CLAY MINERAL FORMATION IN A DEEPLY WEATHERED BOULDER CONGLOMERATE IN NORTH–EAST SCOTLAND*

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Abstract–The clay minerals formed in a deeply weathered boulder conglomerate of Middle Old Red Sandstone (Devonian) age in north–east Scotland have been studied by a variety of physical and chemical techniques. The granite and granulite boulders in this deposit are completely weathered. With the exception of microcline, all the feldspars in these rocks–orthoclase feldspar, orthoclase-microperthite, albite, and oligoclase–weather to a Cheto-type montmorillonite, poor in iron. Electron and optical microscopy indicate that the weathering transformation is a direct one, without the intervention of any intermediate crystalline or well-defined amorphous phase. Structural control of the primary mineral over the formation of the montmorillonite seems to have been a minimal factor and the evidence suggests that the clay mineral crystallized from the soluble or colloidal products arising from the decomposed feldspars. Smaller amounts of kaolinite also formed during weathering but largely from the weathering of muscovite. The environment in which these changes occurred seems to have been alkaline in a relatively closed system. Chemical analyses of related cores and weathered shells of granite and granulite bounders show only a slight decrease of silica and an increase in magnesia. Judging from the extent of alteration to secondary clay minerals, the order of resistance towards weathering of the primary minerals in these rocks is plagioclase = orthoclase < muscovite < biotite < microcline < quartz.

INTRODUCTION

ISOLATED pockets of deeply weathered rock are common in north–east Scotland and have been convincingly interpreted as representing the remnants of a formerly extensive weathered mantle dating from pre-glacial times (Fitzpatrick, 1963). Deep weathering has affected many different rock types but is particularly pronounced in granites. Even though such alteration has often proceeded to a stage where the granitic rock is friable, there is commonly little indication of clay mineral formation from primary minerals such as feldspars and much of the weathering appears to be of a purely physical nature. However, it is certain that the major part of the weathered cover was removed by glacial erosion, probably being incorporated into glacial deposits, and presumably, only the least altered basal parts were able to survive *in situ*.

The deep weathering described in the present paper affects a conglomerate of Middle Old Red Sandstone (Devonian) age near Clunas, Nairnshire. This conglomerate contains large boulders of a variety of rock types and provides an unusual example of their weathering under identical environmental conditions. The fact that weathering has brought about the formation of clay minerals from the primary minerals in some rocks led to a more detailed study of the transformations involved.

MATERIALS AND METHODS

The conglomerate is exposed in a stream section near Clunas, Nairnshire, approximately four miles south–east of Cawdor Castle (Grid Reference NH 908446), occupies a narrow downfaulted outlier in the Moine Schists and is generally covered by glacial drift. The conglomerate contains large rounded boulders up to 1 m in dia. in various stages of decomposition. The boulders most resistant to weathering are composed of banded metaquartzite, metamorphosed grit and silicified volcanic rock. These rock types are always hard and coherent although there may be some degree of surface weathering. On the other hand, boulders of granite and quartz–biotite–granulite are often so thoroughly decomposed that they are completely incoherent even though their original textures and rounded outlines can easily be discerned. Relatively fresh rock may be preserved at the cores of some of the larger boulders and this was compared with the surrounding, friable, weathered material.

Representative samples were collected and studied by X-ray diffraction, X-ray fluorescence analysis, electron and optical microscopy and i.r. spectroscopy. The samples were investigated in bulk, and after fractionation into various particle sizes following standard sedimentation procedures.

X-ray diffraction studies were made through the range $3–75°2\theta$ using a Philips 2kW diffractometer with iron-filtered CoK_α radiation and divergent, receiving and scatter slits of 1°, 0·2 mm and 1°, respectively. Clay fractions were oriented by sedimenting on glass slides, particular attention being paid to basal reflections and the responses to glycerol and heat treatments.

For X-ray fluorescence analysis the method employed was essentially that of Norrish and Hutton (1969). The sample was presented to the spectrometer in the form of a glass disk prepared by fusing the rock powder with lithium borate glass (glass:powder ratio is approximately 6:1) at 1000°C and pressing out the melt on a graphite disk of the same diameter as the sample cup. To ensure oxidizing conditions, a small amount of sodium nitrate was added to the borate glass which also incorporated lanthanum oxide to act as a heavy absorber. The K_α lines of all elements were measured on a Philips PW.1540 spectrometer, equipped with a Cr X-ray tube and flow proportional counter filled with 90% argon plus 10% methane gas and fitted with 3·75 μm mylar window. Pulse height discrimination and vacuum path were employed. Instrumental parameters and counting times are given below.

Oxide	Crystal	Collimator (mm)	Counting time (sec)
Fe_2O_3	(200) LiF	0·16	10
TiO_2	(200) LiF	0·16	10
CaO	(200) LiF	0·16	10
K_2O	PE	0·48	10
SiO_2	PE	0·48	40
Al_2O_3	PE	0·48	40
MgO	ADP	0·48	100

The percentage of each oxide was determined by dividing the number of counts obtained on the sample by the number of counts obtained on the standard (both corrected for dead-time losses) and multiplying the result by the calibration factor for that particular oxide. The standard used was a synthetic glass containing known amounts of the various oxides. The calculations to correct the results for matrix effects were performed on a computer, using the equation and matrix correction coefficients given by Norrish and Hutton

(1969). These results were further corrected for background by subtracting, for each oxide, an amount previously determined on samples free from that particular oxide (these samples were prepared using "Specpure" chemicals).

Electron microscope observations using an AEI EM 6 model were made on clay size material dried down from suspension on a carbon-coated copper grid and also on mineral grains which were hand-picked directly from the weathered rocks. These grains were mounted on a glass slide with Durofix and then coated with layers of carbon and carbon/platinum from five different directions. This ensured a reasonably coherent replica film over the irregular surfaces. The replicas were removed from the surface by dissolution of the substrate in a mixture of 35% HCl and 40% HF. The grains were of such a size that they were held on the surface of the solvent by surface tension until the material had dissolved. The replica film was left to float on the HF/HCl mixture overnight to ensure complete dissolution of the mineral before being transferred to a distilled water bath. The film was then picked up on a specimen support grid. In some cases contrast was enhanced by shadowing the replica films with Ni/Pd. In order to assist in the interpretation of the replicas many plates were recorded in the form of stereo pairs. This was achieved by tilting the specimen approximately 7° between successive exposures of the same field.

Optical observations were made on thin sections of coherent rock and resin-impregnated weathered material.

I.R. absorption spectra of selected samples were obtained from KBr disks using a Grubb-Parsons Spectromaster.

RESULTS

The mineralogy and chemical compositions of relatively fresh core stones and the surrounding weathered shells from granite and granulite boulders were studied in detail.

Optical and X-ray results

Core stones

(a) *Granite.* Thin sections show that the granite is holocrystalline and of medium grain size (0·3–3 mm in dia.). Point count analysis gave the following composition (in per cent) quartz 40·4, orthoclase-microperthite 24·0, microcline 17·0, plagioclase (oligoclase) 10·0, muscovite 6·8, biotite 1·8. Euhedral garnet is present as an accessory mineral.

Both orthoclase–microperthite and plagioclase appear slightly weathered, the weathering product occurring in the form of clusters of small flakes of moderate birefringence. Generally, no orientation relationship is observable between the flakes and

feldspars but where multiple twinning occurs the secondary mineral sometimes appeared to be concentrated along particular twin lamellae. Microcline is unweathered, exhibits typical cross-hatched twinning and does not appear to be perthitic.

X-ray powder photographs were taken of orthoclase-microperthite and plagioclase mixtures. In addition to feldspar lines a strong reflection at approximately 14 Å is also present which moves to 18 Å after glycerol treatment. The weathering product could therefore be provisionally identified as a montmorillonite-like mineral.

Both micas may be altered to some extent. A few flakes of muscovite show peripheral kaolinization, while biotite is occasionally altered to chlorite. Powder photographs of separated biotite and muscovite flakes showed in each instance, a strong sharp 10 Å reflection with no indication of higher spacings.

(b) *Granulite*. Thin section observations reveal a holocrystalline rock of fine grain size (0·15–0·3 mm in dia.). Point count analysis of a biotite-rich granulite yielded the following results (in per cent) quartz 40·0, alkali feldspar 38·4, biotite 19·6, muscovite 1·8. It consists of a granoblastic groundmass of quartz and slightly altered alkali feldspar interspersed with laths of biotite aligned in parallel orientation. In contrast, muscovite occurs in randomly oriented flakes; tiny hexagonal crystals of apatite are fairly common. Boulders of garnetiferous granulite, without biotite, were also found.

An X-ray diffraction trace of the total rock indicated the presence of both orthoclase and albite and this was confirmed by staining tests, which showed that both potassic and sodic feldspars are present. As in the granite, X-ray powder photographs of separated biotite and muscovite flakes contain no lines greater than 10 Å.

Weathered shells

(a) *Granite*. The clay fraction separated from the disaggregated weathered shell consists very largely of montmorillonite. The basal spacing is at 15·2 Å in the untreated state suggesting a calcium-saturated form, expands to 18 Å after glycerol treatment, and collapses to 10 Å after heating at 300°C (Fig. 1). The 060 reflection at 1·500 Å shows a dioctahedral variety. The i.r. absorption spectrum of the mineral, with bands in the OH-stretching region near 3620 cm^{-1} and no band near 870 cm^{-1}, indicated a Cheto-type montmorillonite with a low iron content (Farmer and Russell, 1964). In addition to montmorillonite a small amount of kaolinite was also detected in the separated clay fraction.

A comparison of the diffraction traces (Fig. 2) yielded by the bulk material for the core and the
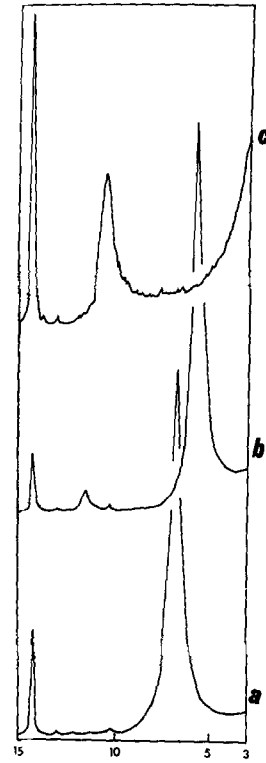

Fig. 1. X-ray diffraction traces for montmorillonite separated from weathered granite boulder: (a) untreated; (b) with glycerol; (c) heated at 300°C. Kaolinite is also present.

weathered shells shows that in the latter the main feldspar reflections become weaker whereas the basal reflection of montmorillonite intensifies. This suggests that the montmorillonite derives primarily from the weathering of feldspar and this was confirmed by X-ray examination of hand-picked feldspar-like crystals from the weathered shells. Only a montmorillonite pattern was observed indicating that the feldspar has been completely pseudomorphed. However, optical microscopy clearly reveals that only orthoclase–microperthite and plagioclase feldspar are affected in this way and that microcline is unaltered (Fig. 3a). The montmorillonite occurs as a dense aggregate of tiny randomly arranged flakes of moderate birefringence and with refractive index less than 1·53. Sometimes the montmorillonite has crystallized in long sinuous microcracks (Fig. 3b), which may traverse a variety of minerals. In such instances the clay mineral is strongly oriented and extinguishes in unison along the whole length of the fracture. The flakes are arranged approximately at right angles to this direction.
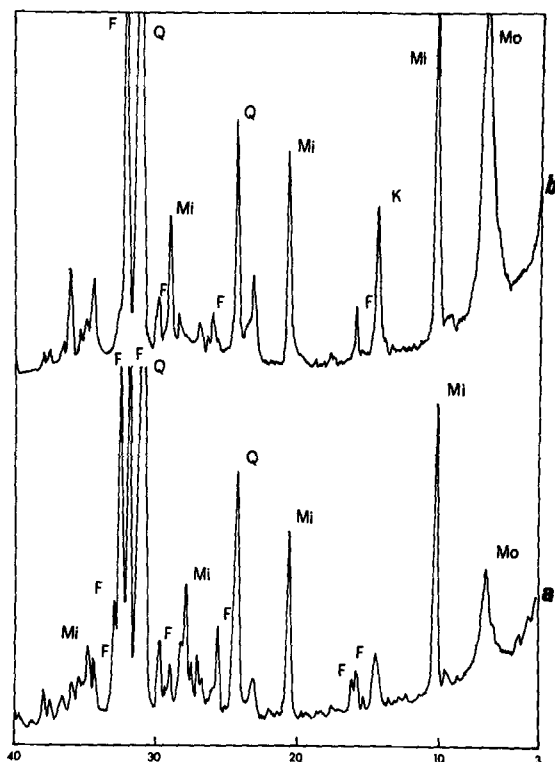
Fig. 2. X-ray diffraction traces of bulk material from (a) core and (b) weathered shell of a granite boulder. *Key* Mo—Montmorillonite; Mi—Mica; F—Feldspar; Q—Quartz; K—Kaolinite.

the absence of vermiculitization and powder photographs of biotite separated from core stones and associated weathered shells are virtually identical. However, the i.r. spectra for biotites from the weathered shell indicate the presence of a small amount of kaolinite, although this could not be observed in thin section. The chloritization of biotite noted in the core stones seems to be the result of late-stage alteration of the granite and not to weathering.

(b) *Granulite*. The clay fraction separated from the weathered shell is predominantly montmorillonite. Comparison of the X-ray diffraction traces for the relatively fresh and weathered material strongly suggests, as for the weathered granite, that the montmorillonite originates from the decomposition of the feldspars (Fig. 4). This was confirmed by optical microscopy which reveals that much of the feldspar in the granulite weathered shell was converted to montmorillonite (Fig. 3f and g). A small amount of kaolinite is present in the clay fraction and this could be traced largely to the weathering of muscovite. X-ray diffraction shows that biotite is not vermiculitized during
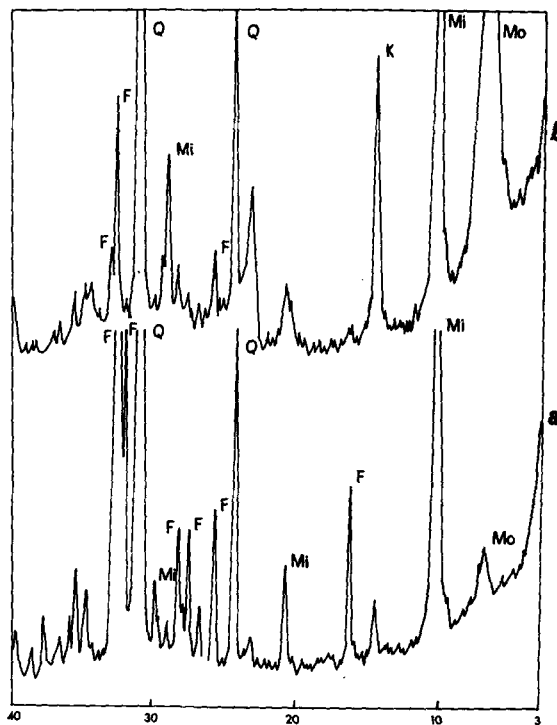
Optical observations also show that most of the kaolinite in the weathered rock derives from the weathering of muscovite. Numerous muscovite flakes could be seen which had been converted to kaolinite along the edges (Fig. 3c) or along narrow zones in the interior of the crystal (Fig. 3d). These zones of kaolinite extinguish in unison with the enclosing muscovite thus indicating a crystallographic relationship between the two minerals. In a few instances kaolinite vermicules could be observed apparently growing from an unaltered base of muscovite (Fig. 3e). It is interesting to note that kaolinitized muscovite is often surrounded by feldspar which has been completely transformed to montmorillonite. Muscovite flakes separated from the weathered material yield a strong, sharp 10 Å reflection on the X-ray diffraction diagram with no indication of higher spacings. It seems that the process of interlayer potassium removal, analogous to the vermiculitization of biotite, does not precede the rather more drastic transformation to kaolinite.

Biotite appears to remain relatively unchanged during weathering. X-ray diffraction demonstrates

Fig. 4. X-ray diffraction traces of bulk material from (a) core and (b) weathered shell of a quartz–biotite–granulite boulder. *Key* Mo—Montmorillonite; Mi—Mica; F—Feldspar; Q—Quartz; K—Kaolinite.
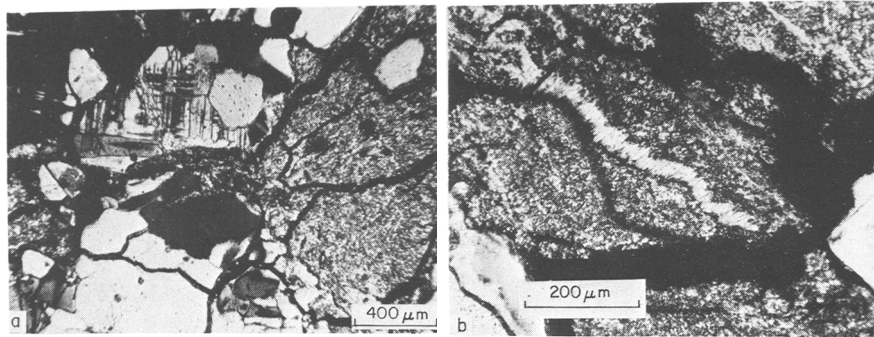
Fig. 3a. Weathered shell of granite boulder showing montmorillonitized orthoclase feldspar (grey) next to fresh microcline. Montmorillonite filled microcracks traversing quartz crystals are also evident.

Fig. 3b. Sinuous microcrack (white) filled with oriented platelets of montmorillonite. The microcrack traverses montmorillonitized orthoclase feldspar.
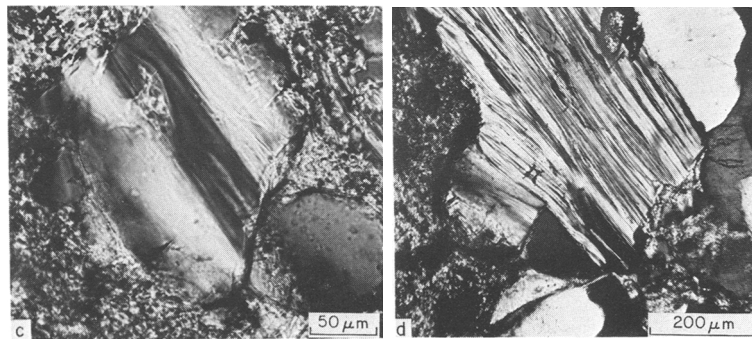

Fig. 3c. Muscovite crystal mainly converted to kaolinite surrounded by montmorillonitized feldspar.

Fig. 3d. Muscovite crystal containing zones of kaolinite (grey) along cleavage traces.
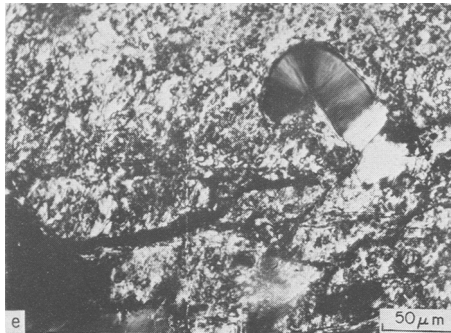
Fig. 3e. Kaolinite vermicule (dark grey) growing from a base of muscovite (white) enclosed by montmoril-lonitized feldspar.
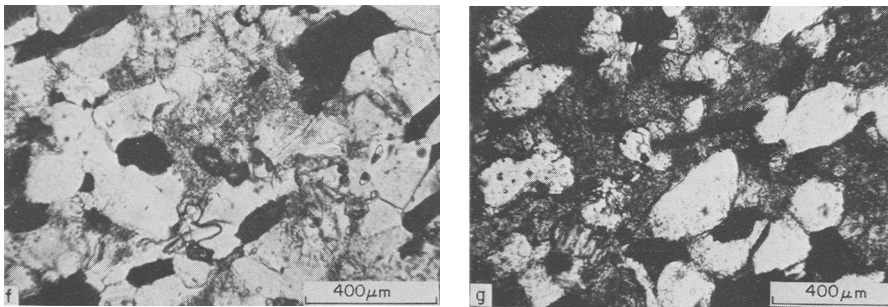

Fig. 3f. Core-stone of quartz–biotite–granulite showing biotite (black), quartz (white) and cloudy areas of alkali feldspar with incipient development of montmorillonite.

Fig. 3g. Weathered shell of quartz–biotite–granulite with dark grey groundmass of montmorillonitized feldspar, clear grains of quartz and dark laths of biotite.
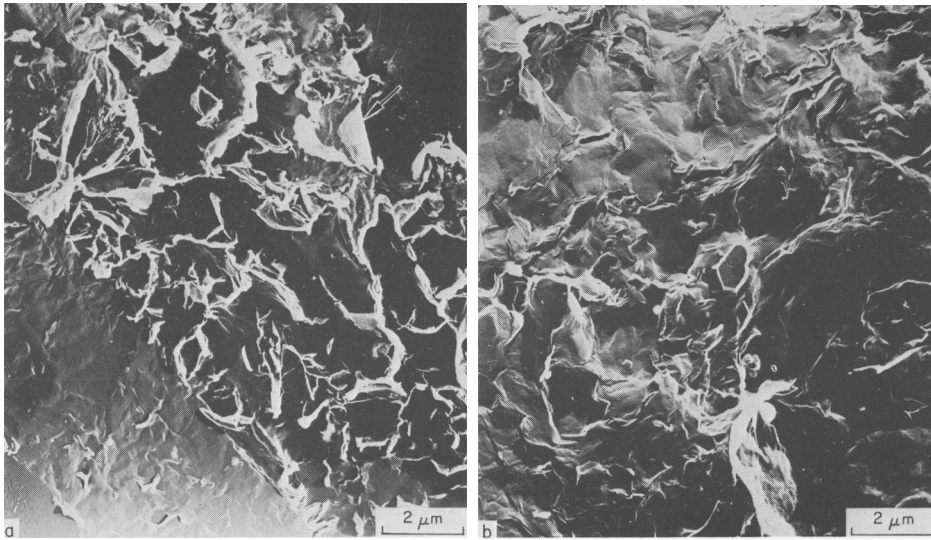
Fig. 5a. Replica of feldspar crystal from core stone of granite. Arrow indicates folded montmorillonite flake protruding from the surface in random orientation but arranged along a band that may have been an albite type twin lamellae.

Fig. 5b. Replica of feldspar crystal from weathered shell of granite. Appearance resembles compacted mass of platy clay particles.
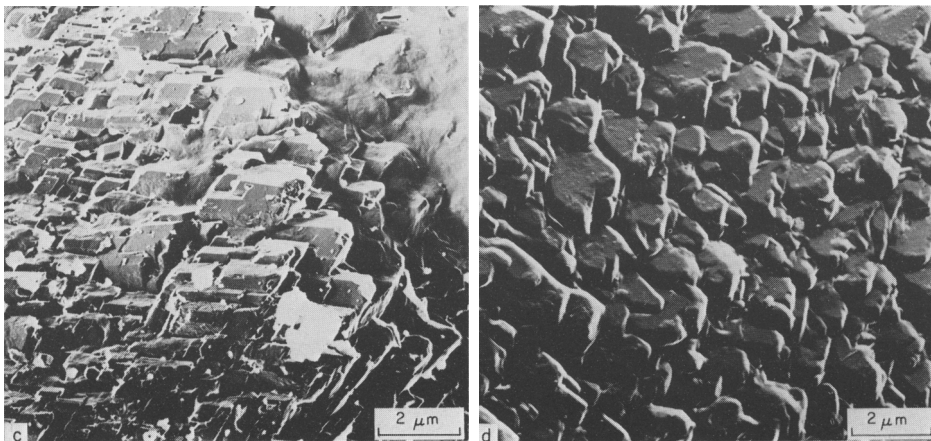

Fig. 5c. Replica of feldspar crystal from core stone of granite boulder after cleaning by ultrasonic treatment. *Note* sharp, angular edges.

Fig. 5d. Replica of feldspar crystal from weathered shell of granite boulder after cleaning by ultrasonic treatment. *Note* smoothed, rounded edges.
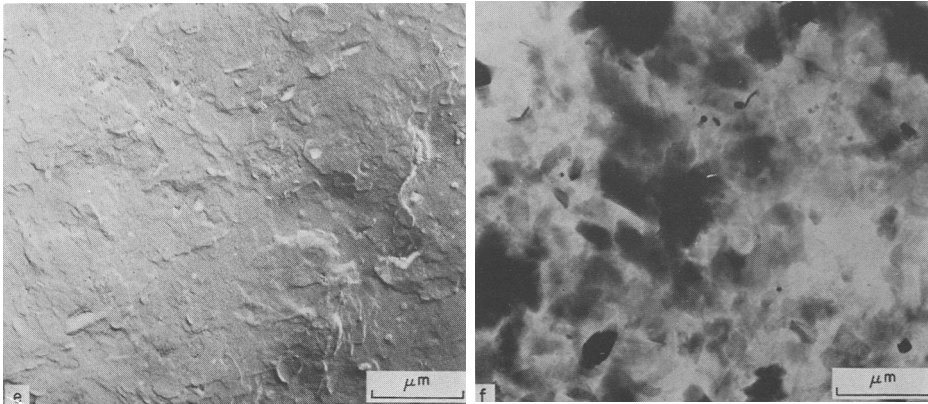
Fig. 5e. Replica of feldspar crystal from weathered shell of granite boulder after cleaning by ultrasonic treatment. Surface morphology shows pitting and etch marks in contrast to the smooth even surface of unweathered crystals.

Fig. 5f. Dispersed clay from feldspar crystals from weathered shell of granite boulders showing poorly-defined aggregates of thin flakes (montmorillonite). The occasional sharply defined laths and plates are possibly mica (arrowed).

weathering although i.r. spectroscopy again indicates trace amounts of kaolinite.

A significant textural feature shown in thin sections of weathered shells of both granite and granulite is a network of microfractures, some of which are filled with a carbonate mineral.

Electron microscope observations

(a) *Core material.* Replicas of hand-picked feldspar grains show a wide variation in morphology. Some areas are smooth and flat whilst others are criss-crossed with spectacular cleavage steps; presumably both represent unweathered material. On the other hand, some areas have a very rough appearance. Figure 5a shows a band 7 μm wide, which extends for several hundred μm through a smooth part of the replica. The morphology of this band is typical of similar more extensive areas. Stereo pairs reveal that the light parts of the replica represent thin flakes of material projecting vertically or enveloping surface protruberances. The arrow in Fig. 5a indicates such a flake that has folded back on itself. This type of morphology is strongly indicative of montmorillonite and the narrow band may represent formation of montmorillonite along particular albite twin lamellae observed in thin section.

(b) *Weathered shell.* Replicas of weathered grains are uniformly rough although individual flakes projecting from the mass are less evident. The appearance suggests that whole grains have been transformed into a compact mass of fine montmorillonite-like particles (Fig. 5b).

(c) *Ultrasonically cleaned grains.* Feldspar grains from both core and weathered material were studied after cleaning by ultrasonic vibration for 1 min at 20 KHz in distilled water. In the replica of the cleaned material none of the rough areas previously noted could be found. This indicates that the clay material was readily loosened from the surface and dispersed by the ultrasonic treatment. Again, a wide variety of morphological features were noted for both the core and weathered material, blocky features being more evident. These are angular in the core material (Fig. 5c) but much more rounded in the weathered material (Fig. 5d) as if they had been dissolved to some extent. At high magnification even relatively smooth and flat areas have a finely etched morphology (Fig. 5e).

(d) *Dispersed clay.* The clay size material dispersed from both core and weathered grains shows typical montmorillonite-like morphology. The particles are diffuse and poorly defined, apart from a few laths of mica and fragments of quartz and feldspar (Fig. 5f).

Chemical results

Chemical analyses of the relatively fresh and weathered material from granite and granulite boulders obtained mainly by X-ray fluorescence are shown in Table 1. For both rocks there is only a slight loss of silica and alumina in the weathered shell. In the granulite there is a loss of calcium, potassium and sodium but an increase in magnesium, as would be anticipated after a feldspar-to-montmorillonite transformation. With the exception of potassium similar trends are also noted for weathered granite. The reason for the increase in potassium is not clear but it may be that the boulder analyzed is heterogeneous, the outer shell containing more microcline and biotite than the relatively fresh core. Also in Table 1 is an analysis for the clay fraction from a weathered garnetiferous granulite boulder. From X-ray evidence the clay is a pure smectite. Both the magnesium content and Si:Al ratio (4·8:2) are consistent with montmorillonite but not with beidellite. The latter is much lower in magnesium with a Si:Al ratio of about 3:2 (MacEwan, 1961). This analysis supports the conclusion reached by i.r. spectroscopy that the smectite is a low iron Cheto-type montmorillonite.

DISCUSSION

The analytical data demonstrate that, with the exception of microcline, the feldspars in the granite and granulite boulders – orthoclase, orthoclase-microperthite, albite and oligoclase – are converted to montmorillonite during weathering.

A similar weathering change involving feldspars

Table 1. Chemical analyses (percentage) of fresh and weathered materials and of montmorillonite (Analyst D. C. Bain)

	1	2	3	4	5
SiO_2	73·2	70·9	69·1	68·9	48·1
Al_2O_3	14·6	13·7	14·8	13·7	20·7
Fe_2O_3*	0·93	1·08	3·98	3·86	1·04
MgO	0·29	0·64	1·25	1·76	3·03
CaO	1·05	0·79	1·93	1·55	5·91
K_2O	4·35	4·60	3·75	1·64	0·61
Na_2O†	1·82	0·57	2·41	0·54	0·02
TiO_2	0·10	0·12	0·66	0·55	0·10
L.O.I.	3·35	5·70	2·05	8·70	20·7
Total	99·69	98·10	99·93	101·20	100·21

1. Core stone from granite boulder.
2. Associated weathered shell.
3. Core stone from quartz–biotite–granulite boulder.
4. Associated weathered shell.
5. Ca-saturated montmorillonite from weathered garnetiferous granulite.
*Total iron.
†Determined flame photometrically.

in granites has been previously reported by Alexanian (1951, 1960). X-ray, optical and electron microscope observations do not reveal the presence of any intervening well-defined crystalline or amorphous phase and the transformation to montmorillonite appears to be a direct one. This contrasts with the findings of Guilbert and Sloane (1968) in their electronoptical study of hydrothermal fringe alteration of plagioclase in quartz–monzonite. As an intermediate stage in the development of montmorillonite they noted the formation of a "hobnail" texture composed of sparse to dense ~ 0.5 μm discoids of amorphous material on fresh feldspar cleavage surfaces. Parham (1969) has also postulated the existence of an intermediate amorphous phase in the tropical weathering of feldspar. This took the form of tiny bumps and tapered projections growing outwardly from feldspar surfaces and often merging laterally to form thin flame-shaped sheets. In this instance the end product was halloysite and kaolinite. Optical and electron-optical observations in the present study indicate that in the feldspar-to-montmorillonite transformation the primary mineral has exerted little structural control although as mentioned above, preferential development of the clay mineral along particular albite twin lamellae is sometimes observed. The presence of oriented montmorillonite flakes infilling long, sinuous microcracks suggests that the decomposition products of the feldspars possessed a certain degree of mobility. Thus, the formation of the clay mineral appears to have proceeded by crystallization from solution or colloidal suspension within disintegrated feldspar grains or microcracks. It is of some interest that the feldspars weather to montmorillonite and not to beidellite. The latter mineral might have been expected to form in view of the negligible magnesium content of feldspars and it seems that the magnesium ions must have been introduced by the weathering solutions.

Formation of montmorillonite during weathering processes is thought to be favored by a relatively closed alkaline environment with retention of alkaline earths and silica (Keller, 1957) and the evidence from the weathered granite and granulite boulders is consistent with this generalization. An alkaline environment is indicated by the presence of carbonate filled microfractures observed in thin section while chemical analyses for core and weathered shells show only a slight decrease in silica and an increase in magnesia. However, calcium is depleted to some extent. On the other hand, numerous studies have shown that kaolinite formation is enhanced by open, acid conditions with the continual removal of silica and metal ions. Keller (1957) suggests that it is especially

important that alkaline earths and ferrous iron be removed if kaolinization is to occur. In the weathered boulders, thin section observations suggest that kaolinite has formed from muscovite at the same time and in the same general environment as montmorillonite formed from feldspars. Certainly, there is no evidence to suggest that weathering proceeded in two distinct and contrasting stages. The explanation of this apparent anomaly is not known, although it may be that kaolinite is able to attain chemical equilibrium in relatively closed, alkaline conditions, as suggested by Zen (1959).

In many weathering studies the primary minerals involved are arranged into an order of stability to weathering. The most commonly occurring order, first observed by Goldich (1938), follows Bowen's sequence of fractional crystallization, and, for the primary minerals of granite, the order of increasing stability is:

$$plagioclase < biotite < orthoclase < muscovite$$
$$< quartz.$$

Specific exceptions to this order have frequently been noted. In the present study the most probable order of stability is:

$$plagioclase = orthoclase < muscovite < biotite$$
$$< microcline < quartz.$$

It is clear that, as suggested by Hénin, Pedro and Robert (1968), the relative stabilities of minerals cannot be considered invariant but must always be assessed in terms of the prevailing weathering conditions. Thus, a stability sequence found in an open, acid environment may be different to that in closed, alkaline conditions like those considered here. In addition, the chemical and structural variability of individual minerals must militate against a fixed order of susceptibility to weathering.

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Résumé – Les minéraux argileux formés dans un conglomérat à galets profondément altéré du niveau Middle Old Red Sandstone (Dévonien) situé au Nord-Est de l'Ecosse, ont été étudiés par diverses techniques physiques et chimiques. Dans ce gisement, les galets de granite et de granulite sont complètement altérés. A l'exception du microcline, tous les feldspaths de ces roches – orthoclase, orthoclase-microperthite, albite et oligoclase – s'altèrent en une montmorillonite du type Cheto, pauvre en fer. Les microscopies électronique et optique indiquent que la transformation qui se passe pendant l'altération est directe, sans aucune intervention de phase à cristallisation intermédiaire ou de phase amorphe bien définie. Le contrôle structural qu'exerce le minéral primaire sur la formation de la montmorillonite semble avoir été un facteur de faible importance et ce que l'on observe suggère que le minéral argileux a cristallisé à partir de produits dissous ou colloïdaux provenant des feldspaths décomposés. De plus petites quantités de kaolinite se sont également formées pendant l'altération, mais essentiellement à partir de la muscovite. L'environnement dans lequel ces changements ont eu lieu semble avoir été un système relativement fermé et alcalin. Les analyses chimiques des parties profondes et des écailles altérées correspondantes des galets de granite et de granulite montrent seulement une légère diminution de la silice et une augmentation de la magnésie. Si l'on se réfère à l'importance de l'altération en minéraux secondaires, l'ordre de résistance à l'altération des minéraux primaires de ces roches est: plagioclase = orthoclase < muscovite < biotite < microcline < quartz.

Kurzreferat – Die Tonminerale, die sich in einem tief verwitterten Geschiebekonglomerat in der Sandsteinschicht der Devonischen Formation von Nordostschottland gebildet hatten wurden mittels verschiedener physikalischer und chemischer Methoden untersucht. Die Granit – und Granulitgeschiebe dieses Vorkommens sind vollständig verwittert. Mit der Ausnahme des Mikroklins, verwittern alle die Feldspate dieser Gesteine – Orthoklasfeldspat, Orthoklasmikroperthit, Albit und Oligoklas zu einem eisenarmen Montmorillonit vom Cheto-typ. Elektronen- und optische Mikroskopie zeigen an, dass die Witterungsverwandlung eine unmittelbare ist, ohne das Dazwischentreten einer kristallinen oder wohlausgebildeten amorphen Zwischenphase. Die Gefügesteuerung des Primärminerals in bezug auf die Bildung des Montmorillonits scheint ein unbedeutender Faktor gewesen zu sein und das vorhandene Material deutet darauf hin, dass das Tonmineral aus den löslichen oder kolloidalen Produkten kristallisiert hat, die sich aus den zersetzten Feldspaten ergeben. Während der Verwitterung werden auch kleinere Mengen von Kaolinit gebildet, jedoch hauptsächlich durch die Verwitterung von Muskowit. Das Milieu in dem diese Veränderungen stattfanden scheint alkalisch gewesen zu sein, in einem verhältnismässig geschlossenem System. Chemische Analysem verwandter Bohrkerne und verwitterter Schalen von Granit- und Granulitgeschieben zeigen nur eine geringe Verminderung an Kieselsäure und eine Zunahme an Magnesia an. Auf Grund des Ausmasses an Veränderung zu sekundären Tonmineralen kann angenommen werden, dass die Widerstandsfähigkeit der Primärminerale gegen Verwitterung in diesem Gestein gemäss der folgenden Reihenfolge vertauft: Plagioklas = Orthoklas < Muskowit < Biotit < Mikroklin < Quartz.

Резюме — С использованием различных физических и химических методов проведено исследование глинистых минералов, образовавшихся в глубоко выветрелых валунных конгломератах девона (Миддл Олд Ред Сэндстоун) северо-востока Шотландии. Гранитные и гранулитовые валуны испытали глубокое выветривание. За исключением микроклина, все полевые шпаты — ортоклаз, ортоклаз-микропертит, альбит и олигоклаз — превращены в монтмориллонит типа цето с малым содержанием железа. Изучение в электронном и оптическом микроскопах показало, что выветривание протекало без образования каких-либо промежуточных кристаллических или аморфных фаз. Влияние структуры первичных минералов на процесс образования монтмориллонита, по-видимому, является минимальным и имеются доказательства того, что кристаллизация глинистых минералов происходила из истинно

растворенных или коллоидных соединений, образовавшихся при разложении полевых шпатов. В процессе выветривания образовалось также небольшое количество каолинита, главным образом, по мусковиту. Среда, в которой протекали изменения минералов, очевидно, была щелочной, а система — относительно замкнутой. Химические анализы свежих и выветрелых частей гранитных и гранулитовых валунов обнаружили лишь незначительный дефицит кремнезема и повышенное содержание окиси магния. Судя по степени изменения в глинистые минералы, по устойчивости к выветриванию первичные минералы образуют ряд : плагиоклаз = ортоклаз < мусковит < биотит < микроклин < кварц.