gms. of manganese dioxide and about 2 gms. of carbon free ground quartz in a porcelain boat and were ignited in the combustion tube of the train at 950° C. with a constant flow of oxygen. Purified carbon dioxide was absorbed in the ascarite tube and weighed. Carbonates of the C horizons were decomposed previous to combustion by sulfurous acid. Results were calculated as per cent of organic carbon on an oven dry 1 mm. carbonate containing basis.

2. pH measurements. 25 gms. of air dry soil were mixed with 25 cc. of distilled water in a 100 ml. beaker and allowed to equilibrate for half an hour. Measurements were made by using a Beckman zeromatic pH meter.

3. Loss in solution. 10 gms. of oven dried soil was placed in 400 ml. preweighed beakers and digested with 10% and 30% of H_2O_2 as described in the method of mechanical analysis. After the organic matter was digested, the samples were oven dried and weighed with the beakers. 100 ml. of 1% HCl were then added and, after adequate stirring, the suspension was filtered and washed free of chlorides in Buchner funnels. The soil was finally transferred back into the beakers, oven dried and weighed. The loss in acid solution was calculated by subtracting from the total loss the loss due to the digestion with H_2O_2. The results were expressed on oven dry basis.

4. Determination of the relative distribution of the alkali soluble silica in the soil profiles.

Amorphous or "free silica" were measured to determine whether they are related to the formation and induration of the fragipans, as they are in certain irreversibly indurated hardpans. A high relative amorphous silica content in the fragipan could possibly contribute to its cementation.

Methods for extracting "free silica" from the soil use alkali extractants - commonly 0.5NNaOH. The solubility of silica increases with pH. The solubility of silica also increases with temperature. Sawney and Jackson (55) removed amorphous silica and alumina from clays by boiling the samples with .5NNaOH for four hours. Hot alkali solvents, however, take silica into solution from silicates and quartz, too. The amount of silica passing into solution increases with decreasing size of the minerals.

Since only relative amounts of free silica were to be determined in this study, it was decided, in order to minimize the solution of crystalline silica, to boil the soil samples with .5NNaOH for only 15 minutes.

The following adapted gravimetric method was followed for the determination of the extracted silica:

Duplicate 5 gm. soil samples were put in 400 ml. nickel beakers. 50 ml. 0.5NNaOH were added and the suspension was boiled for 15 minutes on a hot plate. After boiling the solution was filtered into 100 ml. nickel crucibles 2-4 times until no soil particle was left in the solution. No. 42 Whatman filter paper and polyethylene funnels were used. After each filtration, the soil and the filter paper were thoroughly washed with warm .5NNaOH. The clear filtrate was slowly evaporated on a hot plate to dryness - care was taken to avoid any spiattering - the residue was ignited in an electric furnace for half an hour at 500° C. Alkali soluble organic matter was in this way oxidized. The crucibles were then cooled for 15 minutes, the covers were placed on them, and 15 ml. of 70% perchloric acid ($HClO_4$) were added dropwise under the slightly raised lids. When effervescence ceased, the lids and the sides of the crucibles were washed down with a minimum of water and the crucibles, with the lids covering three-fourths of the top, were placed on the hot plate, and the suspension was evaporated to fumes of $HClO_4$. When dense fumes appeared, the crucibles were covered and the suspension was boiled gently for 15 minutes. When the crucibles were cooled, 20 ml. of distilled water were added and the suspension was carefully mixed and heated almost to boiling to dissolve the salts which have solidified on cooling. The suspension was then transferred to 50 ml. pointed centrifuge tubes. Care was taken that no silica was left in the crucibles. 2 ml. of 6NHCl were added and the suspension was thoroughly mixed and centrifuged at 1800 rpm. for 5 minutes to throw down the dehydrated silica. The supernatant solution containing different salts and nickel taken from the crucibles was carefully sucked off by means of a 50 ml. pipette attached to a rubber suction bulb. The precipitated silica was washed with 1.2NHCl and centrifuged four more times and then the residue was transferred to 30 ml. platinum crucibles. 10 drops of (1+4) sulfuric acid were added and the suspension was slowly evaporated to dryness on an electric hot plate at about 100° C. After the silica had been dried, the crucibles were placed on a silica-tube triangle and heated gently, first with a low flame Mecker burner, and then were heated with strong flame for about 10 minutes during which the crucibles were three-fourths covered. The crucibles were then cooled in a desicator for 5 minutes and weighed. The ignition was repeated until constant weight was obtained. The silica was then moistened with 2 drops of (1+1) sulfuric acid and then 10 ml. of HF were added. The liquid was slowly evaporated to dryness on a hot plate and then ignited on the Mecker burner, cooled in the desicator and weighed.

The loss in weight due to volatilization of silica by HF represents the amount of SiO_2 extracted from the soil.

Any use of glassware before the acid precipitation of silica was avoided. Extracting solutions were kept in polyethylene bottles.

5. Determination of the relative distribution of soluble alumina in the soil profiles.

Soluble alumina was also determined to see if it bore any relationship to the apparent cementation of the fragipan horizons.

Different extracting solutions for "free alumina" have been suggested by different authors. McLean, Henderson, Bartlett and Holowaychuk (47) recommended 1. N CH_3COONH_4 buffered at pH 4.8. They extracted more alumina with pH 4.0 buffer, but they postulated that Al was probably removed from primary and secondary minerals at the lower pH.

0.1 N ammonium acetate (CH_3COONH_4) buffered at pH 4.2 was used in the present investigation for the following reasons: It is relatively weak and, therefore, appreciable decomposition of minerals will be avoided. Hydrous aluminum oxide is amphoteric and its solubility increases with increasing acidity. In the presence of NH_4OH, precipitation begins at pH 3.0 and is completed at about pH 6.5. pH 4.8 was, therefore, considered too high a pH since some free alumina would be precipitated at that pH. Ammonium acetate is free of substances interfering with colorimetric procedures and can be easily destroyed by ignition, and finally, it is well buffered.

Duplicate 15 gms. soil samples were weighed into 250 ml. Erlenmeyer flasks, 150 ml. of 0.1N CH_3COONH_4 buffered at pH 4.2 were added and the suspension was shaken for 72 hours on an electric gyrotary shaker at moderate speed. The extract was then filtered 2 to 4 times through No. 42 Whatman filter paper until no soil particles were left in the solution, which was then evaporated to dryness. The residue was then ignited for one hour in an electric furnace at 500° C.

to destroy coloring organic substances and organic acids. After cooling, 5-7 drops of 5 N HCl were added (in the samples of the calcareous C horizon, more HCl was added until effervescence ceased), followed by addition of 100 ml. distilled water. The solution was then gently boiled for one hour, filtered and brought to 150 cc. volume.

The extracted alumina was determined by using the colorimetric method developed by Robertson (53):

Reagents.

(1) Composite solution. 107 gms. of ammonium chloride (NH_4Cl) were dissolved in 1 l. of 4 N ammonium acetate. The solution was shaken and filtered. 10 gms. of powdered gum arabic were dissolved in 100 ml. of water and added to the filtered buffer solution. 0.4 gms. aluminon (aurin tricarboxilic acid) were dissolved in 25 ml. of water to which 1 drop of NH_3 had been added, boiled until no smell of NH_3 persisted, and then this was added to the buffer solution and the whole diluted to 1750 ml. Finally, HCl was added until a pH 4.4 was obtained, and the whole was then diluted to 2 l, mixed well and allowed to stand 3 days before use. 10 ml. of this solution diluted to 100 ml. had a pH 4.5 to 4.8.

(2) Thioglycolic acid. 80-90%

Standard solution: 1.860 gms. of potash alum were dissolved in water containing 50 ml. of 5 N.HCl and this was diluted to 1 l. 1 ml. of this solution is equivalent to 0.2 mg. Al_2O_3.

Procedure.

An aliquot containing .02 - .08 mg. Al_2O_3 was transferred to 100 ml. conical flasks. One drop of thioglycolic acid and water were added to make the final volume 55 ml. (± 2 ml.). 10 ml. of composite solution were added and the flasks were immersed in boiling water for 30 minutes. They were then cooled in running water to 15-18° C. The solution was then transferred into a 100 ml. volumetric flask, made up to volume and mixed well. The color was determined without delay by means of a Coleman Universal Spectrophotometer, Model 14, using wave length of 530 m μ.

Eight standards containing .01 - .08 mg. Al_2O_3/100 ml. were prepared. All steps described in this procedure were followed in developing the color of the blanks and of the standards.

One drop of thioglycolic acid was adequate to eliminate completely the interfering Fe^{+++} by reducing it to the ferrous state.

III. MINERALOGICAL ANALYSES

1. X-ray determinations of clay minerals.

The Na-saturated clay fraction from the mechanical analysis was carefully separated from the silt by repeated decantations. About five ml. of the suspension containing 30-40 mg. of clay were transferred to test tubes. 5 drops of glycerol were added, the suspension was shaken and let stand overnight. A porous ceramic plate was placed on a holder and attached to a vacuum. The clay suspension was poured into the well of the holder. When the clay was all deposited on the porous plates, it was leached with three increments of .1 N $CaCl_2$ containing 3% glycerol by volume, followed by 3%, 10% and 40% glycerol solutions. The plates were then removed and left overnight in a desicator containing $CaCl_2$. The samples were then mounted on the Norelco X-ray spectrometer, using a 1/4" divergent slit, 0.003" receiving slit, and 1/4" scatter slit in the beam collimating system. The diffraction unit was operated at 20 milliamperes and 35 kilovolts using a copper target tube. The recording unit circuit panel was set at time constant four, multiplier one, and scale factor four. Clay samples were scanned from two to thirty degrees. After irradiation, the ceramic plates were replaced in the holders and the clay was leached three times with 10-15 drops of .1 N K Cl and then washed with distilled water, dried for 4 hours in the desiccator, and then placed in 110° C. oven for four hours and left to cool in the desicator. The samples were then scanned again. Finally these samples were heated to 550° C. for one hour, cooled and scanned for the third time.

2. Differential thermal analysis of clay minerals.

The temperature changes in 0.25 gm. of air dry clay samples compared to the temperature changes in aluminum oxide were recorded. The clay samples and aluminum oxide were heated to 1000° C. Standard samples were prepared by mixing different amounts of kaolinite with aluminum oxide. Model DTA-CS-2 and DTA FM, built by R. L. Stone of Austin, Texas, and a Brown recorder were used for the measurements. Clay samples were run at atmospheric pressure with a resistance of 50 ohms in the recording unit. The amplitude of the endothermic and exothermic peaks was used as an approximate quantitative measure of the substances reacting at the specific temperatures of the peaks. Samples of the Nester profile were run on a different sample holder than the one used for the other two profiles. A new set of standards was run as a basis of comparison for the Nester profile.

3. Total specific surface of clays.

The ethylene glycol method proposed by Bower and Geschwend (6) was used.

0.5 gm. of air dry clay were placed in weighing bottles and were evacuated over P_2O_5 until constant weight was obtained. 20 drops of ethylene glycol were added and the bottles, with covers on, were placed in a desiccator with $Ca\ Cl_2$ and let stand overnight. The covers of the weighing bottles were then removed and a vacuum was applied at a temperature of 25° C until the excess of ethylene glycol was removed. The samples were then weighed at hourly intervals until the loss of weight became smaller than 3% of the weight of the retained ethylene glycol. Total surface was calculated by using the formula.

Area m^2/gm. = (wt. of ethylene glycol retained (gm.)) $\div$ (wt. of vacuum dried clay x 0.00031)

4. Total potassium in clay.

A modified method proposed by Webber and Shivas (63) was used.

0.2 gm. of oven dry clay were weighed in platinum crucibles and heated to redness for one minute to destroy organic matter. When cooled, 1 ml. 1:5 H_2SO_4 was added and the mixture was stirred with a platinum wire. 5 ml. of concentrated hydrofluoric acid were added and evaporated slowly to dryness on a hot plate. The same treatment was repeated once more. The crucibles were then placed in a 200 ml. beaker and the residue was removed with a solution of 200 ml. H_2O + 10 ml. HNO_3, and heated. When hot, the crucibles were removed and rinsed with water. The solution was then evaporated to dryness and the residue was taken up in 0.1N HCl, heated, filtered and diluted to a volume of 250 ml. Potassium was determined by means of a Perkin

Elmer flame photometer, Model 52 A. Standard potassium solutions containing 5 & 40 ppm were prepared in 0.1NHCl. A standard concentration vs. transmission curve was plotted.

5. <u>Mineral analysis of the fine sand</u>.

The minerals of the find sand fraction which was about 50% of the total sand in the profiles studied, were identified, counted and their per cent frequencies in the light and heavy fractions were determined. Fine sand samples pretreated and separated as in the mechanical analyses were used. Iron and other coatings were removed from the fine sand according to the method suggested by Kilmer (personal communication). Two gms. of fine sand were placed in 200 ml. Erlemayer flasks. Two gms. of sodium hydrosulfite ($Na_2S_2O_4$) plus 75 ml. of water were added. The flasks were stoppered and shaken for one hour. The suspension was then transferred to 250 ml. beakers, the pH was adjusted to 3.5 - 4.0 by adding 10% HCl. The suspension was let stand for one hour during which it was stirred several times. The supernatant liquid was then decanted and the sands were washed with water 3 times. They were then oven dried.

Heavy minerals were separated from the light ones by centrifuging 1 gm. of cleaned fine sand in a 15 ml. Jeffries' double centrifuge tube which contained a tetra-bromo-ethane, nitrobenzene mixture of specific gravity 2.8. The heavy minerals were washed with acetone, oven dried, weighed, and mounted on glass microscopic slides by using 1 drop of 0.1% gelatin solution and 1 drop of formaline solution as described by Marshall and Jeffries (41). The grains were thus stuck on the slide without being immersed in gelatine.

Feldspars and quartz were determined in the light fraction with the aid of the petrographic microscope. An immersion oil of index 1.543 was used. Five to seven hundred grains from each horizon were counted.

Heavy minerals were determined in the same way by using an immersion oil of refractive index 1.665. All the heavy grains separated from the 1 gm. sample were counted. Their numbers ranged between 300 and 600.

IV. THIN SECTIONS OF SOILS

Horizontal and vertical thin sections, 0.03 mm. thick, from each horizon were studied under the petrographic microscope.

Air dry undisturbed lumps of firm horizons were trimmed with sand paper to about 20 x 30 x 7 mm. slices. Loose or friable horizons were sampled with the aid of 1.5" x 1" x .5" aluminum frames to secure undisturbed blocks. The air dry samples were then impregnated with Lakeside No. 70 C cement according to the method proposed by the manufacturer.

After air drying the soil samples were heated for 15 minutes on a hot plate with surface temperature of 180° - 200° C. and were then dropped quickly into a vessel containing xylene, to drive out the air. Crushed Lakeside 70 C cement was placed in a pyrex crystallizing dish which contained 8 parts of absolute ethyl alcohol. This mixture was placed on a hot plate with surface temperature of 130° C. When the effervescence of the soil samples ceased, indicating complete replacement of the air by xylene, the samples were transferred into the alcohol-cement mixture. The mixture was allowed to boil gently until the spirits were completely evaporated. This left the cement in molten condition and it replaced the xylene in the pores of the samples. The samples were lifted out of and immersed again in the melt, until all the large pores were impregnated, and then removed and allowed to cool to room temperature. The aluminum frames were removed by quick heating of their edges on a bunsen burner and pushing out the impregnated blocks. Care was taken that the soil would not be heated.

The impregnated samples were shipped to CAL-BREA Laboratories, where the thin sections were prepared.

RESULTS

1. Physical Properties

The average of measurements on six core samples from each horizon are given in table 1 .

Bulk density of the podzol sequa (A_1, A_2 and Bhir horizons) of all three profiles is considerably lower than the bulk density of the gray brown podzolic sequa (B_m, $A2_m$, $A3_m$, A & B, B_t and C horizons). Isabella and McBride show a definite maximum in their A_{2m} and A_{3m} horizons.

Non-capillary porosity is high in the podzol sequa and decreases sharply on the top of the fragipan (B_m or $A2_m$ horizons). There is a minimum of non-capillary porosity in the B_t horizons at Nester and McBride, while in Isabella the C horizon has a slightly lower value than the B_t.

Capillary porosity does not show as great differences among the different horizons as the non-capillary porosity does, but there is a definite minimum in the fragipan horizons of all three profiles. The A_1, A_2 and C horizons have the highest capillary porosity in all three profiles.

Water permeability follows parallel trends with non-capillary porosity. It is very high in the podzol sequa, shows a sharp decrease in the pan, and reaches a minimum in the B_t and C horizons. It must be mentioned, however, that the replicate cores of the fragipans showed the biggest variability of all the other horizons. Their values were as extreme as e.g. 0.2 - 2.3 cm./hour. This variability in water permeability was due to the presence of cracks and worm and/or root holes in some of the cores while they were absent from others.

It has been observed that the pan inhibits the internal drainage to a certain degree during the spring months when the soil is water saturated. Dr. A. E. Erickson (18) has observed in the Upper Peninsula of Michigan that in spring the part of the profile above the fragipan was water saturated while the part below the fragipan was at or below field capacity. He also has observed that on exposed profiles of roadcuts springs form on top of the fragipan and that water drains laterally.

The absences of mottling in the three profiles studied excludes the existence of seasonal poor drainage, possibly because of the adequate surface drainage and the possible internal drainage due to the presence of vertical cracks in the profile.

Hardness or Cone Penetration Resistance data generally agree with observations made in the field. The hardest or fragipan horizons coincide with the horizons of highest bulk density. The hardness, however, does not exclusively depend on bulk density, as there is only a slight difference in bulk density between the A_{2m} and A_{3m} horizons of Isabella and McBride, while there is a very sharp difference in their hardness. In the Nester profile the A_{2m} horizon is more than twice as hard as the B_t horizon in spite of the fact that its bulk density is lower than the one of the B_t.

The transitional B_m horizons varied in thickness from less than one inch to two inches, and they could not fill a core. Given values of physical properties actually correspond to a three inches thick layer consisting of Bhir, B_m, and $A2_m$ horizons of the McBride profile. The upper part of certain cores of the Isabella profile consisted entirely of the transitional B_m horizon and hardness tests were conducted on them. It must be admitted, however, that due to the fact that it was impossible to have core samples made of materials from the B_m horizon only, the other values obtained are somehow different from the true ones.

2. Mechanical Analysis

The Isabella and McBride soils which have well developed bisequa profiles, show a definite maximum content of total sand in their B_m and A_{2m} horizons. The Nester soil, which has a rather weakly developed bisequum profile, shows a gradual decrease of the total sand content with increasing depth with a minimum in the B_t horizon and a very small maximum in the A_2/Bhir. The content of total silt is higher in the podzol sequa of all three profiles than in their gray brown podzolic sequa. The A_1 horizons of McBride and Nester and the A_2 of Isabella have the maximum relative concentration of silt in the particular profiles. The different sand fractions, the 50-20 μ and 20-5 μ silt fractions follow in a general way the trends of total sand and total silt contents respectively. Table 4 shows that there is a redistribution of the 5-2 μ fraction of silt in all three profiles. There is a loss of the 5-2 μ sized silt in the podzol sequa of the three profiles and a definite gain in the gray brown podzolic of McBride and Nester. The results of Isabella are inconclusive as to whether there is a gain of 5-2 μ silt in the gray brown podzolic sequum of the profile. This is probably due to differences in the present material of the particular horizons, as it will be shown later.

Table I. Physical Properties

McBride						
Horizon	Depth inches	Bulk Density	% Non-capillary porosity	% Capillary porosity	Permeability cm/hr	Cone penetration Resistance Kg/cm
A_1-A_2	1-5	1.19	20.6	28.8	21.09	--
Bhir	5-17	1.38	20.5	25.5	29.00	8.5
B_m	17-19	1.61	8.5	20.1	6.77	--
$A2_m$	19-24	1.82	8.1	17.0	1.45	31.0
$A3_m$	24-35	1.86	3.6	21.3	0.13	122.6
B_t	35-53	1.78	3.2	23.4	0.11	18.2
C	+ 53	1.74	5.8	25.2	0.24	
Nester						
A1	1-5	1.03	20.5	32.7	52.53	--
A2/Bhir	5-9	1.38	16.7	26.8	15.82	8.3
$A2_m$	9-16	1.61	9.3	25.5	1.56	26.3
A & B	16-27	1.65	7.4	29.4	3.11	20.2
Bt	28-48	1.66	4.5	32.3	0.92	11.65
C	48-65	1.60	5.4	33.0	0.15	--

Table I. continued

Isabella						
Horizon	Depth inches	Bulk Density	% Noncapillary porosity	% Capillary porosity	Permeability cm/hr	Cone penetration Resistance Kg/cm
A_1-A_2	1-5	1.108	16.9	36.2	22.26	--
Bhir	5-11	1.43	17.0	26.7	14.63	10.9
Bm	11-13	--	--	--	--	14.9
A_{2m}	13-21	1.87	7.7	16.15	0.84	33.3
A_{3m}	21-34	1.85	8.9	19.6	1.04	77.9
A & B	34-42	1.78	3.9	28.6	0.10	25.8
B_t	42-55	1.71	2.4	34.2	0.16	16.6
C	+ 55	1.76	1.6	34.2	0.07	--

Table Ia. Per cent Hygroscopic water

Horizon / Profile	A_1	A_2	A_2/Bhir	Bhir	Bm	A_{2m}	A_{3m}	A & B	B_t	C
McBride	1.14	0.62	--	0.66	0.38	0.21	0.48	--	0.69	0.71
Isabella	1.63	0.31	--	2.67	0.29	0.30	0.65	0.97	1.23	0.65
Nester	1.72	--	0.77	--	--	0.40	--	1.43	1.60	1.48

Clay content shows two definite minima and maxima in the Isabella and McBride profiles. The first minimum is in the A_2 and the second in the B_m and $A2_m$ horizons. The first maximum is found in the Bhir and the second and highest one in the B_t horizon. The Nester profile shows only one minimum in the A2/Bhir horizon and one maximum in the B_t horizon.

The results of mechanical analysis suggest that a downward movement of clay and very fine silt takes place in all three profiles. The B_t horizons constitute the zone of maximum clay accumulation. The fragipan horizons have lower clay content than the parent material, and if we assume that the profiles were formed from uniform parent material, they constitute an eluvial zone. Fine sand makes up the bulk of the sand fraction and its distribution is fairly uniform in all the horizons of the three profiles, as shown in table 3.

3. Chemical Properties

The pH values of table 5 show that Isabella has the most leached and consequently weathered profile of the three soils. The differences in the chemical properties among the different horizons are also more pronounced in the Isabella than in the other two soils.

Organic carbon and solution loss values suggest that the podzol sequum is better developed in Isabella than in the other two profiles. This conclusion is in accordance with the field description of the soils.

Alkali soluble silica increases with depth and show a maximum concentration in the B_t horizons of McBride and Nester and in the A & B horizon of Isabella. The $A2_m$ horizons of all three profiles have

Table 2. Mechanical Analyses

McBride	A_1	A_2	Bhir	B_m	A_{2m}	A_{3m}	B_t	C
Depth	1-3	3-5	5-17	17-19	19-24	24-35	35-53	+ 53
F.G-C.S. 2-0.5 mm.	7.85	8.76	8.64	9.90	9.98	8.77	8.28	8.48
M.S .5-.25 mm.	14.41	15.64	16.09	18.47	18.21	16.91	15.08	16.46
F.S. .25-.1 mm.	43.09	42.18	42.40	44.58	45.33	42.10	38.45	40.48
V.F.S. .1-.05 mm.	8.64	13.33	12.40	12.42	12.56	10.50	9.40	9.91
Total sand	73.99	79.91	79.99	85.37	86.08	78.28	71.21	75.33
Silt								
50-20 μ	9.24	5.33	5.18	1.55	2.66	0.87	2.09	2.02
20-5 μ	8.04	7.35	5.42	4.26	4.02	4.31	3.34	6.21
5-2 μ	2.93	2.80	1.84	2.50	2.28	3.48	2.25	2.41
Total silt	20.21	15.48	12.44	8.31	8.96	8.66	7.68	10.64
Clay	5.80	4.61	7.57	6.32	4.96	13.06	21.11	14.03

Table 2. continued

Isabella	A_1	A2	Bhir	B_m	A_{2m}	A_{3m}	A & B	B_t	C
Depth	1-3	3-5	5-11	11-13	13-21	21-34	34-42	42-55	+ 55
F.G.-CS 2-0.5 mm.	10.35	9.36	9.97	10.63	10.43	9.07	8.26	6.55	7.50
M.S. .5-.25 mm.	18.88	17.34	16.40	20.15	17.67	16.40	14.75	12.06	15.92
F.S. .25-.1 mm.	36.89	36.78	34.41	41.69	39.95	36.03	35.77	31.96	30.57
V.F.S. .1-.05 mm.	4.75	6.23	8.62	10.17	7.36	5.98	5.89	4.81	3.43
Total sand	70.88	69.72	69.11	82.65	75.41	67.48	64.68	55.38	57.42
Silt									
50-20 μ	9.10	10.46	6.03	4.02	4.95	4.16	2.74	4.36	4.58
20-5 μ	10.37	12.03	9.92	5.92	8.36	7.43	5.33	6.61	5.58
5-2 μ	3.52	3.54	4.52	3.30	3.71	3.24	2.78	4.68	5.50
Total silt	22.99	26.46	20.47	13.24	17.02	14.83	10.85	15.65	15.66
Clay	6.13	3.82	10.42	4.11	7.57	17.69	24.47	28.97	26.92

Table 2. continued

Nester	A_1	A_2/Bhir	A_{2m}	A & B	B_t	C
Depth	1-5	5-9	9-16	16-27	27-48	48-65
F.G-C.S. 2-0.5 mm.	7.64	8.43	7.46	6.72	5.23	6.06
M.S .5-.25 mm.	14.15	13.28	13.63	10.52	5.72	9.09
F.S. .25-.1 mm.	32.54	32.55	30.42	21.89	21.14	24.65
V.F.S. .1-.05 mm.	5.78	8.22	6.19	4.07	5.87	6.25
Total sand	60.08	62.48	57.70	43.20	37.96	46.05
Silt						
50-20 μ	11.18	9.53	8.95	5.90	6.76	5.63
20-5 μ	12.66	12.34	13.07	8.12	8.56	9.32
5-2 μ	5.38	6.31	5.36	5.53	4.58	4.02
Total silt	29.22	28.18	27.38	19.55	19.90	18.97
Clay	10.70	9.34	14.92	37.25	42.14	34.98

Table 3. % of Fine Sand in the Total Sand Fraction

Horizon / Profile	A_1	A_2*	Bhir	B_m	A_{2m}	A_{3m}	A & B	B_t	C
McBride	58.23	52.78	53.01	52.22	52.66	53.77	--	53.21	53.74
Nester	54.15	52.10	--	--	52.72	50.92	--	56.04	53.58
Isabella	52.04	52.76	49.40	50.47	52.97	53.38	55.27	54.70	53.24

Table 4. Per cent of 5-2 μ silt in the total silt fraction

Horizon / Profile	A_1	A_2*	Bhir	B_m	A_{2m}	A_{3m}	A & B	B_t	C
McBride	14.5	18.1	14.8	30.1	25.4	40.2	--	29.3	22.7
Isabella	15.3	14.4	22.1	24.9	21.8	21.8	25.6	29.9	35.5
Nester	18.4	22.4	--	--	19.6	--	28.3	23.0	21.2

* A_2 corresponds to A_2/Bhir in Nester.

soluble SiO_2 content lower than the immediately overlying and underlying horizons. The A1 horizon of Isabella has a remarkably high alkali soluble silica content.

Soluble alumina data show maximum concentrations in the Bhir and Bm horizons of the Isabella and McBride profiles. The A_1, A_2 and C horizons of all three profiles are relatively poor in soluble alumina. In all three profiles there exists a zone in which soluble alumina accumulate. This zone extends from the Bhir down to the B_t horizon. The fragipan horizons are located in this zone, but they do not coincide with the part of the profile which has the maximum soluble alumina content. The A_{2m} horizons of Isabella and McBride have lower soluble alumina content than the immediately overlying and underlying horizons. The distribution of the soluble alumina in the profiles does not follow the distribution of clay and, therefore, the given values contain very little if any aluminum extracted from the lattice of the clays.

The data of table 5 did not reveal outstanding accumulations of SiO_2 and/or Al_2O_3 in the fragipan horizons to justify the assumption that they are major factors of cementation. Their role, however, will be discussed in the next chapter.

4. X-ray determination of clay minerals

The glycerated and calcium saturated clay samples of all the horizons of the three profiles produced diffraction maxima at 10 Å and 7 Å. The 7 Å peak disappeared upon heating the sample to 550° C. These peaks suggest the presence of illite and kaolinite, respectively, in all the horizons of the three profiles. The area under each peak

Table 5. Chemical Properties

McBride

Horizon	Depth inches	pH	Loss in acid solution %	Organic carbon %	Soluble SiO_2 %	Soluble Al_2O_3 mg./100 gm. soil
A_1	1-3	5.4	0.72	4.44	.176	5.0
A2	3-5	5.2	1.63	2.00	.145	6.0
Bhir	5-17	5.3	1.80	1.15	.206	20.0
B_m	17-19	5.6	.90	.27	.272	20.6
$A2_m$	19-24	5.8	.68	.13	.137	13.0
$A3_m$	24-35	5.6	.45	.11	.290	14.2
B_t	35-53	5.2	.66	.16	.417	14.0
C	53+	7.8	3.60	.15	.204	7.0

Isabella

Horizon	Depth inches	pH	Loss in acid solution %	Organic carbon %	Soluble SiO_2 %	Soluble Al_2O_3 mg./100 gm. soil
A_1	1-3	4.7	0.73	5.12	1.000	3.4
A_2	3-5	4.7	0.12	.98	.305	5.3
Bhir	5-11	4.6	2.45	2.63	.415	36.7
B_m	11-13	4.6	1.38	.20	.360	36.0
$A2_m$	13-21	4.9	.93	.15	.320	26.4
$A3_m$	21-34	5.0	1.40	.16	.540	33.0
A & B	34-42	4.8	1.67	.18	.725	26.6
B_t	42-55	5.3	1.53	.13	.645	12.2
C	55+	7.9	9.20	.12	.250	4.2

Table 5. continued

Nester						
Horizon	Depth inches	pH	Loss in acid solution %	Organic carbon %	Soluble SiO_2 %	Soluble Al_2O_3 mg./100 gm. soil
A_1	1-5	6.0	1.24	5.12	.232	4.3
A_2/Bhir	5-9	5.4	2.26	.73	.345	8.1
A_{2m}	9-16	5.4	1.16	.25	.315	9.75
A & B	16-27	5.0	1.81	.51	.630	16.2
B_t	27-48	5.0	2.08	.26	.720	13.4
C	48-65	7.6	5.77	.22	.490	6.4

is related to the amount of the particular mineral present. Other factors, however, such as amount of iron oxides present, the orientation of the clay particles on the porous plate, the crystallinity of the minerals, etc., strongly modify the area and the sharpness of the peaks. Accurate quantitative determination, therefore, of the clay minerals, based only on X-ray data is very difficult. From the X-ray patterns which are shown in the appendix, it can generally be concluded that the amount of illite is lower in the podzol sequa of Isabella and McBride than in their gray brown podzolic sequa.

Any conclusion on the amounts of kaolinite present in each horizon is less certain, as the intensity of the 7 Å peak is partly due to the second order diffraction of the X-rays by the basal planes of minerals having 14 Å basal spacing (chlorite, vermiculite). The differences in the 7 Å peaks of the No. 2 tracing for each sample (K saturated and heated to 110° C) and the No. 3 (heated to 550° C) patterns show that kaolinite is relatively low in the A_1 and A_2 horizons of Isabella and in the A_1 of McBride.

Assumptions regarding the amounts of illite and kaolinite, based only on X-ray data, cannot be made for the Nester profile.

Well expressed peaks corresponding to the 17.7 Å spacing were produced by the glycerated and Ca saturated samples of the A_1, A_2, and B_m horizons of Isabella, by the A_1 and A_2 of McBride, and by the A_1 horizon of Nester. These data suggest the presence of montmorillonite in these upper horizons as a pure mineral. The repeated applications of glycerol, however, were able to expand the lattice of montmorillonite of the A_1 horizons of Isabella and McBride only to 17.0 Å. The strongly absorbed organic matter probably inhibited the expansion of some of the lattices to 17.7 Å basal spacing which is typical of the glycerated montmorillonite. The resulting 17.0 Å peak may then represent the results of random interstratification of montmorillonite capable of absorbing two layers of glycerol and other expanding layers which could probably take only one.

Montmorillonite is also present as interstratified with layers of chlorite and/or vermiculite and possibly of illite in most of the other horizons of the three profiles, as indicated by the broad high and low bands located between 17.7 Å and 14 Å levels of basal spacing. These bands are higher and better pronounced in the podzol sequa than in the gray brown podzolic seque. The X-ray patterns of the A_{2m} horizons of Isabella and McBride do not show the presence of discrete montmorillonite in these two horizons. The patterns are inconclusive as to the presence of interstratified montmorillonite with chlorite and montmorillonite in the Bt horizons of Isabella and McBride and the C horizon of Nester. The 14 Å peak, however, could be partly due to diffraction from an interstratified system of illite-montmorillonite. X-ray patterns of the <.2 micron clay of the above horizons showed that interstratified complexes of expanding and non-expanding clays predominate in this fraction.

The presence of vermiculite was determined in each horizon by comparing the following ratios: Amplitude of the 14 Å peak / Amplitude of the 3.35 Å peak of quartz, of the Ca saturated and glycerated sample against the same ratio of the sample when K saturated and heated to 110° C. A decrease of this ratio by heating and K saturation of the clay would indicate the presence of vermiculite. The amplitudes of the 14 Å peaks as such could not be compared because a significant change of the amplitudes of all peaks resulted by heating and replacing the exchangeable Ca by K.

The absence of any peak at the 14 Å basal spacing point in the X-ray patterns of the A1 and A2 horizons of Isabella suggest the absence of both chlorite and vermiculite from these two horizons. Vermiculite was found in the Bhir and B_m horizons of Isabella and in the A1 horizons of Nester and McBride. The broad bands between the 10 Å and 14 Å basal spacing of the collapsed clays (patterns No. 2 and 3) of the above horizons indicate that vermiculite is interstratified with chlorite. The broad bands between 14 Å and 17.7 Å indicates (pattern No. 1) that vermiculite is also probably interstratified with montmorillonite.

The existence of broad bands between 10 and 14 Å produced by the heated to 110 and 550° C samples of the horizons of gray brown podzolic sequa suggests the possible presence of vermiculite as interstratified with chlorite and montmorillonite in these horizons. Chlorite was detected by the presence of the 14 Å basal spacing, which persisted upon K saturation and heating to 110° C and 550° C (patterns 2 and 3).

X-ray patterns indicate the absence of chlorite from the A_1 and A_2 horizons of Isabella, and probably from the A_1 of McBride. All the other horizons of the three profiles produced X-ray patterns indicating the presence of chlorite, which seems to be interstratified with vermiculite and montmorillonite in the podzol sequa and with montmorillonite and possibly vermiculite in the gray brown podzolic sequa.

Iron oxides interfered strongly in the Bhir and Bt horizons of Isabella and they were removed from the samples of these two and of the A_{3m} and A & B horizons of this profile. By removing the iron, higher and more distinct peaks were obtained.

5. Differential Thermal Analysis of Clays

Clays of all the horizons of the three profiles produced endothermic peaks at temperatures of 100-200° C, which correspond to the loss of interlayer water. The fragipan layers of all three profiles produced relatively small peaks at the above range of temperatures, indicating a low amount of expanding clay minerals. The A_{2m} horizons of all three profiles and the A_{3m} of McBride showed definite minima of loss of interlayer water within their own profiles.

Clays of the horizons of the podzol sequa produced strong exothermic peaks at temperatures between 300° C and 400° C, which are due to the combustion of the associated organic matter. This organic matter resisted the H_2O_2 treatments during the preparation of the samples for mechanical analysis. The A1 horizons of Isabella and McBride have also organic matter strongly absorbed by their clays as indicated by the exothermic peaks at temperatures between 600° C and 700° C (33).

Endothermic peaks at temperatures between 550° C and 600° C were also produced by the clays of all horizons. These peaks correspond to the loss of the OH water from the lattice of kaolinite mainly. Since, also, other clay minerals as illite, chlorite and vermiculite (22) undergo loss of OH water at the same as above range of temperatures, the areas under these peaks have only limited value for the quantitative determination of kaolinite. Curves of standard samples of kaolinite are given in the appendix along with curves of soil clays for comparison.

Based on the results of D.T.A., we can conclude that expanding minerals are present in all horizons but their amounts are very small in the fragipan horizons. We can also conclude that the quantities of kaolinite are smaller in the A1 and A2 horizons of Isabella and McBride, and in the A1 of Nester, than in the rest of the horizons.

6. Total Specific Surface and K Content of Clays.

Total specific surface data show a distinct minimum in the $A2_m$ horizons of the three profiles and in the $A3_m$ horizon of McBride. The values show the presence of expanding minerals in all horizons, with a possible exception in the above mentioned fragipan horizons. Both the podzol sequa and the illuvial zones of the gray brown podzolic sequa seem to be enriched with expanding clays. The C horizons of all three profiles have smaller surface areas than the B_t and A & B horizons.

The potassium content of the clays is relatively low in the podzol sequa and rather high in the gray brown podzolic sequa. The clay of the pan of McBride has the maximum K_2O content in the profile, in Isabella and Nester, however, there is a second and higher K_2O content in the clay of the parent material.

The above data suggest that illitic clays undergo a rather drastic weathering and loss of K in the podzol sequa, while this weathering is not detectable in the gray brown podzolic sequa.

It must be noticed here that the A_{3m} horizon of the McBride profile which is the hardest of all the horizons tested has the maximum K_2O content of all horizons of the three profiles.

The measured K can be assumed to come from the clay only, as no feldspars were detected in the X-ray patterns.

7. Summary on Clay Analyses

Comparing the results of the different methods followed in clay analysis, we notice that the amplitudes of the 10 Å peaks of illite in the X-ray patterns do not correlate with the K_2O content of the particular samples. The lack of correlation is probably due to the fact that the degree of orientation of the clay particles and the amount of iron oxides present had strongly influenced the amplitudes of the X-ray peaks.

There is a rather satisfactory correlation between the total specific surface area of the clays and the area under the 100° C -

Table 6. Total K content and total specific surface of the clay

McBride			Isabella			Nester		
Horizon	% K_2O	Total sp. surface $m^2/gm.$	Horizon	% K_2O	Total sp. surface $m^2/gm.$	Horizon	% K_2O	Total sp. surface $m^2/gm.$
A_1	3.12	259	A_1	2.24	218	A_1	3.48	217
A2	3.48	255	A2	3.32	180	A2/Bhir	3.48	204
Bhir	3.48	203	Bhir	2.76	294	$A2_m$	4.20	126
B_m	3.96	252	B_m	3.84	214	A & B	4.08	260
$A2_m$	4.80	120	$A2_m$	4.20	139	B_t	4.08	252
$A3_m$	5.04	114	$A3_m$	4.20	201	C	4.32	215
B_t	4.20	266	A & B	3.96	273			
C	4.20	221	B	4.68	218			
			C	4.68	217			

Table 7. Per cent of heavy minerals in the fine sand

Horizon / Profile	A_1	A2	A2/Bhir	Bhir	B_m	$A2_m$	$A3_m$	A & B	B_t	C
McBride	.55	.70	--	.66	.65	.70	.65	--	.62	.68
Isabella	1.75	2.20	--	2.4	1.30	1.35	.78	.55	.72	.78
Nester	1.70	--	1.20	--	--	1.25	--	1.00	1.15	1.10

200° C endothermic peak of the D.T.A. patterns as it is shown in figure 1 .

The relatively low surface area of Isabella's A_2 horizon (180 m^2/gm. clay) in which the X-ray patterns show that montmorillonite is rather abundant, can be explained by assuming that the absorption by the clay of organic matter inhibited the penetration of ethylene glycol into the interlayer space of montmorillonite. The large exothermic peak at 300° - 400° C of the D.T.A. pattern of the above horizon confirms the presence of large quantities of organic matter associated with the clay.

In spite of the above shortcomings, the following conclusions can be derived from the clay studies:

(a) Illite and chlorite and interstratified systems are the main clay minerals which weather and their relative amounts are small in the podzol sequa of the profile. The small 10 Å and 14 Å peaks in the X-ray patterns, the relatively high surface area, and the low K_2O content of the clay of the podzol sequa support the above conclusion.

(b) Distinct X-ray maxima corresponding to the 17.7 Å and 14 Å basal spacing, the disappearance of these peaks from the patterns of the heated samples, and the relatively high specific surface of the clay indicates that montmorillonite and vermiculite are the product of the above mentioned weathering. The process of weathering and the formation of new minerals will be discussed in the next chapter.

(c) Montmorillonite is present in most of the horizons of the gray brown podzolic sequa and in the parent material as randomly interstratified layers with chlorite, and possibly with vermiculite and illite, too. This conclusion is based on the presence of broad bands

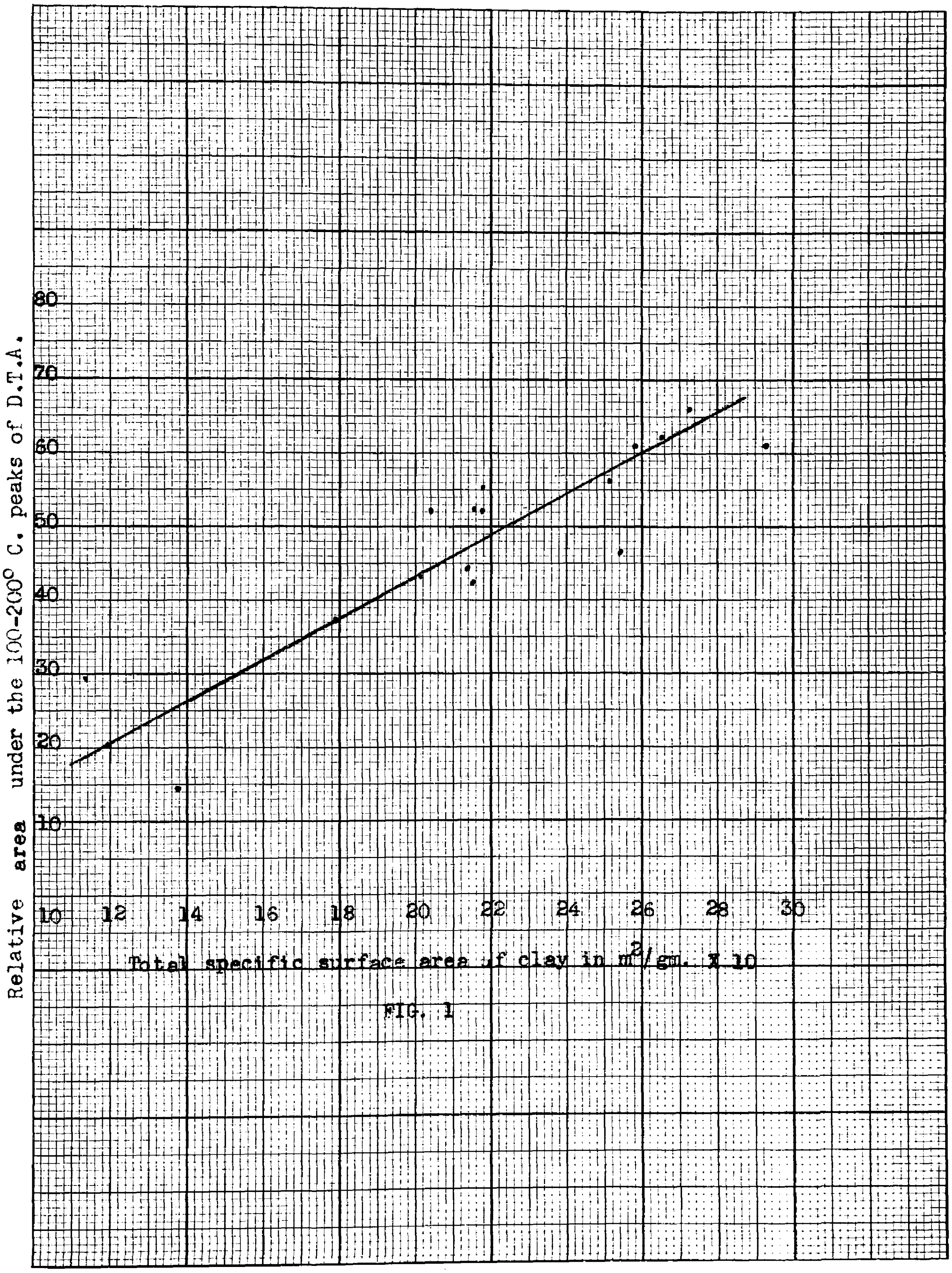
Relative area under the 100-200° C. peaks of D.T.A.
80
70
60
50
40
30
20
10
10
12
14
16
18
20
22
24
26
28
30
Total specific surface area of clay in m²/gm. X 10

FIG. 1

in the X-ray patterns of these horizons, corresponding to interstratified lattices of 17.7 Å and 14 Å basal spacing, the relatively high total specific surface of the clay, and the relatively large endothermic peaks at temperatures of 100 - 200° C in the D.T.A. patterns.

(d) A high K_2O content and relatively low total specific surface of the clay, along with well expressed 10 Å peaks and absence of 17.7 Å peaks in the X-ray patterns suggest that a relative concentration of illitic clay takes place in the fragipan.

(e) The peaks at 500° - 600° C of the D.T.A. patterns are the result of the additive endothermic reactions of kaolinite and illite. By rough comparisons of the above peaks with those of standard samples of pure kaolinite, it could be postulated that the amount of kaolinite in the clay fraction of the A_1 and A_2 horizon of Isabella and McBride and of the A_1 of Nester is smaller than 10-15%, while in the deeper horizons it can be as high as 20-30%.

(f) The less than .2 microns clay of the gray brown podzolic sequa consists mainly of interstratified expanding and non-expanding minerals.

8. <u>Mineral Analyses of Fine Sand</u>

Mineral analyses were made on the portion of the fine sand which resisted the 1% HCl treatment during the preparation of samples for mechanical analysis. Calcite and other acid soluble minerals were eliminated by the above treatment.

(a) <u>Heavy Minerals</u>. A relatively high per cent weight of heavy minerals were found in the podzol sequum of Isabella, while the A_{3m} and its underlying horizons had distinctly smaller amounts of heavy minerals. Table 7 .

McBride and Nester showed a rather uniform distribution of heavy minerals within their profiles.

All three soils show significant differences in the per cent frequency of less resistant minerals in the different horizons (Table 8). Hornblende, olivine and epidote weather rapidly. Among the most resistant heavy minerals are magnetite, zircon, garnet, and tourmaline. The most pronounced differences in the distribution of the easily weathered minerals were found in the Isabella profile.

Weathering of the less resistant minerals takes place in all horizons which overlie the B_t horizon. The intensity of weathering, however, decreases with increasing depth.

Olivine grains were very highly weathered and more or less opaque because of their weathered surface. It must be admitted, however, that the accurate determination of their optical properties was not always possible. Some of the grains called olivine, therefore, could actually have been highly weathered hornblende or epidote. When observed under the petrographic and binocular microscopes, the grains of the less resistant minerals showed a decrease in the weathering with increasing depth. The grains of hornblende, augite, epidote, and hematite were considerably weathered in the podzol sequa, less weathered in the $A2_m$, $A3_m$ and A & B horizons, and hardly weathered in the Bt and C horizons.

The ratio of magnetite to garnet was used as a test of the geological and lithological uniformity of the respective profiles. Cady (10) found that magnetite, garnet and zircon were among the most resistant minerals to podzolic weathering. Garnet was chosen instead

Table 8. Per cent Frequency in the Heavy Fraction of Fine Sand

McBride								
Horizon / Minerals	A_1	A_2	Bhir	B_m	A_{2m}	A_{3m}	B_t	C
Magnetite	53.8	47.3	50.1	47.7	48.9	48.0	38.3	40.5
Garnet	7.2	7.2	9.3	8.5	8.6	8.8	6.6	7.4
Hornblende	22.9	24.2	19.1	19.6	21.0	22.3	29.2	27.9
Olivine	4.9	7.2	7.2	7.8	6.9	7.0	9.1	7.7
Epidote	3.1	5.8	6.2	5.8	5.5	5.7	7.6	6.9
Hematite	4.9	6.1	6.4	8.0	7.2	6.0	6.6	6.9
Augite	1.6	0.8	1.0	1.1	0.9	0.8	1.8	1.3
Zircon	0.3	0.4	0.2	0.4	0.5	0.8	0.5	0.8
Tourmaline	0.3	--	0.5	1.1	0.5	0.6	0.3	0.6
Magnetite / Garnet	7.5	6.5	5.4	5.6	5.7	5.4	5.8	5.5

Table 8. continued

Isabella									
Horizon / Minerals	A_1	A_2	Bhir	B_{1m}	A_{2m}	A_{3m}	A & B	B_t	C
Magnetite	76.8	77.5	57.0	59.4	60.9	45.3	41.6	38.9	36.9
Garnet	6.6	6.5	5.5	5.2	6.1	9.1	4.7	4.1	4.4
Hornblende	4.2	6.3	15.1	10.7	9.0	21.2	22.7	24.6	23.8
Olivine	4.0	3.1	7.5	7.5	8.0	7.4	11.5	12.1	10.8
Epidote	1.6	1.2	7.0	6.8	6.6	7.6	9.5	11.1	11.8
Hematite	5.0	3.9	3.0	5.8	5.5	3.7	7.2	6.7	9.2
Augite	0.6	0.5	3.0	2.6	2.1	2.3	2.3	1.7	1.7
Zircon	0.6	0.5	0.6	0.6	0.4	1.2	0.3	0.4	0.7
Tourmaline	--	--	0.5	--	0.6	0.6	0.2	0.2	0.7
Leucoxene	0.6	--	--	0.2	0.6	--	--	--	--
Rutile	--	--	--	0.6	--	--	--	--	--
Staurolite	--	--	--	0.1	0.2	--	--	--	--
Enstatite	--	0.5	--	--	--	0.2	--	0.2	--
Biotite	--	--	0.8	--	--	1.4	--	--	--
Magnetite / Garnet	11.6	11.9	10.4	11.4	9.9	4.97	8.8	9.5	8.2

Table 8. continued

Nester						
Horizon / Minerals	A_1	A_2/Bhir	A_{2m}	A & B	B_t	C
Magnetite	39.8	39.5	36.9	37.4	32.2	30.5
Garnet	7.5	7.2	6.9	7.5	6.3	5.4
Hornblende	23.5	23.3	26.6	26.9	35.4	38.8
Olivine	12.9	13.2	12.2	9.6	10.5	10.0
Epidote	8.5	10.5	9.9	9.3	8.5	8.3
Hematite	6.1	4.0	6.3	4.5	4.8	4.4
Augite	1.4	1.9	0.9	3.3	1.9	2.0
Zircon	--	0.4	0.2	0.6	0.2	0.4
Tourmaline	0.3	--	0.2	0.9	0.2	0.2
$\frac{\text{Magnetite}}{\text{Garnet}}$	5.3	5.5	5.4	5.0	5.1	5.6

Table 9. Per cent Frequency in the Light Fraction of Fine Sand

McBride			Isabella			Nester		
Horizon	Quartz	Feldspar	Horizon	Quartz	Felds.	Horizon	Quartz	Felds.
A_1	83.6	16.4	A_1	83.7	16.3	A_1	83.4	16.6
A2	85.0	15.0	A2	86.0	14.0	A_2/Bhir	85.5	14.5
Bhir	83.7	16.3	Bhir	84.7	15.3	$A2_m$	83.2	16.8
B_m	84.0	16.0	B_m	84.8	15.2	A & B	83.9	16.1
$A2_m$	83.9	16.1	$A2_m$	83.0	17.0	B_t	83.5	16.5
$A3_m$	83.1	16.9	$A3_m$	83.5	16.5	C	83.5	16.5
B_t	83.4	16.6	A & B	83.6	16.4			
C	83.3	16.7	B_t	83.4	16.6			
			C	83.4	16.6			

of zircon because the latter was present only in very small quantities. Data show that Nester and McBride have uniform profiles, while Isabella's A_{3m} horizon is distinctly different from the overlying and underlying horizons which also differ from each other. The magnetite-garnet ratio and the total weight of heavy minerals suggest that the podzol sequum and probably the B_m and A_{2m} horizons of Isabella are petrographically different from the lower part of the profile.

(b) Light minerals. The per cent frequency of quartz and feldspar is rather uniform throughout the three profiles. A slight decrease in feldspars is noticeable in the A_2 horizons of all three profiles. Table 9 .

The refractive indices of the feldspars were below those of quartz. This indicates that only K and Na feldspars are present in the profiles studied. Qualitatively identified feldspars were orthoclase, microcline and albite.

(9) Description of the Thin Sections

Thin sections were studied with the aid of the petrographic microscope, using magnifications x 50 to x 1940. Mineralogical observations were of qualitative nature. Average distances between sand grains and pore sizes were estimated.

(a) Isabella

A1 Microstructure: Crumbly and very loose. Consists of aggregates 1.0 - 5.0 mm. in diameter, which are separated from each other by empty pores and cracks of various shapes and sizes. The pores have diameters ranging between 0.5 mm. and 1.5 mm. The primary binding agent of the aggregates is organic matter. The distances between the neighboring sand grains of the aggregates range between 50 microns and 600 microns with a rough average of 200 µ. Inside the aggregates there are numerous pores of varying sizes. A rough average estimate of their diameters is 150 µ. Neither the pores nor the grains have coatings of oriented clay. The intergranular spaces are filled with a porous matrix consisting of organic matter, silt, clay and iron oxides. The clay lacks of any orientation and it is associated with the organic matter, so that it cannot be distinguished. Individual particles of coarse clay can only be seen under crossed nicols and high magnification. Iron oxides also stick on the decomposed organic matter.

Organic Matter: It occupies most of the matrix and it consists of fine free particles of decomposed organic substances mixed with egg-shaped orange droppings of orthropods. Eggs of nematodes and fungus hyphae, with septa and fruit bodies, are also present. A few plant materials are not completely decomposed and include, in their decomposed cavities, free or cemented droppings of arthropods. Some plant residues have a whitish nucleus of residual cellulose network, which is optically active. The nucleus is surrounded by red brown lignin. These residues do not contain droppings and, according to Hartmann (25), have been decomposed by fungi. The humus of this horizon consists mainly of lignin and coprogenic elements of arthropods, and according to Hartmann (25) and Kubiena (38), can be classified as arthropods - fine moder.

Mineralogy: The bulk of the sand fraction consists of quartz and feldspars (Microcline, Orthoclase and Albite). Some hornblende grains are disintegrated into silt-size prisms. A few concretions of precipitated iron oxide are present but they are hard to distinguish from lignin.

A2 Microstructure: Aggregates are absent and a rather massive microstructure characterizes this horizon. The average distance between the sand grains is about 0.1 mm. Many cracks and pores are present. Their average diameter or width is about 0.2 mm. No coatings of well oriented clay are found around the sand grains or the pores. Some of the sand grains have around them diffuse and discontinuous coatings of weakly oriented clay. These coatings are formed, according to Kubiena (37), by alternate drying and wetting of the soil. The matrix consists mainly of silt, in which are randomly intermixed particles of coarse clay, lath-shaped clay aggregates 10-20 microns long, and very finely divided organic matter. The clay aggregates seem to have the clay particles oriented along their long axes. Fractures of some quartz and feldspar grains contain clay.

Organic Matter: Most of it consists of red brown lignin aggregates of less than 50 microns diameter, and of broken arthropods droppings. No preserved plant tissues are visible, except a few red brown root barks. The amount of organic matter is considerably smaller in this horizon than in the A_1. There are few fungi hyphae with septa.

Mineralogy: Same as in A_1, but most of the sand grains are cracked. There are numerous prismatic grains of silt-sized hornblende. Very little iron oxide is associated with the organic matter.

Bhir Microstructure: Loose, rich in cavities and spongy in fabric. Average distance between the sand grains is about 0.2 mm., but it ranges from 0.05 mm. to 0.40 mm. There are numerous larger pores 0.2 - 0.6 mm. in diameter, and many tiny ones confined within the floculated matrix. The pores do not have oriented coatings but most of the sand grains are surrounded or coated by a mixture of clay, organic matter and precipitated iron. The clay of these coatings shows a weak orientation on the surface of the grains. Their thickness ranges between 10 and 50 microns. The intergranular spaces between the coated sand grains is rather filled with a highly porous and aggregated matrix. The microaggregates of the matrix are 20-100 microns in diameter and consist of the same materials as the sand coatings plus embedded silt grains.

Organic Matter: It consists of highly dispersed red brown colloidal substance, well mixed with clay and iron oxides, so that it is difficult to be distinguished from them. Few organic particles of 10 microns diameter and of dark brown red color are not mixed with minerals and can be distinguished as such. Fungi hyphae and animal droppings are absent.

Mineralogy: Same as in A2 but only very few quartz and feldspar grains are fractured and much more iron oxide is associated with clay and organic matter in this horizon.

B_m Microstructure: The B_m horizon is a little denser than the Bhir. The average distance between the sand grains is about 0.15 mm. Many pores are also present in this horizon. Their diameter varies from 0.1 to 1.0 mm. A few of the pores and channels have on their periphery discontinuous 5-10 microns thick layers of well oriented clay. Some of the pores are partially or entirely filled with silt grains. The sand particles have around them 2-5 microns thick coatings of weakly oriented clay. The intergranular matrix is porous and consists mainly of silt which is intermixed with un-oriented clay. In a few narrow intergranular spaces and in parts of pores with small radii are menisci of well oriented clay. Some of these menisci act as bridges binding the neighboring sand grains. In the matrix are also spread small clay aggregates of different shapes and sizes which seem to have their clay oriented along an axis or around a nucleus.

Organic Matter: The organic matter is of the same nature as that of the Bhir but it is confined to only a few spots of the matrix and its amount is significally smaller than in the Bhir.

Mineralogy: Same as in the Bhir. Many hornblende grains are fractured into silt-sized prismatic grains and some of them show release of iron oxide around them and formation of clay which is heavily coated with iron oxides. Generally the amount of iron oxides is significantly smaller than in the Bhir.

A2m Microstructure: A striking characteristic of this horizon is its dense fabric, which in certain areas approaches the fabric of sandstone. The distance between the sand grains ranges between 10 μ and 80 μ., with a rough average of 30-40 μ.

This massive microstructure is broken by different cracks and large pores (1.0 mm. - 1.5 mm. in diameter), which produce the vesicular macrostructure. This horizon, however, has much lower porosity than the overlying ones. More pores and especially small ones contain (10-20 microns thick) layers of well oriented clay than in the B_m. The large pores have coatings of fine silt mixed with un-oriented clay and in some parts with sharp curvatures they have discontinuous coatings of well oriented clay. A number of pores are filled with silt-sized grains. Sand grains have thin coatings of weakly oriented clay similar to those described in the B_m.

In vertical sections are seen long, narrow and horizontally oriented planes of weakness, which have larger intergranular spaces and different cracks in which fine silt and coarse clay is deposited. These planes outline the coarse platy units of the macrostructure. The matrix has fewer pores, little more clay and higher density than in the B_m, and forms several solid bridges between the sand grains. There are also here more meniscus-shaped bridges of well oriented clay than in the B_m.

Organic Matter: Very few and sporadic red brown aggregates.

Mineralogy: Same as in B_m with less iron oxide, which is associated mainly with some well oriented clay coatings. There are a few disintegrated hornblende grains, but there is no evidence of chemical weathering and formation of iron oxides or clay.

A_{3m} Microstructure: The arrangement of the skeletal elements (sand and coarse silt grains) and the porosity of this horizon is much the same as in the A_{2m}. The matrix of the intergranular spaces and the films of oriented clay, however, show distinct differences in certain parts of the section, while in other they are very similar to the ones in the A_{2m}.

Most of the pores have on their periphery films 20-40 μ thick of well oriented (birefringent) clay. A few pores have thicker films which are exfoliated into two or three parallel sheets. Coatings of well oriented clay are also found around the edges of sand grains, which are located in the vicinity of the pores. Some of these coatings form bridges between the grains. Most of the larger pores have thick deposits of fine silt mixed with un-oriented clay. Most of the sand grains have coatings of weakly oriented clay.

The matrix in certain areas is denser and richer in clay and forms more solid bridges than in the A2m. The menisci of well oriented clay and other aggregates of oriented clay are also more abundant in this horizon. Some of the menisci have parallel exfoliated sheets. There are also in this horizon some large aggregates very rich in unoriented clay. Within these aggregates are found tiny root holes outlined by thin films of well oriented clay.

The packing of the sand grains, the dense silt-clay matrix and the large number of bridges which bind the sand particles correlate with the high induration of this horizon.

<u>Organic Matter</u>: Not visible.

<u>Mineralogy</u>: Same as in $A2_m$ with fewer disintegrated hornblendes and more iron oxide associated with clay.

<u>A & B</u> <u>Microstructure</u>: This horizon is distinctly less compacted than the $A2_m$ and the $A3_m$ horizons. There are numerous pores, cracks and channels of all kinds and shapes, ranging in width or diameter from 50 microns up to 1 or 2 mm. Practically all the pores and cracks have comparatively thick coatings of well oriented clay. The clay coatings are particularly thick in the corners of the pores or generally in places where the periphery of the pores shows strong curvature. The thickness of these coatings ranges from 30 microns to 150 microns. A great number of sand and coarse silt grains are coated with the same type of oriented clay. The number of oriented clay aggregates within the intergranular spaces is considerably higher than

in the previously described horizons. Most of the oriented clay coatings or aggregates are exfoliated into 2-5 parallel sheets or cracked into smaller pieces. Many of the coatings of the grains are detached and have a very thin empty crack between them and the surface of the sand grains. The most common distance between the neighboring sand grains ranges roughly between 0.15 - 0.25 mm. In the intergranular spaces are numerous round pores 30-50 microns in diameter. All of these tiny pores are coated with oriented clay and presumably have been formed by root hairs. The matrix of the intergranular spaces consists of clay and silt but the clay fraction is the dominant constituent. This clay is more or less a mixture of aggregates of oriented clay and un-oriented clay, which has more or less the same appearance as in the $A3_m$ horizon. The aggregates of the oriented clay are of various sizes (from 5 to 100 microns) and are well distributed throughout the matrix. Some of them are fragments of different clay coatings and some have their clay oriented around a point. Sand grains, which are not coated with well oriented clay, have around them weakly oriented clay films as described previously.

Flow structures described by Kubiena (37) are present in this horizon especially in the vertical sections. They are mostly conducting channels formed beside decayed roots. Their deposits consist of an initial layer of mixed fine silt and clay on top of which is a layer of well oriented clay. These features are similar to the ones found by Raeside (52) in Australian soils.

In spite of the fact that the matrix is quite rich in clay, there are not many solid bridges connecting the sand grains, because of the great number of micropores and microfissures which break these bridges.

The described microstructure is the predominant one for this horizon; some sites, however, have microstructure similar to the one of A_{2m} and A_{3m}.

<u>Organic Matter</u>: Not visible except in a few root channels which have dark brown coatings which are regarded to be lignins and other products of decomposition of the root bark.

<u>Mineralogy</u>: Same as in A_{3m} with still fewer disintegrated hornblendes and more iron oxide associated with clay.

<u>Bt</u> <u>Microstructure</u>: Nuciform with clay crusts on the aggregates, as described by Frei and Cline (20) in gray-brown podzolic soils of New York. The aggregates have a spongy fabric with many pores of various sizes, and they are separated by large cracks. Larger pores and conducting channels are also abundant. All these pores, cracks, etc., have exfoliated films of well oriented clay. The conducting channels have laminated flow structures of well oriented clay but silt deposits are missing. The amount of well oriented clay in this horizon is the highest in the profile, and the thickness of its films ranges between 30 and 150 microns.

The distance between the sand grains is usually 0.2 to 0.5 mm.

The matrix consists again of a clay-silt mixture and contains a large number of well defined and clay coated fine pores of 30-100 microns in diameter. Its structure is more uniform and it does not contain as many microfissures as the A & B horizon. Menisci of oriented clay are not common. The general appearance of the matrix suggests that it has not suffered serious movement and rearrangements of the original clays. The oriented clay of the pores, etc., originates, therefore, from outside the B_t horizon origin.

Organic Matter: Same as in A & B horizon.

Mineralogy: Same as in A & B but no disintegrated grains of hornblende have been observed.

C Microstructure: Nuciform without clay crusts on the surface of the aggregates. This horizon shows the same arrangement of the skeletal elements, pores and cracks and of the silt and original clay in the matrix, as the B_t horizon. A striking difference is the absence of the oriented clay from the majority of the pores and cracks. A few pores in the upper part of this horizon have thin coatings of oriented clay similar to those described in the A_m and AB_m horizon. A thin section taken a few inches deeper was free from oriented clay coatings.

The matrix clay consists again of original fine clay, of oriented very fine aggregates of original clay and of coarse clay particles. It seems that in this horizon, the original clay shows more areas of weak orientation which produce under crossed nicols a cloudy picture of the matrix. Probably these weakly oriented areas are a result of aggregation of clays. Tiny calcite crystals also add to the anisotropism of the matrix. Sand grains usually have coatings of oriented clay.

Organic Matter: Not visible.

Mineralogy: The difference between the C and B_t is that the amount of iron oxide is smaller in the C and it occurs in the form of isolated concretions. The C is rich in Ca carbonates. Few limestone grains are present but most of the calcite is in form of fine silt-sized crystals, which are spread through the matrix.

(b) Nester

<u>A1</u> <u>Microstructure</u>: It is similar to the microstructure of Isabella's A1, but the sand grains, here, are embedded in a denser matrix of silt, clay, organic matter and iron oxides.

<u>Organic Matter</u>: It is more decomposed and dispersed than in the A1 of Isabella. It consists of widely spread droppings of arthropods and dispersed fine lignin fragments of plant residues. Only very few plant residues reveal the structure of their partly decomposed tissues. The fungi hyphae are more common than in the A1 of Isabella. The humus of this horizon can be classified as arthropods-Mull, according to Hartmann's (25) scheme, or as Moder-Mull, according to Kubiena (38).

<u>Mineralogy</u>: Quartz and K, Na feldspars are the predominant minerals of the sand fraction. Some of the hornblende grains are disintegrated into silt-sized prisms. Iron oxide is associated with colloidal organic matter.

<u>A2/Bhir</u> <u>Microstructure</u>: Massive but with many pores and cracks. Average distance between the sand grains about 0.1 mm. The pores and cracks have diameters or widths ranging from 50 microns to 0.6 mm.; most of them, however, are about 0.20 - 0.25 mm. in size. Some of the sand grains have coatings of weakly oriented clay, while a very few small pores and sand grains have around them discontinuous films of well oriented clay.

The matrix is rather dense and silt is its main constituent. Coarse clay particles and micro-aggregates of clay are also intermixed with silt. Some of these clay aggregates show under crossed Nicols orientation along their long axes, as described in the A2 horizon of

Isabella.

Organic Matter: Its amount is much smaller than in the A1, and it is found in the matrix as isolated spots of red brown colloidal substance which is only locally intermixed with clay. A few septated fungi hyphae are present.

Mineralogy: Some as in A_1. Only very few hornblendes are disintegrated but there is an abundance of silt-sized prismatic hornblendes in the matrix.

A2m Microstructure: This horizon does not exhibit a uniform microstructure. Certain parts of it resemble the $A2_m$ or $A3_m$ and others the Bt of Isabella. The distance between the sand grains ranges from about 30 to 400 microns. There are numerous horizontal cracks, 0.2 - 0.6 mm. wide, which outline the platy units of microstructure. Pores are also abundant and their diameters range from 50 microns to 1.5 mm. Most of the large cracks and pores have deposits of silt and un-oriented coarse clay. In certain parts of the section the pores and sand grains are surrounded by films of well oriented clay 10-100 microns thick. Flow structures of silt and well oriented clay are also present in some cracks and conducting channels.

The silt-clay matrix is not uniform but in certain areas is dense and in others fissured. There are spaces, 2-4 mm. in diameter, which are filled with un-oriented clay and fine silt. Within these spaces are found pores 20-100 microns in diameter, which have films of well oriented clay 10-20 microns thick.

Some sand grains have coatings of weakly oriented clay.

Organic Matter: Same as in the overying horizon but its amount is considerably smaller.

Mineralogy: Same as in the A2/Bhir. Iron oxides are associated with the well oriented clay films. A rock fragment shows alteration of hornblende on its edge and cleavage lines. Iron oxide and some clay are the products of this alteration.

A & B Microstructure: Nuciform with and without clay crusts on the surface of the aggregates. Few spots have microstructure similar to the one of Isabella's $A3_m$ horizon. Sand grains are at distances ranging from 50-400 microns with a rough average of 200-250 microns. There are a great number of pores which have diameters ranging from 50 microns to 2.0 mm. Cracks and conducting channels 200-500 microns wide are also abundant. The microstructure of this horizon generally is very porous, and resembles the microstructure of the A & B horizon of Isabella but it has higher clay content.

Most of the pores have exfoliated and fractured films of well oriented clay. Many sand grains are coated by well oriented clay, too. Conducting channels have flow structures of laminated and irregularly fractured, well oriented clay and of silt deposits. Exfoliated menisci are also present especially in the narrow intergranular spaces. The thickness of the different films of well oriented clay ranges between 20 and 200 microns.

The matrix of silt and original clay contains many different films and aggregates of well oriented clay.

Organic Matter: Very few isolated spots of red brown colloidal substance associated with iron oxides and clay.

Mineralogy: Composition same as in overlying horizons. More iron oxide is associated with oriented clay in this horizon, than in the $A2_m$. There are also some aggregates of precipitated iron oxides. Some magnetite grains seem to diffuse iron oxides from their surface.

Bt Microstructure: Nuciform with clay crust on the surface of the aggregates. Average distance between sand grains about 0.3 mm. There are numerous pores and cracks of which the sizes vary from 20 microns to 1.5 mm. The abundance and the thickness of the different films of well oriented clay and of the flow structures is unique in this horizon. All the pores, channels, cracks and most of the sand and coarse silt grains have coatings of well oriented clay. The thickness of these coatings ranges between 20-300 microns. There are also quite a few pores filled completely with well oriented clay.

The intergranular matrix consists of silt, original clay and of well oriented clay which forms coatings or deposits around the micropores and sand grains, and in the microfissures. It seems that the original clay is more mixed with well oriented clay in this horizon than in the Bt of Isabella.

The matrix is highly porous and occupies a much larger area than the sand grains.

Organic Matter: Not visible.

Mineralogy: Same as in the overlying horizon.

C Microstructure: Nuciform with only few and discontinuous clay crusts on the surface of some aggregates, which themselves have a spongy interior fabric. The average distance between the sand grains is about 300 microns. There are a great number of pores, the diameters of which range from 0.1 mm. to 1.5 mm. Only a few pores and cracks have films of well oriented clay and flow structures. Around certain pores are found carbonate deposits which consist of irregularly-shaped calcite crystals of less than 1 micron to about 5 microns in size, and which show high birefrengence.

The matrix is highly porous and fissured and consists of silt and clay which is similar to that described in the C horizon of Isabella.

Some sand grains are coated with weakly oriented clay.

Organic Matter: Not visible.

Mineralogy: Same as in Bt but with less iron oxide and with a number of limestone grains of various sizes.

(c) McBride

A1 Microstructure: Similar to the microstructures of the A1 horizons of Isabella and Nester. The aggregates are separated from each other by 0.5 to 1.0 mm. wide cracks. Large pores 0.5 to 1.5 mm. in diameter are abundant. 200 microns is an average estimate of their diameter. The distance between the sand grains is quite variable (50-400 microns). Pores and sand grains do not have coatings of oriented clay.

The matrix consists of a mixture of silt, clay, organic matter and iron oxides. The clay and oxides are well mixed with organic matter and cannot be distinguished. Only particles of coarse clay can be seen under crossed nicols.

Organic Matter: The humus can be classified as arthropods-Mull (25), but the number of the droppings is considerably smaller here than in the A_1 of Isabella and Nester. Most of the organic matter consists of finely divided lignin-like amorphous aggregates which are associated with clay and some iron oxides. It seems that the decomposition of the organic matter is in more advanced stage here than in the other two profiles. A few fungi, with septa, and eggs of nematodes are present.

Mineralogy: Quartz and feldspars are the main primary minerals. Feldspars are mainly microclines and albites with some orthoclase. Some of the hornblende grains are disintegrated.

A2 Microstructure: Rather massive with numerous large pores, 0.5 - 2 mm. in diameter and 0.5 to 1.0 mm. wide cracks. In addition to large pores, there is a great number of smaller pores of which the average diameter is about 0.2 mm. The average distance between the sand grains is about 0.1 mm.

Pores and sand grains are free of well oriented clay coatings. Some sand grains have coatings of weakly oriented clay.

The matrix of the intergranular spaces is similar to the matrix of Isabella's A2 horizon but it is richer in organic matter.

Organic Matter: It consists of highly decomposed and dispersed red brown ligninous substance, mixed with clay. A few arthropods droppings and fungus hyphae, with septa, are also present. The amount of organic matter is considerably higher in this horizon than in the corresponding A2 of Isabella.

Mineralogy: Same as in A1 with less iron oxide.

Bhir Microstructure: Loose and spongy fabric. It differs from the Bhir of Isabella in having less clay and organic matter and more empty spaces in its matrix. The average distance between the sand grains is about 0.2 mm.

The matrix consists of silt and clay. The clay and fine silt are well mixed with red brown amorphous organic matter, and precipitated iron oxide. Most of the matrix substance surrounds the sand and coarse silt grains, and forms 20-60 microns thick coatings leaving empty spaces of different shapes and sizes. The average size of these spaces is about 0.5 mm. The coatings show a weak orientation of their clay on the surface of the grains and they do not act as cementing agents.

Organic Matter: It is of the same nature as that described in the Bhir horizon of Isabella, but its amount is smaller here. It is also smaller than in the overlying A2 horizon. No fungi are present.

Mineralogy: Same as in the previous horizons. Only few hornblende grains are disintegrated. Some iron oxides form silt-sized aggregates which are not mixed with clay and organic matter.

Bm Microstructure: It is conspicuously more packed than the Bhir but it still has a great number of pores and empty spaces of 0.1 to 0.3 mm. in diameter. An approximate estimate of the distance between the sand grains is about 50 microns. The sand grains have thin coatings of weakly oriented clay. The pores do not have films of well oriented clay.

The matrix consists of a mixture of silt and big aggregates of oriented clay 10-50 microns in diameter. In narrow spaces between the sand grains are found menisci-shaped clay aggregates in which the clay particles are oriented parallel to the surface of the menisci. Iron oxides are associated with this type of clay. Most of the menisci do not form bridges between the sand grains.

Organic Matter: Few aggregates of highly decomposed red brown substance mixed with clay and iron oxide. Its amount is considerably smaller here than in the overlying horizons of the profile.

Mineralogy: Same as above but less iron oxides than in the Bhir. No disintegrated hornblendes were observed. The silt of the matrix, however, is rich in prismatic tiny hornblende which under crossed nicols can be confused with aggregates of oriented clay. Some magnetites have diffused iron oxide around them.

A2m Microstructure: It is as packed as the Bm above and the A2m of Isabella. The number of the pores is a little smaller than in the overlying Bm. Their diameters range from 0.1 mm. to 1.5 mm. but the majority of them have diameters of 0.1 to 0.2 mm. The average distance between the sand grains is about 50 microns. A few of the pores have discontinuous films of well oriented clay. Their thickness is about 10 microns. Some of the pores are filled with silt and most of them have deposits of fine silt mixed with clay. On the vertical section are seen horizontal planes of weakness in which the distance between the sand grains is about 0.3 mm. Many sand grains have coatings of weakly oriented clay.

The matrix is rather loose and forms only a few solid bridges between the sand grains. It consists of silt mainly. The clay is either mixed with the silt without any orientation or in form of small aggregates which show optical anisotropism (oriented clays). More menisci of oriented clay are present in this horizon than in the overlying one but very few of them form bridges between grains.

Organic Matter: Very few isolated red brown fine aggregates.

Mineralogy: Same as in Bm but the amount of iron oxide associated with clay is considerably smaller here. Very few hornblende grains are disintegrated.

A3m Microstructure: The degree of packing of the sand and coarse silt grains and the porosity of this horizon are very similar to the overlying A2m and the corresponding horizons of Isabella. The number of the pores which have films of well oriented clay, however, is greater in this horizon than in the A2m, and the films tend to be more continuous here. The thickness of these films ranges between 5 and 20 microns. The distance between the sand grains ranges mainly between 20 and 100 microns. In the vertical section are seen horizontal cracks 0.1 - 0.2 mm. wide, having deposits of fine silt and of un-oriented clay. These cracks contribute to the platy macrostructure of the horizon.

The menisci of well oriented clay are more abundant here than in A2m and form several solid bridges between the sand grains.

The matrix is dense and forms solid bridges firmly connecting neighboring sand grains. In narrow intergranular spaces the original clay tends to form menisci which show a weak anisotropism (orientation of their clay), producing cloudy illumination under crossed nicols. These menisci also form solid bridges between the sand grains. Sand grains have coatings of weakly oriented clay.

The microstructure of this horizon suggests that its extreme hardness is mainly due to the close packing of the sand grains, the rearrangement of the matrix and the formation of numerous solid bridges connecting firmly the sand and coarse silt grains.

Organic Matter: Not visible.

Mineralogy: Same as in overlying horizons, but no disintegrated hornblende grains have been noticed in this horizon. Iron oxide is mainly associated with the well oriented clay of the films and menisci. A few isolated iron oxide aggregates are randomly scattered throughout the thin section.

<u>Bt</u> <u>Microstructure</u>: Somewhat nuciform, but the aggregates are not as well defined as in the Bt of Isabella and Nester, and they are only partially coated with clay crusts. This horizon is distinctly less packed than the overlying fragipan horizons.

The average distance between the sand grains is about 0.15 mm. In some sites, however, these distances are as small as 30-50 microns.

The pores are more abundant here than in the overlying horizon and their sizes range from 20 microns to 1.0 mm. The cracks are irregular and have random orientation.

Practically all the pores and most of the cracks have films (20-100 microns thick) of well oriented clay. Conducting channels have laminated flow structures, but silt deposits are missing. Many sand and coarse silt grains are coated by well oriented clay. Menisci of well oriented clay are more abundant and bigger than in any other horizon of the profile. Most of the above films, coatings, etc., are exfoliated or fractured.

The matrix is highly porous and fissured, and it is impregnated by a network of fissured films and laminae of well oriented clay. In only a few sites the matrix has not suffered rearrangement of its constituents. Because of the exfoliations and fissures, only very few solid bridges connect sand grains in this horizon.

<u>Organic Matter</u>: Not visible.

<u>Mineralogy</u>: Same as in overlying horizons. More

iron oxides are associated with the well oriented clay. Some magnetite grains diffuse iron oxide around them.

C Microstructure: Nuciform without clay crusts on the surface of the aggregates. The fabric of the aggregates is spongy. The average distance between the sand grains is about 0.2 mm. Pores are abundant and their diameters range mostly between 0.1 and 0.5 mm. There are no clay films, flow structures and coatings of well oriented clay in this horizon except in its upper part. Sand grains have coatings of weakly oriented clay.

The matrix consists of a mixture of silt and clay and it is highly fractured or fissured and forms empty spaces 10-50 microns in size. The clay of the matrix shows cloudy, illumination under crossed nicols as described in the C horizons of Isabella and Nester. No depositions of carbonates have been observed in this horizon.

Organic Matter: Not visible.

Mineralogy: It differs from the Bt in having limestone and calcite grains, and less iron oxide.

GENERAL DISCUSSION AND EVALUATION OF THE RESULTS

1. Changes due to soil formation

(a) Uniformity of the profiles. Changes occurring in the profile during the development of a soil can be fully evaluated only when the parent material is known. If the parent material is represented by the C horizon, we will be able to evaluate objectively the changes, which have occurred in the particular horizons, only if we prove that the whole profile had, at time zero, composition identical to the present composition of the C horizon. That is to show that the profile has been formed in uniform parent material.

Sand size distributions and the quartz/feldspar ratios are rather uniform throughout the three profiles. The distribution of the total heavy mineral fractions and the magnetite/garnet ratios, however, show that only Nester and McBride have been formed from uniform parent materials, while Isabella consists of the following three different strata:

1st - The 0 to 21" layer, including the A_0, A_1, A_2, Bhir, Bm and A2m horizons is characterized by a relatively high amount of heavy minerals in the fine sand fraction and a magnetite/garnet ratio of 11 to 9.9.

2nd - The 21-34" layer consists of the A_{3m} horizon and is characterized by a small amount of heavy minerals and a magnetite/garnet ratio of about 5.

3rd - The material below 34", including the A & B, Bt and C horizons, is characterized by a small amount of heavy minerals and a magnetite/garnet ratio of 8.2 - 9.5. The qualitative mineralogical composition of this stratum is similar to the composition of the first stratum.

Soil genesis, however, proceeds regardless of the uniformity of the parent material, and consequently, it will be studied in all three profiles.

(b) Changes in physical properties. The five soil forming factors as described by Jenny (31) control the changes in physical as well as in all the other properties of the soil. The physical properties which have undergone significant changes during the development of the studied profiles are: bulk density, pore size distribution, mechanical composition, and arrangement of the soil constituents. The magnitude of other physical properties such as water permeability and hardness depend on the magnitudes of the above properties.

Bulk density data show a significant increase in volume in the podzol sequa and a decrease in volume in the well developed A_{2m} and A_{3m} horizons. If we regard quartz as a resistant mineral in the podzol region, we can calculate the volume in which one gram of fine quartz sand is confined in each horizon. Table 10 shows the above mentioned changes in volume of the McBride profile.

Table 10. Volume occupied by one gram of fine sand sized quartz

			McBride				
Horizon	A_1-A_2	Bhir	B_m	A_{2m}	A_{3m}	B_t	C
Volume c.c./ gr. quartz	2.48	2.11	1.66	1.44	1.54	1.80	1.77

The increase in volume in the podzol sequa is due to the increase in non-capillary porosity and in the formation of loose crumbly or spongy structure. Processes which produced these changes are: (1) loss of clay, (2) addition of organic matter, (3) biological activity, (4) alternate wetting and drying, (5) freezing and thawing and rearrangement of the soil constituents. How these processes develop the soil structure is well described by Baver (4).

The increase in the bulk density of the $A2_m$ and $A3_m$ horizons is mainly the result of the close packing of the sand and coarse silt and secondarily of the filling of the pores with silt as it has been described in the microscopical studies.

The packing of the sand grains has not been inherited from the parent material but it has been developed during the formation of the soil. The distances between the sand grains, as seen in the thin sections, are considerably greater in the C horizons than in the pan horizons.

Water permeability depends on the volume of the non-capillary pores, and therefore, it has been greatly increased in the podzol sequa. In the pan horizons, the water permeability is controlled by the cracks, root holes and/or worm holes.

Mechanical analyses and thin section studies show that the horizons which overlie the Bt horizon have lost various amounts of clay. Isabella and McBride show a small addition of clay in their Bhir horizons but the amount of clay added has not compensated the amount of clay lost. The only truly clay enriched horizons are the Bt horizons.

The bisequa profiles, therefore, have two zones of illuviation:

the Bhir horizon and the Bt horizon. The bulk of the illuvial clay, however, is deposited in the latter.

The films of well oriented clay, which are seen in the thin sections, have been regarded by many authors as Brewer (7), Cady (11), Frei and Cline (20) and Raeside (52), as consisting of illuvial clay deposited by percolating waters. If this is true, we must admit that clay is being deposited in all horizons but the A1, A2 and C, and that eluviation and illuviation have taken place either simultaneously or at different stages during the soil formation, in the part of the profile which includes the Bhir - A & B series of horizons.

The abundance and thickness of the clay films increases with depth. The films of the pan horizons are discontinuous and thin - but they do not show any evidence of erosion which would lead to the conclusion that these horizons were illuvial at previous times and that they are being eluviated at the present stage of soil genesis.

The menisci of well oriented clay of the pan horizons could be formed by local rearrangement of the original clay through dispersion in water and subseouent concentration and efflorescence in certain narrow intergranular spaces as described by Kubiena (37).

Yarilova and Parfenova (69) studied the clay films of a wide range of soils of the podzol and gray brown podzolic region of Russia. Their studies showed that the clay films always consisted of a rich in iron clay mineral of the montmorillonite group which, they suggest, is of synthetic origin. They have named this mineral as Polynite in honor of Polynov.

The most logical assumption is that all the above described processes take place during the soil formation.

Field studies and thin section observations showed that the illuvial clay is not uniformly distributed in the illuvial zone (20), but it is deposited along conducting channels, pores and in the vertical cracks.

We can conclude from the above discussion that the only purely eluvial horizon is the A2 and the only purely illuvial horizon is the Bt.

The podzol sequa of Isabella and McBride show a certain enrichment in silt, which probably is due to the disintegration of gravelly rock and cherty fragments which are abundant in these profiles. Besides clay, very fine silt is the only other fraction of the soil particles which undergoes redistribution in the profile. Table 4 shows an enrichment of the $A3_m$ and A & B horizons in very fine silt.

The downward movement and deposition of the very fine silt is probably facilitated by the presence of the vertical cracks.

c. Changes in mineralogy. In the case of McBride and Nester profiles, the mineralogical changes can be evaluated on the basis of the mineralogical composition of the C horizons (parent material). In the case of Isabella, however, the mineral changes can be evaluated with only relative accuracy.

1. Primary mineral changes in the fine sand fraction. As it was shown in the previous chapter, weathering of primary silicate minerals takes place only in the part of the profile which overlies the Bt horizon. When considering calcite, however, the Bt horizon is included in the zone of weathering.

The rate of weathering decreases with increasing depth from the surface of the soil. This decrease in weathering should be expected as the intensity of leaching is higher near the surface than in the subsoil.

The minerals which show most weathering in the studied profiles are calcite, olivine, hornblende and epidote. Resistant minerals are quartz, magnetite, garnet, zircon, tourmaline and K-Na feldspars. This classification of the minerals is in agreement with the weathering sequences worked out by different authors and summarized by Jackson and Sherman. There is a disagreement, however, regarding garnet, which some people classify as moderately resistant. Matelski and Turk (43) found that garnet decreases in size due to weathering. In the studied soils, however, there was very little evidence of weathering of garnet. Probably because this garnet is different in composition than the garnet studied by the above authors.

The decrease in the number of K-Na feldspar grains in the A_2 horizons indicates a slight weathering of the above minerals in this part of the profiles.

In thin sections it was observed that both physical (disintegration of hornblende) and chemical (release of iron and formation of clay) weathering of the minerals takes place in the profile. Evidence of chemical weathering was seen only in a few thin sections of the gray brown podzolic sequa, while this evidence has been obscured in the podzol sequa by leaching and/or mixing of the products with organic matter. The increased roughness of the surface of the weathered minerals of the podzol sequa is an indication of the importance of the chemical weathering in this part of the profile.

Regarding the fact that the easily weathered primary minerals, with the exception of calcite, represent a very small fraction of the soil constituents, we can conclude that their role in soil genesis is secondary.

2. Clay mineral changes. The results of the different methods of clay analysis indicate that a weathering of clays takes place in the profile. The rate of this weathering decreases again with increasing depth from the surface of the soil.

The principal clay minerals which weather are illite and the interstratified complexes of illite-chlorite-vermiculite-montmorillonite, which are also present in the parent material. The amounts of illite and of the interstratified complexes sharply decrease near the surface of the soil and discrete particles of montmorillonite become the dominant minerals, and presumably are the products of weathering. This sequence of weathering has also been found in soils of Indiana by Murray (50) and in soil of Wisconsin by Whitting and Jackson (65). In cases of advanced weathering, as in the A_1 and A_2 horizons of Isabella, vermiculite also weathers and montmorillonite remains as the only end product.

Wurman (68) found an increase in the amount of montmorillonite near the surface of the Wallace and Montcalm series of Michigan. It is obvious, therefore, that montmorillonite is forming in the podzols of Michigan, which have been developed on parent materials ranging from sand to sandy clay or clay loam.

Another strong indication of the genetic origin of montmorillonite is that on the surface of the Nester profile, which is significantly less leached and weathered than the Isabella profile, it is mostly interstratified with other minerals, possibly because it has not been subjected to the degree of weathering impressed on the other profiles. If the montmorillonite of the Isabella surface had been brought in by wind, we should expect to find discrete montmorillonite also in Nester, since the two profiles are only one mile apart.

The weathering sequence of clays of the studied profiles is in agreement with the stability sequence of clays suggested by Jackson and Sherman (28).

Walker (62) found in soils of Scotland that biotite weathers to vermiculite. Mortland (49) formed discrete particles of vermiculite by leaching biotite flakes with 0.1N Nacl. Murray (50) suggests that the initiating mechanism for the formation of montmorillonite from illite is the oxidation of the ferrous iron in the octahedral layers. Mortland (48) also attributes the decrease in total charge, which is a result of the transformation of biotite to vermiculite by plant growth, to the oxidation of the octahedral iron.

Some of the clay minerals are probably synthesized from Si, Al and Fe oxides of the soil solution which are the products of the complete decomposition of the primary and clay minerals. Yavilova and Parfenova (69) have proposed the synthetic nature of the clay films, of the Russian soils. Henin (26) has synthesized montmorillonite from dilute solutions of SiO_2, Al_2O_3 and Fe_2O_3 under atmospheric conditions.

Clay analysis data showed a preferential removal of expanding clays from the fragipan horizon and a relative accumulation of illite and other non-expanding clays. The exfoliation of the clay films seen in the thin sections of the illuvial zones indicates that expanding clays constitute a significant portion of these films. The expanding clays expand and contract upon alternate wetting and drying and cause the breaking of the films into parallel sheets. Assuming that the clay films have been formed by physical illuviation of clay through the percolating waters, we can explain the relative accumulation of non-expanding clays in the fragipan. Montmorillonite minerals are generally smaller than the non-expanding minerals (22).

X-ray patterns of the <.2 microns clay show that it consists mainly of interstratified complexes of illite-chlorite and expanding clays, while illite and kaolinite are present in much smaller amounts than in the total clay fraction. The expanding clay, therefore, being of smaller size than the non-expanding clay, is removed from the fragipan horizons by percolating waters more easily than the non-expanding one.

The accumulation of illite and other non-expanding clays in the fragipan also indicates that there is no significant alteration of the clays in this part of the profile.

The decrease of the amounts of kaolinite near the surface of the soils cannot be attributed to chemical weathering as kaolinite is regarded as a very stable mineral in the podzol region, as Jackson and Sherman (28) have found. Bloomfield (5) found that leaf leachates exert a marked deflocculating effect on kaolinite suspensions. It is logical, therefore, to assume that kaolinite is being removed from the surface of the soil by percolating water.

According to the hypothesis that there has been preferential removal of the expanding clay in the fragipan, we might expect that such removal should also be taking place in the podzol sequa and illuviation occurring in the underlying fragipan. Some such a removal undoubtedly took place in previous times, as this part of the profile has lower clay content than the C horizon, but it seems that the removal of clay was either by solution or that it was not deposited until it reached the B_t horizon or it was deposited only in the vertical cracks and not in the mass of the fragipan horizons.

The relative increase in expanding clays found today in the podzol sequa is an indication that the rate of their formation exceeds the rate of their removal. In the thin sections it has been observed that clay and organic matter form stable complexes and aggregates. The aggregation of the clay seriously inhibits its removal from the podzol sequa at the present stage. The increase in clay content at the podzol Bhir horizons compared to the two overlying and underlying horizons indicates that clay is being deposited there either as discrete particles as a result of physical illuviation or is being formed by precipitation from the solution or both.

(d) Chemical changes. The chemical changes are the result of the chemical weathering, addition of organic matter, solution, chemical reaction between the soil constituents, leaching and precipitation.

The main changes detected in this study are:

1. Loss of carbonates from the horizon overlying the C horizon and increase of their acidity.

2. Addition of organic matter to the horizons overlying the C horizon and mainly in the podzol sequa.

3. Formation of clay-organic matter complexes especially in the podzol sequa.

4. Formation of sesquioxide-organic matter complexes

and precipitation of them in the Bhir horizon.

5. Accumulation of "free" alumina in the zone of the profiles occupied by the Bhir, E_m, $A2_m$, $A3_m$ and A & B horizons.

6. Accumulation of alkali soluble silica in the B_t horizons.

7. Loss of sesquioxides from the A2 horizons and accumulation of iron oxides in the Bhir horizons where they are associated with organic matter and clay and in the B_t where they associate with the clay films.

8. Thin section studies and the light color of the pan indicate that the $A2_m$ and $A3_m$ horizons suffer a loss of iron oxides, too.

2. <u>Formation of the fragipan</u>

Investigations carried out in other parts of the country admit that the fragipan is a reversibly indurated pan which owes its induration to the peculiar arrangement of the soil particles. Silica is not assumed to have a cementing role in the fragipan.

Many authors as Carlisle (14) consider the compaction of the fragipan as a major factor of cementation. Others (36) suggest that clay and especially illite is the binding agent.

Results of this study showed that the fragipan constitutes the second eluvial zone of the bisequum profile as Grossman et al (34) have found in soils of Illinois. Bulk density measurements showed distinct maxima in the A2m and A3m horizons of the pan, but hardness data suggest that high bulk density alone is not enough to produce maximum induration. Results of chemical analyses failed to reveal any significant concentration of alkali soluble silica in the pan.

Extractable alumina, however, showed a remarkable increase in the area of the pan.

Figure 2 shows that with a more or less constant bulk density, the hardness of the fragipan increases with clay content until an "optimum" is reached and then it decreases with increasing clay content. The "optimum" amount of clays for fragipans having mechanical compositions analogous to the studied ones seems to be about 15%. The greatest differences in hardness with changing clay content fall between 7 and 22 per cent of clay. The "optimum" clay content which is necessary for the maximum hardness of the pan has also been postulated during the field studies. Results obtained by Grossman (23) did not show any "optimum" clay content, because he tested dried samples of fragipan and because he did not measure hardness of the pan but the firmness of the dried soil clods, which under dry conditions normally increases with increasing clay content.

Figure 2 also shows that within the narrow ranges of clay content, hardness increases with increasing bulk density, especially in the range of 4-10% clay.

High bulk density and optimum clay content are, therefore, the main and necessary conditions for the induration of the pan. Alumina might act as a cementing agent but its role appears to be of secondary importance.

Thin section studies revealed that the most important feature of the pan horizons is the close packing of the sand and coarse silt grains, which is responsible for the high bulk density of the pan. Deeper horizons, however, in spite of their high bulk density, have low hardness and much less packed sand grains than the pan. It

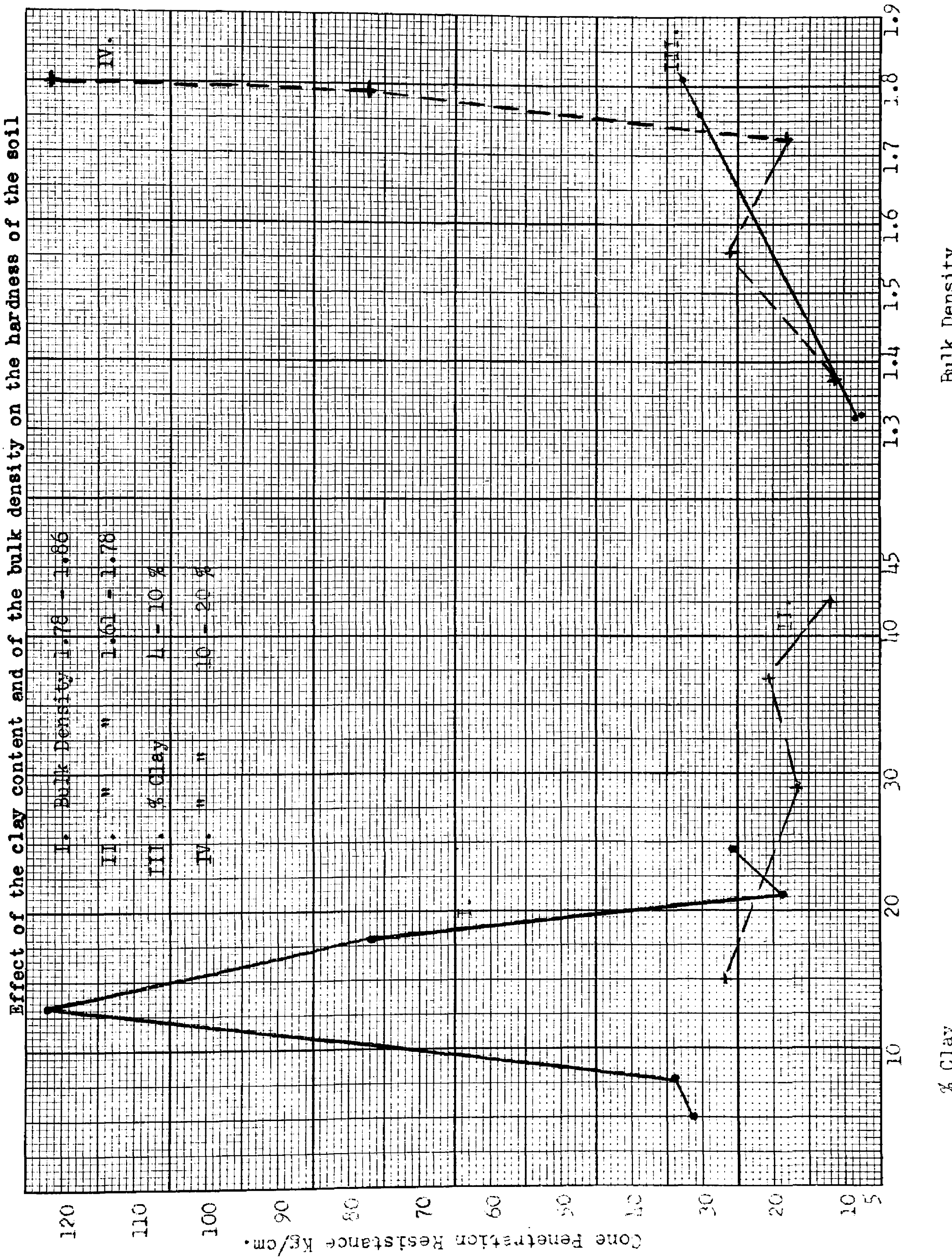
Effect of the clay content and of the bulk density on the hardness of the soil
I. Bulk Density 1.78 - 1.86
II. " " 1.61 - 1.78
III. % Clay 4 - 10 %
IV. " " 10 - 20 %
Cone Penetration Resistance Kg/cm.
120
110
100
90
80
70
60
50
40
30
20
10
5
% Clay
10
20
30
40
45
1.3
1.4
1.5
1.6
1.7
1.8
1.9
Bulk Density
I.
II.
III.
IV.

FIG. 2

appears, therefore, that the close packing of the sand and coarse silt grains is the important factor of the induration and not the high bulk density itself.

In order that the close packing be obtained, the clay content must not exceed a certain amount. We have, therefore, another support of the idea of "optimum clay content".

The clay acts as a cementing agent by forming solid bridges connecting the neighboring sand grains. The increase of hardness with increasing clay content can be attributed to the formation of more clay bridges. If the clay content exceed the "optimum", larger intergranular spaces will be required and fracture and discontinuity of the clay bridges will occur, because of their larger size and of the alternate wetting and drying, as it has been seen in the thin sections of the illuvial Bt horizons.

Clay analyses have shown that the clay of the A2m and A3m horizons consists largely of non-expanding species. Knox (36) also found in fragipans of New York that illite was the material which holds together the grains of sand and silt. Clay bridges formed in the pan, therefore, are not fractured by wetting and drying, because they consist of non-expanding minerals. This is true only if we assume that dispersion does not take place.

Upon water saturation the cores of the A2m and A3m horizons did not show any change of volume as did the cores of other horizons containing expanding clays. This means that once the structure of the fragipan is formed it cannot be changed by mere wetting and drying.

Hypothesis of the genesis of the pan

In the preceding discussion we have shown that close packing of the sand and silt grains, a certain optimum clay content and a proper arrangement of the soil particles are the main factors responsible for the induration of the pan.

The parent materials of the studied profiles do not have the above three properties combined. That is, the properties of the pan, which cause its induration, have been developed during the soil formation. The fragipans that were studied, therefore, are genetic soil formations and not geologic formations.

The genesis of the fragipan horizons takes place parallel to the genesis of the other horizons. After the leaching of the carbonates and acidification of the profile, the following steps are postulated for the formation of the pan:

(a) Removal of a part of the clay fraction and preferentially of the expanding clay.

(b) Contraction following the removal of clay step by step. This contraction which resulted in the close packing of the grains was gradual and not uniform. Forces which caused this contraction were the gravitational forces within the horizon, the load of the overlying horizons, pressures exerted by tap root of the trees, and pressures developed during wetting and drying plus freezing and thawing of the soil during the early stages of development. The contraction, therefore, caused by forces acting at different directions, resulted in a three dimensional shrinkage of the pan and in the formation of vertical cracks and the coarse columnar structure. It is known that the formation of a hexagonal pattern of cracks causes the least cracking due to shrinkage.

In case of a uniform body being gradually contracted from the top to the bottom a hexagonal prismatic structure is produced. In this way the formation of polygonal pattern of cracks found in many fragipans throughout the country and the vertical cracks of Michigan fragipans can be explained.

(c) Following the contraction and the close packing of the skeletal elements, the matrix substances (fine silt and remaining clay) undergo a rearrangement.

The close packing of the sand has provided the capillary intergranular spaces, in which the soil suspension is confined at moisture levels below field capacity. Upon evaporation of the water, the clay is deposited forming optically anisotropic menisci which serve as bridges connecting the neighboring sand and coarse silt grains.

The clay of the anisotropic menisci is partly the clay of the original matrix and partly illuvial clay brought in from overlying horizons by the percolating waters during the stage of contraction.

The A_{3m} horizon of Isabella has a considerable amount of illuvial clay.

(d) During the course of the soil development, aluminum is released from the decomposing minerals, and a part of it is precipitated from the soil solution in the area of the pan, possibly adding to the cementation of the pan.

The above hypothesis differs basically from the hypothesis proposed by Carlisle (14) in the following two points: The compaction of the studied fragipans of Michigan soils has not been inherited from the parent material but it is the result of soil genesis. The other point is that the vertical cracks are the result of the contraction due to loss and rearrangement of the constituents of the pan and not of the alternate wetting and drying. Experimental evidence and the type and amount of clay of the pan exclude volume changes of the pan during wetting and drying which could account for the cracking.

The softening of the pan upon wetting can be explained by assuming that water acts as a lubricant decreasing the adhesion forces between the soil particles and possibly by dissolving or hydrating the Al_2O_3, as the pH of the pan favors its solution.

The platy and vesicular structure of the pan has been explained by Fitzpatric (19) as due to frost action. He proved that the vesicular pores have been formed by the dissolved gases during the freezing of soil water.

Czeraski (16) in Germany has done a complete study of the frost action and its effect on the soil structure. He describes the action of soil frost as accompanied by the following phenomena:

(1) Expansion of water by freezing (9% of its volume).

(2) Rise of water from the underlying horizons toward the frozen zone and deposition of this water in form of ice sheets.

(3) Lifting of the soil through the freezing of the original and of the water that rises by capillarity from below.

The most effective phenomenon, however, is the second one, which produces the following structures:

a. Massive or homogenous structure which is characteristic of the sandy soils and

b. Laminated or heterogenous structure which is characteristic of the finer soils.

The heterogenous structures are better developed on compact soils than on loose soils. The particular type (platy, polygonal, polyhedral, etc.) depends on the texture of the soil and on the rate of freezing.

The maximum rise of water and the best developed platy structures occur on compacted loess and loams.

Czeraski (17) also produced and photographed the development of frost structures in the laboratory. Soil from A3 horizon of a Parabraunerde formed on loess and having similar properties to the studied fragipans produced upon freezing a network of horizontal and zigzag ice sheets.

The platy structure, therefore, and the thin horizontal cracks seen in the fragipan and mainly in its $A2_m$ horizon are probably caused by frost action.

During the winter of 1959, Ken Mittert and Steve Shetron, soil scientists with the Soil Conservation Service in Osceola County, Michigan, found these soils were not frozen because of a thick snow cover. Data of previous years in the vicinity of East Lansing and observations made by K. Mattert, chief of the Osceola soil survey party, verify that freezing does occur at depths where the pan is located.

It seems, therefore, that soil frost may cause the disintegration of the pan by breaking its massive structure. This disintegration is more pronounced in the B_m and $A2_m$ horizons of the pan.

3. <u>Classification and Horizon Nomenclature</u>

The studied profiles fall within the group of soils named by Gardner and Whiteside as double (bisequa) profiles of podzol-gray-brown podzolic intergrades, which represent the zonal soils of the studied area. Such soils have also been found in New York and Ontario.

The fragipan is a genetic formation in the studied profiles, formed in the eluvial zone of the Gray Brown Podzolic sequum, and falls within the concept of fragipan horizons defined in the Soil Survey Manual.

The typical sequence of genetic horizons of the soils of Northern Michigan which have the textural range of the studied profiles are:

First, a Podzol sequum characterized by maximum physical, chemical and biological activity or changes, and by an increase in volume.

A_{oo}	A very thin layer of undecomposed litter. The proper genetic designation of this horizon is Od*.
A1	A crumbly and loose mineral horizon of acid reaction. It has been enriched by arthropods fine moder or arthropods mull humus. Intense chemical weathering and formation of discrete particles of expanding clay minerals, decomposition of organic materials and formation of clay-organic matter are the predominant processes which take place in this horizon. The genetical designation of this horizon is Vh.
A2	A bleached acid horizon characterized by clay and sesquioxide eluviation, massive friable structure,

* These genetic designations have been recently proposed by Dr. E. P. Whiteside in his article published in Soils and Fertilizer, V:XXII, 1959, 1-8.

and intense chemical weathering as in the A_1. Its genetic designation is Em.

Bhir An acid horizon of loose spongy structure, richer in iron, alumina and colloidal organic matter. It is characterized by a secondary increase in clay content and by the formation of clay-iron-organic matter complexes. The formation of discrete particles of expanding clay is less pronounced here than in the overlying horizons. Its genetic designation is ↓Iibh.

B_m An acid horizon, rich in alumina and transitional between the podzol sequum and the pan. This horizon is, insofar as sesquionides are concerned, illuvial but it has lost most of its clay through eluviation. Its sand is somewhat close packed, has a coarse platy structure and is slightly indurated. The genetic designation for this horizon is ↓Ibi Eq

Second, a Gray-Brown Podzolic sequum, characterized by high physical activity and relatively low chemical and biological activities. There is no strong evidence of formation of expanding clay in this part of the profile.

A_{2m} An acid, bleached, eluvial horizon which has suffered preferential losses in expanding types of clay and iron oxides, a relative increase in non-expanding clay, close packing of sand and coarse silt grains with a loss in volume and rearrangement of the matrix substances. The above changes have resulted in the reversible induration of the horizon under dry conditions. This horizon has a coarse platy and vesicular structure produced by frost action. Its genetic designation is Eql

A3m — Same as above, but with more poorly expressed platy structure, higher clay and free alumina content and with a small amount of illuvial clay in form of films. This horizon is considerably more indurated than any other horizon in the profile. Its genetic designation is Eq /$\downarrow\overrightarrow{I}$bt.

A & B — An acid horizon which is partly eluvial and partly illuvial. It constitutes a transition between the overlying A3m and the underlying Bt. Its genetic designation is $\downarrow$Iti & Eq .

Bt — An acid horizon that constitutes the zone of maximum clay illuviation. Iron oxides also accumulate in this horizon and they are mainly associated with the clay films. Except for the decomposition and leaching of the carbonates, there is no significant weathering of primary and clay minerals in this horizon. The sand grains are not packed. This horizon is characterized by the abundance and thickness of flow structures and films of well oriented clay. Its structure is usually blocky and the root distribution is higher here than in any other horizon of the Gray-Brown Podzolic sequum. The genetic designation for this horizon is $\downarrow$Iti.

Third, unaltered parent material.

C Calcareous glacial till. It constitutes the parent material (P).

The podzol sequa of the three profiles studied and generally of the Michigan soils which fall within this lithosequence, have not the characteristics of the classical podzols of Russia and Europe. Namely, they do not have accumulation of raw humus on their surface and their Bhir horizons are not cemented. Bloomfield (5), however, does not accept that the presence of raw humus is important in calling a soil podzol. According to him, Russian podzols, gray wooded and Australian podzolic soils are morphologically similar and the same processes are responsible for their formation. We can classify, therefore, the upper sequa of the studied soils as podzols.

Among the studied three profiles, only Isabella has the typical sequence of genetic horizons as described above. Its A_{3m} horizon, however, is geologically different from the overlying and underlying horizons and its designation according to Whiteside's (64) system, should be II Eq $/\downarrow \overrightarrow{I}$bt.

McBride is the next best developed profile but its A2 horizon contains much more organic matter than a typical A2 should have, and its genetic designation should be EmVh. The A & B horizon is not well defined in McBride.

The least developed profile is the Nester profile. It is lacking typical and separable A2 and Bhir horizons in its podzol sequum. Instead, it has a gradation or mixture of these two horizons, of which the genetic designation is Em/$\downarrow$Ihi. In the gray-brown podzolic sequum, the A3m horizon has not yet been developed.

SUMMARY - CONCLUSIONS

The three profiles studied have been developed on calcareous till and they represent different stages of weathering and soil development. The Isabella profile is the most weathered and best developed and the Nester profile is the least developed.

During the development of the profiles, the carbonates were dissolved and removed from the zone which overlies the C horizon. As a result, an acidification of the profiles took place. Clay was also removed from the zone overlying the B_t horizon by either physical illuviation or complete decomposition. A part of the removed clay was deposited in the Bt horizons which have the highest clay content in each horizon.

The expanding interstratified complexes of illite-chlorite-vermiculite-montmorillonite being small in size were preferentially removed from the eluvial $A2_m$ and $A3_m$ horizons, which thus show a relative increase in non-expanding clays. The intense weathering of the clay and of the less resistant primary minerals in the upper part of the profiles resulted in the release of "free" **Fe oxide, alumina and silica** and in the formation of discrete particles of vermiculite and montmorillonite. Consequently, an increase in the amount of these minerals took place near the surface of the soil.

The addition of organic matter formed the humus of the A_1, A2 and Bhir horizons and initiated the formation of clay-organic matter and iron-organic matter complexes of the podzol sequa.

In the eluvial zone of the gray-brown podzolic sequa, a close packing of sand and coarse silt grains took place and resulted in the reduction of the volume of that layer. Following or during this contraction, a rearrangement of the clay and fine silt took place, which resulted in the formation of solid clay bridges connecting the neighboring sand grains and thus a reversibly indurated pan was developed in the A2m and A3m horizons.

The hardest pan has been developed in the McBride profile because its parent material had nearly the optimum mechanical composition necessary for the formation of the pan. On the contrary, the pan of the Nester profile is only poorly developed, as its parent material had considerably higher clay content, which has inhibited the adequate translocation and rearrangement of the soil substances.

The fragipan limits the branching and causes a serious deformation of the roots. At first glance, however, no serious decline of the forest growth, due to the presence of fragipan, has been noticed but, before we reach any general conclusion, more information and research is needed. The fragipan can be more harmful in eroded agricultural lands, where its presence limits the physiological depth of the soil.

The nature of the pan is such that it can easily be destroyed by mechanical breaking, when the soil is wet, and by thorough mixing with the overlying horizons. Addition of clay and organic matter could produce and stabilize a favorable soil structure and prevent the reformation of the pan.

Below the fragipan is the zone of maximum clay illuviation characterized by the abundance of flow structures and other clay films which are rich in precipitated iron oxides.

From the above discussion, we can conclude that the Podzol sequa are characterized by high states of physical, chemical and biological activities which result in drastic changes in the physical, chemical and mineralogical properties of the soil.

The underlying Gray-Brown Podzolic sequa are characterized mainly by high physical activity such as clay illuviation, eluviation, contraction, and rearrangement of soil particles.

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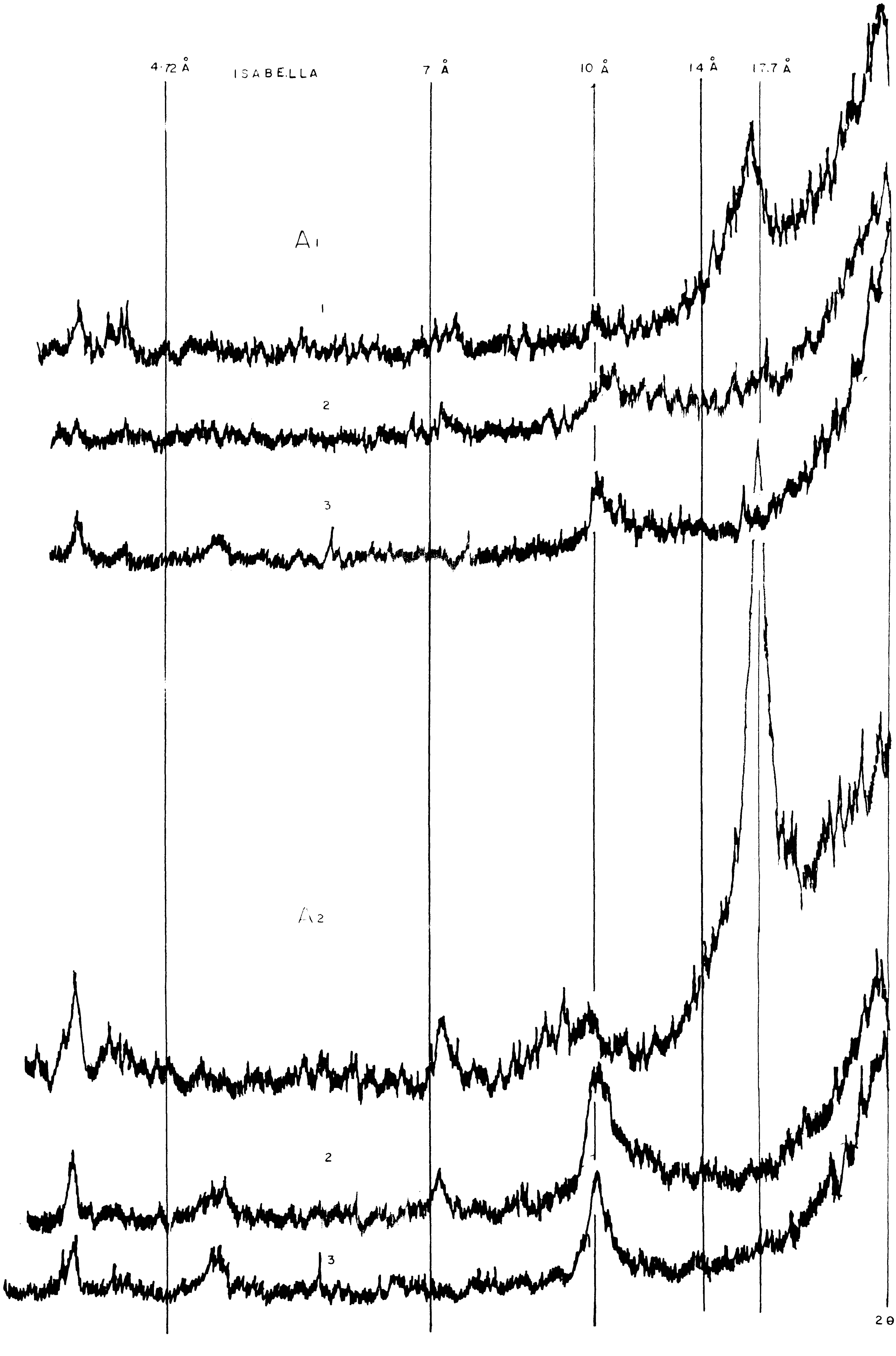
APPENDIX

X-RAY DIFFATION PATTERNS OF CLAY

Patterns No. 1 correspond to Ca^{++} and glycerol saturated samples

Patterns No. 2 correspond to samples which were K^{+} saturated and heated to 110° C.

Patterns No. 3 correspond to samples which were K^{+} saturated and heated to 550° C.



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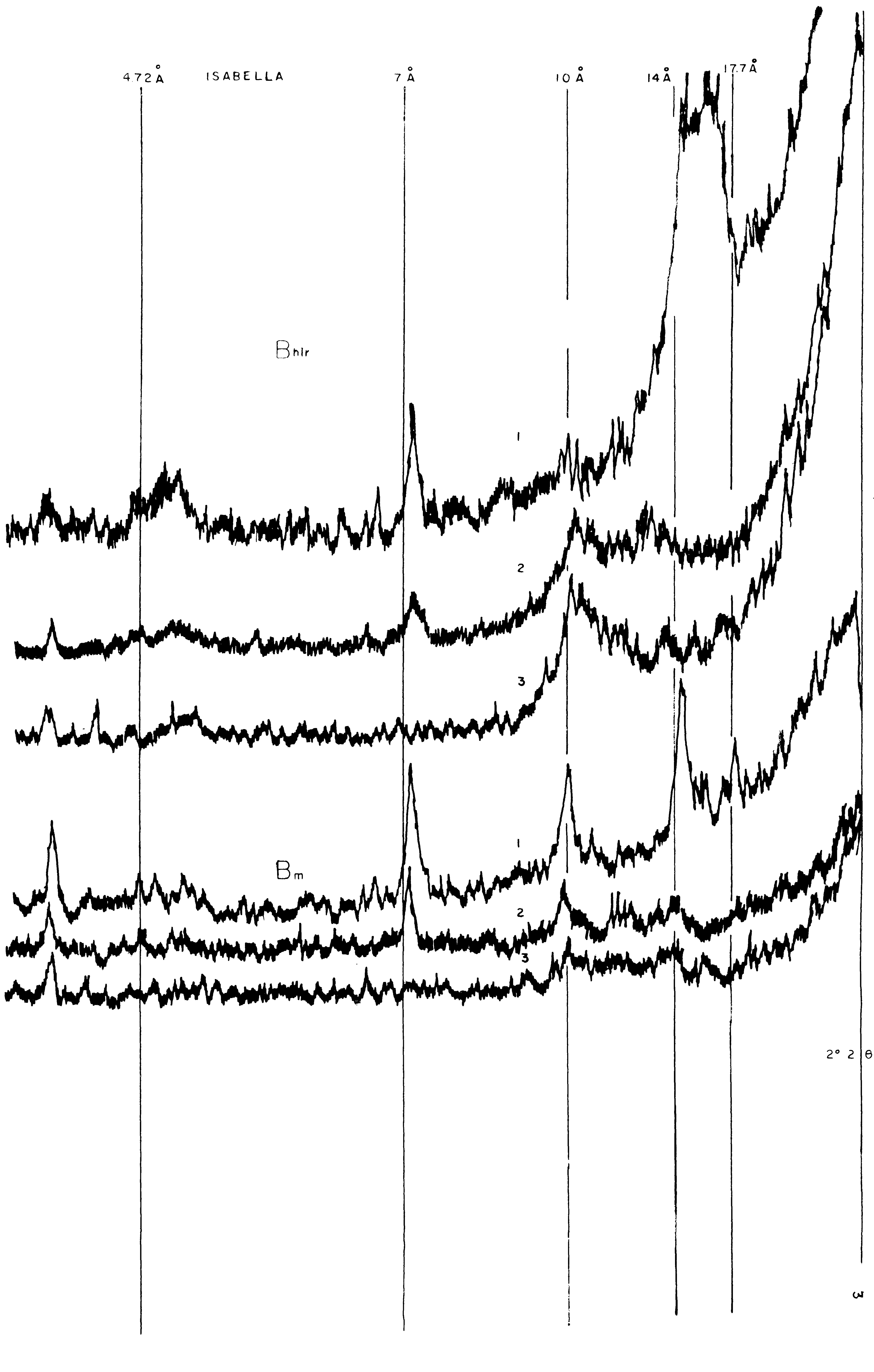
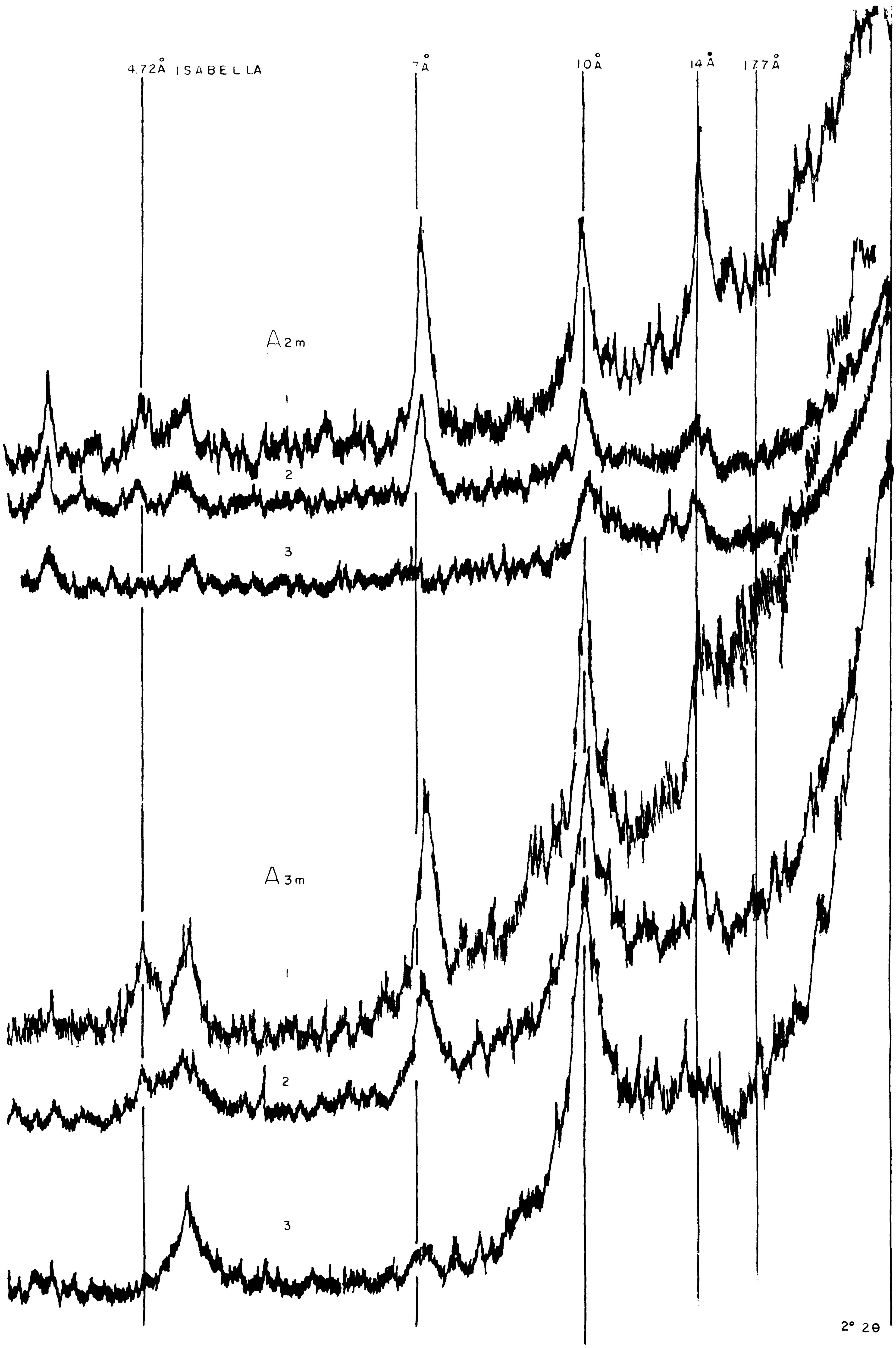
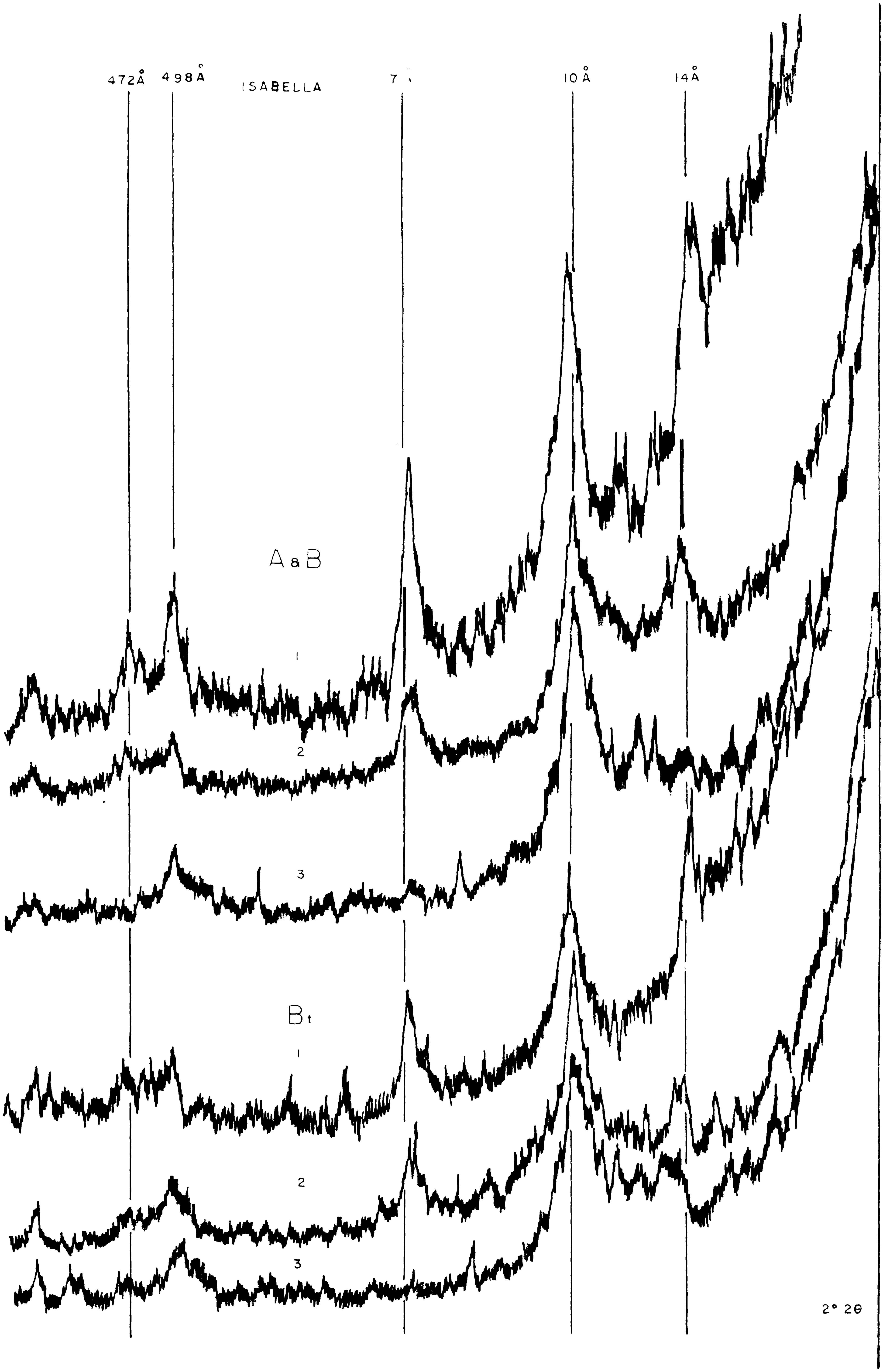
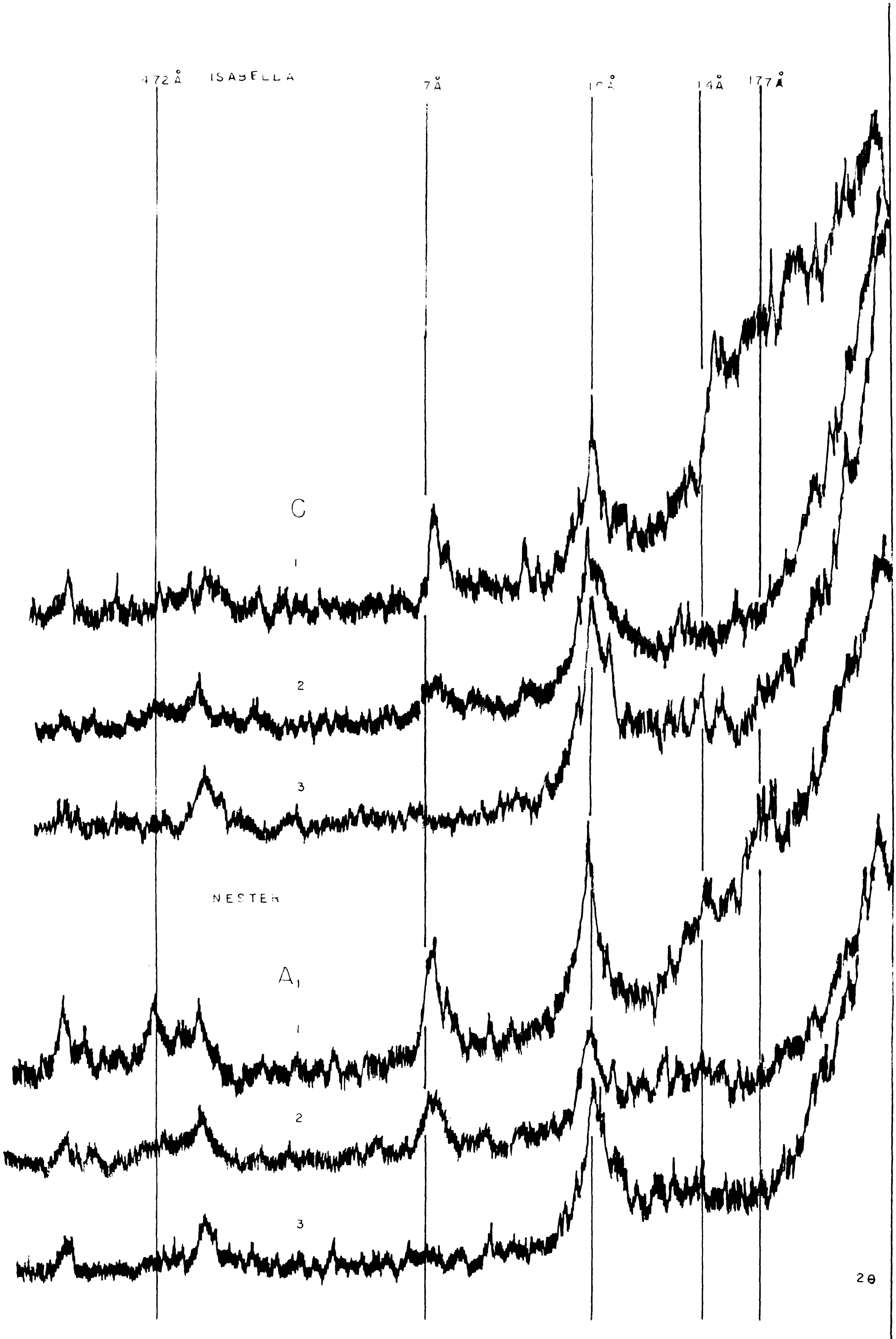

4.72 Å
ISABELLA
7 Å
10 Å
14 Å
17.7 Å
Bhir
1
2
3
Bm
1
2
3
2° 2θ
3

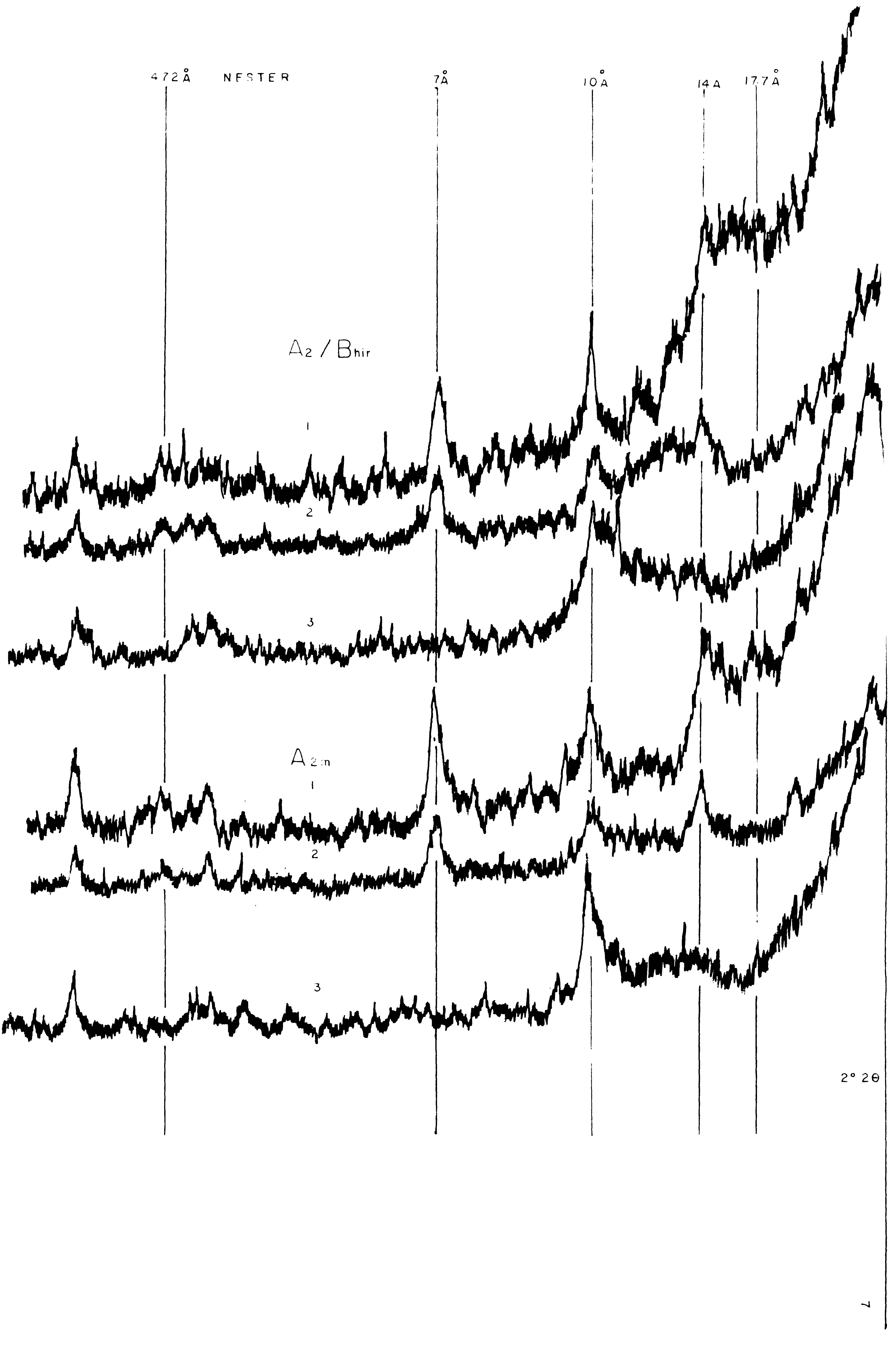


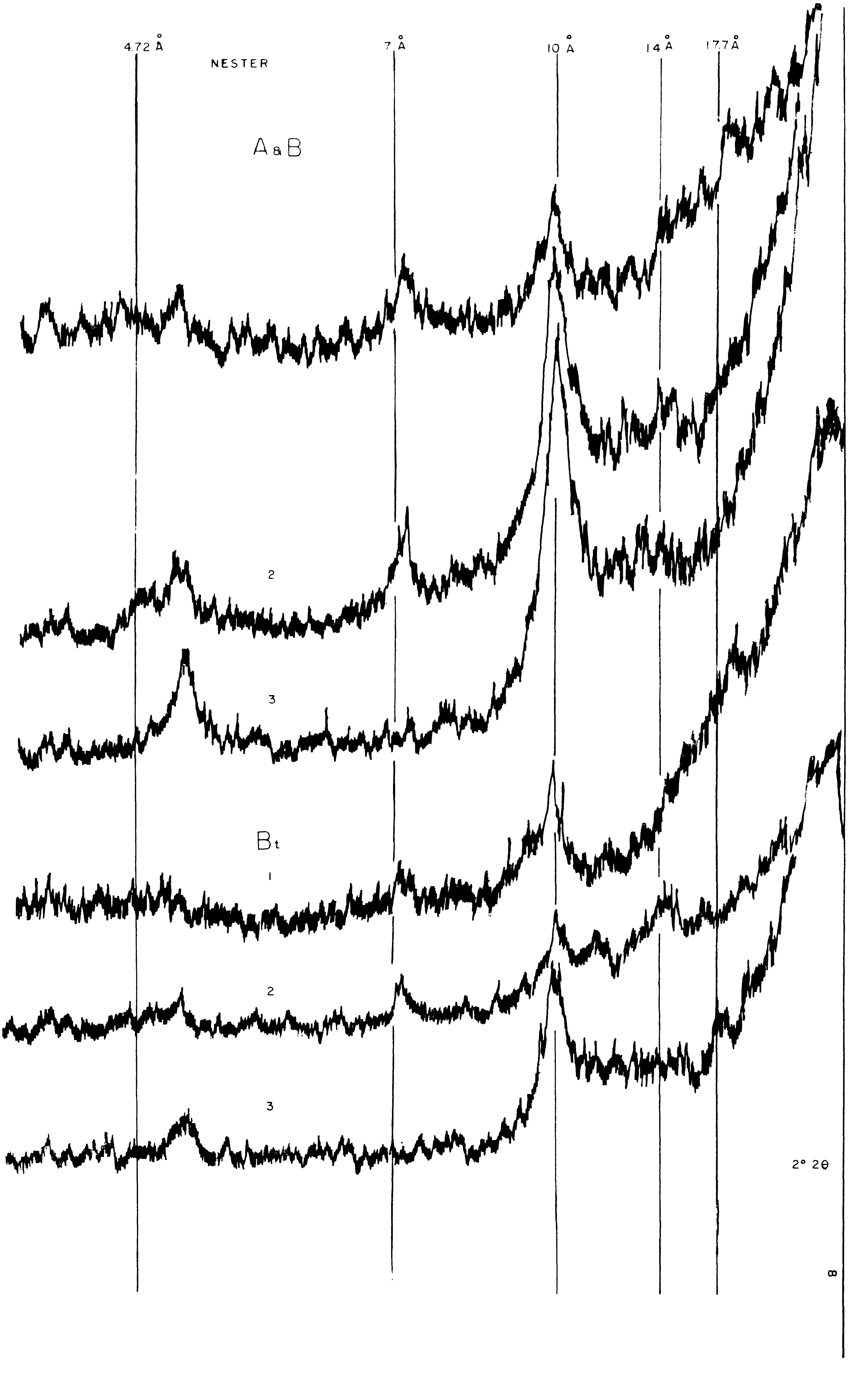
4.72Å ISABELLA
7Å
10Å
14Å
17.7Å
A2m
1
2
3
A3m
1
2
3
2° 2θ

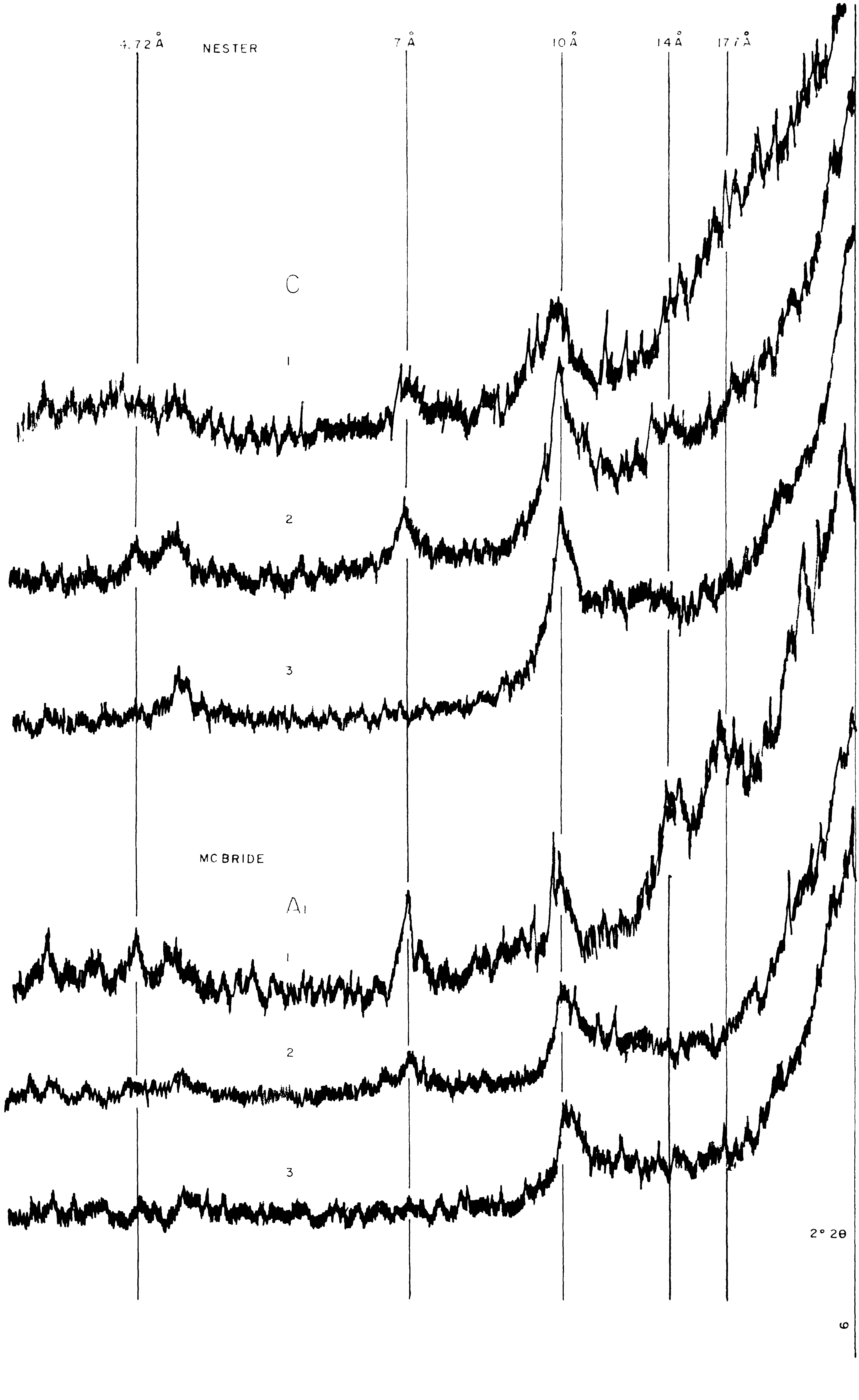


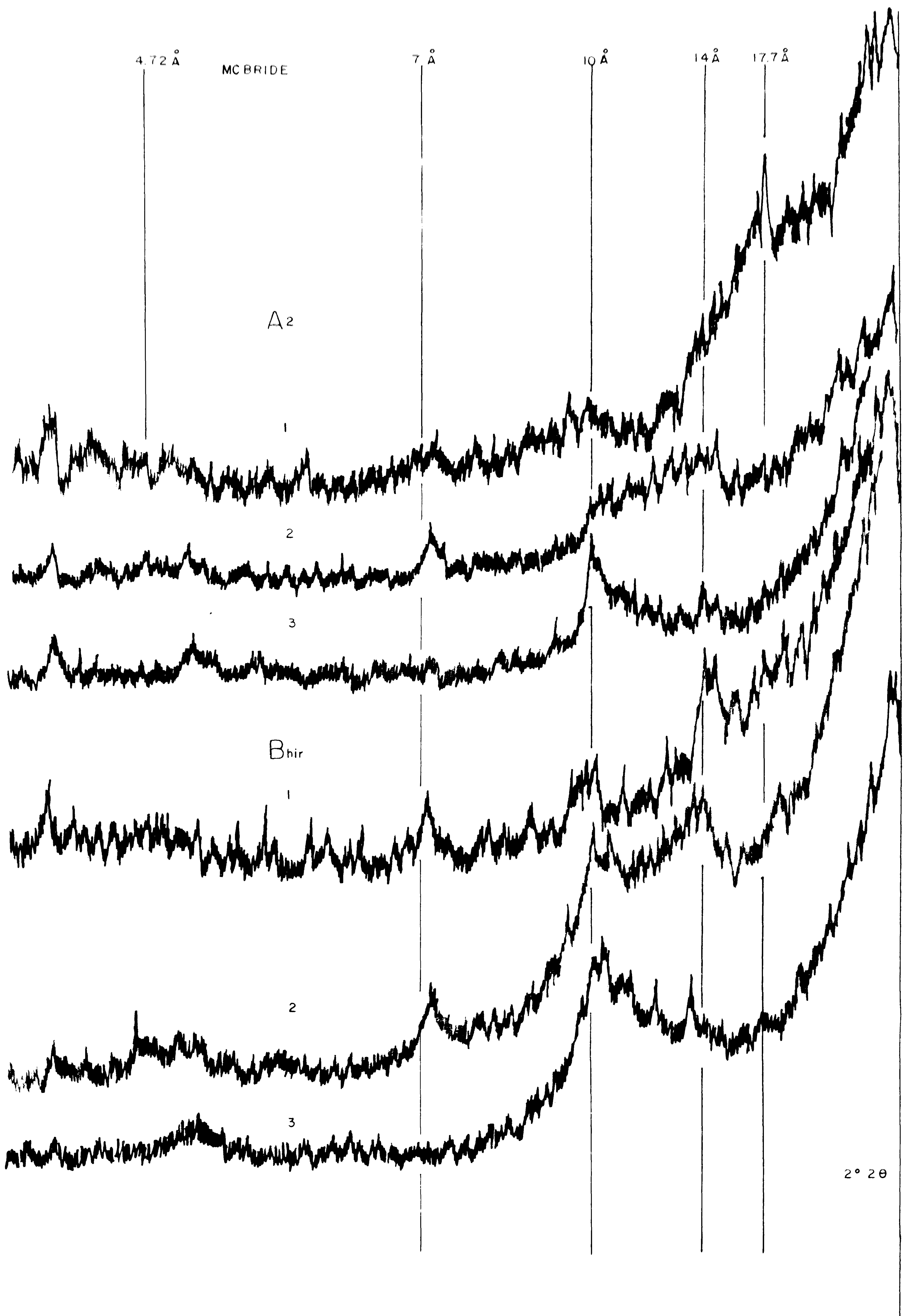
472Å
498Å
ISABELLA
7
10Å
14Å
A & B
1
2
3
Bt
1
2
3
2° 2θ
5


472Å
ISABELLA
7Å
10Å
14Å
177Å
C
1
2
3
NESTER
A_1
1
2
3
2θ

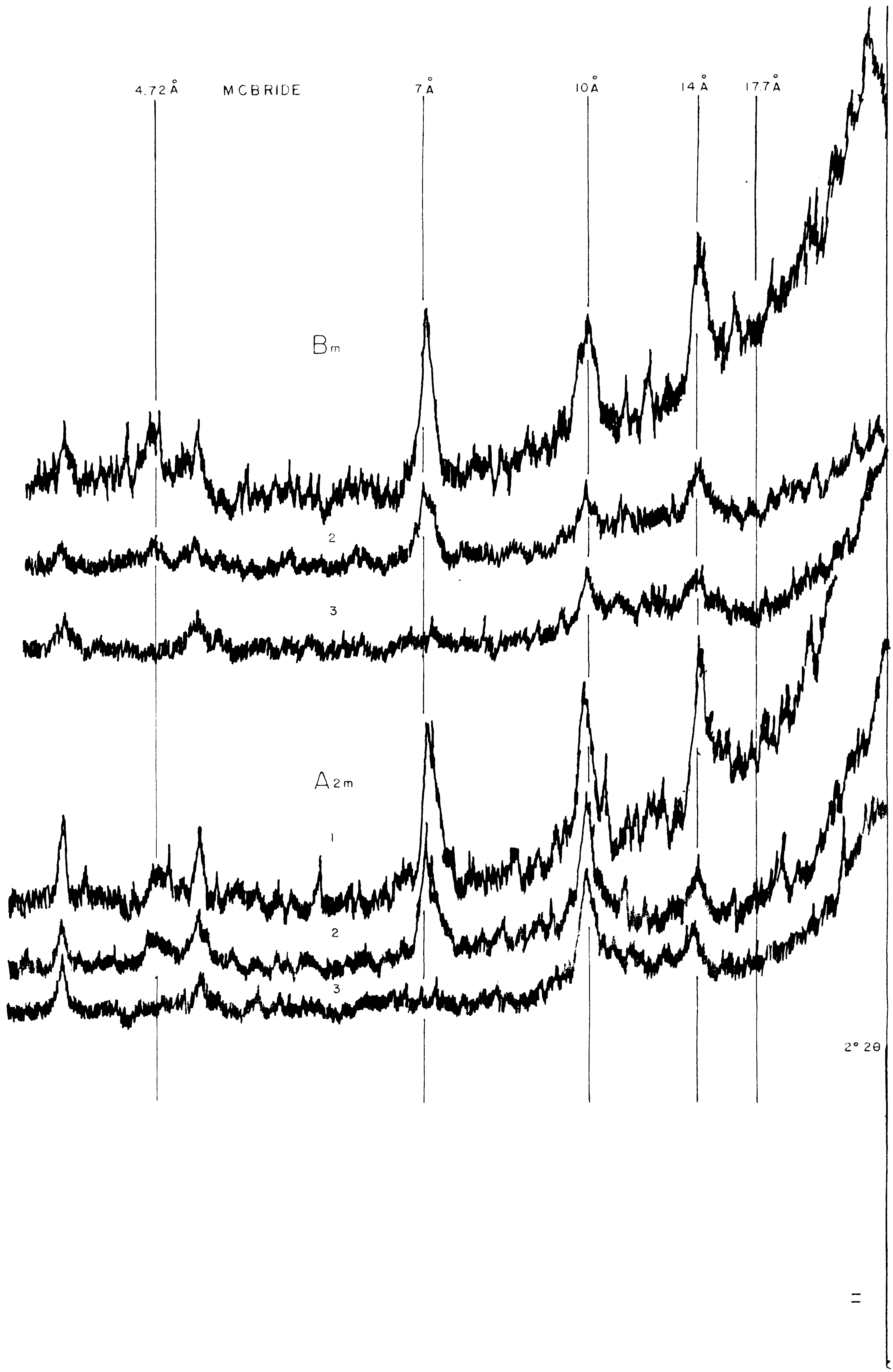

4.72 Å
NESTER
7 Å
10 Å
14 A
17.7 Å
A2 / Bhir
1
2
3
A2:n
1
2
3
2° 2θ
7

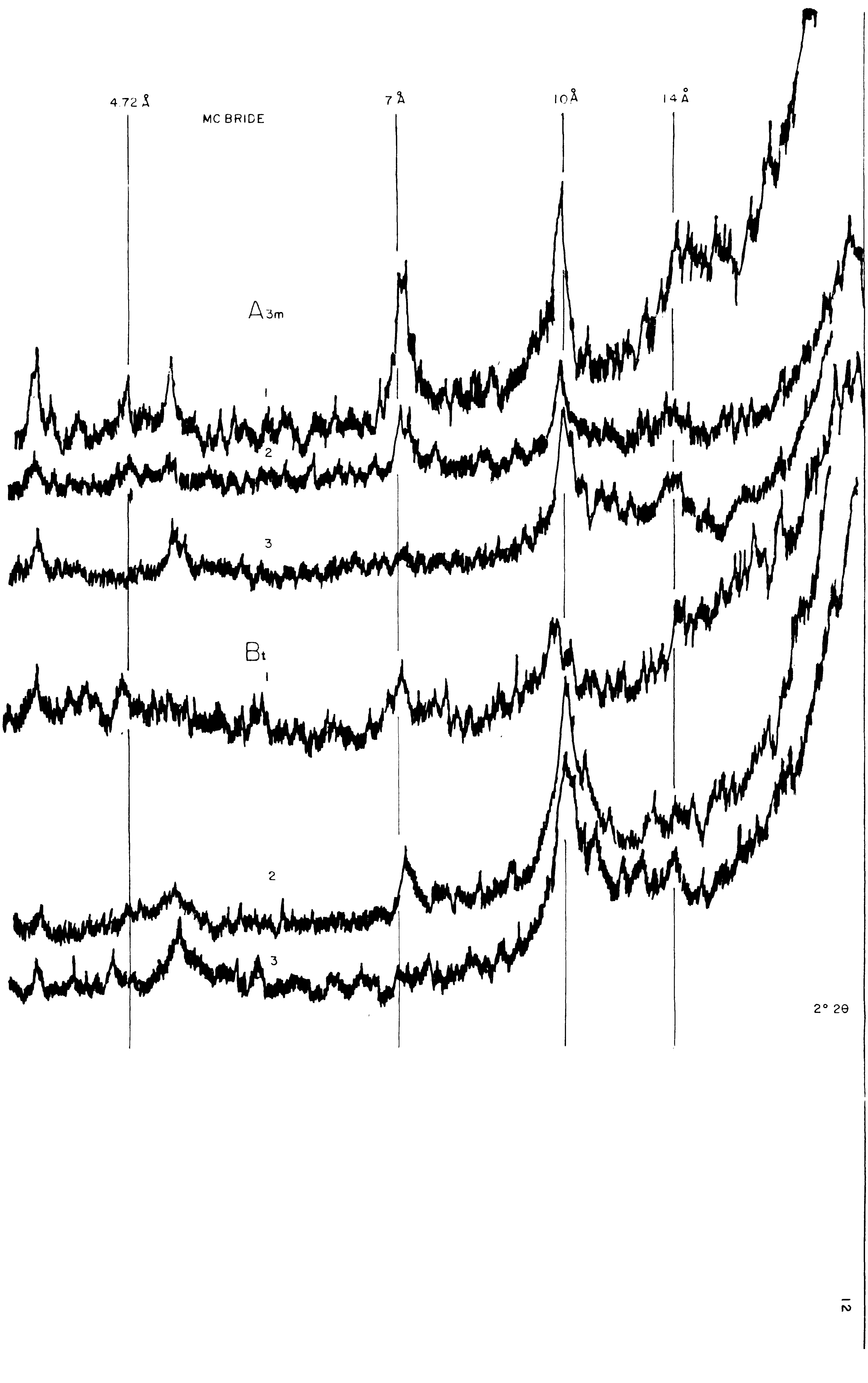

4.72 Å
NESTER
7 Å
10 Å
14 Å
17.7 Å
A & B
2
3
Bt
1
2
3
2° 2θ
8

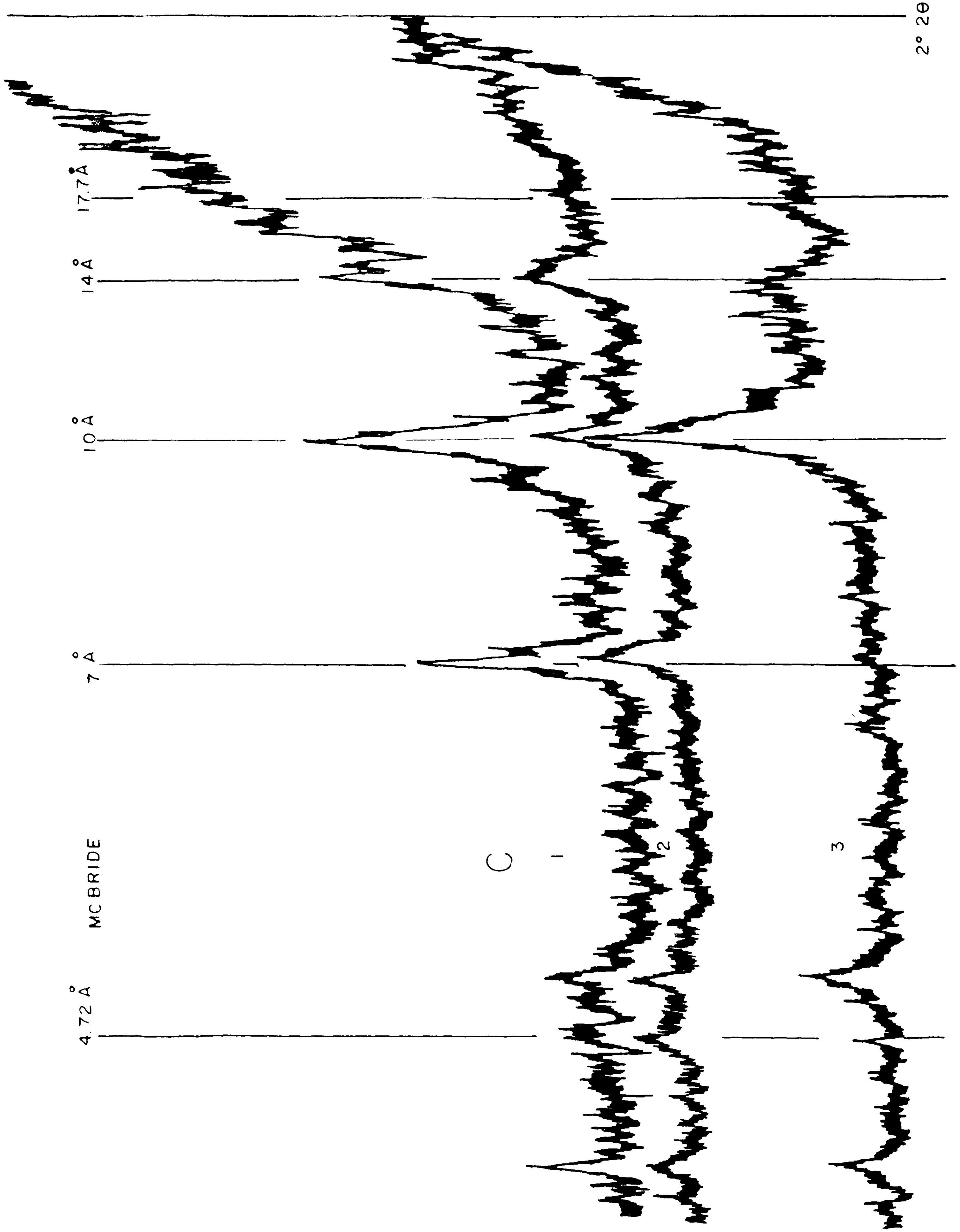

4.72 Å
NESTER
7 Å
10 Å
14 Å
17.7 Å
C
1
2
3
MC BRIDE
A1
1
2
3
2° 2θ
6

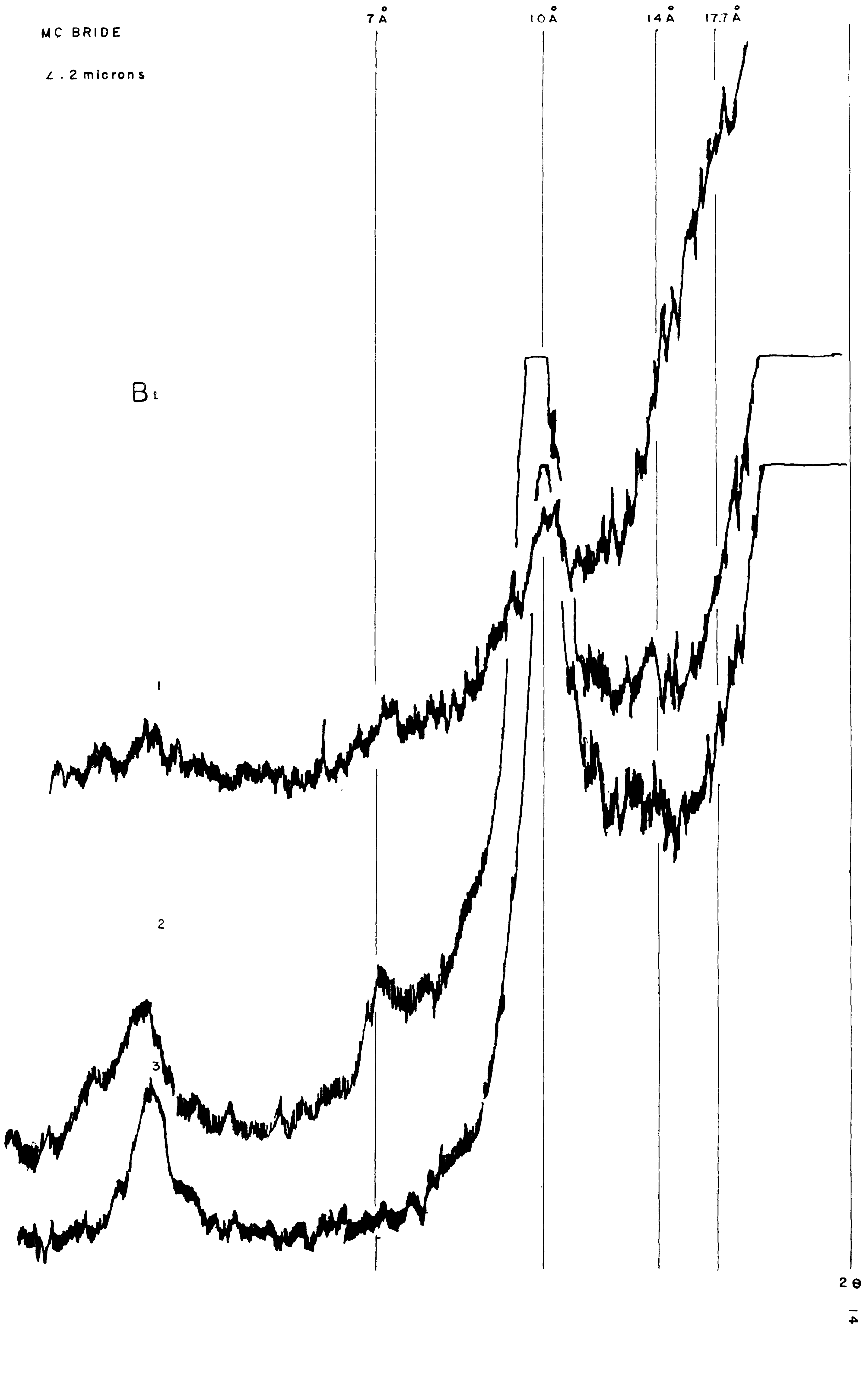


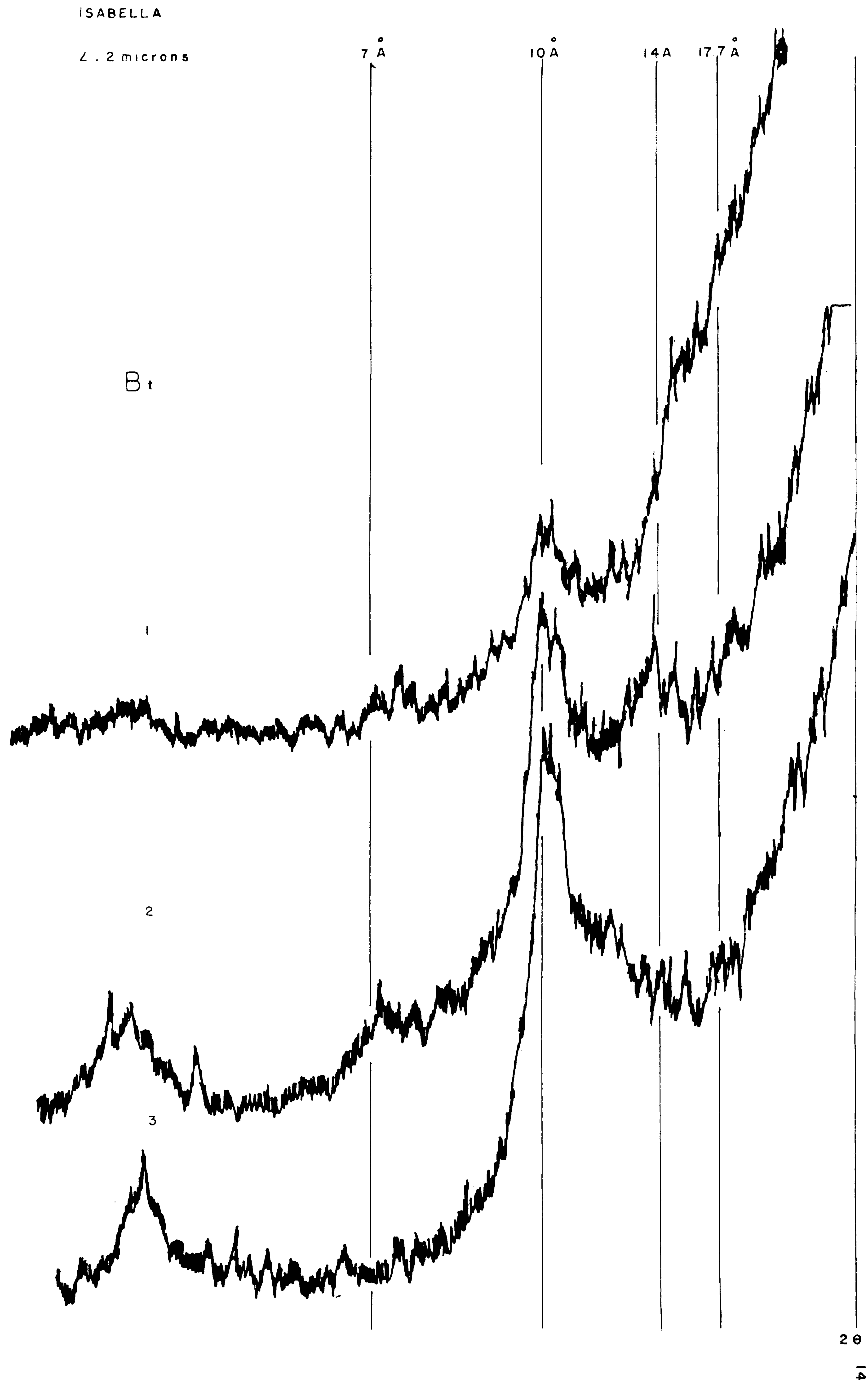
4.72 Å
MC BRIDE
7 Å
10 Å
14 Å
17.7 Å
A2
1
2
3
Bhir
1
2
3
2° 2θ
10


4.72 Å
MCBRIDE
7 Å
10 Å
14 Å
17.7 Å
Bm
2
3
A2m
1
2
3
2° 2θ
11


4.72 Å
MC BRIDE
7 Å
10 Å
14 Å
A3m
1
2
3
Bt
1
2
3
2° 2θ
12


2° 2θ
17.7 Å
14 Å
10 Å
7 Å
MC BRIDE
4.72 Å
C
1
2
3

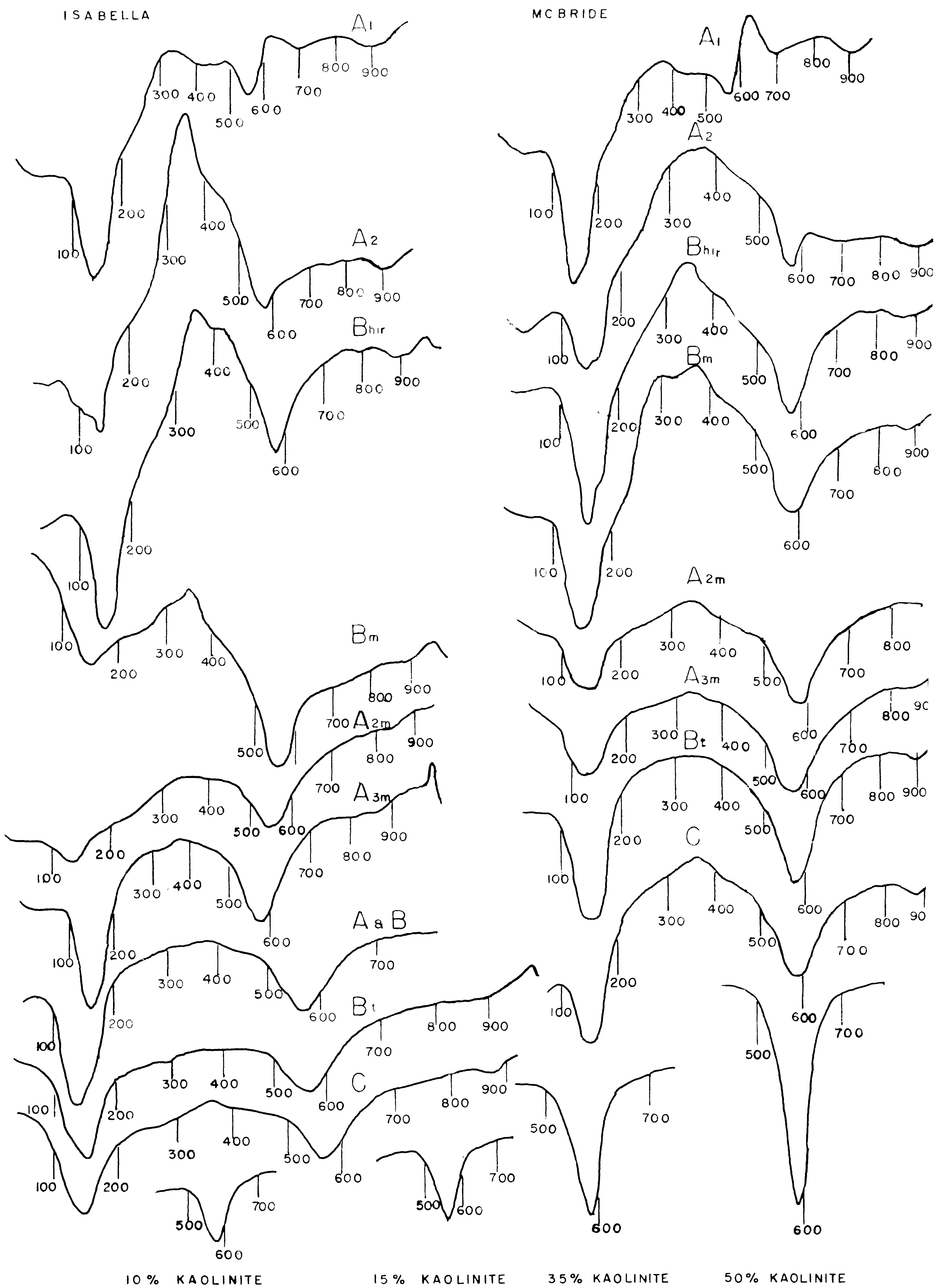

MC BRIDE
< .2 microns
Bt
7 Å
10 Å
14 Å
17.7 Å
1
2
3
2θ
14



ISABELLA
∠ . 2 microns
7 Å
10 Å
14 A
17.7 Å
B t
1
2
3
2 θ

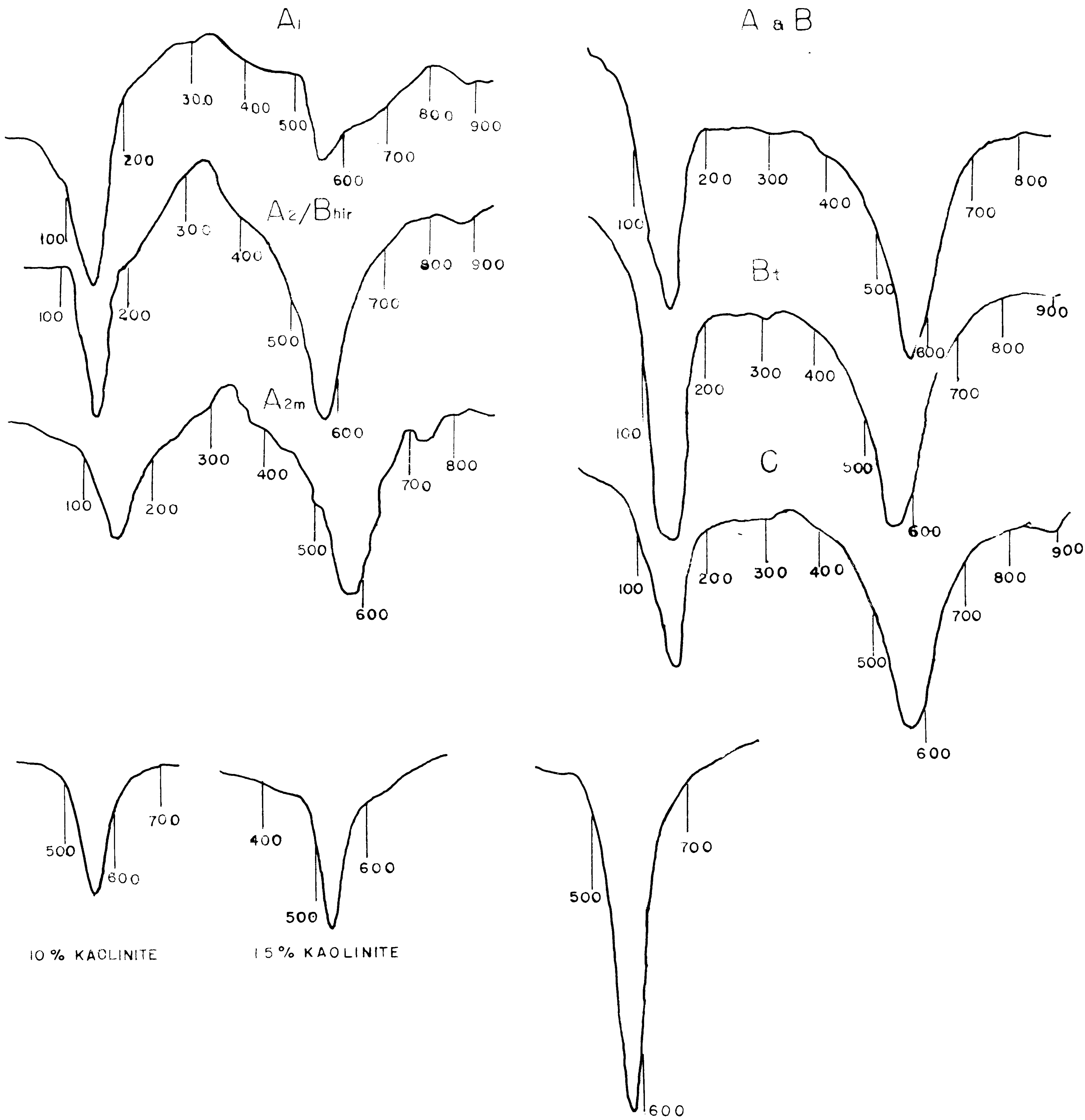
PATTERNS OF DIFFERENTIAL THERMAL ANALYSIS OF CLAY

The numbers correspond to degrees ^{o}C.



ISABELLA
MCBRIDE
A1
A2
Bhir
Bm
A2m
A3m
A & B
Bt
C
10% KAOLINITE
15% KAOLINITE
35% KAOLINITE
50% KAOLINITE

NESTER

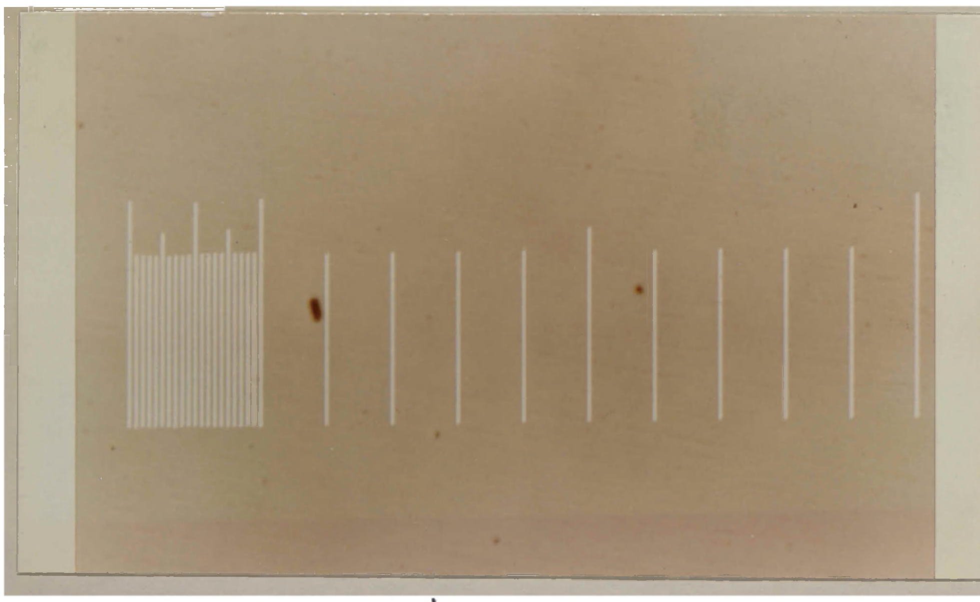


A1
A2/Bhir
A2m
A a B
Bt
C
10 % KAOLINITE
15 % KAOLINITE
35 % KAOLINITE

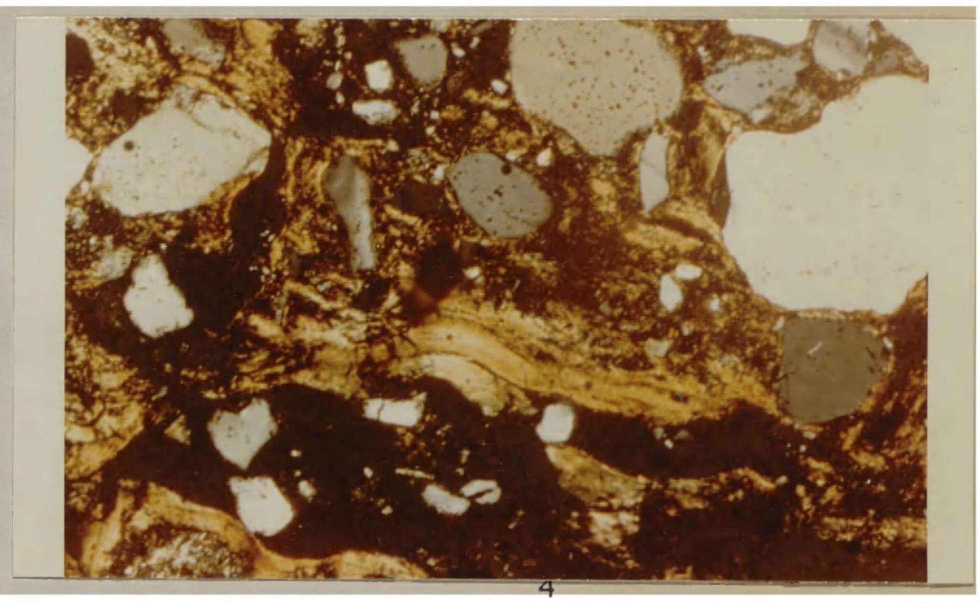
MICROPHOTOGRAPHS OF THIN SECTIONS OF UNDISTURBED SOIL

1.	Scale	Each small division corresponds to 10 microns.
2.	Bhir	horizon of the McBride profile
3.	A2m	" " " " "
4.	Bt	" " " " "
5.	C	" " " " "

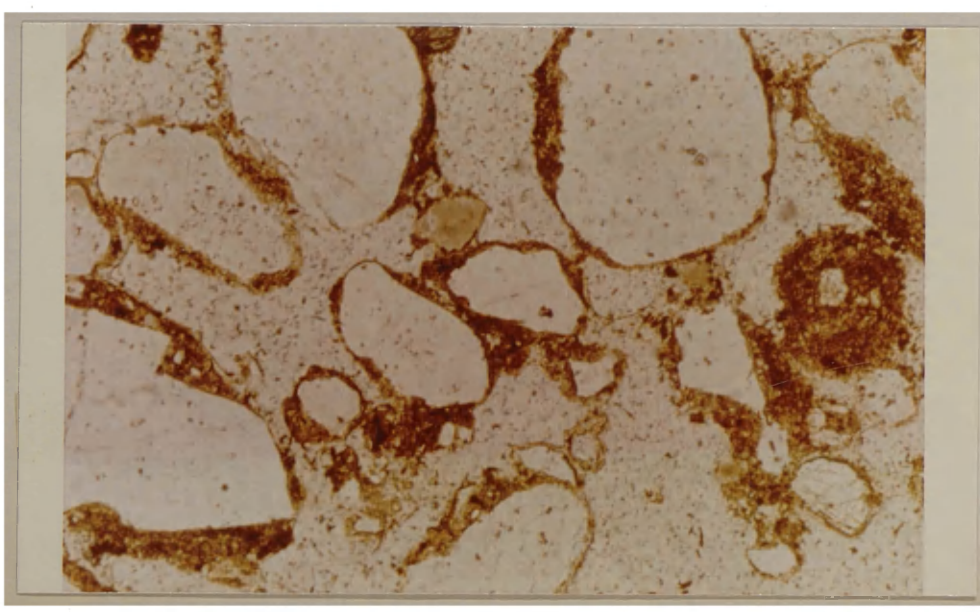
6. Detailed microstructure of the $A3_m$ horizon of the McBride profile. Menisci of clay form solid bridges connecting the sand grains.



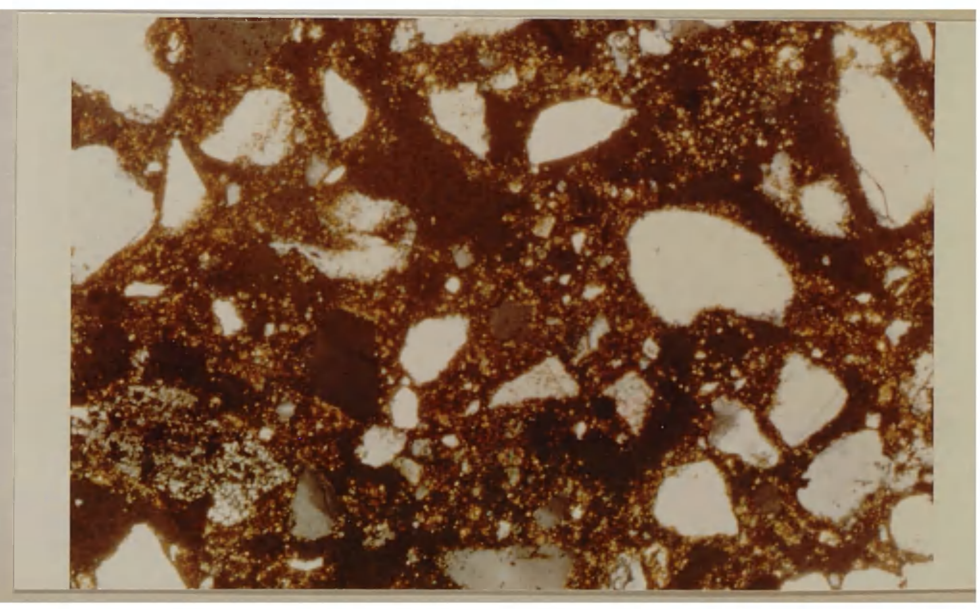
1



4



2



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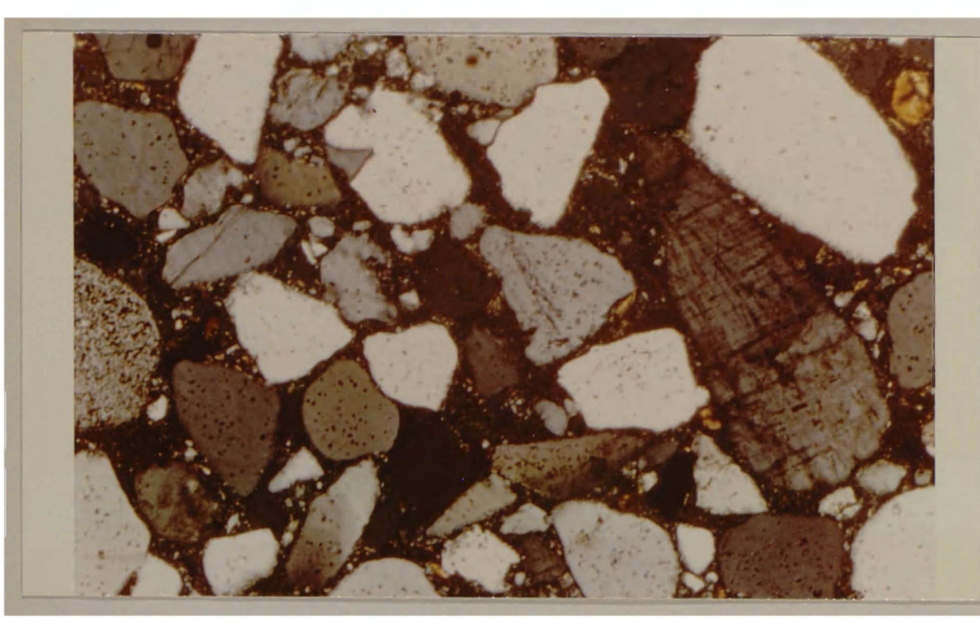
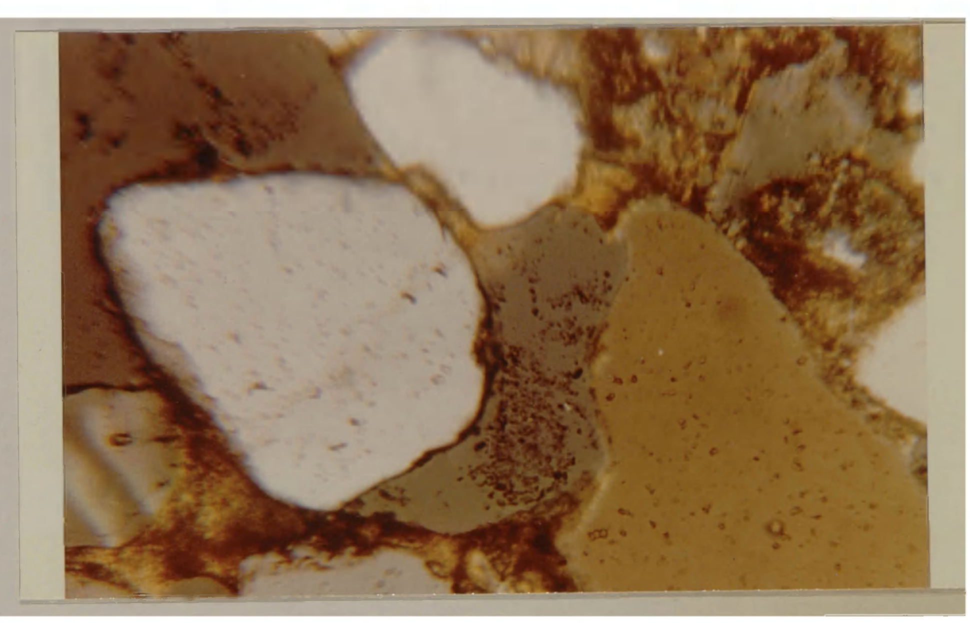


3



6

19