CLAY MINERALS AND THE EVOLUTION OF SEDIMENTARY ROCKS

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It has been estimated that nearly 50 per cent. of all known sedimentary rocks belong to the clay grade and it is therefore a hard fact that our knowledge of the mineralogical composition of approximately half the rocks of the stratigraphical column is still in a rudimentary state. The difficulties of petrographical work on clay grade sediments are all too familiar. The size of the individual particles is extremely small, often below the resolving power of the microscope. Most of the common clay minerals are biaxial and negative. Although minerals of the kaolinite group should be readily distinguishable from illitic and montmorillonoid minerals by their lower double refraction, films of iron hydroxide on individual particles or intimate admixtures of different minerals render observation difficult. In addition the presence of iron hydroxide films or changes in water content can give rise to variations in refractive indices. Petrographical work on clay minerals must be supplemented by other techniques which have been extensively developed within the last 20 years—X-ray analysis, thermal methods, the use of the electron microscope and certain chemical techniques. Despite the progress which has been made, however, the day when quantitative estimations of the mineralogical composition of clay grade sediments can be rapidly and accurately made is still a long way off.

In the absence of mineralogical data, classification of clays and shales has in the past been based on such criteria as colour, texture, structural characteristics and chemical composition. Petrographical studies were largely confined to the detrital or silt grade constituents of the deposit and it was generally only in cases where a faunal assemblage was present and could be recognized as marine, brackish, fresh-water or terrestrial that reliable information regarding the environmental conditions under which the bed was laid down were forthcoming.

With the development of methods for studying the clay minerals themselves it began to be recognized that these might yield valuable evidence of the origin of the sediment. Among early workers J. L. Thiebaut (1925) made an outstanding study of the Mesozoic and Tertiary clays of the Paris basin. He concluded that marine clays in general had a hydrous mica base, that kaolinite was absent from all but shallow-water marine sediments and that fresh-water clays—including refractory clays—consisted essentially of halloysite. Thiebaut's results did much to stimulate further work though not all of his conclusions would be acceptable to-day. For example, subsequent research by Brindley and Robinson (1947) has shown that the characteristic mineral of many fireclays is one intermediate
between kaolinite and meta-halloysite and it seems possible that the presence of this mineral may have important environmental significance.

Ross and Kerr (1931) concluded that kaolinite and halloysite were the normal results of profound weathering of aluminous rocks—especially granitic rocks—but that kaolinite could also be produced from other materials under certain conditions such as those of leaching in a swamp environment. Ross and Hendricks (1945) were also impressed by the importance of the parent material in determining the nature of the clay mineral formed. They regarded igneous rocks containing abundant ferro-magnesian minerals as the commonest source of montmorillonite.

In the task of recognizing the environmental significance of clay minerals in ancient sediments attention was naturally directed to the clay fraction of modern deposits. The work of Correns and his collaborators (1937) on the sea bottom sediments collected by the Meteor expedition from the South Atlantic, showed that hydrous mica was almost universally present. Certain samples consisted predominantly of kaolinite. Others of halloysite but relatively few of montmorillonoid minerals and these mainly in the neighbourhood of areas of basic volcanic activity. Dietz (1941) working on material from the Challenger samples found illitic minerals predominant in the deep sea clays while kaolinite was often abundant in near-shore samples. Grim, Dietz and Bradley (1949) discovered that illite was the commonest and kaolinite the least abundant of the major clay minerals in samples from the Pacific Ocean and the Gulf of California.

A contribution of the greatest importance is that made by Millot (1949) in his careful study of argillaceous sediments of known origin from the Mesozoic and Tertiary rocks of eastern France. He found that in marine sediments illite predominates with kaolinite playing a subordinate role; while in lagoonal sediments illite is again dominant but kaolinite absent. The acid continental facies is characterized by kaolinitic minerals, the basic continental facies most commonly by illite. Montmorillonite was an infrequent component of the samples studied and no general conclusions regarding its origin could be reached.

In the evolution of a sedimentary rock the deposit has passed through three stages—sedimentation, diagenesis and weathering—in all of which changes in the nature of the clay minerals may have occurred. Since the process is cyclical and the products of weathering provide the raw materials for the next generation of clay sediments an understanding of weathering processes is a first necessity. In this field opinion differs regarding the relative importance of the nature of the parent material as compared with other factors. Clearly with short term or incomplete weathering the nature of the parent material is a prime consideration. With increase in time and intensity of the weathering processes this factor becomes less fundamental. Jackson and his colleagues from the University of Wisconsin (1948) suggest
that in soils and sediments a well-defined weathering sequence can be recognized in which essential stages result in the successive production of illite, degraded micas, montmorillonite, kaolinite and gibbsite. The stages from illite to montmorillonite are described as intermediate stages of weathering, those of kaolinite and gibbsite as advanced stages. This sequence normally occurs under conditions of increasing acidity and increasing oxidation. Normal weathering can be interrupted by lack of sufficient intensity or of some other functional factor. Thus the occurrence of large amounts of montmorillonite in geologically old bentonites may be attributed to lack of leaching.

However, there is no general agreement regarding the correctness of this interpretation. Ross (1943) claims that the formation of kaolinite on the one hand, or montmorillonite and beidellite on the other, during weathering is dependent on the order of breakdown of minerals in the parent rock. Simultaneous decomposition of the ferromagnesian minerals and feldspars with release of ferrous and ferric iron, magnesium, alumina and silica leads to the formation of montmorillonite or beidellite. With early breakdown of the ferromagnesian minerals, however, magnesium and iron may be removed in solution before the feldspars decompose with consequent formation of kaolinite. The absence of magnesium, calcium, the alkali metals and ferrous iron is regarded by Ross as an important factor in the production of kaolinite. As a natural consequence kaolinite tends to form under conditions of prolonged weathering and leaching while montmorillonite results where drainage is poor and oxidation restricted.

The weathering cycle may be interrupted at any stage by transport and deposition giving rise to a new generation of sediments. Modern American sedimentationists (see Pettijohn, 1949) stress the intimate relation between the types of deposits formed and the tectonic conditions at the time when they originated. At each stage in the geomorphic cycle a characteristic suite of sediments ranging from coarsest to finest material is produced. For example during the stage of peneplanation when weathering is prolonged and sedimentation slow with continuous re-working, arenaceous rocks are represented by quartzose sandstones. Under geosynclinal conditions unsorted, poorly rounded, material is poured into the basin of deposition with the production of the graywacke type of sandstone. In the post-orogenic stage of the cycle, sediments are the product of incomplete weathering and rapid erosion of newly elevated mountain chains: under these conditions arkoses predominate among the sandstones. The clay grade equivalents of these arenaceous types are still imperfectly understood. It might be anticipated, disregarding diagenetic changes, that the conditions of the peneplanation stage would favour the production of kaolinite rocks, those of the geosynclinal stage of illitic sediments. Furthermore it seems probable that the structural features of the rocks may be influenced by the nature of the clay minerals. Kaolinite with a small ion adsorption capacity, small
water absorption and low plasticity is an inert clay. Montmorillonite with large ion adsorbing capacity, large water absorption and high plasticity is an active clay. Illite is intermediate. It would be interesting to know if, for example, sub-aqueous slumping occurs more commonly in montmorillonitic and illitic clays than in kaolinitic clays. At present no adequate data are available.

Finally there is the stage of diagenesis, supremely important in the evolution of the clay rocks, but one that has only recently yielded to study. Correns (1938) in his examination of the Meteor cores could find no evidence of diagenetic changes. Dietz (1941) working on Challenger samples produced strong evidence for the development of illite on the sea floor, resulting largely, he suggested, from alteration of montmorillonite. Grim, Dietz and Bradley (1949) concluded that kaolinite was transformed into illite during conditions of marine diagenesis and claimed that marine clays should be composed of minerals other than kaolinite: while plentiful kaolinite might provide evidence of non-marine origin. This has been in general confirmed by the work of Millot (1949). However, while Grim and his associates found widespread montmorillonite in the sea-bottom samples from the Pacific, Millot found it to be rare in the Mesozoic and Tertiary sediments he studied. This suggests that montmorillonite is lost at some stage between deposition and lithification though Grim could find no evidence of its destruction in submarine diagenesis.

It appears that diagenesis often involves inversion of the normal weathering sequence (Jackson and others, 1948). Thus montmorillonitic sediments tend to revert to hydrous micas, and gibbsitic sediments (i.e., bauxites) may resilicate to kaolinite. Clearly the specific clay minerals found in sediments are largely the result of conditions within the basin of accumulation. Studies of the processes of base exchange in clays, such as those of Edelman (1935), Kelley (1939) and others may ultimately help in the reconstruction of the geochemical conditions obtaining in oceans of the past. Among subjects still imperfectly understood is that of compaction. Recent contributions to knowledge in this field by Jones (1944) and Skempton (1944) contain little information regarding the clay mineral content of the examples cited. On general grounds it might be anticipated that kaolinitic clays would show a lower degree of compaction than others. Considerable support exists for the claim that the production of a shale is not a simple consequence of pressure on any argillaceous sediment but is controlled by the nature of the clay mineral present (Boswell 1948).

The techniques being evolved by clay mineralogists should be a matter of vital concern to stratigraphers and sedimentationists who are continually faced with the problem of interpreting stratigraphic sequences. Only recently have adequate methods of examining the clay grade portion of those sequences become available. There is an urgent need for a mass of information regarding the distribution of the different clay minerals, particularly of the less common species
such as attapulgite, chamosite or the new mineral of chloritic type recently described from the Keuper Marl (Honeyborne 1951, Stephen and MacEwan 1951). It appears to the writer to be of the utmost importance that adequate geological data should be included in papers dealing with clay minerals. It is vital to the geologist to know, not only the exact location of all samples studied, but also their lithological and petrographical characters as far as determinable, their relations to the beds above and below, how far they are typical of the formation from which they come, their degree of weathering and similar details. It should be the joint responsibility of geologists and clay mineralogists to ensure that such data are available in published work. Only in this way will it be possible to build up the mass of information which will ultimately lead to a full assessment of the environmental significance of the clay minerals.

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References.
Dietz, R. S., 1941. Clay minerals in recent marine sediments. Univ. of Illinois.
Millot, G., 1949. Geologie appliquee et prospection miniere, Vol. II., Nos. 2-4. See also this number of Clay Minerals Bull.

**PROCEEDINGS OF THE CLAY MINERALS GROUP**

**MEETING**

*Held in the Apartments of the Geological Society, Burlington House, London, W.1, on 2nd November, 1951, 10 a.m. and 2.45 p.m.*

About 65 members and guests were present. The meeting was devoted mainly to a discussion of “Geological Aspects of Clay Mineralogy.” After the meeting, a dinner was held at the Strand Palace Hotel.

The following papers were read and discussed, with Dr G. Nagelschmidt in the chair.

1. The contribution of clay mineralogy to the study of diagenesis of sediments: by P. G. H. Boswell.
5. Reaction relations in the finergrained rocks: by J. C. Griffiths (read by S. E. Coomber).
10. The theory of differential thermal analysis: by V. C. Farmer (read by R. C. Mackenzie). The following paper was read by title.
11. Mineralogy and petrology of Ordovician “metabentonites” and related limestone: by C. E. Weaver and T. F. Bates.