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THE PRE-QUATERNARY SEDIMENTARY ROCKS OF SWEDEN

BY

ASSAR HADDING

IV.

GLAUCONITE AND GLAUCONITIC ROCKS

WITH 73 FIGURES IN TEXT

LUND
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Read in the Royal Physiographical Society, April 8, 1931.

Preface.

Regardless of certain carbonates, silica, and the saline residues proper we hardly find any minerals among the autochthonous constituents of the sedimentary rocks that attract our interest in the same degree as the ferruginous silicates. That among these the author has chosen the glauconite and made it the subject of special study does not depend on this mineral being in itself of greater interest than the other iron silicates, for inst. the minerals of the chamosite group. The reason is instead that the glauconite is widely spread in the Swedish sediments and that its occurrence in the sandstones as well as in the limestones is particularly important from a sedimentational point of view. Its occurrence in both the said groups of rocks is the reason why the author has not discussed the mineral more in detail first in the account of the sandstones and then in the investigation of the limestones. He has found it more suitable to take up the investigation of all the Swedish glauconitic rocks in one connection.

The following account is arranged in the sequence in which the work was executed. It is evident from this that the study of literature has been put of till the investigation of the author's own material was finished. In this manner the author intended to gain two advantages — more independence in his own investigations and increased possibilities to understand and estimate the problems and difficulties with which other investigators have had to contend.

By detailed studies of *the glauconite-bearing rocks and series of strata* the author has, in a higher degree than any earlier investigator, tried to explain the conditions, under which glauconite was and is formed. It has not then been possible for him to avoid touching upon problems of a different kind, for inst. the rhythmic deposition of certain limestones, the colour banding, the abrupt transition from alum shale to glauconitic shale, the stratigraphic breaks, etc.

In this work as in the preceding parts of the same series the author has principally interested himself in the problems. By detailed studies of certain characteristic series of strata and an orientation in others he has tried to obtain the surest possible basis for the discussion of the problems. The Swedish sediments, certainly, do not supply the definite solution of these, but they open them again and illustrate them from fresh points of view, adding several new questions to the old ones. In many cases the author has considered that he might draw fairly certain conclusions, but he regards the work as more valuable from the point of view that it indicates lines for a continued glauconite investigation, not least in the areas where the mineral is still forming.

IV.

GLAUCONITE AND GLAUCONITIC ROCKS

CONTENTS.

The Glauconitic Rocks and the Glauconite-bearing Series of Strata.

In order to understand the conditions under which glauconite is formed it is not sufficient to examine the mineral itself. An examination of the rocks and the series of strata in which it occurs is equally desirable. We may add here that an investigation of the conditions under which the glauconite *does not* occur is also of importance in this connection and on that account a survey of the glauconite-free rocks and the glauconite-free parts of the series of strata will also be given in the following.

The Glauconite-bearing Series of Strata. I.

(Special part.)

In the sedimentary series of strata of Sweden we find glauconite in many horizons from the Lower Cambrian up to the Tertiary. The percentage of glauconite, however, varies greatly. In some places the mineral occurs rock-forming on a large scale, while other and still larger parts of the series of strata are completely free from glauconite.

The parts most abundant in glauconite in the Swedish series of strata are found in the Lower and Middle Cambrian, in the Lower Ordovician, in the Cretaceous (Senonian), and in the Tertiary.

In certain horizons of these series of strata the glauconite appears to be very widely distributed. Thus the Ceratopyge stage for inst. is highly glauconitic in the greater part of Sweden (Öland, Vestergötland, Östergötland, Nerke, Dalecarlia, Jemtland) as well as on the other side of the Baltic in Esthonia.

In other cases the occurrence of the glauconite is more restricted or more sporadic though abundant in some places. This is the case in the Lower and Middle Cambrian.

In order to clear up the conditions under which the glauconite was formed it is of interest, as mentioned above, to observe the rocks and the series of strata in which it occurs. An account will therefore be given in the following, partly of a couple of glauconite-rich series of strata studied in detail, the one calcareous the other arenaceous, and partly of the different types of rocks to which the glauconite is connected.

The Glauconitic Strata in the Lower Ordovician of Öland.

Nowhere in Sweden is there a series of strata as rich in glauconite as the Lower Ordovician in Öland. The thickness and the glauconite content of the strata may change from one place to another but they are always glauconite-bearing and as a rule a few beds at least are rich in glauconite. In Öland the lower part of the Asaphus limestone (the Planilimbata limestone)[1] is generally also developed as a glauconitic limestone.

Glauconite is also found in other parts of the Cambro-Silurian series of strata in Öland, for inst. in the Middle Cambrian Tessini sandstone, but no continuous formation of glauconite like the Lower Ordovician has taken place.

The sharp limit between the glauconitic strata and their substratum is characteristic of all the Ordovician occurrences of glauconite in Öland. The glauconite occurs abruptly. Glauconite-rich strata are often found resting directly on an absolutely glauconite-free alum shale and intraformational conglomerates (see Fig. 1 and 3).

The substratum, however, varies somewhat and an examination of the series of strata shows that this has been formed under a somewhat varying sedimentation. In order to understand the changes from one place to another, shown by the glauconite-bearing part of the series of strata, it may be important also to know the different sedimentary conditions in these places during the time immediately before the deposition of the glauconitic strata.

The adjoining drawing, Fig. 2, is a diagram of the sedimentation in Öland during *the Upper Cambrian* (i. e. during the time before the formation of the glauconite) on five points fairly evenly distributed along the western shore of Öland (map p. 44). It is evident from the drawing that the sedimentation farthest south has been relatively undisturbed while in the north it has been interrupted by longer and longer periods with no or negative sedimentation. Intraformational conglomerates with fragments of the disintegrated beds give us a fairly clear idea of the procedure of deposition in the different places. Fine clayey mud and bitumen have been deposited in the entire region during the sedimentary periods and the supply of such material has no doubt been relatively uniform. At any rate the uneven deposition may not be owing to local variations in the supply but to varying possibilities of settling.

Thus it is evident from the substratum of the glauconitic series, the Upper Cambrian series of strata, that the conditions of deposition have been considerably more favourable in southern than in northern Öland. We may also conclude that this is due to the fact that the water in which the deposition took place was considerably stiller and probably deeper in the south than in the north. The conglome-

[1] Moberg (1906, 43) called in question whether the lower part of the Planilimbata limestone should not be counted to the Ceratopyge region.

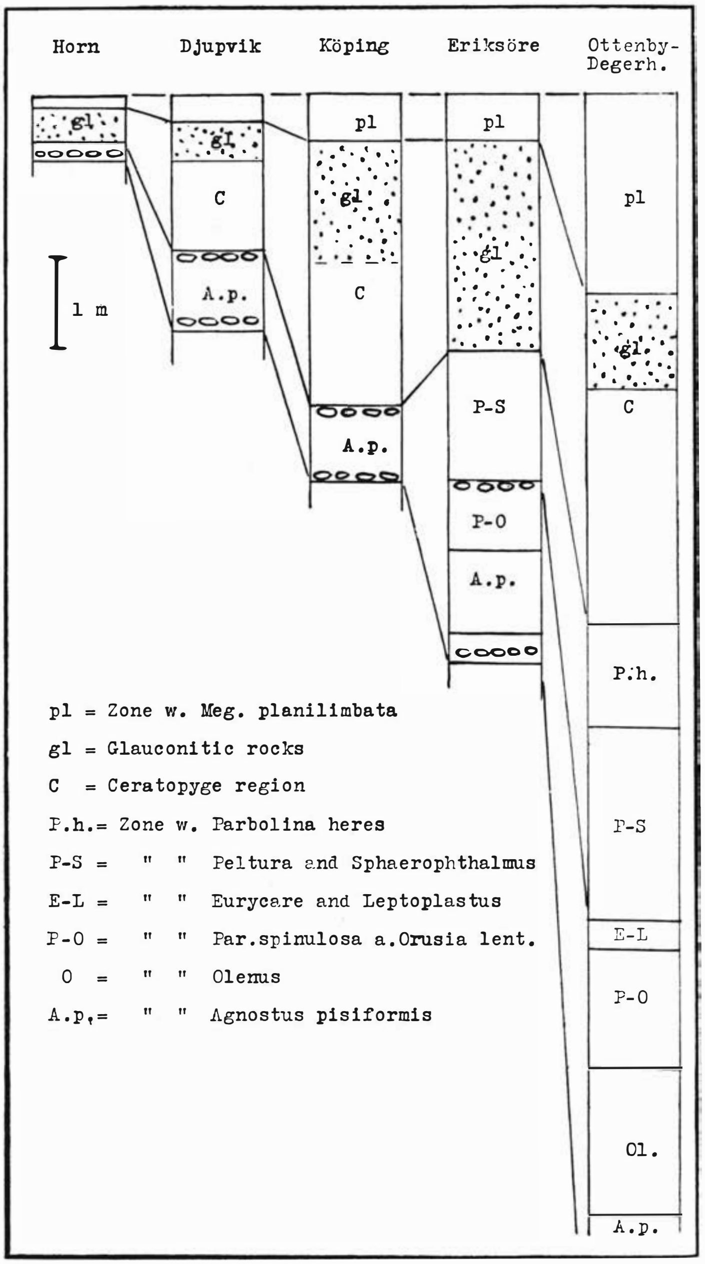

Fig. 1. The Upper Cambrian of Öland and its relation to the Lower Ordovician glauconitic strata.

rates present in the Upper Cambrian series of strata in central and northern Öland show that the movement in the water in this part of the region was strong enough to break up the previously deposited beds.

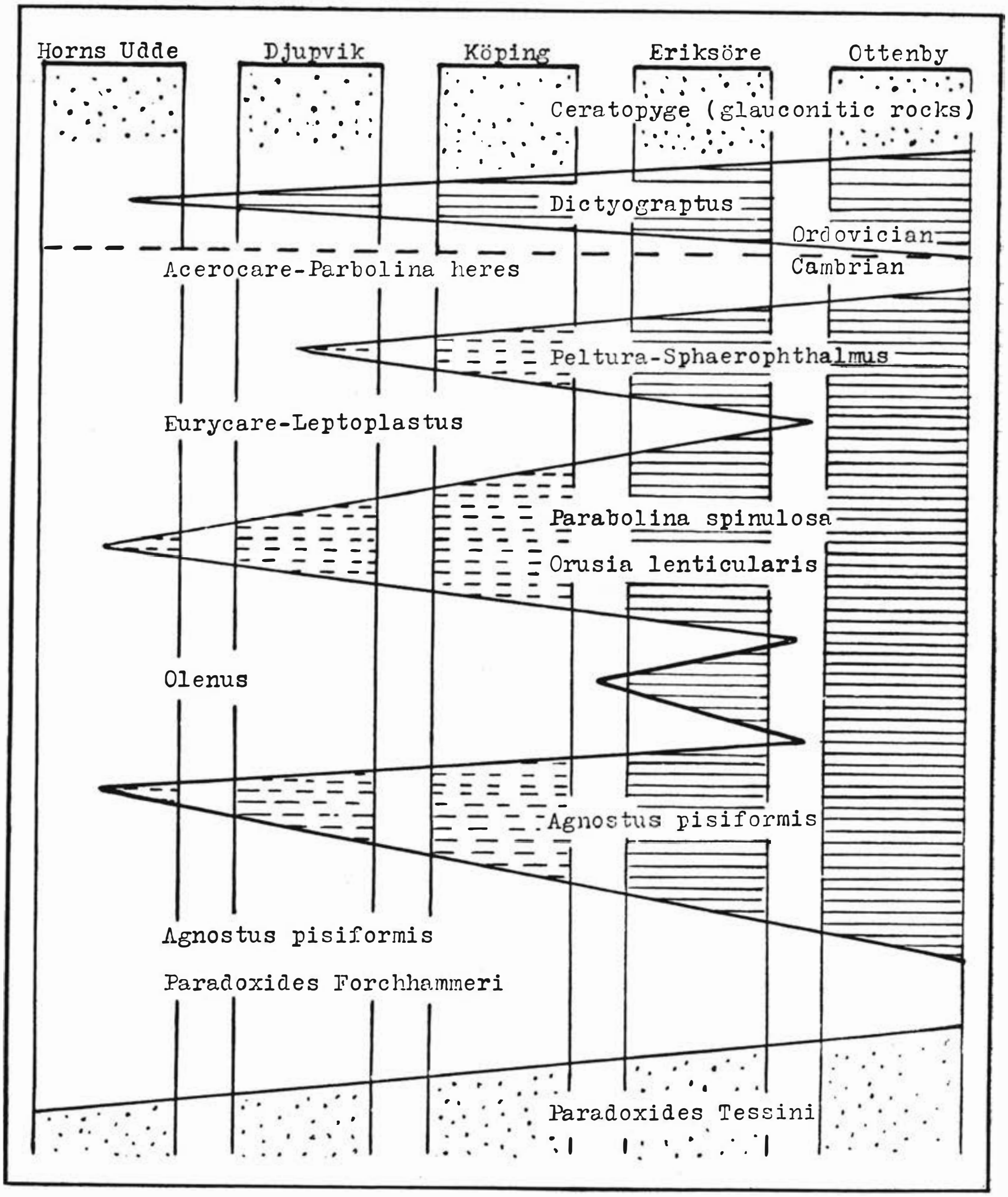

Fig. 2. The fluctuation of positive and negative sedimentation at Öland during the Upper Cambrian. *Hatched areas* = alum shale and stinkstone; *Broken lines* = the same sediments, wholly or partly destructed by negative sedimentation; *White areas* = no or negative sedimentation (gaps).

Then the basin of deposition becomes comparatively free from both clayey mud and bitumen. The water becomes clear. Sedimentation does not, however, cease completely but it becomes of course quite different from before. Detritus no longer dominates in the deposited sediments but authigenic minerals instead, especially calcite and glauconite. How this change in the sedimentation appears in the preserved series of strata is seen partly from the adjoining diagram, Fig. 3, of the occurence of the glauconitic rocks at a number of places in Öland, and partly from the following account and the added sections of details from the shore of Ottenby

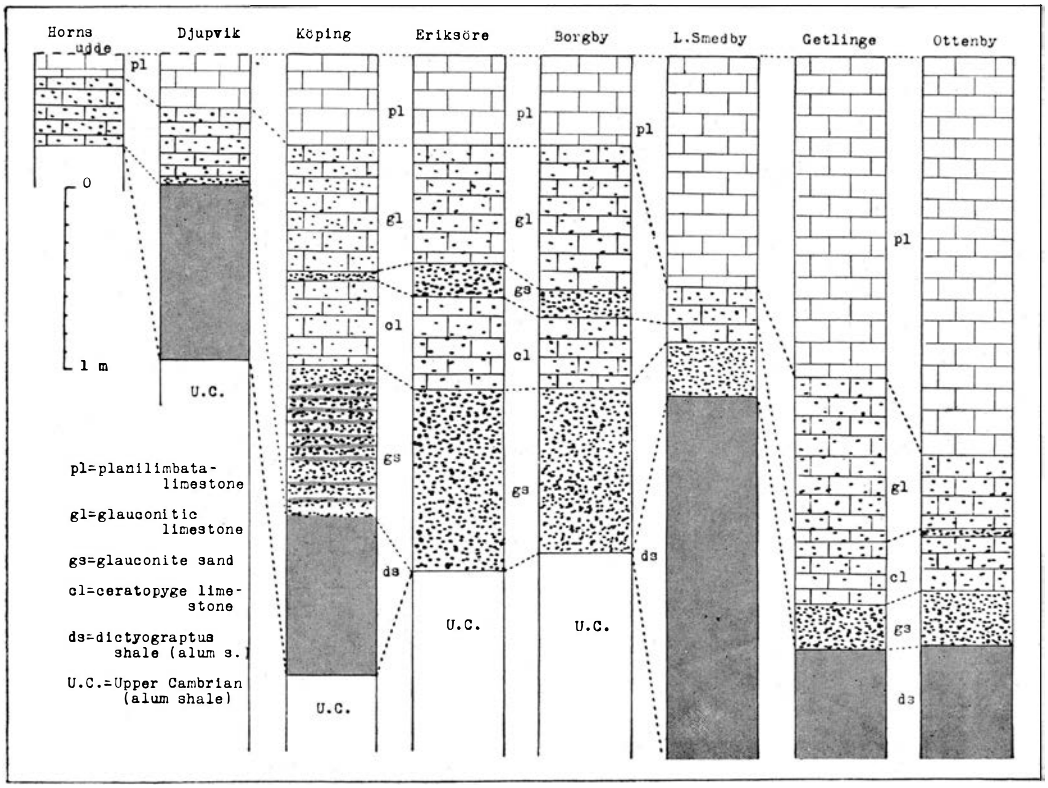

Fig. 3. The glauconitic Lower Ordovician series of strata at different parts of Öland. Above the upper limit of the drawn series red »Limbata limestone» follows.

in the south of Öland, from Köpings Klint in central, and from Horns Udde in northern Öland.

The section at Köpings Klint, east of Borgholm, shows a sedimentary progress differing in many respects from that estimated from the series of strata at Ottenby and Horns Udde. The glauconitic series is thicker at Köpinge than in other places and it also contains a great number of glauconite-free or glauconite-poor detritus beds which further increase the thickness of glauconite-bearing series of strata. The three sections from Öland, published and discussed in the following, complete each other in a fortunate manner.

The Series of Strata at Ottenby in the South of Öland.

On the shore west of Ottenby the lower Ordovician strata crop out in a low cliff. About 1 km NW of the hall the adjoining section was measured (the strata stated from the top downwards): —

Stratum	13.	Limestone, gray	11	cm	Planilimbata limestone
»	12.	Glauconitic limestone	11,5	»	Ceratopyge limestone
»	11.	Glauconitic limestone	5,5	»	
»	10.	Limestone, gray	2,5	»	
»	9.	Glauconitic limestone	10	»	
»	8.	Glauconitic limestone	9	»	
»	7.	Glauconitic limestone	6	»	
»	6.	Glauconitic limestone	7	»	
»	5.	Glauconitic shale	2,5	»	
»	4.	Glauconitic limestone	7,5	»	
»	3.	Limestone, gray	8	»	
»	2.	Limestone, gray	10	»	
»	1.	Glauconitic limestone	4,5	»	
»	0.	Glauconitic shale	30	»	Ceratopyge shale
»	—1.	Alum shale	—		Dictyograptus shale

A somewhat closer knowledge of the nature of the different beds in the glauconite-bearing series of strata is of importance for the discussion of the relation between the character of the rocks and their percentage of glauconite or the relation between the formation of glauconite and of other sediments, especially the deposition of detritus. The account of the said series of strata, however, has been abbreviated and schematized as far as possible and in this way the author hopes not only to have saved space but also to have succeeded in making the account clearer. After a short characterization of the *macroscopical* qualities of the rock the result of the *microscopical* exami-

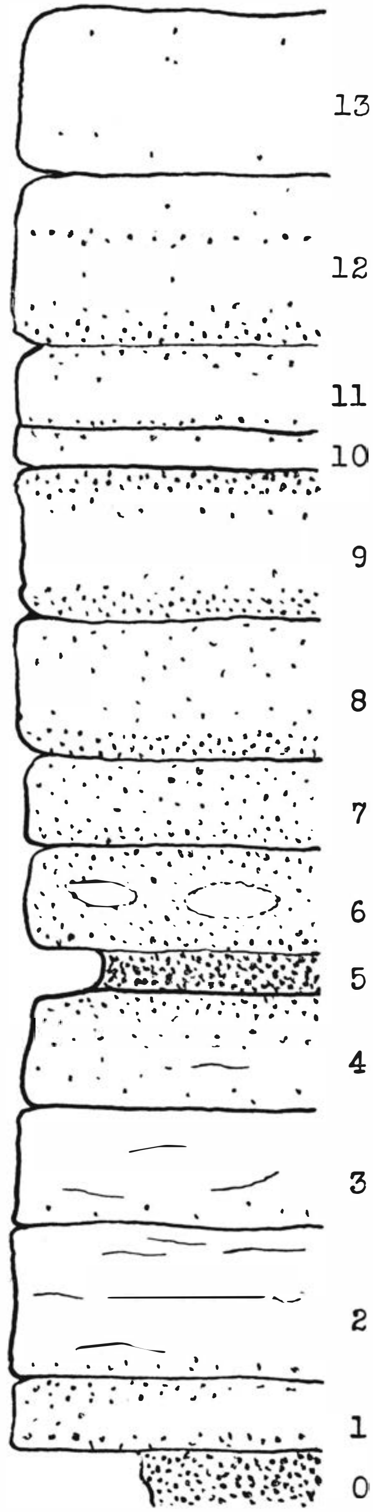

Fig. 4. The glauconitic series of strata at Ottenby.

nation is stated only with regard to *ground mass* (calcareous mass or matrix) and the contents of *fossils, pyrite, and glauconite.*

The above-mentioned series of strata on the shore at Ottenby, described more in detail below, is covered by a dense, hard, grayish lilac limestone: ground mass microscopically distinctly crystalline. In this rock,

Fossils: numerous fragments of shells, partly recrystallized.
Pyrite: very sparingly present in small aggregates.
Glauconite: only in single grains, rounded and without cracks, undoubtedly in a secondary place of deposition; diameter about 0,07 mm.

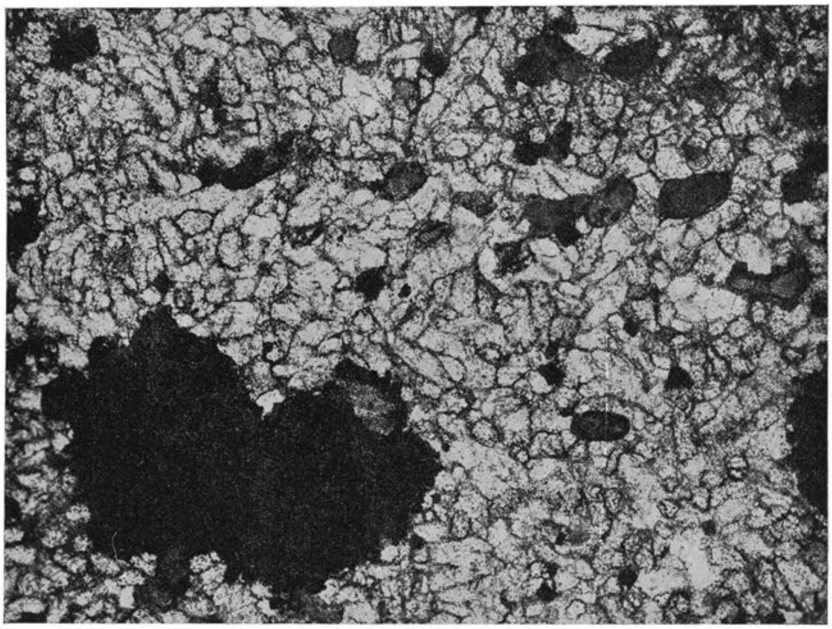

Fig. 5. Small grains of glauconite and (to the left) an aggregate of pyrite. Ottenby, stratum 13. (Pr. 3007 b. Pl. 528.) — 60 ×.

Stratum 13. Gray, fine-crystalline (granular) limestone with scattered grains of glauconite.
Ground mass: calcite grains 0,1—0,4 mm, without pigments.
Fossils: very sparse fragments of shells.
Pyrite: in small cubes, about 0,05 mm in diameter, and in round aggregates, about 1 mm in diameter.
Glauconite: grains, rounded, tabular or angular (fragments), generally less than 0,2 mm in diameter (fig. 5); often with a dark-pigmented peripheral zone, sometimes enclosed in pyrite; allochthonous glauconite. Less than 1 per cent of the mass of the rock.

Stratum 12. The upper part: dense gray limestone with scattered grains of glauconite.

Ground mass: fine-crystalline, granular, with crystals 15—30 μ.

Fossils: not observed.

Pyrite: sparingly in fairly evenly distributed crystals and small aggregates (about 30 μ).

Glauconite: grains, 0,4—1,2 mm in diameter rounded and tabular, strongly worn, sometimes with an uneven dark zone. Glauconite 2 per cent; in the lower part a narrow band with 30 per cent.

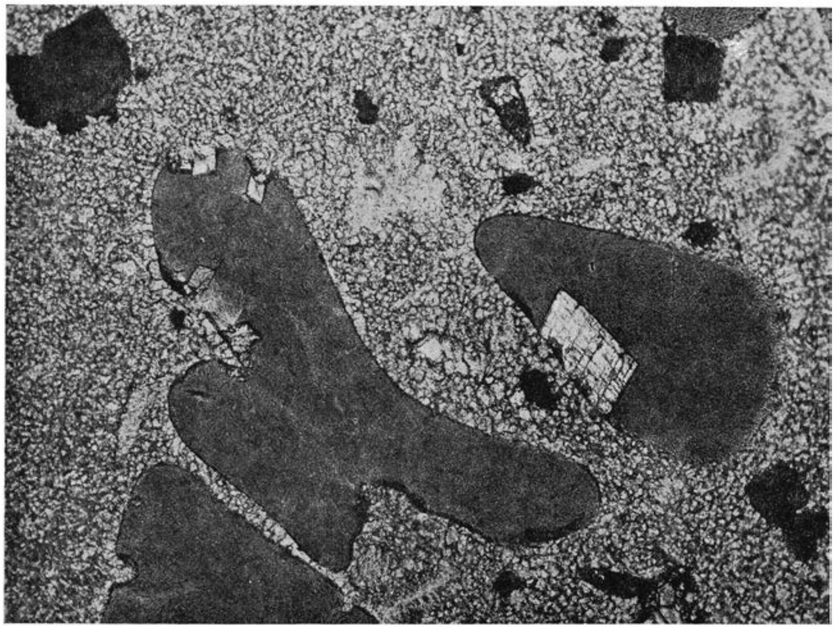

Fig. 6. Glauconite grains (with secondarily formed siderite crystals) and pyrite in a fine-crystalline limestone. Ottenby, stratum 12. (Pr. 3005. Pl. 527.) — 60 ×.

Stratum 12. The lower part: glauconitic limestone, passing downwards into consolidated glauconite sand.

Ground mass: fine-crystalline calcite (grains 50 μ); distinct recrystallization.

Fossils: fragments common; trilobites, brachiopods with calcareous as well as phosphatic shells.

Pyrite: Sparse cubes (0,1 mm) and small aggregates.

Glauconite: mostly irregular, tabular grains, distinctly worn and without marked cracks, diameter commonly 0,7 mm, at most 2 mm, sometimes dark marginal zone, often corroded, with enclosed, secondarily formed crystals of siderite (see fig. 6); as inclusion also pyrite. Glauconite 40 per cent, in the lower part 80 per cent.

Stratum 11. Glauconitic limestone with the content of glauconite decreasing towards the centre and increasing towards the bed surfaces.
Ground mass: granular calcite, grains about 15 μ.
Fossils: not observed.
Pyrite: scattered crystals, 10—16 μ, and small aggregates.
Glauconite: tabular or irregular grains, 0,3—1 mm, with dark marginal zone and enclosed rhombohedrons of siderite, sometimes transformed into reddish brown haematite. Content of glauconite close to the bed surfaces 85 per cent, in the central parts 2 per cent, for the rest 60—80 per cent.

Stratum 10. Fine-crystalline, gray limestone with a thin layer of glauconitic grains at the upper bedding surface and a coating of glauconite (glauconite skin) on the walls of cracks.
Ground mass: granular, with slightly pigmentary filling between the crystals of calcite.
Fossils: fragments of brachiopod shells, often with a margin of radiate calcite.
Pyrite: cubes with 5—50 μ long edges and small aggregates.
Glauconite: in worn, round or tabular grains, 0,1—1,5 mm, sometimes broken, often containing rhombohedrons of siderite. Glauconite about 2 per cent

Stratum 9. Limestone bed rich in glauconite and distinctly spathic in the upper part, poor in glauconite and dense in the middle, and in the lower part coarsely spathic and rich glauconite but with enclosed lumps of dense, gray, glauconite-free limestone.
Ground mass: crystalline with varying size of grains, recrystallized with certain crypto-crystalline parts preserved. Single grains of quartz, about 0,03 mm in diameter.
Fossils: only small fragments of phosphatic shells (brachiopods).
Pyrite: small crystals and aggregates, mostly in the lower part of the bed.
Glauconite: rounded grains, often completely jagged by secondarily formed rhombohedrons of siderite. Grains up to 2 mm in size. Sometimes crystals with distinctly fibrous or foliaceous structure. Glauconite in the upper part 50 per cent, in the middle 3 per cent, and in the lower part 40 per cent.

Stratum 8. Glauconitic limestones with fairly evenly distributed content of glauconite.
Ground mass: recrystallized with occasional crypto-crystalline residuary lumps.
Fossils: not observed.
Pyrite: scattered aggregates, often enclosing grains of glauconite.
Glauconite: rounded grains, often with the edge jagged by secondarily formed crystals of siderite. Grains seldom exceeding 1 mm in size. Glauconite in the upper part 25 per cent, in the lower part 35 per cent.

Stratum 7. Glauconitic limestone, passing into glauconitic shale towards the bedding surfaces.

Ground mass: gray, fine-grained; crystals about 0,15 mm. Occasional grains of quartz, about 0,07 mm in diameter.

Fossils: not observed.

Pyrite: scattered small aggregates.

Glauconite: irregular grains deformed at the edges by rhombohedrons of siderite, which have often been transformed into limonite or haematite (fig. 7). The size of the glauconitic grains mostly 0,05—0,1 mm, at most

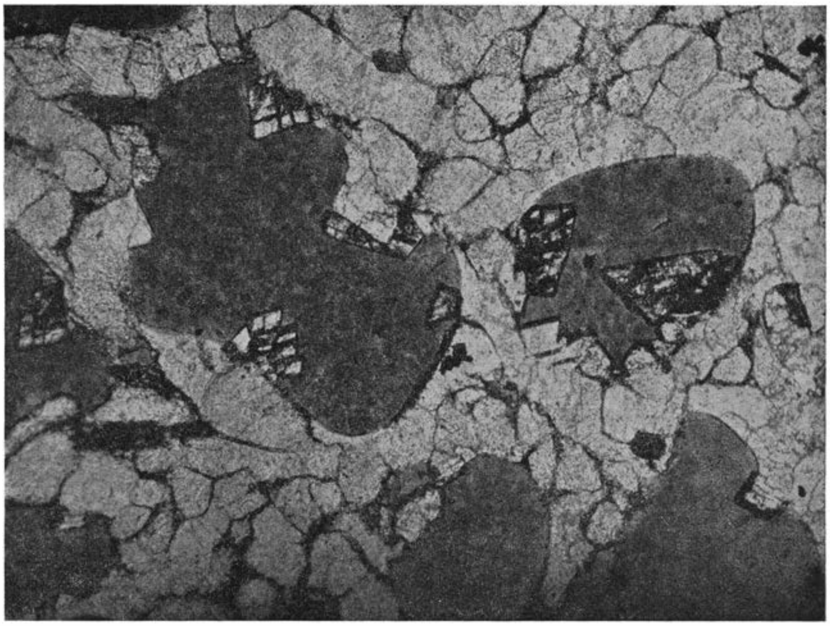

Fig. 7. Glauconite grains with crystals of siderite, partly transformed into limonite and haematite. Limestone grainy. Ottenby, stratum 7. (Pr. 2999. Pl. 524). — 60 ×.

1,5 mm. Glauconite in the upper half 35 per cent, in the lower half 20 per cent, close to the bedding surfaces 70 per cent.

Stratum 6. Glauconitic limestone, for the most part distinctly crystalline but enclosing dense, gray portions.

Ground mass: gray, grained; size of grain varying.

Fossils: phosphatic brachiopod shells.

Pyrit: small aggregates, common.

Glauconite: large, rounded grains, 0,5—2 mm, and small angular fragments, about 0,05 mm. Enclosed rhombohedrons of siderite, often transformed into limonite. Glauconite in the dense lumps 2 per cent, in the bulk 50 per cent, close to the bedding surfaces 70 per cent.

Stratum 5. Glauconitic shale with fairly loosely cemented grains. Radial aggregates of marcasite in the shale.

Ground mass-Cement: dark calcite, in transmitted light dark brown.

Fossils: not observed.

Pyrite: partly small crystals and aggregates, marcasite in larger crystals (10 mm) gathered up in stellate aggregates.

Glauconite: grains $0{,}3$—$1{,}5$ mm, often with a dark margin and a similar net of crack fillings. The smaller grains are fragments of larger ones and have

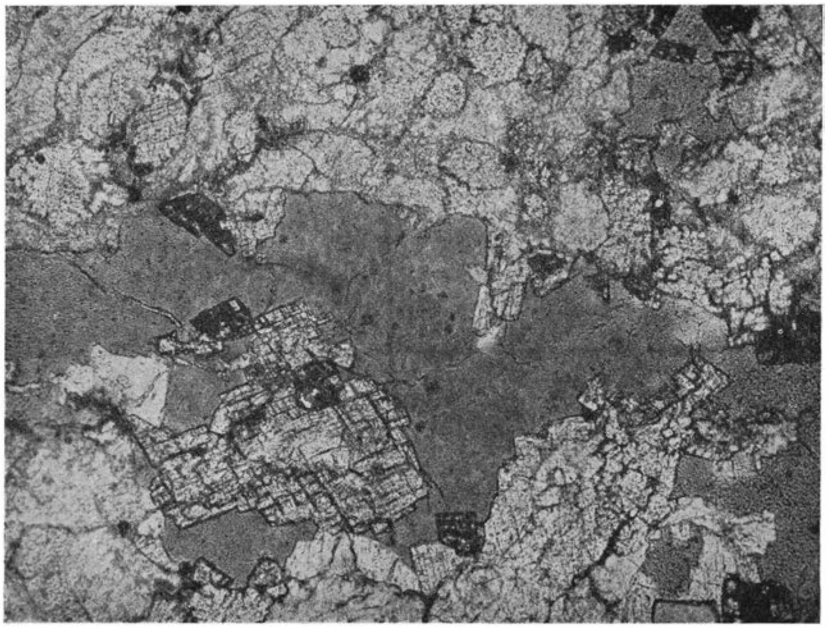

Fig. 8. Glauconite grains, partly replaced by crystals of siderite and calcite. Ottenby, stratum 4. (Pr. 2996. Pl. 523.) — 60 ×.

a one-sided dark zone. Crystals of siderite are sparingly present as inclusions in the glauconite. Glauconite 80 per cent.

Stratum 4. Glauconitic limestone, the upper part distinctly crystalline, the lower part dense.

Ground mass: recrystallized but containing occasional crypto-crystalline, grayish brown, muddy residual portions.

Fossils: brachiopods, with phosphatic shells.

Pyrite: small cubes, 1—10 μ, and aggregates.

Glauconite: grains as a rule completely skeleton-like, jagged by secondarily formed crystals of calcite and siderite (fig. 8). The siderite is partly transformed into limonite. Glauconite in the upper part 15 per cent, in the lower

5 per cent but on the whole an even increase from the lower bedding surface towards the upper.

Stratum 3. Highly fossiliferous, dense, gray limestone with green glauconite skin in cracks.

Ground mass: fine-crystalline, grains about 1 μ.

Fossils: numerous trilobite fragments, partly recrystallized, together with calcareous and phosphatic shells of brachiopods.

Pyrite: an abundance of evenly distributed crystals, about 15 μ, and small aggregates, 20—80 μ.

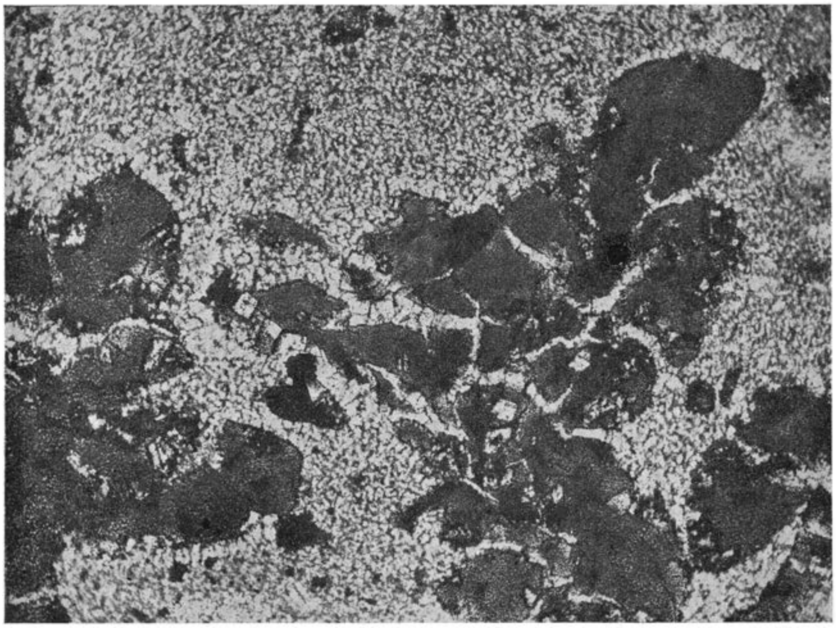

Fig. 9. Glauconite grains, strongly cracked. Ottenby, stratum 1. (Pr. 2992. Pl. 522.) — 60 ×.

Glauconite: grains uncommon, more generally as a green, crypto-crystalline coating on walls of cracks and as pigment in the calcite close to these.

Stratum 2. Fossiliferous, dense, gray limestone.

Ground mass: crypto-crystalline in the upper part of the bed, distinctly granular in the lower (crystals about 2 μ).

Fossils: numerous, well preserved, non-recrystallized fragments of trilobites, brachiopods (calcareous and phosphatic shells), and discs of crinoid stems.

Pyrite: small cubes, often concentrated in swarms.

Glauconite: impregnation in and coating on fossil fragments, a layer of glauconitic dust at the upper and lower bedding planes. Glauconitic grains wholly absent with the exception of occasional grains full of cracks in the lower part of the bed.

Stratum 1. Glauconitic limestone with unevenly distributed glauconite and passing upwards into dense, gray limestone, covered by a thin layer of glauconitic shale.

Ground mass: fine-crystalline.

Fossils: numerous fragments of trilobites and brachiopods; the calcareous shells frequently recrystallized.

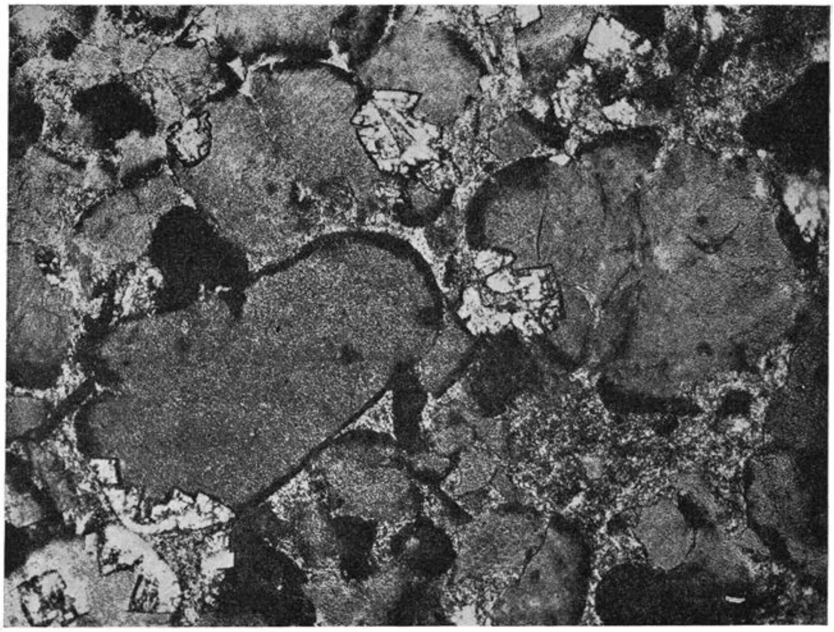

Fig. 10. Glauconitic shale. Glauconite grains with dark (pyritic) margin and small, secondarily formed siderite crystals. Ottenby, stratum 0. (Pr. 2991. Pl. 251.) — 60 ×.

Pyrite: scattered small aggregates.

Glauconite: grains with deep cracks (fig. 9) and dark-pigmented margin often enclosing crystals of siderite. Size of grains 0,06—2 mm. Glauconite 2—35 per cent.

Stratum 0. Glauconitic shale, with large crystals of marcasite.

Ground mass-Cement: dark, in transmitted light, brown, crypto-crystalline.

Fossils: brachiopods, with phosphatic shells.

Pyrite: scattered small dense aggregates (1 mm); large crystals of marcasite in stellate aggregates.

Glauconite: grains 0,3—1,5 mm with dark margin and rhombohedrons of siderite (fig. 10). Glauconite 85 per cent.

The alum shale, forming the substratum of the glauconitic series, is perfectly free from glauconitic grains. Its upper part belongs to the Ceratopyge stage and is partly developed as Dictyograptus shale.

A Survey of the Glauconitic Series at Ottenby.

It is evident from the preceding account that the lowest part of the Ceratopyge stage at Ottenby is developed as *alum shale* (Ceratopyge and Dictyograptus shale), and that this shale is directly overlain by one of the glauconite-richest rocks of the series of strata, a *glauconitic shale* 30—40 cm thick. Above this relatively soft rock follows the *Ceratopyge limestone* proper, a hard, frequently dense, gray or slightly grayish lilac rock, with or without grains of glauconite. The uneven distribution of the glauconite is also macroscopically visible. An especially noticeable fact is that glauconite-free portions often occur in a glauconite-rich bed. The glauconite-free portions are sometimes irregularly bounded, often resembling dense, gray lump in the rock, coloured green by the glauconite, and sometimes the glauconite-free part occupies a (generally central) layer in the bed.

The limestone is as a rule distinctly crystalline, obviously recrystallized. Denser portions, non or less distinctly recrystallized, are, however, to be found here and there. These portions show an even pigmentation. In the recrystallized limestone the pigment is gathered between the calcite crystals. On that account the rock shows microscopically a granular structure. Where solid particles have formed nuclei in the calcitic mass during the recrystallization, a radiate structure has arisen. This is specially noticeable in beds containing abundant fragments of calcareous shells from brachiopods.

The percentage of mud is remarkably low in all the glauconitic rocks. The dark colour of the cement in the glauconitic shale originates no doubt from the calcium phosphate, which, in its turn, is derived from the phosphatic shells of brachiopods.

The bedding is very marked and the bedding surfaces often highly glauconitic. Not infrequently unconsolited glauconite sand lies between the beds.

The fossils occur in different quantities in different beds. Some of the limestones are so rich in fragments that they may be termed *fragment limestones.* Often, however, the preparation of the fossils is difficult, owing to the above-mentioned recrystallization of the calcitic mass when shells have frequently formed the nucleus of radiate calcite aggregates.

At Ottenby the Ceratopyge beds have been examined as to their content of fossils in a higher degree than at any other place in Öland. From this place Moberg & Segerberg mention 22 species of trilobites and 6 of brachiopods. The commonest trilobites are *Euloma ornatum* Ang., *Ceratopyge forficula* Sars, *Dicellocephalus Bröggeri* Mbg & Sbg, *Harpides rugosus* Sars & Boeck, *Symphysurus angustatus*

SARS & BOECK, and *Megalaspis planilimbata* ANG., the two last-mentioned in the upper part of the Ceratopyge limestone.

Of brachiopods we have two kinds, the lime-shelled and the phosphate-shelled. Among the former *Meristella ? diformis* MBG & SBG, *Strophomena (Eostrophomena) Walcotti* MBG & SBG, and *Orthis (Eoorthis) Christianiae* KJERULF, particularly common at Borgholm, are to be noticed. The phosphate-shelled brachiopods are little known and uncertainly determined. As the most common from Ottenby are mentioned *Acrothele barbata* MBG & SBG and *Lingula ? ordovicensis* MBG & SBG.[1]

The brachiopod shells are often poorly preserved. The phosphate shells are as a rule crushed or strongly dissolved, and the calcareous shells show sometimes an almost complete recrystallization. In rock slices, however, they are distinctly noticeable on account of the radiate structure of the limestone around the place which has been occupied by a shell.

The occurrence of *pyrite* and *marcasite* in the glauconite-bearing strata is of interest as it shows that iron has taken part in the formation of other authigenic minerals than glauconite. Pyrite is present in all beds but only in the form of small crystals and slightly larger spherical or irregular fine-crystalline aggregates. The pyrite is formed later than the glauconite, which is evident from the manner in which it impregnates or encloses, wholly or only partly, the grains of glauconite.

As far as the author has been able to find out, the *marcasite* occurs only in the glauconitic shale, not in the limestone. The radiate aggregates with relatively large crystals are typical and also easy to observe macroscopically.

The glauconite occurs mainly in the form of grains, in smaller quantities as impregnation or coating on crack and bedding surfaces. The grains are rounded or tabular and seem as a rule to be worn. Deep cracks are uncommon but a relatively superficial network of shallow furrows is frequently seen. Sometimes the grains show a dark marginal zone, the pigmented zone, occurring one-sidedly in the broken grains (angular fragments).

The glauconite is always green and its structure as a rule crypto-crystalline, more seldom foliate or fibrous.

The formation of *siderite* in the glauconite is a phenomenon, which has assumed unusually large proportions in the beds discussed here. The siderite is always developed into rhombohedrons. As a rule the crystals lie only in the marginal zone of the glauconite grains but in some of the beds they fill up the bulk of the grains, sometimes completely breaking them up. The siderite may in its turn be wholly or only partly decomposed to limonite or haematite. In this place the calcite crystals have as a rule not encroached upon the glauconite, not even on the recrystallization of the ground mass.

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[1] *Acrothele barbata* MBG & SBG is possibly identical with *A. Ceratopygorum* BRÖGGER, and *Lingula ordovicensis* MBG & SBG identical with *Lingulella lepis* SALTER (cf. WALCOTT 1912, 514 and 640).

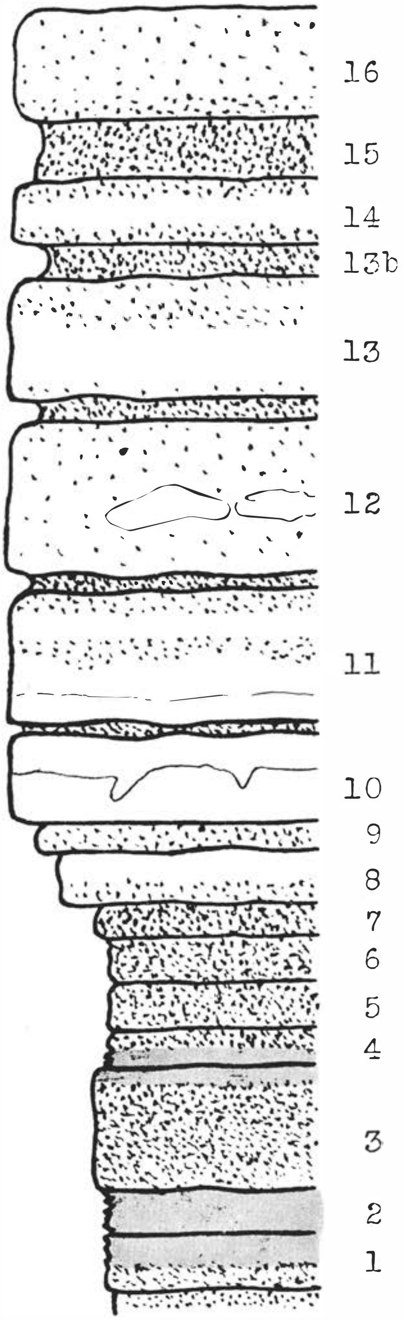

Fig. 11. The glauconitic series of strata at Köpings Klint (central part, cf. the section fig. 3).

The distribution of the glauconite in the glauconite-bearing series of strata is very uneven. Some beds are rich in grains of glauconite, while in others they are almost completely absent. As pointed out above, the distribution is also uneven in each separate bed. The bedding surfaces and the portions close to them are often richest in glauconite. The central portion may be poor in or free from glauconite either wholly or only here and there. A structural peculiarity catches the

Stratum	16.	Glauconitic limestone	7 cm ↑	Planilimbata limestone ?
»	15.	Glauconitic sand	4 »	Ceratopyge limestone
»	14.	Glauconitic limestone	4,5 »	
»	13 b.	Glauconitic sand	2 »	
»	13 a.	Glauconitic limestone	8 »	
»	12 b.	Glauconitic sand	1,5 »	
»	12 a.	Glauconitic limestone	10 »	
»	11 b.	Glauconitic sand	1 »	
»	11 a.	Glauconitic limestone	9 »	
»	10.	Gray limestone	6 »	
»	9.	Glauconitic limestone	2 »	
»	8.	Glauconitic limestone	3,5 »	
»	7.	Glauconitic sand	2 »	Ceratopyge shale
»	6.	Glauconitic shale	3 »	
»	5.	Glauconitic shale	3 »	
»	4.	Glauconitic shale on gray clayey shale	2,5 »	
»	3.	Glauconitic shale	8 »	
»	2.	Gray clayey shale	3 »	
»	1.	Clayey shale on glauconitic shale	3,5 » ↓	

eye immediately: the glauconite-rich parts are more coarse-crystalline throughout than the glauconite-free. It is obvious that a recrystallization has occurred in the rock after the deposition of the calcareous mud, and it is specially noticeable in the relation between the ground mass and the grains or fossil fragments enclosed in this. We shall not here discuss the reason why there are considerably smaller crystals in the glauconite-free parts than in those rich in glauconite. The question will be taken up in the discussion of the limestones and their diagenesis.

The enrichment and development of the glauconite is discussed below, p. 43, in a summary of the observations made at different places in Öland.

The Series of Strata at Köpings Klint in Central Öland.

Along the high way about 3 km E of Borgholm there is a cliff, Köpings Klint, several meters in height. In this the strata shown in fig. 11 are to be seen. The lower glauconitic beds are for the most part covered by talus, the upper on the contrary are easy of access. In order to illustrate the occurrence of the glauconite at this place a detailed account of the middle and, from many points of view, most interesting part of this series of strata is given below.

Concerning the separate beds the following observations may be stated.

Stratum 16. This glauconitic limestone forms the lower bed in a glauconite-rich limestone series, looked upon by some investigators as the lowest part of the Planilimbata limestone, while others have regarded it as a passage series between the Orthoceras and the Ceratopyge limestone (the sections fig. 3 on p. 13).

This series may be observed in several places in Öland and is nearly always separated from the underlying Ceratopyge limestone by a bed of relatively unconsolidated glauconitic sand or glauconitic shale.

Macroscopically stratum 16 is a dense, hard, calcitic mass characterized by strong variations of colour. This is yellow in the upper part, and green with a dark red layer in the lower. Grains of glauconite are abundantly present in the entire bed, but more in the lower part than in the upper. A layer of pure, coarse-crystalline calcite is enclosed in the lowest part.

Ground mass: microscopically crystalline, partly distinctly recrystallized, sometimes radiate. Pigment, in the yellow part brownish yellow limonite and siderite, in the red part dark red haematite, enriched between the calcite grains or in their peripheral part.

Fossils: occasional fragments of shells.

Pyrite: absent.

Glauconite: mostly tabular, worn grains, $0{,}5$—$1{,}5$ mm in diameter (fig. 12). Bright green, with no dark margin but frequently corroded and replaced by calcite. Content of glauconite in the upper part 30 per cent, in the lower 60 per cent.

Stratum 15. Glauconitic sand, see stratum 7.

Stratum 14. Glauconitic limestone with its central part relatively poor in glauconite. In the upper part of the bed the ground mass is green with a yellow layer, in the middle and lower parts grayish lilac.

Ground mass: microscopically distinctly crystalline with lighter yellowish brown and darker brownish red pigment, sparse small grains of quartz, about 0,05 mm in diameter.

Fossils: not observed.

Pyrite: only sparingly.

Glauconite: worn, as a rule flat grains, often with a network of shallow

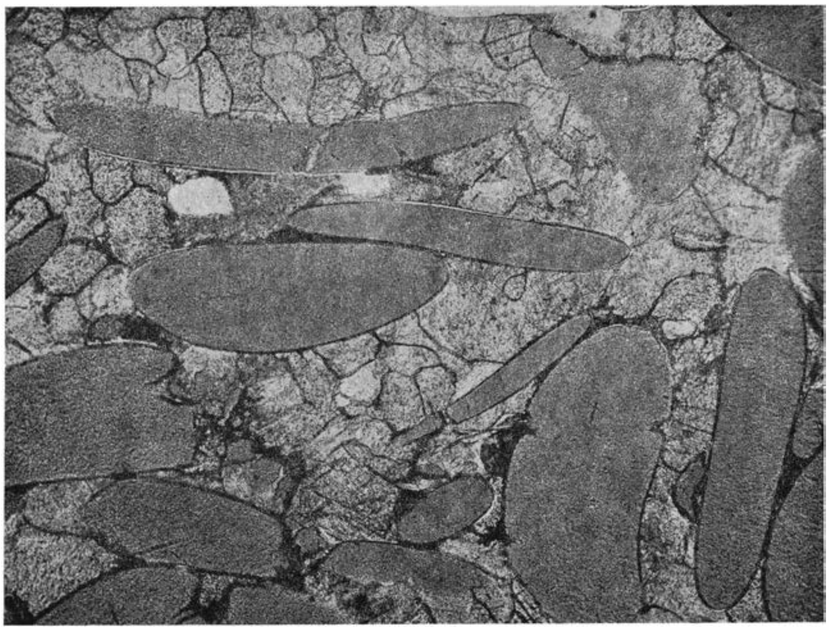

Fig. 12. Glauconitic limestone; glauconite grains flat lenticular. Köpings Klint, stratum 16. (Pr. 3028. Pl. 529.) — 60 ×.

furrows on the surface but without cracks. Size mostly 0,5—1,0 mm. No dark-pigmented margin. Content of glauconite in the upper part 50 per cent, in the middle 5 per cent, and in the lower part 30 per cent.

Stratum 13. Glauconitic limestone, crystalline, dark, passing downwards into glauconite-poor dense, gray limestone.

Ground mass: relatively coarse-crystalline in the dark part at the top of the bed, with slightly coloured calcite crystals separated by dark pigment zones (with haematite dust), fine-crystalline in the lower part of the bed and locally in the upper also, sometimes granular with pigment only between the calcite grains, and sometimes evenly pigmented. Portions (lumps)

richer in pigment occur within those poorer in the same. Radiate structure common around the fragments of shells.
Fossils: numerous fragments of shells in the dense, glauconite-poor limestone, none observed in the glauconite-rich.
Pyrite: Not observed.
Glauconite: Grains as a rule less than 1 mm, occasionally, however, up to 2 mm. Rounded, partly flat, frequently full of cracks or broken, sometimes reduced to small fragments enclosed in the crystals of calcite. Dark marginal zone as a rule absent. The grains appear sometimes as if corroded.

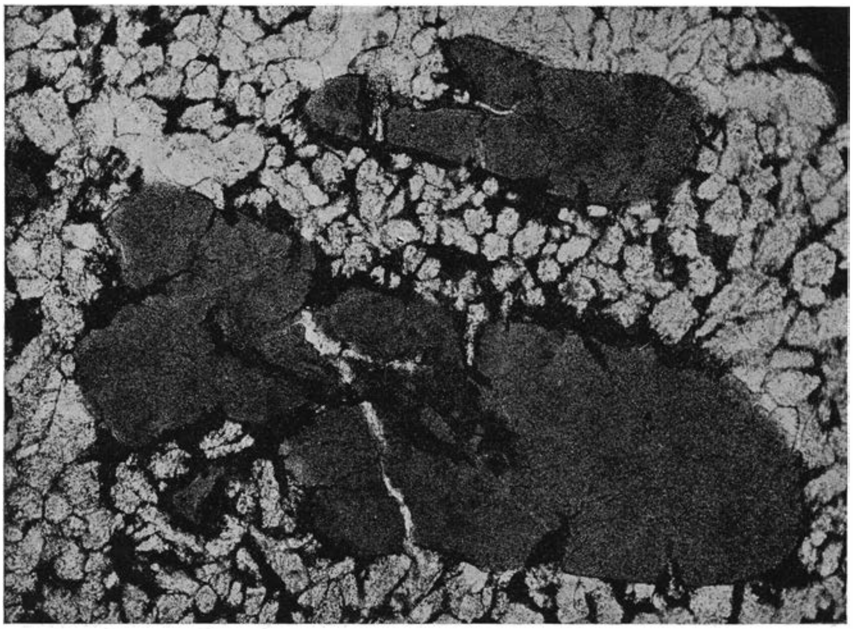

Fig. 13. Cracked glauconite grains in haematite-pigmented limestone. Köpings Klint, stratum 13. (Pr. 3026. Pl. 530.) — 60 ×.

The surrounding calcite is often rich in pigment (fig. 13). Content of glauconite in the upper part 50—70 per cent, in the lower 2 per cent.

Stratum 12 b. Glauconitic sand.

Stratum 12. Glauconitic limestone, relatively coarse-crystalline, dark, rich in glauconite with dense, light, glauconite-poor portions enclosed in the middle part of the bed.
Ground mass: the crystals of calcite as a rule 0,1—0,3 mm, sometimes more than 3 mm large. Dark pigment, haematite, evenly distributed in the dense limestone, unevenly between the crystals in the crystalline, sometimes so abundant that it forms cement between the grains of glauconite.
Fossils: fragments of shells are fairly common in the dense limestone.
Pyrite: not observed.

Glauconite: grains full of cracks, strongly lobate in the cross sections, often disintegrating into small fragments. The unbroken grains are generally about 1 mm large, the fragments as a rule about 0,1 mm.

Secondarily formed glauconite occurs as filling in the cracks on the older grains (Pr. 3025), apparently also as filling between calcite crystals in recrystallized ground mass (Pr. 3024). Content of glauconite 50 per cent, in the central, dense part 3 per cent.

Stratum 11 b. Glauconitic sand.

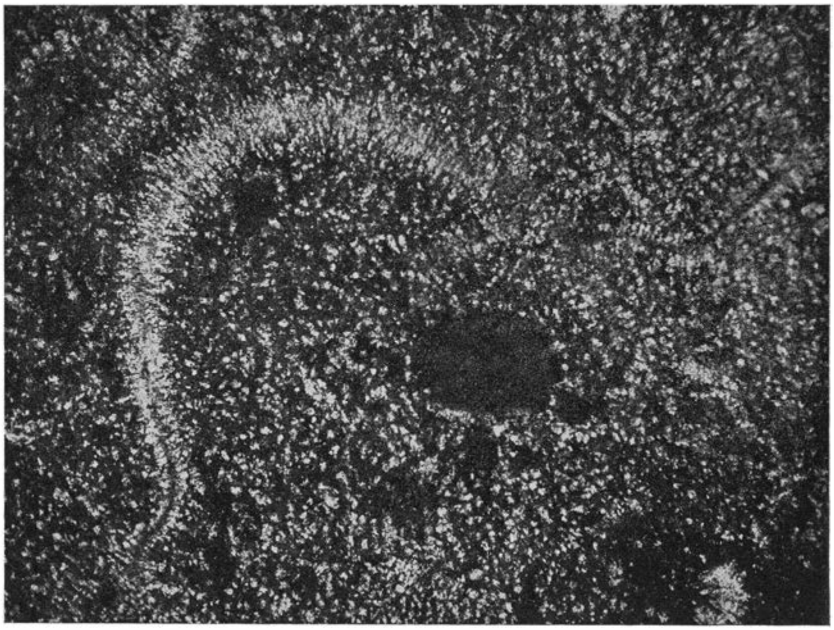

Fig. 14. Fine-grained limestone with solitary, small, rounded glauconite grains and recrystallized shell fragments. Köpings Klint, stratum 11. (Pr. 3018. Pl. 532.) — 60 ×.

Stratum 11. Glauconitic limestone, passing downwards into dense, glauconite-poor limestone with distinct yellow and red layers.

Ground mass: in the glauconite-rich part more coarse-crystalline than in the glauconite-poor. The pigment, yellowish brown or red, filling up the space between the grains (fig. 15).

Fossils: recrystallized shell fragments (fig. 14).

Pyrite: not observed.

Glauconite: often strongly lobate, larger grains (0,7 mm) or small fragments of such (0,05 mm). Colour bright green; dark zone absent. Content of glauconite in the upper part 25 per cent, in the lower 2 per cent.

Stratum 10 b. Glauconitic sand.

Stratum 10. Limestone, dense, grayish lilac.

Ground mass: fine-crystalline, relatively free from pigment.

Fossils: abundant fragments of shells, sometimes recrystallized.

Pyrite: not observed.

Glauconite: exceedingly sparse in small grains. Content of glauconite < 1 per cent.

Stratum 9. Glauconitic limestone, dense, brownish red.

Ground mass: fine-crystalline, rich in pigment (haematite dust).

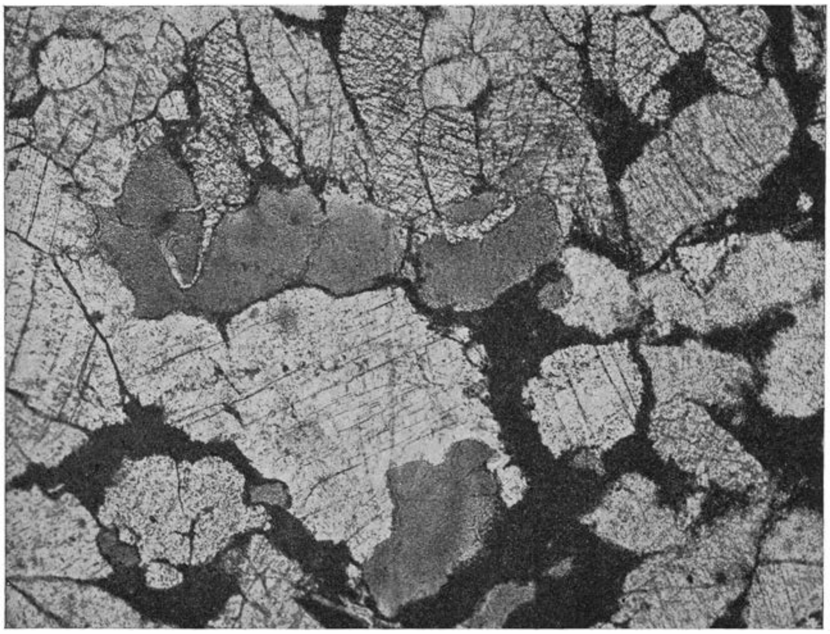

Fig. 15. Glauconite grains in strongly pigmented, crystalline limestone Köpings Klint, stratum 11. (Pr. 3022. Pl. 531.) — 60 ×.

Fossils: a few shell fragments.

Pyrite: scattered small aggregates.

Glauconite: scattered large grains (2 mm), as a rule flat, with deep cracks, and abundant fragments of disintegrated grains. Content of glauconite 30 per cent.

Stratum 8. Glauconitic limestone with a glauconite-poor middle portion.

Ground mass: fine-crystalline.

Fossils: numerous shells of brachiopods, mostly calcareous.

Pyrite: small aggregates, frequently around the grains of glauconite.

Glauconite: mostly small fragments, often with deep, dark-pigmented margin and sometimes a pigment crust around the grains. Content of glauconite at the top 85 per cent, below that 8 per cent, and in the lower part about 50 per cent.

Stratum 7. Glauconitic sand, as in the above-mentioned similar beds unconsolidated, somewhat argillaceous.
Ground mass: Matrix: crypto-crystalline argillaceous, bituminous, brown in transmitted light.
Fossils: not observed.
Pyrite: not observed.

Fig. 16. Glauconitic shale. Köpings Klint, stratum 6. (Pr. 3019. Pl. 533.) — 60 ×.

Glauconite: fragments as a rule less than 1 mm in diameter. Content of glauconite varying, sometimes less than 50 per cent.

Stratum 6. Glauconitic shale, grayish green, only slightly cemented, and not very distinctly bedded.
Ground mass-cement: crypto-crystalline, brownish green in reflected light, dark brown in transmitted light, argillaceous.
Fossils: not observed.
Pyrite: not observed.
Glauconite: principally small fragments of larger grains. Colour uneven, green. Marginal zone absent but the cement often darkest in the immediate vicinity of the glauconite grains. Content of glauconite 65 per cent.

Strata 5—1. Glauconitic shale and sand with clayey matrix (also cement) interstratified with glauconite-free, bituminous beds of clayey shale. The glauconitic shale in these strata as well as in the underlying (cf. the series of strata fig. 3 on p. 4) is of the same nature as in stratum 6. The clayey shale is soft, brownish gray, and without distinct bedding surfaces towards the glauconitic rocks (fig. 17). Fossils occur both in the argillaceous and in the glauconitic shale, sometimes abundantly (in the lower strata). In the glauconitic shale we find well preserved shells of *Orthis (Eoorthis) Christianiae* KJERULF and several phosphate-shelled brachiopods are also present.

Fig. 17. Glauconitic shale with clayey layers. Köpings Klint, stratum 3. (Pl. 599.) — 1/1.

Graptolites belonging to the Ceratopyge stage have been found in the shale, among others *Clonograptus heres* WESTERGÅRD. From the lowest shale bed WESTERGÅRD (1922, 36) mentions *Dictyograptus flabelliformis norvegicus*.

A Survey of the Glauconitic Series at Köpings Klint.

The diagram fig. 3 on p. 13 shows that the glauconite-bearing, lower Ordovician strata are considerably thicker at Köpings Klint than at Ottenby.

As is evident from the descriptions given, the strata are also differently developed at the two places. A broadly outlined comparison is however possible. Thus there is hardly any doubt that strata 1—7 (and the underlying ones of the same character) at Köpings Klint were deposited at the same time as stratum 0 and the underlying Dictyograptus shale at Ottenby. Whether strata 8—16 at Köpings Klint correspond to strata 1—9 at Ottenby, or possibly to the entire series described (strata 1—13), may be left undecided here. The content of fossils seems to speak for the latter alternative, the number of beds and in a certain degree their petrographical development, for the former. The part of the Köpings Klint series discussed more in detail here may at any rate be quite justly compared with the series at Ottenby discussed above.

At Ottenby the lower part of the Ceratopyge stage, the Ceratopyge shale, is divided into two petrographically very different parts, a lower part consisting of alum shale and an upper one of relatively pure glauconitic shale. This petrographical-stratigraphical division is not found at Köpings Klint. At this place the Ceratopyge shale is a series of interbedded glauconite-free and glauconite-rich shales with no sharp limits towards each other. This shows that the deposition of glauconite began earlier at Köpings Klint in central Öland, than at Ottenby in the south. In the following we shall also discuss the relation between the supply and deposition of mud and the formation of glauconite as far as this relation is illustrated by the two series of strata already described.

The limestone beds at Köpings Klint are somewhat different in colour from those at Ottenby, they show, above all, more red and yellow at the first-mentioned place. A common feature is their varying percentage of glauconite and especially a frequently very distinct increase of the quantity of glauconite close to the bedding surfaces. At Köpings Klint this periodical enrichment of glauconite is further emphasized by the layers of glauconitic sand which often separate the beds of glauconitic limestone.

In structure the limestone at Köpings Klint resembles that at Ottenby. Recrystallization of the ground mass and enrichment of the originally relatively evenly divided pigment between the secondarily formed calcite crystals is a common phenomenon at the last described locality also. Relatively dense portions are found enclosed in the more coarse-crystalline mass and as a rule these denser portions are less glauconitic than the more coarse-crystalline part of the beds.

The varying colour in the limestone beds originates from yellow or red pigment, in the former case iron hydroxide, in the latter iron oxide. Sometimes varying yellow and red bands occur, at times green ones also, the latter colour caused by fine dust or small fragments of glauconite. How and in what form the red and yellow pigment has arisen will be briefly discussed elsewhere (p. 50). Attention may, however, be called here to the fact that the distribution of the pigment in coloured bands indicates that this may be caused by weathering or oxidation phenomena during the deposition. In this connection it should be pointed out that strata at Köpings Klint do not generally contain *pyrite*, a mineral which on the contrary is not absent in any of the beds at Ottenby.

Fossils abound in some of the limestone beds at Köpings Klint. As at Ottenby they occur mostly in the glauconite-poor dense part, and only seldom are they observed in the more coarse-crystalline glauconitic limestone. It might be imagined that the shells were obliterated during the recrystallization of the rock, but this is probably not the case. For where fossils have existed they can be traced distinctly enough in the recrystallized rock, owing to the orientation (radiate) of the calcite crystals around the shell fragments (see fig. 14, p. 28). The phenomenon may also be observed when the shells themselves have been transformed into a granular aggregate by the recrystallization, with no traces of the original structure of the shell.

Whether the content of fossils is the same at Köpings Klint as at Ottenby has not been investigated. In their monograph on the fauna of the Ceratopyge region MOBERG & SEGERBERG have derived their Ölandic material almost exclusively from Ottenby. There is, however, no occasion for us to presume any greater difference between the two places with regard to the fauna of the limestone.

The contents of fossils in the Ceratopyge shale at the two places mentioned is partly different. A certain faunistic dissimilarity accompanies the different petrographical development of the rocks, both are factors of the mutually different sedimentary conditions at the sites of deposition. The series of partly clayey shales at Köpings Klint contains beds very rich in brachiopods, sometimes with calcareous and sometimes with phosphatic shells. The bedding surfaces are often covered by *Eoorthis Christianiae* KJERULF and *Eoorthis Wimani* WALCOTT. The calcareous shells, however, are in most cases dissolved but the moulds show all the details of the ornamentation of the shell. As this is also the case when the brachiopods lie enclosed in glauconitic shale, we can gain an idea of the content of clay in the same. All the sharply modelled moulds of the shells are namely in clay.

Phosphate-shelled brachiopods occur partly together with the lime-shelled ones, partly alone in certain beds. The most common are *Acrothele Borgholmensis* WALCOTT, *Obolus (Bröggeria) Salteri* HOLL., and *Lingulella lepis* SALTER.

Graptolites are sometimes abundantly present in the clayey shale interbedded with glauconitic shale. Besides *Clonograptus (Staurograptus?) heres* WESTERGÅRD, mentioned by MOBERG & SEGERBERG from Köpings Klint, branched fragments of one or a couple of other non-determined species have been found. According to WESTERGÅRD (1922, 36) *Dictyograptus flabelliformis norvegicus* occurs in the basal bed.

Glauconite occurs differently developed in the series of strata at Köpings Klint, namely as

grains, full of cracks
grains, worn, often lenticular
fragments of grains
crack filling in older grains
pigment on bedding surfaces and in the rock
pigment in and crust on fossils.

The grains are no doubt primary formations and those very full of cracks are possibly in a primary site of deposition. A transport must have caused either wear of the grains or their disintegration into smaller fragments. Some of the limestone beds show preferably worn grains and the bulk of the glauconitic shale contains almost exclusively small fragments of larger grains, and we may suppose that the glauconite in these beds has, after the formation of the cracks in the grains, been exposed to wear or disintegration in connection with transportation. It may therefore be presumed that the glauconite in these beds is in a secondary site of deposition.

The presence of a secondary generation of glauconite is positively proved when the cracks in a grain of glauconite are found filled up with glauconite, distinctly separate from that present in the grain. Whether the glauconite occurring as pigment also belongs to the latter generation or represents an individual one is not evident from the material examined.

Fig. 18. Glauconitic limestone. The central part of the bed holds no glauconite. Köpings Klint, stratum 14. (Pl. 595.) — $^1/_1$.

The crumbled grains of glauconite, *the glauconite fragments*, form, as mentioned above, the bulk of the glauconitic shale and occur in a secondary site of deposition. Sometimes the fragments are found mixed with rounded grains of glauconite of about the same size as the fragments (about 0,3 mm), and in some parts of the series of strata these grains even dominate. Whether they have also been transported before the final deposition is not quite evident from the character of the grains, for parts of them are so cracked that they can hardly have been disturbed after the formation of the cracks, while some of them appear to have been worn, probably during transportation. It is of course not excluded that primarily occurring glauconite may also occur in beds with principally secondary grains, as well as that beds with mainly autochthonous grains may contain grains deposited at an earlier time elsewhere or in other beds.

Between the grains of the glauconitic shale an abundance of fine *glauconitic* *dust* is frequently found. This is probably derived from the abraded or crumbled grains. The slightly green portions and thin green bands in the limestone beds may have obtained their colour from such secondary glauconitic dust. It is, however, wrong to interpret all the finely divided glauconite in these beds as residues of crumbled grains. The pigment in many limestones as well as the impregnation in the shells and the filling in the cracks of older grains are no doubt primary formations of glauconite (see further p. 45 a. o.).

The glauconite in Köpings Klint seldom shows any dark-pigmented zone or inclusions of secondarily formed siderite. It differs in both these respects from the glauconite at Ottenby.

Foto Sv. Holgersson.

Fig. 19. The cliff at Horns Udde: Upper part red Orthoceras limestone, zone with *Megalaspis limbata,* lower part glauconitic Ceratopyge limestone.

The distribution of the glauconite at Köpings Klint is, as at Ottenby, uneven. In the limestone series it is so similar in both places that one might feel inclined to parallel the different beds. (Cf. fig. 3, p. 13, with figg. 4 and 11.) The central part of the limestone beds is poor in glauconite throughout, while the highest percentage is found close to the bedding surfaces (fig. 18). As is seen from the section fig. 11, p. 24, thin beds of glauconitic sand occur between the limestone beds at Köpings Klint. Already from this fact we may infer that the conditions for the deposition of glauconite have been more favourable here than in the southern part of Öland (Ottenby). As already mentioned, however, this is most distinctly seen on a comparison being made between the series of shales at the two places. It is also of the greatest interest that the deposition of glauconite has been rhythmic in the series of shales too. But as the glauconite in the shale mainly occurs in a secondary site of deposition, the rhythmic deposition must not necessarily mean that the primary formation of glauconite has also been rhythmic. The absence of bedding planes between the clayey and the glauconitic shale and the presence of a relatively abundant argillaceous matrix in the glauconitic shale close to the clayey shale shows, in the author's opinion, that no essential change in the sedimentary conditions has taken place on the transition from glauconite-free to glauconitic shale. The change is the same as on the transition from the glauconite-free or glauconite-poor (central) part of a limestone bed to the glauconite-rich one (situated closer to the bedding surface). Layers of the glauconitic shale free from or poor in clay, correspond directly to the glauconitic sand between the limestone beds or to the interruption in the deposition of limestone and to the origin of the bedding surfaces in the cases in which no glauconitic sand has been deposited (Ottenby) (see further p. 46).

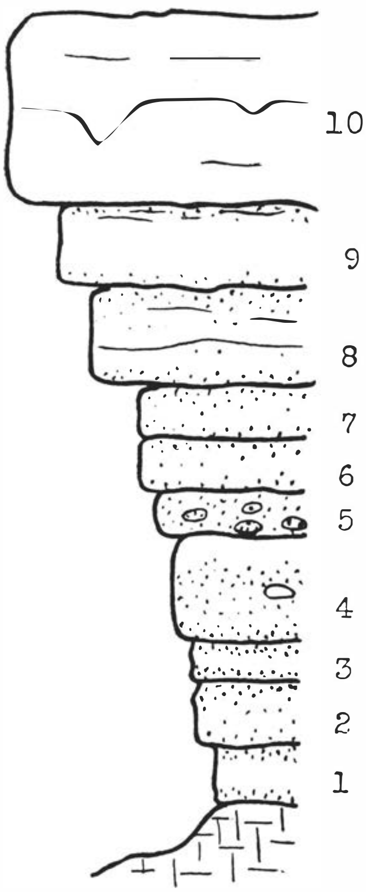

Fig. 20. The glauconitic series of strata at Horns Udde.

The Series of Strata at Horns Udde in the North of Öland

The most northerly point in Öland at which the Ceratopyge beds have been observed in situ is Horns Udde, about 35 km north of the section at Köpings Klint (see the map, p. 44). The series of strata was measured at two points.

Section A.

Stratum	10.	Limestone, variegated, dense, almost free from glauconite grains	12,5 cm.
»	9.	Limestone, variegated, dense, poor in glauconite	5,5 »
»	8.	Limestone, variegated, dense, glauconitic	6,5 »
»	7.	Limestone, green, with grains of glauconite	3,5 »
»	6.	Limestone, dense, poor in glauconite	3,5 »
»	5.	Glauconitic limestone, partly conglomeratic	3 »
»	4.	Glauconitic limestone	7 »
»	3.	Glauconitic marl and limestone	2,5 »
»	2.	Limestone, poor in glauconite, with marl	4,5 »
»	1.	Glauconitic limestone	3,5 »
—	—	Stinkstone, radiate, grayish green, or brown	—
—	—	Sandstone, shaly	—

Section B.

Strata	10—8	the same as section A.	
»	7—1.	Conglomeratic bed	7 cm.
—	—	Stinkstone, radiate, grayish green	—

From the notes on the different beds the following may be cited.

Stratum 10. Limestone bed, the upper part reddish gray, with increasing red colour downwards. In the middle of the bed a yellow stripe, diffusely limited downwards, upwards separated from the red part by a very thin, green layer. Irregular gray portions are to be found in the lower, flamy red part of the bed.
Ground mass: fine-crystalline, rich in pigments.
Fossils: abundant fragments of trilobites and brachiopods (calcareous shells) especially in the lower part of the bed.
Pyrite: not observed.

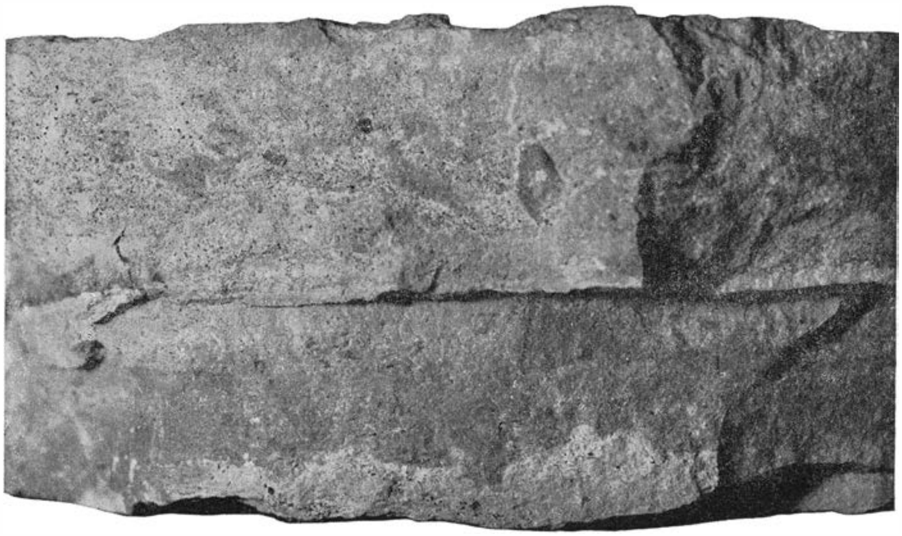

Fig. 21. Glauconitic limestone with gray, red, and yellow parts. In the lower half of the bed from the bottom gray, red, and yellow bands, in the upper half a yellow bottom layer and a gray top layer with diffuse red parts. Horns Udde, stratum 8. (Pl. 593.) — $^1/_1$.

Glauconite: small grains sparingly present in limited portions of the upper as well as the lower part. In the red portions the grains sometimes show a distinct dark-pigmented zone. The green lamination above the yellow stripe consists of glauconitic dust. Content of glauconite 0—2 per cent.

Stratum 9. Limestone, dense reddish gray, with a yellow layer close to the upper bedding surface.
Ground mass: fine-crystalline.
Fossils: fairly abundant shell fragments.
Pyrite: not observed.
Glauconite: small grains in the upper and lower parts of the bed. As a rule with dark-pigmented skin. An indistinct stripe of glauconitic dust above the yellow layer. Content of glauconite 0—5 per cent.

Stratum 8. Limestone with alternating reddish gray, yellow, and red bands (fig. 21).

Ground mass: fine-crystalline, scattered grains of quartz, 0,1 mm in diameter.

Fossils: fragments of shells sparingly present in the upper part of the bed, more abundant in the lower part. Recrystallization usual.

Pyrite: not observed.

Glauconite: the upper half of the bed fairly rich in small grains (0,1—0,5 mm), the same in the lower part where we also find large grains (fig. 22).

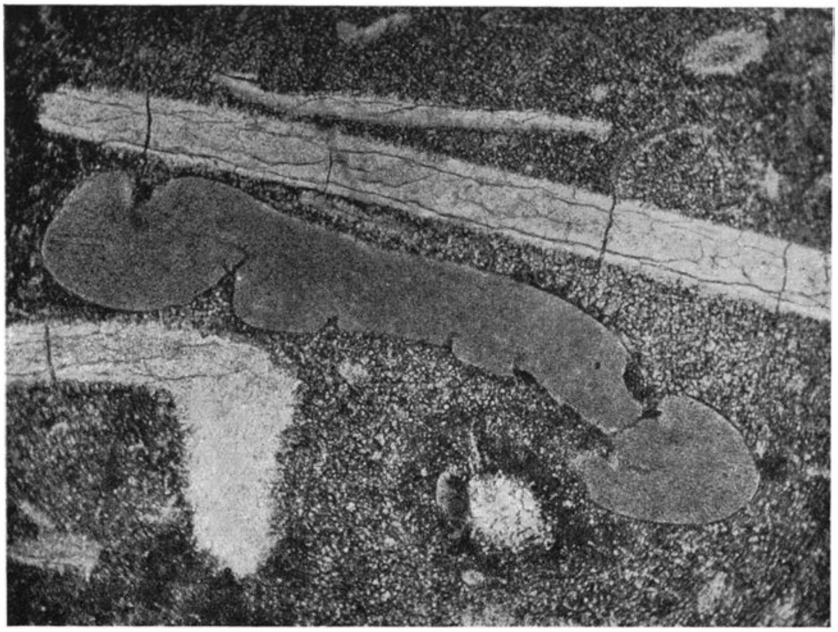

Fig. 22. Glauconite grain in fine-crystalline Ceratopyge limestone. Cross-section of a large, flat grain. Horns Udde, stratum 8. (Pr. 3016. Pl. 535.) — 60 ×.

The middle portion almost free from glauconite. This also occurs as dust between the grains of calcite and sparingly as impregnation in shells. Dark-pigmented skin common on the grains. The content of glauconite in the upper half and at the bottom 10—25 per cent, for the rest 2 per cent.

Stratum 7. Limestone, somewhat argillaceous, grayish green, dense, fairly hard with varying thickness and uneven bedding surfaces.

Ground mass: fine-crystalline, granular.

Fossils: shell fragments only very sparingly present.

Pyrite: occasional small aggregates.

Glauconite: small grains (about 0,15 mm in diameter) distributed in spots. Glauconitic dust on scattered surfaces in the bed. Content of glauconite about 2 per cent.

Stratum 6. Limestone with a reddish gray, relatively mud-free middle portion and grayish green, marly parts close to the bedding surfaces.
Ground mass: fine-grained. Scattered grains of quartz, 0,1—0,2 mm.
Fossils: fairly abundant fragments of shells in the lower part of the bed.
Pyrite: occasional small aggregates.
Glauconite: scattered small grains (0,06—0,6 mm) distributed in spots and most abundant close to the bedding surfaces. Glauconitic dust on certain parts of the upper bedding surface. Content of glauconite 4 per cent.
Phosphorite: sparingly in small grains.

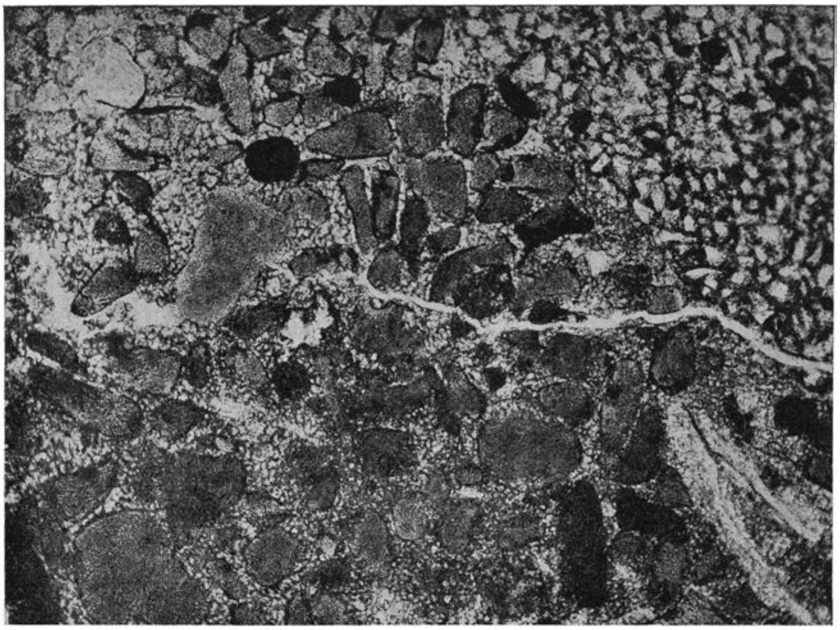

Fig. 23. Conglomeratic limestone with small glauconite grains. In the upper right part of the fig. a pebble of phosphorite sandstone. Horns Udde, stratum 4. (Pr. 3015. Pl. 536.) — 60 ×.

Stratum 5. Glauconitic limestone with pebbles of dense, gray limestone.
Ground mass: fine-crystalline, sparse small grains of quartz (about 0,1 mm).
Fossils: not observed.
Pyrite: not observed.
Glauconite: small grains (< 0,5) distributed in spots or lumps. Content of glauconite 20 per cent, in the upper and lower parts increased to 50 per cent.
Phosphorite: sparingly in small grains (< 1,0 mm).

Stratum 4. Glauconitic limestone with scattered pebbles, of phosphorite also, sometimes conglomeratic (fig. 23). The upper part of the bed dense or distinctly crystalline, glauconite-poor, gray limestone.

Ground mass: the glauconite-rich part finely crystalline; in the gray limestone, sometimes fairly coarse-crystalline, sparingly small round grains of quartz (0,05—0,2 mm).
Fossils: shell fragments rather common.
Pyrite: small irregular aggregates (often enclosing grains of glauconite).
Glauconite: flat or round, irregularly distributed grains, often pigmented. Varying in size but seldom exceeding 0,5 mm. Content of glauconite 55 per cent, in the upper part, however, only 2 per cent.
Phosphorite: small grains rather common. The boundary between phosphorite and glauconite in some of the grains indistinct.

Stratum 3. Glauconitic marl with a central layer of dense, gray limestone poor in glauconite.
Ground mass: for the most part fine-crystalline, to a smaller extent relatively coarse-crystalline. Scattered small grains of quartz (0,1 mm).
Fossils: shells common in the middle portion, the limestone.
Pyrite: not observed.
Glauconite: as a rule very small grains, $<$ 0,3 mm. Content of glauconite in the upper and lower parts 30 per cent, in the middle 5 per cent.

Stratum 2. The same as stratum 3. Content of glauconite, however, somewhat lower.

Stratum 1. Glauconitic limestone with a glauconite-poor middle portion of dense, gray limestone.
Ground mass: partly relatively coarse-crystalline (grains 0,5—2 mm), partly fine-crystalline (grains $<$ 0,02 mm). Occasional small grains of quartz (0,15 mm).
Fossils: shells common in the middle portion, often crystalline.
Pyrite: absent.
Glauconite: flat and round grains, as a rule less than 0,7 mm in diameter. Sometimes with pigmented skin. Content of glauconite in the upper and lower parts 25 per cent, in the middle 2 per cent.

— — — Radiate limestone of brown or grayish green colour, in the form of large nodules of concretionary character. The upper surface undoubtedly a denudation surface. Age: Younger Cambrian.

— — — The sandstone beneath the radiate limestone belongs to the lower part of the Middle Cambrian and in consequense there are large breaks in the series of strata under the glauconite-bearing series.

Section B. The conglomerate bed which in this section occupies the same place as strata 7—1 in section A, consists of a glauconite-rich ground mass with an abundance of pebbles — frequently more than 5 cm large — of sedimentary rocks principally of dense, reddish gray limestone and glauconitic limestone.

A Survey of the Glauconite-bearing Series of Strata at Horns Udde.

Of the three glauconite-bearing series of strata in Öland, mentioned somewhat more in detail here, that at Horns Udde is least important in thickness and content of glauconite. The development of the rocks as well as the character and occurrence of the glauconite differ in a certain degree from those at the two above described localities, and the strata at Horn may therefore, from this point of view also, complete the picture of the glauconite's mode of occurrence. This northerly locality is of special interest, for it makes it possible to judge the horizontal variations of the deposit of glauconite, i e. its greater or lesser enrichment at different places under one and the same period of deposition. When we have succeeded in collecting a sufficiently large material of this nature we shall be better able to judge how the formation of glauconite has varied with and been dependent on the local sedimentation and thus also on the milieu conditions in general.

As characteristic of the series of strata at Horns Udde we must first, from the above mentioned points of view, call attention to the formation of conglomerates and the obvious breaks in the series of strata. The conglomerates and the conglomerate-like beds were no doubt formed without the strata's elevation to the surface of the sea but they show that the sedimentation occurred at such a slight depth that already deposited layers could be broken up. Whether these intraformational conglomerates are regression conglomerates or were formed without connection with a migration of the shore-line, is certainly not immediately evident from their character but the author considers that they show changes in depth and in the position of the shore-line.[1] It is then hardly possible to avoid reckoning with the same (contemporaneous) oscillations at the above mentioned, more southerly places. The abscence of corresponding intraformational conglomerates at these places can only be interpreted in one manner, viz.: at the north of Öland only (not at the middle or south) was the water so shallow that an elevation of land, occurring during the time when the Ceratopyge beds were deposited, caused the formation of conglomerates.

A further proof of the sedimentation at the north of Öland occurring in shallower water than at central Öland and of the sedimentation at the south of Öland taking place in deeper water than farther north may be found in the connection between the above related facts and what we have learnt earlier of the development of the Upper Cambrian strata. The gaps in the series of strata are largest at the north of Öland and smallest at the south (fig. 2 p. 12, cf. Hadding 1927, 86). The intraformational conglomerates also show that the positive sedimentation during the Upper Cambrian was exceedingly unimportant at the north of Öland, and that it increased towards the south. The negative sedimentation, the washing away and redeposition of sediments already deposited, is least noticeable farthest

[1] This is worthy of further investigation. Increased current and wave action may possibly have given the same result without any change of the sea level.

north, where few strata were deposited, and farthest south, where the positive sedimentation was interrupted for only short periods.

The petrographical development of the rocks in the Ceratopyge stage at Horns Udde differs also, from other points of view than the last mentioned (formation of conglomerate, etc.), from that at Köpings Klint and Ottenby. No real glauconite rock, glauconitic sand, or glauconitic shale are to be found. The glauconitic limestone is also less glauconite-bearing than farther south. It is first in the strata above the glauconitic zone proper that the rocks obtain a more uniform character at the different places.

In neither of the two sections (measured 1928) from Horns Udde was alum shale or bituminous shale present. On visiting the place in 1915 the author, however, observed a thin bed with alum shale belonging to the lower part of the Ceratopyge stage. From Djupvik, about 20 km south of Horns Udde, WESTERGÅRD (1922, 37) mentions a 1 m thick bed of alum shale, at the bottom of which *Dictyograptus flabelliformis norvegicus* KJERULF has been found. The occurrence of blocks of shale along the shore also indicates that alum shale was deposited so far north as at Horns Udde (J. G. ANDERSSON 1896, 170). We may, however, safely say that the formation of shale has been considerably less than at the south, for inst. at Köpings Klint or Ottenby.

Fossils are not so abundantly present in the Ceratopyge beds at Horns Udde as at the other places. Trilobite fragments and brachiopods with calcareous shells are most common.

Regardless of scattered small aggregates, *pyrite* does not occur either at Horns Udde or at Köpings Klint. *The glauconite* is most usual in small grains, seldom exceeding 0,5 mm. Occasional larger grains, 2 mm or more in diameter, may, however, be found in the majority of the glauconite-bearing beds. The small grains are not, as in the glauconitic shale at Köpings Klint, angular fragments of larger broken grains. They are rounded and otherwise without any signs that could give us occasion to interpret them as fragments of larger ones, nor are there any transitions in magnitude between these small grains and the sporadically occurring larger ones mentioned above. Such transitions are not lacking where the larger grains have to a larger or smaller extent disintegrated into smaller fragments.

The glauconitic grains are often worn, which is quite natural as the deposited sediments have no doubt been repeatedly stirred up after the first deposition.

A dark-pigmented zone may sometimes be traced on some of the glauconite grains but is absent on most of them. This is remarkable because it shows that this zone or crust was not formed at the shallowest sites of deposition. In the Ölandic beds described here *the dark-pigmented margin of the glauconite grains is most frequently found and is best developed* at Ottenby, i. e. *in the beds deposited at the greatest depths.*

The coatings of glauconitic dust on bedding and crack surfaces are of the same nature at Horns Udde as at other places. Pigmentation in shells is uncommon. But glauconitic dust is not seldom found as an inconsiderable filling between the grains in the recrystallized calcitic ground mass and has probably been derived from the abrasion of the glauconitic grains.

The distribution of the glauconite in the different beds is of the same type as at the above mentioned places. Thus the central part in the beds is poorest in glauconite. A decided and striking exception is found in one bed, stratum 4, the upper part of which is in this case practically free from glauconite. The explanation of this is that the present upper part of the bed once formed the central part, which was covered by a band rich in glauconite. This glauconite-rich part, however, was destroyed before or at the formation of the overlying bed (stratum 5), which is conglomerate-like and contains both lumps rich in glauconite and parts of the glauconite-free limestone.

Summary and Conclusions based on Observations of the Glauconite-bearing Series of Strata in Öland.

Summary of the Observations.

1. Glauconite is often secondarily enriched. Its secondary occurrence is shown in some of the beds in its development as small fragments of larger broken grains. In others the grains of glauconite are distinctly worn by transportation.
2. Glauconite is abundantly present at bedding planes and on denudation and corrosion surfaces.
3. Beds rich in glauconite are sometimes developed as conglomerates.
4. When glauconite and argillaceous sediments occur together they alternate rhythmically: glauconitic beds poor in clay are interstratified with argillaceous layers free from glauconite.
5. Rhythmic interstratification also occurs between glauconitic layers and limestone beds. The sedimentation has ranged between maximal limestone formation (with minimal deposition of glauconite) and maximal deposition of glauconite (with minimal limestone formation) in rhythmic alternation.
6. Glauconitic beds (and the glauconite itself also) not infrequently contain minerals formed in reduction environment, for inst. pyrite and siderite. These minerals are generally formed after the glauconite.
7. Minerals formed in oxidation environment (haematite, goethite, limonite) are not primarily present in glauconite nor in beds with autochthonous glauconite.
8. The formation of alum shale or, more correctly, the deposition of bituminous mud ceases when the formation of glauconite begins. An exception from this is seen in the series of strata at Köpings Klint, in which bituminous clay layers are interstratified with glauconitic ones.
9. In many places on the boundary between the glauconitic series and its substratum, the alum shale, a stratigraphic break is to be found. Such also occur in different horizons above and below the said boundary, in the alum shale as well as in the glauconitic series. These breaks are largest in the north of Öland and decrease towards the south.

10. Faunistic as well as petrographic changes occur on the formation of the glauconitic series. As a rule the beds of glauconite are poor in fossils, unless they have been formed by a secondary accumulation of earlier deposited material. The rhythmic alternation of glauconite sand and limestone is often at the same time a rhythmic alternation of fossil-free and fossil-rich beds.
11. All the fossil forms present in the glauconite-bearing series of strata belong to the shallow-sea region.

Discussion of the Conditions of Formation.

The observations related here may give rise to several questions and reflections as to the conditions under which the glauconitic series was deposited and the glauconite formed. These conditions will be shortly discussed in the following.

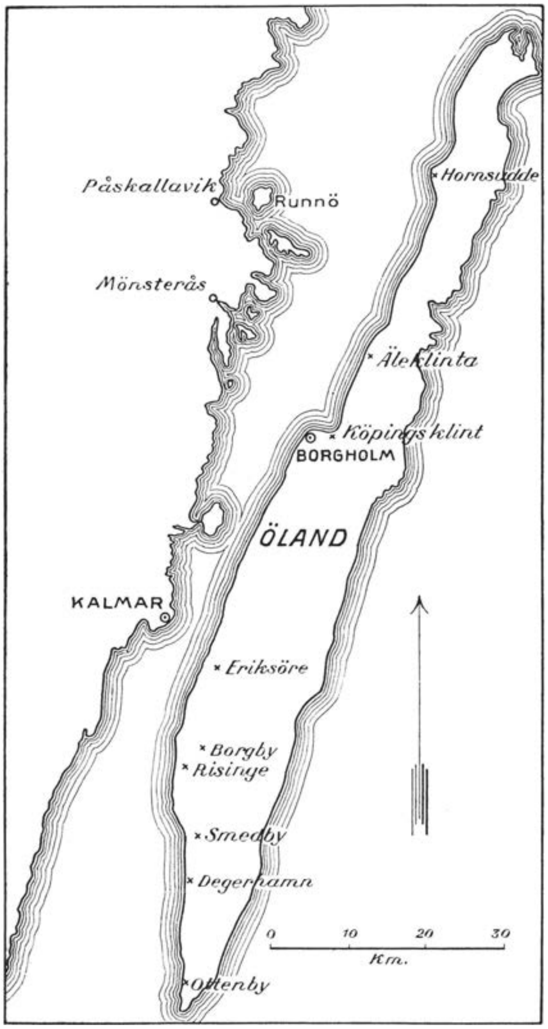

Fig. 24. Map of Öland.

At what depth have the glauconitic beds been formed? The glauconitic series and its substratum, the alum shale, exhibit stratigraphic breaks and intraformational conglomerates. These indicate a deposition in relatively shallow water, probably mainly less than 100 m deep. The series of strata show that the depth has been smallest at the north and greatest at the south of Öland.

The series of strata at the north of Öland (Horns Udde) has probably been formed at a depth of only a few tens of meters. These strata, however, contain principally allochthonous glauconite, and its occurrence in the beds deposited at a shallow depth naturally does not convey to us that the formation of glauconite has taken place in equally shallow water. But the strata contain a certain amount of autochthonous glauconite, which shows that the mineral has also been formed in the shallowest parts of the region subjected to our investigation.

The beds formed at the greatest depth, at Ottenby, contain both autochthonous and allochthonous glauconite. They are possible formed below the 100 meters limit; hardly any traces of negative sedimentation are to be seen in them. Neither the glauconite series nor its hanging-wall, the orthoceras limestone, speak for a greater difference in depth at the north and at the south of Öland during the deposition of these sediments. It may therefore be inferred with a certain degree of probability that the beds of glauconite were mainly deposited at a depth of less than 100 m. As the strongest enrichment of glauconite is found in central Öland we may also venture to infer that the very formation of glauconite must have taken place in the area of deposition. Judging from the series of strata in Öland, then, the glauconite has principally been formed at a depth of less than 100 m, partly, probably, at a depth of only a few tens of meters.

Were the Beds of Glauconite Formed in Tranquil Waters or in Currents?

Several of the observations made on the glauconitic series show that the beds were formed in relatively agitated water. A rather considerable power of transportation, i. e. a not inconsiderable current, in the water is a necessary condition for the secondary enrichment of the glauconite grains. The formation of conglomerate also shows that the movement of the water in the shallowest region has at times been specially strong.

In order to estimate the movement of the water it is necessary to mark the relation between the glauconitic strata and the layers of shale interstratified with them. The clayey mud must have been deposited in periods with tranquil water. During these periods no deposition of glauconite took place. It goes without saying that beds consisting of secondarily enriched grains of glauconite must be poor in clayey mud. Beds containing both allochthonous grains of glauconite and clayey matter have probably been formed in this manner, the clayey matter deposited on glauconitic sand making its way down between the grains of glauconite. Consequently these beds give us no proof that glauconite can be deposited together with fine-detritus, i. e. in tranquil water.

The enrichment of the glauconitic grains at the bedding planes in a limestone series or between the limestone beds may have taken place during periods with relatively agitated water. As will be shown in the following, the author nevertheless thinks that the occurrence of the glauconite in this case is partly due to other conditions.

Not infrequently autochthonous glauconite is present as coating on denudation or clean-washed corrosion surfaces. In such cases the glauconite has been formed while the agitated (probably current) water had not yet allowed a deposition of the fine-detritus present in the water. A deposition of glauconite in cracks is not uncommon.

What is the Cause of the Rhythmic Alternation in the Series of Glauconitic Limestones?

As mentioned above, the enrichment of glauconite at the bedding planes of the limestones may partly be explained by the supposition of increased current in the water. This supposition, however, does not tell us, why the deposition of calcium carbonate ceases at times.

The bedding planes and the layers of glauconitic sand between them have not arisen by a secondary dissolution of the limestone. They have been primarily formed as they are now found, which does not prevent, however, that a dissolution of limestone could take place when the water circulated in the sandy beds.

What is now the reason of a temporary cessation of the limestone formation? Changes in the temperature, salinity, and depth of the water are no more able to give us an acceptable explanation than the increase of its current action. Calcium carbonate is precipitated in waters of varying salinity and of very different temperature and depth, in strong currents as well as in relatively tranquil parts of the sea. The author for his part considers that the explanation is to be sought in an increased acidity at the place of sedimentation. We know that neutral calcium carbonate is precipitated under certain conditions from a water solution of bicarbonate:

$$Ca(HCO_3)_2 \rightleftarrows CaCO_3 + H_2O + CO_2.$$

We also know that this reaction is reversible in so far that calcium carbonate is dissolved in water containing CO_2 under formation of bicarbonate.

Carbon dioxide present in the water has not only a dissolving action on limestone, it also counteracts the precipitation of the carbonate. In this case an increased hydrogen ion concentration involved by the presence of CO_2 must probably be taken into account. An increased content of hydrocarbons creates a reducing environment, an oxygen blockade. In this acid and reducing milieu the neutral carbonate was not precipitated.

An increase of the carbon dioxide content of the water may therefore cause a decreased deposition of calcium carbonate. The question is then, Is there any reason for us to calculate with occasional increases in the content of carbon dioxide on the formation of the beds discussed here? To this question we must answer that under certain conditions the content of carbon dioxide may have been fairly considerable, and that variations in its content are quite natural.

The bituminous mud of which the alum shale was formed is no doubt the source of the carbon dioxide. Its evolution was probably strongest where the bituminous beds are thickest, i e. in the deepest parts of the area. The cover of non-bituminous strata was also thinnest there. In periods when, owing for inst. to low temperature, the water's power of retaining the carbon dioxide was relatively great its content of this increased. In the area where the glauconitic limestone was deposited a maximal concentration of carbon dioxide was probably obtained when cold bottom currents, after having swept over the bituminous mud, reached the glauconitic zone situated at a somewhat shallower depth.

As the glauconite-free limestone beds are interstratified with glauconitic layers poor in calcium carbonate, there is reason to conclude that conditions counteracting the deposition of the limestone favoured the formation of glauconite, and that conditions favouring the formation of limestone counteracted that of glauconite. Consequently glauconite may be formed in water rich in carbon dioxide. As this may be followed by a relatively high content of hydrocarbons, we may say that glauconite is not formed in oxidation environment but in oxygen-blocked, possibly in reduction environment. There may, however, be reason to investigate, whether such a conclusion is supported by other conditions noticeable in the series of strata.

Is Glauconite Formed in Reduction or in Oxidation Environment?

The above related facts seem to prove that glauconite is most probably formed in reduction environment. Several investigators, however, have supposed that the mineral is formed in oxidation environment (see the historical summary, p. 133 seq.), and even if the author considers the arguments presented by them to be rather weak, he cannot of course abstain from investigating whether any support to this opinion can be found in the series of strata discussed. Two facts exist which in his eyes can give some guidance for the estimation: the occurrence of ferric and ferrous minerals and the occurrence of bituminous matter.

The iron minerals present in the series of strata are as follows:

ferrous minerals: siderite, pyrite, marcasite;

ferric-ferrous mineral: glauconite;

ferric minerals: haematite, goethite, limonite.

Supposing that the solution from which the deposition took place has primarily contained both ferrous and ferric matters, the former minerals have been formed when a reduction environment was created, the latter, on the contrary, when an oxidation environment existed. The question is now, Are the said minerals present in the series of strata in such a manner that we can infer from them which parts of the series of strata have been formed in the one or the other environment?

No definite, immediate answer can be given to this question, for the said minerals can occur in different manners, namely as

1. Authochthonous minerals a. formed at the same time as the rock,
   b. formed after the deposition of the rock.
2. Allochthonous minerals (occurring at secondary place = redeposited).

The first mentioned group of minerals is the only one from which we can gain an answer to our question. We must therefore try and find out how the minerals occur in the different beds.

The pyrite (and the marcasite) occurs in such a manner in the series of strata examined that we must presume the mineral was formed or recrystallized in the rocks after their deposition. Ferrugineous solutions circulating in the mud were subjected to a reduction by hydrocarbons and hydrogen sulphide, evolved in the bituminous sediments. The formation of pyrite is strongest in the beds formed at the greatest depth, i. e. in the more southerly part of the discussed area. The more abundant occurrence of pyrite (and marcasite) in the glauconitic beds than in the pure limestones does not necessarily mean that the former were form-

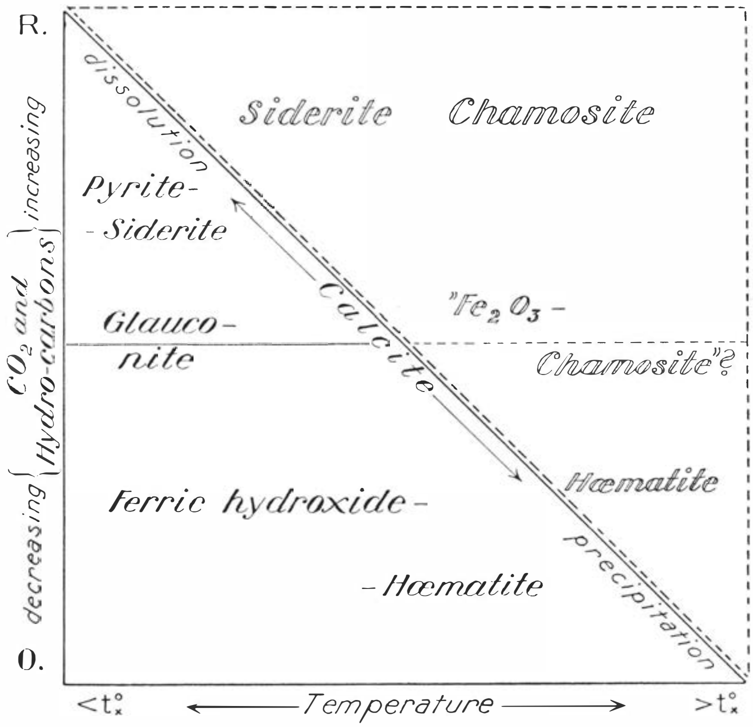

Fig. 25. Diagram of the relation between temperature and content of CO_2 + hydrocarbons at the formation of some sedimentary iron minerals and calcite. The lower left half refers to the glauconite-bearing limestones of Öland, the upper right half to the iron oolite series of Scania.
R = reducing milieu;
O = oxidizing milieu.

ed in a more pronunced reduction environment than the latter. It may be dependent on a stronger circulation of substance necessary for the formation of iron sulphides in the beds of glauconite.

The siderite observed in the glauconitic series occurs partly as crystals, secondarily formed in the peripheral part of the glauconite grains, partly in yellow limestone bands, formed there by reduction of the ferric hydroxide pigment. Like the formation of pyrite the metasomatic process resulting in an exchange of glauconite for siderite occurred in strongly reducing environment with the co-operation of carbon dioxide. In the two first-mentioned cases we must probably count with the chemically strongly active solution of H_2CO_3, which can be formed of CO_2 *in statu nascendi* and water (STEBUTT 1930, 192).

A strong increase in the content of carbon dioxide and a concentration of hydrocarbons in the water may perhaps also have had the effect of transforming the limestone with ferric hydroxide pigment, formed in relatively warm and oxygenous water, into a limestone mixed with siderite. However, the change has often wholly or partly stopped at a formation of ferric hydroxide richer in water (limonite, see below).

Neither pyrite nor siderite show that the rocks in which they occur were, like the minerals themselves, formed in reducing environment. On the contrary, there is reason to suppose that, as shown above, wherever they are present in limestone, this was formed in an environment with a relatively low content of carbon dioxide and hydrocarbons. As the grains of glauconite were embedded in the calcareous mud on its deposition, their formation took place before the beginning of the strong reduction under which the pyrite and the siderite were formed. This agrees well with the fact that the glauconite in itself is essentially a ferric silicate. On the other hand, the said facts are inconsistent with those mentioned before, which show that the glauconite and limestone are interbedded, and that the glauconite is then formed during periods with an increased content of carbon dioxide. This contradiction will be discussed later on, we shall first see how the ferric minerals occur in the series of strata.

Irrespective of the beds in which the limonite occurs as a weathering product of pyrite, we find that the mineral, as in other cases the siderite, occurs in defined, not very thick beds, nearly always together with haematite-rich portions. The haematite and limonite frequently form a very pronounced stratification of colours. But sometimes the red-pigmented, haematite-rich parts are found irregularly mixed with gray or green ones. In such cases pyrite together with the haematite is also met with, undoubtedly these beds were formed by redeposition of material deposited earlier under different conditions.

The pure, undisturbed haematite-pigmented beds were deposited in oxidation environment or at any rate in a non-reducing environment.[1] Consequently the haematite has in all probability been primarily formed as goethite [2] in an environment also favourable for the formation of limestone. This is probably the reason, why it never occurs strongly enriched but only as pigment in the limestone.

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[1] The author considers that the water has principally contained iron in ferric form (ferric oxide or ferric hydroxide in colloidal form and ferric sulphate in solution). Therefore no oxidation proper has been necessary for a deposition of ferric oxide or ferric hydroxide.

[2] The red pigment may consist partly of haematite, partly of goethite. The author had no occasion to investigate the varying per cent of water in the different layers.

It is questionable whether the ferric pigment has not been formed after the deposition of the calcium carbonate by an oxidation process. As a matter of fact, such an explanation of the colour stratification has been resorted to by more than one investigator. Sometimes a subaerial oxidation has even been considered to have taken place. Though the author has had the opportunity to study desiccation fissures in haematite-pigmented limestone and by no means doubts the exposure of the calcareous mud in such cases to subaerial influence immediately after the deposition, he is nevertheless sceptical as to whether the haematite pigment has arisen during the occasional drying. In the glauconite-bearing series of strata discussed here a subaerial formation of the pigment is excluded, as the strata have surely not been laid bare in the course of their formation and the stratification of colours occurs in such a manner that it can not have been formed after the deposition of the series of strata in its entirety. It is also difficult to find an acceptable explanation of a secondary submarine oxidation and formation of pigment within the calcareous mud already deposited. Consequently it remains to investigate, whether the pigment could have been formed contemporaneously with the limestone.

It is known that the ferric hydroxide sol is relatively mobile, and that it sometimes disperses and sometimes coagulates under the influence of electrolytes (STEBUTT 1930, 275).[1] On precipitation it can give water-poor red or water-richer yellow and brown ferric hydrates. The red ones are as a rule formed at a higher temperature than the yellow. It may be called in question whether the formation of pigment in its entirety has not been caused by an increase in temperature. For a rising temperature is liable to cause an aggregation within the ferric hydroxide sol. The same factor has also counteracted the origination of a reduction environment, having on the one hand prevented the enrichment of CO_2 and the increasing content of hydrocarbons and on the other hand created vertical currents, which have carried oxygen to the sea bottom, in this case at a relatively shallow depth.

In the colour-stratified glauconitic limestones we often find a thick red layer covered by a thinner yellow one, which in its turn is superstratified by a thin green crust of glauconite. The latter lies on a distinct corrosion surface with numerous more or less deep grooves. As the yellow layer fairly evenly follows all the irregularities of the corrosion surface, we must suppose that it has been secondarily developed in connection with the corrosion. It is probable that this bed originally contained the same red, water-poorer ferric pigment as the substratum, but that the latter has been transformed into a hydroxide form richer in water. From our knowledge of the above mentioned conditions of temperature, on which the formation of the different hydrates depends, we may also suppose that the formation of the yellow bed has taken place during a period with falling temperature. We must then also suppose that the corrosion has occurred under a relatively lower temperature. This supposition is further corroborated by the fact that it renders a

[1] Is perhaps this fact the cause of the pigment's distribution in spots in certain beds?

natural explanation of the corrosion. For owing to the falling temperature the solubility of calcium carbonate increases as well as the content of carbon dioxide and a dissolution of the deposited calcareous mud take place. Only at scattered points, probably, has this dissolution reached any greather depth in the mud. As the alteration frequently does not stop at the formation of limonite but continues to the formation of siderite, we have further evidence that the transformation was due to a beginning reduction, increased content of carbon dioxide and hydrocarbons.

The green crust of glauconite covering the corrosion surface was certainly formed under conditions not greatly differing from those under which the corrosion took place. The glauconitic crust sometimes contains an abundance of pyrite.

On trying to form an opinion of the extent to which the different beds were formed in oxidation or reduction environment in accordance with the above points of view, we can hardly avoid regarding the haematite- and limonite-pigmented ones as formed in a relatively oxygen-rich environment and, contrary to this, the pyrite- or siderite-bearing in an oxygen-poor one.

Glauconite occurs in both types of rock, principally as allochthonous mineral. It has not been observed as determined autochthonous mineral in the red or yellow beds. The thin laminations of autochthonous glauconite found here and there in the limestones never contain haematite or limonite but often pyrite. This form of glauconite is commonest in the gray limestones (without ferric oxide or ferric hydroxide) and on the above-mentioned corrosion surfaces.

It is evident from the preceding that the autochthonous glauconite does not occur in pure oxidation environment but often together with minerals formed in reduction environment. That it does not belong to the reduction environment proper is evident from the fact that it is essentially a ferric mineral. According to the conditions in Öland there is consequently reason to suppose that *the glauconite was formed in an indifferent or slightly reducing environment.* The position of the glauconitic series between the alum shale, formed in a pronounced reduction environment, and the red Limbata limestone, deposited in a typical oxidation environment, also indicates this, and its strong enrichment during periods with corrosion or with decreased deposition of calcium carbonate gives us occasion to presume a formation under an increasing concentration of carbon dioxide.

Under which Conditions of Temperature has the Glauconite been Formed?

This question has been touched upon in the preceding. We have shown that in the colour-stratified limestones the series red-yellow-green is often found, which was interpreted as a result of the transition from warm water poor in carbon dioxide to cold water rich in the same. Under these circumstances the green bed consisting of autochthonous glauconite has been formed in relatively cold water.

The increase in carbon dioxide (and the fall in temperature), supposed to cause a decrease in the deposition of calcium carbonate and an increase in the formation of glauconite, gets its natural explanation by the supposition of a fall of temperature in the water. By this means it has been able to retain a larger amount of carbon dioxide in solution.

The series of strata in Öland thus indicates that *the glauconite was formed in relatively cold water.* As will be shown later the composition of the glauconite confirms this, and it also agrees with the observations made on the forming conditions of recent glauconite.

Does the Presence of Organic Matter Favour the Formation of Glauconite?

As a rule the glauconite-rich strata are not bituminous, and they seldom contain a larger amount of fossil fragments. The only exceptions from this are beds consisting of secondarily redeposited material. As far as the author has been able to see, the autochthonous glauconite in the Ölandic strata never occurs together with organic matter. Even if no general conclusions can be drawn from this series of strata, the said circumstances show nevertheless that the *formation of glauconite is not favoured by a direct presence of organic matter* and on that account the presence of such matter in the glauconite-bearing deposit is unnecessary.

The slight reducing environment, in which the Ölandic series of glauconite was formed, owes its origin to the mud beds rich in organic matter, which were deposited earlier in the same area of deposition. Consequently organic matter has indirectly made the formation of glauconite possible in this case (p. 69).

Has the Connection between the Deposition Area and the Ocean Changed at the Time of the Glauconite's Formation.

At the time when Ölandic glauconite series now discussed began to be formed, a complete alteration of the sedimentation took place within almost the entire Baltic area. Before the appearance of glauconite a deposition of mud rich in organic remains took place in the area, and of this mud the alum shale was formed. After the beginning of the glauconite formation such mud was only deposited within certain limited areas, for inst. in Scania, Jämtland, and the north of Lapland. The change in the sedimentation may be owing to the altered possibilities of deposition, altered supply, and altered conditions for the formation of the autochthonous substance.

As the deposition of fine-detritus continues within certain parts of the area, the supply of such material to the sedimentary basin cannot have ceased at the first appearance of glauconite. It is more probable that this material could not settle in all the places, where it had previously been deposited, and that the obstacle to this was an increased movement in the water (currents). The secondary redeposition of the glauconite grains, which has occurred in almost every place where glauconite sand has been deposited on alum shale, shows that the water was strongly agitated. A deposition of fine-detritus contemporaneous with that of glauconite grains was excluded. Quite different conditions must have prevailed in the areas where the deposition of mud continued. This has possibly taken place in sheltered bays, behind lee-giving bars, barriers, etc. but hardly exclusively on account of the protection from currents a greater depth can give.

The alteration in the autochthonous material of the sediments, which characterizes the transition from the alum shale to the glauconitic series has been touched upon above in the discussion of the forming conditions of the glauconite. The change in the bentogenous as well as the planktogenous constituent in the rocks is also of interest.

The different forms characteristic of the Olenus stage (Upper Cambrian) also disappear within the parts of the area, that show a continued deposition of fine-detritus and organic mud. Of determinable fossils in these sediments phosphatic shells of brachiopods (*Obolus*, *Lingulella*, a. o.) and graptolites (*Dictyograptus*, *Clonograptus*, *Bryograptus*, etc.) only are generally found, but fragments of trilobites have also been met with occasionally (int. al. in Jämtland and Scania).[1] These changes may be wholly ascribed to the time factor. They indicate, like the rock, a fairly unaltered environment. This is also shown by the continued deposition of the organic material (planktogenous?), which gave rise to the content of bitumen in the shales.

The change in the sedimentation from the formation of alum shale to the deposition of glauconite may therefore hardly be ascribed to an alteration noticeable within the entire sedimentary basin. There is no reason to resort to a general change in temperature, an increase or decrease in salinity, etc., as an explanation. As seen above, however, it is indisputable that a great revolution must have occurred in the very circumstances that might have acted upon the current conditions or some other activity of the waters in the area. An increased possibility of the admission of a (cold) ocean current may be imagined to have caused the alterations in the sedimentation. The author has tried to map down this current or area of strong activity with guidance of the glauconitic series' development within different parts of the Baltic area, but he considers a further completion of the present material necessary to make the picture sufficiently clear. He hopes to be able to return to this in the account of his general paleogeographical studies on the Swedish sediments.

The breaks in the series of strata demonstrable both in and specially below, sometimes also above the beds of glauconite must of course be of great interest for the interpretation of the current conditions. For Öland's part these breaks have already been illustrated in a couple of diagrams (p. 11 and 12). In Gotland the break

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[1] From Scania only one form has been satisfactorily described: *Hysterolenus Törnquisti* Mbg (Moberg 1898, 317). This may be regarded as a predecessor of the Ordovician trilobite fauna or as its oldest representative. Its occurrence together with the first graptolites is a good reason, in the author's opinion, for placing the boundary between the Cambrian and the Ordovician below the Dictyograptus shale.

below the glauconitic series is very large (Hedström 1923); according to the drilling core from Visby it comprises the whole of the Upper Cambrian and the upper part of the Middle Cambrian. Above the glauconite beds also there is a large break here comprising the greater part of the Lower Ordovician.

The petrographic character of the glauconitic beds shows that they must have been formed in open water with free passage for currents. The breaks in the series of strata noticeable everywhere, in many places very large ones, only confirm this.

Conclusions based on the observations.

After the observations made on the Lower Ordovician series of glauconite in Öland and in accordance with the above related points of view the author thinks he is justified in drawing the following conclusions on the formation of the said glauconitic series and the glauconite:

1. The glauconite-bearing series of strata is wholly marine.
2. Glauconite often occurs allochthonously (= secondarily deposited and enriched).
3. The beds of glauconite were deposited at a depth of probably less than 100 m, and the formation of glauconite took place at the same slight depth.
4. The beds of glauconite were deposited and the glauconite formed in agitated open water, probably in an ocean current.
5. The formation of glauconite took place in relatively cold water.
6. The formation of glauconite was favoured by a slightly reducing milieu effected by hydrocarbons. The water holds a relatively high content of carbon dioxide.

The disappearance of the carbon dioxide involves a new deposition of calcium carbonate, sometimes coloured red by ferric oxide and consequently formed in non-reducing environment.

In occasional limestone beds a recurrence of the crust of glauconite and the yellow band may be found. The denudation has then been of short duration in each separate case.

The Glauconite-bearing Strata in the Lower Cambrian at Brantevik in Scania.

The Lower Ordovician strata are no doubt the richest in glauconite in Sweden. The mineral occurs there in limestone and shale. It is also abundantly present in other limestones, for inst. in the Senonian limestones of SE Scania, in the Paleocene marl, in the Eocene limestone, etc. In these cases the glauconite is fairly evenly distributed in the rocks and only locally enriched. The series of strata are in most cases inaccessible for closer study, and therefore they will only be discussed in the following in the account of the glauconite-bearing rocks.

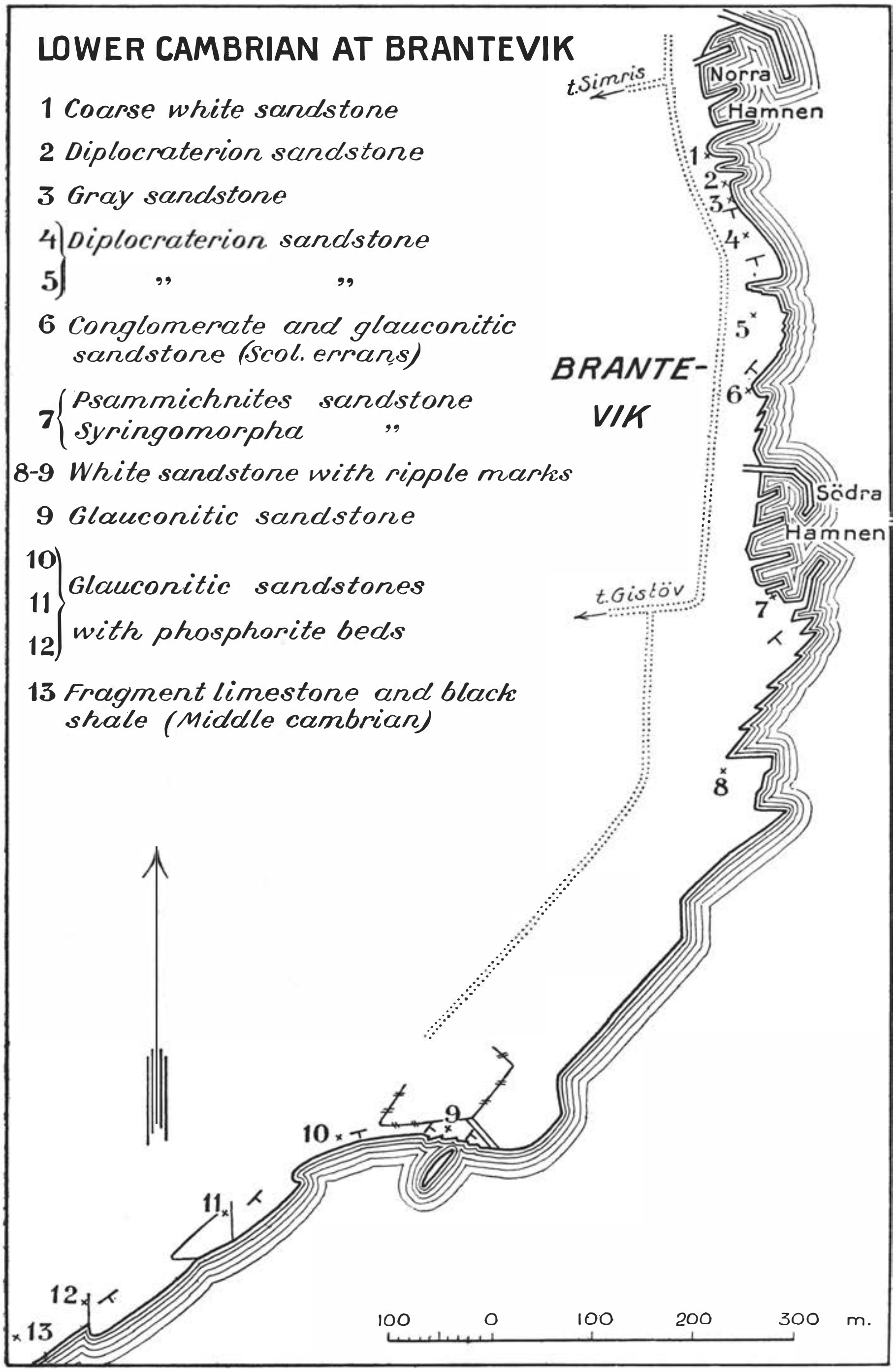

Fig. 26. Map of the coast at Brantevik. Localities 1—13 according to HADDING 1929.

The series of strata, which next the Lower Ordovician contains the largest amount of glauconite, is perhaps the Lower Cambrian or, more exactly, the upper part of it. The glauconite is widely spread in this series of strata: it has been found in the extreme north of Lapland as well as in Scania. In the following an account will be given of the occurrence of the glauconite in this series of strata but in one place only, Brantevik in SE Scania. The author desists from an account of its occurrence in the same series of strata in other places also partly because there is little to be gained from it and partly from lack of space. Otherwise it is tempting to give a survey of the Lower Cambrian glauconite-bearing series of strata in Öland, recently made known by a deep-drilling. This has been described by

Fig. 27. Lower Cambrian beds on the shore SW of Brantevik. The low cliff in middle distance = loc. 11.

Westergård (1929), who has also kindly placed his material at the author's disposal. Though the drilling core shows a more complete series of strata than the sections at Brantevik, the author has nevertheless chosen the latter for discussion, as they have yielded a richer material.

The glauconite-bearing series of strata at Brantevik differs essentially from that described above in Öland. The strata at Brantevik are namely developed as sandstones, while the strata in Öland consist of limestones. Some of the strata at Brantevik are calcareous sandstones but the percentage of limestone is not high enough for the rock to be termed arenaceous limestone. Besides that calcite is completely absent in certain beds. In many cases the cement has exerted a secondary influence on the glauconite but the glauconite's formation and embedding in the sand has occurred before the deposition of the cement and consequently independent of it. Only in cases when the cement was formed by calcareous mud deposited contemporaneously with the sand do we find the same form of the glauconite as in the limestones. We proceed, however, to an examination of the series of strata.

The Series of Strata at Localities 9—12 at Brantevik.

Along the shore of the fishing-village of Brantevik the Lower Cambrian strata with glauconitic rocks crop out in a couple of places (fig. 26). Farthest to the SW the glauconitic strata are specially easy of access (fig. 27 and 28). The series of strata communicated below no doubt only comprehends a smaller number of the glauconite-bearing beds but both the rocks and the glauconite occurring in them may in every essential respect be fully illustrated by what these beds show. At localities 10—12 the same beds are present. They form the upper part of the glauconite-bearing series. Between localities 12 and 9 a fault is found. The strata at

Fig. 28. Shaly glauconitic sandstone. Brantevik, loc. 9.

locality 9 (fig. 28) are older than those at locality 10. The interjacent strata have not been accessible for observation. The following list refers to the strata at localities 11, 10, and 9.

Stratum	11 e.	Sandstone, white and gray, glauconite-bearing	105 cm.
»	11 d.	White and gray sandstone with phosphorite nodules	8 »
»	10 c.	Glauconite sandstone, shaly, arenaceous, with phosphorite nodules	11 »
»	10 b.	Glauconite sandstone, with phosphorite nodules in the upper part	23 »
»	10 a.	Glauconite sandstone, shaly, arenaceous	15 »

»	9 h.	Glauconite sandstone, dark gray.
»	9 g.	Glauconite sandstone, dark grayish green.
»	9 f.	Shaly glauconite sandstone, gray and green.
»	9 e.	Calcareous glauconite sandstone, with the glauconite in laminae.
»	9 d.	Glauconite sandstone, grayish green, with *Scolithus errans*.
»	9 c.	Shaly glauconite sandstone, grayish green.
»	9 b.	Glauconite sandstone, grayish green, with phosphorite nodules.
»	9 a.	Glauconite sandstone, calcareous with phosphorite nodules.

The following description of the strata is schematized in accordance with the description of the glauconitic beds in Öland. There is no need to discuss the percentage of fossils here, as we only find fragments in the calcareous strata. Tracks have been observed in a few beds. Pyrite is generally absent.

Stratum 11 e. White and gray, partly quartzitic sandstone with glauconite in scattered small grains. The darker portions of the sandstone are sometimes »blue-quartz»-like.

The quartz grains are well rounded, about 0,5 mm in diameter.

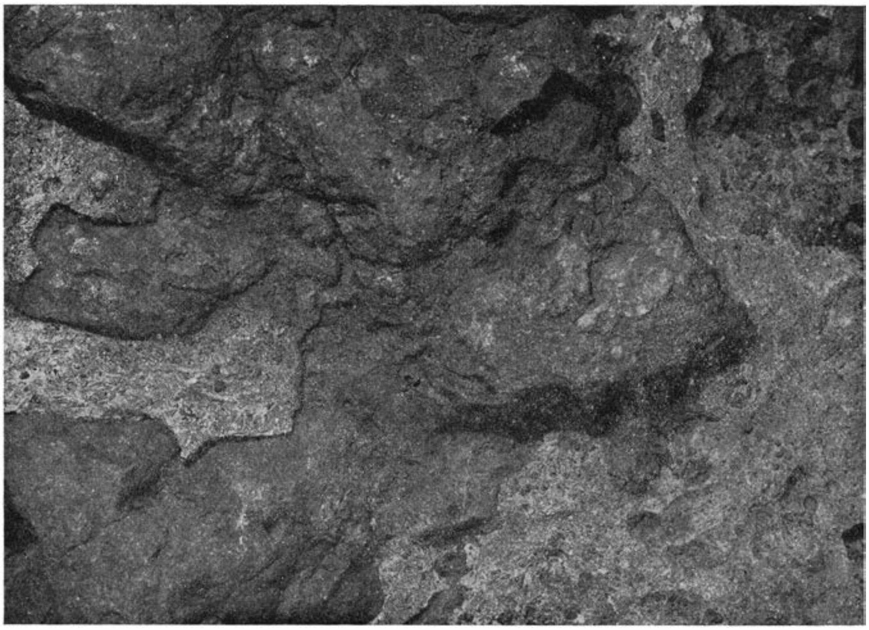

Fig. 29. Glauconitic fragment limestone with large phosphorite nodules. Brantevik, stratum 11 d. — $^1/_1$.

The cement consists of quartz, secondarily enlarging the quartz grains but not always entirely filling up the space between them. In the white part of the sandstone the remaining space is occupied by calcite, in the gray sandstone the pores as well as the quartz cement enclose dark flocks of organic substance. (Photo, HADDING 1929, fig. 59.)

Phosphorite nodules occur in the upper part of the bed.

Glauconite in scattered grains, seldom exceeding 0,3 mm in diameter but often less than 0,1 mm.

Stratum 11 d. White and gray sandstone with large and small nodules of phosphorite and a layer of dark gray fragment limestone (fig. 29).

In the white, more coarse-grained part of the rock *the quartz grains* are rounded and about 0,5 mm large, in the gray part they are angular and smaller.

The cement consists of quartz, secondarily enlarging the grains of sand.
In the gray part a dark (organic) pigment is to be found between the grains.
The phosphorite occurs primarily as well as secondarily. The nodules contain abundant small quartz grains and glauconite.
The grains of *glauconite* are in the sandstone partly squeezed out between the grains of quartz and partly round or angular; the latter are fragments of larger cracked grains. In the fragment limestone the grains are rounded with dark-pigmented margin (fig. 30).

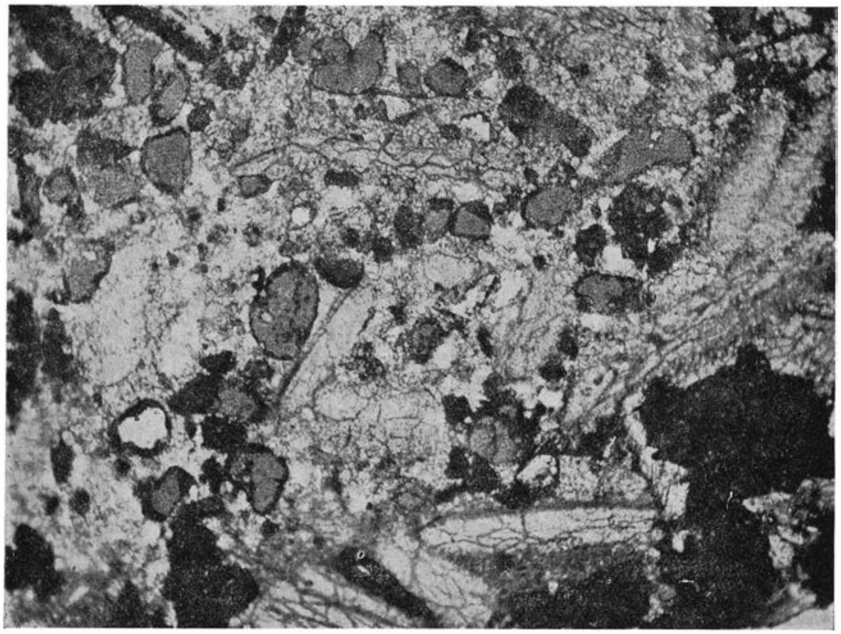

Fig. 30. Fragment limestone with pyrite aggregates and small glauconite grains. Brantevik, stratum 11 d. (Pr. 2866. Pl. 546.) — 60 ×.

Stratum 10 c (= stratum 11 c). Grayish green, fine-grained, partly shaly calcareous sandstone with centimeter-large crystals of calcite studded with grains of quartz. Phosphorite nodules, 1—2 cm in size, are scattered in the bed.
The quartz grains are of two different sizes, part of them about 0,2 mm and part about 0,08 mm. The larger grains are rounded, the smaller angular. The grains are secondarily enlarged after the deposition.
The cement consists partly of quartz but principally of calcite.
The phosphorite nodules occur in secondary site of deposition. They are well rounded and sharply demarcated from the surrounding rock. They contain abundant small grains of quartz and glauconite.
The glauconite grains are partly squeezed out between the quartz grains but partly, lying enclosed in calcitic cement, they have retained their round form.

Sometimes the glauconite is partly replaced by calcite, which then occurs in the form of crystals in the glauconite grains.

Stratum 10 b. Greenish gray, fine-grained sandstone, with thin, black, out-thinning layers, small nodules of phosphorite and winding tracks *(Scolithus errans).*
The quartz grains are angular, 0,05—0,1 mm in diameter.
The cement and matrix consists of calcite, bitumen, and glauconite, possibly also silica and clayey substance.
The glauconite occurs abundantly. It is as a rule squeezed out between the quartz grains.

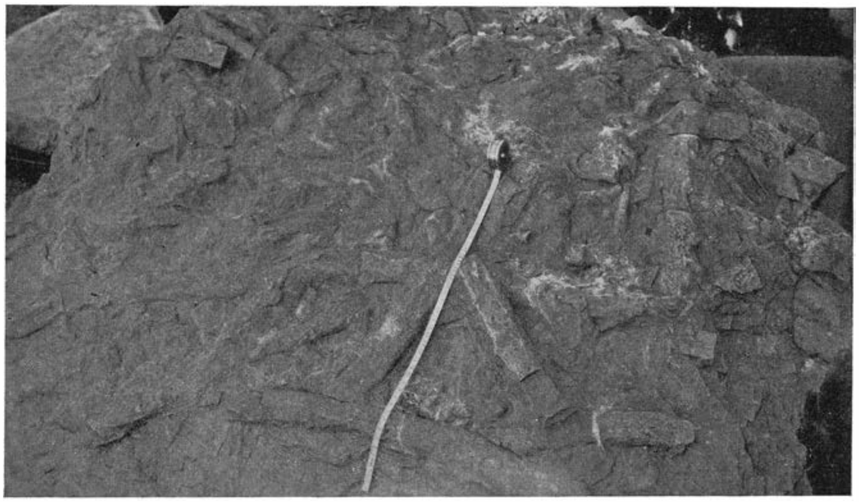

Fig. 31. Glauconitic, shaly sandstone with large winding trails of *Psammichnites gigas* type. Brantevik, stratum 10 a. (Pl. 632.) — C:a 1/8.

Stratum 10 a. Dark gray and grayish green, fine-grained glauconitic sandstone, shaly and fairly rich in small scales of mica. Large, winding worm trails of the *Psammichnites gigas* type (fig. 31).
The quartz grains are angular, about 0,05 mm large.
The cement consists partly of quartz, secondarily enlarging the grains, partly of crypto-crystalline, silicified clayey substance. Calcite is absent.
The glauconite occurs partly as relatively round grains without distinct outline, partly as irregularly formed masses squeezed out between the quartz grains. The grains of glauconite are about 0,2 mm in diameter.

Stratum 9 h. Dark gray, white and green spotted sandstone, with sporadically occurring black trails *(Scolithus errans).*
Quartz grains angular, about 0,1 mm in diameter.
Cement of quartz, secondary growth of the quartz grains, with dark pigment in flocks. Scales of muscovite.
Phosphorite layer with large nodules in the upper part of the sandstone.

Glauconite in grains, 0,1—0,2 mm in diameter. They are sometimes round but more frequently irregular, squeezed out between the surrounding quartz grains. Light green in colour, in the superficial layer sometimes brown. In strongly pigmented parts of the rock the glauconite grains also contain an abundance of black pigment (iron sulphide) and are then frequently surrounded by a black crust. As a rule the grains are fine-crystalline aggregates but occasional larger crystals occur.[1]

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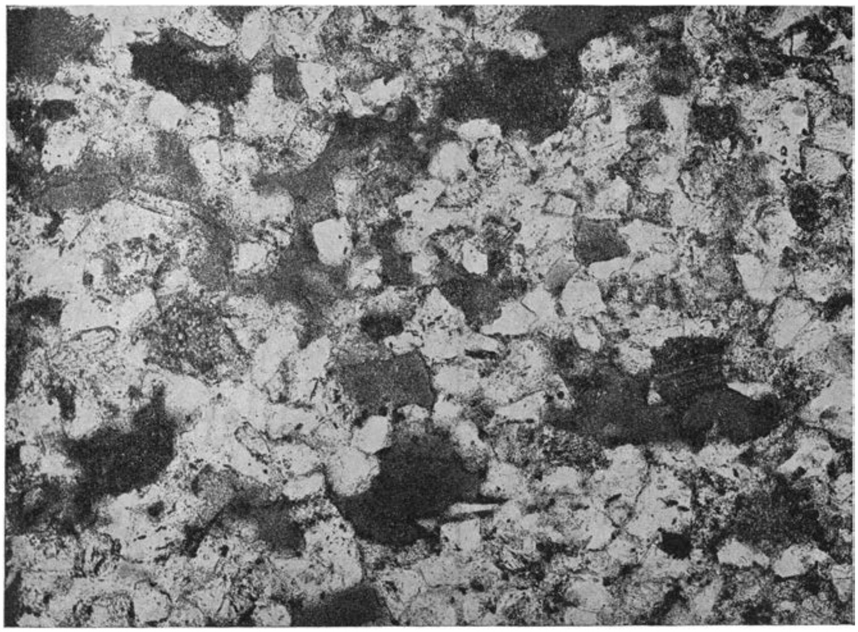

Fig. 32. Fine-grained glauconitic sandstone with clayey and bituminous matrix. Glauconitic grains partly squeezed out between the quartz grains. To the right a foliated glauconite crystal. Brantevik, stratum 9 g. (Pr. 3115. Pl. 538.) — 60 ×.

Stratum 9 g. Dark, grayish green, fine-grained sandstone, partly brecciated and containing crystals of galena and sphalerite.

Quartz grains angular, the majority of them less than 0,1 mm.

Cement of quartz. Here and there more strongly enriched pigment of bitumen and clayey substance (fig. 32). Muscovite in single scales.

Glauconite is abundantly present, mostly squeezed out between the quartz grains.

[1] Here as in the following the expression »larger crystals» refers to the grains of glauconite, which are not sub-crystalline aggregates but single crystals. The size of these grains is as a rule only 0,1—0,2 mm.

Stratum 9 f. Shaly, gray and green, banded sandstone.

Quartz grains angular, about 0,07 mm in diameter. Besides these, larger, rounded grains and grains of other minerals (felspar, zircon, turmaline, muscovite) are rather common.

Cement of calcite, sometimes in large crystals, studded with grains of sand.

Glauconite, as a rule squeezed out between the grains of quartz but also in round, undeformed grains. Not infrequently in »larger crystals». Size of grains 0,05—0,2 mm. The grains are sometimes bright green and sometimes dark from pigment, the latter is specially the case in the round grains. Two

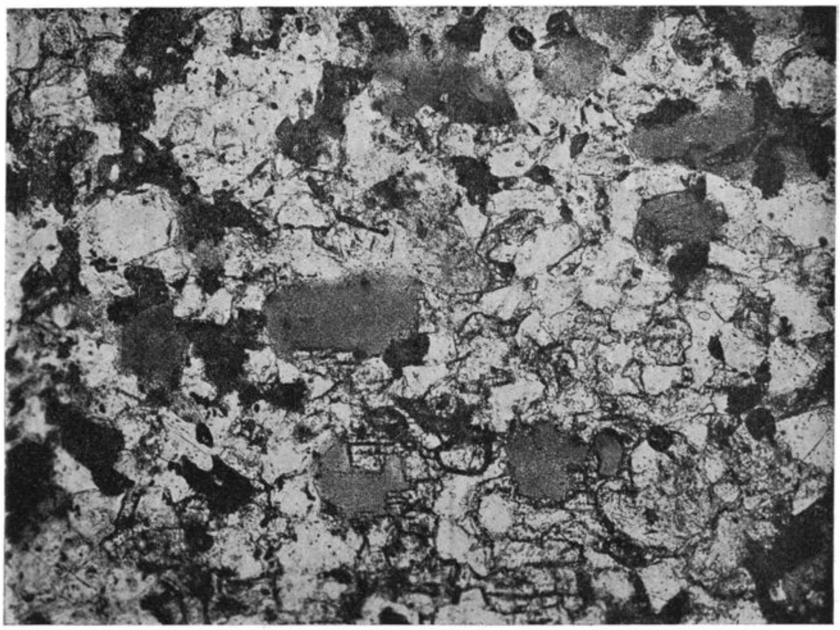

Fig. 33. Glauconitic sandstone with calcareous cement. Brantevik, stratum 9 d. (Pr. 2800. Pl. 539.) — 60 ×.

different types of glauconite, the one autochthonous, the other allochthonous, occur in this stratum.

Stratum 9 e. Fine-grained, spathic, grayish green, calcareous sandstone, partly shaly or distinctly bedded, with the glauconite strongly enriched in thin laminae.

Quartz grains rounded, 0,2—0,5 mm large, slightly enlarged by secondary growth.

Cement of calcite, abundant and developed in large crystals.

Glauconite in round grains, about 0,2 mm in diameter. The outline as a rule irregular, as if corroded. The glauconite is often partly replaced by calcite.

Stratum 9 d. Fine-grained, dark grayish green, calcareous sandstone, with black worm trails *(Scolithus errans)*.

Quartz grains angular, about 0,07 mm large.

Cement mainly of fine-crystalline calcite, a smaller part of quartz. Abundant dark pigment.

Glauconite squeezed out between the quartz grains, sometimes also deformed by crystals of calcite (fig. 30). The grains are 0,05—0,2 mm large. »Larger crystals» not uncommon.

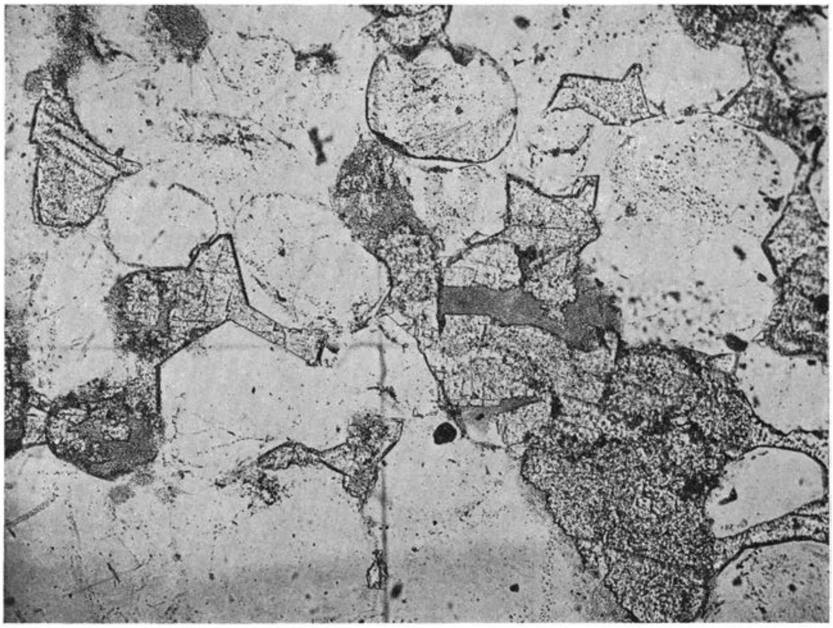

Fig. 34. Glauconitic, calcareous sandstone with secondarily enlarged quartz grains. The glauconite grains are more or less replaced by calcite. Brantevik, stratum 9 c. (Pr. 3117. Pl. 542.) — 60 ×.

Stratum 9 c. Fine-grained, stratified or shaly, light green and white calcareous sandstone, partly distinctly spathic. Uneven surfaces with a dark, argillaceous or bituminous coating are seen in the sandstone.

Quartz grains rounded, 0,1—0,4 mm in diameter, often secondarily enlarged.

Cement of fairly coarse-crystalline calcite, often so abundant that the quartz grains do not touch each other. Here and there calcite grains occur, distinguishable by their pigmentation from the surrounding cement, with which they form large, homogeneous crystals. These pigmented grains are formed by the replacement of the glauconite by calcite (see below).

Glauconite in round grains, sometimes wholly or partly replaced by calcite (fig. 34). The mineral also occurs in irregularly formed aggregates between the quartz grains (fig. 35). In this form also it may be more or less replaced by calcite.

Stratum 9 b. Grayish green, spathic, calcareous sandstone with phosphorite nodules in the upper part of the bed. Glauconite is abundantly present in the upper and lower part of the bed but only sparingly in its middle part.

Quartz grains rounded, 0,2—0,7 mm large.

Cement of relatively coarse-crystalline calcite, often so abundant that the quartz grains do not touch each other.

The phosphorite is partly undoubtedly allochthonous, partly probably autochthonous. Nodules of the latter type contain smaller pebbles of the former.

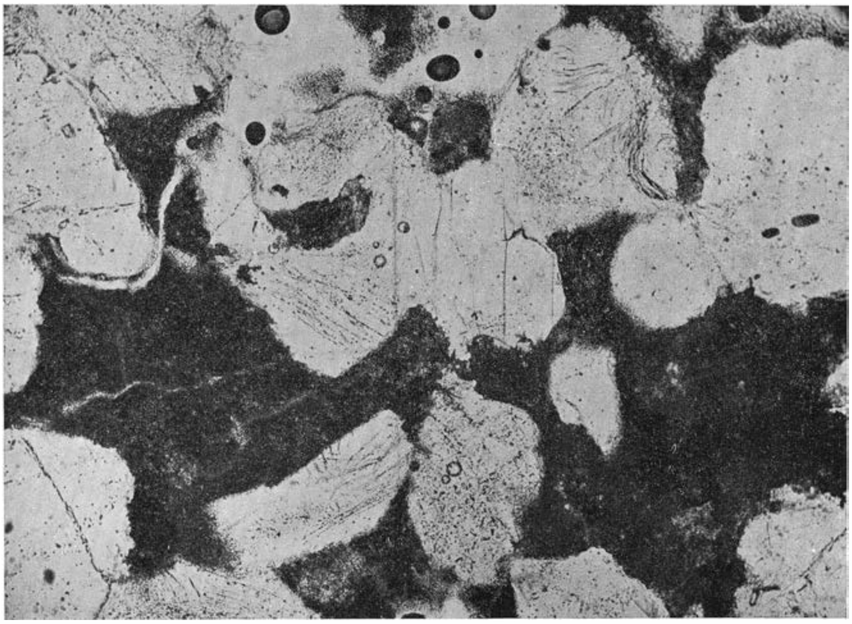

Fig. 35. Glauconitic sandstone. The glauconite (dark) is irregularly squeezed out between the quartz grains. Brantevik, stratum 9 c. (Pr. 3118. Pl. 540.) — 60 ×.

The glauconite occurs almost exclusively as a network or irregularly formed masses in the interior of the calcite crystals (fig. 36). It has been replaced, more or less, by the crystallized calcite. Glauconite also occurs squeezed out between the grains of quartz. In both cases it is autochthonous. Scattered round allochthonous grains are, however, to be found.

Stratum 9 a. White, fairly coarse sandstone, partly rich in calcite.

Quartz grains rounded, 0,3—2 mm large, often secondarily enlarged.

Cement partly of quartz, partly of calcite.

Phosphorite in larger and smaller allochthonous nodules, rich in small, angular quartz grains, less than 0,1 mm in size.

Glauconite is only sparingly present, partly in the form of round grains (fig. 37), partly as indistinctly limited small aggregates. The grains are about 0,3 mm large.

A Survey of the Glauconitic Series at Brantevik.

As already preliminarily pointed out, the glauconite-bearing part of the series at Brantevik comprehends several strata besides those described here. Glauconite also occurs in another, older part of the Lower Cambrian sandstone at Brantevik (see Hadding 1921, p. 97). The account given may, however, suffice to illustrate the character of the glauconite-bearing rocks and the development and occurrence of the glauconite, the more as other accessible glauconitic rocks present nothing essentially new.

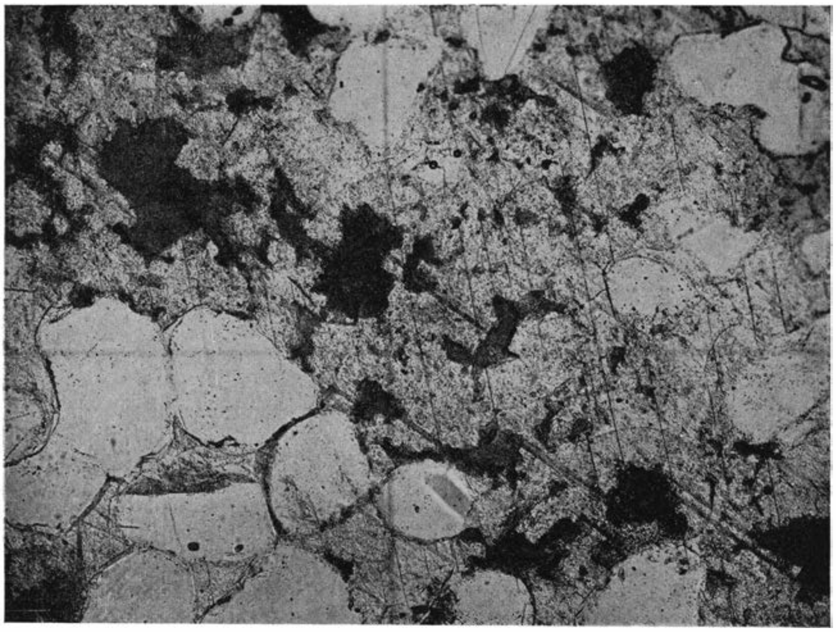

Fig. 36. Calcareous glauconite sandstone. The larger part of the glauconite grains being replaced by calcite, only small irregularly formed masses remain. Brantevik, stratum 9 b. (Pr. 3119. Pl. 543.) — 60 ×.

What first strikes us when, after studying the glauconite in the limestones, we turn to the glauconite-bearing sandstones, is the development of the glauconite. Neither the large grains full of cracks, nor the round or tabular ones with distinct demarcation, which dominate in the limestones, are to be found in the sandstones. The development of the glauconite in the sandstones is such that we frequently feel inclined to characterize it as cement or matrix.

We shall, however, return to the glauconite's forms of development in a later chapter and pass on to an examination of the glauconite-bearing rock, the sandstone.

As is evident from the account given, the glauconite-bearing sandstones are of different coarseness.[1] The fine-grained with grains 0,05—0,2 mm in diameter are as a rule muddy and contain angular or only slightly rounded grains of quartz. The somehwat more coarse-grained, with quartz grains 0,2—2 mm in diameter, are less muddy and have generally well rounded grains. The latter have, of course been deposited in a more agitated water than the former.

In the described series of strata the lower as well as the upper part consists of relatively coarse-grained beds with rounded grains, while the middle part contains only fine-grained layers. The cause of this variation may have been a subsidence

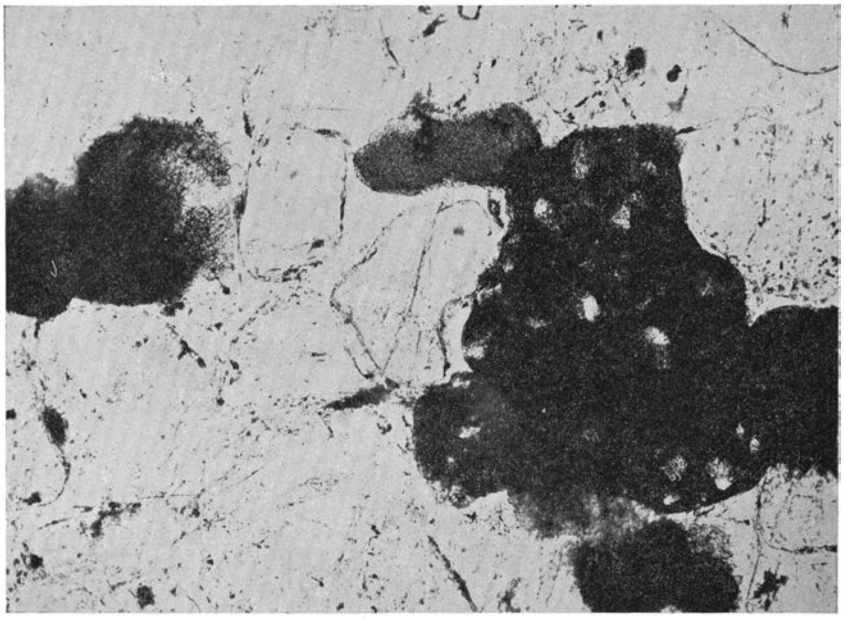

Fig. 37. Quartzitic sandstone with glauconite grains and allochthonous phosphorite (the larger dark mass enclosing small grains of quartz). Brantevik, stratum 9 a. (Pr. 2804. Pl. 545.) — 60 ×.

of land which took place during the deposition. Strata 9 a—c were deposited before the subsidence of land had made the deposition of the fine-grained material possible, strata 9 g—10 b after the subsidence of land, and finally strata 10 e and overlying ones after the succeeding elevation.

On the transition from the one sandstone type to the other, mixed forms of both occur, as might be expected. Strata 10 c—d contain both larger rounded and smaller angular grains. This is also the case with stratum 9 f. The progress of the said change in the character of the rocks shows that they originate from general, slow changes in the sedimentary conditions and not from occasional disturbances. We should, however, not be astonished to find traces of the influence of

[1] The relation in size between the grains of quartz and those of glauconite has already been illustrated (Hadding 1927, 22).

more occasionally acting factors on the deposition of sediments. The formation of a fine-grained bed (9 e) between two coarser ones (9d and f) may be ascribed to an occasional change in the sedimentary conditions for inst. alterations of a current. Perhaps the variation mentioned may be ascribed wholly to locally working changes.

The investigation of the formation of glauconite is in no way affected, whichever interpretation we may prefer.

Of greater interest is it that the subsidence resp. elevation of land, which the author considers to be evident from the described series of strata, can also be traced in the surrounding, next older and next younger, non-glauconite-bearing beds. Below stratum 9 a and above stratum 10 e coarse sandstones follow without mud (and without glauconite). The upper and still more the lower beds show the successive decrease resp. increase of the size of the grains from bed to bed. In 9 a the larger quartz grains are 2 mm in diameter, in stratum 9 b $0{,}_7$ mm, in stratum 9 c $0{,}_4$, and in stratum 9 d less than $0{,}_1$ mm.

From the above related facts certain inferences may be drawn as to the forming conditions of the glauconite. As long as the deposition takes place in such shallow and agitated water that only coarse grains are deposited and no mud, no formation or embedding of glauconite occurs at the site of deposition. Not until the diameter of (the bulk of) the grains of quartz has been reduced to 1 mm or somewhat less are enclosed grains of glauconite found among them.

Before passing on to a discussion of the influence of the depth of deposition (and of its changes) on the formation of glauconite, it is necessary to be fully aware that glauconite does not always occur in primary site of deposition.

Is it then possible to determine whether the glauconite occurs as autochthonous or allochthonous mineral in the sandstones? The author considers that, in many cases at least, it is possible.

As already shown, glauconite is present in almost all the sandstones, squeezed out between the sand grains in a manner revealing that, on the embedding, it was a plastic mass. It had undoubtedly the character of gelatinous lumps, into which the sand grains could easily be pressed when the deposit was exposed to the pressure of later superstratified detritus.

Besides such outsqueezed glauconite, however, round grains that have resisted the pressure of the surrounding quartz grains also occur. Consequently this glauconite must have gained a certain solidity already on the embedding in the sand. It has passed the gelatinous stage into its present crystalline or crypto-crystalline.

What conclusions, then, may be drawn from these facts? Firstly that the embedded crystalline glauconite is, from a genetic point of view, older than the gelatinous. An embedding of glauconite in its gelatinous form means that the embedding occurred during or immediately after the formation. We do not know at what rate the crystallization and solidification have passed off in the lumps of glauconite and are therefore also unable to decide how long and how far the glauconite could have been transported before becoming so hard that it could no more be squeezed out between the quartz grains on its embedding in sand. On that account we may not say, either, that all the glauconite squeezed out and therefore embedded in a gelatinous state is at a primary site of deposition. The author considers it more probable that a certain transportation has as a rule taken place before the solidification of the glauconite, and that the occurrence of outsqueezed grains in the coarse sandstones speak especially in favour of this. Nevertheless he regards *the appearance of outsqueezed grains as a practically reliable sign of a formation of the glauconite together with the deposition of the sandstones.*

The allochthonous character seems still more certain to him, if the glauconite grains embedded in the sand show no influence of the pressure exerted on them by the surrounding grains of sand. The solidification has no doubt lasted so long that the grains could in the meantime be transported a considerable distance from the place of formation. The transportation may then have taken place from a greater depth to a lesser and of course vice versa also, if the conditions for it existed. It is not altogether unimagnable that the intact, round grains were kept in motion (for inst. by repeated washing) at their place of formation for such a length of time that they could be solidified. More probably, however, has a transportation taken place in connection with the movement, and there is, on that account, every reason to suppose that *the glauconite grains not squeezed out in the sandstones are allochthonous.*

On examining the described series of strata at Brantevik from the above mentioned points of view, we find that autochthonous glauconite occurs throughout the entire series. Most prominently, however, is it found in the fine-grained sandstones, deposited at greater depths. Allochthonous glauconite has also been observed in almost every bed. But by no means does it play the same prominent rôle in the fine-grained as in the coarser sandstones, deposited at lesser depths.

The series of strata at Brantevik shows that glauconite was formed on a large scale when the depth was greatest, and that the formation was reduced when the depth had decreased, whereupon it fairly soon ceased altogether.

It would of course be of great interest to establish at what depth the different beds were formed. This is hardly possible, at any rate not if we lay claim to any greater exactness. It may, however, be stated that all of them were formed outside the littoral zone but at a relatively slight depth, in the opinion of the author only a few tens of meters. The nature of the rocks as well as the abundance of worm tracks (*Psammichnites gigas* and *Scolithus errans*) in the fine-grained beds contradict a formation at greater depth.[1]

In the other series of glauconite at Brantevik, somewhat older than that described here, we find a perhaps still surer support of our opinion that the beds of glauconite were deposited at slight depth. The basal bed of the said series of glauconite consists of an intraformational conglomerate with pebbles of phosphorite and glauconite-bearing sandstone. The conglomerate is formed by a breaking-up of

[1] Both *Psammichnites* and *Scolithus errans* are often found in glauconite-free, coarse-grained sandstones formed in or close to the littoral zone.

sediments deposited immediately before, and this breaking-up must have occurred at a shallow depth.

The sandstone deposited before the formation of conglomerate and now included in the conglomerate as pebbles contains a small amount of glauconite, while the beds above the conglomerate are rich in glauconite. As may be inferred from this the conglomerate has been formed during a short period of strongly moving water, perhaps during an occasional elevation in a period of subsidence. In the earlier described series of strata we find that stratum 9 e, in itself relatively coarse-grained but embedded in fine-grained glauconitic sandstone, forms a certain correspondence to the conglomerate. Both stratum 9 e and the conglomerate are glauconite-bearing. But the grains of glauconite are no doubt partly allochthonous. In the conglomerate, however, some of the pebbles are covered with a thin coating of glauconite, which of course must be autochthonous. Consequently the formation of glauconite has not ceased with the formation of the conglomerate.

If we, irrespective of the percentage of glauconite, make a comparison between the glauconite-bearing and the glauconite-free rocks in the series of strata at Brantevik, we shall find certain differences between them which are important for the interpretation of the glauconite's forming conditions. It has been related above how the size and wear of the grains changed in such a manner that a depression of land may be supposed to have occurred when the formation of glauconite began. From the description of the strata it is also evident that an increased deposition of mud took place simultaneously with the formation of glauconite.

The deposited mud was rich in organic substance, and the residues of this are found in the sandstones as dark bituminous flocks. As these flocks terminate in the series of strata simultaneously with the glauconite, just as they both entered into it at about the same time, it may be supposed that the formation of glauconite was in some way or other dependent on the occurrence of organic substance. This supposition is further confirmed, if we examine the other glauconite-bearing rocks in the Cambrian sandstone series. Almost everywhere are these rocks dark and bituminous, or else they occur together with bituminous beds.

The above-mentioned observations lead to the question, What significance has the occurrence of organic substance had for the formation of glauconite? We have discussed this question already in connection with the Ölandic glauconite beds, and it may be sufficient to refer to the points of view advanced then. In the author's opinion the organic substance has played a similar rôle in the Lower Cambrian as in the Ordovician formation of glauconite, i. e. it has created a *milieu* of slight reduction favourable for the formation of the glauconite.

Even though the organic substance might have acted in the same manner during the formation of glauconite at Brantevik and in Öland, its modes of occurrence in the said places differ, nevertheless, greatly. In Öland the organic substance is essentially accumulated in the substratum of the glauconitic series, the alum shale, but in the Cambrian sandstones the organic substance most frequently occurs in the glauconite-bearing strata proper. Thus the comparison between the conditions at the different places shows partly that the presence of organic substance in a bed may under certain circumstances create a possibility for the formation of glauconite in the same bed, and partly that the organic substance may have the same effect, if occurring in other, older beds. The essential for the formation of glauconite is therefore not the organic substance itself but the effects this may produce. As mentioned above, the evolution and concentration of carbon dioxide in and above the deposited sediments or, more correctly perhaps, the content of hydrocarbons in the water may be exactly the effects which created the conditions necessary for the formation of glauconite.

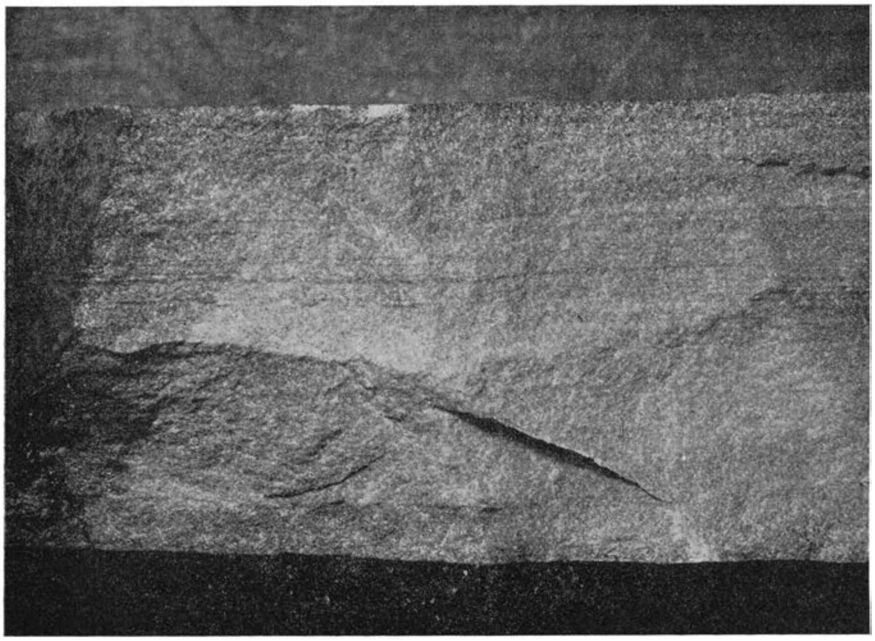

Fig. 38. Parallel-bedded, green and brown sandstone with glauconite laminae. This finely stratified sandstone occurs in the upper part of the Lower Cambrian in different parts of Scania and on Kalmarsund. Hardeberga. (Pl. 275.) — 1/1.

Glauconite is, however, not always formed where the above mentioned conditions prevail. Others are also required, and the rocks do not always inform us of them. Thus the purely chemical progress in the formation of the glauconite is not evident from the study of the glauconite-bearing rock, no more does this reveal to us in what form the silica, the iron, and the alkali appeared before their formation of the combination called glauconite. This question will, however, be taken up in the chapter on the formation of the mineral, and in connection with it an account will also be given of the occurrence of the iron and the autochthonous silica in the series of strata.

Other Swedish Glauconite-bearing Series of Strata.

The two glauconite-bearing series of strata, the Lower Ordovician in Öland and the Lower Cambrian at Brantevik, of which an account is given above, are far from being the only ones that are worthy of a discussion in detail. They may, however, be counted as types of two different series of rocks among which the majority of other occurrences may be included. Of the latter a few will be shortly mentioned.

Fig. 39. Glauconitic limestone with phosphorite nodules. Between the limestone (Lower Ordovician: Ceratopyge-stage) and its substratum (Upper Cambrian: zone with *Peltura scarabaeoides*) there is a considerable break in the sedimentary series. Uddagården, Västergötland. (Pl. 96.) — $^1/_1$.

In the upper part of the Lower Cambrian sandstone, *the Olenellus beds,* one or two glauconite-bearing divisions are generally found. The conditions often resemble those at Brantevik. This is of course especially the case in the occurrences in Scania — Simrishamn, Kivik, Hardeberga — but they have also been refound outside Scania, for inst. on deep drilling in Öland (fig. 40).

In the drilling section communicated by WESTERGÅRD (1929) two glauconitic horizons are to be found, one at the boundary between the Middle and Lower Cambrian, the other some meters below. The Ölandic like the Scanian Lower Cambrian glauconitic sandstones are phosphorite-bearing.

The petrographical development of the Lower Cambrian sandstone is different in Västergötland than in Scania and Öland, essentially dependent on the fact that the Cambrian transgression reached Västergötland considerably later than Scania and Öland. On the formation of the glauconitic strata in the Lower Cambrian of Scania and Öland, littoral or sub-littoral sandstones adjacent to the shore were deposited in Västergötland. In these, the Mickwitzia as well as the Lingulid sandstone, scattered grains of glauconite occur, still without any glauconite-bearing series being brought into question. It is not altogether impossible that an investigation of the glauconite's distribution may give a certain basis for paralleling the beds in the Cambrian sandstones of Öland and Västergötland with the corresponding ones in Scania.

Lower Cambrian sandstones of the same type as in Västergötland and without glauconitic accumulations proper occur in Östergötland and Nerke.

In Dalecarlia the basal beds in the Cambro-Silurian series of strata consist of Lower Ordovician rocks, and on that account no Cambrian glauconitic beds are present there.

In the sandstone series of the Gävle region glauconite-bearing rocks occur, but they are only known as erratic blocks, and their ages is not definitely determined.

Glauconitic rocks are also to be found in the wide Cambro-Silurian zone of Norrland. Lower Cambrian glauconite-bearing sandstone has been observed as far up as Torne Träsk (Hadding 1929, 141).

Thus, the glauconite is widely spread in the Olenellus stage. The development of the glauconite-bearing rock is throughout of the same type as at Brantevik.

A great part of the *Middle Cambrian* series of strata, the Paradoxides beds, is developed in Sweden as alum shale and black, bituminous limestone. No occurrence of glauconite can be reckoned with in these rocks. In some places, however, the Paradoxides beds are developed as relatively bitumen-free shales and sandstones, and the series of strata is then as a rule glauconite-bearing. This is for inst. the case in Öland, where both the lower part of the Paradoxides stage, the Oelandicus zone, and its middle part, the Tessini zone, consist of fine-grained, glauconitic sandstones and limestones. The rocks are as a rule thin-bedded, sometimes shaly, often argillaceous and not infrequently rich in tracks of different kinds. In a sandy marl-shale from the Oelandicus zone at Borgholm and in limestone beds enclosed in the same shale small grains of glauconite ($0{,}_{03}$ mm) are sparingly present but still in sufficient quantities to give the rock a green tint.

In the Tessini zone the glauconite is sometimes abundant. It has also been observed in the calcareous sandstone at Köping, in the fragment limestone at Äleklinta and at Risinge, as well as at several places in the calcareous sandstone shale. Nor is the mineral absent in the lower part of the Tessini zone, the intraformational Acrothele granulata conglomerate, but there it mostly occurs as crust on shells and on conglomerate pebbles.

In the upper part of the Paradoxides stage, the Forchhammeri zone, as well as in the Olenus stage glauconite is absent. The rocks in this upper part of the Cambrian series of strata consist, where they are to be seen, of bituminous limestones and alum shale.

The lower part of the *Ordovician* is glauconite-bearing in almost all Sweden. This is specially the case in the Ceratopyge stage and in some places in the lower part of the Asaphus stage also. The strongest development of the glauconite is found in the Ölandic strata of which an account is given above, the weakest in

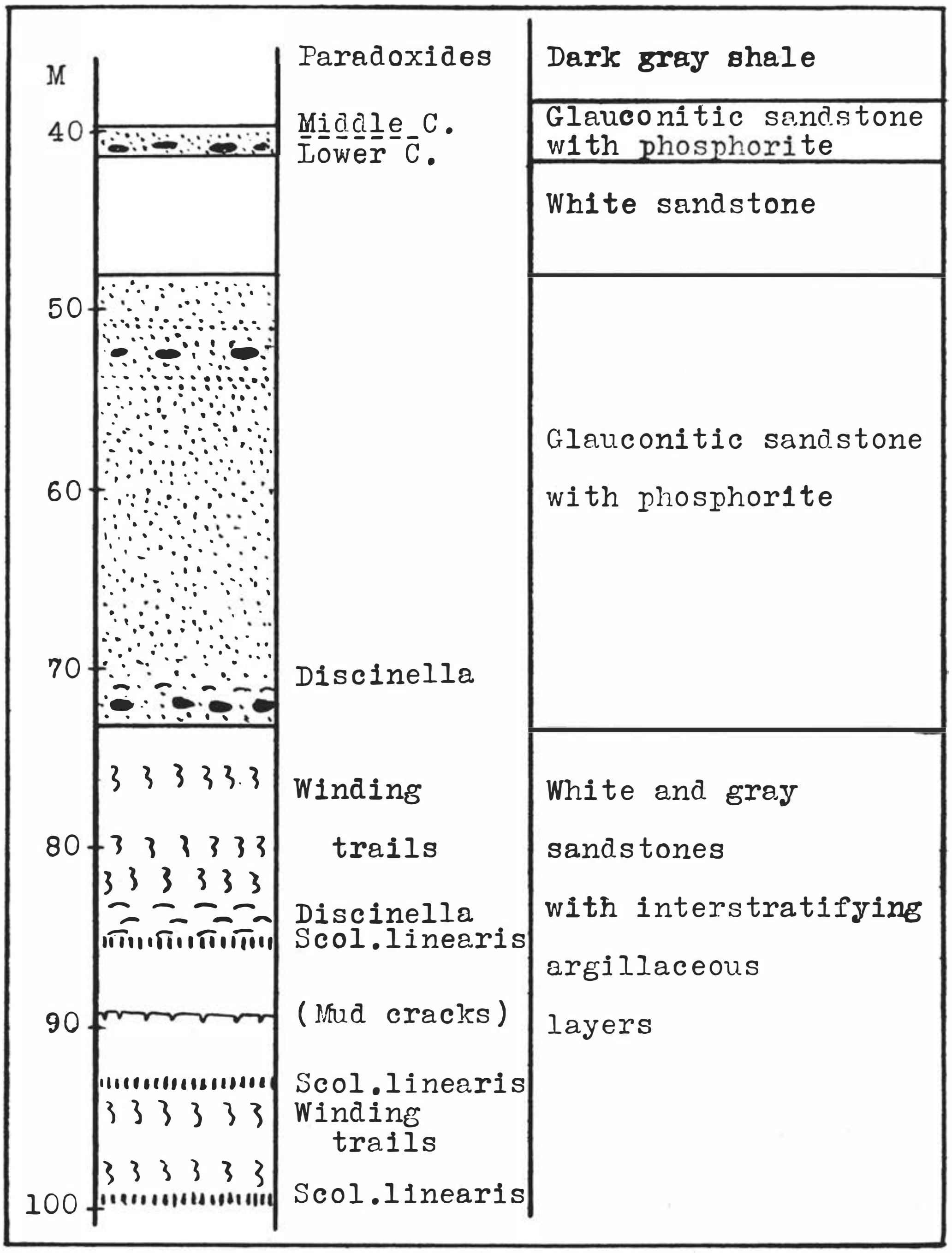

Fig. 40. The glauconitic series in the upper part of the Lower Cambrian at Borgholm, Öland, as seen in the drilling core.

Scania and Norrland where bituminous limestones and clayey shales play a greater rôle. In Västergötland and Östergötland the beds of glauconite form a not very thick but very prominent zone between the alum shales and stinkstones of the Olenus stage and the limestones of the Asaphus stage. The lower part of the glauconitic series consists generally of glauconite sand or glauconitic shale containing as a rule nodules of phosphorite and scattered aggregates and crystals of pyrite. The upper part of the glauconitic series, the Ceratopyge limestone, is less rich in grains of glauconite. Thus the series is practically of the same type as the Ölandic ones.

The thickness as well as the development of the different beds vary somewhat from place to place. On Kinnekulle the thickness is stated to be about 2 m at Hellekis but less than 0,5 m at Gösäter (Holm 1901, 33). From the north end of Billingen Westergård (1922, 60) communicates the following section:

Orthoceras limestone	—
Argillaceous shale (the Lower Didymograptus shale)	1,35 m.
Limestone, the lower part rich in glauconite and nodules of phosphorite	0,75 »
Alum shale with stinkstone (the Olenus stage)	—

On the eastern side of Billingen the glauconitic strata are less thick. Measurements made at Gullhögen (Westergård 1922, 66) showed the following series of strata:

Orthoceras limestone	—
Glauconitic limestone with nodules of phosphorite	0,15—0,25 m.
Alum shale with stinkstone (the Olenus stage)	—

At Stenåsen SE of Billingen the series of strata is as follows (Westergård 1922, 67):

Orthoceras limestone	—
Argillaceous shale (the Lower Didymograptus shale)	1,3 m.
Glauconitic limestone with nodules of phosphorite	0,8 »
Conglomeratic stinkstone (the Olenus stage)	—

At Ödegården, about 8 km S of the preceding place the series of strata is:

Orthoceras limestone	—
Glauconitic limestone with nodules of phosphorite and thin lenses of coal	0,3 m.
Stinkstone, partly conglomeratic, with crack filling of glauconitic limestone	—

At Stenbrottet, about 12 km SW of Ödegården and 10 km SE of Falköping the series of strata is as follows (as well as the preceding and the following according to Westergård's measurements):

Orthoceras limestone	—
Greenish gray argillaceous shale (the Lower Didymograptus shale)	0,65 m.
Glauconitic limestone with phosphorite	0,20 »
Alum shale with stinkstone (Dictyograptus shale)	0,32 »
Alum shale with stinkstone (the Olenus stage)	—

From Östergötland the section at Knivinge only will be mentioned:

Orthoceras limestone, greenish gray	—
Glauconitic limestone and glauconitic sand	0,2 m.
Glauconitic clay with fragments of alum shale and argillaceous shale (disturbed beds)	0,1 »
Alum shale with stinkstone and gray calcareous sandstone (Dictyograptus shale)	2,5 »
Stinkstone pebbles and alum shale (the Olenus stage)	—

In Nerke the glauconitic strata have been observed in several places, always with the same occurrence and development as in Östergötland and Västergötland. The thicknes is slight, 0,1—0,3 m. As a rule the glauconitic limestone rests directly on the stinkstones of the Olenus stage and is covered with Orthoceras limestone.

In Dalecarlia the glauconite-bearing Ceratopyge beds form the basal part of the Cambro-Silurian series and are only underlain by weathering gravel in a more or less redeposited form and by a relatively insignificant conglomerate of the type termed by the author intraformational conglomerates with sedimentary base removed by erosion (HADDING 1927, 88, 151 a. o.). The thickness and development of the strata are of course somewhat different in different places but the profile from SJURBERG, communicated below and measured by HEDSTRÖM (1896, 567) may be regarded as typical of the region:

Orthoceras limestone, yellow and red, without glauconite	—
Glauconitic limestone, the lower part conglomeratic and rich in glauconite	0,55 m.
Glauconitic sand	0,10 »
Obolus conglomerate with pebbles of int. al. phosphorite and limestone	0,15—0,80 »
Granite, at the top weathering gravel	—

At Tossåsen in Jämtland a glauconite limestone of no great thickness occurs in the following series of strata (WESTERGÅRD 1922, 90):

Orthoceras limestone.
Argillaceous shale, greenish gray (the Lower Didymograptus shale).
Glauconitic calcareous sandstone, with nodules of phosphorite.
Alum shale with stinkstone (the Olenus stage).

In northern Norrland the Ceratopyge stage seems to be more quartzitic and without glauconite.

* *
*

No glauconitic horizon younger than the said one in the lower part of the Ordovician has been found in the Cambro-Silurian. Of the younger sedimentary series of strata in Sweden the Keuper and Rhaetic-Liassic strata are free from glauconite, while the Cretaceous limestones and the Tertiary rocks are to a large extent glauconite-bearing.

In the *Lower Senonian* in SE Scania, the oldest Cretaceous series in Sweden, the series of strata is as follows:

Glauconite-bearing calcareous sandstone, zone with *Belemnitella mucronata.*
Sandstone and conglomerate with glauconite, zone with *Actinocamax mammillatus.*
Fragment limestone and sandstone with conglomerate, somewhat glauconitic.
Sandstone and conglomerate partly glauconitic, zone with *Actinocamax Westphalicus.*

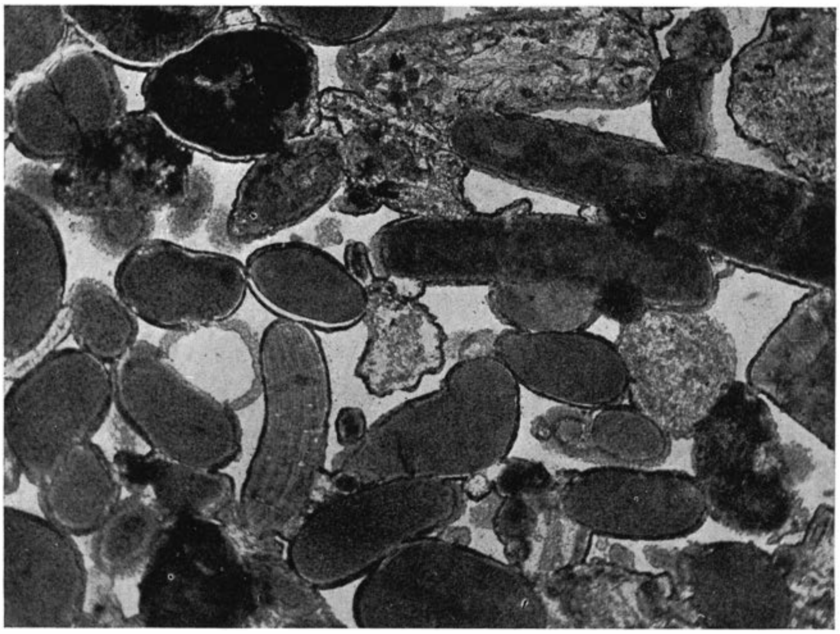

Fig. 41. Glauconite grains and rounded fragment of fossils and limestone. Cement: clear, colourless chalcedony. Tertiary. Erratic pebble. Ystad. (Pr. 2259. Pl. 623.) — 60 ×.

The thickness of the glauconite-bearing Senonian strata is great but varying. It has not been possible to show any strong enrichment of glauconite in certain beds. It is most abundantly present in the upper part of the series of strata, the calcareous sandstone, generally termed the Köpinge sandstone.[1]

The Senonian shell fragment limestone, most widely spread in NE Scania, contains here and there smaller amounts of glauconite. No glauconitic limestones proper occur in it.

The Senonian writing chalk is devoid of glauconite, and so are, practically, the Danian limestones also, the coccolith limestone as well as the bryozoan limestone and the coral limestone enclosed in these.

[1] Of the same age is a glauconitic marl, often strongly silicified, occurring as erratic blocks in Scania (Germany and Denmark) and generally known as »harte kreide» (GRÖNWALL 1912, 11 a. o.).

The trifling remainder of *Paleocene* marl, found resting on the Danian limestone at Klagshamn, is highly glauconitic, partly best designated as glauconite sand. It frequently occurs in cracks and corrosion grooves in the underlying limestone (fig. 42). Its hanging-wall has never been observed but Eocene rocks have been found as erratic blocks, which are to a large extent glauconite-bearing (fig. 41 and HADDING 1929, 258, fig 135—138). We do not know in what relation they occurred in a series of strata, and they will therefore only be discussed in the following chapter on the glauconite-bearing types of rock.

Fig. 42. Glauconitic marl (Paleocene) filling up corrosion grooves in coccolith limestone (Danian). Klagshamn, Scania. (Pl. 598.) — 1/1.

The Glauconite-bearing Series of Strata. II.

The General Occurrence of the Glauconitic Beds and their Relation to Conglomerates and Breaks in the Series of Strata.

The account given in the preceding chapter of the occurrence of the glauconite-bearing beds in the different series of strata may in certain respects give us a picture of the general occurrence of the glauconitic beds. This can also be completed in some points. The author will specially dwell on the occurrence of the glauconitic beds together with conglomerates and their relation to encountered gaps in the series of strata.

The General Occurrence of Glauconitic Strata.

The general occurrence of glauconitic beds estimated according to the Swedish series of strata, may be characterized as follows:

marine,
sublittoral, shallow sea,
regionally developed,
vertically distinctly limited,
locally varying.

In other respects also the glauconite-bearing series of strata can show characteristic features, which, however, often vary widely with the local sedimentary conditions. The series of strata described show that

grains of glauconite occur mainly in rocks deposited in a relatively agitated water,

glauconitic crust on fossils and pebbles was only formed on negative sedimentation taking place (as a rule with formation of an intraformational conglomerate),

glauconitic dust was deposited together with fine-detritus when the motion of the water was relatively weak,

the beds of glauconite contain fossils or bitumen or they rest on bituminous or fossiliferous beds.

As regards the first mentioned items it is unnecessary to go further into their significance. A reference to the series of strata described will suffice.

Concerning the variations shown by the glauconite when occurring in rocks formed under different conditions (more or less agitated water) we refer partly to the description of the series of strata and partly to the account of the glauconite's different forms of development and to the discussion on their origin (p. 145 seq.).

Of the said items only the last one remains, that concerning the occurrence of the glauconite in relation to fossiliferous or bituminous strata. This will be shortly illustrated; as to details we refer to the above descriptions.

A typical example of the occurrence of the glauconite in beds, that are neither bituminous nor contain any larger amount of fossils, is presented by the glauconitic sand and partly the glauconitic limestone of the Ceratopyge stage. The series of strata is in this case

Limestone, without glauconite (orthoceras limestone),
Glauconitic limestone and eventually,
Glauconitic sand,
Alum shale with stinkstone.

The importance of the highly bituminous substratum of the glauconitic series has been discussed in detail in the preceding.

A typical example of the occurrence of the glauconite in beds that are in themselves bituminous but lie enclosed in bitumen-free ones is to be found in the glauconitic sandstones of the Olenellus stage. The series of strata in the lower glauconitic zone of this stage is as follows:

White sandstone without glauconite and bitumen,
Dark glauconitic sandstone, bituminous,
White sandstone without glauconite and bitumen.

In the upper glauconitic zone the hanging-wall consists of argillaceous shale, not of sandstone but in both cases the glauconite is limited to the bituminous sandstone beds.[1]

The glauconitic beds in the Cretaceous and Tertiary are rich in fossils. The majority of the glauconitic beds in the Middle Cambrian in Öland are neither rich in fossils nor bituminous. Nor do the strata rest on bituminous or highly fossiliferous beds, consequently they occupy an exclusive position and, apparently at least, they form an exception to the above stated rule. They are, however, not quite free from fossils (certain beds are rich in fossils) and possibly they have contained a richer organic material than the rock now shows.

The Occurrence of the Glauconite in Intraformational Conglomerates and its Formation in Connection with Negative Sedimentation.

The occurence of glauconite in connection with traces of negative sedimentation (stratigraphical breaks and intraformational conglomerates) can be studied in several places in the Swedish series of strata. The Acrothele granulata conglomerate in the lower part of the Ölandic Tessini zone is an example illustrating this, the conglomerate in the zone of *Actinocamax mammillatus* at Tosterup in Scania is another, and that in the Ceratopyge region at Horns Udde in Öland a third.

It is only under particularly favourable conditions that a negative sedimentation leads to the formation of an intraformational conglomerate. In most cases the deposited loose mud is probably washed away without leaving any solid lumps (whether cemented parts of the mud or concretions) forming pebbles in a conglomerate. The complete washing-away to a certain depth leaves only a break in the series of strata, which is occasionally, though not always, demonstrable in some way or other. If the series of strata is fossiliferous and the gap large, it can be shown as lacking zones (see the scheme p. 12), if it is smaller it may be seen in a bedding plane or in an altered sedimentation. In the last-mentioned case the sequence of strata can become similar to that obtained if the sedimentary conditions are successively changed only in such a manner that easily suspended material does not settle. The position of the bedding plane can sometimes tell us in which way the series of strata was developed.

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[1] It is, however, not excluded that the argillaceous shale in the hanging-wall contains glauconitic dust, though it can not be microscopically shown. In a younger bed of bituminous, silicified limestone both glauconite and pyrite occur.

The glauconite very often occurs in such a manner that it must have been deposited in connection with a reduced deposition of detritus and other substances. In the series of strata described in detail from the Ceratopyge stage in Öland the percentage of glauconite in the limestone beds increases from the centre towards the bedding planes. The thin layers of glauconitic sand, that sometimes separate the limestone beds, mark the maximal formation of glauconite and at the same time the minimal deposition of limestone. Negative sedimentation has as a rule taken place on the formation of the bedding planes. These have arisen as a result of the altered sedimentation, which in its turn was caused by the changed conditions in the sedimentary basin, in the author's opinion in consequence of variations of int. al. the concentrations of carbon dioxide (see p. 46).

Occasionally, however, the limestone beds show that a negative sedimentation has taken place. This is for inst. the case in stratum 4 of the already mentioned series of strata at Horns Udde (see p. 43 and fig. 20). There is no proof that the formation of glauconite was in progress while the calcareous mud was being washed away but there is reason to suppose that the formation of glauconite was relatively strong when the positive sedimentation began to succeed the negative: the percentage of glauconite is highest immediately above the denudation surface and decreases gradually according as the deposition of limestone increases.

On trying to estimate the forming conditions of the glauconite after its occurrence in the sedimentary series of rock one must of course be able to establish whether the glauconite occurs in a primary site of deposition or if it has been transported after its formation. When investigating the occurrence of the glauconite together with intraformational conglomerates or other signs of negative, interrupted, or otherwise changed sedimentation, one must also pay attention to eventually occurring allochthonous glauconite. A negative sedimentation with or without formation of conglomerate not infrequently involves a deposition of relatively coarse grains in regions where earlier only fine mud was deposited. An enrichment of glauconite grains in connection with the ceasing of the deposition of mud or with the removal of muddy deposits is therefore only what is to be expected. The examination of the grains of glauconite in the investigated series of strata has also shown that allochthonous glauconite occurs in abundance but besides that the investigation shows that the enrichment of glauconite is not wholly explained by the mechanical washing-together of the grains. An increase in the very formation of the glauconite must also have taken place. This is not least evident from an investigation of its occurrence as coating on conglomerate pebbles and shells accumulated during a negative sedimentation. The often observed thin laminae or crusts of glauconite dust in glauconite-bearing rocks (especially in glauconitic limestone) also give us certain evidence of an increase in the formation of glauconite during or immediately after periods of negative sedimentation. The last mentioned facts will be more closely illustrated.

The above mentioned Acrothele granulata conglomerate contains pebbles of the shales and sandstones of the Oelandicus zone and of calcareous concretions from these. The pebbles are generally tabular but worn. The larger ones have always a nucleus of unaltered rock but as a rule their peripheral part is quite different in character. It is grass green in colour like the glauconite, and on examination turns out to be strongly impregnated with glauconite (fig 43). In the smaller or thinner pebbles the nucleus is also impregnated. The matrix around them consists to a large extent of fossil fragments (of trilobites and brachiopods), generally with no or only a slight coating of glauconite. Grains of glauconite are also found in this matrix. The cement consists of calcite.

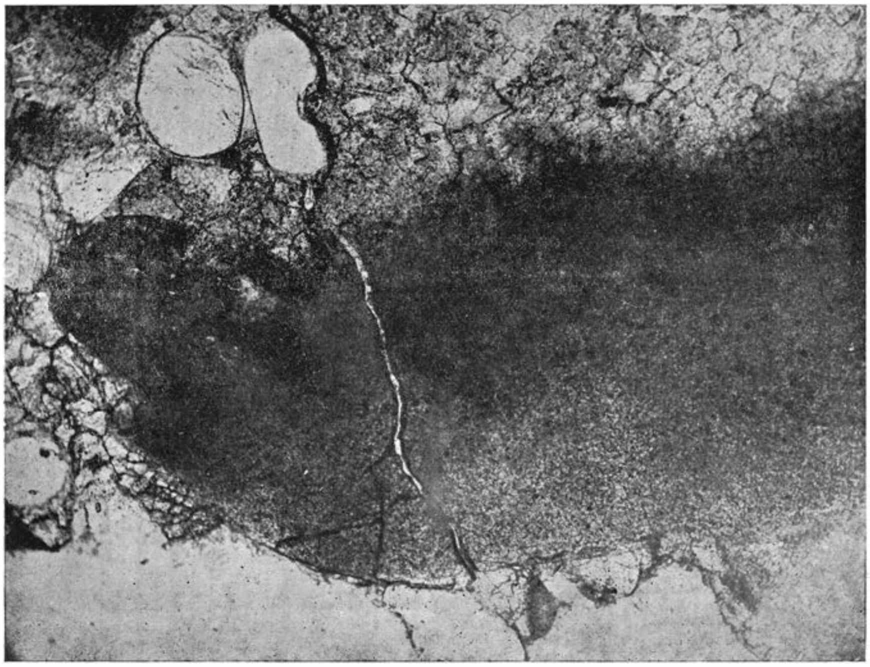

Fig. 43. Fragment of argillaceous limestone, in the upper (dark) part strongly impregnated with glauconite. Acrothele granulata conglomerate, Köping, Öland. (Pr. 3189. Pl. 573.) — 60 ×.

The history of the conglomerate's formation can be reconstructed to a certain extent (Hadding 1927, 74), and this enables us to estimate the formation of the glauconite also. The grains of glauconite occur in secondary site of deposition and are therefore of less interest here but the glauconite impregnating the conglomerate pebbles is no doubt autochthonous. It occurs, as mentioned above, most strongly enriched in the peripheral part of the pebbles and is gradually reduced towards the nucleus. The zonal structure reproduces in all parts the exterior contour. It may be inferred from this that no formation of glauconite took place in pebbles until they had been washed free and obtained their rounded or corroded form, which occurred during the negative sedimentation.

Glauconite as impregnation occurs in the same manner as limonite in many weathering limestones or calcareous sandstones, i. e. as a substance that has penetrated the rock from outside and is most abundantly present in the rocks which have been strongly porous or broken up by peripheral decomposition. (See further p. 110 on the development and occurrence of the glauconite as impregnation.)

Thus the glauconite zone appears like a weathering zone, even though it, as has undoubtedly been the case, has been formed by means of a submarine deposition of an autochthonous mineral. As shown above, this deposition has taken place after completed negative sedimentation but before the subsequent positive sedimentation with its deposition of sand and calcite had begun. Consequently the formation of glauconite has occurred in this case during a transitional period when the disintegrating action of the water had ceased but it was nevertheless still relatively strongly agitated, so strongly that the detritus suspended in it could not settle. The condition for a retention of newly formed glauconite in this agitated water was its formation on larger grains or pebbles or in the interior of pores or cracks in blocks and shells. Glauconite formed as a loose dust or in free flocks must necessarily have been washed away.

In conglomerates in the Senonian deposits of Scania glauconite is sometimes (Tosterup) found occurring in the same manner as in the above described Acrothele granulata conglomerate. The glauconite impregnation, however, is in some conglomerates seldom found in the pebbles, as these generally consist of crystalline rocks, but is mainly seen on coarse shell fragments with a porous structure. Sometimes the shells (and the pebbles) can also be covered with a thin crust of glauconite. This is for inst. the case at Tormarp in Halland (Hadding 1927, 125), in the conglomerates from Istaby in Blekinge, Barnakälla in Scania, a. o. As far as we can see the mode of formation has been similar in all the cases.

Thus, on studying the autochthonous occurrence of the glauconite in the conglomerates, we arrive at the same opinion as on the investigation of its occurrence in connection with gaps in the series of strata formed during negative sedimentation: the formation of glauconite has been relatively strong immediately after periods with negative sedimentation.

The question is now inevitable whether the glauconite has not always been formed under conditions resembling those mentioned above, i. e. in relatively agitated water with slight deposition of detritus. As regards several occurrences of glauconite it is obvious that this must have been the case, others are more questionable. Besides that we are again placed face to face with the necessity to determine to what extent the occurrence of the glauconite is autochthonous or allochthonous. Only occasionally is it possible to draw any certain conclusions but the glauconitic rocks and the series of strata in which they occur speak very often in favour of forming conditions resembling those related above. But they are of course more or less and in different manners characterized by the local sedimentary conditions.

Series of Strata without Glauconite.

Just as a study of the glauconite-bearing series of strata can contribute to the knowledge of the forming conditions of the glauconite, a comparative investigation of the non-glauconite-bearing series of strata can inform us of the conditions under which the glauconite can not be formed. Attempts have been made above to interpret the evidence of the glauconitic series on the formation of glauconite and on the causes of the alternation between glauconite-rich and glauconite-poor or glauconite-free beds. In the following, different types of glauconite-free series of strata will be mentioned and the causes of the absence of glauconite if possible stated.

Glauconite is never present in the series of strata that are *continental deposits.* The Keuper of Scania, the Visingsö series, and the pre-Cambrian, continental series of strata are devoid of glauconite. Consequently the Swedish sediments do not contest the prevalent opinion that glauconite is a pure marine formation.

As a rule glauconite is never present in the real, primary *basal beds* in the marine series of strata. There is none to be found in the Lower Cambrian basal conglomerates and sandstones under the oldest fossiliferous strata. The oldest conglomerates and sandstones in the Cretaceous series are also free from glauconite. Wherever this mineral occurs in a »basal conglomerate» the remains of an older, wholly or partly disintegrated series of strata are included in the same. This is for inst. the case with the Obolus conglomerate in Dalecarlia (see HADDING 1927, 88 and 148).

In the coarse sediments in the youngest part of a series of strata, i. e. in the real *top beds,* the glauconite is also absent. The youngest sandstones of the Silurian series give a good example of this. We might perhaps be inclined to regard the glauconite-rich Paleocene marl, covering parts of the Senonian-Danian series in Scania, as an exception. Even though we leave the gap in the series of strata between the glauconitic marl and its substratum out of the question and look upon these as parts of the same series, we still have not found the youngest sediments of this series. We do not even know how the series of strata was concluded but we have reason to suppose that in Paleocene and Eocene times positive and negative sedimentation alternated, creating favourable conditions for a formation of glauconite. In certain regions the marine period of sedimentation is not to be seen concluded by depositions of coarse sediments (top beds) but by other sediments, i. e. glauconite-bearing beds possibly laid bare by negative sedimentation and subaerial denudation.

The reason why bottom beds as well as coarse top beds are devoid of glauconite is no doubt that they were deposited like the continental deposits in shallow and oxygenous water.

Between the bottom and the top beds glauconite can occur in different horizons, as we have seen this is the case in the Cambro-Silurian series. But the series of strata only contain glauconite in a relatively small number of beds, and some series contain none at all. It is, however, not easy to allege what is characteristic of the glauconite-free part in contradistinction to the glauconite-bearing. We could possibly advance the opinion that the beds of glauconite belong to periods of disturbances or currents while those free from glauconite comprise tranquil periods, periods with even, rhythmic changes and slow alterations. The beds of glauconite belong as a rule to periods and areas with only a slight primary deposition of detritus. A secondary deposition of detritus, on the contrary, has often occurred in connection with the formation of glauconite. Series of strata formed close to land during a powerful deposition of coarse detritus are no more glauconite-bearing than series of strata formed in relatively enclosed or from some other cause relatively tranquil basins with abundant deposition of fine detritus or organic mud. Free from glauconite is consequently the entire Rhaetic-Liassic series in Scania. Free from glauconite are also the alum shale and the argillaceous shales in the Cambro-Silurian as well as most limestones and the thick series of interbedded limestone and shale occurring in the Silurian.

The study of the series of strata in a certain stratigraphical horizon, a certain zone or stage, is specially interesting, if this is glauconite-bearing in one place and glauconite-free in another. As pointed out before, the occurrence of the glauconite is periodical and comprises large areas, therefore its absence in some part of the common basin of deposition is remarkable.

That the Lower Cambrian glauconite-rich sandstone is limited to the extreme South or South-East of Sweden is owing to the fact that in this region only had the Cambrian transgression progressed so far that the first sedimentary stage, the formation of the basal beds was accomplished.

Another example: in Scania, glauconite-free rocks such as alum shale with stinkstone, bituminous limestone, and sometimes sandstone correspond to the Middle Cambrian glauconite-bearing sandstones in Öland.

The Ceratopyge series is, as shown before, built up of glauconite-rich rocks in almost the whole of Sweden. This glauconitic series is particularly well developed in Öland but in the adjacent Scania only insignificant traces of glauconite are found. The series of strata is there developed as clayey shale and dense limestone rich in mud, which are practically free from glauconite.

The lower part of the Asaphus stage (the Orthoceras limestone) is in Öland partly developed as a limestone rich in glauconite. In Scania the corresponding part of the series of strata consists of glauconite-free shale.

The Cretaceous beds are limited to a small area in the most southerly part of Sweden, principally to Scania, and we can therefore hardly expect a simultaneous development of glauconite-rich and glauconite-free parts of the series of strata in the area. A great difference in the quantity of glauconite can, however, be found in different parts of it. For inst. the zone with *Belemnitella mucronata* in SE Scania is developed as calcareous sandstone rich in glauconite while in NE Scania it essentially consists of a glauconite-poor shell fragment limestone with occasional glauconite-bearing beds, and in SW Scania of writing chalk free from glauconite.

The zone with *Actinocamax mammillatus* also shows similar variations in the percentage of glauconite.

The said examples of simultaneous formation of glauconite-free and glauconite-bearing strata can be explained in accordance with the general conditions for the formation of glauconite, knowledge of which we gain from the Swedish series of strata in the manner shown above.

Glauconite-bearing and Glauconite-free Types of Rock.

In the preceding the occurrence of glauconite in different series of strata has been discussed. Quite naturally its presence in rocks of different types has also frequently been mentioned. No further detailed account of it is necessary but a summary of the different observations is no doubt appropriate. An account of the glauconite's occurrence in phosphorite-bearing rocks and its relation to rocks with different characteristic contents of fossils will be added to this summary.

The conglomerates in the Swedish series of strata are often glauconite-bearing. But this only holds true of the intraformational, not of the basal conglomerates. In intraformational conglomerates with their sedimentary base removed by erosion, apparent basal conglomerates, glauconite may of course occur just as well as in the other intraformational ones.

Glauconite-bearing a. o.:

Phosphorite conglomerates. Lower Cambrian. Scania.
Sandstone conglomerates. Lower Cambrian. Scania.
Acrothele granulata conglomerates. Middle Cambrian. Öland.
Obolus conglomerates. Lower Ordovician. Dalecarlia.
Conglomerates in the Ceratopyge stage. Lower Ordovician. Öland, Västergötland a. o.
Conglomerates in the Mammillatus zone. Senonian. Scania.
Conglomerates in the Mucronata zone. Senonian. Scania.

The sandstones are for the most part non-glauconitic. As a rule the glauconite-bearing ones are calcareous sandstones, with more or less abundant calcitic cement and matrix, not infrequently passing into arenaceous limestone. The glauconite-bearing sandstones are often free from clayey matter but contain sometimes bitumen and pyrite dust.

Glauconite-bearing a. o.:

Lower Cambrian sandstone. The Olenellus stage. Scania, Öland a. o.
Middle-Cambrian sandstone. The Paradoxides stage. Öland.
Senonian calcareous sandstone. The Mucronata zone. SE Scania.
Tertiary sandstone. Eocene? Erratic blocks. Scania.

The limestones contain the largest amount of glauconite but they are nevertheless only to a small extent glauconite-bearing. Glauconite-bearing are pigmented as well as pure limestones, partly dense, relatively thin-bedded, sometimes fossil-free, and partly highly fossiliferous, in which case they are developed as fragment limestone. Frequently arenaceous, seldom highly argillaceous.

Glauconite-bearing a. o.:

Phosphorite-bearing limestone. Lower Cambrian. Scania.
Limestone in sandstone. Middle Cambrian. Öland.
Fragment limestone, from conglomerate. Middle Cambrian. Öland.
Ceratopyge limestone. Lower Ordovician. Öland a. o.
Shell fragment limestone. Senonian. Scania.
Arenaceous limestone. Senonian. Scania.
Fragment limestone, arenaceous. Eocene? Erratic blocks. Scania.

The argillaceous shales are as a rule free from glauconite. The only certain exceptions are the shales interbedded with glauconitic sand in the Ceratopyge stage of Öland. Whether the green, subcrystalline substance, occurring at times in argillaceous rocks (mostly in marls), occasionally consists of glauconite can hardly be decided, as it can not be isolated from the argillaceous mud.

The result of an attempt to find a definite relation between *the content of fossils* in the rocks and the occurrence of glauconite has not been such that the forming conditions of the glauconite can be determined from the said relation. Certain facts, however, are so extremely interesting that they are worthy of notice.

In the Swedish series of strata glauconite is found in rocks rich in the following fossils:

Trilobites.
Lamellibranchs.
Gastropods.
Brachiopods.
Foraminifera.

More seldom and in smaller quantities do the following fossils occur in the glauconite-bearing rocks:

Ostracods.
Cephalopods.
Crinoids.
Cup corals.
Sponges.

The following fossils are unfamiliar to the glauconitic rocks:

Bryozoa.
Corals, branched.
Stomatoporoids.
Graptolites.
Coccoliths.
Fossil plants.

As the glauconitic grains as well as the fossils can occur at secondary site of deposition or can have lodged for some time on another part of the sea bottom than that in which the zone was formed or the animals lived, one must be critical with regard to eventual conclusions on similar environment for the formation of the glauconite and the thriving of certain animal forms. Somewhat more certain are the inferences we can draw from the fact that glauconite practically never occurs together with certain rock-forming animal forms.

The occurrence of the above mentioned different types of fossils together with glauconite or without connection with the glauconite-bearing rocks will be shortly exemplified.

Fig. 44. Glauconite in a Foraminifera shell. Upper Crania limestone. Copenhagen, Denmark. (Pr. 2300. Pl. 570.) — 60 ×.

The Trilobites are the most characteristic faunal ingredient in the glauconitic Cambro-Silurian rocks. They occur as loose shields and pleuras, that in some cases are not exposed to any transportation worthy of notice after the death of the animal (in the Middle Cambrian sandstones and the Ceratopyge limestone in Öland), and in other cases are secondarily enriched and distinctly worn during transportation (for inst. in the Acrothele granulata conglomerate).

Brachiopods abound sometimes in the trilobite-bearing rocks. Species with phosphatic shells and small species with thin, calcareous shells are specially frequent.

Lamellibranchs constitute the bulk of the Cretacean shell fragment limestone. The shells are, to a large extent at least, secondarily enriched, and the glauconite found here and there in the rock is also undoubtedly to be found in several cases at secondary site of deposition. Primary, however, is the occurrence of a glauconitic crust on the shells as well as the impregnation of glauconite in part of the shells. The Tertiary glauconitic rocks occurring as erratic blocks in Scania are often rich in Lamellibranchs.

Gastropods are abundantly present in the Tertiary glauconitic rocks, and their shells are sometimes filled with grains of glauconite.

Foraminifera are known from recent as well as fossil glauconitic strata, and in certain quarters it has even been called in question whether the glauconite has not always been formed as filling in foraminiferal shells.[1] Of the Swedish glauconitic rocks the Cretaceous as well as the Tertiary limestones sometimes contain an abundance of foraminifera.

It is hardly necessary to point out that the above mentioned fossils, found in abundance in glauconitic rocks, also occur in series of strata devoid of glauconite. In fact, only a relatively small part of the series of strata containing trilobites, brachiopods, lamellibranchs, etc. is also glauconitic. This is the case in a still higher degree in rocks characterized by the fossils of the other group: ostracods, cephalopods, crinoids, etc.

The ostracod, crinoid, etc. limestones proper contain no glauconite, but smaller quantities of ostracods, crinoid fragments, cephalopods, etc. are not infrequently present in the glauconite-bearing rocks. Sometimes they show a pigmentation of glauconite, this is especially the case when they occur secondarily enriched in more or less conglomerate-like rocks or fragment limestone. Glauconitic pigment, however, is not only found in cup corals, sponges, and disks of crinoid stems, etc. but fragments of the fossils mentioned in the third group, for inst. bryozoan branches, can also be seen pigmented in the same manner. The latter fossils are then always at secondary site of deposition.

As far as the author's investigations go, glauconite, at any rate autochthonous glauconite, is never contained in primarily formed bryozoan beds, coral and stromotoporoid reefs, coccolith limestones or graptolite shales.

The sediments containing plant fossils are not glauconite-bearing. This is a natural consequence of the different conditions under which the formation of glauconite and the deposition of plant residues generally takes place. Occasional finds of plant fragments in glauconitic rocks, for inst. of *Dewalquea Nilssoni* leaves in the glauconitic Köpinge sandstone, do not by any means contradict the general rule. The primary character of the bitumen in certain glauconitic rocks is not made clear and must therefore be left out of account here.

In connection with the presented survey of the occurrence of different fossils in glauconite-bearing rocks the occurrence of *the worm trails* in the same rocks is also worthy of mention. In the description of the Lower-Cambrian glauconitic series at Brantevik (p. 60) attention was called to the occurrence of

[1] See p. 129 seq.

Scolithus errans as well as *Psammichnites gigas* trails in the glauconitic shale. This is more rich in bituminous mud than any other glauconitic rock known to the author (regardless of certain parts of the glauconitic shale in Öland). The tracks were, however, formed after the deposition of the glauconitic sediment and possibly under conditions differing from those, under which the formation of glauconite took place.

Where the glauconite occurs in conglomerate-like beds or in other relatively coarse strata formed by negative sedimentation *Serpula* tubes are not infrequently found.

Glauconite—Phosphorite.

Glauconite in phosphoritic rocks is such a common phenomenon that, on finding the one mineral, it can almost be taken for granted that the other will also be found. They are, however, not quite so inseparable: not infrequently glauconitic rocks without phosphorite as well as phosphoritic beds without glauconite are met with. In several cases they have been formed in the same milieu or enriched together in conglomerates and conglomerate-like beds.

Beds with both autochthonous and allochthonous phosphorite are to be found in the older part of the Lower Cambrian sandstone series of Scania. In these beds glauconite is generally absent. First in the upper part of the Lower Cambrian sandstone is it generally present together with the nodules of phosphorite. In this part also of the series of strata the glauconite and phosphorite differ partly in time of formation and on that account in forming conditions too. The lower glauconitic series at Brantevik can serve as an example of this (cf. Hadding 1929, 100 seq.). An intraformational conglomerate forms the base of the glauconitic series. The pebbles in this conglomerate consist of sandy phosphorite and sandstone with a small percentage of glauconite. The sandstone, its glauconite, and the phosphorite were formed contemporaneously and in the same environment. During the negative sedimentation, which gave rise to the conglomerate, the formation of phosphorite ceased but the formation of glauconite continued, though in a new form: it settled as a thin crust on the enriched pebbles. After the formation of conglomerate, i. e. after the negative sedimentation was replaced by a new deposition of sand, the formation of glauconite increased without any phosphorite being formed. The conglomerate is covered with a glauconite-rich, phosphorite-free sandstone dark from bitumen and pyrite dust. The subsequent glauconitic beds are also devoid of phosphorite.

In the upper glauconitic series at Brantevik, described more in detail above (p. 57) phosphorite occurs in several horizons separated by beds rich in glauconite. This is more widely or more generally spread than the phosphorite in these series.

On continuing our investigation of the occurrence of the phosphorite and the glauconite in relation to each other in other series of strata, we find the same state of things as in the said Lower Cambrian. The Middle Cambrian glauconite-bearing sandstone is, as far as the author knows, completely devoid of phosphorite. This has not even been observed in the intraformational conglomerate, the Acrothele granulata conglomerate, of this series. But it occurs, on the contrary, in different horizons in the glauconite-free Olenus stage (for inst. in the Exporrecta and the Obolus conglomerates at Äleklinta). It should be noticed that not even the phosphorite pebbles of these conglomerates contain grains of glauconite.

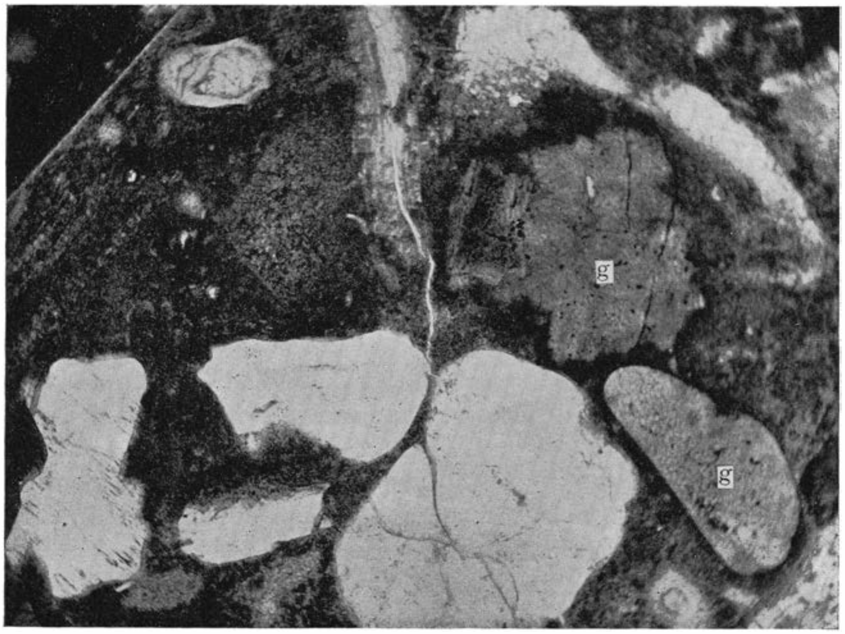

Fig. 45. Phosphorite nodule with grains of glauconite (g) and quartz. On the right side of the large quartz grain an allochthonous glauconite grain and above the quartz a probably autochthonous glauconite grain. Senonian conglomerate. Bjärnum, Scania. (Pr. 2022. Pl. 615.) — 60 ×.

In the glauconite-rich Ceratopyge stage phosphorite is generally absent except in the relatively insignificant conglomerate beds, for inst. at Horns Udde in Öland and in Västergötland, Östergötland, and Nerke. In Dalecarlia phosphorite occurs in the conglomerate below the glauconitic sand.

Glauconite is absent in the Middle Ordovician but phosphorite occurs int. al. as a continuous bed in black graptolite shale, the zone with *Nemagraptus gracilis*, at Fågelsång in Scania.

In the Senonian rocks the glauconite is considerably more widely spread than the phosphorite. Both of them, however, occur together here also. In one and the same phosphorite nodule we may find strongly worn (allochthonous) as well as indistinctly formed (autochthonous) grains of glauconite (fig. 45).

On summing up the observations from the Swedish series of strata we can say that *glauconite and phosphorite certainly often occur together, but that the phosphorite sometimes occurs alone, and that only a minority of the glauconitic strata are phosphorite-bearing.* However, the relationship between the two minerals or, more correctly, their formation under similar conditions is evident from the fact that the nodules of phosphorite are to a large extent glauconitic. As this is the case even if the nodules occur in rocks otherwise devoid of glauconite, we may infer

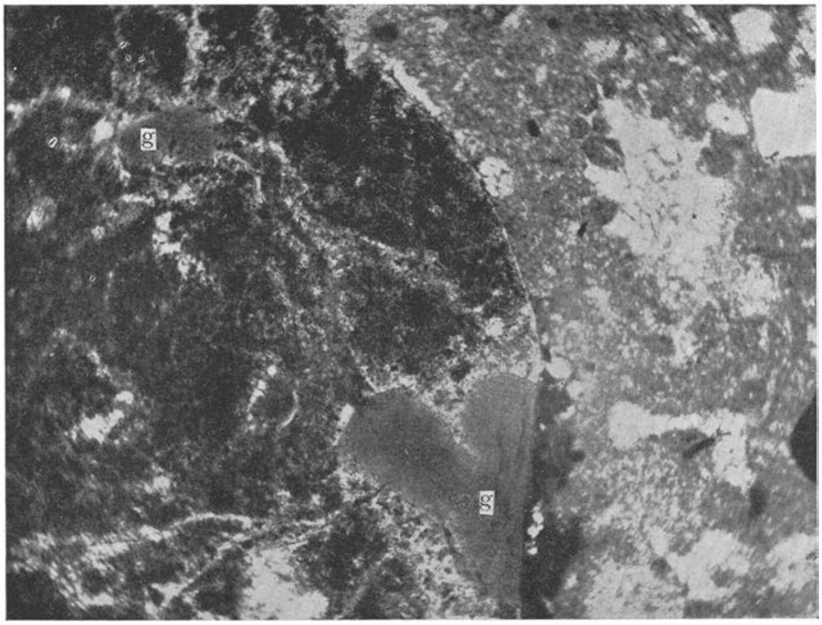

Fig. 46. Phosphorite nodule (left, dark part of the fig.) with grains of glauconite (g). The grain at the right margin of the nodule is worn with this. Senonian conglomerate. Ignaberga. (Pr. 2481. Pl. 617.) — 60 ×.

partly that the phosphorite is in these cases at secondary site of deposition, and partly that it was formed in an environment, in which glauconite had also been deposited (fig. 46).[1]

[1] The occurrence of glauconite grains in the phosphorite pebbles implies that the grains had been present in a fully developed stage when the phosphorite nodules were formed. There are also examples of younger glauconite, formed as crack filling in phosphorite nodules.

Glauconite as Mineral.

(Development, physical qualities, and chemical composition).

An account of investigations on glauconite-bearing rocks and series of strata and on the glauconite's occurrence in these has been given in the preceding. In the following the observations made on the development of the glauconite and the investigation of its physical qualities and chemical composition will be reported.

Development of Glauconite.

On a macroscopic examination the glauconite gives the impression of a compact mineral, occurring either in the form of small, as a rule dark green grains or as earthy aggregates. Microscopically the mineral proves to be crypto-crystalline, more infrequently developed in such coarse-grained aggregates or in such large crystals that a more extensive optical examination of them can be made.

The forms of development mentioned below will be illustrated in the following:

1. Grains of a freely developed, as a rule rounded form.
2. Irregular aggregates whose form is dependent on the surrounding grains of detritus.
3. Irregular aggregates whose form is dependent on a secondary formation of crystals in the glauconite.
4. Earthy aggregates (crusts) and pigment of glauconite.
5. Impregnations of glauconite and glauconite filling in shells.

Grains of Glauconite.

Glauconite is most frequently observed in the form of grains. This may be true in the same degree of the recent as of the fossil occurrences of the mineral and of the arenaceous as well as the calcareous sediments. If glauconite, in immediate connection with its formation, is embedded in sand, its form is nevertheless altered in a manner that will be shown below. Does the embedding, on the contrary, take place in calcareous mud or at a relatively late stage after the formation in sand, the mineral retains its more or less round form.

On a closer examination of the glauconitic grains, especially under the microscope, we find their form rather varying. In one and the same petrographical unit (the same limestone bed, etc.), however, the grains are as a rule of the same or similar form, and this shows that the form is to a certain extent a result of the conditions prevailing on the formation of the one or the other rock unit. We shall illustrate this with a few examples.

The different types of grains most frequently found in the glauconite are the following:

a. Grains full of cracks.
b. Rounded, smooth, or shallowly furrowed grains.
c. Tabular (disk-shaped or watch-glass-shaped) grains.
d. Angular grains.

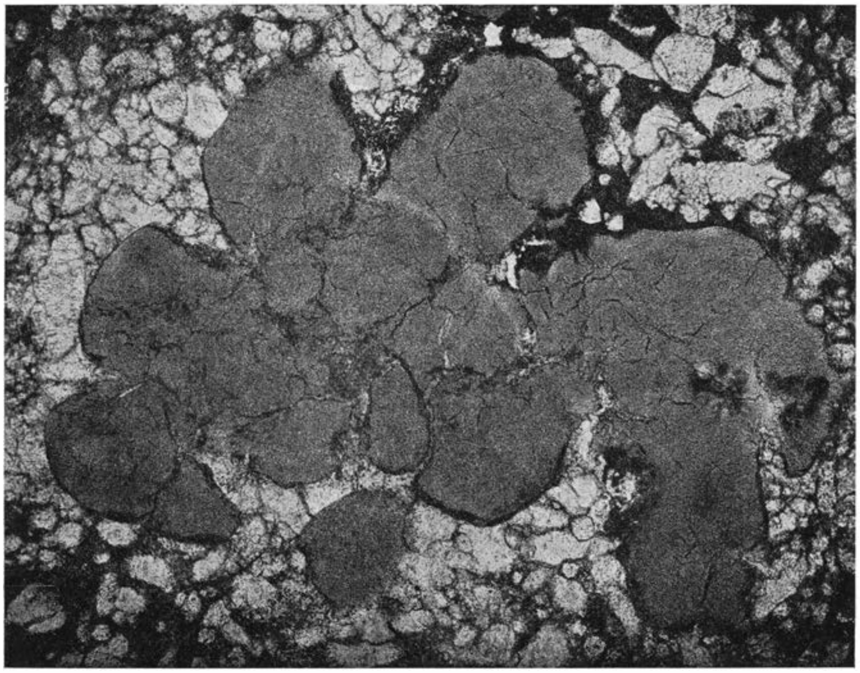

Fig. 47. Large glauconite grain with deep cracks (lobate grain). Granular limestone with haematite pigment. Köpings Klint, 12. (Pr. 3025. Pl. 557.) — 60 ×.

Grains full of cracks are as a rule larger than the others (fig. 47). The cracks are frequently very deep. They are widest at the peripheral part of the grain and thin out towards the centre. In their form and occurrence they remind us in some degree of the cracks in septaria. It is undoubtedly correct to interpret this crack formation as a result of a dehydration process in a strongly hydrous, probably gelatinous glauconite. The larger the grains, the wider and deeper are the cracks. As will be seen, the other types of grains may often be derived from this.

The furrowed grains have a smooth surface with rounded prominences separated by shallow furrows, sharp at the bottom. A comparison between these grains and

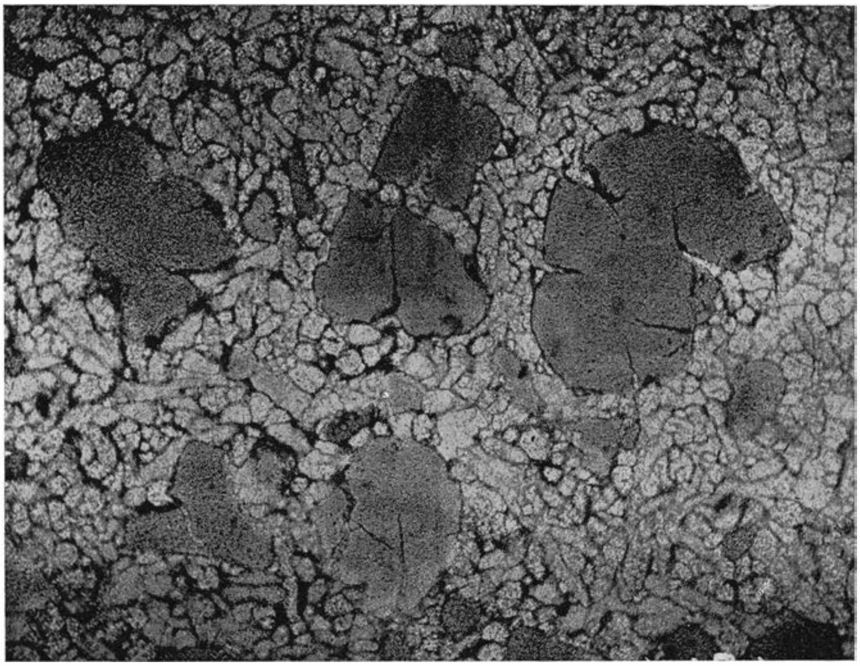

Fig. 48. Furrowed glauconite grains with smooth surface. Granular limestone. Köpings Klint, 11. (Pr. 3023. Pl. 556.) — 60 ×.

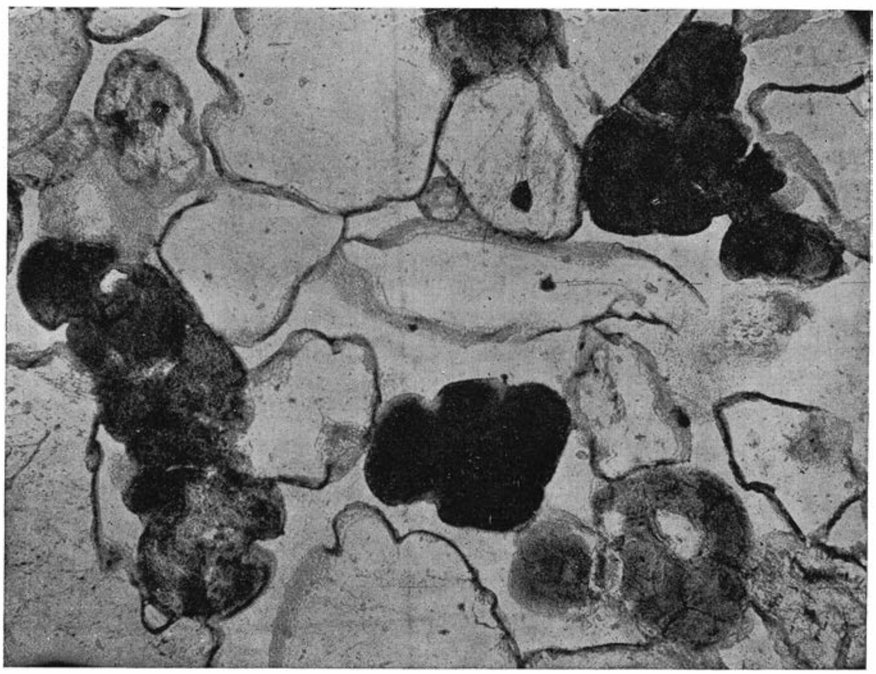

Fig. 49. Lobate grain of glauconite built up by smaller grains. Senonian sandstone with chalcedony cement (»Harte Kreide»). Erratic block. Lund. (Pr. 2717. Pl. 577.) — 60 ×.

the cracked ones shows that the difference between them is unessential (fig. 48). Had the cracked grains been subjected to a general wear at the same time as the formation of cracks stopped, they would have obtained the form and development shown by the furrowed grains.

The furrowed grains have either solidified without any strong formation of cracks (lobate grains are often built up by several smaller ones (fig. 49)) or they have cracked during the solidification and then been exposed to wear. If this wear has been sufficiently strong or lasting, the traces of the crack formation can have

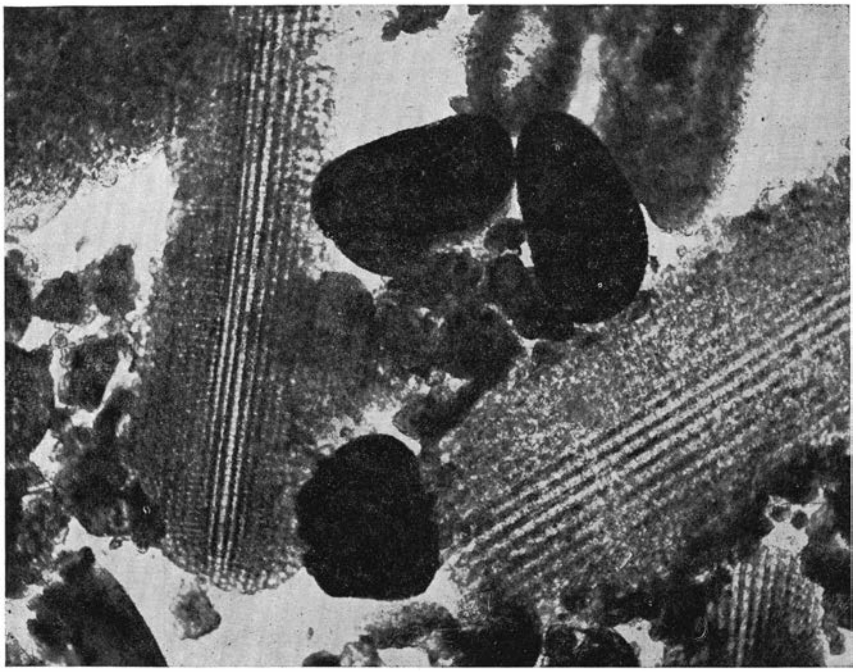

Fig. 50. Rounded glauconite grains and strongly worn fossil fragments without glauconite impregnation (cf. fig. 64). Siliceous rock (white parts chalcedony). Tertiary. Ystad, Scania. (Pr. 2762. Pl. 585.) — 60 ×.

been completely obliterated. The grains have then become *smooth* and more or less *rounded.* The smooth, rounded grains are always relatively small, and this indicates also that our interpretation of their formation from the larger grains by wear is correct (figs 50—52).

The tabular grains have, like the rounded ones, smooth surfaces but they are often jagged at the edges by cracks. Their outline is as a rule irregular but the cross section is flatly fusiform or, if the disks are curved (watch-glass shaped), sickle-shaped (figs. 53 and 54). The tabular grains do not lie orientated in relation to the bedding planes. Consequently they have not obtained their flat form by means of one-sided pressure in the bed. Their smooth, even surface can speak for wear, certainly, but it does not explain the origin of the tabular form. The wear

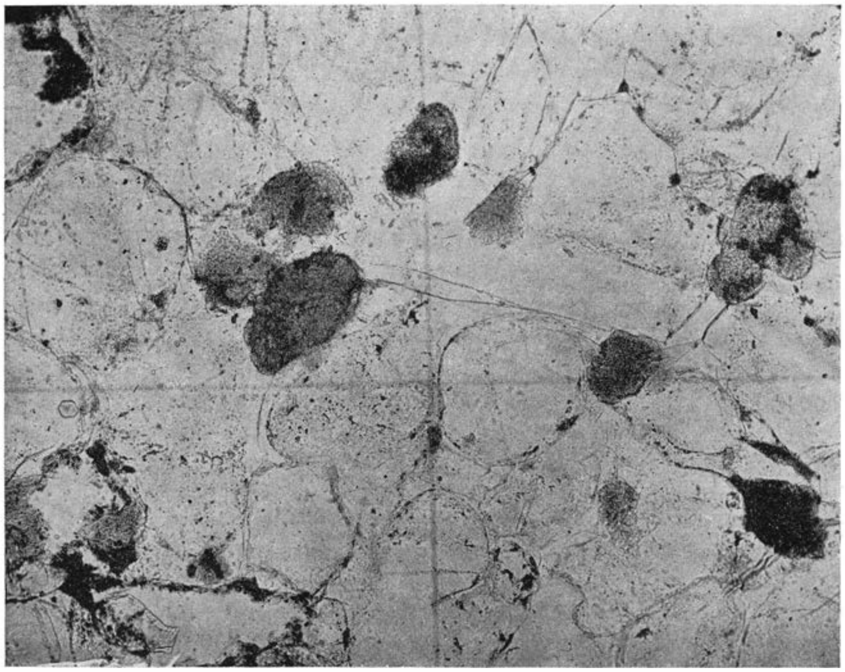

Fig. 51. Small rounded grains of glauconite in quartzitic sandstone. Brantevik, 11 d. (Pr. 2851. Pl. 549.) — 60 ×.

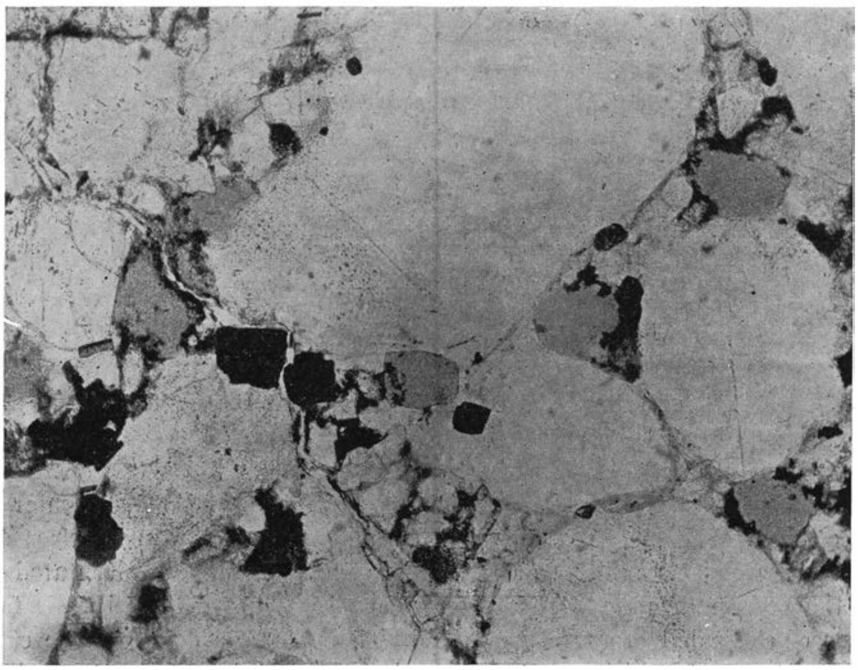

Fig. 52. Small rounded grains of glauconite with crystals and aggregates of pyrite. Lower Cambrian sandstone. Hardeberga. (Pr. 2226. Pl. 589.) — 60 ×.

Fig. 53. Tabular grains of glauconite. Glauconite sand. Ceratopyge stage. Pålstorp, Östergötland. (Pr. 3192. Pl. 569 a.) — 60 ×.

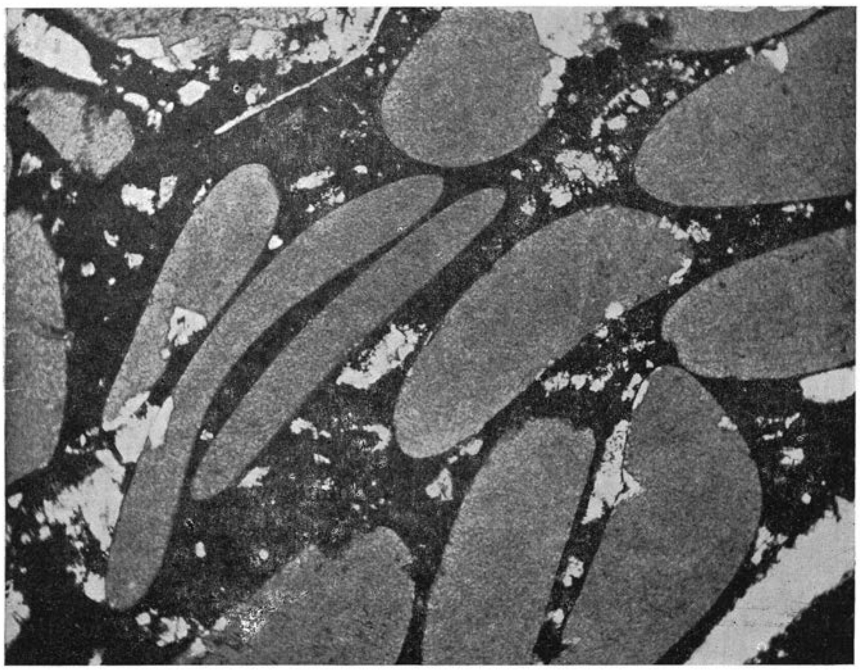

Fig. 54. Tabular grains of glauconite in limestone with haematite pigment. White parts (in the glauconite also) = calcite crystals. Hulterstad, Öland. (Pr. 2235. Pl. 588.) — 60 ×.

of stationary or now and then overturned grains might probably give rise to a tabular development. We leave, however, the question of the origin of this form open, even though it is obvious that no distinct difference exists between the rounded, smooth grains and the more flat ones.

The angular grains of glauconite are fragments of larger, cracked grains (fig. 55). One side of the grains is often found evenly curved, while the others are uneven. The curved side sometimes shows a dark stained zone (pigment zone), which is absent on the other sides. It is therefore indubitable that the curved side

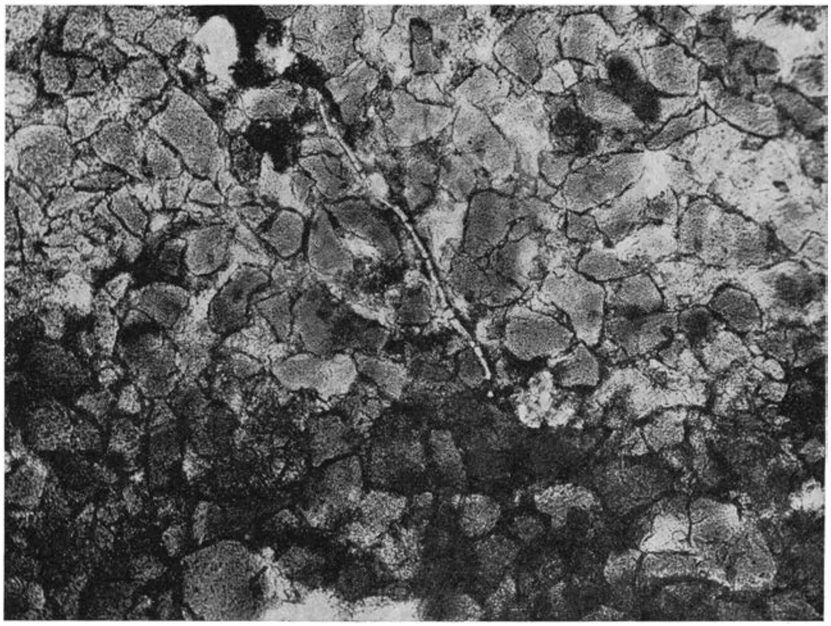

Fig. 55. Small angular grains of glauconite, fragments of larger grains. Glauconite sand. Köpings Klint, 3. (Pr. 3020 a. Pl. 534.) — 60 ×.

is a part of the original, rounded grain's periphery. Sometimes we find, together with the small fragments, single grains which, in spite of their deep cracks, have not completely disintegrated. A comparison between the lobes in these grains and the smaller fragments is a further support of the said interpretation.

If the angular grains are exposed to wear, they become rounded, and round grains formed in this manner are as a rule relatively small. The peculiar furrows characteristic of several of the larger grains are never seen in them. In some of the glauconitic beds small, rounded ones are found, which in spite of the wear, show traces of the previous angular form.

It is evident from the preceding that the author considers the usually large grains full of cracks to be the primary aggregates, and that these have cracked on the dehydration of the mineral formed as a gelatinous mass. The other grains have been formed from those mentioned above by their disintegration or wear.

Judging from their form, there is reason to suppose that the glauconite in many cases perhaps as a rule has not been immediately embedded in the mud but has been washed about by motions in the water. The strong enrichment of the grains in some places is also naturally explained in this way.

Glauconitic Aggregates whose Form is Dependent on the Surrounding Grains of Detritus.

When grains of glauconite lie embedded in a sandstone the grains of sand are not infrequently more or less pressed into the glauconite (fig. 56). This must, therefore, have been plastic on being embedded in the sand. In some sandstone beds, however, we find that the grains of glauconite show no traces of such impressions. The glauconite has then solidified (been dehydrated) before the embedding. On observing these different forms of development dependent on the degree of the grains' plasticity at the time of the embedding, we also understand how the irregular aggregates mentioned below have obtained their form.

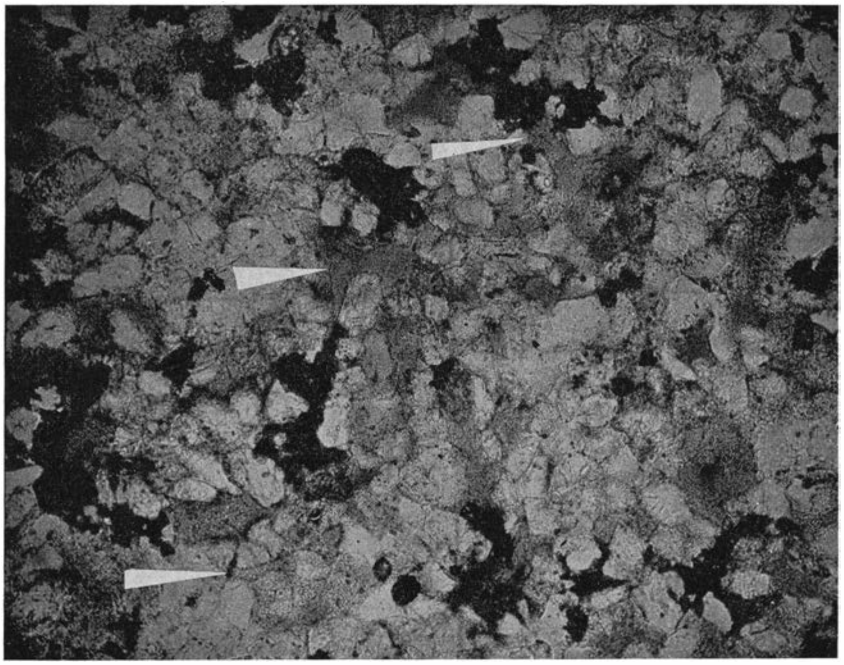

Fig. 56. Glauconite squeezed out between grains of quartz. Lower Cambrian sandstone, rich in glauconite (three of the glauconite grains are pointed out in the fig.). Simrislund, Scania. (Pr. 2050 a. Pl. 550.) — 60 ×.

The glauconitic aggregates referred to here occur as matrix between the grains of quartz. The distribution of the separate aggregates is very restricted, as a rule not exceeding 1—2 mm. Frequently they are abundantly present on a sandstone bed and lie scattered in the same manner as the rounded grains of glauconite in other rocks.[1] Thus they have been formed as small lumps and not as continuous beds. It might possibly be imagined that these aggregates were formed between the grains of sand already deposited, but it seems to the author that the above mentioned observations rather speak for the opinion that the glauconite was embedded in the sand as small gelatinous lumps and squeezed out between the grains of sand before the dehydration and solidification began.

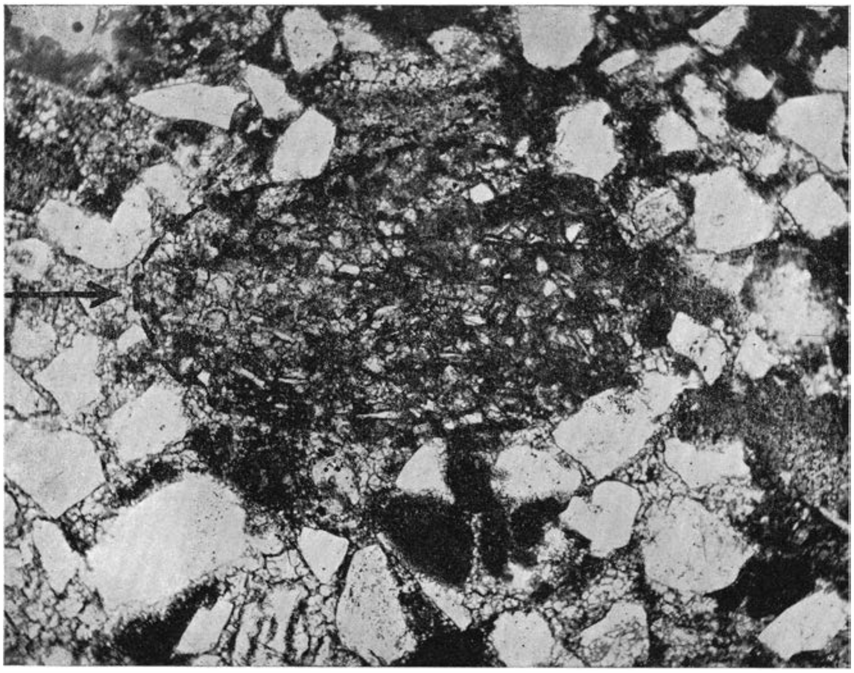

Fig. 57. A small ball (coprolite?) with quartz fragments in glauconite. Calcareous sandstone. Senonian. Erratic block. Lund. (Pr. 2515. Pl. 571.) — 60 ×.

As the glauconitic aggregates occurring as matrix between the grains of sand were, according to the said interpretation, embedded at an early stage, probably immediately after the formation of gel, the glauconite occurring in this manner may be regarded as autochthonous, while the glauconite that solidified and was possibly worn before the embedding may be suspected to be at secondary site of deposition.

[1] The author has not observed glauconite in this form in rocks built up by fine-detritus. In the coarse grained rocks he has, however, found small balls of glauconite and fine-detritus (fig. 57). They are always found at secondary site of deposition. [Cayeux, 1916, pl. XII, fig. 16 is of the same type.]

Glauconitic Aggregates whose Form is Dependent on Secondary Formation of Crystals.

In some places the glauconitic grains are found to enclose secondarily formed crystals of siderite or calcite. The crystals are generally situated in the peripheral part of the grains (fig. 58), and when their number is large the grains can become entirely jagged.

The same phenomenon, though still more advanced, may be the reason why the glauconite is only traced in a network or in an aggregate that otherwise is very

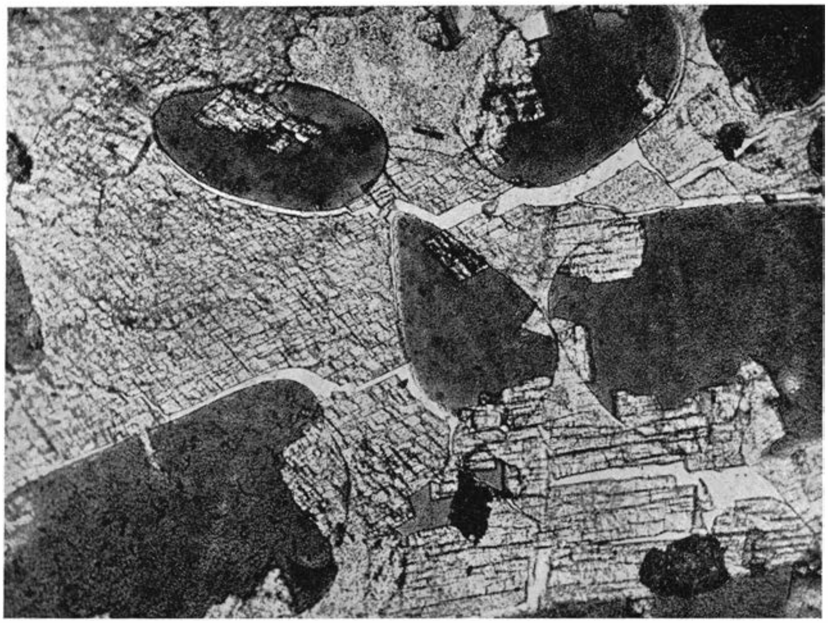

Fig. 58. Grains of glauconite with crystals of siderite and calcite. Below the grain in the middle of the fig. we see the small rest of another grain, the greater part of which is replaced by calcite. Glauconitic limestone. Ottenby, 8. (Pr. 3000. Pl. 525.) — 60 ×.

irregularly formed. Sometimes, however, it is possible to observe the outline of the original glauconite grain. This is especially the case when the peripheral zone of grains of glauconite has been dark-pigmented (fig. 59). The pigment in this (pyrite or haematite) has not been transformed by metasomatosis of glauconite into siderite or calcite. In the rocks, where the irregular glauconitic aggregates are enclosed within a still distinguishable outline of the original grain, traces of completely transformed grains of glauconite are generally also found. Only the remaining pigment zone reveals that glauconite has been present, the glauconitic matter has completely disappeared (see fig. 59 and 60).

(On the formation of crystals in the grains of glauconite and on the glauconite's transformation on the whole, see p. 157 seq.)

Fig. 59. Glauconite grains (dark in the fig.), partly replaced by calcite. The primary size and form of the grains is to be seen in the pigment zone around the remaining glauconite. In the middle of the lower half of the fig. we see the pigment shadow of a wholly replaced grain. Calcareous sandstone. Lower Cambrian. Brantevik, 9 b. (Pr. 3120. Pl. 544.) — 60 ×.

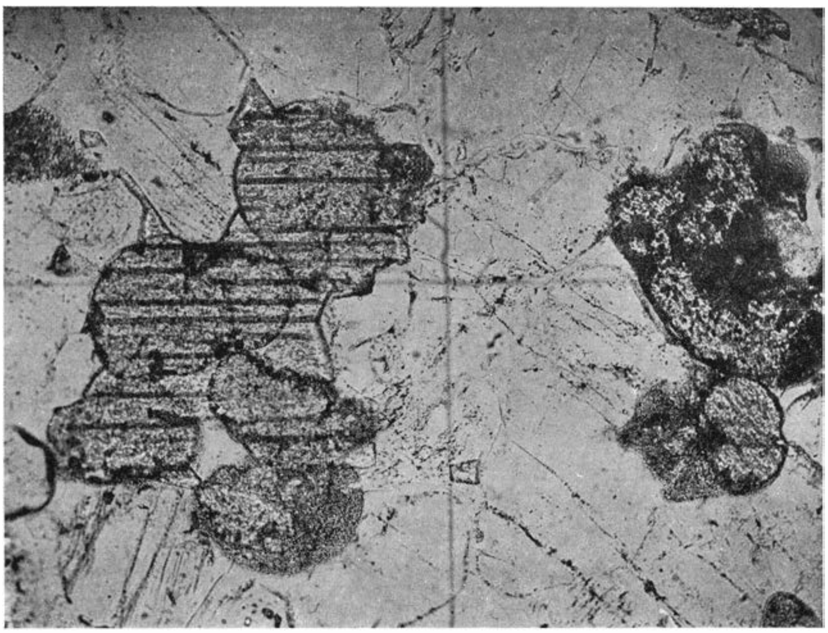

Fig. 60. Grains of glauconite replaced by calcite. Lower Cambrian sandstone, partly calcareous, partly quartzitic. Brantevik, 9 c. (Pr. 3117. Pl. 541.) — 60 ×.

Glauconite in the form of Earthy Aggregates (Glauconitic crusts).

Fossil fragments coated with a crust of earthy glauconite are not infrequently found in limestones containing grains of glauconite. If the rock is conglomeratic, part of the pebbles can also be covered with such a crust. An examination shows that this green crust is principally found in pebbles of limestone and calcareous sandstone.

Analysis (HADDING 1927, 125) has established that the earthy substance is in this case really glauconite.

The earthy glauconite has been found in many places in the Senonian limestones, especially in the shell fragment limestone. It is most strongly developed in the Cretaceous conglomerate at Tormarp in Halland. Not infrequently is the crust there a couple of millimeters thick while, in other cases, it only measures some tenths of a millimeter.

The glauconitic crust seems to be specially common in intraformational conglomerates. Thus it is found in the Mammillatus conglomerate at Tosterup, in conglomerates of the shell fragment limestone in north-eastern Scania and in Blekinge (int. al. at Istaby), in conglomerates of the Crania limestone, in the Acrothele granulata conglomerate in Öland (int. al. at Köping), and in the conglomerate of the Lower Cambrian sandstone (Brantevik). The deposition of the glauconitic crust on the pebbles is of course of the greatest interest for the interpretation of the conditions for the formation of these conglomerates.

In some cases the author has found fragments of an earthy glauconite crust lying free in the rock. This glauconite has been connected with a shell (or a pebble), which has been dissolved later on, or from which the crust has loosened.

The crust of the glauconite has also frequently been formed directly on a surface of the rock. This surface can be a bedding plane but as a rule it is not. Generally it is unevenly curved and furrowy but practically parallel to the bedding planes. It would hardly be incorrect to interpret this glauconite-coated surface as an occasionally and locally formed corrosion and denudation surface. If this is the case, the deposition of the glauconite on it has been analogous to its formation as crust on the conglomerate pebbles: it has been deposited on a consolidated rock after a negative sedimentation.[1]

As far as we can see from the investigations made, glauconite crust on such denudation surfaces is only found in limestones. It is specially common in the Lower Ordovician glauconitic zone, i. e. in the dense Ceratopyge limestones and the petrographically similar lower part of the Orthoceras limestone, possibly because in all probability this rock has consolidated very quickly. Suitable conditions for the formation of glauconite crust have namely presented themselves whenever the thin layer of loose mud has been washed away.

[1] Glauconite crust is also to be found on other surfaces, for inst. on gliding surfaces or in cracks formed during the diagenesis probably at the same time as the crust on denudation surfaces.

There is reason to ask, whether the thin green laminae, sometimes occurring in the limestones just mentioned, have not obtained their colour from glauconite deposited in the manner indicated above. The author considers it very probable, even though the question requires further investigation. In the cases observed the green substance is sometimes found as a very sharply outlined crust or pellicle between yellow, gray, or red portions of the limestone (cf. p. 37) and sometimes as a green zone fading gradually towards the hanging-wall. In the last mentioned case the formation of glauconite has begun spontaneously with the formation of the thin crust and it has not ceased, as is usually the case, when the deposition of calcareous mud began. On that account the limestone obtained a green pigmentation from glauconite dust. As will be shown in the following, however, this pigmentation with glauconite is not exclusively connected with the said green crusts or pellicles.

Glauconitic Dust as Pigment in Limestones.

In the glauconite-bearing series of strata strong variations in the size of the glauconite grains are sometimes found in the different beds. This is for inst. the case in certain parts of the Lower Cambrian sandstone. As a rule the grains are normal in size, 0.5—2 mm in diameter, but in some beds they are so small that they can hardly be distinguished even with the help of a pocket lens. This type of glauconite grains occurs in exceedingly fine-grained calcareous sandstones, for inst. in a fine-grained form of the sandstone with *Discinella (Mobergella) Holsti.*

A further decrease in the size of the glauconitic aggregates would lead to their reduction to pigments only. That the glauconite really occurs as dusty pigment is evident from what has been said of the fading of certain glauconitic laminae in limestone. Besides these relatively unimportant occurrences there are others in which the pigmentation with glauconite plays a by far greater rôle.

Glauconite in the form of dusty pigment seems to be essentially present in marly rocks in the glauconite-bearing series of strata. In the Middle Cambrian sandstones in Öland there is an abundance of beds containing grains of glauconite, and in the most fine-grained, calcareous, and argillaceous beds (the zone with *Paradoxides Oelandicus*) a microscopical, green pigment is sometimes found together with very small grains of glauconite (about 0.05 mm in size). The same is the case in the zone with *Megalaspis planilimbata* where this zone has a more marly development than the Ceratopyge limestone.

The glauconite pigment only occurs in small quantities, and as it is mixed with clayey matter, it is almost impossible to positively prove its presence by means of chemical analysis. The colour and occurrence of pigment, however, make the interpretation of its character appear correct. Where the pigment occurs in the above mentioned manner together with thin laminae (crusts or pellicles) of earthy glauconite it is quite evident that the green substance is a dusty glauconite mixed with the calcareous and argillaceous mass.

On account of the great difficulties, which make it almost impossible to prove the presence of the glauconitic pigment, small notice has only been taken of this. We do not know the extent of this occurrence but we may venture to say that the green pigment interpreted as glauconite occurs only in sediments formed under the conditions favourable to a formation of glauconite. Where these conditions have existed, however, glauconite has no doubt in most cases been formed as grains. As the very small grains and the pigment seem to be connected with the sediments partly built up by argillaceous detritus, it may be imagined that an occurrence and deposition of fine detritus during the formation of glauconite has prevented the appearance of gelatinous lumps, from which, in the author's opinion, the grains of glauconite have been formed. The condition for the formation of the gelatinous lumps is a strong flocculation of the glauconitic matter. Has this flocculation been prevented by the presence of fine detritus the glauconitic matter has been deposited in a fine-divided state together with the detritus mass.

It is of course not necessary to interpret the glauconitic dust as a primary formation. During the wear to which a large part of the glauconite grains has undoubtedly been exposed, a no slight amount of dust has surely been formed. This is probably present in the form of pigment in the rocks containing the worn grains or at any rate in rocks belonging to the same zone as these. Frequently, however, glauconite-pigmented beds occur in such parts of the series of strata as do not contain any abraded grains of glauconite. This is for inst. the case in the Middle Cambrian of Öland. In such cases the secondary formation is no doubt excluded.

As the glauconitic crust on certain bedding and denudation surfaces is to all appearances similar in formation to the glauconitic crust on conglomerate pebbles and shell fragments, it cannot be interpreted as an accumulation of matter abraded from glauconite grains but rather as a primary deposition. From this follows that the pigmentation occurring together with glauconite crusts must also have arisen by means of a primary deposition of glauconitic substance. Collet and Lee discuss (1905—6. 249) the question of the formation of the glauconitic pigment and contend that a direct deposition from solution is improbable, as it would have given rise to a homogeneous, compact crust. This point of view is partly correct, and we have also, as already shown, examples of such a glauconite. However, it is undoubtedly evident that a relatively slow precipitation does not result in compact layers, if it is contemporaneous with a relatively strong deposition of fine detritus. The latter has influenced both the very process of precipitation and the occurrence of the precipitated matter in the rock. It is therefore not an accidental circumstance that the glauconitic pigment is found in rocks containing fine detritus: clayey substance or exceedingly fine-grained sand.

Glauconite occurring as impregnation in porous or cracked fossils, in minerals, or rock fragments cannot always be distinguished from that occurring in the above mentioned manner (as pigment). Its development is, however, frequently so peculiar that it is worthy of a somewhat closer illustration.

Impregnations of Glauconite.

Shell fragments coated with a crust of glauconite often show an impregnation of the mineral. The green substance has been infiltrated wherever the colloidal solution has been able to penetrate these fragments. The impregnation is variously developed according to the different structure of the shells (foliate, tubular, etc.).

A similar impregnation appearing as a pigmentation, is also seen in conglomerate pebbles coated with glauconite crust. This, like the crust itself, has been

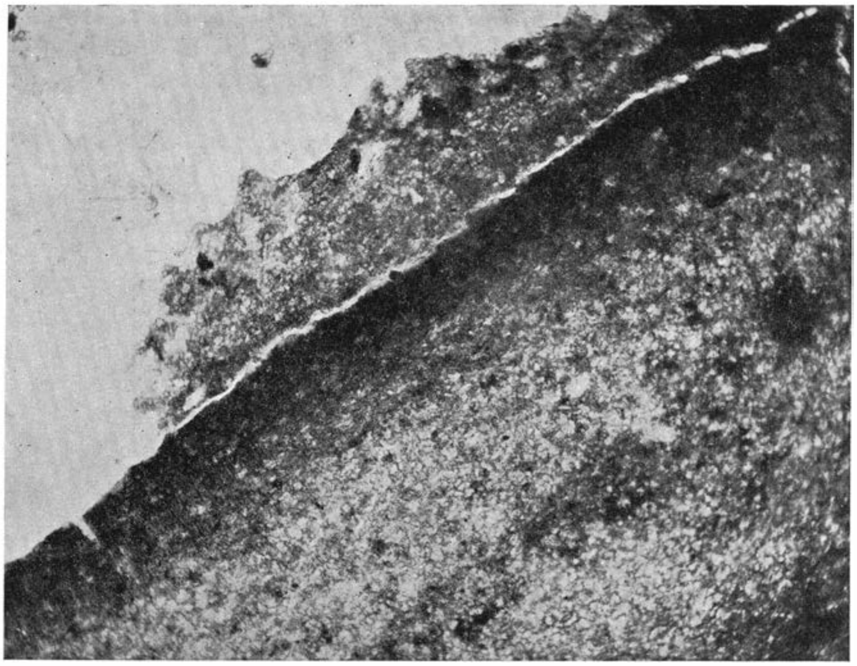

Fig. 61. Impregnation of glauconite in the peripheral part of a calcareous pebble. Mammillatus conglomerate. Senonian. Tosterup, Scania. (Pr. 2468. Pl. 582.) — 60 ×.

formed after the abrasion of the pebble has been finished. In this case, consequently, the pigment is younger than the pigmented rock, while, in the previously described cases, it has been formed contemporaneously with the rock.

Impregnations of the above mentioned kind also occur without connection with glauconite crust (fig. 61). Its demonstrability, however, is to a large extent dependent on the character of the impregnated body. In dark, opaque minerals or rocks the pigment zone formed during the infiltration is easily overlooked, in light and transparent minerals and in fossils, on the contrary, it is often very distinct.

Infiltrations in quartz and felspar, like those described by Cayeux (1897) and Collet & Lee (1905—6), as well as fillings of fine cracks in phosphorite pebbles have been observed in several samples (fig. 62). Glauconite occurring as lamellae or irregular fillings in calcite crystals can be of the same type but it is often only apparently so. As shown above (p. 101) it constitutes in certain beds the last remains of glauconite grains, that have been replaced by calcite.

Fossils are very differently susceptible to an impregnation of glauconite. Compact shells (for inst. of phosphate-shelled brachiopods) seldom show any impregnation. The impregnation with glauconite makes the study of the original structure of the fossils sometimes possible, even if this has been obliterated by recrystallization or dissolution. In the following a few examples of impregnations of glauconite will be given.

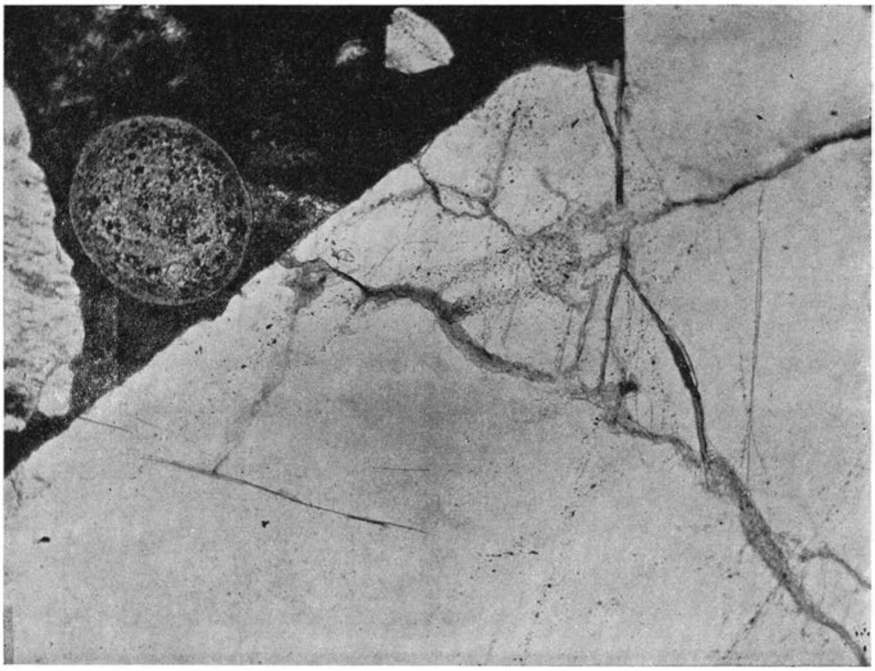

Fig. 62. Glauconite in the cracks of a quartz pebble. To the left a small phosphoritic coprolite. Senonian conglomerate. Bjärnum, Scania. (Pr. 2022. Pl. 586.) — 60 ×.

The pebbles in the Acrothele granulata conglomerate at Borgholm and at Köpinge in Öland are impregnated with glauconite in their peripheral part. Rounded fossil fragments derived, like the pebbles, from the disintegrated beds are also impregnated. This, however, is the case only in the more porous fragments, not in all of them. The phosphate shells of certain brachiopods are hardly ever impregnated. The fossils occurring *primarily* in the conglomerate are also devoid of glauconitic impregnation. Scattered grains of glauconite occur in the matrix of the conglomerate.

The Lower Cambrian phosphorite-bearing limestone at Andrarum, the zone with *Holmia Kjerulfi,* contains an abundance of glauconitic grains. The phosphorite nodules are primarily free from glauconite, i. e. they contain no grains of glauconite. They have not been formed together with glauconite, and they occur at secondary site of deposition. In these phosphorite pebbles we find cracks entirely or partly filled with glauconite deposited from infiltrating solution. In the peripheral part of the pebbles the crack filling often consists of calcite or, more correctly, of the rock's matrix and cement.

The Cretaceous fragment limestone (Senonian) in north-eastern Scania shows, in many places, impregnations of glauconite in shells, phosphorite nodules, and conglomerate pebbles (fig. 62). This is for inst. the case in the limestone and conglomerate at Bjärnum. The impregnated fragments (mostly shells of lamellibranchs)

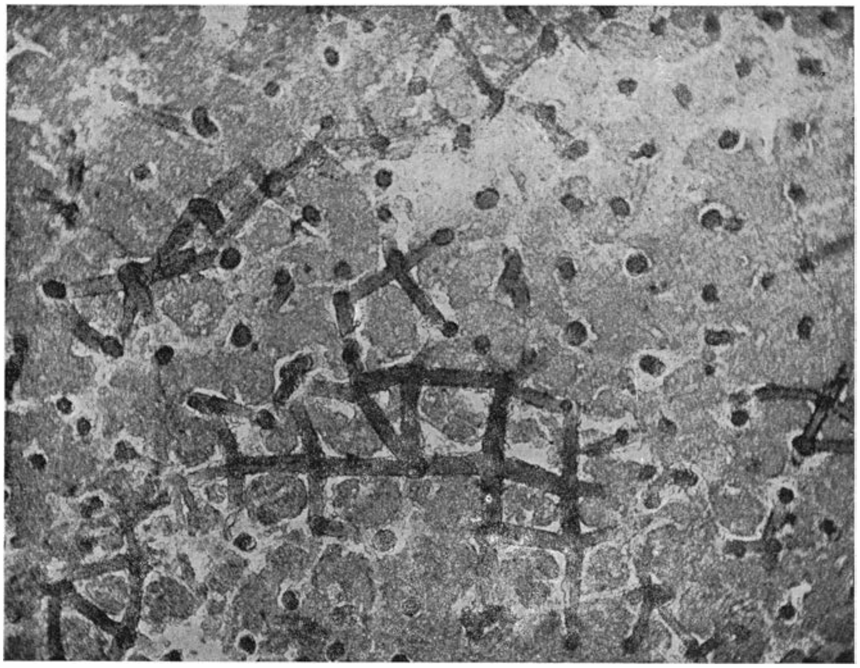

Fig. 63. Glauconite in the canals of a siliceous sponge. Flint nodule in shell fragment limestone. Oppmanna, Scania. (Pr. 2240. Pl. 563.) — 60 ×.

as well as the pebbles are distinctly rounded or worn. Grains of glauconite occur in the same rock, though not very commonly. They vary in size and are no doubt partly at secondary site of deposition.

In flint from the shell fragment limestone (Senonian) at Oppmanna a number of fossils can be traced, owing to the fact that the calcareous shells have been impregnated with glauconite before they were replaced by silica. We find in the same flint a network of glauconitic matter formed by infiltration in the canals of a sponge *(Hexactinellidae)* (fig. 63). The sponge structure is otherwise completely obliterated.

In conglomerate-like upper Crania limestone (Danian), found in blocks at Klagshamn, an abundance of rolled and worn fragments of echinids is present. These

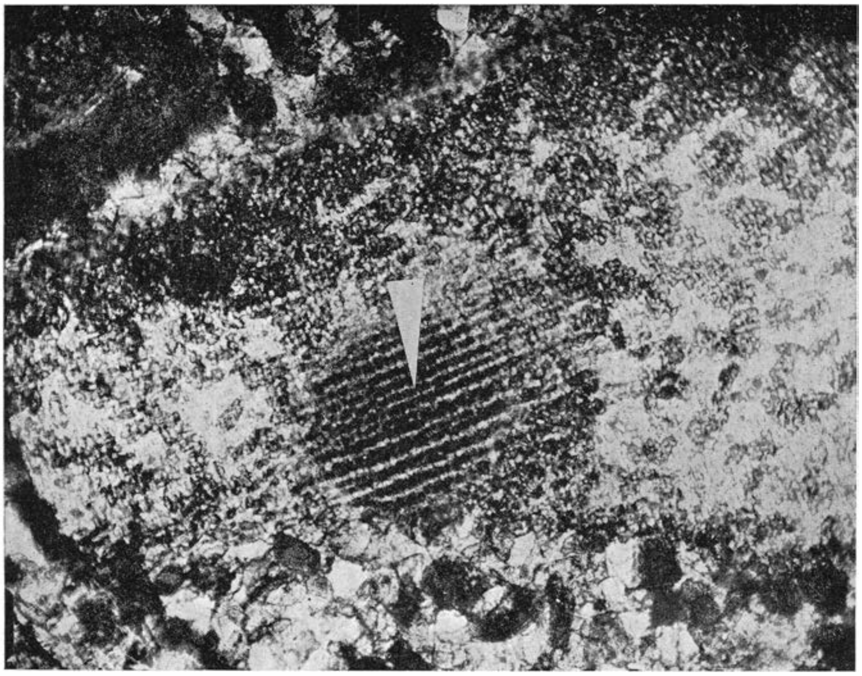

Fig. 64. Typical glauconite impregnation in porous fossil fragment. Glauconitic arenaceous limestone. Tertiary. Erratic block. Ystad, Scania. (Pr. 2263. Pl. 562.) — 60 ×.

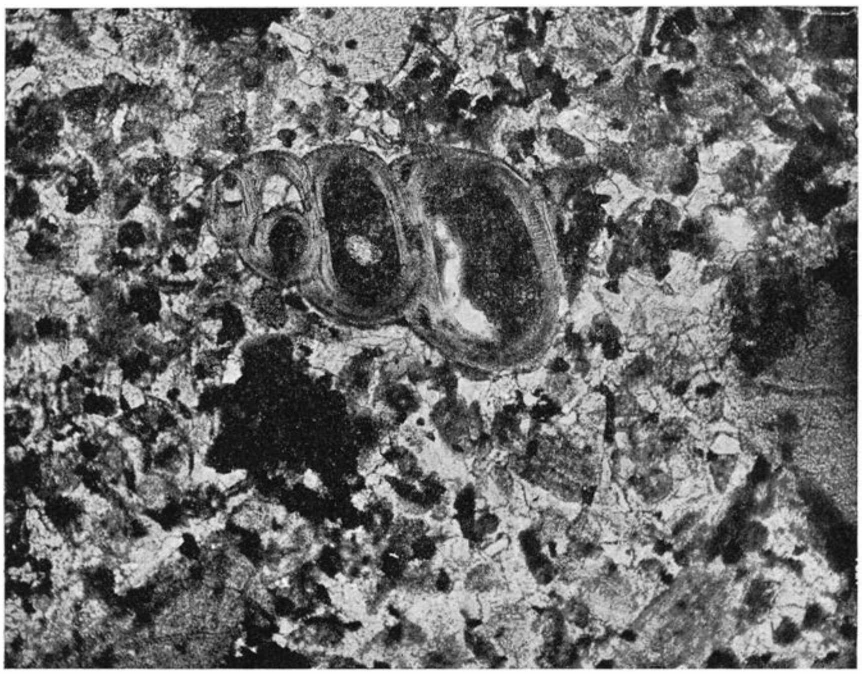

Fig. 65. Glauconite in a small gastropod shell. Glauconitic limestone. Tertiary. Erratic block. Ystad, Scania. (Pr. 2261. Pl. 561.) — 60 ×.

fragments are to a large extent impregnated with glauconite. It is to be noticed that glauconite is never found in the Foraminifera abounding in the rock. Grains of glauconite are only sparingly present.

The upper Crania limestone in the south harbour of Copenhagen shows the same state of things as the above mentioned rock, which it also resembles in other respects. In the abundant, small, smooth, phosphoritic coprolites crack fillings of glauconite are noticeable. Thus, these coprolites are, like the rolled fragments of echinids, at secondary site of deposition or, more correctly, they were, before the embedding, in another sedimentary environment than that in which they were finally deposited. In the limestone conglomerate small calcareous pebbles also occur, derived, according to Rosenkrantz (1920, 14), from disintegrated parts of the lower Crania limestone. These pebbles are as a rule impregnated with glauconite in the surface, and sometimes they have also a crust of glauconite. Fragments of such a crust lie scattered in no small quantities in the rock.

The Tertiary blocks found on the southern shore of Scania are often rich in grains of glauconite. Sometimes they also show glauconite as impregnation in fossil fragments (fig. 64), as a rule distinctly rounded. In these rocks also an abundance of Foraminifera shells without glauconite is found together with the impregnated fragments of lamellibranchs. Shells filled with glauconite may also be found (fig. 65).

The study of glauconite as impregnation has led us to the following conclusions:

1. Impregnations of glauconite can be formed in minerals and rocks as well as in fossils.
2. The impregnations are formed in fine cracks or in pores, and the impregnating glauconitic substance has acquired the form of these voids.
3. In crack-free, porous bodies the impregnation is strongest in their peripheral part and sometimes continues outwards in a crust surrounding the body and consisting of earthy glauconite, probably identical with the impregnating one.
4. The impregnations were deposited from (colloidal) solution, not by enrichment of dust from crumbled grains of glauconite.
5. The impregnations are mainly (only?) to be found on secondarily occurring or enriched fossils, rock fragments, etc.
6. The progress of the sedimentation before, during, and after the formation of the impregnations has in many cases been as follows:
    a. A normal deposition of fine-grained detritus or calcareous mud takes place, possibly with formation of glauconitic grains. Limestone lumps, newformed by cementation or crystallization in the mass and primarily embedded fossils are enclosed in the deposited beds.
    b. The deposited beds are exposed to a disintegration by increased motion in the water. On this taking place loose mud is washed away, and the con-

solidated lumps together with larger fossils present in the mud are enriched. Grains of glauconite and other mineral grains can also be enriched in the same manner, eventually also transported (together with fossils) from some other place to the site of deposition.

c. After the enrichment of the coarser material and its abrasion during the enrichment and transportation, a deposition of glauconite takes place first as impregnation and then possibly as crust. During this deposition of glauconite the motion of the water has still been so strong that no fine sediments have been deposited.
d. After the formation of the impregnation and eventual crust of glauconite, a new deposition of fine detritus and calcareous mud takes place, sometimes with formation of pigment or grains of glauconite.
e. Thereupon the sedimentation may be continued without interruption, or it is interrupted by a second period of negative sedimentation. In the latter case the previously pigmented fossils and pebbles are redeposited, on which the relatively loose crust of glauconite that is eventually present is broken up. If the action to which the material is exposed is not strong, fragments of the glauconitic crust can also be embedded in a recognizable state in the mud, which is deposited after the negative sedimentation (for inst. in the Crania limestone).

7. *The impregnations of glauconite in fossils and rock fragments etc. are thus formed in connection with changes in the sedimentation or, better defined, after and possibly during periods of negative sedimentation.*
8. The impregnations are formed in relatively agitated water with slight or no deposition of fine detritus.
9. Glauconitic grains occurring together with fossils impregnated with glauconite etc. are not formed in the environment and under the same conditions as the impregnations. They often occur at secondary site of deposition. Like the fossils and rock fragments they can have a crust of secondary glauconite.

The Formation of Glauconite Estimated after the Development of the Mineral.

An account of the different forms in which the glauconite is found developed is given in the preceding, and in connection with this account the conditions for the development of the one or the other form have been discussed. In some cases, for inst. concerning the glauconite as impregnation, the general conditions for the deposition of glauconite have also been discussed. A more continuous survey of the observations made on the glauconite's development and of the conclusions as to the formation of the mineral justified by these observations will be given in the following.

When the glauconite occurs as impregnation, as coating on bedding and denudation surfaces, as aggregates squeezed out between grains of sand, and as large, cracked grains it is autochthonous. Among other forms of development the glauconitic crust on fossils and rock fragments is as a rule autochthonous. The same can be the case in the glauconitic pigment in limestones and marls but an allochthonous occurrence is by no means excluded. The glauconitic dust (the pigment) can be derived from crumbled grains, it can also be redeposited in its finedivided form.

The occurrence of the rounded, smooth grains of glauconite may as a rule be *allochthonous*. The same holds true of the tabular ones with a smooth, polished surface. The rounded grains with shallow furrows have probably also been exposed to abrasion before the embedding. The angular grains, that are fragments of larger ones, have not become noticeably worn but in several of the occurrences containing small, rounded grains these have no doubt been formed by wear of angular fragments. Consequently the last-mentioned three forms of glauconite are essentially allochthonous.

Glauconite as impregnation as well as crust is deposited directly from colloidal solution in the impregnated body.

The glauconitic aggregates squeezed out between the sand grains in a sandstone show that the glauconite was plastic, probably gelatinous on the embedding. The mode of occurrence of the aggregates shows that they appeared as small, scattered lumps, in the same manner as the glauconite grains in other rocks.

The larger (non-disintegrated) grains of glauconite are always full of cracks. These have been formed during the dehydration of the mineral on its transition from the gel stage to the crystalline stage.

From the above mentioned facts we can infer that glauconite in granular form has been formed by means of flocculation from colloidal solution, by the clustering together (Zusammenballen) of the floccules into gelatinous lumps, and finally by a crystallization process in these lumps.

On the formation of the glauconitic pigment in for inst. marly rocks the flocculation and formation of the gel lumps have been prevented by fine detritus suspended in the water. The deposition of glauconite has taken place according as it has been formed in exceedingly small aggregates of glauconite and detritus.

The formation of new minerals in the glauconite have occurred when it was still in the gel stage. Thus a dark pigmented zone has in many cases been formed before the formation of cracks (see p. 98). The metasomatic processes, through which glauconitic matter was exchanged for siderite or calcite, have possibly taken place after the dehydration of the glauconite (see p. 101).

The form af the glauconitic grains — round, tabular, etc. — has probably been fixed already during the gel stage.

As shown above, the formation of glauconite as impregnation in fossils and rock fragments has taken place in connection with negative sedimentation and in relatively agitated water.

The glauconite as crust on fossils and rock fragments and as coating on denudation surfaces has, like the impregnation, been formed in connection with negative sedimentation and in such agitated water that fine detritus was not deposited contemporaneously with the formation of glauconite.

The glauconite as grains has probably also been formed in relatively agitated water. This supposition is the best explanation of the form af the gelatinous lumps and the abrasion of the aggregates consolidated by dehydration and crystallization.

The glauconite as pigment in fine-detritus rocks may have been deposited in tranquil water.

The Physical Properties of Glauconite.

An account of the glauconite's physical properties falls, strictly speaking, beyond the scope of this work but naturally the author could not omit to make a number of observations on these properties. A short summary of them will therefore be given in the following.

Specific gravity. By means of Thoulet's solution the specific gravity of a number of grains from different localities was determined with the following results:

	Glauconite from:	Sp. gr.
1.	Orthoceras limestone, Lower Ordovician, Öland	2,863
2.	Ceratopyge » » », Karlsfors, Västergötland	2,856
3.	» » » », Bjällum, »	2,856
4.	» » » », Berg, Östergötland	2,827
5.	» » » », Boda, Dalecarlia	2,781
6.	Marl, Senonian, Eriksdal, Scania	2,855

In all the cases investigated the grains of glauconite were dark green without traces of pigmentation or any noticeable impurities. In all the cases except the first one the glauconite-bearing rock was a gray limestone containing some clay and small grains of pyrite. The first-mentioned rock, the Orthoceras limestone, was dark red and strongly pigmented with haematite dust. It is not excluded that the cracks in the glauconitic grains picked out from this rock have also contained some haematite, and that this explains the high specific gravity of the grains. The author thinks it also possible that the grains with especially low specific gravity (Boda and possibly Berg) have enclosed secondarily crystallized calcite. On account of the character of the material and the values obtained the author is inclined to estimate the specific gravity of the glauconite to 2.84 $\pm$ 0.02. The values published by GLINKA (1896, 21), varying from 2.867 to 2.645, may be mentioned in comparison with these. According to him the specific gravity of weathered brown and yellow grains only amounts to 2.4—2.5. GLINKA's determinations, like the author's, are performed on fossil material. On recent material LACROIX has found that the specific gravity varies between 2.2 and 2.3 (COLLET and LEE 1906, 240). According to CAYEUX (1916, 244) the specific gravity of the glauconite is 2.2—2.83, the lowest values thus referring to recent and the highest ones to fossil material. The greater density of the fossil material is probably owing to recrystallization and dehydration.

Hardness. An estimation of the hardness of the glauconite is not easy to make, as the mineral principally occurs in dense aggregates, often of earthy consistence. On worn, relatively solid grains of glauconite the hardness was determined to less than 3 but more than 2. Cayeux (1916, 244) states the value to be 2. Unfortunately the crystals found are too small to be used on determination of the hardness according to the prevalent methods.

Optics. The colour of the glauconite varies a little. In the dense, compact aggregates the colour in reflected light is blackish green, almost black, in the loose,

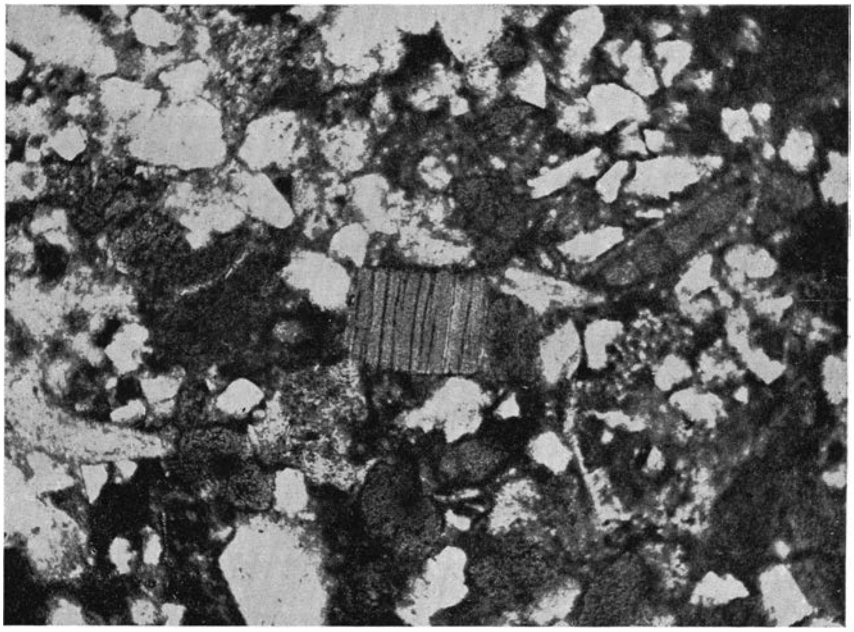

Fig. 66. Glauconite crystal, typical form. Arenaceous and glauconitic limestone. Senonian, Mammillatus zone. Tosterup, Scania. (Pr. 2694. Pl. 583.) — 60 ×.

earthy aggregates grass-green or light bluish green. In transmitted light the unweathered aggregates exhibit a strong, grass-green colour. Weathered grains are as a rule yellow or brown. The Swedish Cambrian and Ordovician glauconites are generally intensely green. Collet and Lee (1906, 242) have found English Paleozoic glauconites to be almost colourless, and from this they have inferred that the colour fades with the age of the mineral (cf. also Cayeux 1916, 244). The Swedish occurrences show that this inference is too hasty. But the cause of the decolourization is no doubt correctly found in a metamorphosis of the glauconite-bearing rock. Collet and Lee themselves call attention to this.

The simple crystals show a distinct *pleochroism* (fig. 67): yellow or slightly yellowish green for light vibrating parallel to the cleavage, bluish green at right angles to this. (α bluish green, $\beta \leqq \gamma$ yellow or yellowish green.)

In order to determine the glauconite's *refraction* it would have been desirable to isolate a few crystals. This, however, did not succeed, and on that account the author had to be contented with a few determinations on cryptocrystalline grains. These were examined according to the method of SCHROEDER van der KOLK with mixtures of iodobenzene and bromobenzene. The result recorded was

$$1.602 < n < 1.610.$$

Thus the value often stated in literature, $n = 1.61$, may, in some cases at least, be somewhat too high.[1]

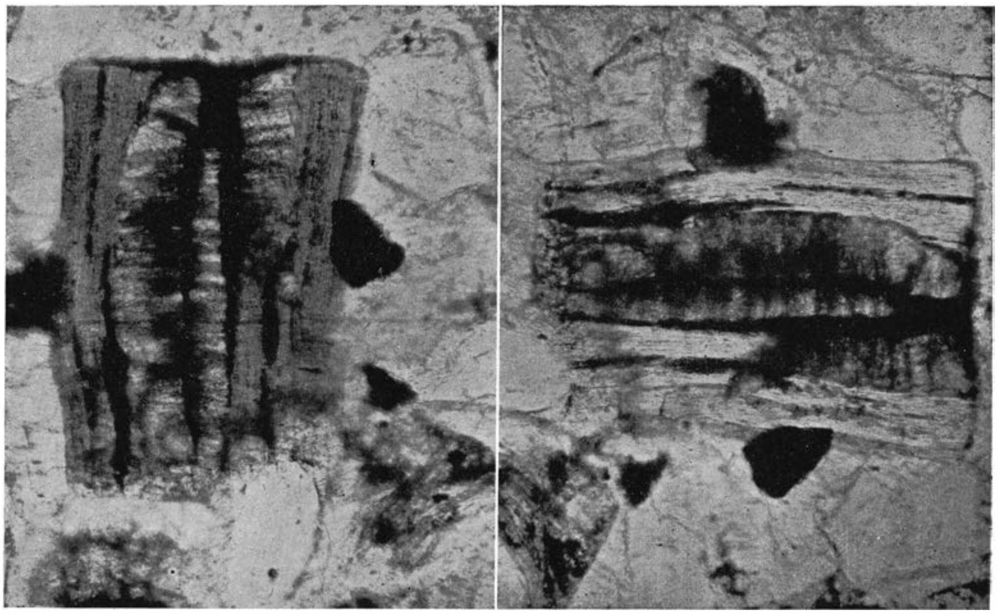

Fig. 67. Glauconite crystal, enclosing phosphatic fragment. The two fig. show the pleochroism of the crystal: left grassy-green, right pale yellow. Vibration-plane of the nicol: left-right. Lower Cambrian sandstone. Simrislund, Scania. (Pr. 2690. Pl. 580 & 581.) — 200 ×.

That the glauconite is not optically isotrope is evident already from the study of the cryptocrystalline aggregates. These show namely a distinct *double refraction* between crossed nicols. They are, however, not suitable for an estimation of the magnitude of the double refraction but this can be fairly well performed on the glauconite crystals sparingly found in certain of the rocks (fig. 66—70).

On glauconite crystals in Lower Cambrian sandstone at Brantevik (loc. 9, stratum h) the following determinations of the double refraction were made:

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[1] During the printing the author has received a new paper by HUMMEL (1931) with numerous determinations on the indices of refraction of glauconites, also swedish. Glauconite from Byerum, Öland (Orthoceras limestone): $n = 1{,}610—1{,}618$; from Degerhamn, Öland (Ceratopyge limestone): $n = 1{,}602—1{,}610$; Laesaa, Bornholm, Denmark (Lower Cambrian): $n = 1{,}602$ (approximately).

1) section almost parallel to the cleavage planes, double refraction	0,007
2) » not » » » » » » »	0,024
3) » » » » » » » » »	0,025
4) » » » » » » » » »	0,027

The first stated, low value indicates that the mineral has no or extremely slight double refraction in sections parallel to the cleavage planes. This also agrees well with the observation that the mineral in the cases examined is either optically uniaxial or has a very small axial angle.[1]

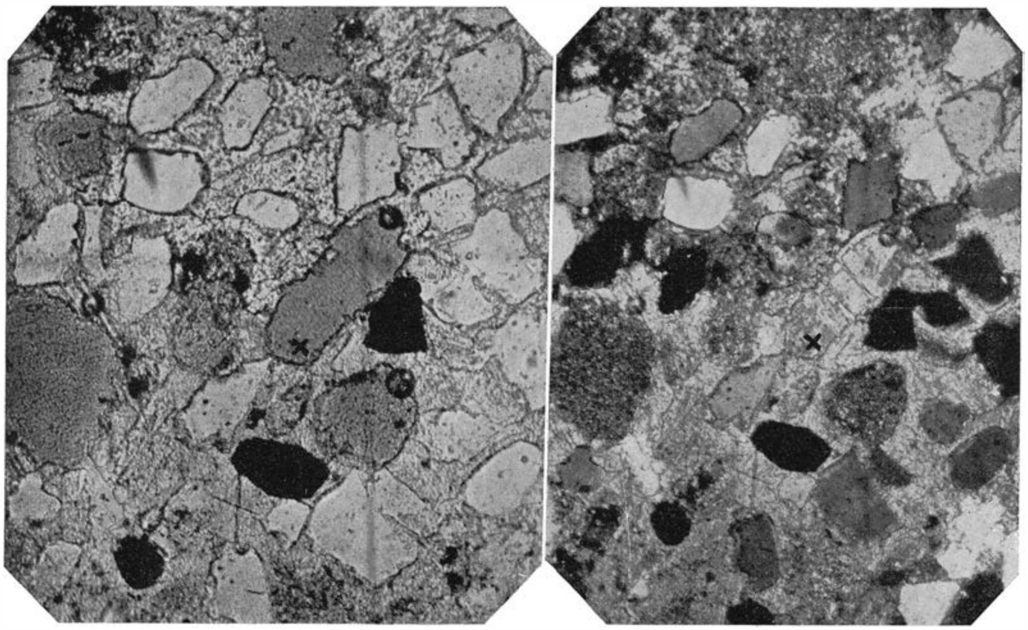

Fig. 68. Glauconitic sandstone with a crystal of glauconite (×). Left part: only polarizer (110 ×); right part: nicols crossed (95 ×). Lower Cambrian. Simrislund, Scania. (Pr. 2690. Pl. 621 & 622.)

The optic axis or acute bisectrix is apparently perpendicular to the cleavage planes.

As the mineral shows an *optically negative* character, the optic orientation and the double refraction may be stated thus after the values found:

$$\gamma \geqq \beta \parallel \text{cleavage planes}; \quad \alpha \perp \text{cleavage planes}.$$
$$\gamma - \beta \leqq 0{,}007; \quad \gamma - \alpha \geqq 0{,}027.$$

On a glauconite crystal in Tertiary calcareous sandstone from Ystad the double refraction was determined to 0.019. This value agrees well with that stated by Lacroix as approximate, 0.02, but it may not be the maximum value of the double refraction, as the determination is made on a non-orientated section.

[1] In the crystals examined the axial angle cannot have exceeded 10°.

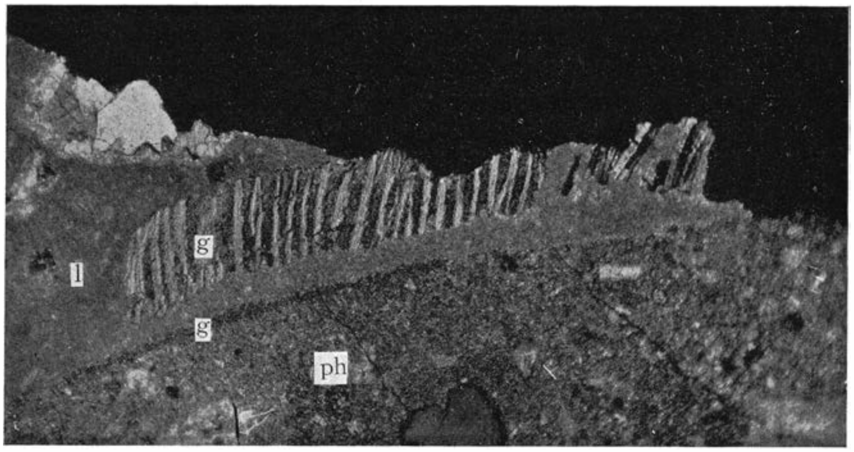

Fig. 69. Phosphorite nodule (*ph*) with crust of glauconite (*g*), the upper part lamellar (polysynthetic twinning?). *l* = limestone. Senonian conglomerate. Bjärnum, Scania. (Pr. 2022. Pl. 614.) — 60 ×. Nic. +.

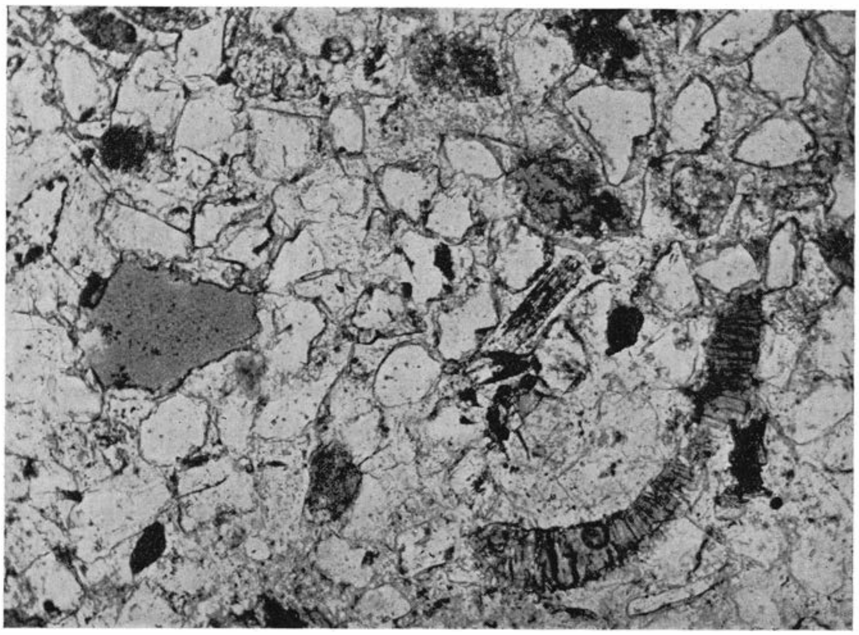

Fig. 70. Glauconitic sandstone with curved foliated crystal (lower right part of the fig.). Lower Cambrian. Simrislund, Scania. (Pr. 2690. Pl. 620.) — 100 ×.

The great agreement in optic respects between glauconite and certain chlorites is remarkable. In thin cleavage flakes the minerals show a pale green colour and no distinct pleochroism. Like the glauconite several chlorites are optically negative and (apparently) uniaxial, with their optic axis practically at right angles to the cleavage planes. Thus an examined clinochlore from Pfitschthal and another sample of the same mineral from Achmatowsk showed the same colour and the same optic orientation as the glauconite. The two chlorites mentioned were optically negative, with a very small axial angle and the acute bisectrix closely coincident with the normal to the cleavage plane.

Some agreement also exists between the glauconite and some micaceous minerals among others the vermiculite or lennilite from Lenni, Penn. spoken of as altered phlogopite (Tschermak 1879, 58, 1891, 64--66). Like the glauconite this mineral is apparently optically uniaxial, negative, with the optic axis at right angles to the cleavage surface. Like the previously mentioned minerals it has the colour of glauconite. As will be seen in the following from the X-ray investigation its structure is similar to that of glauconite, but they have different chemical composition and different refraction and double refraction.

The Structure of the Glauconite.

No direct determination of the glauconite's structure can be made as long as material suitable for a morphological or complete X-ray investigation is not available. The material we have at our disposal is only appropriate for an examination according to the Debye-Hull method. By this method it is possible to form an opinion of the glauconite's structural relationship to other minerals, but hardly to clear up the molecular structure. Schneider (1927, 308) has shown the great conformity existing between the X-ray patterns of glauconite and Zinnwaldite. The author, however, fully agrees with Hallimond that too great value must not be attached to this conformity. The latter (1928, 590) writes: »Without a complete solution of the structure it seems doubtful whether similarity in X-ray pattern possesses any value as evidence of equality either in the molecular volume or in the number of oxygen atoms in the molecule».

The author has made a number of X-ray powder photographs of glauconite and of minerals belonging to the mica and chlorite groups and found that certain structural features may be traced as common to several of the minerals. The diagrams of Vermiculite from Lenni show the greatest conformity to the diagrams of glauconite. The measurements of those diagrams, however, will not be published here.

Like Schneider the author considers that *the X-ray patterns distinctly prove the glauconite to be a definite compound and not a mechanical mixture.* He also thinks that the powder patterns are to a certain extent useful for identification of the mineral.

Chemical Composition.

On a closer study of glauconite it is hardly possible to avoid this reflection: It may be almost impossible to obtain for chemical analysis an absolutely pure material. We have to reckon here not only with inclusions of detritus grains, often mentioned in literature (as a matter of fact these inclusions hardly play any rôle in the material investigated by the author) but with the pigmentation in the peri-

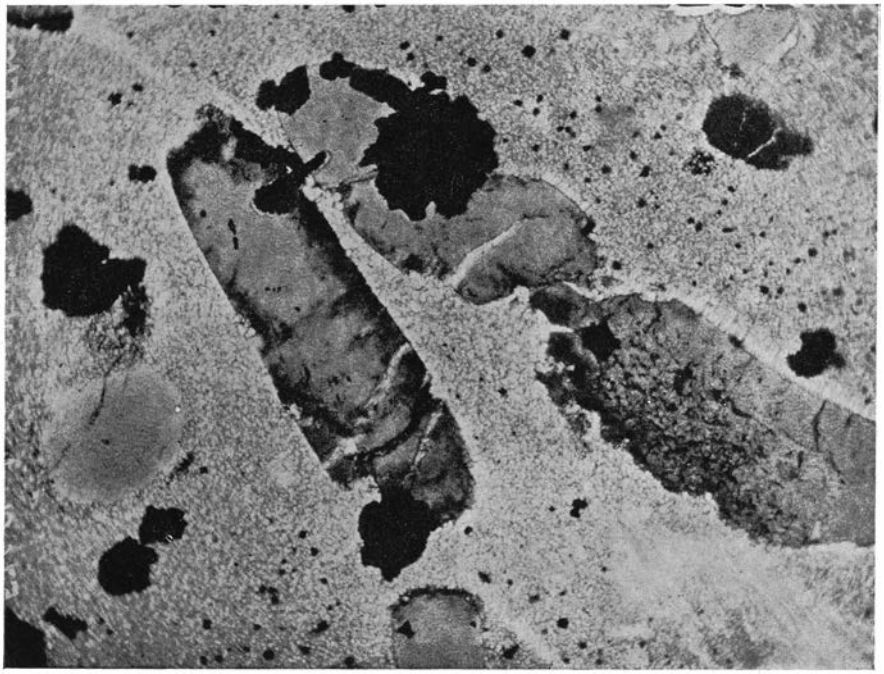

Fig. 71. Pigmented glauconite with pyrite. Ceratopyge limestone. Käpplunda, Vestergötland. (Pr. 2510. Pl. 576.) — 60 ×.

pheral part of the grains (fig. 71 and 72) which of course influences the results of the analysis, especially as the grains have sometimes been impregnated, superficially at least, with the substance forming the cement in the rock. It is further quite obvious that the cracks in the grains are filled with the cement and matrix of the rock in a manner that precludes its complete removal.

It is evident from the preceding that it does not suffice to make a careful choice of the material for the analysis. In order to estimate this it is also necessary to know, in what degree its result could have been influenced by impurities of some kind or other. Thus the high percentage of iron in the glauconite from Hulterstad ($Fe_2O_3 = 24.31\%$, see the analysis 49, p. 124) is explained by the fact that the grains of glauconite are not free from haematitic dust, which is also abundantly present in the glauconite-bearing limestone. The glauconite from Eriksdal (see analysis 53, p. 124) gives us an example of admixture of silica. The rock is a sandy marl, in which a silicification of shells and porous grains is sometimes noticeable. In the sample analysed the glauconite is present in abundance and part of the grains show a distinct, thin crust or impregnation zone of silica, developed as chalcedony. This is also the case to a certain degree in the glauconite of a Tertiary limestone from Ystad (see analysis 54, p. 124). The rock shows a strong silicification (formation of chalcedony), and part of the silica has

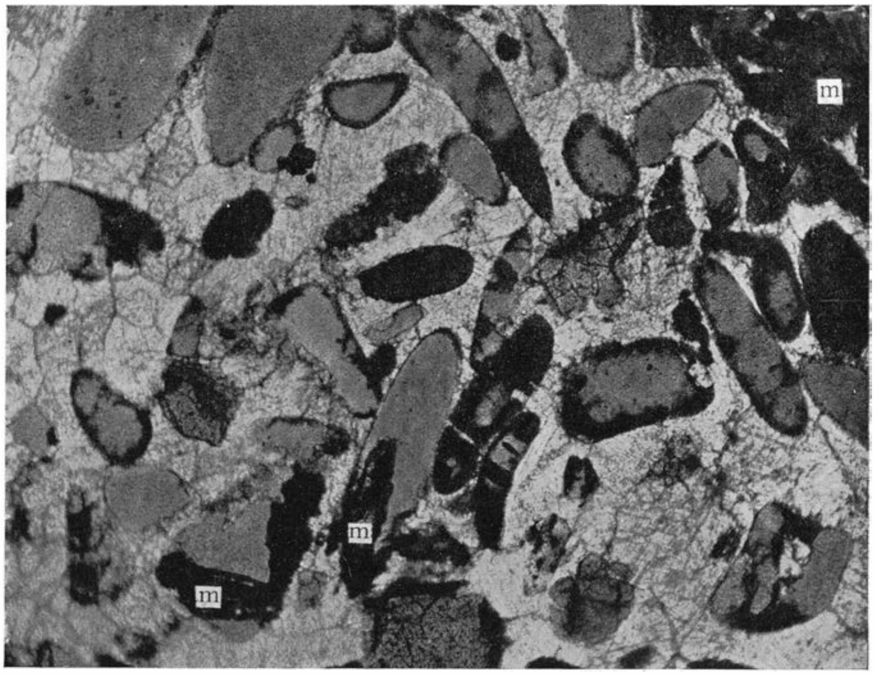

Fig. 72. Pigmented glauconite grains with marcasite (*m*). Ceratopyge limestone. Karlsfors, Vestergötland. (Pr. 2256. Pl. 560.) — 60 ×.

no doubt adhered to the grains selected for analysis. The sample also contains a considerably higher percentage of CaO than other Swedish glauconites, the cause of which is seen on making a microscopic examination of the rock. The glauconite occurs namely to a large extent as impregnation in shells and other fossil fragments of calcium carbonate. The impregnation has frequently been so complete that the result has become a grain resembling common glauconitic grains and containing a varying amount of calcite. It is more than probable that some grains of this type have been included in the sample for analysis and caused a higher percentage of lime than would have been obtained without them.

The examples given may suffice to illustrate the rôle impurities can play in an analysis of glauconite, even though the material for the analysis is chosen with care. In all the above related cases a sorting has been made by means of heavy liquids before the material was picked out with a pincette under a magnifying glass.

An examination of the older and the more recent analyses of glauconite, however, shows that the varying composition can not be simply ascribed to the impurities. The variations in the percentage of potash from less than 4% to more than 9% cannot be exclusively owing to a greater or lesser purity of the mineral. The variations in the percentage of Al_2O_3 from less than 2% to more than 20% are probably partly owing to impurities but no doubt also to differences in the composition of glauconite from different localities. A high percentage of alumina can be accompanied by a high percentage of silica (analysis 2, p. 122), and there is then a certain probability that, partly at least, it is caused by admixed clayey substance. In other cases the increased percentage of alumina is accompanied by a decrease in the percentage of silica in the glauconite (see analysis 24, p. 123), and in such cases it is no doubt impossible to explain the abnormal composition by supposing an admixture of clayey substance. An increase in the percentage of Al_2O_3 is often accompanied by a decrease in the percentage of Fe_2O_3 (cf. the analyses 18 and 19 with the analyses 26 and 27, p. 123) in such a manner that any doubt that the said components cannot replace each other in the glauconite as in so many other minerals is excluded. This is perhaps best seen on a comparison between an analysis of glauconite with normal composition and GLINKA's analysis of the glauconite from Kosolapowo (anal. 25).

There is reason to suppose that FeO, MgO, and CaO can replace each other in the glauconite within certain limits. It is, however, difficult to decide from the analysis to what extent the two last-mentioned components are included in the glauconite molecule, or how much of them is derived from impurities in the mineral. HAUSHOFER points out as early as 1866 (p. 601) that the percentage of lime and magnesia in the glauconites is to be regarded as a remainder of the parent rock, and in works of later date the same opinion is expressed, especially with regard to the percentage of lime (for inst. by SCHNEIDER 1927, 297).

It is evident from the preceding that the variations in the chemical composition of the glauconite are explicable to a certain degree. An examination of the analyses, however, also shows that it is impossible to find a formula exactly agreeing with all glauconites. The inference that the chemical composition of the glauconitic substance can vary within certain limits is inevitable.

In the adjoined tables the majority of the analyses of fossil and recent glauconites hitherto published is collected. Six new analyses of Swedish glauconites are added to them. The analyses are made at the Mineralogical Institute of Lund by SVEN PALMQVIST.

TABLE 1.

	1	2	3	4	5	6	7	8
SiO_2	47,46	56,62	55,17	51,80	50,85	46,90	51,15	49,12
Al_2O_3	1,53	12,54	8,12	8,67	8,92	4,06	7,61	7,09
Fe_2O_3	30,83	15,63	21,59	24,21	24,40	27,09	18,83	25,95
FeO	3,10	1,18	1,95	1,54	1,66	3,60	2,78	0,89
CaO	—	1,69	1,34	1,27	1,26	0,20	—	—
MgO	2,41	2,49	2,83	3,04	3,13	0,70	4,54	3,10
K_2O	7,76	2,52	3,36	3,86	4,21	6,16	7,80	7,02
N_2O	—	0,90	0,27	0,25	0,25	1,28	—	—
H_2O	7,00	6,84	5,76	5,68	5,55	9,25	7,56	7,12
	100,09	100,41	100,39	100,32	100,23	99,24	100,27	100,29

Analyses of glauconites. 1—8 recent glauconites, 9—54 fossil glauconites.

1. »Tuscarora» at Lat. 6°53'N., Long. 123°24'W at a depth of 317 m. COLLET et LEE 1906, 258.
2. »Challenger» at Lat. 34°13'S., Long. 151°38'E., 410 fathoms. MURRAY and RENARD 1891, 458 (Analysed by L. SIPÖCZ).
3. »Challenger» at Lat. 34°13'S., Long. 151°38'E., 410 fathoms. As nr 2.
4. » » Lat. 34°13'S., Long. 151°38'E., 410 » As nr 2.
5. » » Lat. 34°13'S., Long. 151°38'E., 410 » As nr 2.
6. »Gazelle» at Lat. 34°13,6'S., Long. 18°0,7'E., 217 m. (Agulhasbank). GÜMBEL 1887, 437.
7. »Pieter Faure», Lat. 34°38'S., Long. 8°33'E., 110 fathoms. (Agulhasbank). CASPARI 1909, 366.
8. »Albatross» at Lat. 6°53'N., Long. 81°42'W, 556 fathoms. (Pacific off Panama). CASPARI 1909, 366.

	9	10	11	12	13	14	15	16	17
SiO_2	50,62	49,10	50,80	48,90	49,43	50,20	47,60	49,50	43,60
Al_2O_3	3,80	7,05	6,70	6,40	7,07	1,50	4,20	3,20	5,10
Fe_2O_3	21,03	23,60	21,80	25,80	20,07	28,10	21,60	22,20	32,80
FeO	6,03	3,25	3,10	4,80	3,80	4,20	3,00	6,80	3,00
CaO	0,54	—	—	0,70	—	—	2,40	—	—
MgO	0,57	—	4,20	—	—	—	1,40	—	1,50
K_2O	7,14	5,75	3,10	5,18	5,77	5,90	4,60	8,00	5,60
H_2O	9,14	10,10	9,80	8,90	12,77	8,60	14,70	9,50	7,70
	98,87	98,85	99,50	100,68	98,91	98,50	101,90	99,20	99,30

9. Le Havre. Cenomanian. HAUSHOFER 1868, 360.
10. Bindlacher Berg, Bayreuth. Muschelkalk. HAUSHOFER 1866, 601. Med. 2 anal.
11. Sorg by Kronach. Jurassic. » » »
12. Ortenburg, Passau. Cretaceous. » » »
13. Roding. Cretaceous. » » » Med. 3 anal.
14. » » » » »
15. Benedictbeuern. Cretaceous. » » »
16. Kressenberg. Nummulitic limestone. » » »
17. » » » » » »

	18	19	20	21	22	23	24	25	26	27
SiO_2	48,95	49,75	49,53	51,00	47,88	42,31	41,01	42,35	47,59	52,96
Al_2O_3	7,66	7,82	5,84	9,93	14,94	16,51	22,19	21,43	17,99	12,76
Fe_2O_3	23,43	22,26	20,06	18,69	17,13	18,91	18,49	8,17	13,95	13,56
FeO	1,32	2,36	5,95	1,97	2,68	2,80	2,06	5,78	3,70	2,34
CaO	0,56	—	0,56	0,87	0,56	2,20	1,96	8,36	1,22	—
MgO	2,97	3,25	2,92	3,85	2,45	1,74	0,68	1,93	1,80	4,11
K_2O	9,54	9,01	9,31	7,66	8,04	7,49	5,74	7,16	7,21	8,69
Na_2O	0,98	0,30	0,46	0,35	0,43	0,42	0,38	0,42	0,42	0,77
$H_2O +$	4,93	5,16	4,91	5,83	5,90	7,48	7,88	4,45	5,27	4,91
$H_2O -$	(4,43)	(3,58)	(3,45)	(3,65)	(5,12)	(5,86)	(7,77)	(2,46)	(4,91)	(3,16)
	100,34	99,91	99,54	100,15	101,01	99,86	100,39	100,05	99,15	100,10

18. Padi, government Saratow — Sp. gr. 2,711 — GLINKA 1896, 29.
19. Nasonovo, » Smolensk — » 2,798 — » » »
20. Ural — » 2,790 — » » »
21. Trakterniroff, government Kiew — » 2,675 — » » »
22. Tschernofskoje, » Nijni-Novgorod, Jurassic — » 2,550 — » » »
23. Karowo, » Kaluga » — » 2,551 — » » »
24. » » » » — » 2,400 — » » »
25. Kosolapowo, » Nijni-Novgorod, » — » 2,749 — » » »
26. » » » » » — » 2,634 — » » »
27. Udrias, Estland. Ordovician. — » 2,867 — » » »

	28	29	30	31	32	33	34	35	36	37
SiO_2	50,42	49,09	40,00	52,86	51,56	49,67	49,23	50,58	49,47	48,12
Al_2O_3	4,79	15,21	13,00	7,08	6,62	9,29	7,11	6,72	5,59	9,60
Fe_2O_3	19,90	10,56	16,81	7,20	15,16	19,88	20,89	19,50	19,46	19,10
FeO	5,96	3,06	10,17	19,48	8,33	1,28	3,06	2,96	3,36	3,47
CaO	3,21	0,55	1,97	trace	0,62	1,95	trace	0,34	0,60	0,76
MgO	2,28	2,65	1,97	2,90	0,95	4,03	3,44	4,10	3,96	2,36
MnO	—	—	—	—	—	—	trace	—	—	—
K_2O	7,87	6,05	8,21	2,23	4,15	3,68	8,51	8,26	8,04	7,08
Na_2O	0,21	1,21	2,16	trace	1,84	3,00	0,11	0,04	0,16	0,22
$H_2O +$	5,28	11,64	6,19	8,43	10,32	7,88	4,88	7,76	8,54	10,06
$H_2O -$	—	—	—	—	—	—	1,83	—	—	—
CO_2	—	—	—	—	—	—	—	0,30	0,56	—
P_2O_5	—	—	—	—	—	—	—	0,27	1,06	—
	99,92	100,02	100,48	100,18	99,55	100,66	99,06	100,83	100,80	100,77

28. Antwerp. Pliocene (Diestien). CAYEUX 1916, 243 (after DEWALQUE).
29. Ashgrove, Scotland. Cretaceous. » » » (» HEDDLE).
30. Woodburn, Antrim, Ireland. » » » » (» HOSKINS).
31. French Creek, Pennsylvania. » » » (» KERR and SCHOENFIELD).
32. Hannover County, Virginia. CLARKE, 1924, 522 (CORSE and BASKERVILLE). 8,22 % of the silica is stated separately as quartz.
33. Kurische Nehrung. A. JOHNSEN: Zeitschr. Kryst. **50**, 90.
34. Big Goose Canyon, Wyoming. Sp. gr. 2,73. CLARKE: U. S. Geol. Surv., Bull. 419, 296 (STEIGER).
35. Sewell, New Jersey. MANSFIELD 1922, 128. Magnetically separated.
36. Elmwood Road, N. J. » » » » »
37. Lewes, Sussex, England. HALLIMOND 1922, 330. (RADLEY). Purified by washing and screening. (Ac. to SCHNEIDER 1926, 299.)

	38	39	40	41	42	43	44	45	46	47	48
SiO_2	49,0	48,5	49,2	33,1	49,4	47,6	49,42	51,24	49,76	51,35	52,74
Al_2O_3	9,2	9,0	10,7	13,57	10,2	9,9	10,23	12,22	8,18	9,47	12,29
Fe_2O_3	19,5	20,0	16,2	11,5	18,0	21,9	16,01	13,44	16,00	16,37	9,35
FeO	3,3	3,1	3,1	2,9	3,1	1,5	3,00	3,06	3,77	4,75	6,30
CaO	0,5	0,4	2,4	12,3	0,6	0,8	0,31	0,10	0,41	0,63	0,55
MgO	3,6	3,7	4,0	2,7	3,5	3,7	3,78	3,93	3,97	3,17	4,05
K_2O	6,3	6,1	6,2	5,1	5,1	5,3	7,91	7,50	7,57	7,34	7,97
Na_2O	0,9	1,5	1,2	1,5	1,4	1,4	0,26	0,31	0,52	1,22	0,09
H_2O	7,6	7,3	6,4	7,0	8,3	7,7	8,08	8,20	9,82	4,85	5,93
P_2O_5	—	—	—	9,73	—	—	—	—	—	0,35	—
Fl_2	—	—	—	—	—	—	—	—	—	—	0,13
	99,9	99,6	99,4	99,4	99,6	99,8	99,00	100,00	100,00	99,50	99,40

38. Woodstown, New Jersey. Cretaceous. SCHNEIDER 1927, 296. (TH. B. BRIGHTON). Separated magnetically, tested for purity under a microscope.
39. Norwalk, Wis. Cambrian. SCHNEIDER 1927, 296. (As nr 38.)
40. Folkstone, England. Cretaceous. SCHNEIDER 1927, 296. (As nr 38.)
41. New Braunfels, Texas. Eocen. » » » »
42. Norwalk, Wis. Upper Cambrian. » » » »
43. San Pedro, Calif. Pleistocene. » » » »
44. Swir River, Russia. KUPFFER: Jahresb. Chemie, 1870, 1307. (Ac. t. MANSFIELD 1922, 128.)
45. Ontica, » » » » » » » » » »
46. Grodno Valley, » » » » » » » » » »
47. Eriksöre, Öland, Sweden. Lower Ordovician. Sp. gr. 2,82. SAHLBOM 1916, 212.
48. Tosterup, Scania. Senonian. » 2,73. » » »

	49	50	51	52	53	54
SiO_2	47,84	51,53	49,13	48,99	53,14	51,30
Al_2O_3	7,16	17,00	9,96	10,91	10,25	5,15
Fe_2O_3	24,31	6,32	16,67	17,21	17,84	16,02
FeO	0,33	1,68	1,29	0,55	0,32	3,99
CaO	0,82	0,53	0,95	1,23	0,19	2,30
MgO	2,80	0,99	3,01	3,95	trace	1,74
K_2O	9,23	7,98	8,87	8,41	7,16	8,34
Na_2O	0,50	0,36	0,49	0,48	0,34	—
$H_2O +$	3,85	7,09	5,03	4,70	5,50	5,32
$H_2O -$	4,11	6,13	4,34	3,69	3,74	4,86
	100,95	99,61	99,74	100,12	98,48	99,02
Sp. gr.	2,863		2,825	2,781	2,855	

49. Hulterstad, Öland, Sweden. Lower Ordovician. Sp. gr. 2,863. (SV. PALMQVIST.)
50. Storberg, Östergötland, » » » »
51. Berg, » » » » Sp. gr. 2,825. »
52. Boda, Dalecarlia, » » » » 2,781. »
53. Eriksdal, Scania, » Senonian. » 2,855. »
54. Ystad, » » Tertiary. »

Many attempts have been made by different investigators to find a formula for the glauconite in accordance with the analyses. The author considers that they have been relatively successful, as successful as they practically could be. He hardly thinks it possible to state in detail in a formula all the variations in which the mineral can occur. Such a formula would, at any rate, be of small value. Though the one calculated by Ross (see below) no doubt agrees in many cases with the results of the analysis, as in certain cases those of HALLIMOND and SCHNEIDER also do, the author nevertheless prefers a generalized form of the simple formula composed by CLARKE. The reason for this will be stated in the following but a short summary of different attempts to calculate the formula of the glauconite will first be given.

HAUSHOFER (1866) says that all glauconites are probably of the same kind in spite of all the variations in their composition. The formula

$$R_2O_3 . 2\,SiO_3 + RO . SiO_3 + 3\,HO$$

fits in with several but not with all of them.

CLARKE writes (1924, 521 [1]): »According to the best analyses, glauconite probably has, when pure, the composition represented by the formula

$$\overset{\text{III}}{Fe}KSi_2O_6 . aq.$$

in which some iron is replaced by aluminium, and other bases partly replace K. This formulation is not final; neither does it suggest any relationship between glauconite and the micas. It rests upon Glinka's analyses of Russian glauconite, in which the material was freed from impurities by means of heavy solutions. The water in the formula is probably for the most part »zeolitic» and not constitutional as in the case of analcite, a silicate of similar chemical type.»

CASPARI'S (1910, 367) opinion on the composition of the glauconite is the same as CLARKE'S. He writes: »It will be observed that the composition of glauconite is subject to small variations ..., the general composition of glauconite may now be considered to be firmly established. If we regard Al_2O_3 as replacing Fe_2O_3, and CaO, MgO, and FeO as replacing K_2O, the formula

$$KFeSi_2O_6 . H_2O$$

agrees tolerably well with these analyses.»

Concerning the percentage of water and with regard to CLARKE'S opinion on it CASPARI writes (ibid. p. 367, note): »As a matter of fact, glauconite can take up several molecules of »zeolitic» water, but the one molecule which persists in the sharply dried mineral would rather seem to be water of constitution»:

HALLIMOND proposed (1922) the following formula:

$$R_2O . 4(RO, R_2O_3) . 10\,SiO_2 . nH_2O.$$

In a critical examination of SCHNEIDER'S formula (see below) he writes a few years afterwards (1928, 590): »I would suggest that glauconite is derived from mica by

[1] Already in 1903 CLARKE proposed the formula mentioned here.

the addition of an acid clay molecule, thus $K_2O . 3Al_2O_3 . 6SiO_2$ aq + Al_2O_3 . . $4SiO_2$ aq = $K_2O . 4Al_2O_3 . 10SiO_2$ aq. This will account for the replacement R_2O_3/RO, the peculiar hydration and the structural similarity, without departing from the empirical formula required by the chemical composition.»

NIGGLI and FAESY (1922, 434) classify recent analyses of glauconite and write in this connection: »Die Analysen umfassen verschiedene Stadien dieser Umbildung und sind wohl selten an reinem Material ausgeführt worden. Immerhin scheint den Referenten den Tendenz sichtbar zu sein, eine Verbindung vom Charakter

$$8\,SiO_2 . 2\,R_2O_3 . RO . R_2O . 4\,H_2O$$

oder wenn $\overset{\mathrm{I}}{R}$ und $\overset{\mathrm{II}}{R}$ als substituierbar angenommen werden, von der Zusammensetzung:

$$4SiO_2 . (Fe, Al)_2O_3 . (Fe, Mg, K_2, Na_2, Ca)\,O . 2H_2O$$

zu bilden. Die Formel liese sich in Analogie zur Chlorit-, Talk- und Kaolingruppe etwa schreiben als:

$$\left[SiO_6 . 3SiO_2\right] \begin{matrix} (Fe, Al)_2 . 2H_2O \\ (K_2, Fe, Mg, Na_2, Ca). \end{matrix}$$

Bekanntlich hat FR. W. CLARKE ... eine Formulierung vorgeslagen die der obigen entspricht.»

SCHNEIDER (1927, 302) makes the following summary of his investigation of the glauconite's composition: »The composition and variability of glauconite are more accurately expressed by the formula

$$(K, Na)\,(Fe, Mg)\,(Fe, Al)_3Si_6\,O_{18} . 3H_2O$$

than by the formula ... proposed by Clarke ... or by the formula ... proposed by Hallimond. ... The variability indicated by the formula (SCHNEIDER's) is in harmony with either the atom for atom replacement theory or valence control theory of isomorphism.»

ROSS (1927) has distinguished between water of constitution and of crystallization in his formula and given good reasons for doing so. He writes further »that the chemical composition of glauconite can be completely explained if it is considered to be an isomorphous mixture of two end members with the formulas

(A) $2H_2O . K_2O . 2(MgO, FeO) . 2(Fe_2O_3, Al_2O_3) . 10SiO_2 + 3H_2O$

and

(B) $2H_2O . K_2O . (MgO, FeO) . 3(Fe_2O_3, Al_2O_3) . 10SiO_2 + 3H_2O.$

The formulas may also be written: —

$$A = 4H . 2K . 2Mg . (\overset{\mathrm{III}}{Fe}O) . 3\overset{\mathrm{III}}{Fe} . 10[SiO_3] + 3H_2O$$

$$B = 4H . 2K . Mg . 3(\overset{\mathrm{III}}{Fe}O) . 3\overset{\mathrm{III}}{Fe} . 10[SiO_3] + 3H_2O.»$$

It is certainly not impossible to find examples of the analyses of glauconites agreeing with one or other of the above quoted formulas. On calculating according to the said formulas to which chemical composition they correspond, they are found, as is seen in table 2, to be fairly alike. The variations shown in them are no greater than in the analyses. Under such circumstances the simplest formula, i. e. CLARKE's, is of course preferable. This formula — $KFeSi_2O_6 . aq$ — can be more generally formulated: $(R_2O, RO) R_2O_3 . 4SiO_2 . aq$. The new analyses on

TABLE 2.

	I	II	III	IV	V	VI	VII	VIII
SiO_2	50,6 [1]	51,9	54,6	52,6	52,9	48,9	50,9	47,4
Al_2O_3	4,5	4,4	3,7	4,5	3,6	5,0	4,3	1,5
Fe_2O_3	28,3	27,5	23,1	27,9	22,4	31,1	26,75	30,8
FeO	4,0	3,9	6,5	5,2	6,3	2,9	4,6	3,1
MgO	2,2	2,2	3,6	2,9	3,5	1,6	2,55	2,4
K_2O	10,4	10,1	8,5	6,9	8,1	7,6	7,85	7,8
H_2O	—	—	—	—	3,2	2,9	3,05	7,0
	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0

I—VI. The chemical composition of glauconite is calculated in accordance with the formulas stated for the mineral by different authors. Where the ratio between the bases is not stated this has been calculated according to the norm:

$$K_2O : FeO : MgO = 2:1:1, \quad Fe_2O_3 : Al_2O_3 = 4:1.$$

The calculation is made from:

I. HAUSHOFER: $RO . R_2O_3 \; 3SiO_3 + H_2O$
II. CLARKE: $K . Fe . 2SiO_3 . aq \; (= K_2O . Fe_2O_3 . 4SiO_2 . aq)$
III. HALLIMOND: $R_2O . 4(RO . R_2O_3) . 10SiO_2 . nH_2O \; (RO : R_2O_3 = 1:1)$
IV. SCHNEIDER: $K . Mg . Fe_3 . 6SiO_3 . 3H_2O \; (= K_2O . 2MgO . 3Fe_2O_3 . 12 SiO_2 + 3H_2O)$
V. ROSS I: $2H_2O . K_2O . 2MgO . 2Fe_2O_3 . 10SiO_2 + 3H_2O$
VI. ROSS II: $2H_2O . K_2O . MgO . 3Fe_2O_3 . 10SiO_2 + 3H_2O$
VII. ROSS I + II in the ratio 1 : 1.

In comparison analysis of glauconite is stated from:

VII. The Tuscarora expedition in 1873 (acc. to COLLET & LEE).

Swedish glauconites (see table 1, p. 124, nr 49—54) do not show that part of the glauconite's water must be regarded as water of constitution. It is not always stated in the older analyses how the estimations of the water were made but probably the given amount is partly water of constitution (cf. ROSS 1927). In the recent Swedish analyses the ratio of the molecular quantities $SiO_2 : H_2O_{+110°} = 8:3$, and on that account the author considers that CLARKE's general formula may be written as follows:

$$2(R_2O, RO) . 2R_2O_3 . 8SiO_2 . 3H_2O.$$

[1] SiO_3.

In the adjoning table 3 the chemical composition has been calculated according to this formula under the supposition that $K_2O : RO = 1 : 1$, and that the ratio $MgO : FeO = 4 : 1$ and $Al_2O_3 : Fe_2O_3 = 1 : 1$. It is unlikely that exactly these proportions would be present in any sample, and the agreement between the calculated values and those found on analysing the glauconite from Berg is as great as is practically possible.

TABLE 3.

	I	II
SiO_2	51,37	51,49
Al_2O_2	10,88	10,44
Fe_2O_3	17,01	17,48
FeO	1,53	1,35
CaO	—	1,00
MgO	3,43	3,16
K_2O	10,03	9,30
Na_2O	—	0,51
$H_2O + 110°$ C	5,75	5,27
	100,00	100,00

I. The chemical composition calculated in accordance with the formula: $3H_2O . K_2O . (MgO, FeO) . Fe_2O_3 . Al_2O_3 . 8SiO_2$, with the ratio $MgO : FeO = 4 : 1$.
II. Analysis of glauconite from Berg, Östergötland (cf. Table 1, nr 51).

As a rule glauconite is counted among the mica group. Tschermak-Becke (1921, 647) say that the chemical composition of the mineral resembles that of the meroxene. Lacroix (1893, 407) a. o. have called attention to the optic agreement between glauconite and mica, and Ross says (1926, 8): »Glauconite is a finely micaceous mineral». Glinka (1896, 128) considers that glauconite and seladonite are identical in composition and properties.

The author's investigations of the physical qualities of the mineral also indicate a relationship to the micaceous minerals. Chemically, however, there is a distinct difference, shown in the glauconite's higher percentage of silica. The oxygen ratio is 1 : 1 in mica and 11 : 16 or 3 : 4 in glauconite.

Summary of the Opinions of Different Investigators on the Formation of Glauconite.

A great number of investigators have been interested in the glauconite problem and many have felt themselves called upon to publish their reflections on the question. Instead of repeating them all here the author will attempt to give a summary of the more significant works produced in order to explain the formation of glauconite.

The first conclusion to which research on glauconite led was that *the glauconite is formed in the interior of shells* from certain organisms, especially in foraminiferal shells. EHRENBERG's works (1854 and 1855) contain reports on all the different species, in which he has found glauconite. After that the opinion prevailed for a long time that the glauconite was only formed in the interior of shells. Certainly, BAILEY points out as early as 1856 that the form of several glauconite grains is such that no resemblance between them and the shells in which glauconite is formed can be traced, but he does not venture to think that the formation has taken place independent of the shells. MURRAY and RENARD (1891) explain the frequent anomaly of the grains as a result of their growth after they have split the shells, in which they were first formed. Among the investigators who adhered later to the opinion that the primary occurrence of the glauconite was localized to the interior of the shells may be mentioned FISCHER (1901), THOULET (1904), and COLLET and LEE (1906).

As mentioned above BAILEY (1856) was in some doubt as to the opinion on the formation of glauconite prevalent after the investigations of EHRENBERG. REUSS (1860), however, was the first who positively denied it and declared that *glauconite is formed independent of shells,* in his opinion *as concretions.*[1]

GÜMBEL (1886) also speaks in favour of a glauconitic formation free from formative organisms. He supposes that *the deposition of glauconite begins on the surface of gas-bubbles formed in the mud* rich in organic substance.

New proofs of a glauconite formation independent of formative shells were given by GLINKA (1896) and CAYEUX (1897). The latter has shown in his excellent and convincing descriptions how varying the occurrence of the glauconite can be already from its formation. It might also be said that after the publishing of

[1] By means of his microscopic investigations of a couple of glauconitic rocks ANGER (1875, 157) also arrives at the opinion that the grains of glauconite were not formed in shells of foraminifera.

Cayeux's investigations no one, with the exception of Collet and Lee, has made independent investigations of glauconite, leading to a result opposed to the opinion of Cayeux.

Among other circumstances of importance for the formation of glauconite *the presence of terrigenous material and organic substance* was proved already from the beginning of the glauconite research. On the whole it has been generally understood that the terrigenous minerals have yielded material for the formation of glauconite, and that the organic mud has created certain chemical conditions for the process of formation. Opinions have differed, however, when it has been a question of stating the rôle these constituents played otherwise in the formation of glauconite. It may be said that the different opinions can be referred to two groups or schools: an older one proceeding from Murray and Renard and their investigation of the bottom samples of the *Challenger* expedition, and another one proceeding from (Murray and) Philippi and the investigations of the bottom samples from the *Valdivia* expedition (the German deep-sea expedition) and the *Gauss* expedition (the German antarctic expedition). Besides these two schools more independent investigators exist, for inst. Glinka, Cayeux, Goldman, and Mansfield, all of whom have essentially investigated fossil glauconites. In the following a short resumé will be given on the conclusions, to which their investigations led them in the above mentioned respect.

Murray and Renard give the following summary of their investigations concerning the formation of glauconite (M. and R. 1891, 387): »It appears certain that glauconite is principally developed in the interior of foraminiferous shells and other calcareous structures and that all transitions can be observed from chambers filled with a yellowish brown mass to grains that have almost completely lost the impress of the organisms in which they were formed.

— — — little probable, that there are any minute grains of glauconite formed in free state in the mud.

— — — some grains, which may be regarded as glauconite, appear to be highly altered fragments of ancient rocks, or coatings of this mineral on these rock fragments. It appears that the shells are broken by the swelling out of the growth of the glauconite, and that subsequently the isolated cast becomes the centre upon which new additions of the same substance take place, the grain enlarging and becoming rounded in a more or less irregular manner.

The initial stage of the formation of glauconite in these shells are, in all probability, due to the action of organic matters.

— — — the organic matter inclosed in the shell, and in the mud itself, transforms the iron in the mud into sulphide, which may be oxidised into hydrate, sulphur being at the same time liberated, this sulphur would become oxidised into sulphuric acid, which would decompose the fine clay, setting free colloid silica, alumina being removed in solution; thus we have colloid silica and hydrated oxide of iron in a condition most suitable for their combination.

To explain the presence of potash in this mineral we must remember that — — —

— — — there is always a tendency for potash to accumulate in the hydrated silica

— — — this potash must have been derived from the sea-water

— — — (there is a) relative abundance of potash in the deposits where glauconite is forming.»

The description of the formation of glauconite in the works by FISCHER 1901 (p. 54 seq.), THOULET 1904 (p. 162), and COLLET and LEE 1906 is strongly influenced by MURRAY-RENARD. While the two first-mentioned are only reviewing works, COLLET and LEE give, in their treatise, an account of their own valuable investigations as well, principally on material from the *Challenger* expedition.

Though COLLET and LEE mainly agree with MURRAY and RENARD in their explanation of the formation of glauconite, they give nevertheless a new interpretation of the chemical process itself. Thus they consider that the colloidal primary substance has not been free silica but instead of it clayey mud. They distinguish three different phases in the formation of glauconite, all of them in their opinion distinctly noticeable in the investigated material:

1) Silicate of aluminium (clayey substance) forms a gray filling in the interior of foraminiferous a. o. shells.

2) In the silicate of aluminium Al_2O_3 is exchanged for Fe_2O_3 and it is then successively transformed into brown ferric silicate. This contains no potash.

3) The ferric silicate adsorbs potash (and water?) and is transformed into green glauconite.

It may be appropriate to make a few statements here as to how the above mentioned interpretation of the glauconite formation was received by other investigators.

The general opinion has been that potash was adsorbed directly from potassic salts dissolved in sea water, even though, as will be shown, the occurrence has sometimes been considered to be caused by potash-yielding mineral present in the deposit.

More seldom has the clayey matter been regarded as the ground material for the formation of glauconite (GOLDMAN 1916, MANSFIELD 1922). MURRAY and PHILIPPI consider this improbable, as glauconite is absent in many places, where otherwise every condition for its formation may have existed, and where clayey matter has also been deposited.

COLLET and LEE have avoided counting with sulphuric acid in their theory on the formation of glauconite, and in this way they have escaped the weakest point in MURRAY-RENARD's theory. Attention has been called from different quarters to the absurdity that the relatively resistant clayey matter should have been decomposed by sulphuric acid formed in the above-mentioned manner (p. 130), while the calcareous mud and the foraminiferal shells remained unaffected.

The formation of sulphuric acid presumed by MURRAY-RENARD required a strong oxidation, i. e. a highly oxygenous water. With the rejection of the hypothesis of the sulphuric acid there was no need of presuming oxidation, which must always have appeared unnatural in an environment strongly characterized by organic material in a state of decomposition. As will be seen, however, the theory of highly oxygenous water reappears in the following also, specially in the school of PHILIPPI.

When PHILIPPI stayed with MURRAY at Edinburgh in 1900 in order to study the methods for investigation of bottom samples from the oceanic expeditions, MURRAY had already been entrusted with the bottom samples of the *Valdivia* expedition. Probably he had already then modified his earlier opinion on the formation of glauconite, and it is possible that the description of the glauconite formation, published in 1908, by MURRAY and PHILIPPI in common, would have been formulated in a similar manner, had it been carried out by MURRAY alone. But it does not seem improbable that the new points of view originate principally from PHILIPPI, who as a partaker in the *Gauss* expedition 1901—1903 as well as later on has had ample opportunity to form his own opinion of different sedimentation problems. In his account of the bottom samples of the *Gauss* expedition PHILIPPI (1910) has further declared his attitude towards certain facts concerning the problem of the glauconite (for inst. the percentage of oxygen in the cold sea currents), and this agrees in all essential conditions with that published two years previously by MURRAY and PHILIPPI.

After the death of PHILIPPI in 1910 his ideas have been repeated by colleagues and disciples at first or second hand. Thus ANDRÉE has related in a number of papers (see list of works of reference) his opinion of int. al. the formation of glauconite, possibly in a somewhat distincter form. HUMMEL also, to whom we shall return later, may be regarded as a mouthpiece for PHILIPPI'S opinion, even though his ideas are considerably advanced.

Where, then, is the main point in PHILIPPI'S opinion of the glauconite formation? We may say that PHILIPPI has partly called attention to *the connection between the cold oceanic currents and the occurrence of the glauconite* and partly presumed a *direct connection between the formation of glauconite and a submarine weathering* of terrigenous material.

MURRAY and PHILIPPI (1908, 177) write concerning the submarine weathering's significance for the formation of glauconite: — »Es scheint, dass Glaukonit sich nicht aus schon vorhandenem Tone bildet, sondern mit Vorliebe bei der Zersetzung ursprünglich frischer Kali-Tonerdesilikate in statu nascendi des Tones entsteht», and further (p. 176): — »Der Kali-Gehalt des fertigen Glaukonits und seine Entstehung aus einem Tonerdesilikat lassen vermuten, dass die Mineralien, die seine Bildung begünstigen, Kali-Tonerdesilikate sind». *As probable parent minerals of the glauconite are mentioned orthoclase and potassic mica*, both abundantly present in the continental rocks. That they, like other potassic minerals, are only sparingly present in the recent igneous rocks is a fact regarded by MURRAY and PHILIPPI as an explanation, why glauconite is hardly ever found around the volcanic, oceanic islands.[1] The presence of the potassic silicates of alumina in the beds of glauconite

[1] Attempts to explain the glauconite as being formed by weathering of igneous products have nevertheless been made. Thus GOOCH (1876, 140) writes: »In der (Lava-) Breccie von

and their significance as a direct source of the content of potash in the glauconite have been further discussed by HUMMEL (see p. 137). That these potassic silicates have constituted the ground material for the formation of glauconite has not been presumed by other investigators, who have considered the formation of glauconite a result of submarine weathering. Both GLINKA (1896) and HUMMEL (1922) state iron aluminium silicates to be parent minerals of glauconite (see p. 135 and 137).

The map of the distribution of the recent glauconite, published in 1906 by COLLET and LEE, reveals, as shown by HUMMEL, that glauconite is specially common on the continental shores, outside which cold currents have been shown to exist. MURRAY and PHILIPPI write (1908, 176) that *glauconite occurs preferably* (together with phosphorite) *where cold and warm currents meet,* and in addition to this that *cold, highly oxygenous currents seem to favour the formation of glauconite* (»kalte, sauerstoffreiche Strömungen scheinen die Glaukonitbildung zu begünstigen»).

MURRAY and PHILIPPI have considered it accurate to explain the fact that glauconite is a ferric silicate by the supposition that *a strong oxidation has taken place on the formation of glauconite.* They are, however, not blind to the circumstance that the formation of glauconite has occurred in places where an abundance of organic material has been accumulated, i. e. in places where a reducing environment might be expected. They declare that the possibility of oxidation has been created by a continually fresh supply of water by means of strong currents (»reissende Meeresströmungen»).

It should be noticed that MURRAY and PHILIPPI know, that the water in which the glauconite is formed is relatively cold, but they only suppose it is highly oxygenous; this supposition was unavoidable, for they postulated that an oxidation of the iron must have taken place on the formation of the glauconite. Had they been able to keep away from this compulsory idea, the difficulties that arise on trying to explain the high percentage of oxygen in the water could have been avoided. This is by no means satisfactorily explained by the strong currents and the low temperature in the water (cf. p. 139). PHILIPPI must also have been aware of this when he resorted to such an extraordinary *source of the oxygen in the deep sea water* as *the Pleistocene ice-cap.* He writes (1910, 610): »Wahrscheinlich gehören demnach die unteren Schichten (des Tiefenwassers) noch der quartären Eiszeit an, in der Zone, in welcher das Oberflächenwasser zur Tiefe hinabstieg,

Indefatigable sehen wir Glaukonit oder eine ähnliche Substanz thatsächlich in dem Processe der Bildung und so scheint es, dass Glaukonit und ähnliche Silikate im Allgemeinen, ob sie nun in vulkanischen Gesteinen oder in sedimentären Ablagerungen vorkommen, die Zersetzungsprodukte der vulkanischen Bestandteile seien. In beiden Fällen ist die Einwirkung atmosphärischen Wassers, welches Kohlensäure im aufgelösten Zustande mit sich führt, vollkommen hinreichend, diese Veränderung zu veranlassen; Augit, Olivin, Feldspath etc. würden unter Abgabe von Kieselsäure in Form des Chalcedon, der so oft Glaukonit begleitet, zersetzt werden, Kalk und Magnesia verlieren und Kali behalten, so wie thonartige Erden Kali behalten und Kalk und Magnesia unter ähnlichen Umständen verlieren». GOOCH bases his opinion of the glauconite formation on investigations of igneous rocks from the Galapagos island. The investigations were carried out in TSCHERMAK's laboratory under his guidance. No chemical analyses, however, appear to have completed the microscopical examination, and consequently it cannot be considered certain that the said green substance is actually glauconite.

sehr viel weiter von den Polen entfernt lag als heutigen Tages. Das kalte Wasser legte also bis zu einem bestimmten Punkte der gemässigten oder tropischen Zone einen viel kürzeren Weg zurück als heute, büsste also auch dementsprechend viel weniger von seiner niedrigen, polaren Temperatur und von seinem hohen Sauerstoffgehalt ein.»

Attention should be called to the fact that the above quoted oxygen theory did not arise in immediate connection with a discussion of the glauconite's formation but in order to explain another circumstance, viz. that low temperature and scant deposition of limestone are always found together. PHILIPPI (1910, 609) supposes that the limestone-dissolving action of the cold deep-water is owing to its power of oxidation. It may be difficult to follow his chain of reasoning here. Most likely the presence of oxygen will have favoured a deposition of limestone, while the presence of free carbon dioxide ought to have had a checking or directly dissolving influence on already deposited limestone. Obviously PHILIPPI was fully aware of this when he declared (p. 593) that a highly oxygenous water oxidizes the organic matter to carbon dioxide, which in its turn has a dissolving influence on the calcium carbonate. Elsewhere (1910, 592), however, he calls attention to the fact that only a small amount of organic matter occurs where the dissolution of limestone is strongest, i. e. in the regions where the red deep-sea clay is deposited. A supply of highly oxygenous water in these sedimentary regions would not involve a strong evolution of carbon dioxide with accompanying dissolution of limestone.

PHILIPPI thus considered it probable that the cold deep-sea water is highly oxygenous; he attempted to explain the source of the oxygen, called attention to certain facts speaking for and to others speaking against the supposition that a higher percentage of oxygen accompanies the low temperature in the deep-water, and he admitted that until then no certain evidence for the supposition existed (1910, 609), and added: »Wir sind über den Sauerstoffgehalt des Tiefenwassers noch sehr wenig unterrichtet». These statements should be compared with those made for inst. by HUMMEL (see p. 139).

It may be appropriate to mention, in connection with the account of PHILIPPI's oxygen theory, that organic matter can decompose while the formation of carbon dioxide is taking place, the presence of free oxygen not being necessary. The progress varies with the starting material, local conditions, bacterial influence, etc., and the final result can also be different, mineral oils, bitumen, or other carbonic combinations. As typical of such a transformation we shall only mention the transformation of cellulose under formation of marsh gas (methane) and carbon dioxide: —

$$C_6H_{10}O_5 + H_2O = 3\,CH_4 + 3\,CO_2$$

Consequently there is no reason to suppose that the bituminization in the bottom mud and the formation of for inst. the alum shales have taken place under an ample supply of oxygen, even if by this means the oxidation as well as the evolution of carbon dioxide would unquestionably have become stronger.

In some measure GLINKA occupies an isolated position in the glauconite research. His studies were exclusively performed on fossil material, he made a number of good analyses of this, examined the chemical and physical character of the mineral, and finally also gave his opinion on its formation. This opinion he (1896, 127) sums up as follows: 1) Glauconite is not a precipitated mineral, it only occurs as detritus; 2) *glauconite is formed by metamorphosis of augites* and perhaps of hornblendes also.[1] Thus GLINKA is perfectly sure of a formation of glauconite by means of submarine weathering of ferric aluminium silicates, especially augites. He even believes it is possible to trace the crystal form of the augite in several of the glauconitic grains. The glauconite's content of potash he considers to be added to the mineral by adsorption. In order to examine the possibility of this he made an interesting experiment (p. 119): — Brown (potash-poor) grains of glauconite were treated with a solution of potassium carbonate. After this they became intensely green and the content of potash in them increased. The reaction was stronger with an increasing content of calcium in the glauconite. GLINKA considered it very probable that a chemical fixation of the potash had taken place, and that the calcium of the glauconite had then been transformed into normal Ca-carbonate, while its magnesium had remained in the silicate on account of its closer relationship to silica than to carbon dioxide.

In his extensive investigations of glauconite CAYEUX has, like GLINKA, wholly restricted himself to fossil material. CAYEUX's account (1897) of the development of glauconite is the best published. On the very formation of glauconite, on the contrary, he has but little to say. He mentions that terrigenous material is present in the glauconitic beds, especially orthoclase and light mica which, owing to its content of potash, has been of importance for the formation of glauconite. He shows that the grains of glauconite have sometimes become enlarged by secondary growth, and he believes he has found that minerals (calcite crystals) as well as organic remains (calcareous shells and silicic skeletons) can be epigenetically transformed into glauconite. CAYEUX considers *the formation of glauconite most likely to be a diagenetic process.* He writes (1897, 179): — »... je croix, que des grains de glauconie ont pris naissance ou ont continué à s'accroître, non sur le fond de la mer, mais lorsque tous les éléments du sédiment étaient en place, comme ils le sont dans le dépôt consolidé.»

CAYEUX's studies led him to the conclusions that *glauconite can also be formed where organic matter is absent.* He sums up his opinion on this as follows (1897, 184): »Il se peut que la matière organique soit le plus souvent la condition primordiale de toute production de glauconie, mais qu'il est bien certain que dans plusieurs cas, cette substance n'a point présidé à la genèse de ce minéral».

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[1] A similar opinion has been published by GOOCH (1876, 139). He considers the formation of glauconite to be »eine Zersetzung in situ von vorher existierenden Mineralien und nicht eine Ablagerung einer Auflösung». Augite int. al. is mentioned as parent mineral. — Cf. note p. 132.

Even if we do not agree in every respect with the opinions expressed by CAYEUX, we must admire his magnificent work, and the author for his part desires especially to emphasize the importance of the large material of direct observations, with which CAYEUX has enriched science. He also wishes to endorse CAYEUX's opinion that the study of fossil sediments should be pursued side by side with the oceanographic investigations, because, as CAYEUX says (p. 183), »la considération des sédiments océaniques n'eclair qu'imparfaitement l'historie des dépôts anciens».

The points of view on the formation of glauconite presented by HUMMEL in 1922 are worthy of notice, even though they are not based on new and direct studies of the mineral. Though HUMMEL does not distinguish himself as much by originality in his chain of reasoning as by audacity in his conclusions, he can still have a stimulating effect on research. Nevertheless the author must reject his theory, as it is inconsistent with the observations made on the Swedish glauconite material. Even without this direct observation material the author would have criticized HUMMEL's general theory of the glauconite formation, for it is based, as will be shown in the following, on inferences drawn from partly wrong premisses.

With regard to the terrigenous starting material and the agency of the organic matter on the formation of glauconite HUMMEL agrees with the opinion of other investigators. He also embraces the opinion that the formation takes place in colloidal substances, and that a gel-like ferric silicate is first formed, which afterwards adsorbs potash from the sea water. In connection with the review of the statements on the occurrence of the recent glauconite he points out that its formation is restricted to regions close to the shore with relatively cold water (cold currents). So far HUMMEL's view practically agrees with earlier presented opinions as well as with the opinions, at which the author has arrived by means of his studies.

On passing on to the points of view more or less specific for HUMMEL, we find that they affect three different phases in the formation of glauconite: — 1) the origin of the potash-free iron silicate; 2) the oxidation of the iron; and 3) the reduction of part of the iron. Instead of these we may mention three phases, which according to HUMMEL characterize them, viz.: —

1. the halmyrolysis or the submarine decomposition;
2. the oxidation environment or the highly oxygenous water;
3. inclusions of organic matter in the glauconite.

Undeniably a decomposition of minerals and rocks can take place on the sea bottom also, and, as we have seen, several investigators have counted with this. We have every reason to feel grateful to HUMMEL for providing us with a special name for this process, halmyrolysis, and for making it the subject of a close study, but in this case as in others it holds good that a thing is easily overestimated when it becomes the topic of the day and is given a new name. In the author's opinion, the example of halmyrolysis, presented by HUMMEL himself in his account of the formation of glauconite, is just as poor as an example of the process in question as it is unsatisfactory as an explanation of the formation of glauconite.

According to HUMMEL *the glauconite is formed directly from terrigenous minerals, more exactly from ferruginous aluminium silicates, and in such a manner that these minerals are deprived of alumina and silica* [1] *by means of halmyrolysis under the influence of decomposing organic matter.* Consequently the iron is enriched in the remainder. During this process all the components of the mineral, the removed silica and alumina as well as all else that remained, interpreted as a higly ferruginous silicate, have passed into colloidal form. The high percentage of *oxygen in the cold currents acts so strongly oxidizing during the process that ferric silicate is formed in spite of the presence of large amounts of organic matter.* Finally the gel-like iron silicate adsorbs potash from the sea water, and in this manner it is transformed into glauconite.

If all the components pass into colloidal form and none of them is left in place of the original mineral, it is meaningless for us to say that either the one or the other of them is removed from disintegrating mineral. The author therefore supposes that HUMMEL states the iron silicate to be the residual product, because he considers it is lying, together with the glauconite formed by its adsorption of potash, in the same place or at any rate in the same bed as the disintegrated, primary, ferruginous aluminous silicate mineral. The whole of this halmyrolysis, however, is hypothetical and, in the author's opinion, so improbable that it would have been advisable to try to find out whether the glauconite-bearing beds really justify our taking this halmyrolysis into consideration. HUMMEL desists from this and is content to say that the formation of glauconite shows »gewisse Ähnlichkeiten mit manchen Erscheinungen der lateritischen Verwitterung». What about the glauconite-bearing series of strata, then, do they give us any guidance for the estimation of the halmyrolysis theory?

If the glauconite were formed by means of halmyrolysis in the manner asserted by HUMMEL, we might expect to find: — 1) grains of glauconite with a nucleus of incompletely decomposed, primary mineral; 2) single, non-glauconiticized, slightly transformed grains of such minerals as must have been abundantly present in the glauconite-rich beds; 3) an abundance of grains of these minerals in the beds that, without being glauconite-bearing in themselves, are interbedded with the glauconitic rocks and are petrographically similar to them, the percentage of glauconite not being taken into consideration.

In the Swedish glauconite-bearing series of strata none of the said signs of glauconite formation by means of halmyrolysis is to be found. The beds of glauconite contain only a scarcity of terrigenous iron aluminium minerals, and the glauconite grains never show any primary residual core [2]; this is not explained

[1] Cf. GOOCH's theory, 1876, according to which glauconite is formed by submarine weathering under removal of int. al. silica. (See note p. 132.)

[2] MANSFIELD has examined a very large glauconitic material without finding any core of mineral matter (1922, 139).

by a presumption that the halmyrolysis is so complete that all traces of the primary minerals have been entirely obliterated. Nor are the minerals sought for to be found in the glauconite-free but otherwise petrographically equivalent beds.

Now it may be said, and with every reason, that the investigations made by the author must not necessarily be of general application, as they have been exclusively restricted to Swedish series of strata. Attention may also be called to the fact that ferrigenous iron aluminium silicates have sometimes been found in beds of glauconite together with quartz and fragments of felspar and mica. There are not many reports on the weathering of these different minerals extant but they all seem to indicate — and HUMMEL also calls attention to this (p. 69) — that, while orthoclase and mica are strongly affected, other minerals are relatively fresh. As orthoclase and mica, the only minerals showing a strong transformation, are never glauconiticized, *the halmyrolytic progress of the glauconite formation* stated by HUMMEL *must for the present be regarded as pure imagination.* There is no evidence for the disintegration of the orthoclase and mica by halmyrolysis and not by subaerial weathering. The author will not deny by this that a submarine disintegration of mineral can take place. On the contrary, he is convinced that this actually occurs, and he considers that it essentially finds expression in a dissolution, which can also be of indirect importance for the new formation of mineral at the sea bottom.

The second of the above mentioned factors, taken into account by HUMMEL on the formation of glauconite, is *the highly oxygenous water.* No determination of the percentage of oxygen in the water exists, nor was there any when PHILIPPI produced his theory of the highly oxygenous, cold deep-sea water (see p. 133). As reasons why he takes a high percentage of oxygen into account HUMMEL states as follows: — 1) the iron is present in the glauconite as a ferric compound; 2) the water in which the glauconite is formed is cold.

It has undeniably been established by means of a number of analyses that glauconite is essentially a ferric compound, and it has been shown that its formation takes place in relatively cold sea water, but nevertheless it is incorrect to infer from these facts that glauconite is formed in highly oxygenous water.

As long as no analyses have been made to show that the iron occurred as a ferrous compound immediately before entering into the glauconite, we cannot maintain that the formation of glauconite occurred during an oxidation of the iron from ferrous to ferric salt. As far as the author knows, nothing in the reports from the oceanic expeditions indicates that the iron in the starting material for the glauconite formation occurs as a ferrous compound, but ferric hydroxide, on the contrary, has been shown in the still imperfect glauconite as well as otherwise in the bottom mud. As besides this the iron has occurred in the primary material, i. e. in the minerals disintegrated by subaerial weathering or by halmyrolysis, in the form of ferric compounds, *it is obviously incorrect to infer from the composition of the glauconite that the mineral was formed in a highly oxygenous water.*

As a second argument for his supposition that glauconite is formed in a highly oxygenous water HUMMEL states that the water in which the formation takes place is relatively cold, according to estimation 3—15° C. HUMMEL says (p. 67): — »Das Meerwasser ist um so sauerstoffreicher je kühler es ist; bei 0° enthält es fast doppelt so viel Sauerstoff als bei 30°C». It would be equally correct to say that the water contains twice as much carbon dioxide at 0° as at 30°, or that it contains six times as much sodium sulphate at 30° as at 0° C. The fact that the power of the water to dissolve a certain substance changes with the temperature does not justify the inference that an increase of the power of dissolution (for inst. by a change in the temperature) must necessarily imply an increase in the amount of dissolved substance. It is therefore *incorrect to say that water contains a large quantity of oxygen, because it has a low temperature.*[1] The author would have considered it more reasonable, if the assertion had been made without any direct observations, that the cold, rising currents outside certain continental shores contain water relatively poor in oxygen. This is partly directly added to the water on its contact with the air and partly by means of tributary streams of fresh water and melting ice. Consequently the addition of oxygen takes place exclusively in the superficial layer of the seas. The loss of oxygen in the sea water occurs partly in the superficial layers and partly in deeper layers and at the bottom of the sea. On that account there is reason to suppose that the water rising from great depths towards the surface may be compared to the blood in the veins: it has given off its oxygen and runs its course towards a new oxygenation. Below the zone of green sand and mud there is a zone with blue mud, containing organic remains in a state of decay. If any oxygen has remained in the rising water, it has no doubt been greedily absorbed in the blue mud. From this, as well as from other deposits containing organic mud, the water has undoubtedly received carbon dioxide in return. Consequently a general estimation leads to the supposition that *the cold water rising from the deep-sea at certain shores is probably poor in oxygen but relatively rich in carbon dioxide.* It is to be hoped that future investigations will inform us, whether the actual and the supposed conditions agree. A complete investigation of this question would be extremely interesting, for there are certain conditions in the glauconite-bearing, fossil series of strata that speak for the formation of glauconite occurring in places and during periods with a high content of carbon dioxide in the water.

Finally a few words on HUMMEL's explanation of the glauconite's content of FeO. The iron occurs mainly in trivalent form in the glauconite but besides that always, though to a smaller extent, in divalent form. As HUMMEL states that glauconite has been formed in strongly oxidizing environment, he must necessarily have presumed that a reduction took place after the formation of glauconite in order to explain the occurrence of divalent iron. He considers (1922, 67) that organic matter has been enclosed in the glauconite during its formation, and that this matter has

[1] Cf. PHILIPPI's attempt to explain the supposed content of oxygen (see p. 133).

effected a reduction in the interior of the mineral. In support of his opinion he points out that FeO is usually more abundantly present in fossil than in recent glauconite. Examples of the contrary, however, are not uncommon (see the analyses p. 122), and as no organic matter has been shown in the glauconite, *nothing speaks for a secondary formation of FeO.* If HUMMEL's theory on the formation of glauconite in oxidation environment is looked upon as not only unconfirmed but probably incorrect, which is also the author's opinion, it is meaningless to talk of a secondary reduction in the interior of the glauconitic grains.

It is evident from the preceding that the author does not approve of HUMMEL's attempts to interpret the formation of glauconite, but at the same time he considers them, with their lively, energetic style, important as a stimulus in the glauconite research. They actualize PHILIPPI's theories and enforce special investigations on different lines. It would be desirable that HUMMEL could gain an opportunity to make personal investigations in the areas where glauconite is being formed and then make direct determinations as well of the content of oxygen and other properties of the water as of the halmyrolysis in the bottom deposits.

Before HUMMEL published his reflections on the formation of glauconite BERZ (1921) had presented the result of his investigations. A few years later (1926) he had the opportunity to return to the glauconite problem in connection with his account of the nature and mode of formation of the marine iron silicates, especially the chamosites.

BERZ's views on the formation of glauconite differ on many essential points from those of HUMMEL. Thus BERZ refuses to take the halmyrolysis into account as a main factor, nor does he think that the formation is caused by a high content of oxygen in the water, and he makes no mention of any secondary reduction of the iron in the grains of glauconite. BERZ also looks critically upon the deficiencies in the different opinions presented on the formation of glauconite. Thus he points out (1926, 411) that the connection between the three stages in the glauconite formation distinguished by COLLET and LEE is quite unknown: — 1) the gray alumina substance; 2) the brown ferric silicate; and 3) the green potassic ferric silicate, the glauconite. He doubts the occurrence of a successive formation of glauconite, such as the said investigators believed they had found.

BERZ is also sceptical towards the long prevailing opinion that glauconite obtained its content of potash by means of adsorption from the sea water. As a reason for his scepticism he states (1926, 466, note) the fact that potash is absent in other marine iron silicates, for inst. in chamosite. The author, who in the last few years has had reasons for making a fairly detailed study of the Swedish oolitic iron silicates and the series of strata in which they occur, can not completely agree with BERZ's views concerning the mutual relation between the glauconite and the chamositic minerals, nor can he understand that a content of potash in the glauconite originating from adsorption implies that the chamosites must also be potassic.[1]

The opinion presented by BERZ on the formation of glauconite may be summed up thus: —

1) glauconite is formed by one single precipitation (1926, 412);

2) the grains of glauconite are formed by aggregation of gel flocks in eddying water, not as concretions in the interior of the mud (ibid. 465);

3) at the formation of glauconite ferric oxide sol, which stands under influence from organic protective colloids, has acted upon potassic silicate sol (ibid. 466);

4) the glauconite's content of iron is mainly and directly derived from continental regions, not from halmyrolytically weathered minerals (ibid. 419).

As we shall see in the following BERZ's view on the formation of glauconite is the one in closest argreement with that of the author.

In his account of the greensands in New Jersey MANSFIELD (1922) dwells mainly on the investigated series of strata and their content of glauconite and potash. But he also expresses his opinion on the formation of glauconite, which he considers to have taken place *in tranquil water* and under subsidence of land. Thus he writes (p. 137): — »The presence of the clay and glauconitic mud included with the greensand indicates generally quiet waters. The maintenance of these conditions long enough to build up such an extensive and relatively thick deposit suggests a slow subsidence of the bottom on which the deposits were accumulating or a gradual transgression of the sea upon the land».

MANSFIELD has consequently arrived at a result quite contrary to the older view that glauconite is formed in agitated water, in strong sea currents. All the observations made at the places, where recent glauconite has been found, speak for the older opinion, and in many cases the investigations made by the author on Swedish glauconitic rocks give distinct evidence of a formation of glauconite in connection with strong currents in the area of deposition. Among the Swedish series of strata, however, there are also glauconitic rocks which, like those described by MANSFIELD, have been deposited in relatively tranquil water. This is for inst. the case in the glauconite-bearing series of shales at Köpinge in Öland (Ordovician) as well as in certain parts of the glauconitic marl at Eriksdal (Senonian). The author has nevertheless been able to establish that the amount of glauconite in these series of strata increases during periods with diminished depositions of fine-detritus and decreases or ceases entirely when the water has become sufficiently tranquil to allow of a heavy deposition of mud. The series of strata described by

[1] The chamosites and glauconite have been formed under different conditions, and particularly in a wholly different environment, the former probably in warm, shallow bays. The former have been formed (like the glauconites in the author's opinion) in an oxygen-blocked area, often in a strongly reducing environment. The author hopes in the earliest future to be able to present the observations, on which he bases his opinion.

MANSFIELD also exhibit variations, probably of a similar kind. Thus he writes (p. 138): — »the glauconite-forming agencies were at times interrupted or impeded by reversal of conditions ... Minor reversals or oscillations of conditions during the deposition of the greensand are indicated by the presence of sandy or gravelly layers». It is therefore not excluded that the glauconite in the New Jersey greensand has also been principally formed during periods when (cold) currents have occurred in the area of deposition. No doubt MANSFIELD's quiet water hypothesis does not pretend to be universal.

MANSFIELD also has interpreted the forming process in a curious manner. Like COLLET and LEE he thinks that *glauconite is formed from clay*, but contrary to the said investigators, who regard glauconite as a purely marine formation, he considers that the mineral has *partly* been formed *by changes in the strata after their elevation above the surface of the sea.* According to MANSFIELD glauconite is partly a marine and partly a continental formation. He writes (p. 134): — »When the marl beds became part of the land area and were subjected to the action of meteoric waters the processes of oxidation and leaching of certain layers began. Some potash with other constituents went into solution and circulated through the marl beds. The potash-bearing solutions reacted with the clay to form new glauconite, and the action was more pronounced in the more clayey layers — for example, the green marl bed. Some of the new glauconite formed additions to existing grains, some of it formed amorphous or colloidal glauconite such as that which now constitutes a so marked feature of certain beds».[1]

In some cases in the Swedish series of strata the author has been able to establish that grains of glauconite exhibit as secondary growth, but this growth took place before the grains were definitely embedded in the rock (mud or sand). He has also been able to establish an uneven distribution of the amount of glauconite in different strata in a glauconite-bearing series and varying development of the mineral in rocks of somewhat different character, for inst. clayey and clay-free rocks. In all these cases, however, the formation and development of glauconite

[1] MANSFIELD has obviously obtained the impulse to his theory on continental formation of glauconite from CLARKE (1924, 522) who suggests that perhaps the formation of glauconite is one of the works by which potassium is withdrawn from its solution in the ground waters. CLARKE in his turn bases his opinion on CAYEUX's observation that glauconite is frequently present in arable soils, in all conditions from perfect freshness to complete alteration into limonite. Unfortunately the author has not had access to this work by CAYEUX, but there must surely be a misunderstanding here, as in his second treatise, CAYEUX, certainly, speaks of a secondary, diagenetic glauconite but nevertheless makes the the following remark on it: — »qu'elle est par excellence un produit caractéristique des sediments accumulés dans la mer» (1916, 251). CLARKE writes further (1924, 522): — »when glauconite appears as a late product, the action of percolating waters upon the hydroxide would account for its formation», and TWENHOFEL says (1926, 341) in his quotation from CLARKE that the formation of glauconite also takes place »in soils through the action of organic matter carried by circulating ground waters». Contrary to CLARKE and TWENHOFEL, MANSFIELD bases his opinion on his own studies of glauconite, and the author therefore considers it most correct to make the latter the subject of his criticism.

has been naturally explained. There has never been any reason to suppose that the formation has not occurred exclusively in a marine environment of a nature that is shown to be most suited for recent formation of glauconite. Nor can the author find that MANSFIELD has given any positive reasons why this opinion should be abandoned. The enrichment of glauconite in a bed has no doubt occurred in connection with the sedimentation, otherwise traces of it would have been found in other beds also. MANSFIELD himself says of the enrichment of potash: »There seems to be no readily distinguishable zone of enrichment unless the green marl bed may be so considered».

In this connection the author will warn against interpreting, as MANSFIELD among others does, the present analyses thus, that the content of potash is lower in recent than in fossil glauconites, or in other words the content of potash in the glauconite has increased after the formation of the mineral. Fossil glauconites may have a relatively low content of potash, as is for inst. the case in the analyses 31—33 in table 1, with K_2O 2,23, 4,15, and 3,68, while recent glauconites have sometimes a high content of potash, for inst. the pure glauconite from the *Tuscarora* expedition, $K_2O = 7{,}76$ and the glauconite mentioned by CASPARI from the Agulhas bank, $K_2O = 7{,}80$ (analyses 1 and 7, table 1, p. 122). It is the decided opinion of the author that the content of potash in the glauconite can be higher or lower already on the formation of the mineral, owing to variations in forming conditions and in the supply of potassic material. A later leaching is certainly possible but as a rule it is no doubt of small significance, an increase after the consolidation of the mineral to a crystalline aggregate need hardly be taken into account.

The above criticism of MANSFIELD's theory on the formation of glauconite may be summed up as follows: —

MANSFIELD's opinion that glauconite can be secondarily formed under the influence of exclusively atmospheric (meteoric) water is not confirmed and is not probable. In the author's opinion it is incorrect.

MANSFIELD's statement that the New Jersey glauconite has been formed in relatively tranquil water may to a certain degree be regarded as confirmed, but his investigations interfere by no means with the opinion that glauconite has essentially been formed in agitated water.

Conclusions and Reflections concerning the Formation of Glauconite.

The short review of different investigators' opinions on the formation of glauconite, presented in the preceding chapter, shows how views may vary. The different interpretations can no more be explained as dependent on a varying nature in the mineral itself, than on inappropriate methods of investigation or insufficient material of the mineral. But there is reason to say that in no case have the investigations been so extensive that a sure basis for the more or less determined opinions formed has been gained.

Here as otherwise it is a case of distinguishing between directly made, properly controlled observations of facts, conclusions drawn from sure premisses, conclusions drawn from uncontrolled or otherwise uncertain premisses, suppositions apparently probable, which, however, cannot be or, at any rate, have not been directly confirmed and, finally, idle fancies, sometimes presented as rather alluring hypotheses. As is evident from the short review in the preceding chapter, a critical examination of the works gives us many examples of more or less well-grounded statements as to the formation of glauconite.

When the author now presents his opinion on the glauconite problem in its present state, he has the advantage to be able to base his statements not only on his own investigations but also on the numerous and important results gained by other investigators. It will, however, be evident from the following that there is still much work to be done before we arrive at a complete understanding of the conditions and progress of the formation. The author is especially anxious to try and show what is *known* of the formation of glauconite, and what is only *supposed* and by this means to state the points, to which the continued investigations should in the first hand be directed.

From several points of view it will be found suitable to divide the summary of the formation of glauconite as follows: —

- Conditions of formation
  - Environment
    - Currents
    - Temperature
    - Acidity of the water
    - Content of oxygen in the water

Presence of organic matter
Depth
Material
Progress of formation
Development of forms and diagenesis
(Metasomatosis and weathering.)

Environment.

According to older statements glauconite is formed in the shallow sea close to the shores of the continents, especially on rising, cold currents in the temperate or warmer zones. The water is sometimes supposed to be highly oxygenous (the school of PHILIPPI), sometimes »neutral» (GOLDMAN), and the formation is said to have generally taken place under the co-operation of organic matter abundantly present in the bottom mud. Glauconite is not formed in fresh or brackish water nor in the seas near the mouth of large rivers or in other places with a strong deposition of mud.

The environment, the *milieu,* in which glauconite is formed cannot be determined by an investigation of the mineral itself but by the study of the rocks or the material in which it lies enclosed.

The author's studies of the Swedish glauconite-bearing rocks have enabled him to prove that the grains of glauconite often lie in secondary site of deposition. It is a matter of course that in such cases the environmental conditions under which the glauconite was formed can not be directly inferred from the nature of the glauconite-bearing rock. *On investigating the conditions it is therefore necessary to find out first of all, whether the glauconite, be it fossil or recent, remains in the milieu in which it was formed.*

Currents.

Can it be proved that the recent glauconite abundantly present at certain places near the shores of the continents is at primary site of deposition? We may agree that no serious attempt has been made to investigate this question. At the same time we may say that the material in which the recent glauconite occurs has very frequently the character of a concentration formed in agitated water. A correspondence to this is also found in the fossil series of strata in which, as the author has shown above, a secondary enrichment of glauconite is very common. The mineral is often found in connection with intraformational conglomerates (Brantevik, Äleklinta, Tosterup, a. o.) or on breaks in the series of strata. In addition to the investigation published here the author wishes to refer to the convincing account given by GOLDMAN (1922) of the association of certain types of glauconite with breaks in a stratigraphic succession. Attention will also be called to the fact that FEARNSIDES as early as 1907 (264—267) shows in his study on the lower Ordovician series of strata in Sweden that as a rule glauconite occurs immediately on surfaces with erosion pockets. MARR (1929, 118) also considers that »the glauconite has frequently been concentrated by erosion of earlier deposits, with removal of the finer material, leaving the coarser grains behind».

Another fact to be noticed in this connection is the occurrence of the recent glauconite as filling in foraminiferal shells, etc. As is known, this occurrence is so typical that it has even been called in question whether glauconite can be formed in any other way at all. We know now that this is possible. It has been distinctly shown that glauconite can be formed not only as pigment, impregnations or earthy masses, but also as freely formed grains, no doubt originating as gelatinous lumps. In many cases neither the dust nor the gelatinous matter can have been deposited in the environment in which the glauconitic grains were enriched, the current being too strong there. This is perhaps the explanation why freely formed (= not enclosed in shells) grains of glauconite are infrequently found in the recent glauconitic beds. But it is no proof that the very formation of glauconite takes place in moving water. It is not even known whether the glauconite-filled foraminiferal shells were empty when they were deposited on the (future) glauconitic beds. Probably they were not.. Collet and Lee have shown that the non-glauconite-filled shells contain gray clay or a brown, highly ferruginous matter and they consider, possibly correctly, that clay is the primary filling. Then the question presents itself, Could the shells obtain this clay filling in their present environment? This is impossible when they occur in pure glauconite sand, and in other cases we can only say that the question requires direct investigation. Have the shells obtained their clay filling in another environment than that in which they are found (for inst. more tranquil water), they may also have obtained their glauconite filling under other conditions than those, under which the final deposition took place.

Thus the investigations hitherto made on the recent occurrences of glauconite give us no certain proofs that glauconite was formed where we find it deposited, for inst. in relatively swiftly moving water. However, it is known that the distribution of glauconite is very restricted, and the limits within which it must have been and is still formed may be inferred with tolerably great certainty. Future investigation should tend to establish where within these limits the glauconite is at primary site of deposition, and where it is being formed, and as far as possible explain the current and other environmental conditions prevailing there (temperature, salinity, content of oxygen, hydrogen ion concentration, content of carbon dioxide and hydrocarbons, content of detritus, etc.).

In the fossil series of strata distinct proofs that the glauconite is at primary resp. secondary site of deposition may sometimes be found. The former mode of occurrence is naturally of greatest interest, especially if it is possible to infer from the rock the conditions under which the autochthonous glauconite was formed

Neither the recent nor the fossil glauconite sand give us any proofs that the glauconite was formed while the water was as agitated as when the grains were deposited under enrichment. But sometimes certain proofs may be found that autochthonous glauconite can occur in beds formed in swiftly moving currents or otherwise agitated water. In the intraformational conglomerates, in which the pebbles were formed and enriched under the stirring up and washing out of all the fine material not yet cemented, primary deposited glauconite, forming an impregnation in the pebbles and a crust on them and on the fossil fragments, sometimes occurs, together with secondarily deposited grains of glauconite. It is excluded that these glauconite-coated pebbles were redeposited after the formation of glauconite, and it is equally excluded that the glauconite was deposited before the formation of conglomerates began. We can infer from the occurrence of the glauconitic coating that it was formed just when the formation of conglomerates terminated. It is possible that the movement of the water had decreased already at that time but no deposition of the sediments now covering the conglomerate had as yet begun.

The said example shows that glauconite can be formed as a consequence of strong movements in the sea, in this case resulting in the formation of intraformational conglomerates.

Evidence identical with this is given by the glauconite when it occurs as a thin coating on the corrosion and denudation surfaces. In this case also it can be definitely inferred that the glauconite is in primary site of deposition. For it lies as a thin layer or cover of about uniform thickness over the curved, furrowed surface, without filling up cavities. It is therefore excluded that this layer could have been formed of secondarily deposited powder from crushed grains of glauconite. The mode of occurrence of the glauconitic cover shows that it was deposited as a crust or a gelatinous pellicle. The erosion surface on which it is found may principally have been formed by chemical dissolution but the absence of detritus on it shows that it was washed perfectly clean before the deposition of glauconite started. As no deposition of detritus took place during the formation of the glauconitic crust either, we may infer that currents still agitated the water so much that the mud carried by it could not settle.

The last-mentioned example also shows that glauconite can be formed after and possibly during a relatively strong motion in the sea water of the sedimentary region. The motion is in this case confirmed by clean-washed corrosion surfaces.

In none of the said examples is there any possibility to estimate the strength of the current prevailing just when the glauconite was formed. In the series of strata examined, however, we find rocks that make such an estimation to a certain degree possible. For sometimes the glauconite occurs in relatively even-grained sandstones in such a manner that we may conclude it is there in primary site of deposition (see p. 67).

In many sandstones the glauconite apparently forms a cement between the grains of sand; a closer investigation shows that the sand grains were pressed into the simultaneously deposited, still plastic lumps of glauconite. In these rocks the sand grains are relatively uniform in size and show that the deposition took place in steadily moving water. As the size of the grains expresses the velocity of the current, this can be approximately determined. In five samples examined, with glauconite of exclusively primary occurrence, the size of the sand grains was 0,03—0,10 mm, in five other samples with both primarily and secondarily occurring glauconite 0,08—0,15 mm, and in five samples with only secondarily occurring glauconite 0,15—0,20 mm. All the samples are derived from beds of sandstone in one and the same series of strata (Brantevik). The said samples show that no primary deposition of glauconite has taken place when the current has been strong enough to prevent the settling of quartz grains less than 0,15 mm in diameter. The absence of mud and finer sand grains on the other hand proves that the current has been so strong that grains less than 0,08 mm in diameter could only be deposited in smaller quantities. *Consequently glauconite was formed in a current transporting quartz grains with a diameter not exceeding 0,15 mm and admitted an abundant deposition of grains not less than 0,08 mm in diameter.* The rate of the current has probably been about 0,15 m/sec. or about $^1/_4$ knot.[1]

In a bed with well rounded, larger grains of quartz, 0,5 mm in diameter, glauconite is present in large lumps squeezed out between the grains. These lumps consist of smaller ones clustered together, part of which is possibly in secondary, while another part is undoubtedly in primary site of deposition. In this case the formation of glauconite has consequently taken place in a considerably stronger current (according to the above-mentioned table the velocity would have been about 0,28 m/sec.).

It would of course be extremely interesting, if future expeditions could, in connection with the collection of oceanic deposits, make determinations of the speed of the current close to the bottom. An examination of the reports from the deep-sea expeditions does not tell us much of the facts, which should have completed the statements on the locality and the depth. As shown by the deposits collected by the German deep-sea expedition, the glauconitic area of the Agulhas bank resembles certain fossil occurrences, the mean size of the sand grains int. al. being 0,15 mm. When the quartz grains attain a size of 0,2 mm, only rounded (allochthonous?) grains of glauconite seem to occur in the sand (for inst. from Station 110; Murray and Phillippi 1908, 108).

The report on the deep-sea deposits of the »Challenger»expedition shows that the glauconitic sediments mainly contain grains of quartz a. o. minerals measuring 0,10—015 mm in diameter. The report of the deposit from Station Nr. 190 in the Arafura sea is of particular interest (Murray and Renard 1891, 94). The deposit, brought up from a depth of 49 fathoms (= 90 m), contained 50% mineral grains,

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[1] The value is very uncertain, as we have no reliable results of attempts made to determine the relation between the quality of transported and deposited fine sand and the rate of the current. In the table made up by Twenhofel (1926, 464) brick clay is stated to settle at a rate of 0.08 m/sec., while fine sand, mean diam. 0,40 mm., is transported when the velocity is 0,26 m/sec.

0,10 mm in diameter, 25% fine mineral particles and flocculent green amorphous matter, 23% calcareous organisms and 2% siliceous organisms. In this, as in some other deposits, sandy and calcareous concretions were found, together with large fragments of Lamellibranchs. The following additional observations are made: »The calcareous nodules in this deposit are about 6 inches long in some cases, and are covered with *Serpula,* Corals Polyzoa, *Polytrema, Carpenteria,* and *Hyperammina.* After acid there remained a greenish red residue of imperfect casts of organisms, minerals, &c. There is much amorphous matter in this deposit, some of which is transparent, with a green tint; it shows aggregate polarisation. This matter is probably to be referred to glauconite. There are also present some fragments of calcite.» The calcareous nodules are, no doubt, of the same character as the pebbles of many intraformational conglomerates, for inst. at Brantevik loc. 6 (see p. 68 and HADDING 1929, 100), and the glauconitic matter may be a primary deposition in the mentioned recent sediment as well as in the fossil conglomerates.

The above-mentioned examples of autochthonous glauconite occurring in sandstone show that glauconite can be formed in moving water. In this case the motion is confirmed by a well sorted material of a certain size of grains.

In the series of strata examined, however, examples are also to be found that *glauconite can be deposited in relatively tranquil water,* for inst. together with limestones without other detritus than an exceedingly fine-grained clayey matter. But it is often difficult to show when the glauconite is in such cases at primary place of deposition. The author looks upon two different forms of glauconite in the limestones as probably autochthonous: the pigmentary form occurring in limestone immediately above the afore-mentioned corrosion surfaces with a thin crust of autochthonous glauconite, and the granular form when the grains have not been subjected to transport after they have left the gel stage.

Temperature.

As far as the author knows no systematic investigations of the bottom temperature have ever been performed in the regions where glauconite is formed. It has, however, been possible to establish that the glauconite is to a large extent deposited where relatively cold currents occur. But the mineral has also been observed in regions not characterized by such currents. At some of these places with relatively warm water the grains of glauconite are no doubt secondary deposits, while in other places they are certainly primary. One of the objects of the glauconite research is the solution of the direct connection between the formation of the mineral and the temperature in the region where it is formed. It appears as if the meeting of colder and warmer water would favour the formation of glauconite (see HUMMEL 1922, 53—61).

The fossil glauconitic rocks give us hardly any guidance for the estimation of the temperature of formation. The deposition of detritus has taken place independent of changes in the temperature and the deposition of limestone could take place in cold as well as in warmer water. Possibly, however, variations in the bottom temperature may have influenced the deposition of calcium carbonate so that a lower temperature was accompanied by a slower precipitation. If this is the case, the parts richer in limestone were deposited during relatively warm and those rich in detritus during relatively cold periods. The fact that the deposition of glauconite, as shown by the fossil rocks, increases when the deposition of limestone decreases, may be looked upon as a support of the opinion that *the fossil glauconite was also formed in relatively cold water.*

The occurrence of marcasite in certain glauconite rocks possibly points in the same direction. Marcasite is namely formed at relatively low but pyrite at a higher temperature (Doelter 1926, b, 583).[1] Pyrite occurring in glauconitic rocks was formed by secondary, concretionary enrichment and may have been primarily deposited as marcasite or melnikovite.

However, the above-mentioned facts do not, in the author's opinion, show that the formation of glauconite took place at a particularly low temperature, even though they rather speak for than against such an inference. Both also speak for the acidity of the water due either to acid solutions or to a certain percentage of free carbon dioxide.

The Acidity of the Water.

As mentioned above, the thin crust of glauconite was deposited on a limestone strongly affected by chemical dissolution. The corrosion was probably not caused by water only but by acid solutions. As large quantities of carbon dioxide must have been formed in the strata rich in organic remains, which occur together with or underlie the glauconitic rocks, it is most natural to suppose that the acidity of the water is caused by a certain percentage of carbon dioxide. The fact that the water's power of dissolving carbon dioxide increases with falling temperature makes it probable that a fall of the bottom temperature has involved an increase in the concentration of the carbon dioxide in the bottom layer. *The low temperature and the increased acidity may therefore have cooperated in a decrease of the deposition of limestone at the same time as they have favoured the formation of glauconite and marcasite.*[2]

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[1] The author is not convinced that the relatively small differences in temperature, prevailing on the formation of the marine sediments, play any rôle for the iron sulphide's development as marcasite or pyrite.

[2] As a source of carbon dioxide we have mentioned in the preceding int. al. the mud from which the alum shale is formed. Of recent oceanic deposits there is no mud closer related to this than the blue mud. This contains an abundant fauna and can not therefore be devoid of oxygen but the evolution of carbon dioxide in it is nevertheless obvious. Thus Murray and Irvine write (1893, 496): — »When a large quantity of carbonic acid was found in the oceanic waters it was at the bottom over Blue Muds».

The Content of Oxygen in the Water.

Some scientists have supposed that a high content of oxygen has been characteristic of the water in which glauconite was formed, and sometimes it has been said to be necessary for the formation of glauconite. In the preceding chapter the author has stated the reasons why he thinks this opinion untenable. Direct proofs that the deposition of glauconite ceases when the sedimentation has come to pass from a »neutral» or reducing into an oxidizing environment are often found in the fossil, glauconite-bearing series of strata. The parts of a glauconite-bearing limestone series rich in ferric oxide or ferric hydroxide are as a rule poorest in glauconite. As soon as the formation of products characteristic of the oxidizing environment has ceased, the deposition of glauconite has been able to start again. In connection with the mention of the content of oxygen in the water attention should be called to the fact that glauconite has not been found in the polar zones, which are probably relatively rich in oxygen owing to the supply of melting ice.[1] Glauconite is also absent at the mouths of large rivers,[2] and completely lacking in fresh water. As to the latter relatively oxygen-rich waters, it may of course reasonably be remarked that glauconite can not be formed in water lacking the material necessary for the formation in the form of salts or colloidal substances. Whether the salts which occur in the sea, and which do not yield material for the glauconite, are also of importance for its formation, we do not know.

In order to estimate the content of oxygen in the glauconite-forming environment, we should also investigate the content of benthogenous fossils in those parts of the series of strata, which contain decidedly autochthonous glauconite. If the formation of glauconite has occurred in a highly oxygenous water, this ought also to have been suitable for the development of an abundant animal life, but if the water was poor in oxygen and possibly rich in carbon dioxide, the beds of glauconite ought not to be able to contain any large amounts of benthogenous fossils. What, then, do we learn from the glauconite-bearing rocks?

In the glauconite-bearing limestones with alternating glauconite-rich and glauconite-poor strata the content of fossils is found to decrease in the same degree as the content of glauconite increases. The strata with primary glauconite are as a rule completely devoid of fossils, unless the strata, as nevertheless frequently happens, contain fragments of shells, coprolites, etc., which have been secondarily enriched before or during the deposition of glauconite. These remains have not

[1] PHILIPPI regarded the Pleistocene ice-cap as the source of the high content of oxygen he supposed that the cold deep-sea water possesses.

[2] This opinion so often met with in the glauconite literature appears to be contradicted by the report of the Valdivia expedition from Station 68 (MURRAY and PHILIPPI 1908 103). It is mentioned in this that deposits with distinctly glauconite-pigmented oval, rounded grains, probably echinoderm coprolites, have been obtained at a depth of 214 m outside the mouth of the Congo river. As, however, the observers themselves call attention to the fact that glauconite does not occur, not in larger amounts at any rate, at the mouth of rivers (M. & P., p. 175), they obviously do not attach any greater importance to the said occurrence.

infrequently been impregnated or coated with glauconite, a circumstance which further confirms the fact, obvious also in other respects, that these fossils do not prove the existence of a rich animal life where glauconite was formed.

In beds with allochthonous glauconite we often find both fossils and trails showing that it is possible for a benthogenous fauna to thrive on these deposits of glauconite. The same is exhibited by the coprolites with enclosed grains of glauconite (fig. 57, p. 100), found at several places, just as often at secondary as at primary site of deposition. All these occurrences of fossils, however, are in so far devoid of interest as they tell us nothing of the possibilities for the development of the fauna in a glauconite-forming environment. Consequently the faunistic materials give no more than the sediments any support to the »oxygen theory», and in some cases they speak decidedly against it.

The Presence of Organic Matter.

It has sometimes been said that glauconite requires a direct presence of organic matter for its formation but, as shown in the preceding chapter, it has been emphasized from other quarters that the mineral can be formed even where such a substance is lacking. The Swedish series of strata also give positive evidence of this, and it is obvious that glauconite is absent in beds particularly rich in organic matter.[1] On the other hand it appears as if the occurrence of organic matter in the substratum of the glauconitic series or in adjacent (older) parts of the area of deposition would create favourable conditions for the formation of the mineral. In the preceding the author has spoken in favour of the opinion that the carbon dioxide evolved in the organic mud has most likely played a certain rôle here. The increased content of hydrocarbons may also be supposed to have favoured the formation of glauconite (cf. p. 48 seq.). In this as in so many other respects complete certainty can only be gained by means of continued investigations.

Depth.

To the milieu conditions we must also count the depth at which glauconite is formed. The recent glauconite is found within extensive depth limits, no doubt

[1] It is characteristic that glauconite is absent in the strongly bituminous alum shale, together with which it occurs in the Lower Ordovician. Thus glauconite does not seem to be formed in strongly reducing, no more than in strongly oxidizing environment. In this respect the author's observations agree with those of GOLDMAN (G. 1919, 502): — »glauconite is an intermediate product between high organic content and reducing conditions yielding the sulphide on the one hand, and low organic content with oxidizing conditions producing the hydrous oxides on the other». TWENHOFEL (1926, 339) has called attention to the same fact concerning high content of organic substance when he writes: — »Glauconite does not appear to form where the land derived sediments are present in large quantity or where the quantity of organic matter is large». The statement of the land derived matter is hardly applicable to anything more than the glauconite in the limestones. The authigenic glauconite in the sandstones has been formed under abundant deposition of (relatively coarse) terrigenous material.

owing to its frequent occurrence at secondary site of deposition. The bulk of the mineral, however, is found at a depth of 100—400 m, and somewhere in or in the neighbourhood of these depths the formation of glauconite takes place. The fossil beds of glauconite are frequently formed at considerably shallower depths. TWENHOFEL (1926, 339) mentions mud cracked Cambrian beds of glauconite. The author has also found mud cracks in glauconite-bearing Ordovician limestone (Ölandic orthoceras limestone) but in this rock glauconite occurs at secondary site of deposition, on which account it cannot be regarded as a proof of the glauconite's formation in the littoral zone. The rock shows, however, that the immediately surrounding parts of the series of strata must also have been formed in very shallow water. The no doubt primary glauconite (on corrosion surfaces) present in these beds must have been formed at a depth not exceeding a few tens of meters.[1]

The Deposition of Detritus.

Glauconite often occurs in such a manner as to justify the inference that it was deposited in relatively mud-free water or at any rate under such circumstances that mud was prevented from settling contemporaneously. From natural reasons this is particularly the case in all the occurrences in which glauconite is present as secondarily enriched grains. The grains of detritus in the sediments are then of about the same size as those of glauconite.[2] Several cases, however, have been observed, in which autochthonous glauconite also occurs in such a manner that it must have been formed at times and places where no settling of fine detritus took place. As an example of this the author wishes to count the occurrence of glauconite as coating on corrosion surfaces and on pebbles and fossil fragments in intraformational conglomerates, also its occurrence in the pure (mud-free) sandstones as lumps squeezed out between the grains of quartz.

Glauconite may thus be formed in places where no fine detritus settles. It may, however, also be formed in connection with a deposition of mud. This is particularly evident from those rocks, rich in fine detritus, in which glauconite is present as pigment. It has been shown above (p. 35 and 149) that glauconite, in several cases at least, occurs in these rocks as authigenic mineral and not as secondarily deposited, crumbled fragments of glauconite grains.

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[1] Glauconite is to be found at a very shallow depth in the recent sediments also. Thus MURRAY and PHILIPPI (1908, 107) for inst. mention glauconite from a depth of 40 m in the bay of Algoa, 44 m at the mouth of the Congo river (Station 71), and several samples from a depth of about 100 m at the Agulhas bank. In the author's opinion, however, the samples show that in these places the glauconite probably occurs at secondary site of deposition, and therefore they tell us nothing of the depth of formation. Station 71 is possibly an exception.

In the reports of the »Challenger»-expedition glauconite was found at a depth of 11—14 m in the Torres Strait, station 187 (MURRAY and RENARD 1891, 94), probably allochthonous. Autochthonous glauconite was dredged in the Arafura Sea at a depth of 90 m (cfr p. 148).

[2] A comparison between the grains of glauconite and those of quartz in a number of Swedish glauconitic rocks was published by the author in 1927 (p. 22).

Summary of the Milieu Conditions.

The reflections and conclusions as to the milieu conditions for the formation of glauconite may be summed up as follows:

Glauconite is formed in the shallow sea regions adjacent to the shore, as a rule at a slight depth. In the recent deposits it often seems to have been formed at a depth of 50—200 m, in the fossil strata sometimes almost immediately outside the littoral zone. Its formation frequently takes place in moving water, and several occurrences of the mineral show that it was formed in connection with negative sedimentation, noticeable by breaks in the series of strata, intraformational conglomerates, or some other coarse material, enriched by the washing away of fine detritus. It has, however, also been deposited in relatively tranquil water and together with fine detritus. Restricted quantities of organic mud may be directly present on the formation of glauconite but this is not necessary.

Cold currents ascending at the shores of the continents seem to favour the formation of glauconite. The significance of the cold water lies partly in its power of dissolving carbon dioxide, which is no doubt present in relative abundance where glauconite is formed. The content of hydrocarbons has probably been higher but the content of oxygen lower on the formation of glauconite than on the deposition of certain glauconite-free strata, interbedded with the glauconitic ones.

The environmental conditions should be subjected to repeated examination from every point of view by means of continued direct investigations, not least of recent occurrences, and due regard must then necessarily be paid to the occurrence of the glauconite at secondary or at primary site of deposition.

Material.

All glauconites contain SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, and K_2O. These substances must consequently be present where glauconite is formed and therefore the question arises, In which form do they occur?

The source of the glauconite's content of SiO_2 may be: 1. silica in the form of hydrosol; 2. silicates in solution (also colloidal); or 3. silicates in the form of detritus. The frequent occurrence of authigenic quartz and chalcedony in the glauconite-bearing rocks shows that colloidal silica has been present on their formation. Silicates also, especially aluminous silicates, are often found as detritus in the beds of glauconite. But whether solutions of silicates were present on the formation of glauconite is as yet unknown.

The content of alumina is either derived from aluminous hydrosol or hydrous silicates of alumina, the latter of which, as mentioned above, are frequently found as detritus in the glauconitic rocks.

According to certain investigators the content of iron is derived from iron aluminium silicates, this, however, does not appear to be very probable, as such combinations are either completely absent or occur only in small quantities (and then in a relatively unweathered state) in the glauconitic rocks. It is more probable that the iron was present in the form of solutions of salts, for inst. as ferric and eventually ferrous sulphate.[1] Nor is its occurrence as ferric hydrosol excluded, which, of the weathering products rich in iron, is undoubtedly the one most abundantly formed. In nature it practically never occurs pure but always together with colloidal silica (see LEITMEIER on Limonite in DOELTER 1926 a, 714).

The magnesia and potash in glauconite are derived from sulphates and chlorides present in the sea water. The attempts to trace the glauconite's content of potash directly to potassic felspar and muscovite decomposed by halmyrolysis have, in the authors opinion, not been successful (see p. 138).

All the occasional constituents of the glauconite (CaO, Na_2O, etc.) may be directly derived from the salts of the sea water.

The Progress of Formation.

How the above-mentioned material reacted on the formation of glauconite we do not know. We can only surmise the ways along which the formation progressed.

But we do know that the newly formed glauconite occurred as gel. The coagulation of the hydrosol material (SiO_2, Al_2O_3, Fe_2O_3) may therefore be counted as a primary process in the formation of glauconite.

The next question refers to the mode for the entrance of the material possibly derived from the salts of the sea water (K_2O, MgO, FeO, etc.). Several investigators have supposed that for inst. the content of potash was added to the (otherwise finished) glauconite by adsorption. The fact that potash is adsorbed in gel-like substances with relative ease and in considerably larger quantities than soda undoubtedly supports this supposition. The sequence of formation stated by COLLET and LEE (silicate of alumina $\rightarrow$ silicate of iron $\rightarrow$ potassic silicate of iron) points in the same direction, and so does the experiment performed by GLINKA (see p. 135). It is, however, not excluded that a reaction between the potash and the hydrosol can take place already before or during the formation of gel (cf. p. 140 and BERZ' opinion). The ferric hydroxide especially is inclined to react with potash under formation of (negatively charged) complex ions (ZSIGMONDY 1927, 131). It seems to the author to be a very tempting task for a colloid chemist to make a closer study of the formation of glauconite, and certainly it is not excluded that attempts at synthetizing will succeed. They would at any rate contribute to an explanation of the progress of the formation and also to a better understanding of the significance of the environmental conditions (pressure, temperature, acidity, etc.).[2]

[1] Not much of the occurrence of the sulphates of iron in the sea water is known nor do we find them in the marine precipitates. We know, however, that they are formed as weathering products from ferruginous combinations of sulphur. Attention should be called to the fact that several double salts are known, for inst. the mineral *Roemerite*, acc. to analysis containing Fe_2O_3 20,5 per cent, FeO 4,12, MgO 3,59, SO_3 40,95, H_2O 30,82 (see DOELTER 1929, 576).

[2] Though the author finds the theory plausible that glauconite was formed from a silicate by substitution (for inst. of Al_2O_3 for Fe_2O_3) he nevertheless cannot agree with it, as is evident from the more detailed account of his own observations. Nor can he find that this opinion has hitherto been desirably corroborated by the investigations of other scientists.

Development of Form and Diagenesis.

Irrespective of whether glauconite is formed by one single reaction between the hydrosols and the dissolved salts or whether its formation has occurred successively, the development of form may be discussed as a matter apart.

If the coagulation takes place under favourable conditions, for inst. in a suitably agitated water, an aggregation may easily come to pass. The lumps of gel formed in this manner have composed the natural starting material for the grains of glauconite directly or after further aggregation.

The deposition of the thin, even crust of glauconite on corrosion surfaces or on conglomerate pebbles must have been somewhat different. In such cases no lumps of gel have been formed nor could the coagulation have occurred in the freely moving water above the sea bottom. The occurrence of the glauconitic pellicle shows that its formation must have occurred directly on the object covered by it. The reason why the coagulation has taken place just there is of course impossible to state as long as we do not know why and how the coagulation practically arises. We may, however, suppose that a certain concentration of substance important for the formation of glauconite, possibly only with catalytic effect, has existed just at the porous surface, in and on which the glauconitic matter was deposited.

The impregnations of glauconite in fossil fragments of different kinds may probably be explained in a similar way. The mineral has been formed in the fine pores where it can now be seen. The apparent transformation of another substance (for inst. phosphorite) into glauconite becomes quite natural, if we imagine the formation of glauconite taking place simultaneously with or in the porous parts of this substance.

As the coagulation and formation of glauconite can obviously occur in pores of rocks and fossils, we may ask ourselves whether it cannot also take place in the sediments already deposited. As mentioned before, Cayeux has spoken in favour of this opinion. We must admit that the formation has of course been possible, provided the same conditions have existed in the mud deposited as in the pores in which the mineral was formed. Is there any possibility for us to determine whether this has really been the case?

In his description of the rocks the author has shown that where the glauconite occurs in the pores of the rocks and as coating on their surface, it must have been deposited and consolidated before the deposition of the surrounding detritus. The crust of glauconite never exhibits inclusions or impressions of surrounding material. In these cases, therefore, a formation of glauconite in already superstratified beds is excluded. The fossil fragments impregnated with glauconite show the same when, as is sometimes the case, the deposition of glauconite continues after the filling of the pores so that a crust is formed around the fragment.

On turning directly to the rocks, in which glauconite might be suspected to have been formed after the deposition of the material, we are unable to find any proof of the secondary formation. The investigation has established that glauconite does not occur as a cement, formed after the deposition of the sand, in the sandstones which show glauconite filling up the spaces between the grains of quartz. In these cases the form of the glauconite is dependent on the embedding of the mineral while still in the gel stage. The gel lumps were squeezed out between the grains of sand, or the latter were pressed into the plastic substance.

It is more difficult to decide how the glauconite has been formed when it occurs as pigment in certain limestones. The author has stated in the preceding that the deposition has probably taken place as a successive precipitation under contemporaneous settling of fine detritus, which has counteracted the appearance of lumps of gel. He thinks that the distribution of the pigment in the rock and its occurrence, resembling that of haematite or limonite pigment in other parts of the beds, indicate a formation during the very deposition of mud, and he considers that a diagenetic glauconite would have shown a more concretionary form or, when occurring as pigment, a local (spotty) development.[1]

As is evident from the above, the author holds the opinion, that the glauconite has always been formed before or contemporaneously with the rock in which it is enclosed.[2] The different forms — grains, crust, impregnation, or pigment — are due to the different conditions under which the coagulation and formation of the glauconite gel took place.

The formation of glauconite, however, does not come to an end with the reactions resulting in the formation of the gel-like mineral. This has always and at an early stage undergone certain alterations, especially a dehydration and a hardening, probably in connection with a recrystallization. Traces of these alterations are particularly noticeable in the cracks and shrunken surface of the grains, their hardness and great resistance as well as their crystallinity, frequently noticeable even on relatively slight magnification — all these are characteristics lacking in the mineral while still in the first gel stage. In some cases the secondary alteration has taken place after the embedding of the glauconite in the rock. This must be the case when the mineral occurs for inst. in the manner mentioned above as a cement-like filling between grains in a sandstone. The transformation is then to be counted among the diagenetic processes in the rock.

In other cases the recrystallization[2] of the glauconite has undoubtedly taken place before the enclosure of the mineral in the rock. This is the case in a large number of the glauconitic grains formed from lumps of gel. The fusion of flocks and smaller lumps into larger ones has obviously been favoured by a certain agitation of the water. During this agitation the lumps and later the harder grains also have been worn and rounded during transportation and, above all, they have

[1] As »la meilleure preuve» of the formation of glauconite after the deposition of the glauconite-bearing rock Cayeux (1897, 179) mentions »les grains incomplets». In the author's opinion these grains may very well be deposited contemporaneously with the rest of the rock material. In fact, their incomplete aggregation would be most easily explained, if they were embedded immediately after or during the formation of the glauconite gel.

[2] But also during or after the redeposition (or corrosion) of sediments.

[3] When the author writes »recrystallization» he wishes to convey that he does not consider the glauconitic gel to be amorphous but, like most other gels, sub-crystalline in character.

been enriched. The enrichment may possibly be partly ascribed to the fact that the grains dehydrated by the recrystallization, owing to their increased specific gravity, become more difficult to transport than the lumps of gel. After having become compact and hard the grains of glauconite are thus transported and deposited in a relatively agitated water together with coarse detritus, shell fragments, etc. As the author has pointed out earlier, he considers this occurrence of glauconite as allochthonous, for the deposit in which it was enclosed was not always formed under the same conditions as those prevailing where the glauconite was formed.

Metasomatosis and Weathering.

Though the formation of glauconite is undeniably completed with the above-mentioned processes, a few alterations which can take place in the mineral, sometimes while it is still in the gel stage, ought also to be mentioned in connection with them.

It is not altogether impossible that a substitution of certain constituents can occur at an early stage in the formation of glauconite. No direct proofs of this, however, are known to the author, and therefore this question will not be the subject of further discussion.

On the other hand he has been able to observe in several cases that glauconitic substance has been metasomatically exchanged for another of a quite different character. Calcite generally occupies part of the glauconite's place but siderite has also been observed to occur in the same manner (p. 23 and 101). As shown in the preceding, it is quite excluded that the glauconite was formed between or around the crystals of calcite, as the outline of the replaced grain of glauconite is often visible in the calcite also (figs. on p. 102).[1]

When calcite has metasomatically replaced the glauconite the process has as a rule occurred in connection with a recrystallization of the entire rock. In such cases the crystals replacing the glauconite generally extend far beyond the contour line of the glauconitic grains. In other cases, and always when siderite has replaced part of the glauconite, the crystals lie wholly within the contour of the grains, from which they have grown in towards the centre.

Other alterations in the glauconite may be restricted to weathering processes. The author has not subjected them to any special study, and on that account he will not discuss them. The only weathering product generally observed is ferric hydroxide. For the rest it should be mentioned that glauconite is remarkably resistant to weathering.

The dark pigment in the peripheral part of several glauconitic grains can be

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[1] The case described by CAYEUX (1897, 181), in which glauconite occurs as pseudomorphosis after calcite is probably an infiltration of the same kind as the glauconite in certain fossil fragments (p. 106 and fig. 64, etc.). The glauco-calcite grains reproduced by HEIM (1924, 23) are of the same type as those mentioned here in the Swedish series of strata.

mistaken for a weathering product. The author cannot deny either that a weathering zone may be found on the grains of glauconite but in the majority of cases observed by him the pigment has undoubtedly arisen during a reduction, not during oxidation. It has not been possible to obtain an analysis of the dark substance, but the transformation into a crust surrounding the glauconite and consisting of partly distinctly crystallized pyrite makes it probable that it is composed of powdery sulphides of iron.

The Paleogeographical Significance of the Glauconite.

Our study of the glauconite-bearing rocks has led to the inference that glauconite occurs only in marine sediments, deposited outside the littoral zone but in relatively shallow water. Thus, the fossil glauconites coincide as to the general forming conditions with the recent ones, though these have also been found at greater depths than those at which the Swedish glauconitic sediments were formed.

It is also evident from the study of the glauconite-bearing series of strata that glauconite is most abundantly present in connection with variations in the sediments. The investigation shows that periods with negative sedimentation are often characterized by an enrichment of glauconite or are succeeded by a period with a strong formation of glauconite. Beds of glauconite often reveal the presence of gaps in the series of strata, formed by interruptions in the sedimentation, with or without submarine denudation, with or without the formation of intraformational conglomerates, and with or without the appearance of a discordance.

The extensive distribution of the glauconite during certain distinctly limited periods shows that its formation is not dependent on local conditions only but on factors of more general purport. Smaller variations in depth, distance to the shore, supply of detritus, etc. have been of less account than the general physico-chemical conditions in the area of deposition. These conditions have been discussed in the preceding.

The fact that glauconite neither occurs nor has been formed in certain faunistically characterized conditions is also of paleogeographical interest. It is not found together with the coral reefs, nor in the bryozoan beds or the coccolith limestone. We venture to say that the general conditions, under which these rocks are formed, differ from those under which the glauconite is formed. The said rocks have arisen in relatively warm, oxygenous water, whereas the glauconite was formed in an indifferent or reducing milieu and probably in relatively cold water.

On summing up the inferences that can be drawn from the investigation as to the sediment-petrographical and paleogeographical importance of the glauconite, we can say that the glauconite is

always marine,
always sublittoral,

always a shallow sea formation,
as a rule formed in agitated water,
as a rule formed under decreased deposition of detritus (specially fine detritus),
often formed during negative sedimentation,
most abundant immediately after periods of negative sedimentation,
never formed in environments producing certain forms of animals known as heat-requiring,
never formed in highly oxygenous water (oxidizing environment),
to a large extent allotigenous.

The Relation of Glauconite to other Sedimentary Silicates of Iron.

In addition to glauconite there are in the sedimentary rocks a few other autochthonous silicates of iron, which we for the sake of simplicity sum up under the term chamosites. There can be no question here of giving an account of these or more closely discussing their occurrence and qualities but it may be appropriate to say a few words on their general relation to the glauconite.[1]

The chamosites differ chemically from the glauconite by their lower content of SiO_2, and their higher content of Al_2O_3 and of iron, in addition to which they are devoid of the glauconite's content of potash and are often essentially ferrous silicates. The following two analyses, the one of glauconite and the other of chamosite, may be regarded as typical and serve as examples.

	Glauconite[2]	*Chamosite*[3]
SiO_2	49,13	23,54
Al_2O_3	9,96	18,15
Fe_2O_3	16,67	3,67
FeO	1,29	36,84
MgO	3,01	1,35
CaO	0,95	1,62
K_2O	8,87	—
Na_2O	0,49	—
H_2O	9,37	11,58
	99,88	96,75

frequent occurrence of the former as oolites, an occurrence never found in the

The structural difference between the chamosites and glauconite lies in the latter mineral. The adjoining fig. 73 shows a typical picture of chamosite.

The oolite grains have sometimes been formed around a nucleus of other material, for inst. a quartz grain, a shell fragment, or a grain of siderite. The growth has been due to a successive deposition of concentric crusts of varying thickness and sometimes also of a varying composition.

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[1] The author has had reason to perform a number of investigations on chamositic minerals and will give an account of these elsewhere. One of his pupils has begun a profound study of the chemistry of these minerals.

[2] Glauconite from Berg, Östergötland. Anal. SVEN PALMQVIST.

[3] Chamosite from Schmiedefeld, Thüringia. Anal. E. R. ZALINSKY (quoted BERZ 1926, 377).

The filling matter around the grains may consist of a dense chamosite substance but equally often of some other material. In the Swedish oolites it consists often of siderite.

The structural difference shows that the progress of precipitation and development of form has been quite different on the formation of the chamosites than on the formation of glauconite. The chemical difference, on the other hand, shows that the primary material has possibly appeared in other proportions and been partly of a different character. The structural as well as the chemical difference show

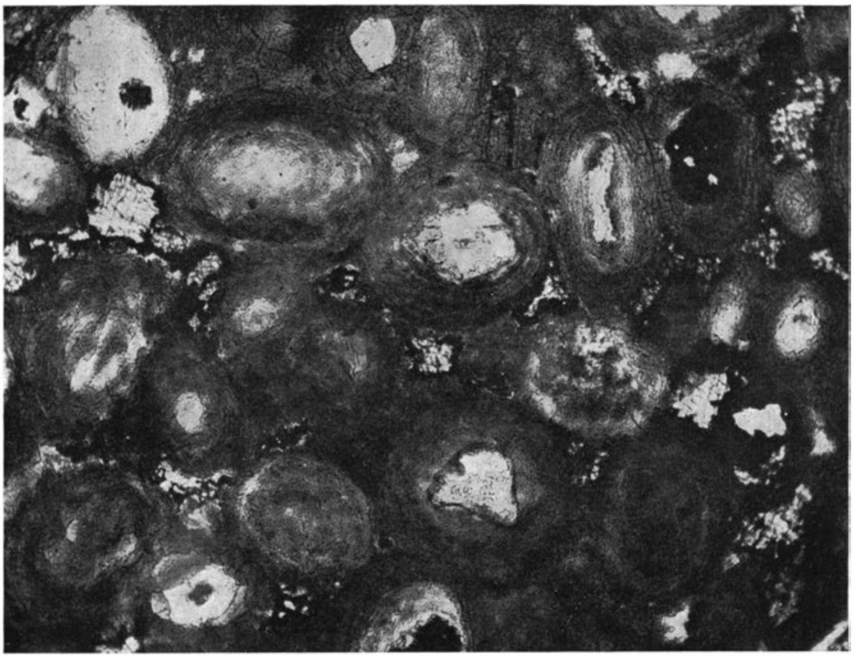

Fig. 73. Chamosite with siderite (clear) and haematite. Oolitic iron ore. Jurassic. Kurremölla, Scania. (Pr. 2539. Pl. 438.) — 60 ×.

that *the chamosite was formed under quite different milieu conditions than the glauconite*. Both are, however, marine formations.

The type of the chamosite-bearing series of strata may, like the glauconite-bearing ones, vary somewhat. We are cognizant of highly calcareous and argillaceous as well as arenaceous rocks with chamosite. In the Swedish Jurassic strata these rocks are of a pronunced shallow water character.

The fact that the chamosites proper are typical ferrous minerals shows that they were formed in an oxygen-free and probably strongly reducing environment. Organic matter is often found in the beds, though never in larger quantities. The series of strata in which they occur are sometimes carboniferous.

Judging from the Swedish series of strata it seems probable that the chamosites were formed in warmer water than the glauconite.[1] Their formation occurs in Scania during a period with relatively high temperature and rich vegetation. The latter has probably played a prominent rôle, directly or indirectly, by the creation of a greater abundance of ferrous salts than would otherwise have been obtained in the sedimentary region. These settle not only in the form of silicates (chamosites) but also as ferrous carbonate (siderite). Occasionally the reduction has been exchanged for oxidation, upon which ferric oxide or ferric hydroxide has been deposited (see fig. 25, p. 48).

Like the glauconite the chamosites also occur highly developed both periodically and locally and not infrequently secondarily enriched. The interpretation of their forming conditions is still vague in many points, so also is the very progress of their formation. The problems are interesting and inviting to continued investigations.

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[1] Hummel (1922, 101 a. o.) thought he might conclude that the chamosite-oolites are formed at a higher temperature than the glauconite.

Appendix.

The Practical Value of Glauconite.

On account of its fairly high content of potash glauconite has been tested as fertilizer. Its value as such, however, seems to be insignificant as only a very small amount of the potash is water-soluble, not exceeding 0,06 per cent of glauconite with about 7 per cent K_2O (MANSFIELD 1922, 129). A number of carefully controlled pot cultures of wheat and red clover,[1] however, have shown that plants in their early growing stages will assimilate potash from greensand as effectively as from ordinary soluble commercial potassium salts. In spite of these favourable experiments, and of the fact that it has proved possible to essentially increase the solubility of potash by composting greensand with sulphur, soil, and manure (MANSFIELD 1922, 114), the beds of glauconite do not seem to have been worked. As long as the usual potash fertilizers can be obtained at the present prices, it would not pay to use glauconite. According to the calculations of MANSFIELD a certain amount of potash on sale as glauconite would cost about twice as much as it does at present in the form of kainite.

The content of potash in glauconite can therefore only under exceptional conditions be worth consideration. On the other hand glauconite is present in such abundance that it undeniably forms an important reserve of potash. As an example we may mention that according to MANSFIELD's calculation New Jersey's greensand would be sufficient to supply the United States with potash for almost 1000 years, provided the annual consumption keeps as high as during the years immediately before 1914 (M. 1922, 107). The calculation only comprises the material obtainable by open-pit methods. Should it become feasible to use underground methods of mining there would be an enormous increase in the available quality of potash. The figures for Sweden would probably be lower but still very high.

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[1] Produced at The Bureau of Plant Industry, United States Department of Agriculture (see MANSFIELD 1922, 113 and Journ. Agr. Research. Vol. 15, 483—492).

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Index.

'' See the notes on the figures.

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