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GLAUCONITE PELLETS: SIMILAR X-RAY PATTERNS FROM INDIVIDUAL PELLETS OF LOBATE AND VERMIFORM MORPHOLOGY*

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Abstract—Glauconite pellets of vermiform and lobate morphology occur together in Eocene geologic formations in Maryland. Morphologically, the vermiform pellets appear to be identical to those that have previously been called "altered biotite". In thin sections these pellets do show a well-defined micaceous morphology with the layers running across the worm-like pellets. Some zones in these pellets appear to be "crystals" that are up to $30 \times 70\ \mu$ and nearly rectangular in cross section. However, there are tiny cracks along cleavage planes within these "crystals". Externally, the lobate pellets have many rounded lobes and are similar to one of the shapes that Burst has called free-form. In thin section under crossed nicols these pellets have a grainy appearance, indicating that the lobate pellets are composed of many small zones, each about 5–20 μ across. Within these zones the mineral glauconite has a single orientation, but the zones are not lined up with each other to give the gross micaceous appearance that is associated with the vermiform pellets.

Random powder X-ray diffraction patterns (prepared with a large 114·59 mm Norelco powder camera) of individual vermiform and lobate pellets are nearly identical. Eight vermiform and 9 lobate pellets gave the same mean 001 (10·2 Å) and 060 (1·518 Å) spacings. The patterns from both kinds of pellets are similar, except for the absence of some weak lines, to Warshaw's (ASTM) pattern for glauconite. The patterns have lines indicating a 1 M polytype, however, *hkl* lines with $k \neq 3n$ are broad indicating some disorder. In addition to X-ray diffraction patterns, the K_2O content (6·7 per cent) and CEC (29 me/100 g as Ca replaced by Mg) of the pellets indicate that interstratified expanded layers may be the main source of the disorder.

If the vermiform pellets are altered mica, the alteration has been sufficient to give a product that is definitely identified as glauconite by X-ray methods. The possibility of mica alteration is suggested by the geographic nearness of the Piedmont (a mica source area) and the occurrence of Piedmont-type quartz with the glauconite pellets. Alternatively, the vermiform pellets may form during glauconite crystallization or recrystallization processes. The probability that both kinds of pellets obtained their morphology before or during, rather than after, the time they became glauconite (mineralogically) suggests that the proper environment may form glauconite from a variety of starting materials.

INTRODUCTION

GLAUCONITE pellets with a worm-like external morphology (e.g. Fig. 2A), here called vermiform, have been observed and variously named, described, and interpreted by many who have studied glauconite. Hadding (1932) observed pellets of this variety in limestone in Sweden and considered them to be large crystals, from which optical data for glauconite could be obtained. Galliher (1935) observed the vermiform type pellets in Monterey Bay, California and considered them to be altered or green biotite. Galliher considered this "altered biotite" to be *the* precursor of glauconite, which, by his view, formed upon further alteration of the green biotite in sea-water—the biotite originally having eroded from an igneous land mass. Burst (1958*a*), gave pictures of four pellet morphologies related to possible glauconite progenitors, among them the "weathered biotite" type of pellets. Light (1952) gave the name "tabular" to pellets occurring in New Jersey, which he described as "... grains that are somewhat elongate along an axis, have parallel grooves at right angles to the long axis, and are cleavable"—a good description of the morphology of the vermiform pellets of this study (Fig. 2A). Owens and Minard (1960) also observed what they called "accordion form" pellets in New Jersey deposits. Bentor and Kastner (1965) have mentioned the occurrence of glauconite in "single crystals", which they say may be mistaken as aggregates

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with unit extinction in polarized light. Triplehorn (1966) has given the name vermicular to pellets like those that are here called vermiform. He interpreted this morphology to result from the expansion and alteration of detrital mica.

The main purpose of this investigation was to compare the morphology and X-ray diffraction patterns of vermiform and lobate pellets, which were found occurring together in Maryland's greensands. The authors are not aware of any previous studies of X-ray diffraction patterns of pellets of a single morphological type. One reason for this lack of data is that many pellets are required to make a single specimen for analysis by the commonly used diffractometer method. In the present study, patterns were prepared with a powder camera. By this method such small specimens could be analyzed that patterns were made for individual pellets. These data, in addition to being useful in understanding the mineralogy of soils developed in greensands, need to be considered in developing theories on the origin of glauconite.

MATERIALS AND METHODS

A bulk sample of the main material used in this investigation was taken from the Nanjemoy Formation of lower Eocene age. This formation, where sampled, is exposed along the Patuxent River in Calvert County, Maryland (Fig. 1). In Maryland the Nanjemoy Formation is overlain by the Fairhaven diatomaceous earth member of the Calvert Formation of the lower Miocene age. Below the Nanjemoy Formation, separated by the Marlboro clays, lies the Aquia Formation of the basal Eocene. This complex dips gently to the southeast. The Nanjemoy, Aquia, and the still lower lying Monmouth Formation of Upper Cretaceous age are three glauconite-bearing formations found in Maryland.

Prior to the separation of the pellets, the bulk sample was treated to remove free iron oxides, using the sodium citrate-dithionite method as described by Kittrick and Hope (1963). Pellets selected for X-ray diffraction studies were of coarse sand size (0·5–1·0 mm dia., separated by sieving). The vermiform and lobate pellets were manually separated from quartz (the main other mineral in the greensands of this area) and from each other under a binocular microscope.

X-ray diffraction patterns (photographs) were prepared of individual pellets using a 114·59 mm powder camera. Pellets were crushed in an agate mortar, mounted in the camera in 0·2 mm glass capillary tubes, and exposed to CuKα radiation, generated at 42 kV and 21 mA, for 3 hr. After the films were developed and air dried, lines were measured on a standard film illuminator and measuring device. Patterns were prepared for 8 vermiform pellets and for 9 lobate pellets. Patterns were also prepared for pellets, unclassified as to morphological type, from the Aquia Formation in Maryland and from the Hornerstown Formation (of Paleocene age) from New Jersey. The Aquia pellets were taken from a profile of the Collington soil developed on this formation. For comparison of 060 spacings, patterns were also prepared for muscovite and biotite from Ward's Natural Science Establishment.

The K_2O content was determined by flame photometry after HF-$HClO_4$ decomposition (Jackson, 1958) and CEC was determined both as Ca replaced by Mg and K replaced by NH_4 (Alexiades and Jackson, 1966) on samples of the Nanjemoy Formation coarse sand glauconite pellets, unseparated by morphological type.

Thin sections, used to study and photograph the internal morphology of the pellets under a petrographic microscope, were kindly prepared by Mr. William Holton of the USDA Soil Conservation Service, Soil Survey Laboratory, Beltsville, Maryland. Initially the pellets were not separated by external morphology prior to sectioning and the two types were distinguished in thin section by their shape and what was considered to be their distinctive internal morphology. Later, to check the initial interpretations, thin sections of pellets that had been separated by external morphology were prepared and examined.

RESULTS AND DISCUSSION

Pellet morphology

The vermiform type pellets (Figs. 2A and 3A), which have been given other names by previous authors, were discussed in the introduction. The thin-section picture (Fig. 3A) shows the well-defined micaceous internal morphology of a vermiform pellet, with the layers running across the pellet. Note that the external segmented appearance of vermiform pellets (Fig. 2A) apparently results from openings (or failures to close) along micaceous cleavage planes, which are transverse to the long axes of these pellets. This interpretation is supported by evidence from the thin section of the purified vermiform pellets. These pellets were sliced along their long axes and almost all of them displayed an internal morphology resembling that of the pellet shown in Fig. 3A. Also Dr. S. W. Bailey has attempted to make single crystal X-ray patterns from segments of the vermiform pellets. His results show that the pellets are very poor single crystals, but that the morphological cleavage is (001). However, many crystallites within the segments deviated from planarity by up to 30°.

Some zones within the vermiform pellet shown in Fig. 3A appear to be "crystals", that are nearly

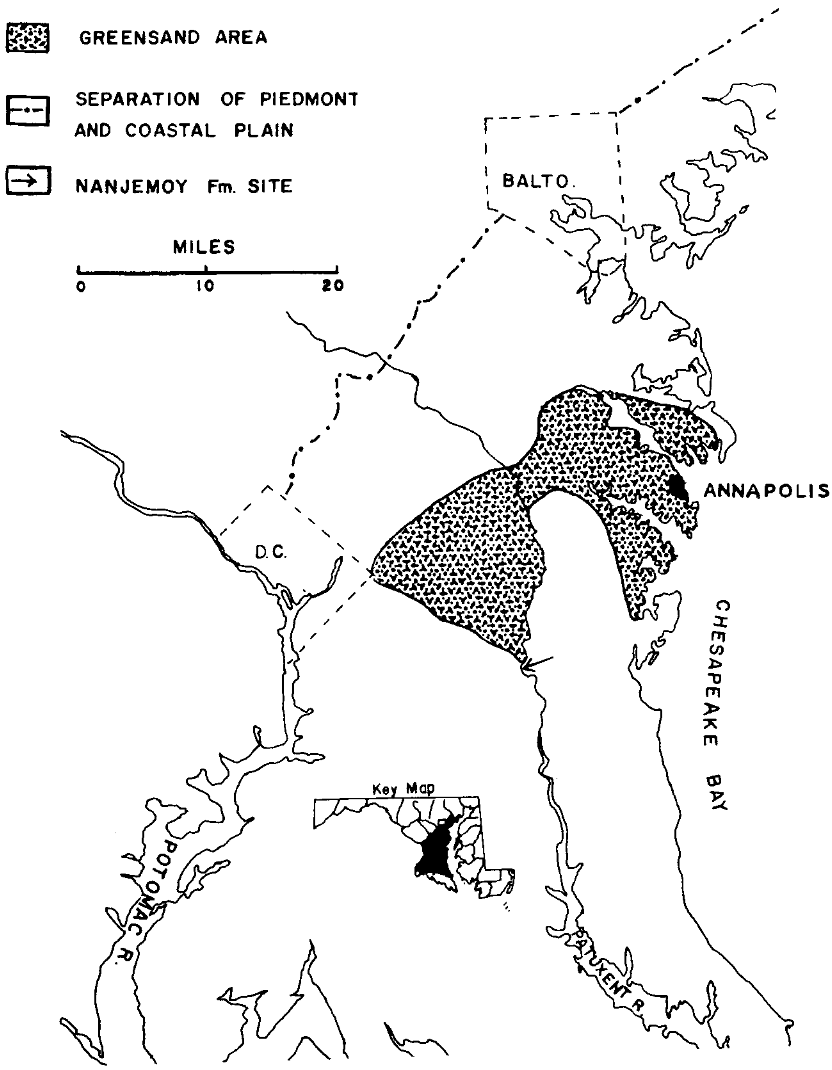

Fig. 1. Map showing the area of Maryland where most of the soils are developed in greensands relative to the boundary between the Piedmont and Coastal Plain. In this study, vermiform and lobate pellets from the Nanjemoy Formation site were compared. Key map shows the area represented on a state map of Maryland.

rectangular in outline. One of these is about $30 \times 70\,\mu$ in cross section. However, even by microscope examination (Fig. 3A), there appear to be microzones and openings along cleavage planes within such "crystals".

The external morphology of the lobate pellets is shown in Fig. 2B. These rounded, somewhat botryoidal, shapes resemble one of the shapes that Burst (1958*a*) has called "free-form". In describing apparently similar pellets occurring in New Jersey deposits, Owens and Minard (1960) have spoken of "rounded or subrounded grains with smooth to grooved surfaces (botryoidal)" and Light (1952) also used the term lobate.

The internal morphology of the lobate pellets also differs from that of the vermiform. In thin section the lobate pellets have an overall "grainy" or "patchy" appearance under crossed nicols (Fig. 3B). This appearance indicates that the lobate pellets are made up of many small zones, perhaps like the microzones described within the "crystals" of the vermiform pellets. However, these small

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zones, often 5–20 or more microns across, are not lined up to give any rectangular "crystals" or to give the overall layered appearance that is associated with the vermiform pellets. However, in parts of occasional lobate pellets a tendency for lining up into larger zones is observed. It is interesting that the 5–20 μ size of the small zones is similar to the size of glauconite crystals encountered by Warshaw (1957), and her size determination apparently was based on X-ray diffraction data.

In the Maryland greensand deposits examined, the vermiform pellets are much less abundant and are usually of smaller size than the lobate. The smaller size of the vermiform pellets may be related to cleavage, by which some coarse sand vermiform pellets may have undergone size reduction and passed into finer size fractions. Some pellets showing such cleavage were observed in the coarse sand. Also many fractured pellets, apparently of both types of morphology, have been observed in finer sand fractions. Vermiform type pellets also appear to be less abundant than the lobate in New Jersey deposits; however, Owens and Minard (1960) observed large concentrations of "accordion forms" in the Merchantville and Marshalltown Formations and in the Red Bank sand, all of which are of Upper Cretaceous age.

X-ray diffraction patterns

The vermiform and lobate pellets gave very similar X-ray diffraction patterns (Table 1). An example pattern, from a vermiform pellet, is shown in Fig. 4. Glauconite lines were obtained from all pellets examined, and only glauconite lines were obtained from most pellets (Table 1 and Fig. 4). Impurities of an amphibole, quartz, and a feldspar (probably labradorite) were found in one vermiform pellet and lines at 4·06 and 2·93 Å were found with two lobate pellets. The latter lines, although they had d spacings close to those of glauconite, were too strong and sharp for nearby glauconite lines at 4·12 and 2·89 Å in the ASTM pattern (Table 1). However, the mineral from which they came could not be identified.

The mean *d* values of given glauconite lines from the vermiform and lobate pellets were identical or nearly so (Table 1). None of the differences in mean values for given lines for the two pellet types were significant at the 0·05 level by statistical *t* tests. Also the intensities from given lines were also similar for the vermiform and lobate pellets (Table 1). The stronger lines (001, 020, 003-022, 130-13$\bar{1}$-200, 13$\bar{2}$-201, and the 060-33$\bar{1}$). appeared in all the patterns from both kinds of pellets (Table 1). However, there was a tendency for some weak lines (111, 11$\bar{2}$, 040-22$\bar{1}$, 13$\bar{3}$-202, 31$\bar{1}$-24$\bar{1}$, 330, and 260-400) to occur more frequently in patterns from lobate pellets, whereas other weak lines (11$\bar{3}$, 005, 22$\bar{4}$, and 170-350-420) occurred more frequently in patterns from vermiform pellets (Table 1). Two of the patterns from vermiform pellets were of poor quality, perhaps because of the small amount of powder available. Only the above listed stronger lines were found in these patterns. Spots along some lines in some patterns, from both kinds of pellets, indicated that some large "crystals" were sometimes present after crushing.

Patterns from the Nanjemoy formation pellets resembled the ASTM pattern for glauconite both in *d* values and intensities of various lines (Table 1). Patterns from the Nanjemoy pellets differed from the ASTM pattern in that some of the very weak lines of the ASTM pattern, namely the 002, 021, 023, and 220-041 (all of which had intensities of 10 or less out of a possible 100), were absent in every pattern from the Nanjemoy pellets (Table 1). Other weak lines of the ASTM pattern were absent in some of the pellet patterns.

The *d* values of given lines for the Nanjemoy pellets were consistently slightly larger than the value for the corresponding line with the ASTM pattern (Table 1). This may indicate slightly larger unit cell dimensions with the Nanjemoy formation pellets. This could possibly be related to a high iron content with the Nanjemoy pellets as discussed later in connection with the 060 spacings. Another possibility is that, since the spacings for the ASTM pattern were determined with a diffractometer, the ASTM spacings may have been shifted to slightly lower values (higher 2θ values) by the diffractometer time constant, or possibly a slight, but constant, inaccuracy may have been involved in the camera or in the measurement of the film (possibly film shrinkage) in this study.

Patterns from the other coarse sand pellets examined, from the Aquia Formation and from the Hornerstown Formation in New Jersey, were very similar to those from vermiform and lobate pellets from the Nanjemoy Formation. This result implies geographic and formation to formation uniformity in the mineralogy of glauconite pellets in the Northern Atlantic Coastal Plain, in addition to the uniformity across pellets of different morphology in the same deposit.

According to Tyler and Bailey (1961), the mineral glauconite is essentially the iron-rich analogue of 1M muscovite. Warshaw's (ASTM) pattern for glauconite (Table 1) is indexed on a 1M cell. The presence or absence of the 11$\bar{2}$ (3·63 Å) and 112 (3·09 Å) peaks in random powder patterns has been used in distinguishing between the 1 M and the 1 Md polytypes in glauconite studies. On this basis Burst (1958*b*) and Bentor and Kastner

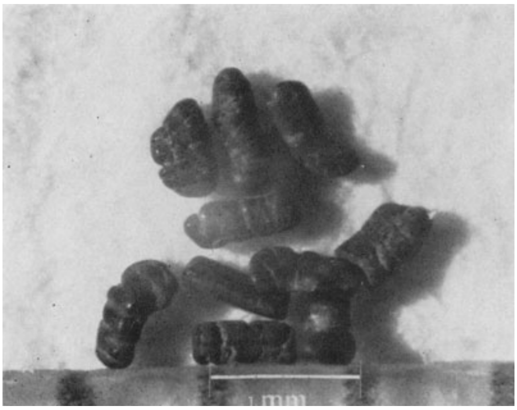

Fig. 2A. Vermiform pellets; note the elongated and segmented shape. X-ray diffraction and thin section studies (see Fig. 3A) indicate that the segments are books of glauconite layers. The pellet at the far right has a longitudinal line dividing a more solid, perhaps more recently crystallized portion, from a rougher, perhaps older portion (epitaxial crystal growth?).

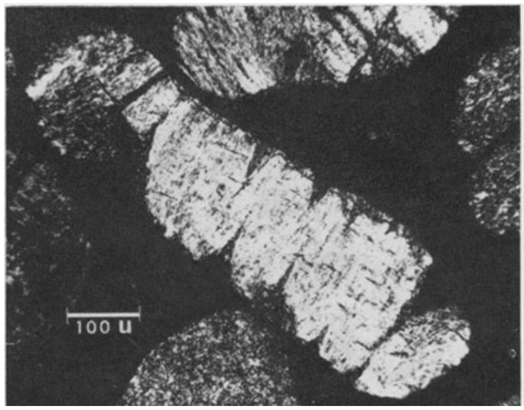

Fig. 3A. Longitudinal section of vermiform pellet showing glauconite layers running across the pellet Thin-section viewed with crossed nicols). Note the appearance of a rectangular "crystal" outline within the pellet just above the center of the photograph. A portion of another pellet with a gross micaceous internal morphology is at the top.

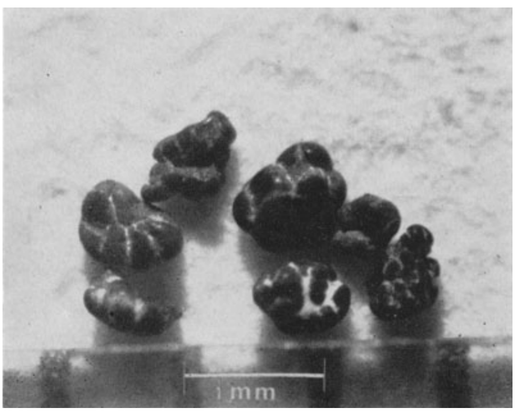

Fig. 2B. Lobate pellets exhibiting their typical rounded botnyoidal shape. Lobate pellets in the Maryland deposits are more numerous and generally larger than the vermiform and also have a different internal morphology (Fig. 3B).

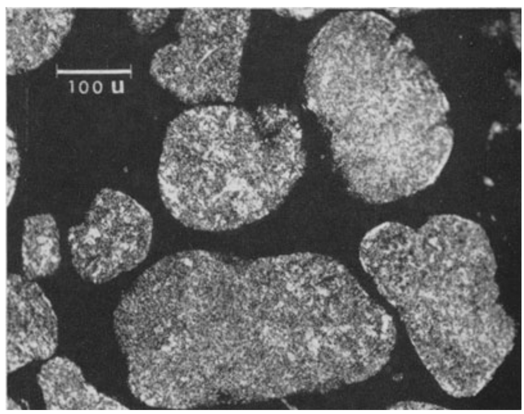

Fig. 3B. Thin section, as viewed under crossed nicols, showing the "grainy" internal morphology that appears to be characteristic of the lobate pellets.

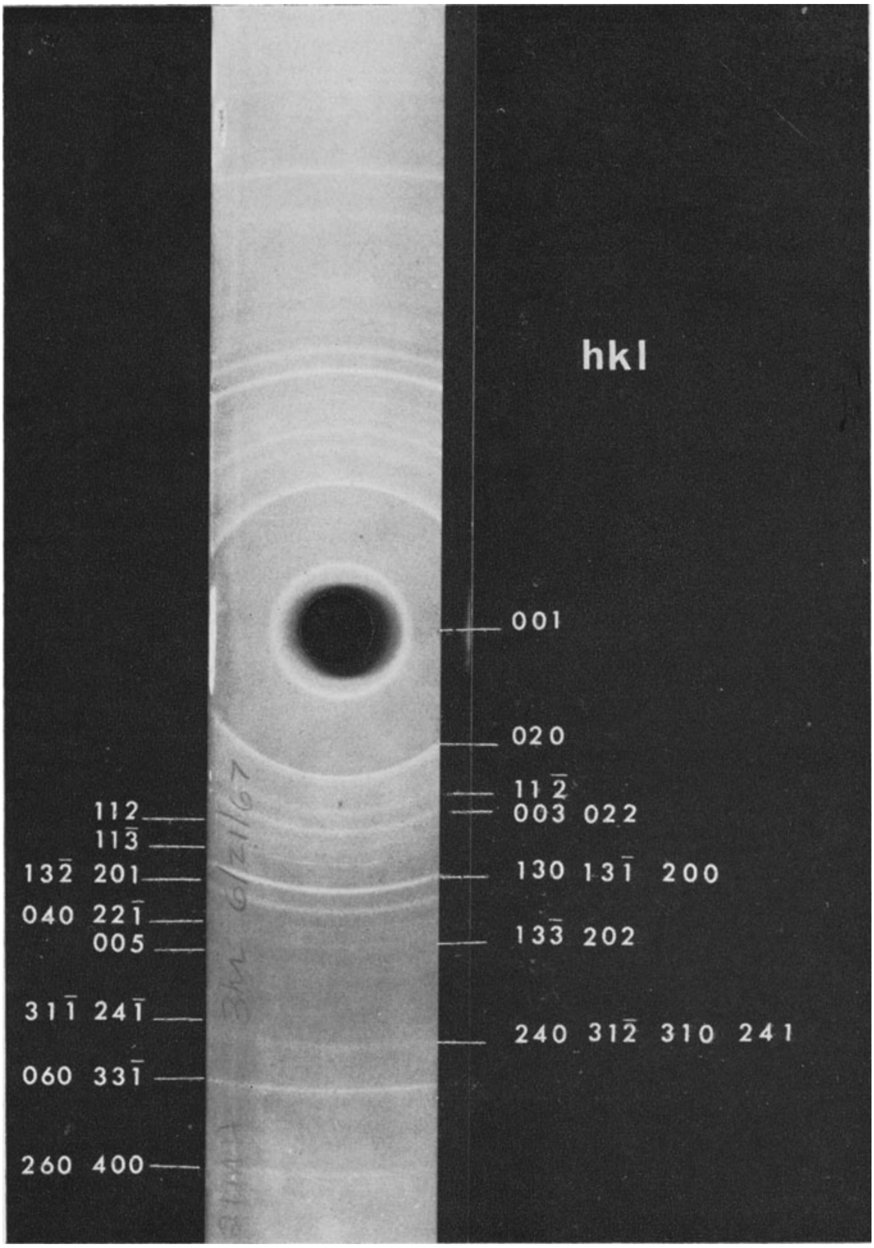

Fig. 4. Random powder X-ray diffraction pattern (photograph) from a single glauconite pellet. For almost every pellet pattern, every line obtained could be matched with a line on Warshaw's (ASTM) pattern for glauconite from which the Miller indices were obtained.

Table 1. Mean d values and intensities for glauconite* lines found on random powder X-ray diffraction photographs of individual vermiform and lobate pellets from the Nanjemoy Formation site, Calvert County, Maryland, compared to values given on The ASTM pattern for glauconite (Warshaw's pattern, ASTM Card No. 9-439)

ASTM			For 8 vermiform pellets†				For 9 lobate pellets†			
hkl	*d* (Å)	I/I_1	*n*	*d* spacing (Å) $\bar{x}$	$s_{\bar{x}}$	*I*	*n*	*d* spacing (Å) $\bar{x}$	$s_{\bar{x}}$	*I*
001	10·1	100	8	10·20	0·03	s, b	9	10·18	0·04	s, b
002	4·98	‡	0	–	–	–	0	–	–	–
020	4·53	80	8	4·54	0·004	s, sh	9	4·54	0·006	s, sh
11$\bar{1}$	4·35	20	4	4·38	0·012	vw, sh	6	4·38	0·011	vw, sh
021	4·12	10	0	–	–	–	0	–	–	–
11$\bar{2}$	3·63	40	6	3·65	0·016	w, b	9	3·67	0·012	w, b
003, 022	3·33	60	8	3·34	0·005	m, b	9	3·34	0·004	m, b
112	3·09	40	6	3·10	0·009	vw, b	7	3·10	0·005	vw, b
11$\bar{3}$	2·89	5	5	2·89	0·006	m, sh	0	–	–	–
023	2·67	10	0	–	–	–	0	–	–	–
130, 13$\bar{1}$, 200	2·587	100	8	2·598	0·0028	s, sh	9	2·595	0·0021	s, sh
13$\bar{2}$, 201	2·396	60	8	2·411	0·0036	m, b	9	2·415	0·0013	m, b
040, 22$\bar{1}$	2·263	20	5	2·272	0·0037	vw, b	8	2·276	0·0028	vw, b
220, 041	2·213	10	0	–	–	–	0	–	–	–
13$\bar{3}$, 202	2·154	20	5	2·154	0·0054	vw, b	8	2·151	0·0023	vw, b
005	1·994	20	4	2·008	0·0158	vw, b	2	1·996	–	vw, b
22$\bar{4}$	1·817	5	1	1·831	–	–	0	–	–	–
31$\bar{1}$, 24$\bar{1}$	1·715	10	3	1·719	–	vw, b	6	1·712	0·0021	vw, b
240, 31$\bar{2}$, 310, 241	1·66	30	4	1·661	0·0017	vw, b	6	1·662	0·0014	vw, b
060, 33$\bar{1}$	1·511	60	8	1·518	0·0013	m, sh	9	1·518	0·0004	m, sh
330	1·495	10	0	–	–	–	2	1·497	–	vw, sh
260, 400	1·307	30	5	1·310	0·0012	vw, b	8	1·311	0·0010	vw, b
170, 350, 420	1·258	10	4	1·273	0·0066	vw, b	3	1·264	–	vw, b

*Lines from other minerals, found with glauconite lines in the patterns of one vermiform pellet and two lobate pellets, are not included.

†n refers to the number of patterns in which the line was found, and $\bar{x}$ and $s_{\bar{x}}$ refer to the mean and standard error of the mean, respectively, based on the patterns in which the line was found. I refers to line intensity and breadth, which were estimated visually; for intensity, s = strong, m = moderate, w = weak, vw = very weak; for breadth, sh = sharp, b = broad.

‡Obtained only with oriented specimen.

(1965) considered their well ordered glauconites (which gave these peaks) 1 M, and their disordered glauconites 1 Md.

The 11$\bar{2}$ and 112 lines were found in most of the patterns from the vermiform and lobate pellets of this study (Table 1). On this basis, and upon the basis that almost the full set of lines given on the ASTM card were found with some pellets, the mineral glauconite of pellets of this study may be considered 1M. Accompanying this evidence for the 1M polytype, however, there was also evidence of disorder (tendency toward 1Md) in the X-ray patterns from both the vermiform and lobate pellets. This evidence was the absence of some of the weak lines of the ASTM pattern and the weakness and broadness of most lines with $k \neq 3n$ (Table 1 and Fig. 4).

Interstratification of expanded layers with the glauconite layers in the Nanjemoy Formation pellets may be the main source of disorder. Spacings for the 001 peak, for both the vermiform and lobate pellets, were usually greater than expected for well ordered glauconite. Mean values for this peak for the Nanjemoy pellets were about 10·2 Å (Table 1), as opposed to a value of 10·1 for well ordered glauconite (ASTM pattern, also the value given by Bentor and Kastner, 1965). The presence of expanded layers was also shown by a shoulder on the low angle side of the 001 peak and a small 14 Å peak in a diffractometer pattern of a parallel oriented Mg saturated and glycerol solvated specimen made from the coarse sand pellets from the Nanjemoy Formation.

Analyses indicated that the Nanjemoy coarse sand pellets contained 6·7 per cent K_2O, had a CaEC (Ca replaced by Mg) of 29 me/100 g, and a KEC (K replaced by NH_4) of 18 me/100 g. Application of the equations of Alexiades and Jackson (1966), to the K_2O and CEC data, indicates that the Nanjemoy pellets are composed of 7 per cent vermiculite, 11 per cent montmorillonite and 74 per cent glauconite (assuming glauconite to be the only K bearing mineral and that pure glauconite contains 9 per cent K_2O). The low total of these three minerals, 92 per cent, may be caused by errors in the analyses, wrong assumptions, or the presence of other minerals. Alexiades and Jackson (1966) have pointed out that the Franconia glauconite of Wisconsin contained 15–24 per cent chlorite by their thermal gravimetric analysis. Based on X-ray diffraction patterns of 550°C heated, K saturated, oriented specimens, a small percentage of interstratified chlorite layers is also likely in the Nanjemoy pellets.

The mean 060 spacing was 1·518 Å for both the vermiform and lobate pellets of this study (Table 2). Muscovite and biotite gave expected 060 spacings when run under the same conditions as the glauconite pellets (Table 2). The 1·518 Å value for the pellets is slightly greater than that for the ASTM glauconite pattern (1·511 Å), or for the iron-rich glauconites (1·511–1·515 Å) studied by Tyler and Bailey (1961), but falls within the range of 1·51–1·52 Å reported by Bentor and Kastner (1965).

There appear to be at least three possible reasons for the large 060 values of glauconites, which are generally considered to be dioctahedral, compared to other dioctahedral layer silicates. First, as suggested by those who have calculated glauconite formulas and found it necessary to have somewhat over 2 out of 3 octahedral sites occupied with cations (Bailey and Tyler, 1961; Bentor and Kastner, 1965), glauconite may not be truly dioctahedral. Sedondly, larger 060 values for glauconite than for muscovite should be expected, even if glauconite is dioctahedral, because of the presence of a more ferruginous octahedral sheet with glauconite (as opposed to aluminous with muscovite or illite), considering the larger size of Fe^{+3} (and any Mg^{+2} and Fe^{+2}) as opposed to Al^{+3}. In this context, a nontronite, another 2 : 1 dioctahedral layer silicate with a ferruginous octahedral sheet, had an 060 spacing of 1·522 Å (MacEwan, 1961, p. 192). An especially high content of ferric iron (about 30 per cent Fe_2O_3) in Maryland glauconite from the Aquia Formation has recently been reported by Wolff (1967). Thus a highly ferruginous octahedral sheet is the most likely explanation for the large 060 spacing of the glauconites examined in this study.

A third possibility, which apparently could cause an increase in d (060) according to Bailey (1966, p. 3), is random distribution of two cations over three octahedral sites. This would be very unusual since detailed structural studies, according to Bailey's (1966) review, have always found the vacant octahedral cation sites of dioctahedral minerals to be ordered.

Genesis considerations

Most of those who have studied glauconite have concluded that it is an authigenic mineral, usually formed under marine conditions. The authigenic origin of glauconite is supported by two especially convincing pieces of evidence. First, as discussed previously, glauconite is a 1M or 1Md polytype mineral. From Bailey's (1966, pp. 21–22) summary of the conditions of formation of the various polytypes, glauconite's 1M polytype indicates that it forms at low temperatures (diagenetically in sediments). Secondly, K-Ar dates of glauconites from various geologic formations, reported by Hurley *et al.* (1960) were similar in age or younger than

Table 2. 001 and 060 spacings for glauconite pellets from the Nanjemoy Formation, mean values from Table 1, and for muscovite and biotite from Ward's Natural Science Establishment determined under the experimental conditions of this study*

	Glauconite pellets			
	Lobate (Å)	Vermiform (Å)	Muscovite (Å)	Biotite (Å)
001 (002 for muscovite)	10·2	10·2	10·0	10·0
060	1·518	1·518	1·504	1·540

*114·59 mm powder camera with powdered mount in a 0·2 mm capillary tube.

the geologic age of the formations from which the glauconites were taken. This indicates that most glauconite has formed in the formations in which it is found. And even if the glauconite in some formations has been re-worked from others, as suggested by Owens and Minard (1960), there is no evidence that glauconite is not a low temperature mineral.

Many (e.g. Burst, 1958*a*; and Hower, 1961) consider montmorillonite or "degraded 2:1 layer silicate lattices" to be the most common starting materials for glauconitization. Porrenga (1966) has reported an example of glauconite presently forming from a montmorillonite at a depth of about 100 fathoms off the Niger delta. Also the present authors are finding montmorillonite (or nontronite) in some soils developed in greensands (to be reported in a later paper), further supporting the existence of a genetic relationship between montmorillonite and glauconite. However, as suggested by Takahashi (1939), it still seems likely that glauconite can form from many starting materials, given a marine environment and a slow sedimentation rate—so that the materials have time to reach or approach an equilibrium with the sea-water.

This study has shown that vermiform and lobate glauconite pellets from the Nanjemoy formation are morphologically different, but that by X-ray data they are composed of the same mineral (or minerals, depending upon how glauconite is defined). These data show the vermiform pellets are not composed of biotite or muscovite. Instead, it must be concluded that these vermiform and lobate pellets represent different habits of glauconite.

Galliher's theory that glauconite forms from biotite cannot be substantiated from this study. However, it likewise cannot be concluded that the vermiform pellets are not an alteration product from some form of mica. Much mica (probably more muscovite and its weathering products than biotite) has been and is today being eroded from the Maryland Piedmont. This area is less than 20 miles from parts of the Maryland greensand area (Fig. 1) and was probably the main source of sediments of the Cretaceous and Eocene seas of the greensand area. Supporting this statement, the quartz, which occurs as sand-size grains with the glauconite pellets in the Nanjemoy and Aquia Formations, appears in thin section to be identical to the quartz seen in thin sections of soils from the Maryland Piedmont. The quartz grains in both occurrences are often zoned (as expected in metamorphic quartz, personal communication with H. G. Siegrist, University of Maryland geologist) and not very rounded. Also occasional muscovite flakes have been observed in soils and sediments in the western part of the Maryland greensand area. However, no mica grains partially altered to glauconite have been observed in the present study. The transformation from muscovite to glauconite would require considerable structural (2M to 1M) as well as compositional (aluminous to ferruginous octahedral sheet and a lowering of the charge on the tetrahedral sheet) change. However, since very few minerals other than quartz and glauconite are found in the greensands, it is concluded that most non-quartz minerals, of the original sediments, have been converted to glauconite.

Other possibilities for the development of the vermiform pellets include (1) crystallization from solution, and (2) recrystallization. No convincing evidence for crystallization from solution was found. However, some vermiform pellets (such as one of those shown in Fig. 2A) do have longitudinal lines that appear to divide a more recently crystallized portion from an older portion. In these pellets, the older portion appears to have acted as a template, or a seed, for the initiation of new crystallization. Such crystallization, if it occurred, probably came from solution. Also the central portion of the pellet shown in Fig. 3A appears as if it could have developed by a screw type of crystal growth with the layers growing at their edges.

Since pellets with a morphology intermediate between vermiform and lobate are seldom found, the development of the external vermiform morphology by recrystallization within lobate pellets does not seem likely. Micaceous internal morphology in pellets that would be classified as lobate by their external appearance is rare in the pellets of this study if it occurs at all.

No new hypotheses can be offered for the origin of the lobate pellets. Whether they are related or unrelated to the vermiform pellets other than being composed of the same mineral and (in the present case) occurring in the same deposit, is not clear. Owens and Minard (1960) apparently consider the lobate morphology to be evidence of marine or fluvial reworking, implying that the glauconite of these pellets formed, perhaps in a vermiform pellet, before the development of the lobate morphology.

Alternatively, and at least equally as likely, the lobate pellets may have obtained their morphology before the material of which they are composed became glauconite. In other words, they may be fecal pellets or clayey pellets that have undergone glauconitization. An interesting implication is that if both the lobate and the vermiform pellets obtained their shape before becoming glauconite (mineralogically), then the proper environment would appear to be capable of converting a variety of starting materials into glauconite. This hypothesis is not new, but in recent years it has received less emphasis than others from most authors.

REFERENCES

Alexiades, C. A., and Jackson, M. L. (1966) Quantitative clay mineralogical analysis of soils and sediments: *Clays and Clay Minerals* **14**, 35–52. [Pergamon Press, New York]

Bailey, S. W. (1966) The status of clay mineral structures: *Clays and Clay Minerals* **14**, 1–23. [Pergamon Press, New York]

Bentor, Y. K., and Kastner, Miriam (1965) Notes on the mineralogy and origin of glauconite: *J. Sediment Petrol.* **35**, 155–166.

Burst, J. F. (1958*a*) "Glauconite" pellets: Their mineral nature and applications to stratigraphic interpretations: *Bull. Am. Assoc. Petrol. Geologists* **42**, 310–327.

Burst, J. F. (1958*b*) Mineral heterogeneity in "Glauconite" pellets: *Am. Mineralogist* **43**, 481–497.

Galliher, E. W. (1935) Glauconite genesis: *Geol. Soc. Am. Bull.* **46**, 1351–1356.

Hadding, A. (1932) The pre-quaternary sedimentary rocks of Sweden. Pt. IV. Glauconite and glauconite rocks: *Lunds Univ. Arsskr.* N. F., Avd. 2, Bd. **28**, No. 2; *Kungl. Fysiografiska Sallskapets Handlingar*, N. F., Bd. **43**, No. 2.

Hower, John (1961) Some factors concerning the nature and origin of glauconite: *Am. Mineralogist* **46**, 313–334.

Hurley, P. M., Cormier, R. F., Hower, J., Fairbairn, H. W., and Pinson, W. H., Jr. (1960) Reliability of glauconite for age measurement by K-Ar and Rb-Sr methods: *Bull. Am. Assoc. Petrol. Geologists* **44**, 1793–1808.

Jackson, M. L. (1958) *Soil Chemical Analysis*. Prentice-Hall, Englewood Cliffs, New Jersey.

Kittrick, J. A., and Hope, E. W. (1963) A procedure for the particle-size separation of soils for X-ray diffraction analysis: *Soil Sci.* **96**, 319–325.

Light, M. A. (1952) Evidence of authigenic and detrital glauconite: *Science* **115**, 73–75.

MacEwan, D. M. C. (1961) Montmorillonite minerals: *In The X-ray Identification and Crystal Structure of Clay Minerals*, G. Brown, ed., Mineralogical Society, London, 143–207.

Owens, J. D., and Minard, J. P. (1960) Some characteristics of glauconite from the Coastal Plain formations of New Jersey: *U. S. Geol. Surv. Prof. Paper* **400**, Part B, 430–432.

Porrenga, D. H. (1966) Clay minerals in recent sediments of the Niger delta: *Clays and Clay Minerals* **14**, 221–233. [Pergamon Press, New York]

Takahashi, Jun-Ichi (1939) Synopsis of glauconite: *In Recent Marine Sediments*, Parker Davies Trask, ed., *Am. Assoc. Petrol. Geologists* 503–512.

Triplehorn, D. M. (1966) Morphology, internal structure, and origin of glauconite pellets. *Sedimentology* **6**, 247–266.

Tyler, S. A., and Bailey, S. W. (1961) Secondary glauconite in the Biwabic iron-formation of Minnesota: *Econ Geol.* **56**, 1033–1044.

Warshaw, C. M. (1957) The mineralogy of glauconite: Ph.D. thesis, Pennsylvania State University, University Park, Pennsylvania.

Wolff, R. G. (1967) X-ray and chemical study of weathering glauconite. *Am. Mineralogist* **52**, 1129–1138.

Résumé – Des pastilles de glauconie de morphologie vermiforme et lobaire se trouvent ensemble dans les formations géologiques de l'écocène dans le Maryland. Morphologiquement, ces pastilles vermiformes semblent identiques à celles que l'on appelait précédemment du nom de 'biotite altérée'. En sections minces, ces pastilles font apparaître une morphologie micacée de type bien défini, les couches traversant les pastilles vermiformes. Certaines zones de ces pastilles ont l'apparence de 'cristaux' d'une taille qui va jusqu'à $30 \times 70\,\mu$ et à section presque rectangulaire. L'on peut cependant discerner des fissures minuscules le long des plans de clivage à l'intérieur de ces cristaux. Extérieurement les pastilles lobaires ont plusieurs lobes arrondis et ressemblent à l'une des formes que Burst appelle 'libre'. En section mince sous nicols croisés ces pastilles ont une apparence granulaire, ce qui montre que les pastilles lobaires se composent de plusieurs petites zones, chacune de 5 à $50\,\mu$ de diamètre. A l'intérieur de ces zones la glauconie minérale a une seule orientation, mais les zones ne sont pas alignées de manière à donner l'aspect general micacé que a l'on associe avec les pastilles vermiformes.

Des modèles de diffraction à rayons X de poudre pris au hasard (préparés avec un grand appareil de photo à poudre Norelco de 114,59 mm) de pastilles vermiformes et lobaires individuelles sont pratiquement identiques. Huit pastilles vermiformes et neuf lobaires ont donné les mêmes écartements moyens 001 (10,1 Å) et 060 (1,518 Å). Les modèles des deux types de pastilles ressemblent, à la seule exception de quelques traits de faible intensité, au modèle de Warshaw (ASTM) pour la glauconie. Les modèles ont des traits qui indiquent un polytype 1 M; cependant les traits *hkl* ($k \neq 3n$) sont larges, ce qui démontre un certain désordre. En plus des modéles de diffraction à rayons X, la teneur en K_2O (6,7%) et l'indice CEC (29 me/100 g. comme Ca remplacé par Mg) des pastilles montrent que les couches dilatées interstratifiées sont peut-être la cause principale du désordre.

Si les pastilles vermiformes sont du mica altéré, l'altération a été suffisamment importante pour donner un produit que les méthodes à rayons X identifient de manière définitive à la glauconie. La possibilité d'altération du mica vient du fait de la proximité géographique de Piedmont (une zone de source de mica) et également de la présence de quartz de type piedmontais avec les pastilles de glauconie. Alternativement, il se peut que les pastilles vermiformes prennent forme pendant le processus de cristallisation ou de recristallisation de la glauconie. La fait qu'il est probable que les deux types de pastilles aient obtenu leur morphologie avant ou pendant, plutot qu'après, la période où elles se sont transformées en glauconie (minéralogiquement) fait penser qu'un milieu approprié peut former la glauconie à partir de produits initiaux varié.

Kurzreferat – Glaukonitteilchen mit wurmförmiger und lappiger Morphologie kommen gemeinsam in den geologischen Eozän-Formationen von Maryland vor. Morphologisch gesehen scheinen die wurmförmigen Teilchen identisch mit den früher als 'veränderter Biotit' bezeichneten zu sein. In Dünnschliffen zeigen diese Teilchen eine wohldefinierte Glimmermorphologie, wobei die Schichten quer durch die wurmformigen Teilchen verlaufen. Manche der Zonen dieser Telichen scheinen 'Kristalle' von bis zu $30 \times 70\,\mu$ und beinahe rechteckigem Querschnitt zu sein. Entlang den Spaltflächen innerhalb dieser 'Kristalle' sind jedoch winzige Risse vorhanden. Äusserlich haben die lappigen Teilchen viele abgerundete Lappen und erinnern an eine der von Burst als freiförmig bezeichneten Formen. Die zwischen gekreuzten Nicols betrachteten Dünnschliffe dieser Teilchen weisen körniges Gefüge auf, was darauf hinweist, dass die lappigen Teilchen aus einer Vielzahl schmaler Zonen von je etwa $5–20\,\mu$ Breite bestehen. Innerhalb dieser Zonen besitzt der Glaukonit eine einheitliche Orientierung, doch sind die Zonen nicht gegeneinander ausgerichtet, um die in den wurmförmigen Teilchen beobachtete glimmerartige Gesamterscheinung zu geben.

Die mittels einer grossen 114,59 mm Norelco Pulver-Kamera erhaltenen Pulver-Röntgenbilder einzelner wurmförmiger und lappiger Teilchen sind nahezu identisch. Acht wurmförmige und neun lappige Teilchen gaben die gleichen durchschnittlichen 001 (10,2 Å) und 060 (1,518 Å) Abstände. Die aus den beiden Teilchenarten erhaltenen Bilder sind, bis auf die Abwesenheit einiger schwacher Linien, dem von Warshaw (ASTM) angegebenem Bild für Glaukonit ähnlich. Die Bilder weisen Linien auf, die einen 1 M Polytyp anzeigen, jedoch sind die *hkl* Linien mit $k \neq 3n$ breit und deuten auf Unregelmässigkeiten hin. Zusätzlich zu den Röntgenbeugungsbildern weisen der K_2O Gehalt (6,7%) und CEC (29 me/100 Gramm als Ca ersetzt durch Mg) der Teilchen darauf hin, dass zwischengelagerte Quellschichten die Hauptursache dieser Unregelmässigkeit sein dürften.

Wenn es sich bei den wurmförmigen Teilchen um modifizierten Glimmer handelt, so ist die Modifizierung genügend weit fortgeschritten, um ein Produkt zu liefern, dass durch Röntgenstrahlenmethoden eindeutig als Glaukonit identifiziert werden kann. Die Möglichkeit einer Glimmerveränderung wird durch die geographische Nähe des Piedmonts (Glimmervorkommen) und das Auftreten von Piedmont-artigem Quarz mit den Glaukonitteilchen nahegelegt. Andererseits könnten die wurmförmigen Teilchen durch Glaukonitkristallisations- oder Umkristallisationsprozesse gebildet worden sein. Die Wahrscheinlichkeit, dass beide Teilchenarten ihre Morphologie bevor oder während, aber nicht nach der Periode der Glaukonitbildung erhalten haben, deutet darauf hin, dass sich Glaukonit in geeigneter Umgebung aus einer Vielzahl von Ausgangsmaterialien bilden kann.

Резюме—Гранулы глауконита червеобразной и лопастной морфологии встречаются вместе в эоценовых геологических формациях в штате Мериленд. С точки зрения морфологии, червеобразные гранулы эти как будто сходны с теми гранулами, которые раньше называли "измененным биотитом". В тонких сечениях, они показывают отчетливо определенную слюдистую морфологию, со слоями проходящими поперек червеобразных гранул. Некоторые зоны в этих гранулах—это вероятно "кристаллы" размером до $30 \times 70\,\mu$ и почти прямоугольны в поперечном сечении. Однако, в этих кристаллах вдоль поверхности кливажа появляются очень маленькие трещины. Снаружи лопастные гранулы имеют много округленных выступов и имеют форму сходную с той, которую Бурст называл свободной. В тонком сечении под скрещенными николями гранулы эти имеют зернистый вид, указывая, что лопастные гранулы состоят из ряда маленьких зон по $5–20\,\mu$ каждая. В пределах этих зон глауконит имеет одиночную ориентацию, но зоны не расположены на одной оси, чтобы дать общий слюдистый вид, который связан с червеобразными гранулами.

Сделанные наугад большой камерой Норелко 114,59 mm порошкограммы отдельных червеобразных и лопастных гранул почти что тождественны. Восемь червеобразных и девять лопастных гранул дали те же средние расстояния 001 (10,2 A) и 060 (1,518 A). Порошкограммы для гранул обоих родов сходные (за исключением отсутствие некоторых слабых линий) с рентгенограммами Варшава (Американское Общество Испытания Материалов) для глауконита. Порошкограммы имеют линии, указывающие политип 1M, однако линии hkl при $k \neq 3n$ являются широкими, указывая на накоторый беспорядок. Кроме порошкограмм, содержание K_2O (6,7%) и CEC (29 млэкв/100 г как Ca замененный Mg) в гранулах указывает что промежуточные пласты с увеличивающейся мощностью могут быть главной причиной беспорядка.

Если червеобразные гранулы это измененная слюда, то изменение достаточно для того, чтобы дать продукт, который определенно отождествляется рентгеновскими лучами, как глауконит. Возможность слюдяного изменения подсказывается географической близостью пиеэмонт (район источника слюды) и залеганием кварца пиеэмору ночо типа с гранулами

глауконита. Альтернативно, червеобразные гранулы могут образоваться во время процессов кристаллизации или перекристаллизации глауконита. Возможность того, что гранулы обоих родов приобрели морфологию свою прежде, чем они (миниералогически) превратились в глауконит или во время этого преобразования, но не после него, подсказывает, что правильная окружающая среда может образовать глауконит из различных исходных материалов.