RADIOGRAPHIES OF CONSOLIDATED CALCAREOUS SEDIMENTS FROM DENMARK

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The paper deals with radiographic investigations, carried out by means of a simple, industrial X-ray unit. Contrary to, what is mentioned in the literature, it was found that the radiographic method is very useful in studying internal structures in consolidated calcareous sediments. This is illustrated by some examples of limestones from the Danish sedimentary sequence.

Introduction of radiography into geology

Today, the absorption of X-rays penetrating larger rocks is used still more extensively for solving scientific problems in geology and paleontology. Since the end of last century fossils have been analysed by means of this method, whereas it is less than 10 years ago, it was discovered that also the structures of sediments could be pictured this way. Hamblin (1962, p. 202) describes how it is possible on radiographs of thin slabs of apparently homogeneous sandstones to make fine structures visible, i.a. concentrations of heavy minerals on bedding planes.

Until today radiography has preferably been used for the investigation of recent and sub-recent unconsolidated sandy to argillaceous sediments; from numerous publications with more or less successful examples, only a few are to be mentioned here: Baker & Friedman, 1969; Bouma, 1963, 1964a, 1964b; Calvert & Veevers, 1962; Werner, 1967, 1968.

On the contrary, only a few attempts have been made so far in order to examine older and consolidated rocks (Bouma, 1969; Hamblin, 1962; Rioult & Riby, 1963). Through these experiments it has turned out that a successful exposure is mainly obtained when the subject is more or less fine-grained sand-, silt- or claystone. All present knowledge about this method and the problems connected hereto have been described extensively by Bouma, 1969 (pp. 140–244).

In spite of the fact that Hamblin (1962, p. 203) states that also limestones can be examined in this way, Bouma (1969, p. 149) summarizes:

"... However, the results obtained from many limestones are poor since variation in absorption between the different grains is often so small that no sedimentary picture is obtained. . ."

Bouma (1969, pp. 194–211) illustrates this statement by placing a number of photographs of limestones against corresponding radiographs. Also Wolf et al. (1967, p. 289) conclude that this method is of no use for investigating most limestones.

In January 1970 a suitable X-ray unit was installed at the Department of Geology, University of Aarhus in order to be used in the current investigations of Danish sediments. Working on this it proved that also structures in very homogeneous, fine-grained limestones can be seen, when using this method.

Methodology

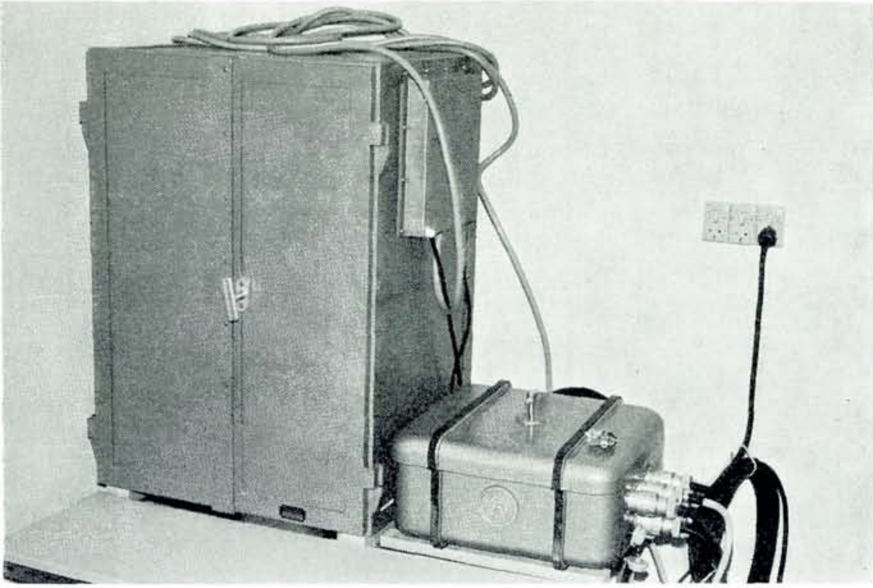
The processing of radiographs is well-known and has been used for several decades within the field of industry, medicine and palaeontology. The advantage of this method is the small use of time and money, and that the equipment necessary to produce radiographs is very simple to work. Important is that the method can be used on both consolidated and unconsolidated sediments. Another important matter is the non-destructive nature of the method. Besides, the exposures, of natural scale, give the advantage of easy and quick interpretation. Furthermore, sharp radiographs with fine contrasts are often enlarged with great success.

By this method it is necessary to be aware of the fact that only absorption differences can be measured. No direct statement regarding the sample material or the single specimen can be obtained, and no successful result must be expected, where no absorption difference occurs. Within the sedimentology this method has gained a special success by the fact that, when interpretating apparently very homogeneous rocks, even very fine inhomogeneities are found.

Suitable equipment for the production of radiographs has been described very little in the geological literature (last by Bouma, 1969); theoretically almost all X-ray equipments usable in medicine and industry are suited (Hamblin, 1962, p. 201).

In the Geological Department of Aarhus University is used a mobile "Leichtgewicht-Industrie-Röntgeneinheit (Typ Eresco 120 der Fa. Rich. Seifert & Co., Ahrensburg/Deutschland) für die zerstörungsfreie Werkstoffprüfung" for voltage up to 120 kV and load up to 5 mA. The X-ray unit consists of a high-voltage aggregate and a control panel.

The high-voltage aggregate holds an X-ray tube, a high-voltage- and a heat-transformer. A fan, rotating in oil, takes care of the dispersion of the



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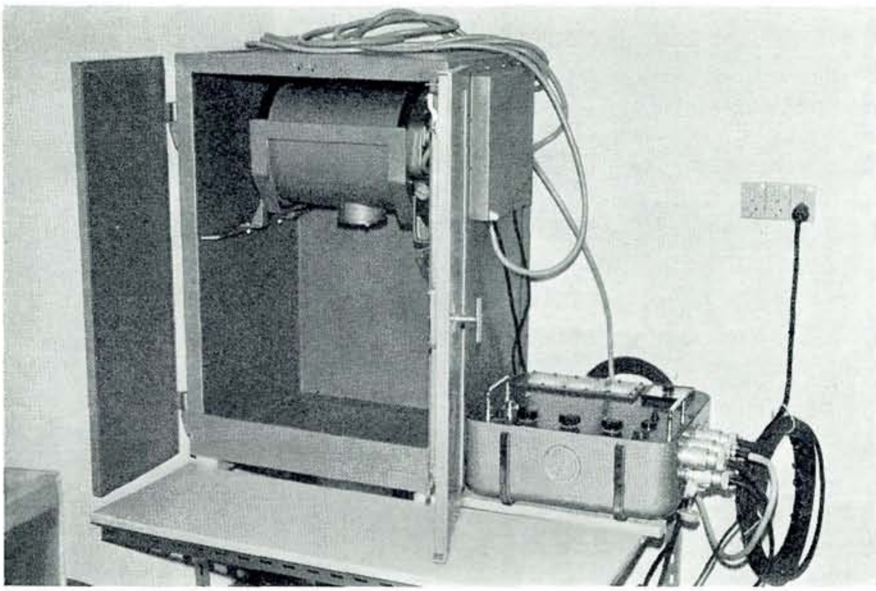

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Fig. 1 and 2. The X-ray equipment in the Department of Geology, University of Aarhus. The high-voltage unit is installed in the protecting box (fig. 2).

heat units appearing by the anode. In order to avoid super-heating, when using the equipment for a long time, the unit can be cooled by use of water.

The control panel holds a mains voltage-meter, a milliammeter and a kilo-volt-meter, for adjustment of the X-rays of the requested value. A built-in electrical stop watch controls the time of exposure indicated, and disconnects the equipment automatically when finished. The voltage is adjustable continuously from about 25–120 kV, the tube current from 0–5 mA. The equipment can be run by an ordinary A.C. net; oscillations of ± 10 % can be equalized through a net-regulation. The total X-ray unit is secured through several fuses, the tube also through a thermal relay.

The high-voltage unit is built-in in a lead-lined protecting box, which flap doors are equiped with safety fuses. Hereby precautionary measures have been followed very carefully. The dimensions of the protecting box allow samples sizes of 400 × 400 mm and fix a maximum distance of 60 cm from the X-ray film to the focus. The high-voltage unit can even be taken out of the protecting box, and also be run somewhere else.

Theoretically fine-grained industry X-ray films are most suitable for the production of radiographs. They are available in different sizes. The exposures at hand are made with Ilford Ilfex, 3M Type T, Ferrania Type Lambda, Delta and Gamma and Kodak Definix Médical.

Radiographs are produced of any shape of sample. But as the different thicknesses of a sample on account of different absorption can be very disturbing, it has proved useful to make plan-parallel rock slices. Of consolidated rocks these slices are very easily made with a simple stone saw. A most suitable thickness for the slices is 2–20 mm (Hamblin, 1962, p. 202); most of the exposures shown here are of slabs with a thickness of 2–8 mm. Any description or remark on the radiograph can be made with lead letters.

Instructive values for connection between rock type and slice thickness are published by Bouma (1969) and Fraser & James (1969). The connection between kV values and contrast of the radiograph is also mentioned.

The X-ray film is protected by a thin, opaque, synthetic foil, which is permeable for X-rays. The rock slice is placed directly on the foil.

The absorption of the X-rays by passage through the slice is dependent on the thickness, the density and the type of material (Bouma, 1969, p. 148). Differences in one of these parameters are consequently pictured on the radiograph. This is especially distinct by occurence of isolated grains of ore and heavy minerals (Bouma, 1969, p. 140; Hamblin, 1962, p. 202). The exposed X-ray films are processed in a dark room. The film may then be used directly for examination, or if wanted, a contact copy can be made. Due to the fine-grained nature of the X-ray film very good enlargements can be produced.

Some illustrations

In order to illustrate the suitability of the radiographic method, some examples of the investigations of Danish limestones will be examined below (see also Thiede & Larsen, 1970).

Middle Cambrian limestone

The Middle Cambrian limestone bed outcropping at Læsaa, Bornholm belongs to the *Paradoxides forchhammeri* Stage (Poulsen, 1966). This bed falls lithologic-stratigraphically into two units: i.e. the Andrarum Limestone above and the, by Hadding (1958) called, "fragment limestone" below. The latter is partly anthraconitic, and holds a phosphorite conglomerate (i.a. Hansen, 1943; Hadding, 1958).

This "fragment limestone" from Læsaa has been examined radiographically with the result shown in fig. 3b. For comparison an ordinary photograph is shown in fig. 3a. It can be seen that the sample consists of a conglomerate resting on an apparently fine-grained limestone. By comparing these two exposures it is noted that the radiograph discloses many more details, especially in the structure of the fine-grained limestone, than the ordinary photograph. Thus the stratification is marked very distinctly by the presence of a zone with a high content of pyrite, which appears black; but also outside the zone a fine lamination is sharply pictured in the radio-

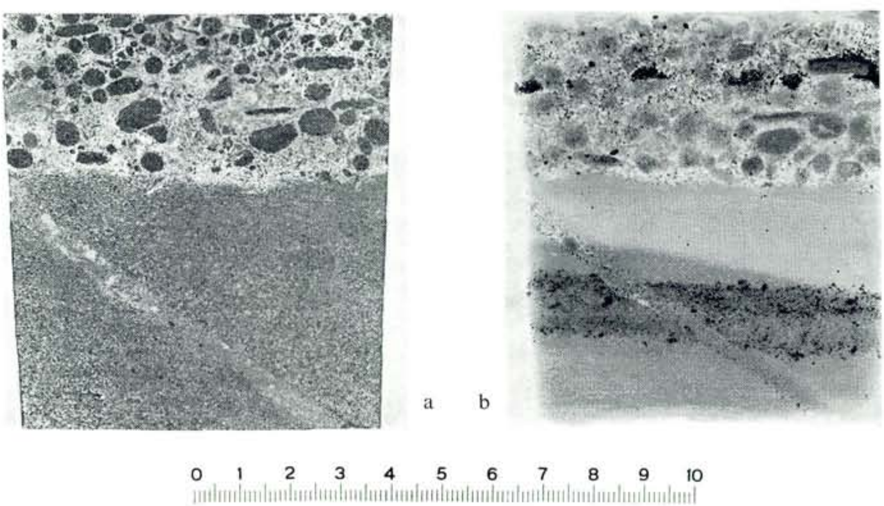
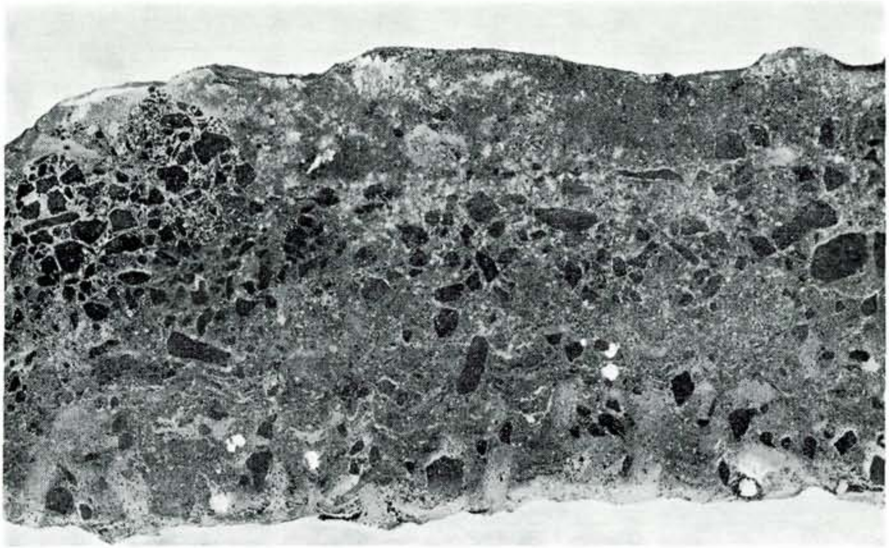


Fig. 3. Middle Cambrian "fragment limestone", Læsaa, Bornholm. *a:* Ordinary photograph. *b:* Radiograph. Thickness of slice: 5.6 mm. Film: 3M Type T. kV: 35. mA: 5. Time of exposure: 4 minutes.



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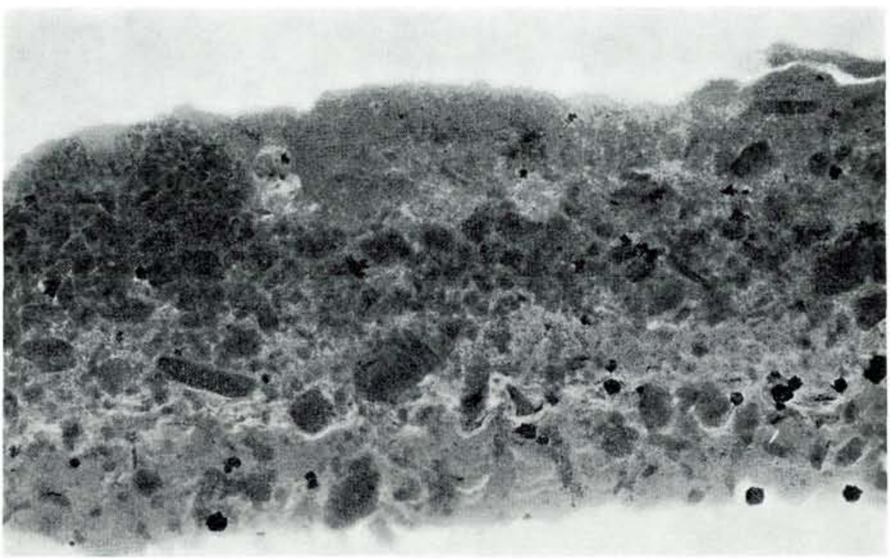

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Fig. 4. Lower Ordovician Skelbro Limestone, Limensgade, Bornholm. *a:* Ordinary photograph. *b:* Radiograph. Thickness of slice: 7.0 mm. Film: Ilford Ilfex. kV: 40. mA: 5. Time of exposure: 2 minutes.

graph. Furthermore, it can be seen that the boundary on to the conglomerate runs irregularly compared to the lamination of the fine-grained limestone. This can be interpreted as a result of erosion before or comtemporary with the deposition of the coarse material. Finally the rock is cut by an oblique structure, ascribable to a later deformation.

Skelbro Limestone.

The Lower Ordovician Skelbro Limestone belongs to the *Cyclopyge stigmata* Zone (Poulsen, 1965). The limestone rests on the likewise Lower Ordovician *Dictyonema* Shale. This boundary zone is exposed in an earlier limestone quarry, Limensgade at Læsaa, Bornholm.

From this locality some samples of the lower part of the Skelbro Limestone are examined radiographically. An example is shown in fig. 4b. Fig. 4a shows an ordinary photograph of the same sample.

It can be seen that the sample consists of a conglomerate superposed by a fine-grained limestone. The conglomerate consists of phosphorite nodules and fragments of phosphorized shale (*Dictyonema* Shale) embedded in a fine-grained lime matrix. The boundary between the conglomerate and the fine-grained limestone is very irregular, which might indicate an erosion in the coarse deposit before the deposition of the fine-grained lime material. In the lower part of the conglomerate several light streaks can be seen; these pass very irregularly in the lime matrix between the larger phosphorite nodules. It seems obvious to explain these streaks as weakly developed stylolite structures; but one cannot completely eliminate the possibility that it is a synsedimentary phenomenon. In this connection it can be noted that discontinuity surfaces, of presumed synsedimentary origin, have earlier been mentioned from the Skelbro Limestone (Poulsen, 1965).

Arnager Limestone

According to Ravn (1918) the Arnager Limestone is of Upper Turonian age. Contrary to Ravn, basing his dating especially on the molluscs, Douglas & Rankin (1969) come to a Coniacian age for this limestone by investigating the planktonic foraminifera; the molluscs are supposed to be reworked forms from Turonian. The lime content of the rocks is 50–60 % (Ravn, 1918). Regarding the environment of the deposition Douglas & Rankin (1969) state that it must be pelagic according to the high content of planktonic foraminifera, coccoliths and radiolarians in the sediment.

A number of samples from the Arnager Limestone has been examined radiographically. All samples have been taken from the cliff at Arnager, on

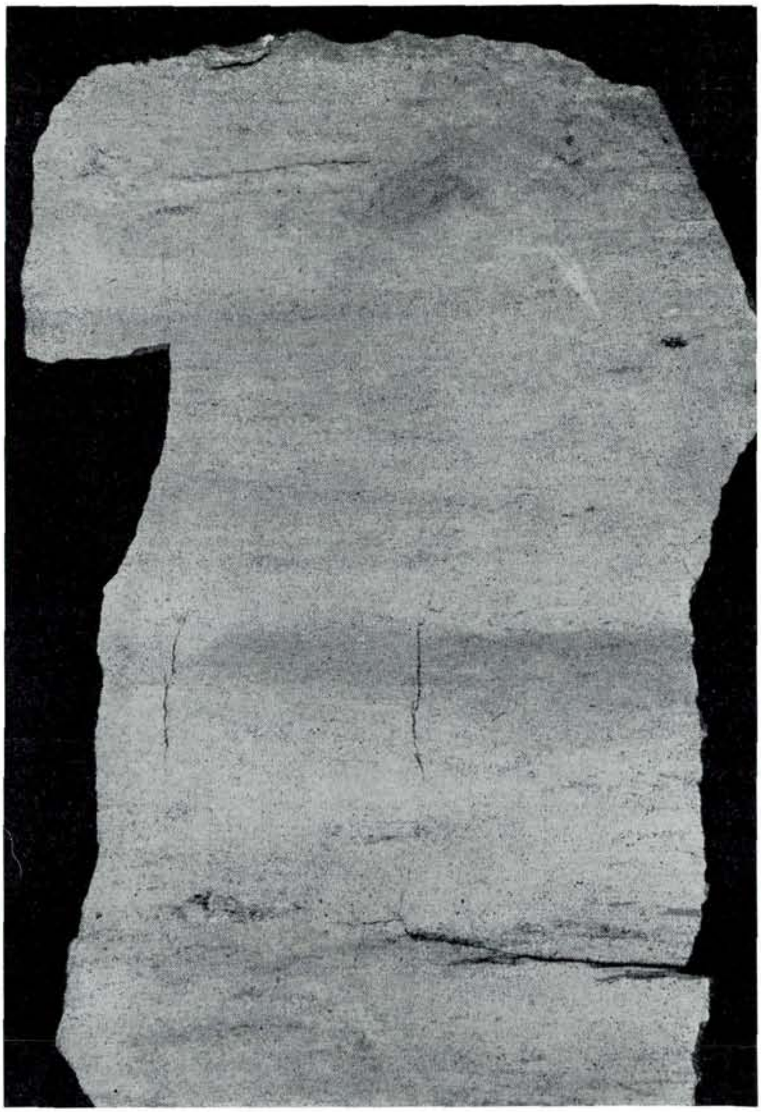

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Fig. 5. Arnager Limestone, Arnager, Bornholm. *a:* Ordinary photograph. *b:* Radiograph. Thickness of slice: 4.0 mm. Film: Ilford Ilfex. kV: 30. mA: 5. Time of exposure: 1 minute.

the south coast of Bornholm. The rock, in this exposure, is light grey to whitish grey without any conspicuous stratification, but with numerous cracks.

One of the samples is shown in fig. 5a and b. On the ordinary photograph (fig. 5a) a *stratification* is faintly pictured by the occurence of a

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little darker zones in the light rock. This stratification can be seen much more distinct on the radiograph (fig. 5b). The prevailing structure is apparently a lamination. However, this is not in all cases continuously, as lenticular structures appear in several places. In the upper part of the rock sample a

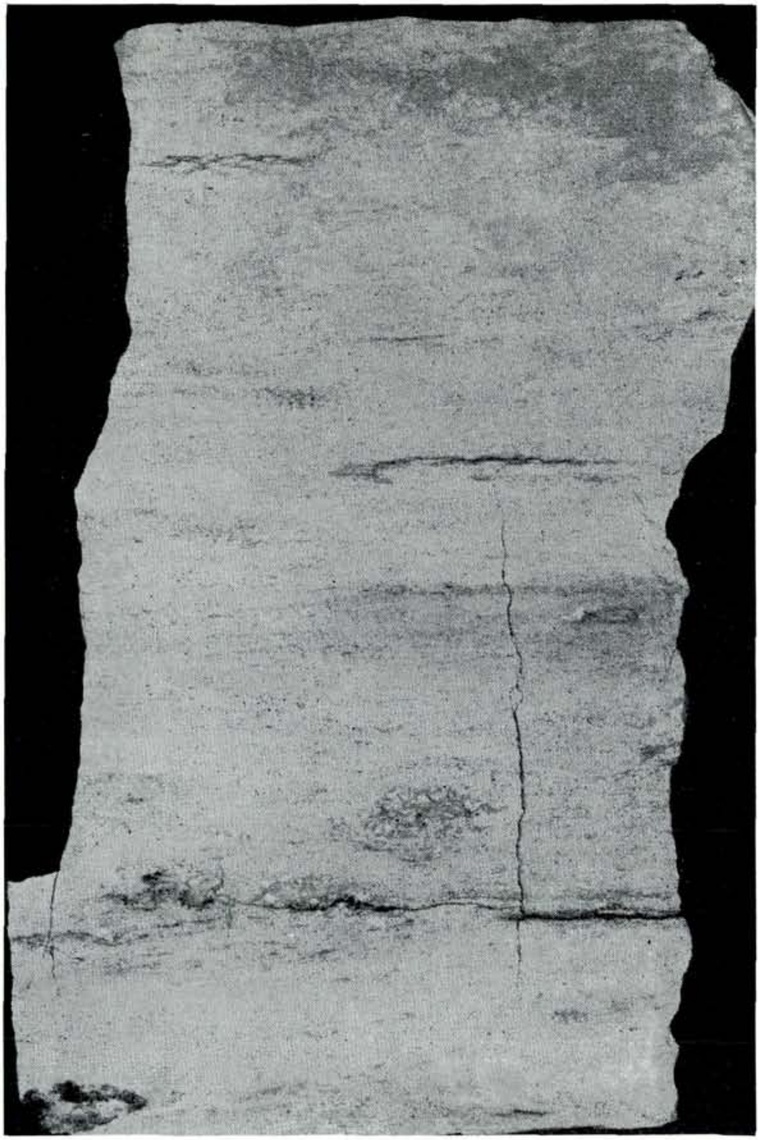

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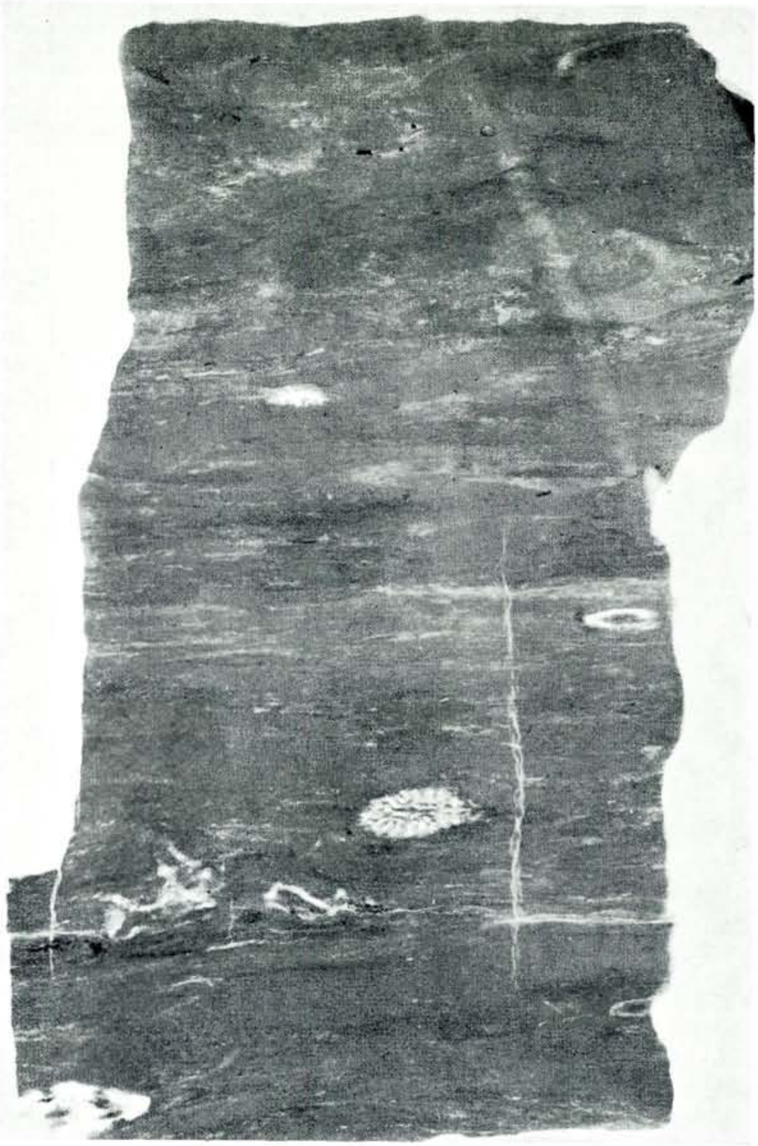
Fig. 6. Arnager Limestone, Arnager, Bornholm. *a:* Ordinary photograph. *b:* Radiograph. Thickness of slice: 4.0 mm. Film: Ilford Ilfex. kV: 30. mA: 5. Time of exposure: 1 minute.

large, edged fragment with an internal lamination is observed. This lamination forms an angle with the stratification in the surrounding sediment. Pyrite can be seen as black spots, with a more or less stratified orientation. Finally



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the occurence of cracks is noted; as these cracks are widest in the middle part and get thinner towards the ends, they might be classified as shrinkage cracks.

Another sample is shown in fig. 6a and b. In fig. 6a, being an ordinary photograph, a cross-section of fossils is seen. In the radiograph, fig. 6b, these fossils are pictured much more detailed. Furthermore, a clear lamination can be seen. Finally a structural form is noted, probably a deformation trace produced by burrowing organisms in the sea floor.

According to these observations it is assumable that the Arnager Limestone has been deposited in an environment influenced by water movements above the sea floor; i.a. erosional forms and traces of the activity of benthonic organisms indicate this. That the environment should be pelagic as stated by Douglas & Rankin (1969) is not the most obvious conclusion taking these observations on sedimentary structures into consideration.

White chalk

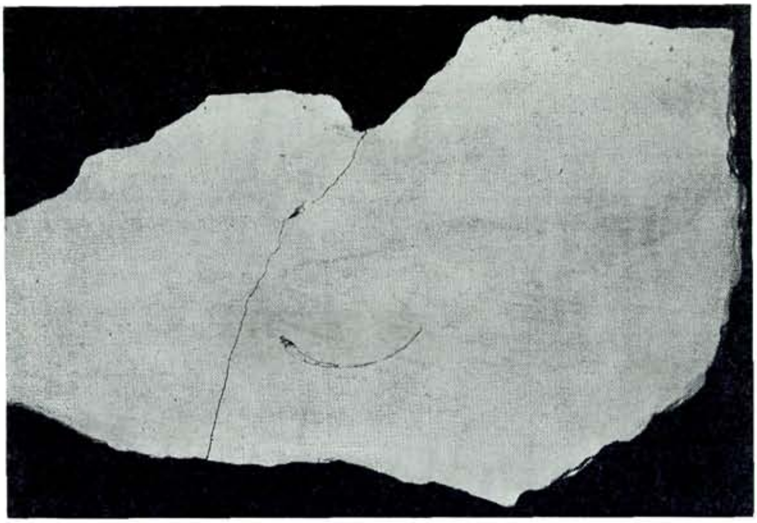
The Senonian white chalk is a white, rather pure, fine-grained chalk (i.a. Gry & Søndergaard, 1958). The lime content is in the central parts of the area of deposition mostly 96–100 % (Larsen, 1965), whereas it is somewhat lower in the marginal areas (Larsen et al., 1968) The lime mud was earlier considered to be precipitated chemically. According to electronic microscopic investigations it is mainly compounded of finely divided parts of pelagic organisms, especially coccoliths (regarding these see Perch-Nielsen, 1969).

Radiographic investigations have been carried out on a number of samples of white chalk from Rørdal chalk pit at Aalborg, North Jutland. The age of this chalk is Lower Maastrichtian; this deposit is among other things characterized by being very poor in flint.

All samples can, according to macroscopic investigations, be classified as almost structureless white chalk. This is illustrated in fig. 7a, showing an ordinary photograph of one specimen. The only detail observed, is a cross-section of a brachiopod shell.

A radiograph (fig. 7b) of the sample shows that the apparently structureless rock has a very distinct stratification. A fine lamination is seen. This is locally disturbed by cloudy structures, probably a trace of burrowing organisms. Besides this, fragments of many, mostly small fossils can be seen. Finally it is noted that lamination structures occur in the sediment around the large brachiopod shell. This structure reflects the influence of the shell on the local conditions of deposition. Thus it is seen that the lamination is weakly bended on the convex side of the shell, probably a deformation due to the load of the shell on the soft sediments. On the concave side of the shell the form of lamination seems to indicate a small scale basinfilling.

Two other rock samples are shown in fig. 8 and 9. Due to the fact that



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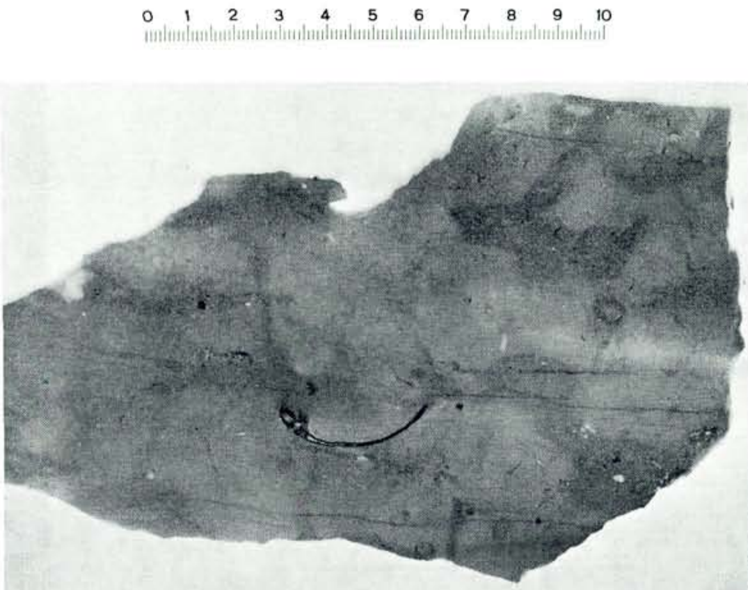

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Fig. 7. White chalk, Aalborg. *a:* Ordinary photograph. *b:* Radiograph. Thickness of slice: 3.2 mm. Film: Ilford Ilfex. kV: 35. mA: 5. Time of exposure: 30 seconds.

both subjects appeared without visible structures on ordinary photographs, only copies of radiographs are reproduced.

In fig. 8 it is seen that the bedding is only weakly implied, except for a

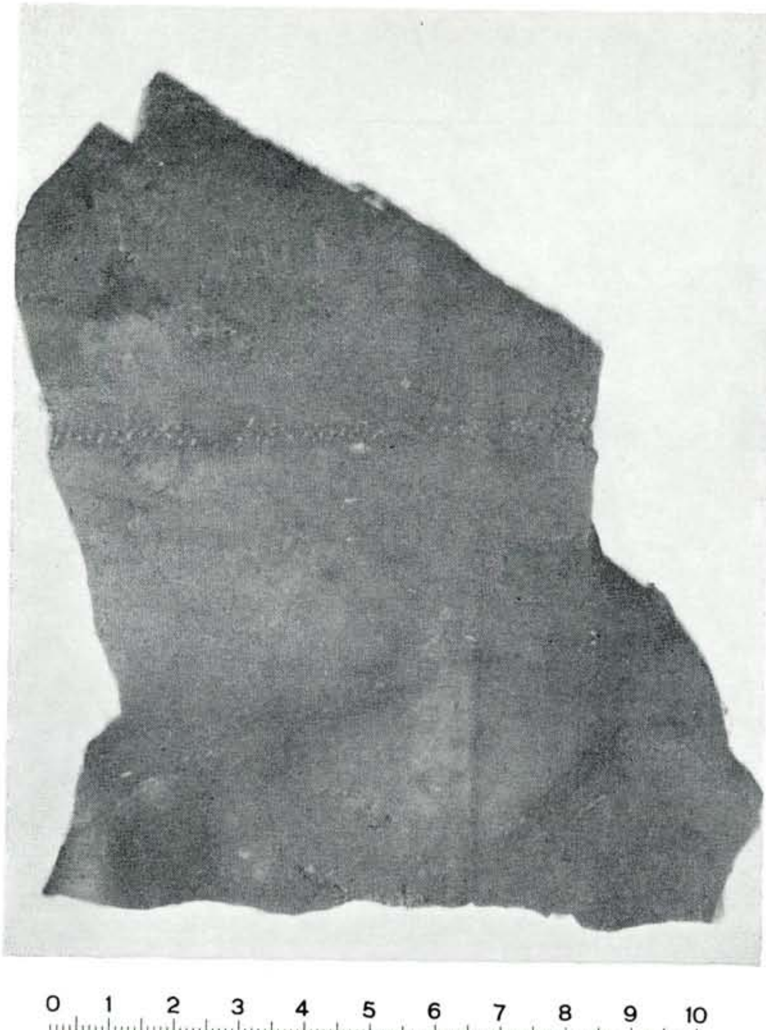

Fig. 8. White chalk, Aalborg. Radiograph. Thickness of slice: 3.6 mm. Film: Ilford Ilfex. kV: 35. mA: 5. Time of exposure: 30 seconds.

thin zone in the middle of the specimen. Here a zone of small, light spots is found, apparently remains of fossils. Obviously this structure is synsedimentary and not diagenetic. This is proved by the occurence of a burrowing structure in this zone. Finally it should be noted that the shape of the specimen does not reflect the bedding in the sediment. This bedding, however, is sharply disclosed in the radiograph.

Fig. 9. White chalk, Aalborg. Radiograph. Thickness of slice: 4.0 mm. Film: Ilford Ilfex. kV: 35. mA: 5. Time of exposure: 30 seconds.

Fig. 9 shows a chalk specimen, apparently without visible stratification, but with several deformations made by burrowing organisms. Furthermore, remains of fossils, i.a. a bryozoan, are seen. However, the most remarkable feature is a swarm of needles, which no doubt are sponge-spicules. The spicules are evidently quite random orientated. This indicate that the spicules have not been sorted during the sedimentation process.

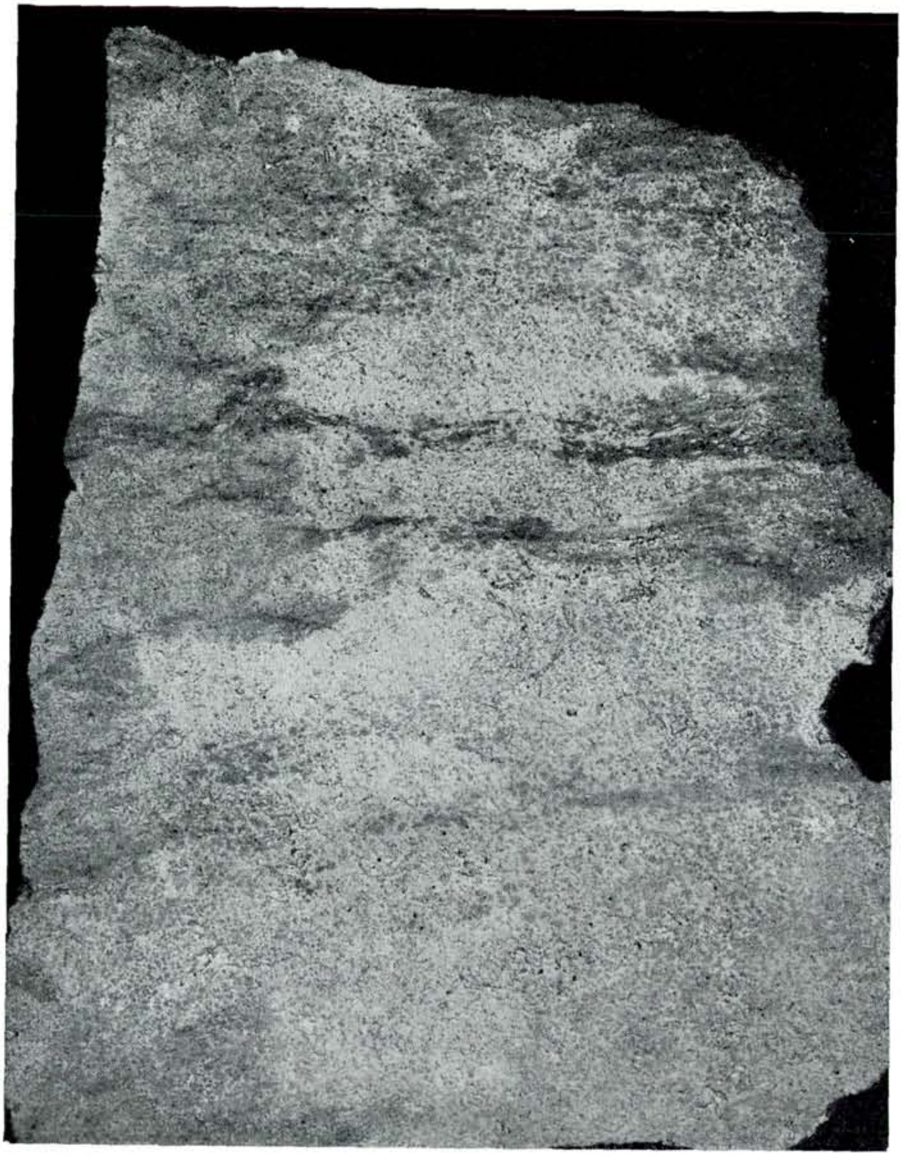

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Fig. 10. Bryozoan limestone, Bulbjerg. *a:* Ordinary photograph. *b:* Radiograph. Thickness of slice: 4.3 mm. Film: Ilford Ilfex. kV: 35. mA: 5. Time of exposure: 1 minute.

According to these few stray observations the apparently homogeneous chalk deposits, consisting mainly of remains of pelagic organisms, are obviously influenced by a vivid activity of benthonic organisms.

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Bryozoan limestone

The bryozoan limestone is one of the most characteristic rock types of the Danian. The bryozoan limestone consists, however, not exclusively of bryo-

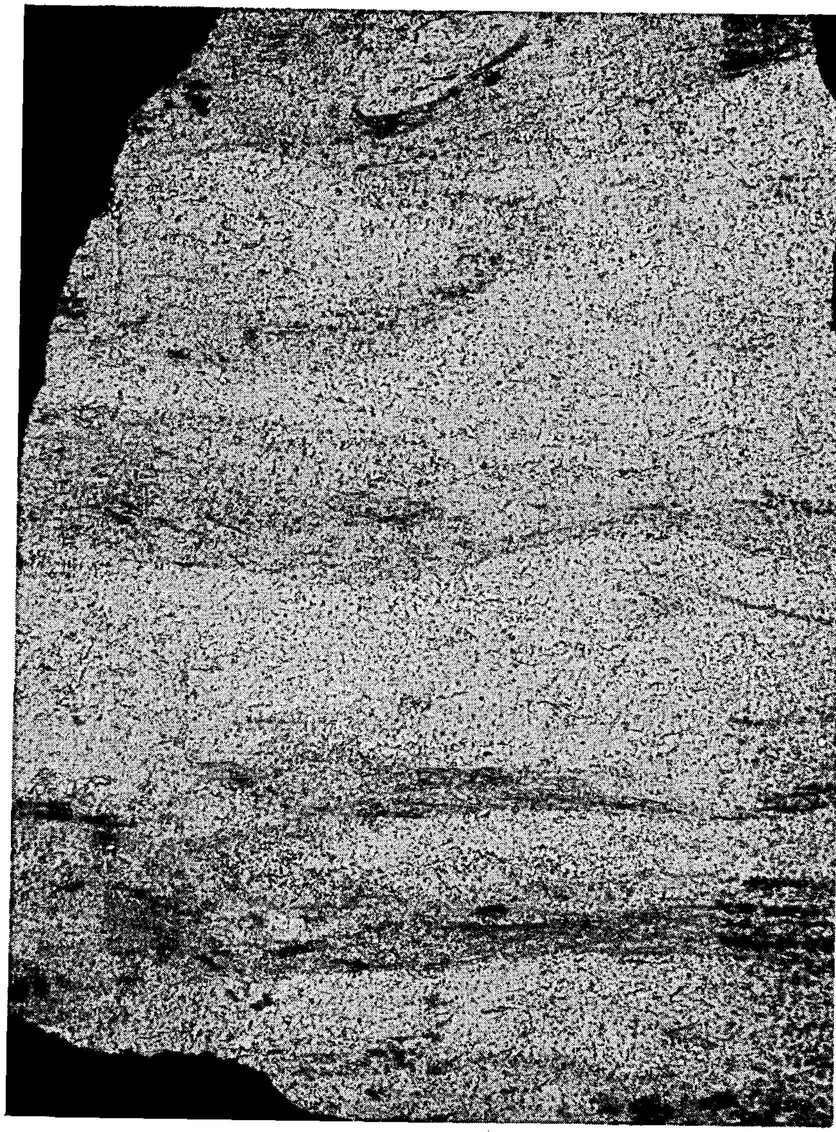

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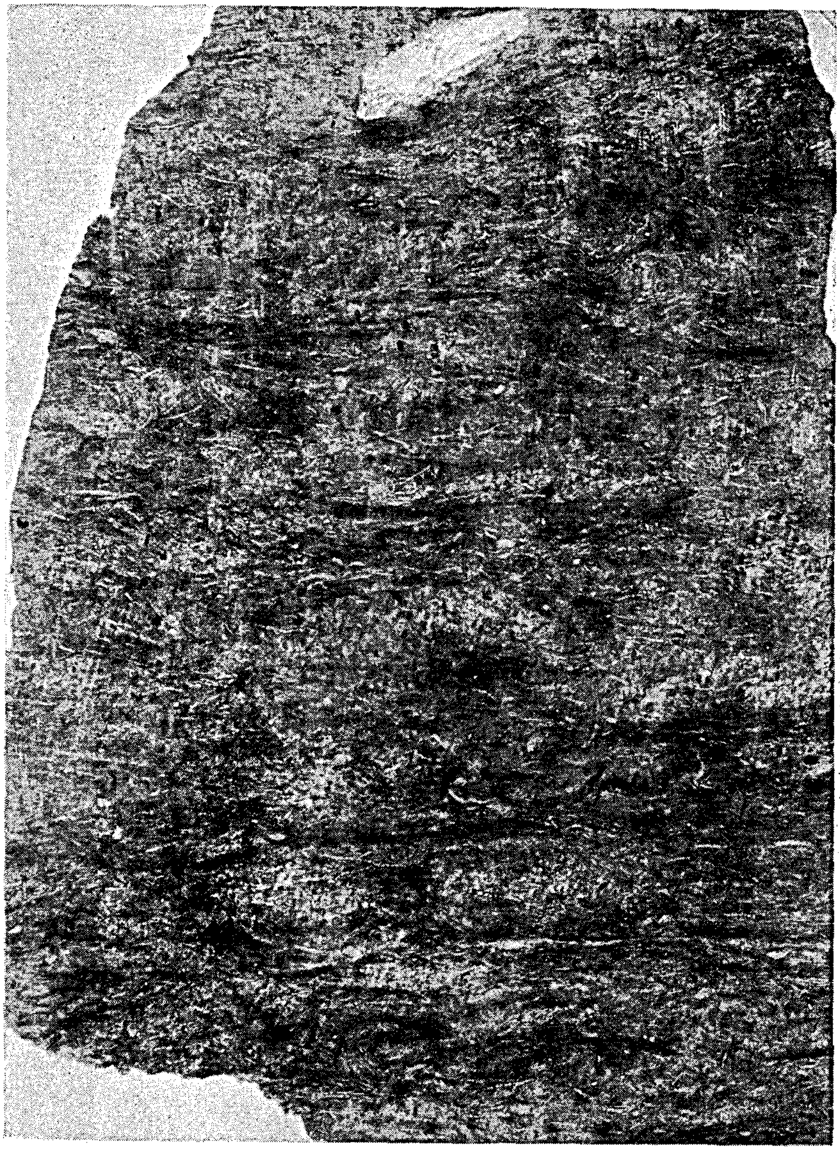
Fig. 11. Bryozoan limestone, Bulbjerg. *a:* Ordinary photograph. *b:* Radiograph. Thickness of slice: 3.5 mm. Film: Ilford Ilfex. kV: 35. mA: 5. Time of exposure: 30 seconds.

zoan fragments; according to Berthelsen (1962) these fossils amount, in fact, to less than 40 % of the rock. In the bryozoan limestone bank-structures occur generally. Johnstrup (1882) and Rørdam (1897) considered the



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limestone to be a sandstone-like rock i.e. obviously an allochthonous limestone deposit. Others, thus Gry & Søndergaard (1958), Brotzen (1959), Rosenkrantz & Wienberg Rasmussen (1960) and Berthelsen (1962) consider the bryozoan banks to be either bioherms or biostromes. To this can be added that no evidence of allochthonous origin of bryozoan limestone has been found by petrographic thin section investigations of a few numbers of specimens (Larsen, 1961).

Radiographic investigations have been carried out on a number of samples of bryozoan limestone from the cliff at Bulbjerg, North Jutland. In this deposit bank-structures can be seen clearly. The limestone belongs to Older Danian, namely zone B (Ødum, 1926), i.e. the *Tylocidaris abildgaardi* Zone.

Of one of the samples is shown an ordinary photograph (fig. 10a) and a copy of a radiograph (fig. 10b). In the former a few dark zones can be seen in the light rock, marking a certain stratification. The radiograph shows beside this stratification also numerous details especially concerning the structure and the orientation of fossils, mainly remains of bryozoans. It is noted that outside the distinct stratified zones the fragments of bryozoans are evidently random orientated. This might indicate that this bryozoan limestone is of an autochthonous origin.

Fig. 11a and 11b show another sample. This one has more distinct stratification than the other sample, a feature which can be seen on the photograph (fig. 11a) as well as on the copy of the radiograph (fig. 11b). On the radiograph it is furthermore noted that almost all fossil fragments are oriented parallel to the stratification. This is a feature corresponding to what Johnstrup (1882) and Rørdam (1897) called sandstone-like. – It is thus possible that the two examples mentioned above (fig. 10 and fig. 11) represent the span from the autochthonous to the allochthonous in the origin of the bryozoan limestone.

Finally an oval, quite white area is observed in the upper part of fig. 11b. This can hardly be seen in fig. 11a. The area is an occurrence of a light, calcareous opal flint. This is an example of, how the occurrence of flint in limestone is very clearly reflected on radiographic exposures.

Closing remarks

The examples described above illustrate that the radiographic method, being quite simple, can contribute considerably to the illumination of the structures of calcareous sediments. It must, however, be emphasized that the method can hardly replace the thin section analysis, when it is a question of detailed studies, but it can be used as a supplement. An important feature is the fact that the radiographic method very quickly gives survey of the internal structure of a larger sample. This is of course important in itself, but beside this the radiography might be used for the selection of subjects for thin section analysis. It will therefore be natural in the future sedimentological investigations of calcareous deposits to link the macroscopic observations in the field together with the thin section analysis in the laboratory by means of the radiographic examination.

Dansk sammendrag

Artiklen omhandler radiografiske undersøgelser udført ved hjælp af et simpelt, industrielt røntgenapparatur. Indenfor geovidenskaberne har denne metode hidtil i det væsentlige været benyttet ved palæontologiske arbejder, samt ved studier over strukturer i finkornede, ukonsoliderede sedimenter. Ifølge litteraturen skulle metoden være lidet egnet til undersøgelse af hærdnede kalksedimenter. Dette svarer imidlertid ikke til forfatternes erfaringer, der netop går ud på, at man ved hjælp af radiografier kan få meget detaljerede oplysninger om de indre strukturer i kalkrige sedimenter. Dette er i artiklen illustreret ved nogle eksempler på undersøgelse af kalksten fra den danske lagserie.

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July 17th, 1970

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