DANMARKS GEOLOGISKE UNDERSØGELSE · SERIE A · NR. 10
MILJØMINISTERIET · Geological Survey of Denmark

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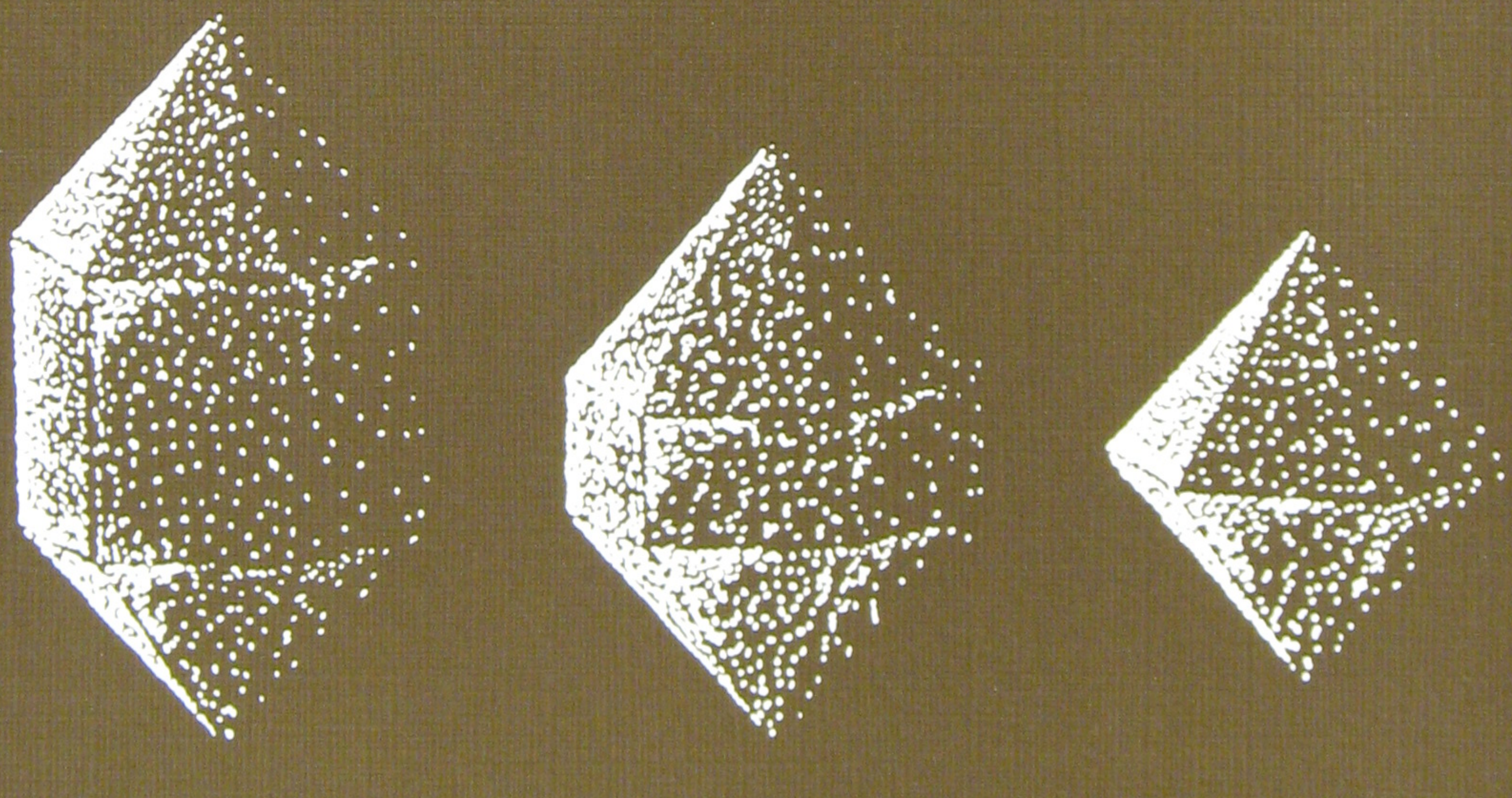
BY
PETER GRAVESEN



I kommission hos C. A. Reitzels forlag · København 1986

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Key words:
Lower Createceous, quartz sand, heavy minerals, provenance

Vignet:
Quartz Crystals

DGU serie A nr. 10
ISBN 87-421-0738-5
ISSN 0901-0270
Oplag: 1200
Tryk: Hertz, Bogtrykkergården
Tegning: Gitte Nicolaisen
Dato: 1986-06-01
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Redaktion: Leif Banke Rasmussen

Contents

Abstract

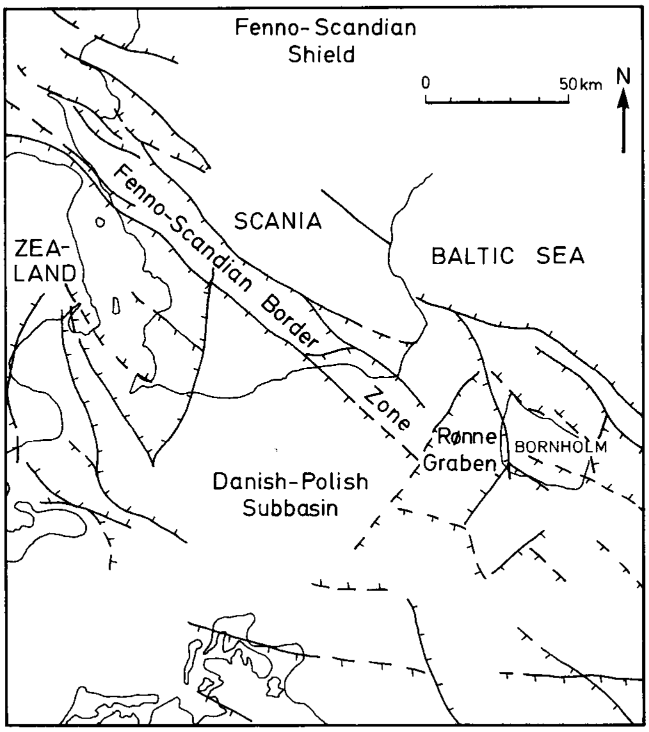
The quartz sand of the Lower Cretaceous Robbedale Formation and lowermost part of the Jydegård Formation in the Arnager-Sose fault block of Bornholm has been investigated with respect to mineralogy, grain-size, grain rounding and grain shape. Analyses of both light and heavy minerals have been carried out for 18 samples from different localities and facies. The purpose of the investigation was to try to recognize the possible types of source rocks and provenance areas.

The Precambrian basement rocks of Bornholm are not the main sources of the sand, especially not the heavy minerals, but parts of the sand may have originated from the basement. The Palaeozoic sandstones and siltstones have delivered only a small amount of material. Parts of the older Mesozoic sediments of the Bornholm Group and Homandshald Member may have been redeposited in the Lower Cretaceous as they contain the same kinds of heavy minerals as the Robbedale and Jydegård Formations, although in differing amounts.

It seems very possible, however, that most of the Mesozoic sediments of Bornholm have had a source area outside Bornholm, and this source area has been nearly the same during the whole span of time. The Fenno-Scandian Shield seems to be the most obvious provenance area, but eastern and southern areas are possibilities too. It is concluded that most of the Lower Cretaceous sands are first deposition cycle sediments of both local and distant origin combined with minor amounts of polycyclic sediments of mainly local origin.

Introduction

The Lower Cretaceous Robbedale and Jydegaard Formations on Bornholm (fig. 1) comprise sand deposits with a very high quartz content which can be classified as quartz arenites (Pettijohn, Potter & Siever, 1972). The formations have been studied for a long time, e.g. by Jespersen (1865), Grönwall & Milthers (1916), Höhne (1933), Andersen (1944) and more recently by Gry (1956, 1960, 1968), Allen (1967), Jux & Strauch (1968), Gravesen (1977a,b, 1982a,b), Gravesen, Bækgaard & Villumsen (1980), Gravesen, Rolle & Surlyk (1982), Piasecki (1984) and Noe-Nygaard & Surlyk (in prep.). The origin of the sand has been discussed by Andersen (1944), Rosenkrantz (in Gry, 1956) and Gry (1956).



Gravesen et al. (1982) subdivided the Berriasian Robbedale Formation into the Østerborg and Langbjerg Members and the Late Berriasian-Valanginian Jydegaard Formation into the Tornhøj and Rødbjerg Members.

The present paper describes the petrographical characters of the white, brown, yellow and reddish non-calcareous sands of the Østerborg and Langbjerg Members and the lowermost five metres of the Tornhøj Member in the Arnager-Sose fault block (fig. 2). The members are mainly deposited in shallow nearshore marine and lagoonal areas (Gravesen, 1982a; Noe-Nygaard & Surlyk, in prep.) The paper deals with the description and discussion of the results of textural analyses and of analyses of the light and heavy minerals. The provenance area and source rocks of the sand are proposed.

Fig. 1.
Part of the Fenno-Scandian Border Zone with adjacent areas. The most important faults are indicated at the map (partly after Gravesen et al. 1982).

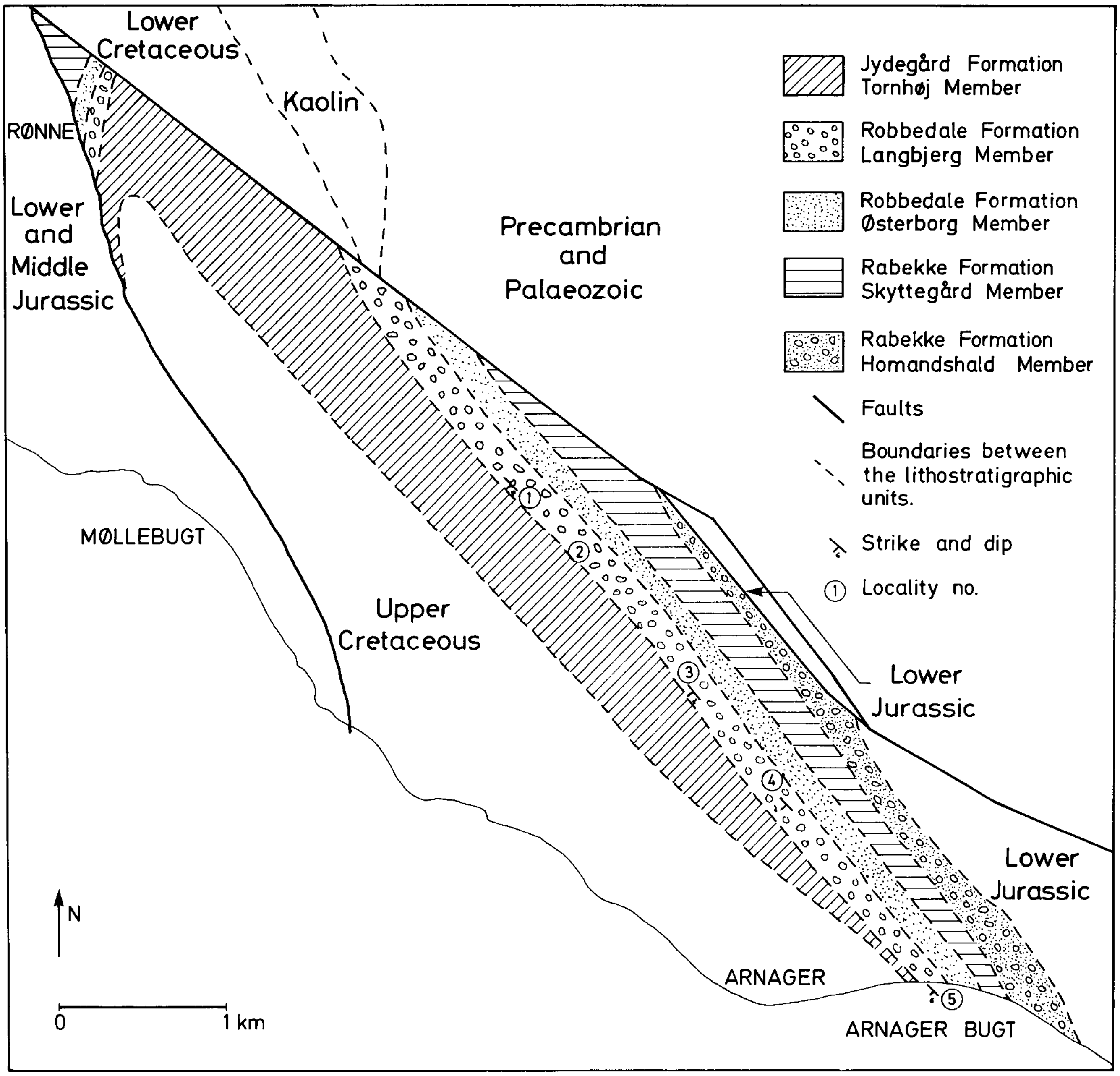


Fig. 2.
Geological map of the Lower Cretaceous deposits of the Arnager-Sose fault block, Bornholm (after Gry 1960, 1969, Gravesen 1982b, Gravesen et al. 1982). Localities: 1) A/S Carl Nielsen's sand pit, Robbedale, 2) Østerborg sand pit, 3) Skrædderbakke sand pit, 4) Vellensbyvej sand pit, 5) Arnager Bugt.

Geological setting and tectonic development

Bornholm is situated in the Fenno-Scandian Border Zone (Tornquist Line) with the Precambrian Fenno-Scandian Shield to the northeast and the Danish-Polish Subbasin to the southwest (fig. 1). The zone is documented back to Late Carboniferous-Permian times (Michelsen & Andersen, 1981) and is characterized by block faulting, which on Bornholm occurred several times during the Triassic, Jurassic and Cretaceous (Gry, 1969; Surlyk, 1980; Gravesen & Bjerreskov, 1984), often along older Precambrian fault-lines (Münther, 1973, Wannis, 1979). Finally, the island was uplifted as a horst during the Laramide tectonic phase, when inversion movements established a system of horsts and grabens in the offshore area around Bornholm (Andersen et al., 1975; Kögler & Larsen, 1979; Wannis, 1979, Kumpas, 1980, Vejbæk, 1985).

The transition between the Jurassic and Cretaceous is marked by strong block faulting (Late Kimmerian tectonic episode). The Arnager-Sose block was down-faulted and the Lower Cretaceous, Berriasian sediments of the shallow marine Østerborg Member transgressed over regressive continental deposits of the Rabekke Formation (Gravesen, 1982a). Syn-tectonic rapid sedimentation continued with the progradation of the shallow marine Langbjerg Member and with the lagoonal sediments of the Tornhøj Member.

Samples and methods

Eighteen samples from four localities representing different depositional environments at the Arnager-Sose fault block have been investigated. Six samples are from the Østerborg Member, ten samples from the Langbjerg Member and two from the Tornhøj Member (fig. 3). The grain-size distributions of sixteen sand samples have been determined by sieve analyses on sieves with 1/2 Φ intervals from +4 Φ to -4 Φ and the mean and sorting have been calculated after Folk & Ward (1957) and Folk (1966) (fig. 4). The grain shape and rounding of the sand have been compared with the scheme in Pettijohn et al. (1972). The grain-size distributions of two silt-clay samples have been determined by elutriation and sieve analyses.

LOCALITY	SAMPLE	LITHOSTRATIGRAPHIC UNIT	DEPOSITIONAL ENVIRONMENT	MEAN (M_Z)	SORTING δ_I
A/S Carl Nielsen sand pit, Robbedale	J15-4	Tornhøj Member	tidal channel	1.90 Φ	0.41 Φ
	J14-1	Tornhøj Member	lagoon-washover	0.80 Φ	0.66 Φ
	C57-6	Langbjerg Member	barrier island beach	0.62 Φ	0.37 Φ
	C57-5	Langbjerg Member	barrier island eolian flat	1.15 Φ	0.40 Φ
	C57-1	Langbjerg Member	barrier island subtidal	0.40 Φ	0.64 Φ
	C56-1	Østerborg Member	intertidal beach	2.55 Φ	0.38 Φ
Østerborg sand pit	Ø19-2	Østerborg Member	intertidal beach	1.80 Φ	0.64 Φ
Skrædder-bakke sand pit	S24-1	Langbjerg Member	tidal channel	0.57 Φ	0.53 Φ
	S21-2	Langbjerg Member	tidal channel	1.00 Φ	0.20 Φ
Vellensbyvej sand pit	V12-1	Østerborg Member	intertidal sand flat	1.65 Φ	0.37 Φ
Arnager Bugt	A100-1	Langbjerg Member	subtidal sand flat	1.40 Φ	0.52 Φ
	A98-1	Langbjerg Member	subtidal sand flat	1.78 Φ	0.34 Φ
	A97-2	Langbjerg Member	subtidal sand flat	1.63 Φ	0.45 Φ
	A96-3	Langbjerg Member	subtidal sand flat	1.38 Φ	0.53 Φ
	A88-8	Langbjerg Member	intertidal beach	2.22 Φ	0.61 Φ
	A85-11	Østerborg Member	clayey lagoon	–	–
	A85-10	Østerborg Member	silty lagoon	–	–
	A81-1	Østerborg Member	intertidal sand flat	3.04 Φ	0.26 Φ

Fig. 3.
Table with informations about the eighteen samples: Locality, lithostratigraphic unit, depositional environment (Gravesen 1977 a, b, 1982 a, b), and the mean and sorting (Folk & Ward 1957, Folk 1966) calculated from the grain-size distributions in fig. 4.

Mineralogical analyses were undertaken on both light and heavy minerals, although the light minerals were only investigated in four samples. The brown, yellow and red colours of the sand are due to a surface coating of limonite (goethite), which was removed by treatment with 15 per cent HCl. The minerals were then separated in bromoform (d = 2.93 g/cm^3) into the light and heavy fractions. The light fraction in the 0.063-0.25 mm grain-size interval was mounted in Canada balsam (n= 1.54), and investigated with a polarizing microscope. The grain-size intervals 0.25-0.5 mm and 0.5-2.0 mm were analysed under a binocular microscope only. One hundred grains were counted in each slide, and minerals and other characteristics were noted.

The heavy minerals in the grain-size interval 0.063-0.25 mm were mounted in Clearax (n= 1.666) and analysed under a polarizing microscope. The ratio of opaque to non-opaque heavy minerals was first determined by counting 100 grains. The relationship between the different non-opaque minerals was then studied by counting a total of 100 grains. This was done in two slides for each sample, and an average was calculated.

The slides were moved with the aid of a mechanical stage, and only the grains passing the intersection of the cross-hairs were counted (Larsen, 1966). Beside noting the different minerals, other characteristics were also described. As claimed by Blatt et al. (1972) it is important to investigate all grain-sizes of the sand, and thus the sand material in silt and clay beds of the Østerborg Member was also analysed.

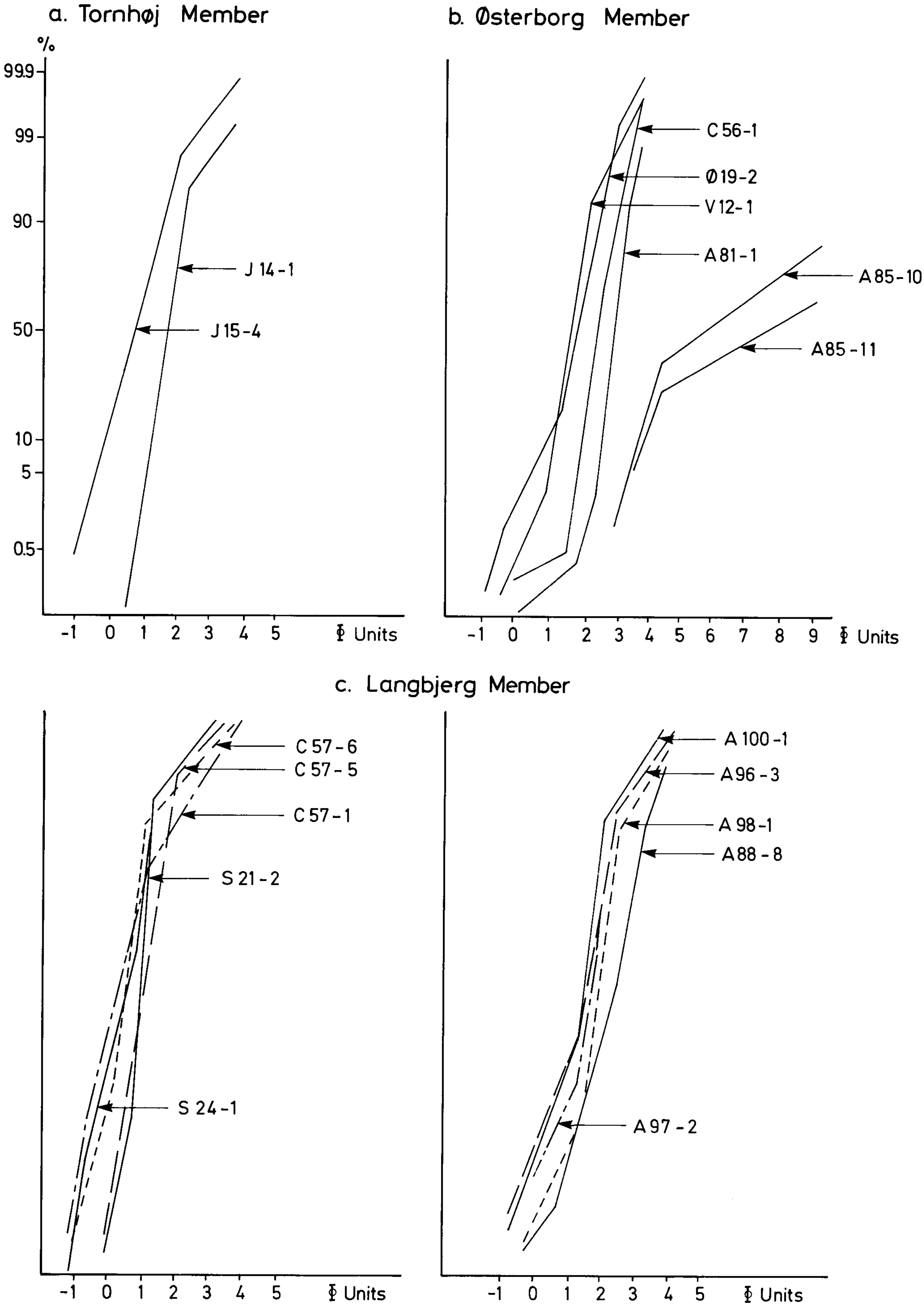


Fig. 4.
Grain-size distributions of the eighteen samples. a. Tornhøj Member, b. Østerborg Member, c. Langbjerg Member.

The light minerals

Description

Four samples from the Østerborg and Langbjerg Members at the Robbedale and Arnager Bugt localities (figs. 2,3) have been analysed. On the average, the light minerals make up 99.1 per cent of the sand.

The mineralogical investigation of the 0.063-0.25 mm fraction in each of the four slides showed that only quartz is present. In the remaining part of the slides are traces of other minerals, such as three feldspar grains, one with Carlsbad twins. A little feldspar was found also by Allen (1967), who has investigated a sample from the Østerborg Member at Arnager Bugt. He writes: "Much of the quartz is deformed, and the little surviving feldspar "untwinned"". Füchtbauer & Elrod (1971) have also analysed a Lower Cretaceous sample from Arnager Bugt east of Homandshald. This sample has about 7 per cent K-feldspar besides quartz, but it could possibly belong to the Homandshald Member of the Rabekke Formation, which normally has a higher feldspar content than the Østerborg Member.

The quartz grains can be characterized by the following parameters:

1. The ratio of monocrystalline to polycrystalline grains
2. For the polycrystalline grains, it was registered whether the crystals were of equal or different size
3. The ratio of grains with undulatory extinction to grains with non-undulatory extinction
4. Authigenic overgrowths on the grain surfaces
5. Visual description of the grain roundness after the scheme in Pettijohn et al. (1972).

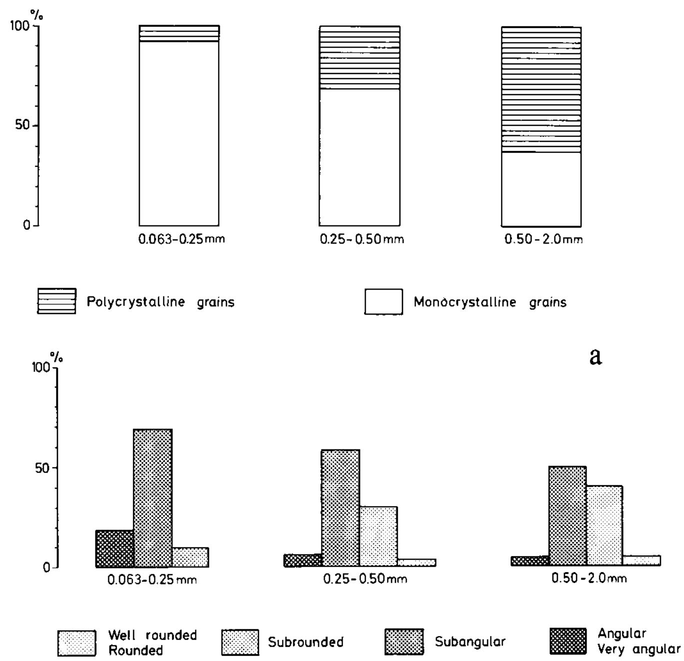
The results can be seen in the scheme (fig. 5).

From the results it is clear that there is a dominance of monocrystalline grains and most of the grains have non-undulatory extinction. In this grain-size interval (0.063-0.25 mm) the very angular and subangular grains are dominating, and some re-entrants (Crook, 1968) in the grain edges can be observed. The authigenic overgrowths have the same optic orientation as the quartz grains and they are often rounded.

For the grains in the fractions 0.25 - 0.5 mm and 0.5 - 2.0 mm the following characteristics in all four samples are registered. After counting 100 grains only quartz was found, but after looking through a larger amount of grains six white and weakly red feld-

	Samples	C57-6	C56-1	A88-8	A81-1
1	Monocrystalline, non-undulatory grains	63	61	64	60
	Monocrystalline, undulatory grains	28	32	33	33
	Polycrystalline grains	9	7	3	7
	Σ	100	100	100	100
2	Polycrystalline, equant size crystals	1	2	0	1
	Polycrystalline, different size crystals	8	5	3	6
3	Authigenic overgrowth	3	4	1	0
4	Very angular - angular - subangular	92	90	84	94
	Subrounded	8	10	16	6
	Σ	100	100	100	100

Fig. 5.
Results of the investigation of the light minerals in the 0.063-0.25 mm fraction by the counting of 100 grains.
1) The amounts of monocrystalline, polycrystalline, undulatory and non-undulatory grains. All the polycrystalline grains are undulatory.
2) Polycrystalline grains with equant or different size crystals.
3) The amounts of grains with authigenic overgrowths.
4) Very angular-angular-subangular grains and subrounded grains.



b

Fig. 6.
a. The ratio of polycrystalline to monocrystaline quartz sand grains in the three grain-size fractions.
b. The rounding of the quartz sand in the three grain-size fractions.

spar grains were observed. The quartz grains are either translucent, smooth and polished on the surface or frosted and dull. The ratio of monocrystalline to polycrystalline grains is shown in fig. 6, where there is a comparison between all three grain-size fractions. This investigation has a degree of uncertainty, when undertaken with a binocular microscope, but a trend in the distribution will always be found, and it is obvious that the monocrystalline grains dominate in the 0.063-0.25 mm fraction, but with the increasing grain-size the polycrystalline grains become dominating.

The rounding of the grains is subangular to subrounded in the fractions 0.25 - 0.5 mm and 0.5 - 2.0 mm and fig. 6 demonstrates that with increasing grain-size the grains become more rounded.

Discussion

Quartz is a mechanically and chemically extremely stable mineral, and it is found in all types of clastic sediments. The high quartz content in the sand classifies it as a quartz arenite (Pettijohn et al., 1972), which is strongly mineralogically and texturally mature sand. However, it can be very difficult to differentiate quartz arenites, which are formed directly from granites and gneisses (first cycle deposits) from quartz arenites which are resedimented from other sand and sandstone sediments (multicyclic deposits).

Andersen (1944) and Rosenkrantz (in Gry, 1956) both have the opinion that the source of the sand of the Robbedale Formation was the kaolin and the Rønne Granite of Bornholm and that the sand, therefore, had a very short transport history before deposition. However, Gry (1956) mentioned that the sediments are well sorted and transported, and that the source area possibly was outside Bornholm.

The present investigation gives the following results as discussed under mineralogy, rounding, grain-size and sorting and possible source rocks.

Mineralogy - Quartz arenites deposited in a first sedimentation cycle have a larger content of polycrystalline and undulatory quartz grains than quartz arenites, which are multicyclic (Blatt, 1967, Blatt & Christie, 1963). Polycrystalline grains disintegrate by weathering and transport as well as by diagenesis caused by structural weakness along the intercrystalline boundaries, so that the net result from this is a strong decline in the polycrystalline component with decreasing grain-size. The content of polycrystalline grains is normally very low in sand deposits (under 10 per cent) and in pure quartz deposits the content is a few per cent on average only. Monocrystalline grains with undulatory extinction are thermodynamically less stable than the non-undulatory, and their number decreases with increasing quartz content. However, quartz arenites contain an amount of non-undulatory grains varying from 14 to 80 per cent (average 43.1 per cent) (Blatt & Christie, 1963).

The granites, gneisses and pegmatites on Bornholm (Callisen, 1934, Noe-Nygaard, 1957, Micheelsen, 1961) might be source rocks for the Robbedale Formation if this was a first cycle deposit. Blatt, Middleton & Murray (1972) describe characteristic features of quartz grains from such basement rocks. Granites in average have 80-90 per cent quartz with undulatory extinction and the ratio of polycrystalline to monocrystalline grains is subequal. The polycrystalline grains consist of a few almost equantly sized crystals. Gneisses yield only 25 per cent monocrystalline grains and 75 per cent polycrystalline grains, almost all with undulatory extinction. The crystals in the polycrystalline grains are often differently sized and elongated.

The samples described above have a rather high percentage of polycrystalline grains in all the grain-size fractions, and this possibly points to a first cycle deposit when comparing with the above-mentioned values. According to Blatt & Christie (1963) the large amount of polycrystalline grains points to plutonic-magmatic rocks as the source rocks. The ratio of undulatory to non-undulatory grains in the finest grain-size fraction is approximately 60 per cent, but when all the polycrystalline grains have undulatory extinction it can be suggested that the amounts of grains with undulatory extinction will increase for the whole sample. The relationship between the undulatory and non-undulatory grains points for the finest fraction to a multicyclic deposit, although the large amount of polycrystalline grains indicates that part of the quartz sand could be of first cycle sedimentation origin.

Rounding - The quartz grains give the impression that they have been water or wind transported over a long distance or over a longer span of time. As earlier described the fine sand grains are angular and subangular, while the medium and coarse sand grains are subangular to subrounded and this phenomenon, where the coarsest grains are the most rounded, is very much like what other workers have observed for sand deposits (Pettijohn, 1957). However, rounding of quartz grains in the sand fraction seems to be a very slow process, which works more slowly when the grains become more rounded. Very well rounded grains are probably the result of many transport and deposition cycles.

Experiments of Kuenen (1959, 1960, 1963) and Dietz (1973) stress this fact, and demonstrate that the eolian and perhaps the marine beach environments are the only fields, where a severe rounding takes place. The rounding of the analysed sand indicates that most of the grains have had a relatively long transport history, and the distance from the kaolin area on Bornholm to the area of deposition seems to be too short, if fluvial transport processes have rounded the sand. The depositional environments of the sand are mainly in the marine shallow water shoreline areas (Jux & Strauch,1968; Gry, 1968, Gravesen, 1982a), where deposition and recycling of the sand is a prominent process (Balazs & Klein, 1972). This can give continued abrasion, sorting and rounding of the quartz sand grains and a removal of unstable rocks and minerals, and can be the explanation of the rounding.

Therefore, intense residual weathering like the kaolinization and a short transport to the deposition site followed by a long period of abrasion in a shoreline area with high energy conditions can also produce a quartz arenite deposit (Pettijohn et al., 1972). Further, Crook (1968) postulates that quartz grains can be rounded by in-situ weathering and the process is called solution rounding. The postulate, which is unconfirmed, has complications for the interpretation of the textural maturity of the sand. Only a few grains in the present study show the characteristic re-entrants of Crook (1968). Another aspect is that Moss (1966) has found well rounded quartz grains leaving granites while angular grains due to breakage are common in mature materials. The concept that grains are derived from source rocks as angular particles and gradually become more rounded with increasing maturity is not right in that case. Further, breakage of grains along fractures seems to be an important process in decreasing the grain-size and the abrasion process gives only the last finishing of the grain shape.

Besides the factors mentioned, the original shape and rounding of the quartz grains have importance for the later abrasion and later on diagenetic processes may play a role as authigenic overgrowth can give a more rounded grain. In any case, abrasion and rounding of such diagenetic overgrowths on the quartz grains (subrounded-rounded) indicate that these grains are multicyclic.

Grain-size and sorting - The grain-size distributions of all eighteen samples show a great variation in grain-size (figs. 3,4) from the fine-grained Østerborg Member to the medium- to coarse-grained Langbjerg and Tornhøj Members, and this has to be considered in an evaluation of the source rocks. It is easy to imagine that the finest quartz grains of the three members may have originated directly from many different older rocks on Bornholm like the basement rocks, kaolin, Cambrian sandstones, Triassic and Jurassic sands and sandstones and the Lower Cretaceous Homandshald Member, but it is more difficult to find the possible source rocks of the coarsest quartz sand of the Langbjerg and Tornhøj Members. Kaolin, granites, gneisses, pegmatites and the Homandshald Member are possibilities. Most of the other sediments are too fine-grained, but disintegrated sandstones can of course produce the more coarse-grained polycrystalline quartz sand.

The sorting is often used as an indicator of the cyclicity of the sediments, and it is regarded as very good (very well sorted, well sorted) in multicyclic deposits. The investigated samples are mostly moderately well sorted and well sorted and seldom very well sorted (fig. 3), and this could perhaps point to a multicyclic sand, but the sorting is also dependent on the hydrodynamic conditions and sorting processes in the depositional environment. The shallow marine transport processes, often influenced by tidal processes with alternation of deposition, erosion and transport can produce a well sorted sand in a first cycle sedimentary phase.

Possible source rocks - The Precambrian basement rocks of the northern part of Bornholm have a quartz content of approximately 10-40 per cent (Callisen, 1934, Noe-Nygaard, 1957, Micheelsen, 1961). The grain-size of the quartz in the granites is 0.25-2 mm, in the gneisses 0.1-0.6 mm and in the pegmatites often more than 2 mm (Callisen, 1934; Bruun-Petersen, 1973; Platou, 1970, 1971), and many of the grains have weakly to moderately undulatory extinction (Jørgart, 1982). This makes these rocks and the kaolin possible source rocks of the quartz in both the Østerborg, Langbjerg and Tornhøj Members.

The Lower Cambrian Nexø Sandstone, Balka Sandstone, Broens Odde Member and Rispebjerg Sandstone Member have a wide distribution on southern Bornholm and a thickness of approximately 263 metres (Gry, 1960).

The Nexø Sandstone consists mainly of quartz with 20 per cent feldspar. The quartz grains are subangular - subrounded, mainly monocrystalline, and the grain-size is 0.05-1 mm. The extinction is only seldomly undulatory (Hansen, 1936).

The Balka Sandstone is a quartz arenitic sandstone with well rounded, monocrystalline grains with a grain-size of 0.1-1 mm (Hansen, 1936; Füchtbauer & Elrod, 1971).

The Broens Odde Member (Green Siltstones) is mainly very fine-grained (0.05-0.5 mm) with approximately 70 per cent quartz. The grains are mostly subangular (Hansen, 1936).

The Rispebjerg Sandstone Member has rounded to well rounded monocrystalline quartz grains in different grain-sizes (0.06-2 mm) (Hansen, 1936, Marino, 1980).

It is not probable that the monocrystalline, rounded to well rounded quartz grains of the Balka Sandstone and Rispebjerg Sandstone can be source material, while the Nexø Sandstone and Broens Odde Member are possibilities.

The 790 m thick Triassic and Lower and Middle Jurassic sands and sandstones of southern and western Bornholm are also rich in quartz, but they are mainly fine-grained (Gry, 1969) and, therefore, probably not source material.

The Homandshald Member (max. 30 m thick) consists of medium and coarse-grained kaolinitic quartz sand, ferruginous sandstone and clay, and part of the medium-and coarse-grained sand in the Langbjerg and Tornhøj Members can have an origin in this material, which probably was delivered directly from deeply weathered Precambrian basement and kaolin of Bornholm.

The heavy minerals

Description

The results of the heavy mineral investigation of the fraction 0.063-0.25 mm are shown in fig. 7, where the relative amounts are specified. Details about the analyses are given in the text to the figure. Two other analyses of the sand of the Østerborg Member have been carried out by Allen (1967) and Bruun-Petersen (1969). Besides registration of the different kinds of non-opaque minerals, other characteristics of the minerals are noted, and these will be described below for the most important minerals.

Lith. Units	Samples \ Minerals	Zircon	Rutile	Anatase	Brookite	Tourmaline	Garnet	Kyanite	Staurolite	Sillimanite	Titanite	Epidote	Zoisite	Hornblende	Monazite	Unknown	Total	Opaque min	Heavy part of the fract.
Tornhøj M.	J15-4	30	22	2	1	7	5	20	3	1	1	1	0	4	0	2	99	86	0.5
	J14-1	46	14	2	0	5	3	22	1	2	1	1	0	1	0	1	99	79	0.5
Lang-bjerg Member	C57-6	54	14	3	0	3	8	9	2	2	3	1	0	0	+	2	101	86	5.2
	C57-5	44	17	0	0	7	0	17	2	0	5	5	0	0	0	2	99	76	0.3
	C57-1	55	22	0	1	6	0	8	2	0	3	0	+	1	0	1	99	73	2.3
	S24-1	77	11	0	0	1	1	5	0	+	2	0	0	1	0	1	99	61	3.6
	S21-2	50	9	1	+	2	30	6	0	0	+	1	0	0	+	1	100	62	1.7
	A100-1	31	17	0	0	16	1	20	1	0	3	0	0	8	0	3	100	74	0.1
	A98-1	31	12	1	0	18	0	27	6	0	1	2	0	0	0	2	100	90	0.7
	A97-2	64	16	0	0	2	1	10	2	+	0	2	0	+	0	2	99	73	1.3
	A96-3	65	11	1	0	5	+	13	1	0	0	+	0	1	0	3	100	73	1.0
	A88-8	74	14	0	+	3	+	3	2	0	+	0	0	0	0	3	99	63	0.3
Øster-borg Member	C56-1	42	26	1	1	10	+	14	2	1	0	0	0	0	0	2	99	80	0.9
	Ø19-2	36	23	2	1	4	10	17	5	1	0	0	0	0	0	2	101	87	1.2
	V12-1	56	22	1	0	4	3	8	1	1	+	1	0	+	0	2	99	84	0.5
	A85-11	47	25	1	0	7	1	9	3	0	2	3	0	0	0	1	99	80	-
	A85-10	45	25	3	0	9	1	7	3	0	1	2	1	0	0	3	100	82	-
	A81-8	18	37	3	0	14	2	16	5	+	+	0	0	1	0	3	99	88	0.5
	Allen 1967	67	17	1	+	5	3	4	1	+	0	+	0	+	+	1	99	62	-
	J B-P 148	52	15	0	0	13	0	9	5	2	0	0	4	1	0	0	101	-	-

Fig. 7.
The heavy mineral distributions in the grain-size fraction 0.063-0.25 mm of the Lower Cretaceous sediments. The non-opaque heavy mineral values are per cent of 200 counted grains with exception of the sample J15-4, J14-1, C57-5, A100-1 and A97-1, where only 119, 186, 140, 171 and 123 grains were counted.

Trace of a mineral is indicated by a cross. The opaque mineral distribution is per cent of 100 counted non-opaque and opaque heavy minerals. The amounts of heavy minerals (weight %) in the fraction are noted in the scheme. Two analyses, Allen (1967) and Bruun-Petersen (1969) (J B-P) are also shown in the scheme.

Zircon - Zircon is the dominating heavy mineral and can make up to 77 per cent of the whole assemblage. Many idiomorphic crystals with prism faces and pyramidal terminations are found, but often the idiomorphic grains are weakly rounded. However, all grades between idiomorphic specimens and well rounded egg-shaped specimens are found in all the samples. Very angular grains and broken fragments are also seen in the samples. The zircons contain inclusions of other minerals or small zircon crystals. The grains can be totally turbid because of numerous inclusions. Zoning of the zircons is a very normal phenomenon. Few diagenetic changes like corrosion and etching in the grain edges and authigenic overgrowths (e.g. "saw fish" type) are seen. The zircon minerals are mostly colourless or weak brown and occasionally brown.

TiO_2 - minerals - This group consists of rutile, anatase and brookite. Rutile is the dominant mineral and reaches 37 per cent of the total non-opaque heavy mineral assemblage. The grains are often elongated idiomorphic, rounded idiomorphic or well rounded. Knee shaped and parallel twins occur occasionally. The colour is yellow, yellow brown and red brown. The pleochroism is always weak. Fine-grained aggregates of anatase and brookite, leucoxene, are registered under the opaque minerals. Leucoxene, anatase and brookite are authigenic minerals, while rutile mainly is clastic.

Tourmaline - The tourmaline minerals are mainly idiomorphic with prism ends and subangular to subrounded, but also well rounded specimens are found. Different kinds of pleochroism occur: Pink to black - blue black, light brown - brown to dark brown - black brown, olive-yellow green to dark olive - dark green and white (clear) to green. Many grains have inclusions, and solution phenomena like etching and corrosion in the grain edges are often observed (Van Loon, 1972). Zonal distribution of the colour is seen in a few specimens and some examples of colourless authigenic overgrowth on grains with pink to black pleochroism are found. The overgrowth can be rounded and corroded. Very few examples of fully new formed crystals are found.

Garnet - The garnet grains are colourless or light red, but in the silt and clay samples two brown and one green grain are found. They are mainly very angular forms without cleavage and only a few rounded grains are present. The grains often contain inclusions and they have conchoidal surface structures. The garnet may also be corroded and have etching figures on the surface.

Kyanite - Kyanite is found as colourless grains with a bluish touch, especially in the grain edges. Cleavage pieces with elongate step-like shape and sharp edges are most abundant, but rounded grains may also be present. Cleavage fractures are characteristic and they are perpendicular to each other. Many grains are diagenetically etched and inclusions of other minerals are common.

Staurolite - The grains have a typical light yellow - yellow to dark yellow pleochroism (Van Loon, 1972). They are either found as very angular grains without inclusions or as angular grains with many inclusions ("Swiss cheese"), and rarely as prismatic grains. Incipient solution may be seen in the grain edges.

Other non-opaque minerals - The following heavy minerals are found in a smaller amount: Titanite, angular brown grains; Sillimanite, often fibrous, colourless grains; Epidote, etched grains with a light yellow to lemon yellow pleochroism; Zoisite, colourless grains with inclusions; Hornblende, rounded grains with green to blue green pleochroism.

Opaque minerals - The opaque heavy minerals are the dominating part of the fraction (61-88 per cent). They have not been investigated here, but they probably contain ilmenite, siderite, pyrite and leucoxene. Allen (1967) described the opaque part of the Østerborg Member as 60 per cent iron ore and 40 per cent leucoxene.

Zircon is the totally dominating mineral of the non-opaque mineral fraction and together with rutile it makes up more than 50 per cent of the minerals in most of the samples. With the third stable mineral, tourmaline, they form a stable and "ubiquitous" group making up more than 60 per cent in all samples. Other characteristic minerals are kyanite and staurolite. Kyanite is abundant in all samples and always in a higher amount than staurolite, which is present in a variable manner. Also garnet is characteristic, but it has a very variable occurrence in the samples. The garnet content is very low for the Østerborg and Langbjerg Members in the Arnager Bugt area and also for the Østerborg Member in the Robbedale area.

The amount of heavy minerals of the fraction 0.063-0.25 mm is between 0.1 per cent and 5.2 per cent, but it is obvious that especially in the coarse-grained samples C57-1, C57-5, C57-6 there are only very few grains to be counted. In some samples the fraction is very small (0.3 per cent), but in others the amount of heavy minerals is rather high. In the silt (A85-10) and clay (A85-11) samples, there are more heavy minerals than in many of the sand samples and the grains are often much better preserved with very small idiomorphic crystals, (zircon, rutile, tourmaline) and often less altered as also recognized by Blatt & Sutherland (1969). However, very etched grains of especially epidote are also found. Some of the tiny idiomorphic crystals of rutile and tourmaline are clearly authigenic. The amount of heavy minerals in the fractions 0.25-0.5 mm and 0.5-2 mm is less than 0.3 per cent in average and they have not been investigated in detail, but most of the minerals are non-opaque.

Discussion

When they survive weathering, transport and diagenesis, the heavy minerals may be rather good indicators of the provenance of the sedimentary deposits and heavy mineral associations may refer to certain source rocks (Pettijohn, 1957, Larsen, 1966, Pettijohn et al., 1972). The various factors, which affect the composition of the final heavy mineral assemblage, are the following: 1. Transport and depositional processes. 2. Weathering and diagenesis and 3. The composition of the source rocks.

Transport and deposition - By water and wind transport of the sediments a sorting and abrasion of the heavy minerals will occur.

Many of the heavy minerals in this investigation are present with all transitions from idiomorphic crystals without rounding to well rounded grains. This is especially the case for zircon, rutile and tourmaline, while kyanite and staurolite are rounded in some cases, and garnet is nearly always angular. The large variation may be due to different reasons. The grains may have been transported over various distances or over various periods of time before deposition. They may also have their provenance in different areas and have inherited their rounding from older sediments. The heavy minerals are not worn and abraded in the same degree by transport, because of their different hardness, cleavage, crystal structure and brittleness, which determine their resistance to rounding and breaking.

Experiments by Dietz (1973) on rounding of minerals show differences for the minerals between long and short transport distances and by comparison with long distance rounding in nature. Zircon in nature in beach and eolian sand is often well rounded. By long distance transport in the experiments zircon had a very low rounding with a high resistance. This phenomenon has caused that zircon can keep the rounding under metamorphism, where it does not recrystallize and the rounding is then inherited from the source rocks. The zircon in the samples may possibly be a mixture of material of long and short transport, but it cannot be determined whether the minerals are of first or multicycle origin.

Rutile is moderately rounded and tourmaline very well rounded by both long and short transport and again the material is probably a mixture of grains of short and long transport. Garnet and kyanite appear to be very weakly rounded by transport, and the well rounded kyanite grains must have been transported over long distances or they have inherited their shape from older rocks. Staurolite gives various results in Dietz (1973), but is possibly very weakly rounded and the few rounded grains in the present investigation have been transported over long distances or their shape is inherited.

The investigation of the shape and rounding of the heavy minerals gives a complex picture of the transport distance/time and -conditions. Generally, it is likely that the idiomorphic crystals have had a short transport (time or distance), while the rounded grains often have been transported over long distances or time or they have inherited their rounding and are multicyclic.

Weathering and diagenesis - Weathering is a rather short chemical process, but it can be very intensive. The strongest influence on the weathering processes comes from the climatic conditions, the terrain and the tectonic conditions (Larsen, 1970). The observations of many authors show that the heavy mineral composition of a weathered sequence becomes poorer from the bottom to the top and the number of corroded grains increases in the same direction (Nickel, 1973; Grimm, 1973). From observations in several weathering profiles numerous attempts have been made to establish a sequence of relative stability for the heavy minerals (e.g. Weyl, 1950, Grimm, 1973). On the other hand, diagenesis is a chemical and mechanical process, which works over geologically long spans of time and therefore, this process may have the strongest influence on the mineralogy of the sediments (Larsen, 1966). The heavy minerals have different resistance to destructive diagenesis, interstratal solution (Pettijohn, 1957), and various sequences of the relative stability of the minerals to interstratal solution have also been established (Nickel, 1973).

Destructive diagenesis phenomena are observed on many minerals in the present investigation, while the results of weathering are probably seen only in a smaller amount. The question is to which degree these two kinds of processes have changed the original heavy mineral association. The most typical indications of destructions in the heavy minerals are corrosion of the grain surfaces, colour changes (bleaching) and internal decomposition.

Zircon, rutile and tourmaline are minerals, which have a high stability to both weathering and diagenesis (Pettijohn, 1957; Wieseneder, 1953). However, Nickel (1973) has made experiments with dissolution of minerals at different pH values, and compared the results with established stability sequences. The experiments have shown that the stability of tourmaline is dependent on the acid pH values and diagenetic dissolution is also registered especially for tourmaline. Also zircon grains show signs of slight dissolution. Oppositely, this phenomenon is very rarely found in rutile grains, which were very resistant in the experiments. The zonal colour distribution in some tourmaline grains indicates that they have been weathered (Grimm, 1973).

The high amount of zircon, rutile and tourmaline in the total assemblage (more than 60 per cent) points directly to a mature assemblage, which is formed by recycling of older sediments or to an assemblage, which has been exposed to a severe weathering or diagenetic dissolution. However, Wieseneder (1953) and Larsen (1970) point out that a mature heavy mineral association is not always a reflection of one of these possibilities, as the source rock could also have had an original mature heavy mineral association.

Garnet is a rather stable mineral at diagenesis, but it is easily dissolved by weathering (Pettijohn, 1957). This corresponds with Nickel (1973), who shows that garnet is easily dissolved at acid conditions, but has nearly the same stability as zircon at alkaline conditions.

In most of the investigated samples garnet is present only in small amounts (1-10 per cent, one sample 30 per cent) and in part of the samples there are traces only. This points to a relatively strong weathering combined with different transport directions. Etching and solution in the garnet grains are related, therefore, to diagenetic processes on the angular, fresh grains.

Kyanite and staurolite belong to an intermediate group of stability to both weathering and diagenesis (Pettijohn, 1957). Etching and solution phenomena in these minerals are probably produced by diagenetic dissolution. The kyanite content is rather large and kyanite is nearly as stable to weathering as to diagenesis, but it is more resistant under acid than alkaline conditions. Staurolite is more resistant to alkaline than to acid conditions (Nickel, 1973).

The subordinate content of titanite, sillimanite, epidote, zoisite and hornblende may suggest that the original heavy mineral association has been more abundant and these minerals could be the last rest, which has survived destruction. Epidote is very sensitive to acid weathering conditions and belongs to the minerals most unstable to weathering and diagenesis. It is remarkable that the hornblende grains do not show signs of dissolution as hornblende is one of the most unstable minerals.

Constructive neoformation of minerals or part of new minerals, which can be related to weathering or diagenesis are a point of confusion in relation to interpretation of the source rocks as it can change the original mineral association (Grimm, 1973; Mader, 1982). Anatase and brookite are possibly formed authigenically and the leucoxene is obviously authigenic. Authigenic overgrowths as rims on zircon minerals and especially on tourmaline grains often occur, and examples of oriented crystals on rutile and tourmaline indicate that part of these minerals can be authigenic. Remarkable examples of neoformation, which also indicate recycling of the minerals, are authigenic overgrowths on rounded and transported tourmaline grains, which again have been rounded by transport and deposition processes. Finally, this often is followed by diagenetic etching in grain edges (Larsen, 1966; Pettijohn et al., 1972).

In spite of a heavy mineral association with relatively high maturity, which is distinctly influenced by weathering and destructive and constructive diagenesis, it is possible that the association can give information about the source rocks, eventually point to the provenance area or exclude certain rocks and areas.

Possible source rocks - The question now is: Which of the older rocks on Bornholm could be source rocks of the heavy minerals? The minerals could have been delivered directly from the Precambrian basement rocks. Information about heavy minerals in the basement is given by Callisen (1934, 1957), Noe-Nygaard (1957), Micheelsen (1961), Jensen (1966, 1968), Jørgart (1982) and Platou (1971) and the following species are noted (without non-opaque minerals, biotite, muscovite and chlorite).

The gneisses and Paradisbakke Migmatite: Hornblende, titanite, apatite, rare orthite, zircon, epidote, fluorite, rutile.

Rønne Granite and Maegaard Granite: Hornblende, altered hypersthen and diopside, titanite, apatite and subordinate zircon, epidote, orthite, rutile and fluorite.

Hallegård Granite: Hornblende, pyroxene, epidote, orthite, titanite, fluorite, apatite, zircon.

The light granites, aplites and pegmatites: Hornblende, titanite, apatite, epidote, fluorite and rare orthite, rutile, zircon.

Diabases: Olivine, pyroxene (augite, hypersthene, pigeonite), hornblende, epidote, apatite, titanite, rutile.

Kaolin: Zircon, rutile, anatase.

According to Jensen (1968), titanite and rutile in the basement rocks often occur as altering products of ilmenite, but as very small crystals (rims) on the surface of the ilmenite grains.

In inclusions of sedimentary and metamorphic rocks in the basement heavy minerals as rutile, hornblende, titanite, zircon, garnet, wollastonite, diopside and epidote are found.

A comparison between the heavy mineral content in the basement rocks and the Lower Cretaceous sediments shows considerable differences. The most common minerals in the basement: Hornblende, titanite and apatite, are very rare in the sediments and zircon and rutile which are dominating in the sediments are subordinate in the basement rocks. Garnet is known only from inclusions. Tourmaline, which often is found in granites, pegmatites and metamorphic rocks, and kyanite, staurolite and sillimanite occurring in metamorphic rocks, are obviously not present in the Precambrian basement of Bornholm. From this it can be concluded that only a small part of the heavy mineral association from the Lower Cretaceous can originate from the basement.

Another possibility is older sedimentary rocks of Bornholm. The Palaeozoic sandstones have a very mature heavy mineral association. Gry (1936, p. 32, sample 1-5) shows an association dominated by zircon with subordinate rutile and tourmaline in the Lower Cambrian Nexø and Balka Sandstones, while Füchtbauer & Elrod (1971) also demonstrate a small anatase content in the Balka Sandstone. Jensen (1977) has found rutile, anatase, zircon and tourmaline in the Nexø Sandstone. In the Lower Cambrian Broens Odde Member (Surlyk, 1980) a small content of amphibole, titanite and zircon are seen by Hansen (1936) and Füchtbauer & Elrod (1971) find a high zircon content and subordinate rutile, tourmaline, garnet and apatite in the fraction < 0.09 mm.

As kyanite, staurolite and sillimanite are totally absent from Lower Cambrian sandstones and siltstones and garnet very rare, these rocks are possibly not the main source rocks of the Lower Cretaceous heavy minerals, but some contributions can of course not be excluded.

Regarding the older Mesozoic sediments, the picture of the heavy mineral associations is different. Besides zircon, rutile and tourmaline Gry (1936) also found a content of kyanite and staurolite in gravel of the Triassic Risebæk Member (fig. 8). In the Lower Jurassic Rønne Formation there is a high tourmaline content and zircon, kyanite and staurolite are other characteristic minerals, while garnet is subordinate. Also hornblende and pyroxene are present (fig. 8) (Bruun-Petersen, 1969). The Lower Jurassic fully marine Hasle Formation has a garnet-zircon association with high tourmaline content and subordinate kyanite and staurolite (fig. 8) (Weyl & Werner, 1952; Bruun-Petersen, 1969). In one of the samples there is a remarkably high hornblende content, and in another a high epidote content, both rather unstable minerals. Larsen (1966, p. 105) has a high garnet and epidote content in the Hasle Formation with zircon, rutile, tourmaline, titanite, kyanite and staurolite in minor amounts.

In the uppermost Lower and Middle Jurassic Bagå

Formation (Hoelstad, 1985) zircon is totally dominant again, but in some samples a high tourmaline and kyanite content is present. The Lower Cretaceous fluviatile Homandshald Member has a heavy mineral association very much like the younger Lower Cretaceous sediments but without garnet (Bruun-Petersen, 1969) (fig. 8) and an interesting point is that the Upper Cretaceous Arnager Greensand has the same species with dominance of zircon, garnet, kyanite and titanite (Weyl & Werner, 1952).

Chronostrat. Units	Lithostrat. Units	Samples \ Minerals	Zircon	Rutile	Anatase	Brookite	Tourmaline	Garnet	Kyanite	Staurolite	Sillimanite	Titanite	Epidote	Zoisite	Hornblende	Pyroxene	Total
Lower Cretac.	Homands-hald M.	J B-P 147	41	16	0	0	9	0	13	11	6	0	0	2	1	0	99
Middle Jurassic	Bagå Formation	J B-P 156	75	4	8	1	5	2	3	1	1	0	0	0	0	1	101
		J B-P 155	33	12	4	1	25	5	10	4	2	2	+	1	1	+	100
		J B-P 154	92	2	2	0	0	0	0	0	0	2	0	+	0	+	98
		J B-P 153	65	15	0	0	4	0	4	0	0	12	0	0	0	0	100
		J B-P 149	25	8	5	0	33	3	15	4	3	0	+	3	+	0	99
		J B-P 146	75	6	8	0	0	2	0	4	0	0	0	2	0	2	99
Lower Jurassic	Hasle Formation	W W 64	15	5	0	0	5	22	5	1	0	7	40	0	0	0	100
		W W 59	26	6	0	0	1	36	1	3	0	17	6	0	0	2	98
		J B-P 162	13	9	0	0	3	39	5	12	1	+	13	2	+	4	101
		J B-P 161	8	6	1	0	8	58	12	6	0	0	0	0	0	0	99
		J B-P 160	9	3	1	0	4	20	1	6	1	+	7	6	34	8	100
		J B-P 158	41	5	0	0	27	18	3	5	1	+	0	0	0	0	100
		J B-P 157	22	16	+	0	7	45	5	3	1	1	0	4	+	0	104
	Rønne Formation	J B-P 159	29	8	2	0	22	10	12	15	0	0	0	0	1	0	99
		J B-P 152	11	3	0	0	52	5	1	17	0	0	0	7	2	2	100
		J B-P 151	10	9	9	0	40	5	9	5	1	0	0	8	4	1	101
		J B-P 150	10	3	2	0	43	3	14	17	0	+	0	2	3	3	100
		J B-P 144	81	1	1	0	4	0	1	1	1	0	1	1	6	1	99
Triassic	Risebæk M.	Gry 7	84	4	0	0	2	0	10	+	0	0	0	0	0	0	100

Fig. 8.
The non-opaque heavy mineral distributions of Mesozoic sediments older than the investigated Lower Cretaceous deposits. Twenty-one analyses from Gry (1936), Werner & Weyl (1952) (WW) and Bruun-Petersen (1969) (J B-P).

The older Mesozoic sediments have heavy mineral associations, which partly are the same as that investigated from the Lower Cretaceous but generally with higher tourmaline and garnet contents and lower rutile contents. They are the same kinds of minerals with high and moderate resistance to weathering and diagenesis and very unstable minerals are present only in a very subordinate amount. The older Mesozoic rocks may be source rocks of the Lower Cretaceous heavy minerals and some are probably derived from them, but a more reasonable explanation is that the provenance area of the Mesozoic of Bornholm has been nearly the same during the whole era, but with different rock types exposed to weathering and erosion from the Triassic to the Cretaceous. It is often claimed that it is not normal to find kyanite, staurolite, sillimanite and garnet in larger amounts in recycled sediments (Pettijohn, 1957, Pettijohn et al., 1972) and this could indicate that Triassic and Jurassic sediments are not redeposited in the Lower Cretaceous. A provenance area outside Bornholm for the heavy minerals, therefore is possible, and Allen (1967) suggests the Fenno-Scandian Shield as the primary provenance area. Probably, there has been direct transport from the shield to Bornholm according to Allen (1967), and the source material could have been granitic gneisses and highly metamorphic schists (Allen, 1967).

Larsen (1968) mentions that epidote and hornblende are characteristic of the present Fenno-Scandian Shield. These minerals occur in a very small amount in the Lower Cretaceous and an explanation may be that the shield has had a different and more varied composition at that time. Older sediments of Sweden (Scania) exposed for erosion in the Lower Cretaceous are another possibility, and information in Larsen (1966, 1968) and Weyl & Werner (1952) shows that Triassic and Jurassic beds (Kågeröd Formation, the Glass sand) have a heavy mineral content very much like that of the Triassic, Jurassic and Lower Cretaceous of Bornholm, but often with a rather high garnet content and zircon, rutile, tourmaline, kyanite and staurolite as the other minerals. Furthermore, nearly the same picture occurs in the Jurassic-Kimmeridgian in the Helsingør-Helsingborg area, which has been exposed to weathering during the Lower Cretaceous (Larsen, 1968).

It can be concluded that the main part of the heavy mineral assemblage originated from areas outside Bornholm, probably from the Precambrian Fenno-Scandian Shield or exposed Palaeozoic and Mesozoic sediments covering the basement, and the minor part came from Bornholm proper and was recycled from older Mesozoic rocks.

Conclusions

The quartz arenitic sand of the Robbedale and Jydegaard Formations consists of approximately 99 per cent quartz grains, and the rest is heavy minerals of which the main part is opaque. The investigation of the mineralogy, grain-size, sorting, and rounding of all the grain-sizes of the sand and of the sand in the few silt and clay beds of the Østerborg, Langbjerg and lowermost part of the Tornhøj Members in the Arnager-Sose fault block has given the following results and conclusions regarding the source rocks and provenance area of the sediments:

The Precambrian basement of Bornholm is not the main source of the Lower Cretaceous sediments. A part of the quartz might originate from the kaolin, pegmatites or granites as the content of polycrystalline quartz points to a first cycle deposition of material from this kind of rocks. The rounding of the grains might be in situ rounding at weathering in kaolinized profiles (Moss, 1966; Crook, 1968) or it might have happened in the foreshore and shallow shoreface at continuous transport, deposition and erosion (Balazs & Klein, 1972; Gravesen, 1982a). However, if the large amount of partly abraded quartz sand is not coming from the basement or the older Palaeozoic and Mesozoic sediments of Bornholm it may have been delivered from denudation areas outside of Bornholm. One possibility is the Fenno-Scandian Shield, which was uplifted during the Late Kimmerian tectonic episode. Other possibilities are more southerly or easterly areas as indicated by palaecurrent measurements (Gravesen, 1982a).

The main part of the heavy minerals does not originate from the basement and Palaeozoic sandstones and siltstones. They might represent resedimented older Mesozoic deposits, but the relatively large content of garnet, kyanite and staurolite indicates first cycle deposits (Pettijohn, 1957, Pettijohn et al., 1972), which have a metamorphic provenance outside Bornholm. It seems very probably that most of the Mesozoic sediments of Bornholm have had source areas outside Bornholm (Larsen, 1966; Graff-Petersen, 1961). The source areas might have been nearly the same during the whole era and this again points to the Fenno-Scandian Shield, where various basement rocks and sediments could have been weathered and eroded and the material transported to Bornholm. However, the presence of idiomorphic crystals and well rounded grains of most of the minerals shows that both local and long distance transported material is found in the sediments.

Finally, it can be concluded that the Lower Cretaceous deposits consist of a combination of mainly first cycle sand of both local and distant origin and subordinate multicyclic sand, which is of mainly local origin. The sand material was deposited in the shallow marine nearshore which allowed repeated transport, deposition and sorting of the sand as the main processes responsible of forming the quartz arenitic sand. Acid weathering and kaolinization combined with tectonic uplift are possible the source processes, whether or not the material is of local or distant origin. Generally, the three lithostratigraphic members have the same zircon - rutile - tourmaline - kyanite association which indicates the same provenance area as the rest of the sediments of the Mesozoic of Bornholm.

Acknowledgements

I thank Lise Holm and Stanley Fine for critical reading of the manuscript and for constructive suggestions. Stanley Fine has kindly improved the English of the manuscript. Anna-Marie Svendsen, Carlos Torres and Gitte Nicolaisen are thanked for technical assistance.

Dansk sammendrag

Der er foretaget en petrografisk undersøgelse af kvartssandet fra Robbedale Formationen og nedre del af Jydegård Formationen i Arnager-Sose forkastningsblokken på Bornholm. Begge formationer er af Nedre Kridt alder. Atten prøver er analyseret med hensyn til indhold af lette og tunge mineraler, kornstørrelse samt sandkornenes afrundingsgrad og form.

Hensigten med undersøgelsen har været at bestemme, hvilke typer bjergarter, der var sandets oprindelsesmateriale samt hvilket område, sandet var transporteret fra til aflejring på Bornholm i Nedre Kridt.

Undersøgelsen viser, at de Prækambriske grundfjeldsbjergarter på Bornholm ikke er hovedkilden til dannelse af sandet, da bl.a. sandets tungmineralindhold afviger væsentligt fra de bornholmske gnejser og granitters, men det er muligt, at en mindre del af kvartsen kommer herfra. De Palæozoiske sandsten og siltsten på Bornholm er andre muligheder som oprindelsesbjergarter, men disse kan også udelukkes. De ældre Mesozoiske sedimenter på Bornholm kan umiddelbart tænkes at have været oprindelsesbjergarter, da de stort set har samme tungmineralselskab som Nedre Kridt kvartssandet. Imidlertid vil en mere sandsynlig forklaring være, at der gennem hele Mesozoikum har været oprindelsesområde udenfor Bornholm, hvorfra der er transporteret materiale til aflejring i et fladvandet hav omkring Bornholm. Dette område kunne være det opløftede Fennoskandiske Grundfjeldsskjold, hvor både grundfjeldsbjergarter og sedimenter har været blottet i hele tidsrummet og dermed udsat for forvitring og erosion.

Den endelige konklusion må således blive, at kvartssandet fra Nedre Kridt har haft en sammensat transport og aflejringshistorie, og det består hovedsagelig af sand af både lokal og fjern oprindelse, som er aflejret i en første aflejringscyklus med en underordnet bestanddel af lokalt sand, der har været gennem flere aflejringscykler.

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**This book gives a discription of the Lower Cretaceous quartz-bearing deposits on Bornholm.
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ISBN 87-421-0738-5
ISSN 0901-0270