Character and provenance of the opaque minerals in the Nexø sandstone, Bornholm

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The Nexø sandstone is a subarkosic sandstone with subangular grains of quartz and feldspar in a red coloured matrix. The sandstone was deposited in Eocambrian or early Cambrian directly on the Precambrian basement rocks of Bornholm, and was thought to have been derived from the breakdown of these rocks.

The amount of opaque minerals in the sandstone is about 1%. Most of the opaque grains belong to one of two groups: (1) ilmenite-hematite exsolution intergrowths with the hematite phase strongly dominant, and (2) martite with extremely fine lamellar structure indicating that the martite originates from titano-magnetite.

The fine lamellar martite could have originated from dolerites on Bornholm as well as from Precambrian dolerites in Sweden, but ilmenite-hematite exsolution intergrowths are not known from any base-ment rock on Bornholm, the nearest exposure of rocks carrying ilmenite-hematite exsolutions lying in Sweden 150 km to the NW of Bornholm. It is suggested therefore that at least part of the material in the Nexø sandstone originated in southern Sweden, a proposal that is consistent with palaeocurrent evi-dence from the sandstone.

The relative amounts of ilmenite-hematite and fine lamellar martite vary strongly, and although the amount of martite is no proper measure of the proportion of material of local Bornholm origin this variation may be an indication of the relative amounts of material of local origin and material of more distant origin.

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The Nexø sandstone is an Eocambrian or early Cambrian deposit lying directly on the Precambrian basement rocks of Bornholm.

In the course of a palaeomagnetic investigation of the sandstone, Dr. S. N. Prasad of the Geophysical Institute of the University of Copenhagen encountered certain difficulties which he thought might arise from the ore mineral content of the rocks. This prompted him to ask the author what ore minerals were to be expected in the sandstone.

Although familiar with the opaque mineral content of the Precambrian crystalline rocks of Bornholm (Jensen 1966, 1968), from which the Nexø sandstone has hitherto been thought to have been derived (Gry 1936), the author was reluctant to use this knowledge alone as a guide to the opaque mineral content of the sandstone. An investigation of the opaque minerals of the Nexø sandstone was therefore undertaken. The results show that the deposit cannot have been derived solely from the basement in Bornholm, but must at least in part have a provenance outside Bornholm, most likely in southern Sweden.

Previous work on the Nexø sandstone

Although references to the Nexø sandstone date back to 1763, the first comprehensive account of the sandstone appeared in the text accompanying the first geological map sheet of Bornholm (Grønwall & Milthers 1916). Stehmann (1934) was the first to consider the lower part of the Nexø sandstone as a terrestrial deposit, a view shared by all later workers. Gry (1936) subdivided the sandstone into a lower terrestrial part, a middle littoral part and an upper marine part; on the basis of heavy mineral analysis Gry suggested that the sandstone was derived from local Bornholm rocks, but he was concerned about the presence of tourmaline in the heavy mineral concentrates as tourmaline is not known from the crystalline rocks of Bornholm, and he stated that a definite conclusion about the source of the Nexø sandstone must await detailed investigations of the accessories in the pegmatites and aplites of the island. Hansen (1938) introduced the name 'Balka quartzite' for Gry's upper ma-

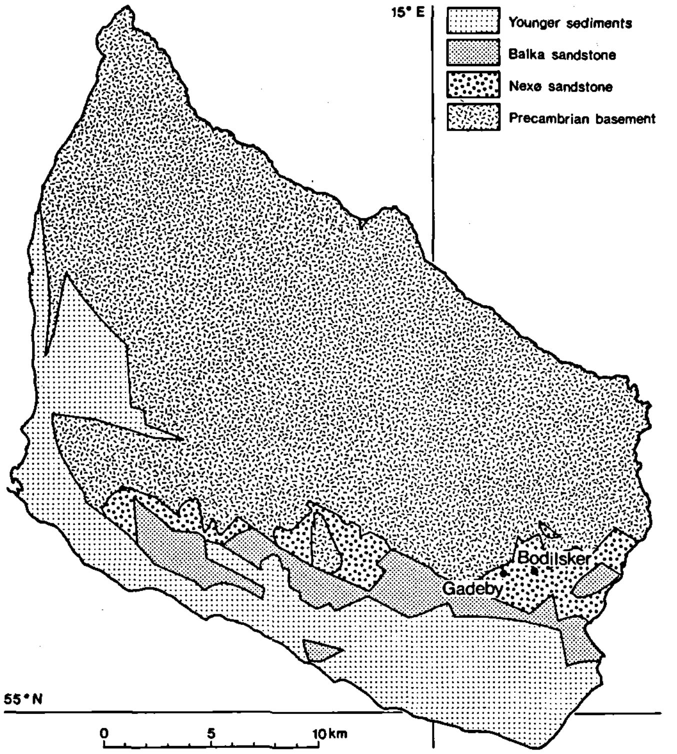

Fig. 1. Sketch map of Bornholm showing the distribution of the Precambrian basement, the Nexø sandstone and the Balka sandstone. After Gry (1960).

rine part, and in 1960 Gry divided the formation into a lower restricted Nexø sandstone and an upper Balka quartzite. This terminology is now widely used with the modification that the upper unit is termed Balka sandstone. However Brun-Petersen (1971) returned to the older usage and included the Balka sandstone in the 'Nexø Sandstone Formation' which he subsequently divided into three informal members (from below): (1) The Bodilsker member – a 60 m thick unit composed of subarkosic sandstone with a large content of clay matrix; the Bodilsker member is thought to have been deposited by braided rivers and corresponds to the lower terrestrial part of Gry (1936).

(2) The Åkirkeby member – a 30 m thick unit composed of subarkosic sandstone with no more than 15% clay matrix; this member is probably a shore-line deposit and it corresponds to the littoral part of Gry (1936).

(3) The Balka member – a 60 m thick unit composed of very pure quartz sandstone with a maximum of 5% feldspar and 5% matrix; this is a marine deposit with trace fossils which corresponds to the upper marine part of Gry (1936).

The distribution of the Precambrian basement, the Nexø sandstone and the Balka sandstone is shown in fig. 1.

Materials investigated

The investigation of the opaque minerals is based mainly on the samples collected by Dr. S. N. Prasad from Gadeby quarry and Bodilsker quarry. The material used comprises polished sections of concentrates of opaque minerals separated from samples from both quarries, and polished sections of whole rock samples from the Gadeby quarry.

In the Gadeby and Bodilsker quarries the Nexø sandstone is brownish red and shows alternating dark brown-red and light reddish laminae. The thickness of the laminae varies from about 1 mm to about 1 cm. The sand particles lie in a red coloured matrix; they are subangular and consist of quartz, feldspar (mainly microcline), and a little muscovite.

In the dark brown-red laminae the sand particles have a smaller grain size, averaging about 0.15 mm, and are better sorted than in the light reddish laminae, the average grain size of which is about 0.30 mm. The colour difference reflects different amounts of matrix, the dark brown-red laminae being richer in matrix than the light reddish laminae.

The opaque minerals of the Nexø sandstone

The amount of opaque minerals present in the investigated part of the Nexø sandstone is a little less than one percent. Based on counting of more than 70 000 points the amount of opaque minerals in a specimen rich in dark brown-red laminae was found to be 0.9%, whereas the counting of more than 70 000 points in a specimen rich in light reddish laminae gave only 0.7%.

The opaque minerals have a grain size which is considerably smaller than that of the quartz and feldspar. The diameter of opaque grains varies from a few μm up to about 0.2 mm. The number of grains with diameter larger than 50 μm about equals the number of grains with diameter smaller than 50μm. The larger grains are generally more or less equidimensional, whereas smaller grains are frequently elongated. The outline of the grains, larger grains as well as smaller grains, is irregular and characterized by many small protuberances.

Table 1 shows the relative amounts of the different types of opaque minerals as percentages of the total amount of opaques for a whole rock specimen rich in dark brown-red laminae, a whole rock specimen rich in light reddish laminae, and for four concentrates of opaques separated from samples from two different quarries. The values in the table are based on the counting of about 500 points in two runs which agree very well.

It is clearly seen that most of the opaque mineral grains belong to one of two groups: ilmenite-hematite exsolution intergrowths and martite with fine lamellar structure. Descriptions are now given both of the minerals listed in the table and of a few opaques occurring in such small amounts that they are omitted from the table.

Ilmenite-hematite exsolution intergrowths

The hematite phase is the dominant phase in these grains, forming more than 90% of the grain area of all but one of the grains investigated. In the single exception the ilmenite phase exceeded the hematite phase in area.

The ilmenite-hematite exsolution intergrowths

Table 1.

	1	2	3	4	5	6
Ilmenite-hematite exsolution intergrowths	46	35	37	51	41	42
Martite with fine lamellar structure	32	52	49	18	27	18
Hematite-rutile intergrowths	8	7	3	11	6	6
Ilmenite with alteration of beach sand type					1	2
Goethite	2	2	1	2	nd	nd
Rutile	1			1	3	3
Anatase	5	4	4	7	7	11
Zircon	5	3	5	7	13	13
Sphene					2	2
	99	103	99	97	100	97

Column 1: Concentrate of sample No. 33014 from Gadeby quarry.
Column 2: Concentrate of sample No. 33015 from Gadeby quarry.
Column 3: Concentrate of sample No. 33025 from Bodilsker quarry.
Column 4: Concentrate of sample No. 33026 from Bodilsker quarry.
Column 5: Whole rock rich in dark brown-red laminae from Gadeby quarry.
Column 6: Whole rock rich in light reddish laminae from Gadeby quarry.

Fig. 2. Polariser only, × 800, oil immersion. Hematite-rich ilmenite-hematite exsolution intergrowth with lamellae of rutile. Polished section of concentrate of sample 33014 from Gadeby quarry.

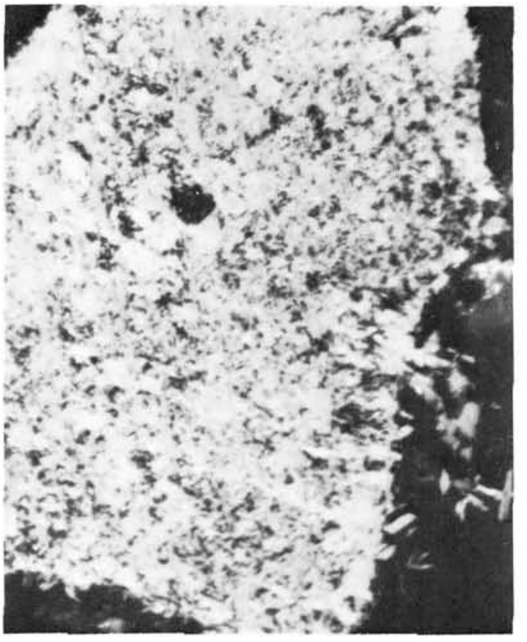

Fig. 3. Polariser only, × 800, oil immersion. Martite with many holes after dissolution. Polished section of concentrate of sample 33014 from Gadeby quarry.

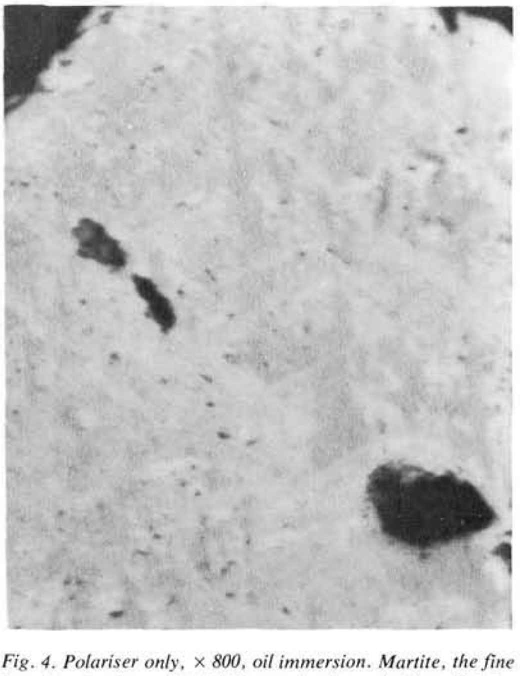

Fig. 4. Polariser only, × 800, oil immersion. Martite, the fine lamellar structure of which is vaguely shown by the reflection pleochroism. Polished section of concentrate of sample 33015 from Gadeby quarry.

Fig. 5. Polars 4° from crossed position, × 800, oil immersion. Martite, the same field as fig. 4, the fine lamellar structure is now clearly shown by the anisotropy effect.

can be divided into four subgroups: (1) grains that only consist of ilmenite-hematite, (2) grains that in addition contain thin lamellae of rutile in up to six directions, (3) grains with smaller masses of rutile as well as lamellae of rutile, and (4) grains with smaller masses of rutile but without rutile lamellae. The first two subgroups occur more frequently than the last two.

The grains of all four subgroups are generally very fresh, but can have smaller or larger holes formed by dissolution, and occasionally part of the ilmenite phase is altered to a fine-grained intergrowth of rutile and hematite.

Ilmenite-hematite with rutile lamellae is shown in fig. 2.

Martite with fine lamellar structure

This martite has an extremely fine lamellar structure indicating that the martite originates from titanomagnetite, the Ti of which is mainly dissolved leaving a pattern of small dissolution holes. This group of grains can be divided into two subgroups: (1) grains without rutile, and (2) grains containing rutile masses. The subgroup without rutile is strongly predominant. During the investigation the author tried to distinguish between grains dominated by dissolution and grains with fewer dissolution holes. Although such a distinction has to be arbitrary, it was found that in the subgroup without rutile most grains had fewer dissolution holes, whereas grains with rutile masses were practically always dominated by dissolution holes.

Martite is shown in figs 3–5.

Hematite-rutile intergrowths

Intergrowths of hematite and rutile occur rather frequently and in these either phase can dominate. It is impossible from the structure to judge whether these intergrowths are derived from original titanomagnetite or original ilmenite, and there may very well be grains of either origin. Fig. 6 shows hematite-rutile intergrowth.

Ilmenite with alteration of beach sand type

In polished sections of whole rocks of Nexø sandstone there are occasional grains of original ilmenite which have been strongly attacked by the so-called beach sand type of alteration (Lynd, Sigurdson, North & Anderson 1954; Bailey, Cameron, Spedden & Weege 1956). Such grains are however very scarce in polished sections of opaque concentrates from the sandstone, possibly because the alteration makes the grains less resistant to crushing. Jensen (1966, 1968) has shown that this type of ilmenite alteration is not confined to beach sands but is also found in rocks collected from the Precambrian of Bornholm.

Goethite

Goethite is found in original titanomagnetite grains which have been so strongly altered that they now consist of goethite with a fine pattern of holes formed by dissolution. Besides the occurrence in former titanomagnetite grains, goethite is also found as envelopes around pyrite grains or as larger masses with small remnants of pyrite.

Goethite/hematite

In polished sections of rock samples of the Nexø sandstone there occur in the matrix numerous tiny blebs with a diameter about 1 μm. These tiny blebs show deep red internal reflections and are grey with a reflectance which is considerably lower than that of the hematite phase in the ilmenite-hematite exsolution intergrowths. Thus the microscopic appearance of the blebs is such that the author would not hesitate to identify them as goethite. However Steinwehr (1954) has investigated the pigment in red sandstones by X-rays and found that the pigment in all cases is hematite, and he considers chemical as well as microscopic identification of pigments in sandstones unreliable. On account of this uncertainty these tiny blebs are not taken into consideration in the values given in table 1 where goethite for whole rock samples is noted as nd – 'not determined'.

Rutile

In addition to intergrowths with hematite and ilmenite, rutile is also found as individual grains of homogeneous rutile. Long thin needles that are also believed to be rutile are found arranged in three directions in some of the quartz grains in the sandstone. Such rutile-like needles have been described from the Rønne granodiorite of Bornholm (Jensen 1965).

Anatase
Anatase is found rather frequently and generally occurs as clusters of idiomorphic grains (fig. 7).

Zircon
Although not an opaque mineral zircon is included here because in the materials investigated the mineral is rather easily identified in reflected light. Grains of zircon are frequently met with. They often show distinct zonal structure, but homogeneous grains are not uncommon. In a few cases grains of zircon are seen carrying inclusions which appear to consist of intergrowths of hematite and goethite.

Sphene
Sphene as so-called turbid sphene (Desborough 1963; Jensen 1966) is found in connection with the martitised titanomagnetite grains, but grains of clear homogeneous sphene are also found. Remnants of ilmenite or magnetite were never observed in such sphene masses, whereas such remnants are common in the sphene of the Precambrian plutonic rocks of Bornholm (Jensen 1968).

Pseudobrookite
The polished sections were carefully searched for pseudobrookite, but only a few grains carrying pseudobrookite have been found. The pseudobrookite occurs intergrown with rutile and hematite. One of the grains carrying pseudobrookite has a structure indicating that the grain was probably derived from original titanomagnetite rather than from original ilmenite. Hematite-rutile-pseudobrookite intergrowth is shown in fig. 8.

Spinel
Spinel was found in a grain of fine lamellar martite where it occurs as small rods arranged after {111} of the original titanomagnetite parallel to the martite lamellae (fig. 9).

Pyrite
Pyrite is the only sulphide mineral found during the investigation. Most of the pyrite seen occurs with a relatively thick envelope of goethite or as remnants inside larger masses of goethite. In a few cases pyrite is found without any connection to goethite. These occurrences include an idiomorphic grain of pyrite.

Finally it should be noted that the assemblage of opaque minerals is so strongly oxidised that no remnants of magnetite were found at all.

Conclusions

As can be seen from table 1, most of the opaque grains in the Nexø sandstone belong to one of two groups: ilmenite-hematite exsolution intergrowths and martite with fine lamellar structure after titanomagnetite.

The opaque minerals in the Precambrian plutonic rocks of Bornholm are mainly magnetite with varying degrees of martitisation, and ilmenite (Jensen 1968). The Precambrian dolerites carry mainly ilmenite and titanomagnetite with many ilmenite lamellae of different sizes (Jensen 1966). However neither ilmenite-hematite exsolution intergrowths nor pseudobrookite, nor individual grains of rutile, are known from the crystalline rocks of Bornholm, so the source of at least some of the material in the Nexø sandstone must be sought outside the island.

The nearest exposures of rocks carrying ilmenite-hematite exsolution intergrowths lie in southern Sweden, about 150 km away. Stumpfl (1958) reports that hematite-rich ilmenite-hematite exsolution intergrowths with lamellae of rutile in up to six directions are known especially from the polymetamorphic rocks of Scandinavia and that such intergrowths strongly characterise the heavy beach sands of the Baltic coast.

Since palaeoccurrent evidence (Bruun-Petersen 1971) indicates that the lower part of the Nexø sandstone was deposited by streams flowing from NNW, it is reasonable to conclude that a considerable part of the Nexø sandstone was derived from Sweden. This implies a distance of transport of at least 150 km.

Although the ilmenite-hematite intergrowths, pseudobrookite and rutile grains in the Nexø sandstone must have come from a source outside Bornholm, there is no reason to suppose that all the material in the sandstone came from distant sources. The fine lamellar martite, for instance, could just as well come from the dolerites of Bornholm as from similar rocks in Sweden.

The ratio between the amounts of ilmenite-hematite and martite varies from 0.7 to 2.8 in samples taken from different stratigraphic levels. Although this variation could be partly due to the

Fig. 6. Polariser only, × 800, oil immersion. Hematite-rutile intergrowth. Polished section of concentrate of sample 33015 from Gadeby quarry.

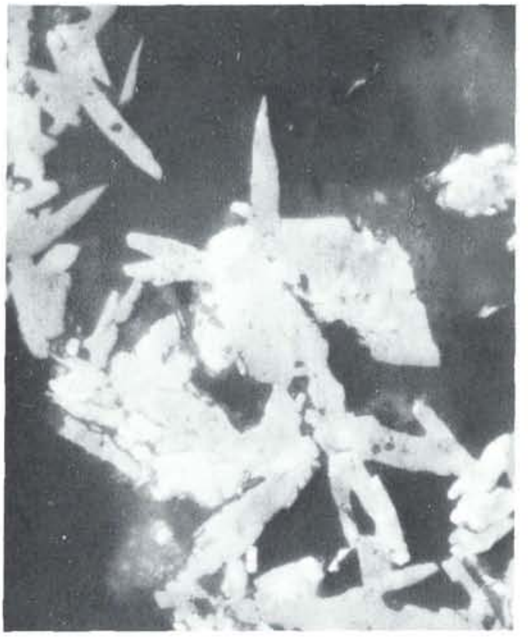

Fig. 7. Polariser only, × 800 oil immersion. Idiomorphic anatase. Polished section of concentrate of sample 33014 from Gadeby quarry.

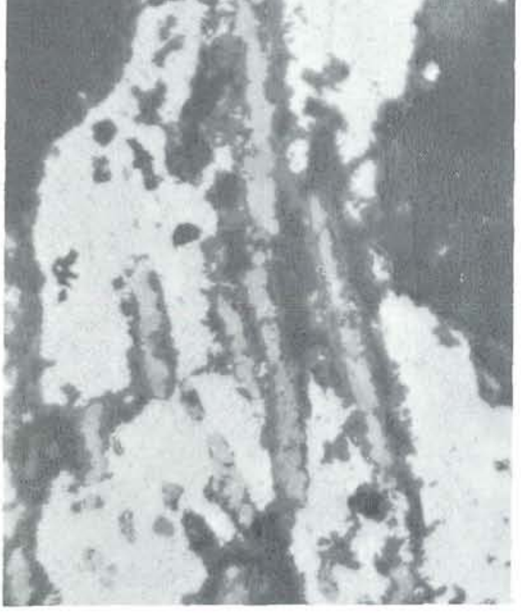

Fig. 8. Polariser only, × 800, oil immersion. Hematite-rutile-pseudobrookite. Hematite is light grey with a heterogeneous structure. Rutile is medium grey and has rims of dark grey pseudobrookite. Holes and silicates are black. Polished section of concentrate of sample 33026 from Bodilsker quarry.

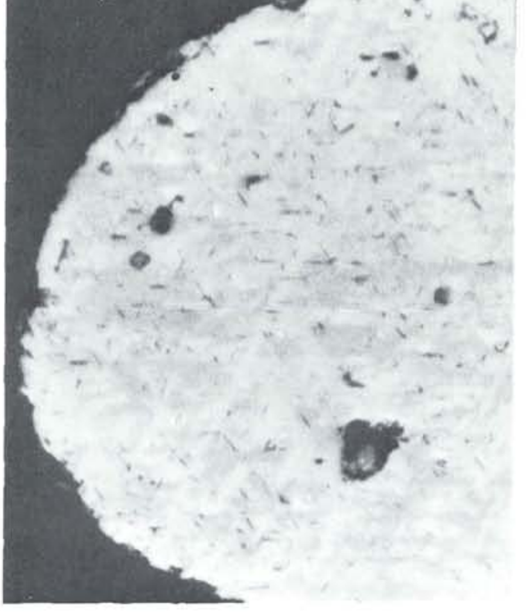

Fig. 9. Polariser only, × 800, oil immersion. Martite with short rods of spinel arranged parallel to 111 of the original titanomagnetite. Polished section of concentrate of sample 33014 from Gadeby quarry.

sporadic nature of the dolerite outcrops, it is so large that it is more likely to reflect more significant changes in stream palaeogeography. High ilmenite-hematite/martite ratios indicate a main provenance in Sweden; low ilmenite-hematite/martite ratios indicate that much of the material was derived from an ilmenite-hematite-free, but martite-bearing, source area such as Bornholm itself. It is the writer's belief that the ilmenite-hematite/martite ratio expresses the partition of material of Swedish and local Bornholm origin, being inversely proportional to the amount of the latter. As such it may be the best available measure of the amount of local material in the sandstone. However, since the ratio varies not only in samples from distinctly different stratigraphic levels but also in different lithologies from the same general level, it will be necessary to make a detailed study of the opaque minerals in samples collected systematically with regard to both stratigraphy and lithological variation before the provenance of the Nexø sandstone is fully understood.

At present all that can be said is that, contrary to earlier belief, a substantial part of the material in the Nexø sandstone has its origin in Scandinavian rocks outside Bornholm, and that the amount of foreign material varies.

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Dansk sammendrag

Der er foretaget en opak-mikroskopisk undersøgelse af såvel prøver af selve Nexø-sandstenen som prøver fremkommet ved separation af den opake fraktion fra nedknuste prøver af Nexø-sandstenen. De undersøgte prøver er alle fra den del af Nexø-sandstenen som Bruun-Petersen (1971) betegner som Bodilsker led. Bodilsker led omfatter den del af Nexø-sandstenen som Gry (1936) betegnede nedre terrestriske serie. Opake korn udgør knap 1% af Nexø-sandstenen. Tabel 1 viser hvorledes opak-indholdet er fordelt på forskellige mineraler. Som det fremgår af tabellen tilhører de fleste opake korn en af to grupper: Ilmenit-hæmatit afblandinger eller finlamellar martit.

Den finlamellare martit kan stamme fra såvel bornholmske doleriter som fra prækambriske doleriter i Sverige, medens ilmenit-hæmatit afblandinger ikke kendes fra nogen af de prækambriske bjergarter på Bornholm, men ifølge Stumpfl (1958) er hæmatitrige ilmenit-hæmatit afblandinger, som de der er fundet i Nexø-sandstenen, især kendt fra polymetamorfe skandinaviske bjergarter. De nærmeste blotninger af bjergarter med ilmenit-hæmatit afblandinger findes i Sverige 150 km nordvest for Bornholm. Det må derfor antages at Nexø-sandstenen har fået i hvert fald en del af sit materiale fra det sydlige Sverige, hvilket er i overensstemmelse med at Bruun-Petersen (1971) har fundet at den nedre del af Nexø-sandstenen er aflejret af strømme fra NNW.

Forholdet mellem mængderne af ilmenit-hæmatit og martit varierer stærkt, og selv om mængden af martit ikke er noget sikkert mål for mængden af lokalt materiale, kan den stærke variation være et udtryk for varierende forhold mellem mængden af mere fjerntransporteret materiale og mængden af lokalt bornholmsk materiale i Nexø-sandstenen.

Forholdet ilmenit-hæmatit/martit varierer ikke alene mellem prøver fra forskellige stratigrafiske niveauer, men også mellem forskellige prøver fra samme stratigrafiske niveau. Det vil derfor kræve en detailleret undersøgelse af prøver indsamlet systematisk med hensyn til såvel stratigrafi som lithologi for at man kan få Nexø-sandstenens oprindelse nærmere belyst på grundlag af indholdet af opake mineraler. Den foretagne undersøgelse, der kun omfatter et lille antal prøver, har imidlertid vist at Nexø-sandstenen, i modsætning til hidtidige antagelser, har fået en væsentlig del af sit materiale fra skandinaviske bjergarter uden for Bornholm, og at mængden af fremmed materiale varierer.

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