GUIDE TO FIELD TRIP OF FOURTH NATIONAL CLAY CONFERENCE: CLAY MINERALS IN SEDIMENTARY ROCKS[1]

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CLAY MINERALS IN SEDIMENTARY ROCKS

Clay minerals occur most commonly as constituents of sedimentary rocks and nearly all the clay mineral species, with the possible exception of nacrite, have been found in sediments. Different clay minerals occur in different kinds of sediments and may be used as one criterion for classifying sediments and interpreting their genesis.

Detrital sedimentary rocks have been classified by Krynine (1948) into four main groups, namely, arkoses, high- and low-rank graywackes, and quartzites. Clays occur in all four kinds. Generally in sandstones the clay minerals form the main constituents of the matrix material but much larger quantities occur in the clays, shales, and silts which in turn comprise the larger volume of sedimentary rocks. For example, about 60 percent of the detrital sediments are low-rank graywackes and some 60 percent of the average low-rank graywacke is silt and shale (clay); hence, on this basis alone, about 50 percent by volume of these sediments is composed of clay-size material and a very large proportion of this material belongs in the clay minerals group. To this must be added a large but so far unknown portion of the high-rank graywackes and arkoses; quartzites contain less fine material but clay minerals occur in small quantity. Finally in rocks that are not detrital, such as limestones, a variable and small proportion (insoluble residue) contains some clay minerals (Grim, Lamar and Bradley, 1937; Robbins and Keller, 1952).

The kaolin group is common and occurs often with bauxitic materials in arkosic sediments (Krynine, 1950; Griffiths, 1942). This association is taken to imply that the products represent the extremes of weathering under humid tropical conditions. Kaolin minerals also occur with illite in about fifty-fifty ratio in many low-rank graywackes (Grim, 1941; Allen, 1932; Frank, 1944). The kaolin in these sediments represents, at least in part, detrital material carried into the basin of deposition.

Small patches of kaolinite of about the same size as the detrital quartz grains occur in many quartzites and presumably represent in situ decomposition of feldspar fragments. Large deposits of kaolin clay together with fine-grained silica (chert) are common in central Pennsylvania and are associated with the Cambrian Gatesburg formation (mainly dolomite and quartzite) and Lower Devonian Oriskany formation (quartzite and siliceous shale). A representative example of each of these deposits was visited during the excursion (Stops 4 and 5).

Kaolin minerals such as halloysite and the "fire-clay" mineral are also com-

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mon in sediments; the former (halloysite sensu lato) occurs as large deposits of indianaite in southern Indiana where it is associated with the Mississippian-Pennsylvanian unconformity and is presumably indicative of residual weathering. Halloysite-type clays also occur in bulk in the regolith and particularly as weathered residual clays in the Appalachians of the Carolinas and Georgia (Sand, 1956). The fire-clay and ball-clay deposits of Pennsylvanian age in Pennsylvania generally contain kaolin as the dominant (and often only) clay mineral.

Occurrences of dickite are usually attributed to hydrothermal processes, perhaps associated with faulting in metamorphic rocks (Dick, 1908) and in sediments (Honess and Williams, 1935) but dickite is also a constituent of normal sediments (low-rank graywackes) in the Pennsylvanian shales of South Wales (Brammall and Leech, 1943). Perhaps dickite will be recognized as a normal sedimentary mineral when similar rocks are examined with greater care.

The illite family has been observed in arkoses, low-rank graywackes, and limestones (Grim, Lamar and Bradley, 1937; Robbins and Keller, 1952). It is perhaps most typical and most abundant in the low-rank graywackes. The illite in these rocks is detrital and there seems to be an illite cycle which is associated with low-rank graywacke and slates. Krynine (1945) has described low-rank graywackes as "autocannibalistic"—sediments that feed upon themselves. During geosynclinal sedimentation the low-rank graywacke is the common sediment and as the margins of the geosyncline are folded the low-rank graywacke is metamorphosed to low-rank metamorphic rocks such as shales, slates, and phyllites; these, in turn, are eroded to form more low-rank graywackes. Commencing with the illite in a slate which is robustly crystalline (Bates, 1947), when the rock is uplifted the illite is eroded, degraded to less well crystallized material with some loss of exchangeable bases and perhaps octahedrally coordinated ions, and deposited in alluvial or shallow-water marine muds and silts. Here it adsorbs potassium and commences to grow (aggrade) once more (Grim, Dietz, and Bradley, 1949) and as the sediment is consolidated diagenesis leads to rebuilding of the illite (Griffiths, 1952b). Graywacke rocks of this type were examined at Stop 2 of the field trip.

Illites of somewhat different type also occur in the K-bentonites or metabentonites which are believed to be volcanic ashes altered to "bentonite" and diagenetically aggraded to a potassium "illite" (Weaver, 1953a, and description Stop 1 of the excursion).

Much of the "illite" that occurs in sediments is of mixed-layer type and is not a "pure" clay mineral. Differences in composition, crystallinity, and ordering of the interlayers probably imply differences in genesis, particularly diagenesis, and, perhaps differences in environments of deposition. Very detailed and intensive investigations of the character of the clay minerals are necessary to elucidate these differences; analysis of bulk samples of many sedimentary rocks by single techniques, such as x-ray analysis, differential thermal analysis, etc., leads to insensitive diagnosis. On this level nearly all fine-grained minerals in sediments will be classed very broadly (probably as mostly "illite").

The third group of clay minerals, the montmorillonoids, are rare as constituents in the commoner sediments but bulk largely in sediments that contain volcanic detritus. Since the high-rank graywackes of the eugeosynclinal troughs are likely to be rich in volcanic debris, then montmorillonoids should be common in these rocks. Insofar as most arkoses also contain penecontemporaneous volcanic materials (basalts and diabases) montmorillonoids may also be expected in these rocks, usually locally concentrated, and generally subordinate in volume to the more characteristic kaolin-bauxite association (Griffiths, 1952a; Griffiths and others, 1954; Keller, 1953).

Many rarer types of clay minerals also occur in sediments and generally carry with them the implications of special origins. Brammallite, the soda-illite, is seemingly associated with shear faulting and low-grade degradational metamorphism of shales (Brammall and Leech, 1943). Roscoelite and vanadium-bearing "illites" commonly are associated with the uranium ores in sediments on the Colorado Plateau. The uranium and vanadium minerals carnotite and tyuyamunite are related to the montmorillonoids and are common in uranium-bearing sandstones (Weeks and Thompson, 1954).

Petrographic analysis of sediments necessitates careful diagnosis of the fine-grained mineral constituents, most of which are clay minerals. Petrogenesis of sediments, reconstruction of paleogeography and effects of diagenesis all require a detailed knowledge of the kinds and amounts of clay minerals. Determination of behavior of sediments both in laboratory testing and in field performance, as oil reservoirs (Griffiths, 1946, 1952) or as hosts to ores (Griffiths and others, 1954; Weeks, 1953) also demands an intimate knowledge of the clay mineral constituents. It is somewhat unfortunate that at present the diagnosis of these minerals is so complex; a simple standardized routine is perhaps too much to hope for, but some kind of sequential analysis which grows in complexity as a function of the difficulty of classifying the constituents, should be established. Furthermore, more attention to the clay minerals as constituents of sedimentary rocks would perhaps lend emphasis to the requirements of techniques for evaluating the complex mixtures that seem to be characteristic of sediments.

Certainly the volumetric importance of clay and silt size sediments cannot be denied; it appears regrettable that most petrographic investigations must ignore the larger proportion of the material because of limitations of technique.

LOG OF FIELD TRIP: CLAY MINERALS IN SEDIMENTARY ROCKS

Miles	
0.0	Leave Nittany Lion Inn (Parking Lot) at 8:00 a.m. Proceed east along Park Avenue; beyond the Campus are fine views of Nittany Valley. On the north side, Bald Eagle mountain forms the north limb of Nittany Valley anticline, and to the south Tussey Mountain forms the south limb. Straight ahead is Nittany Mountain, a small synclinal within the main anticline. Nearly all these ridges are formed of Tuscarora quartzite (Lower Silurian) and a lower secondary ridge is composed of the Bald Eagle or Oswego sandstone (Upper Ordovician). The main anticline is composed of limestones and dolomites of Middle through Upper Cambrian and Ordovician age.
2.2	Passing through roadcuts (on Pa. 545) of Ordovician limestone (Nittany dolomite and Axeman limestone). On the right is a restored iron furnace (Center Furnace), a relic of pre-Lake Superior iron industry of central Pennsylvania.
2.6	Leave Pa. 545 and traverse ascending succession of Ordovician formations (Bellefonte dolomite, Rodman limestone and Reedsville shale) to
4.3	Oak Hall Quarry. Stop 1 (see detailed description). Return along same route to junction of Park Avenue with U.S. 322 and proceed north on U.S. 322.
8.6	Nittany Lion Inn.

8.9 Stonehenge limestone with many layers of "edgewise conglomerates" probably formed by disturbance (slumping?) of wet sediment.

9.2 In a field east of road is a famous collecting locality for siliceous oolites of Cambrian age (Mines dolomite); it is now built over.

10.9 Sand pits in quartzite associated with Upper Cambrian Gatesburg dolomite. This quartzite underlies a wide area called the Barrens. There are some excellent podsol profiles of clean white sand attaining a thickness of 12-18 inches above the eluviated zone (Hagerstown soil profile, Jeffries and White, 1937).

The clay associated with these dolomites and quartzites is a residual (?) kaolin-type clay, and large pockets have been worked along the length of Nittany Valley. The dolomite and quartzite contain quartz and feldspar (largely potassic), and presumably weathered feldspar is the main source of the kaolin clay.

11.5 To the southwest is Scotia Pit which contained kaolin clay and limonitic iron ore (worked by Andrew Carnegie in the past century) with some manganese nodules. Many fragments of iron ore and occasional manganese nodules together with many irregular lumps of secondary silica are widespread over the surface throughout the Barrens.

12.1 Outcrop of Middle Cambrian Warrior limestone, the lowest stratigraphic unit exposed in the area. This limestone contains algal (Cryptozoa) reefs and shaly layers. The shaly layers contain biotite flakes and apatite crystals that are probably of penecontemporaneous volcanic origin.

12.3 Cross Birmingham fault in valley.

13.6-14.2 Reedsville shale (Martinsburg) on right (northeast) in roadcut.

Stop 2 (see detailed description) includes Reedsville, Oswego and Juniata graywackes; over the hill, beyond Skytop, the Tuscarora quartzite is exposed. Fine views of Bald Eagle Valley and the Allegheny Scarp may be seen from the towers at Skytop.

15.0 Return to buses and proceed southwest on U.S. 322.

16.4 Turn left along U.S. 220 at foot of mountain.

17.2-18.8 Roadcuts in Harrell shale at base of Upper Devonian. This is a typical low-rank graywacke composed of very finely bedded shaly sands and silty shales. The mineral composition is typical, namely quartz, very little feldspar and mica, some fine-grained rock fragments of shale, and much matrix. The matrix minerals are largely "illite" (sensu lato) and a little kaolinite.

20.0 Port Matilda; depending on time available the party may proceed right (north) along U.S. 322 to Stop 3 or, if late, will continue southwest along Bald Eagle Valley to Tyrone. The following 8 miles may therefore be omitted.

0.0 Port Matilda.

4.0 Roadcut (optional stop) northeast of U.S. 322 in Mississippian Pocono sediments; this is typical Pocono sandstone (low-rank graywacke) and shale, and the outcrop exposes a very common graywacke feature—disturbed texture. The sandstone bed has slumped and the shales have broken up; in this locality both sandstone and shale broke into fragments, in places forming a breccia or conglomerate by penecontemporaneous sliding. The unusual lensing of the massive sandstone also reflects penecontemporaneous movement while the sediment was wet (see description of Stop 3).

8.0 Port Matilda.

20.0 Port Matilda.

24.0 Burkett black shale (mineral composition unknown).

30.1 Highway overpass above tracks of Pennsylvania Railroad.

32.2 Enter Tyrone.

33.0 Turn right in Tyrone along U.S. 220.

39.9 Type locality of celestite in stream bank to south.

44.5 Commence by-pass around Altoona.

48.6 Turn left toward Hollidaysburg at second traffic light on U.S. 220.

51.4 Enter Hollidaysburg.

51.9 Turn left on U.S. 22.

52.4 Dave's Dream lunch stop. After lunch proceed northeast on U.S. 22.

54.1 Leave U.S. 22 turning right across railroad and stream bridge and left immediately after stream bridge.

54.5 Bear right at fork.

55.1	Many sandpits in friable Oriskany quartzite; the sand is quarried for refractory products.
59.3	Climb to top of Lock Mountain across Oswego-Juniata and Tuscarora formations.
61.0	Crossroads; proceed straight onto dirt road.
62.5	Road bears right at fork.
63.6	Oremenia; Stop 4. Woodbury Clay Pit. See detailed description.
64.7	Leaving Woodbury Clay Pit, proceed back along dirt road and turn right across railroad tracks.
64.8	Turn left on macadam road.
67.8	Intersection with Pa. 866; turn left.
70.2	Williamsburg; turn right following highway; proceed straight through town and take Yellow Springs road.
74.6	Yellow Springs; intersection with U.S. 22, turn right.
79.5	Water Street. Continue on U.S. 22.
83.0	Turn left off U.S. 22 along Frankstown branch of Juniata River.
83.6	Turn right up mountain on dirt road at first bridge across stream.
84.5	Stop 5. Alexandria Clay Pit. See detailed description.
84.5	Leave Alexandria Clay Pit and proceed along U.S. 22 to Water Street.
89.5	Water Street; turn right on Pa. 350.
94.3	Turn right onto Pa. 45 and proceed along Spruce Creek at foot of Tussey Mountain to State College.
114.5	Nittany Lion Inn.

STOP 1: OAK HALL QUARRY, LEMONT

Location

The exposures comprise two sets of quarries on both sides of the road from Lemont to Oak Hall, and approximately 1 mile northwest of Oak Hall. The quarries are operated by Neidigh Brothers and the product is used chiefly for roadstone. This information and the stratigraphy are condensed from Rones (1955, p. 271 ff).

Geology

The section commences in the northeast corner of the quarry on the east side of the road in the Salona limestone of the Trenton group (Fig. 1).

	Thickness (ft.)	
	Unit	Total
Trenton group		
Salona limestone; black, fine grained	5	5
"Bentonite" (0)	–	5
Nealmont limestone		
Rodman member; limestone, dark gray, coarse, crinoidal; with black chert	26	31
Centre Hall member; limestone, medium dark-gray, fine grained, fossiliferous, with clayey layers	41	72
"Bentonite" (N_2)	½	72½
Transition zone limestone, as above	17½	90
Hunter group		
Benner limestone		
Oak Hall member		
"Bentonite" (N_1)	–	90
Limestone, fine grained, dark gray	34	124
"Bentonite" (yellow clay) (A)	1	125
Stover member		
Limestone, fine grained, dark gray	7	132
"Bentonite"; prominent yellow clay	–	132
Limestone, dark gray, fine grained, fossiliferous cherty	30½	162½
"Bentonite," very prominent black ash (F) with 2-inch limestone layers	1½	164

Limestone, medium dark gray, with dolomite patches	54½	218½
Snyder limestone		
Upper bioclastic beds		
Limestone; medium dark gray, varying from fine (calcilutite) to coarse bioclastic (calcarenite), in part with limestone pebbles	10	228½
Mud-cracked beds; limestone, medium olive-gray; mud layers; silt-size quartz grains; cross-bedding, etc.	12	240½
Upper dolomitic beds; limestone with some dolomite, less impure than preceding beds	10	250½
"Bentonite" shaly parting	¼	250¾
Chemical lime beds; limestone, medium dark gray, fine grained, fossiliferous; weathering white	6½	257¼
Lower bioclastic beds; limestone, bedded, medium dark gray		
Lower dolomitic beds; limestone, dolomitic, fine grained, medium dark gray	5½	262¾
Oolite beds; limestone, medium dark gray fine-grained oolitic calcarenite with finer-grained layers (calcilutite)	8	270¾
Hatter limestone		
Hostler member; limestone, medium dark gray, dolomitic; with dolomitic, argillaceous and quartzose laminae; fossiliferous	19½	290¼
Grazier member; limestone, dark gray (calcilutite), silty and clayey	19½	309¾
Unconformity		
Loysburg group		
Clover limestone		
Limestone, medium dark gray, with loamy laminations and stylolites; weathering white	15	324¾
Concealed	40	364¾

The two prominent "bentonite" beds in the Nealmont limestone are typical examples of Ordovician K-bentonite or metabentonite clays.

The clay minerals consist of "randomly interstratified expanded and nonexpanded 2:1 layers in the ratio of 1:4. In addition, many of the samples contain packets of chlorite . . ." (Weaver, 1953a, p. 921).

Petrography of the Rocks

An understanding of the characteristics and genesis of the "bentonites" requires a knowledge of the mineralogy and petrography of the clay and adjacent limestones.

Bulk samples of the "bentonite" comprise quartz—actually fine-grained chert (about 5 percent)—and about 95 percent clay. Accessories include albite, glass shards, idiomorphic apatite, idiomorphic zircon, light pinkish-brown biotite, and leucoxene.

The adjacent rocks are limestones composed of fine-grained calcite crystals with some included clay. The amount of impurity increases toward the "bentonite" layers as shown by the increase in chemically determined silica (Fig. 1).

The insoluble portions of the limestone contain clay minerals, a nonexpanded dioctahedral 2:1 clay (illite) and a chlorite or expanded dioctahedral clay. The light minerals comprise silica as authigenic and detrital quartz and chert, and authigenic albite. Authigenic albite is less common towards the "bentonite" beds.

The albite (high-temperature type) in the "bentonite" layers is seemingly different from the authigenic albite (low-temperature type) in the limestones;

this presumably indicates a difference in origin; the former, detrital, and the latter grown in situ.

Accessory heavy minerals from the limestones are largely authigenic pyrite, with rarer biotite (similar to that in the "bentonite"), zircon, tourmaline, muscovite, chlorite, and rutile. The zircons are of two types, both detrital; the smaller rounded types are typical of most sediments whereas the larger idiomorphic

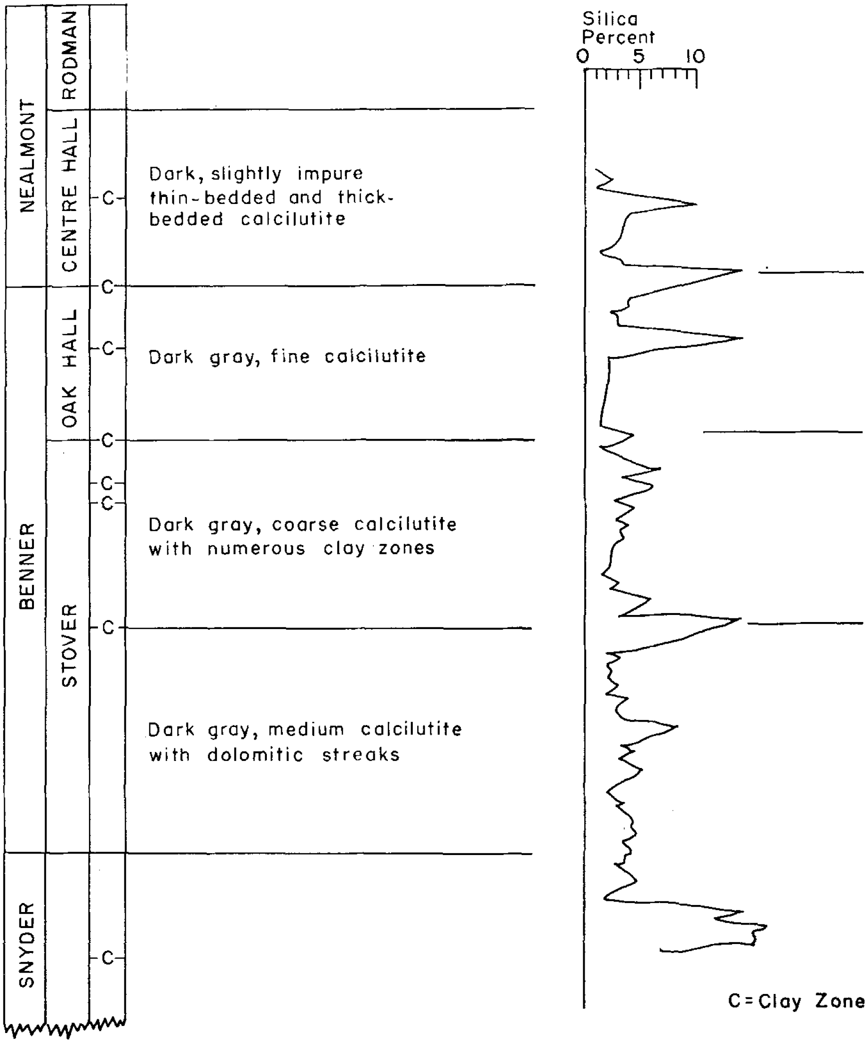

Figure 1. — Stratigraphic succession at Oak Hall Quarry, near Lemont, Pennsylvania (after Rones, 1955, p. 94, Fig. 16).

to hypidiomorphic crystals are presumably associated with the volcanic material in the "bentonites." Tourmaline is rare to absent in the "bentonites" but more common in the limestones.

Comparison of the "bentonite" minerals with those from limestones adjacent to the "bentonite" indicates that the volcanic material, while concentrated in the clay layers, also occurs in the nearby limestones. Apparently the clay layers represent the peak of volcanic outbursts, and volcanic activity covered a wide time interval before and after the peak (at least 21 feet of limestone deposition; see Weaver, 1953a, p. 939, and fig. 5, p. 942; and Folk, R. E., in Krynine and others, 1946).

The distribution of chlorite is also peculiar; chlorite is present in most limestone residues and increases towards the clay layers reaching a maximum frequency at the margins of the "bentonites"; it is rare to absent within the "bentonite" layers.

Petrogenesis

The genesis of these "bentonite" beds is, then, to be attributed to volcanic activity, possibly in the island arc that is presumed to have existed to the east and south during Ordovician time. Volcanism was evidently common and of relatively long duration, each bentonite representing a peak period of activity. The distribution of chlorite has been attributed to the availability of Mg from the sea water; the volcanic detritus where rare (i.e., in limestone away from "ash") decomposed to chlorite, and as the volcanic detritus increased in amount there is accompanying increase in amount of chlorite but when the volcanic outburst reached its peak the supply of decomposition product was so great that chlorite did not have time to develop and the circulation of Mg ion from sea water was restricted (Weaver, 1953a, p. 942-943).

STOP 2: SKYTOP

Location

The exposures are roadcuts along the northeast side of U.S. 322 for 0.4 mile east of Skytop and for about 1 mile on the southwest side of U.S. 322 west of Skytop.

Geology

The first section shows Reedsville shale, Oswego sandstone and Juniata redbeds in ascending succession. These rocks are low-rank graywackes and display a very wide range in texture from shale to medium-grained sandstone.

	Thickness[1] feet
Juniata shales, siltstones and sandstones, red with subordinate green	1025
Oswego sandstone with subordinate shales and clays; green to gray	330
Reedsville shale	440

The Reedsville shale comprises clayey, silty, and some very fine sand layers with occasional richly calcareous layers. The color ranges from dark gray to green and the beds are thinly laminated (varved?). This is typical low-rank graywacke lithology.

The Oswego sandstone is much coarser and ranges from blue gray to green in color when fresh (see Table 1 for composition). Weathering leads to break-

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[1] From Swartz (1955, p. S.I.2).

TABLE 1. — MINERAL COMPOSITION OF SANDSTONES ASSOCIATED WITH CLAY IN CENTRAL PENNSYLVANIA.

	Oswego[1] (percent)	Tuscarora[2] (percent)	Oriskany[3] (percent)
Quartz	28.2-57.1	76.0	77.7
Feldspar	0. - 2.6	—	
Chert and quartzite	16.2-25.0	2.5	1.4
Shale and schist	10.9-55.6	0.2	
Mica-chlorite	0. - 1.5	—	
Matrix	14.4-25.6	12.4	0.5
Carbonate	0. - 3.2	—	10.9
Silica	Present	8.9	9.5

[1] Determined by thin-section point count.
[2] J. A. Cochran, unpublished work.
[3] Rosenfeld, M. A., 1953.

down of pyrite so that the surficial coloring is red, yellow and brown. There are various kinds of efflorescence on the surface of these weathered rocks; the yellow incrustation is melanterite ($FeSO_4 \cdot 7H_2O$) which is dehydrated to siderotil ($FeSO_4 \cdot 5H_2O$?), the white efflorescence.

Many clay-pebble "conglomerates" occur, and at other localities quartz pebbles and pebbles of other rocks ("jaspers") are common, particularly towards the east.

A few layers, up to a foot thick, of an unctuous blue-gray clay are also interbedded with these sandstones. It is of interest to compare the clay minerals in these clays with those from the matrix of the sandstones.

The differences between the Oswego and Juniata formations are largely in color and grain size, the Juniata containing more redbeds and generally less coarse material. These differences almost certainly reflect differences in local environment; in particular the red and green muds (shales) presumably represent subaerial and subaqueous deposition, respectively. Analysis of bulk samples from red and green layers at Milesburg Gap yield no differences in composition. The differences between red and green fine-grained sediments have generally proved elusive and difficult to relate to any specific constituents; the solution to this problem would be of the greatest interest to the geologist concerned with reconstruction of the exact environment and local changes in environment. Much published work exists on this problem but attempts to define the difference with precision appear to be frustrating (Holmes, 1921, p. 461 and Fig. 66; Grim, 1951; Keller, 1953a; Weeks, 1953; Griffiths and others, 1954).

The Tuscarora of this locality is a quartzite (see Table 1 for mineral composition) with a strong binder of silica cement. A few layers of fine-grained material occur throughout the section. Some of these fine-grained layers are composed of silt-sized quartz grains; others are typical mudstones (shales) containing clay minerals. At other localities (e.g., Seven Mountains) the Tuscarora formation contains larger proportions of shale and less true quartzite, indicating that the Tuscarora is probably derived by winnowing of graywackes like the Juniata-Oswego.

Reedsville Shale

The x-ray pattern of the $<4\mu$ fraction of this material is shown in Figure 5, A. Strong diffraction effects representing 10.1 and 7.1 A spacings indicate that illite and kaolinite are the predominant clay minerals. A weak line at 18.6° 2θ suggests that a small amount of chlorite may contribute slightly to the intensity of the 7.1 A peak. There is no evidence of a 14 A chlorite peak. Lines due to quartz and feldspar are evident.

Figure 2A is a typical electron micrograph of the fraction described above. It is characterized by flakes which have sharp edges but irregular outlines. No

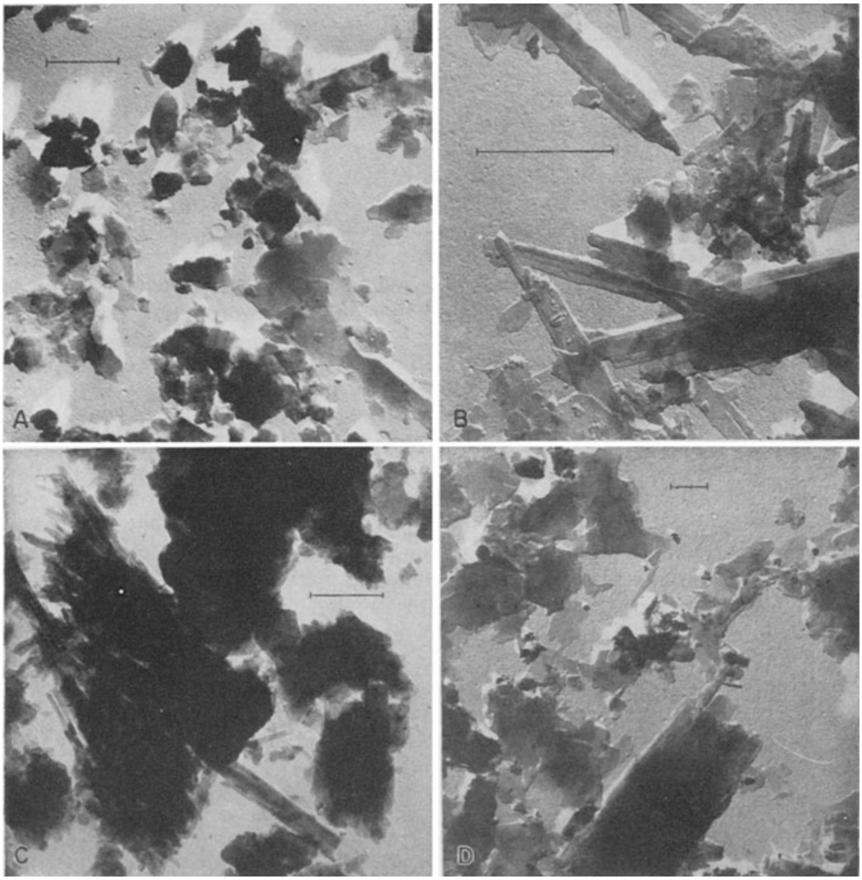

FIGURE 2. — Electron micrographs. A, $< 4\mu$ fraction of the Reedsville shale, "Skytop," State College, Pennsylvania. Uranium shadowed at 20°. 9,600 ×. B, $<4\mu$ fraction from sandstone member of Oswego formation, "Skytop." Uranium shadowed at 20°. 18,000 ×. C, Sample from clay lens of the Oswego formation, "Skytop." Platinum shadowed at 20°. 9,600 ×. D, Sample from clay lens in Tuscarora quartzite, "Skytop." Uranium shadowed at 20°. 4,800 ×.

well-defined hexagons are present here nor were any observed in other fields. In morphology the flakes resemble those of illite found in other shales in the region and in the Ordovician slates of the Lehigh-Northampton district of northeastern Pennsylvania. The micaceous minerals in the slates have been described by Bates (1947).

Oswego Graywacke

The x-ray and electron microscope data obtained from samples of the Oswego graywacke confirm the observations made by Weaver (1953) in his study of this material. The x-ray pattern shown in Figure 5, B, and the electron micrograph in Figure 2, B, were obtained from the $<4\mu$ fraction separated from a sandstone member of the formation. Similar data from a clay lens are presented in Figures 2, C, and 5, C.

The x-ray patterns contain lines of quartz and a 10.1 to 10.2 A clay mineral. The patterns are similar except for a slightly broader 10 A peak in the material from the clay lens. The electron micrographs show the lath-shaped particles, described by Weaver as a nonexpanded dioctahedral 2:1 clay mineral. Figure 2, B, shows both equant flakes and laths. The latter often have steplike features and resemble cleavage fragments from larger flakes. Similar features appear in Figure 2, C, except that here the arrangement of laths in the large "aggregate" is more irregular.

A differential thermal analysis of the clay fraction from the sandstone gives a surprisingly large endotherm at 110° C which cannot readily be explained by the x-ray and electron microscope data. A similar analysis of the clay-lens sample gives a typical illite pattern with a strong exotherm at 475° C, due presumably to the oxidation of FeS_2 or possibly carbonaceous material.

Tuscarora Quartzite

Clay is found in this formation in thin layers and pockets. X-ray patterns are presented in Figures 5, D, and 6, A and B, and electron micrographs in Figures 2, D, and 3, A and B.

Although illite is the predominant clay mineral, some samples contain a significant amount of kaolinite as indicated by the 7.1 A peaks in patterns A and B of Figure 6. Weak diffraction effects at 14 and 4.6 A (6 and 18.6° 2θ) in pattern A, Figure 6, suggest that chlorite is present in small amount. Differential thermal analysis gives typical illite curves.

The electron micrographs show some variation in the morphology of the clay particles. Figure 2, D, shows many equant flakes but laths are also evident. Of particular interest is the large particle near the bottom of the figure which seems to have incipient cleavage parallel to the long dimension. The resemblance to some of the lath-shaped particles from the Oswego graywacke is obvious. Figure 3, B, pictures the material that gives kaolinite as well as illite lines in the x-ray pattern. Although no sharply defined hexagons are present, many of the flakes have angles approximating 60 and 120 degrees.

Petrogenesis

The bulk of the clay minerals in these sediments is probably detrital illite; the clay minerals in the shales and in the matrix of the sandstones of the Oswego

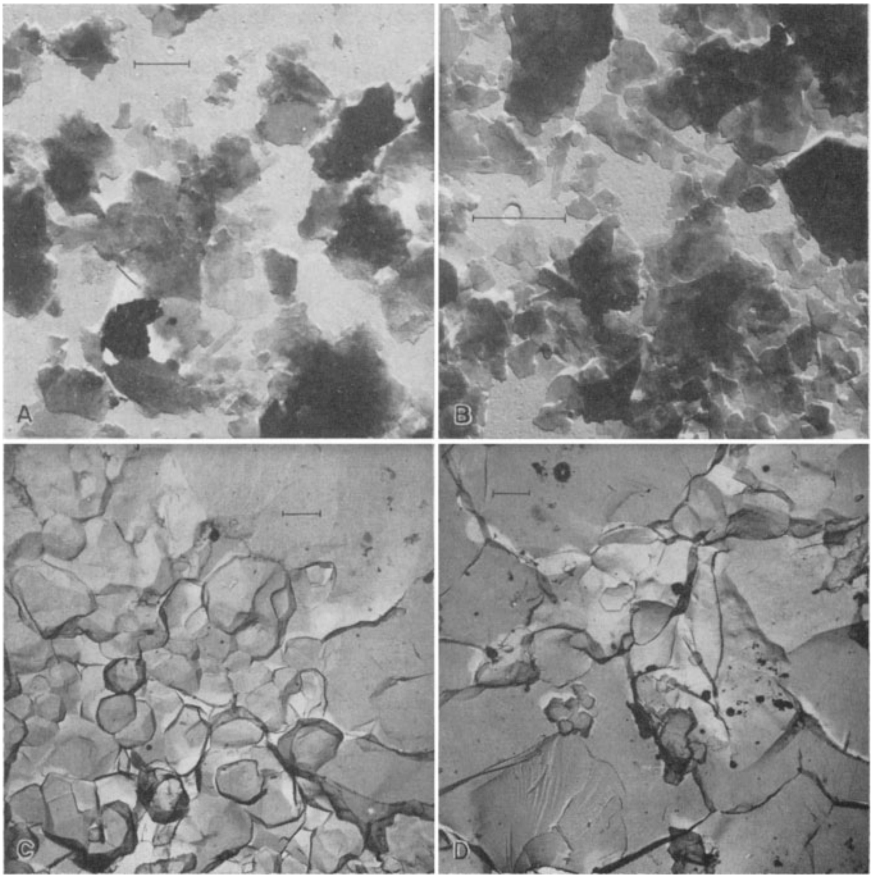

FIGURE 3. — Electron micrographs. A, Sample of dark-purple clay from lens in Tuscarora quartzite, "Skytop." Uranium shadowed at 20°. 7,200 ×. B, Sample of light-gray clay from same lens as above. Uranium shadowed at 20°. 12,200 ×. C, Preshadowed carbon replica of fracture surface of chert from Woodbury clay pit. 4,800 ×. D, Similar to C except for presence of kaolinite crystals projecting from the chert surface. 4,800 ×.

formation are the same and are similar to those in the Juniata redbeds. The Reedsville shale also contains detrital illite but the morphology of the Reedsville illite is different from that in the Oswego-Juniata. This difference in outward expression should be capable of translation into genetic implications but too little is yet known to permit one to interpret morphology with any confidence.

The fine-grained constituents of the Tuscarora quartzite are similar to those in the Juniata-Oswego sediments and this similarity, together with the high quartz content, suggests that the Tuscarora quartzite is derived from sediments similar to the Juniata-Oswego in petrography, by winnowing[1] out the major proportion of the nonquartz constituents.

STOP 3: POCONO, PORT MATILDA

Location

Route 322, 4 miles northwest of Port Matilda.

Geology

Roadcut on northeast side of highway exposing sandstone and shale of Mississippian Pocono sediments. These are low-rank graywacke rock-types (see Table 1 for composition).

Structural Attitude

The rather thick beds of sandstones and shales are disturbed with the sandstone sliding over the shale. This slump structure is contemporaneous and probably took place while the sediments were still wet. When wet unconsolidated sand is associated with wet mud and microseisms cause movement of the jellylike mass, the sand generally breaks into large angular lumps or blocks while the mud flows incoherently. In the present example the sand evidently contained enough matrix so that sand and clay behaved similarly and a very striking slump breccia is formed. It will be noted that the sand is quite coarse and apparently the grain size of the detritus is not the important factor but the amount of matrix clay minerals.

This kind of phenomenon needs careful investigation because the developed textures and structures reflect the conditions of deposition of the sediments, and local differences in behavior of different elements of the sand-clay complex (Boswell, 1949) imply differences in the local physico-chemical environment of the deposits.

Slumped sediments showing disturbed textures and structures are far more common than the published literature suggests. These features are found in graywackes, arkoses, and limestones. They are difficult to diagnose in quartzites because the textural contrasts of lenses and layers are obscure. Massive rocks often possess a disturbed texture but megascopic or field examination generally fails to diagnose such textures. Careful examination frequently reveals that the mica flakes are not oriented in parallel and this is the most obvious field criterion. Measurement of grain orientation in oriented thin sections is necessary in those sediments which show no obvious criteria during megascopic examination.

These slumps or disturbed textures have been mistaken for post-consolidation tectonic movement in the Pennsylvanian sediments (low-rank graywackes) of the Brookville area. In this region about a third of the volume of rocks exposed is disturbed (J. C. Ferm, personal communication).

The most recent interpretation of many of these disturbed textures refers to turbidity-current deposition but generally this infers movement over a con-

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[1] "Winnowing" as here used implies removal of materials by physical processes such as selective sorting and by chemical decomposition of unstable constituents.

siderable distance. Slumped sediments, on the other hand, are likely to be entirely local phenomena and movement for any distance is negligible.

This aspect of sedimentation is dependent upon the kind and amounts of clay minerals and physico-chemical conditions surrounding their deposition and diagenesis and requires familiarity with clay mineralogy and rheological behavior of clay-water mixtures. Much of the published work has been performed with little attention to mineralogy, petrography and textures of the sediments and practically no familiarity with the behavior of clay-water systems. It is interesting to note that some of the earliest observations on colloidal behavior and rheological systems were made by Freundlich (1934) on limestone-water suspensions.

STOP 4: WOODBURY CLAY PIT AT OREMENIA

This clay pit is worked by the Woodbury Clay Company and the product is used for refractory clay in the steel industry. The clay, a kaolin type, occurs as a large elliptical mass associated with Gatesburg quartzite and is representative of a large number of similar deposits that have been worked along the Nittany Valley. The color of the clay ranges from pure white through gray to brown. The deposit contains large numbers of chertlike siliceous nodules which vary in size from a foot or more to the finest silt sizes (62.5 to 3.9 microns). At Scotia and elsewhere concretions of hydrated iron oxide, sometimes in concentrations of economic value, are associated with this clay; manganese nodules also occur. In some clay pits, siliceous oolite rock fragments are associated with the clay.

Mineralogy of the Woodbury Clay

According to Ormsby (1951) the bulk of the clay is poorly crystallized kaolinite with very large quantities of fine-grained quartz.

The fine-grained quartz, perhaps largely chert, has been examined by the electron microscope replica technique (Bates and Comer, 1955) and the fracture surfaces of the chert are illustrated in the electron micrographs of Figure 3, C and D. Such surfaces are typical of cherts from diverse sources (Bates, 1949, Folk and Weaver, 1952). Figure 3, D, shows the relationship of well-defined hexagonal kaolinite crystals to the chert surface. It is hoped that more detailed investigations of these relationships will provide useful information on the origin of the Woodbury clay.

The morphology of the clay particles is also seen in Figure 4, A, and in replica in the paper by Bates and Comer (1955). Sharp, well-crystallized hexagons are typical of many of the kaolinite clays found in this part of Pennsylvania. The high content of fine-grained silica makes purification difficult (Kellogg, 1945).

Petrogenesis

No firm hypothesis which embraces all the observations exists at present, but it seems that this clay, with its high proportion of fine-grained cherty silica, is a residual deposit remaining after the weathering of limestone, dolomite, and quartzite of Cambrian age. The presence of chert in the limestone offers a readily available source for this constituent, and the quartzite and carbonate rocks contain feldspar which may have been the main source of the kaolin clay.

The haphazard distribution of large pockets of the clay throughout the rocks of Nittany Valley suggests that weathering of the carbonates led to collapse structures and sinkholes in which the clay accumulated. The absence of bedding in the clay and the contorted layering and irregular distribution of chert also tend to support this suggestion.

The geological age of the weathering is problematical and various periods from Cambrian to Tertiary have been suggested; tropical weathering associated with peneplanation of central Pennsylvania during Cretaceous time is the most probable (Griffiths, 1952a).

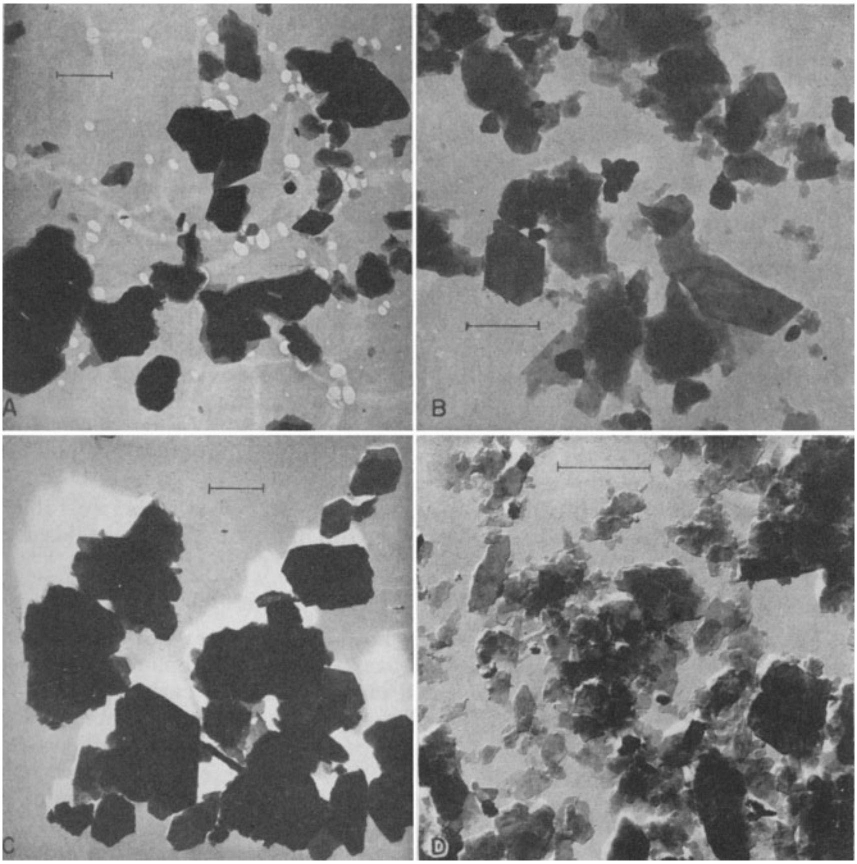

FIGURE 4. — Election micrographs. A, Kaolinite from Woodbury clay pit. 7,500 ×. B, $< 2\mu$ fraction of clay from Alexandria Fire-Clay pit. Platinum shadowed at 20°. 9,600 ×. C, $< 4\mu$ fraction from Oriskany quartzite at Alexandria Fire-Clay pit. Uranium shadowed at 20°. 7,200 ×. D, $< 4\mu$ fraction from shale member of Shriver chert formation at Alexandria Fire-Clay pit. Uranium shadowed at 20°. 12,200 ×.

STOP 5: ALEXANDRIA CLAY PIT; NORTH OF U.S. 22 NEAR ALEXANDRIA

The Alexandria Clay Company pit contains a kaolin-type clay which, in composition, resembles the clay in the Woodbury pit; it is also worked for its refractory properties.

The clay layer varies in thickness (averaging about 50 feet) and purity; it overlies a siliceous shale (the Shriver chert) and underlies the Ridgely quartzite. New workings indicate that the structure is synclinal and whereas the clay is lenslike, wedging out beyond the confines of the pit, it conforms crudely to the structure.

The bulk composition of the clay is again kaolin and fine-grained quartz in a ratio of 25 to 75 percent (Ormsby, 1951, p. 28).

Mineralogy of the Clay and Associated Sediments

A sample of the clay from the workings is pictured in the electron micrograph of Figure 4, B. In addition to the hexagonal crystals, thin irregular flakes and opaque round to irregular particles can be seen.

Clay concentrated in the $<4\mu$ fraction of the quartzite is also predominantly kaolinite. This is evident from the typical hexagonal crystals seen in the electron micrograph (Fig. 4, C) and the strong kaolinite peaks found in the x-ray pattern (Fig. 6, C). A weak diffraction effect at 10.1 A indicates the presence of illite.

The clay in the $<4\mu$ fraction of the siliceous shale is quite different although the x-ray pattern (Fig. 6, D) shows that appreciable kaolinite is present. The broad peak at 10.2 A indicates that illite is the major constituent, and weak effects at 14 and 4.6 A (6 and 18.5° 2θ) are evidence of a small amount of chlorite. As in all the patterns, quartz peaks are prominent.

The electron micrograph (Fig. 4, D) shows the typical irregular flakes characteristic of illite but also contains occasional crystals with poor to well-developed hexagonal outlines.

The Oriskany (Ridgely) quartzite is a typical pure quartz rock (see Table 1 for mineral composition) with very rare patches of kaolin clay after feldspar.

Petrogenesis

The source of the kaolin clay in this deposit is obscure; in the Gatesburg quartzite there is considerably more feldspar (10 percent and more in the finer-grained layers) and there are associated large volumes of carbonate rocks to contribute insoluble residue. In the Oriskany the amount of carbonate does not appear to be large at this locality and the Shriver chert is too siliceous to supply much alumina. If Ormsby's (1951) estimate of 75 percent quartz to 25 percent kaolin is representative, then perhaps the paucity of alumina is responsible for the low proportion of kaolin clay.

The most likely origin again seems to be residual weathering but here the weathering must have followed a layer of unusual composition between the quartzite and siliceous shale. The age of the weathering is presumably similar to that which gave rise to the clay in the Woodbury pit.

From an exploration and development point of view the most important question is how to predict the location and extent of these clay patches. If

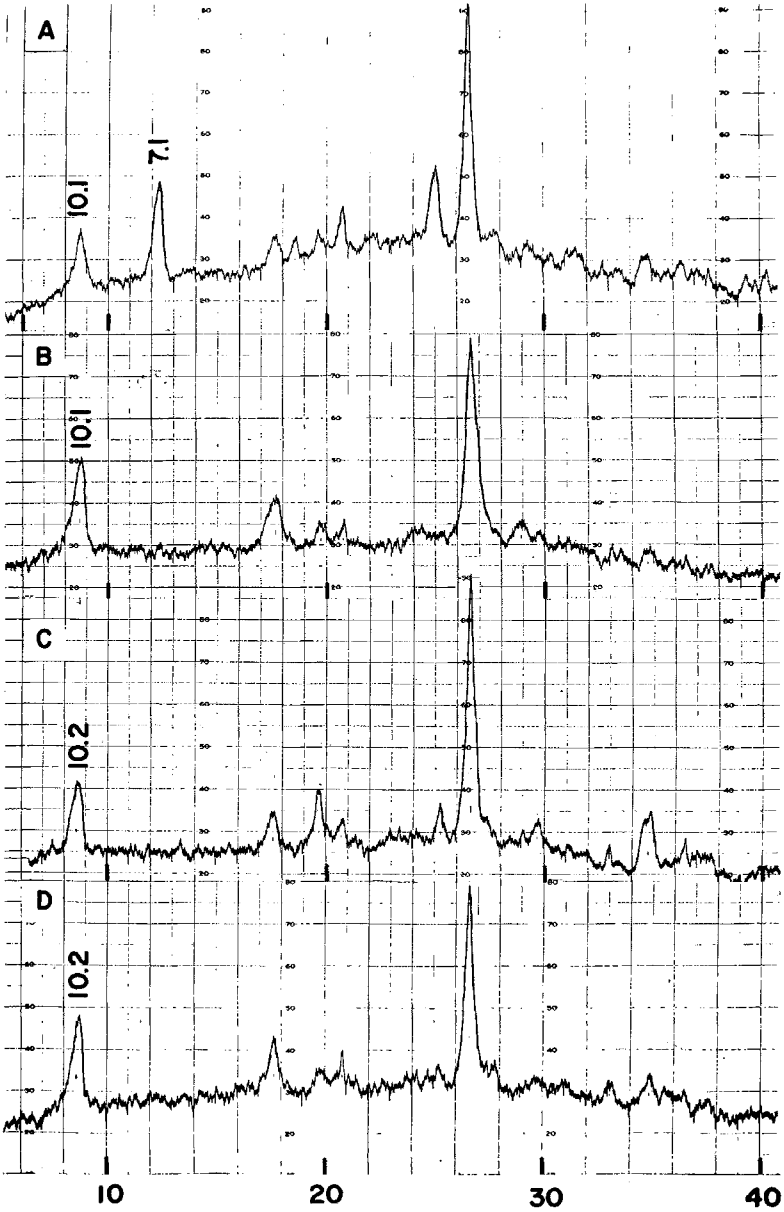

Figure 5.—X-ray diffraction patterns (Cu radiation; scale in degrees 2θ). A, $< 4\mu$ fraction from Reedsville shale, "Skytop," State College, Pennsylvania. B, $< 4\mu$ fraction from sandstone portion of Oswego graywacke, "Skytop." C, Gray clay layer of Oswego graywacke, "Skytop." D, Clay lens in Tuscarora quartzite, "Skytop."

FIGURE 6. — X-ray diffraction patterns (Cu radiation; scale in degrees 2θ). A, Dark-purple clay from lens in Tuscarora quartzite, "Skytop." B, Light-gray clay from same lens as in A, "Skytop." C, $< 4\mu$ fraction from Oriskany quartzite, Alexandria Fire-Clay pit. D, $< 4\mu$ fraction from shale member of Shriver chert, Alexandria Fire-Clay pit.

weathering of quartzite and limestones represents the correct origin of the deposits then there does not appear to be any very tangible criterion upon which to base predictions.

A solution to the problem of origin which includes the exact nature of the parent material would represent a most valuable contribution to the art of prediction.

A second and equally important aspect concerns the purification of the clay and removal of the silica. Kellogg (1945) and Ormsby (1951) have described attempts to use flotation for this purpose but the processes are hardly economic; here again both composition and texture are important properties in deciding the most promising procedure.

It seems likely from the brief examination of these few localities that answers to questions of scientific and industrial interest must await further and more detailed analysis of the fine-grained mineral constituents of sedimentary rocks. It cannot but be emphasized that analytical technique should be devised which will supply, as far as possible, unambiguous definitions of mineral species when the material is fine grained and of heterogeneous composition. These rather difficult obstacles will tax the ingenuity of experts in the field of fine-grained mineral research and it is from the clay mineralogists that we expect to obtain solutions to these complex problems.

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