Heavy-mineral provinces in southern Skagerrak and northern Kattegat

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Bengtsson, H. & Stevens R.L. 1996: Heavy-mineral provinces in southern Skagerrak and northern Kattegat. *Nor. geol. unders. Bull. 430*, 47-55.

Detailed heavy-mineral studies of the bottom sediment in the Skagerrak-Kattegat area have not been previously reported. The heavy-mineral suite in the very-fine-sand fraction (63-125 μm) is dominated (70-91%) by amphibole, epidote and garnet. Based upon mineralogical variations, six distinct provinces have been defined and statistically tested. The distribution patterns of heavy minerals allow preliminary interpretations of the transport pathways and the associated sediment sources. One main source is the mineralogically immature, Quaternary deposits of Scandinavian origin which reflect bedrock composition and show a notably high amphibole content. A second important source is the mature, primarily Tertiary sediments exposed in the southern North Sea and in northwestern Europe. Abundant garnet is characteristic of this source. The distinct mineralogical compositions within all provinces indicate that the sediment transport between the provinces does not occur without considerable modification by hydraulic sorting and mixing of sources. The intra- and inter-province relationships between mineralogy and texture are a necessary basis for quantitative evaluations.

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Introduction

Heavy minerals are often a neglected part of the sediment, but in addition to their traditional use for identifying provenance (sediment source) they may convey valuable information regarding sedimentary processes. The sedimentological information available from grain-size and mineralogical analyses is important in process modelling. This, in turn, is a necessary first step for environmental management of marine resources on a large scale. In this connection, the Swedish Environmental Protection Agency initiated an interdisciplinary project, within which our work has been oriented toward sediment sources, transport pathways and the processes associated with the accumulation of recent deposits. This paper evaluates the heavy-mineral content in the bottom sediments of southern Skagerrak and northern Kattegat, using the mineralogy to classify provinces and identify sources. The heavy-mineral suite is systematically modified along its transport path (Rubey 1933, Rittenhouse 1943) and is also dependent on the specific grain-size distribution of the final deposit (Rittenhouse 1943, van Andel 1950, Milner 1962, Briggs 1965, Morton & Hallsworth 1994). Nevertheless, it is generally possible to establish mineralogical provinces and to characterise sources (van Andel 1950, Briggs 1965, Hubert & Neal 1967, Friis 1974, Mezzadri & Saccani 1989, Morton & Hallsworth 1994). In addition, regional documentation provides a reference for comparing the detailed variations of both mineralogical and textural data. Eventually, when the relationships between these parameters have been well defined, it may be possible to quantify the sediment fluxes into and between the mineralogical provinces presented here.

In the southern North Sea region a detailed study has been made of the heavy-mineral distribution (Baak 1936) at more than 1,000 localities. In the Skagerrak-Kattegat area, on the other hand, the heavy minerals of the bottom sediments have been previously dealt with in only one study (van Weering 1981). In that investigation the dark minerals, carbonates and mica minerals in the very-fine-sand fraction (63-125μm) were not further subdivided, but their concentrations were used as an indication of the general sediment transport pattern. A description of the heavy minerals occurring within the very-coarse-silt fraction (45-63μm) of fine-grained deposits in the

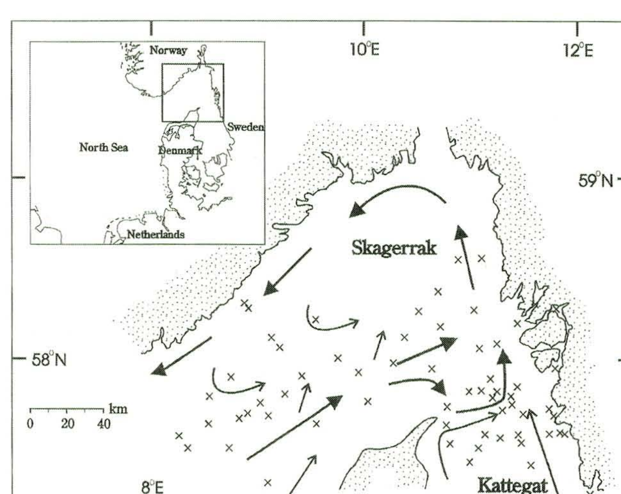

Fig. 1. Sample locations in the Skagerrak-Kattegat area. Analysed samples are marked with a cross. Arrows indicate the main surface currents, where thick arrows are dominant currents and small arrows are episodic (after Svansson 1975, Rodhe 1987).

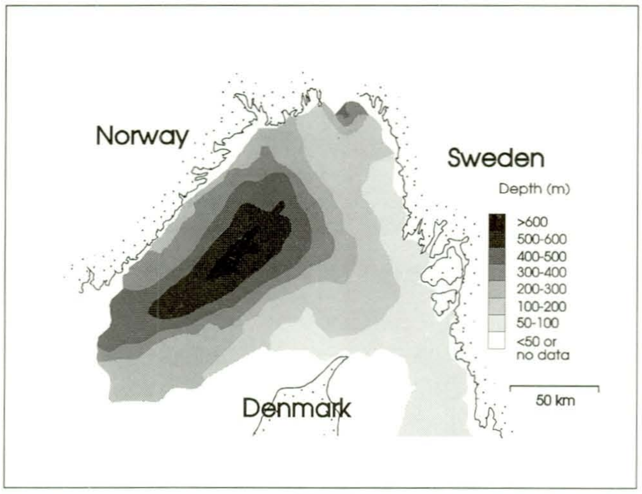

Fig. 2. Bathymetry of Skagerrak and northern Kattegat.

Norwegian sector of northern Skagerrak is presented by Lepland & Stevens (this volume).

Area description

Skagerrak is the eastern extension of the central North Sea (Fig. 1). Kattegat lies immediately to the southeast and connects to the Baltic Sea. Due to the presence of deep basins, of which the Norwegian Trench is by far the largest, this area provides a natural sediment trap for the material transported from the comparatively shallow North Sea and Kattegat, as well as from Scandinavian rivers (Fig. 2). The present pattern of deep-water circulation is believed to have been established at about 8,000 BP (Eisma et al. 1979, Bjørklund et al. 1985), and the present surface circulation developed at about 4,000 BP (Bjørklund et al. 1985, Nordberg 1991). The Skagerrak-Kattegat area is dominated by large-scale atmospheric and oceanic circulation patterns and by the outflow of Baltic water (Stigebrandt 1983). In the eastern Skagerrak, variable bottom (North Atlantic Water Current) and coastal (Jutland Current) currents from the North Sea interact with the northward-flowing surface current from the Kattegat (Fig. 1, Svansson 1975, Rodhe 1987). The thickness of Quaternary deposits in the Skagerrak varies widely, from less than 25 m in the deepest, central Skagerrak to 200 m in the outer depositional basins of the Oslo fjord (Solheim & Grønlie 1983). Large variations of sediment thickness also characterise the southeastern Skagerrak and northern Kattegat area, with up to 160 m of Quaternary deposits between Skagen and Göteborg (Flodén 1973, van Weering 1981). North of Denmark the thicknesses vary from 75 to 200 m (Hempel 1985).

Samples and methods

The upper two centimetres of the sediment were sub-sampled from box cores and multi-core samples collected during three cruises (1988-1992). The samples consisted mainly of sediment from the oxic layer. The coordinates and depths for sample locations from the first two cruises are given in Kuijpers et al. (1993 a). Additional samples have been collected in co-operation with the Geological Survey of Sweden during marine geological mapping along the Swedish west coast. The samples provide a good coverage of the northern Kattegat and southern Skagerrak (Fig. 1). Northern Skagerrak has been investigated by Lepland & Stevens (this volume). The very-fine-sand fraction was selected for documentation since this is the most frequently used size interval in heavy-mineral studies and because this size is readily identifiable with optic microscopy. Morton & Hallsworth (1994) point out that for the determination of provenance-sensitive heavy-mineral ratios, the analysis is preferably carried out within the very-fine-sand fraction, as a narrow size interval helps reduce the effects of hydraulic sorting. It is also necessary to count a specific grain-size fraction in each sample to secure a reasonable correlation between samples (Sindowski 1938 a, b [in Friis 1974], Morton & Hallsworth 1994).

The samples were treated with hydrogen peroxide (H_2O_2) to remove organic matter, dispersed with sodium diphosphate ($Na_4P_2O_7 \cdot n\ H_2O$), and analysed for grain-size using wet-sieving and pipette methodologies (Krumbein & Pettijohn 1938). To separate the heavy minerals in the very-fine-sand fraction (63-125 µm) the non-toxic liquid sodium polytungstate ($3Na_2WO_4 \cdot 9WO_3 \cdot H_2O$, r=2.91 g/cm^3) was used to float lighter components (Callahan 1987, Krukowski 1988). The heavy-liquid suspension was centrifuged at 3,000 rpm for five minutes, then stored in a freezer overnight. The frozen sample was then split, thawed, and each mineral separate was rinsed

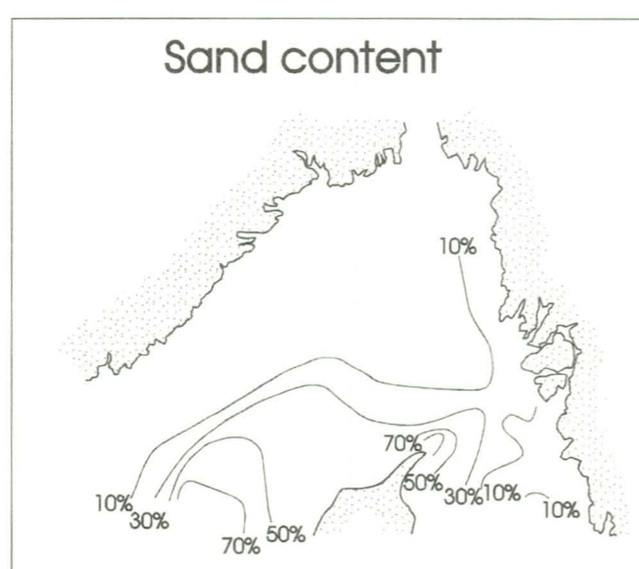

Fig. 3. Sand (63-250 µm) content of the bottom sediments.

Table 1. Heavy minerals and their characteristics in the Skagerrak-Kattegat area. The average content and mineral stability for the heavy minerals are also given. X = excluded from heavy-mineral percentages, - = no information, std. dev. = standard deviation.

Group division	Mineral	Most Important Determination Criteria	Stability (after Hubert 1971)	Ave. % ()= std.dev.
Amphibole	Hornblende -green	Green, pleochroic, 12-34° extinction angle, «own» colour in birefringence, elongated grains	Unstable	33,2 (±7,9)
Amphibole	Hornblende -bluish green	Bluish-green, 12-34° extinction angle, «own» colour in birefringence, elongated grains	Unstable	3,2 (±1,8)
Amphibole	Hornblende -brownish green	Brownish-green, 12-34° extinction angle, «own» colour in birefringence, elongated grains	Unstable	1,6 (±1,2)
Amphibole	Tremolite/Actinolite	Colourless- pale greyish- pale green, 11-21° extinction, 1st-2nd order birefringence	Unstable	5,8 (±2,4)
Epidote	Epidote- green	Bottle green, weak-strong pleocroism, 0-2° extinction degree, 2nd-3rd order birefringence, spherical grains	Semistable	13,2 (±5,1)
Epidote	Epidote- clear	Colourless-, weak pleocroism, 0-2° extinction degree, 2nd-3rd order birefringence, spherical grains	Semistable	6,1 (±3,8)
Epidote	Clinozoisite	Colourless- pale yellow or green, parallel extinction, 1st order birefringence, squarish grain shape	Semistable	9,5 (±4,0)
Epidote	Zoisite	Colourless, parallel extinction (incomplete), 1st-2nd order birefringence, rounded grain shape	Semistable	<0,5
Garnet	Pyralspite	Almandine and spessartine members: clear-pinkish, isothropic, nonpleocroic, concoidal fractures	Stable	8,3 (±3,2)
Garnet	Ugrandite	Grossular and andradite members: brownish-yellowish, isothropic, nonpleocroic, concoidal fractures	Stable	<0,5
Pyroxene	Clinopyroxene-augite	Colourless- shades of green-brown, weak pleochroism, 35-48° extinction angle, 1st-2nd order birefringence, hacksaw terminations	Unstable	6,7 (±3,1)
Pyroxene	Clinopyroxene-titanaugite	Violet brown, weak pleochroism, 35-48° extinction angle, 1st-2nd order birefringence, hacksaw terminations	Unstable	<0,5
Pyroxene	Clinopyroxene-diopside	Colourless- pale green, weak pleochroism, 38-48° extinction angle, 1st-2nd order birefringence	Unstable	<0,5
Pyroxene	Orthopyroxene-hypersthene	Pink- green, pleochroic, parallel extinction, 1st order birefringence, elongated shape,	Unstable	1 (±0,5)
Pyroxene	Orthopyroxene-enstatite	Colourless nonpleochroic, parallel extinction, 1st order birefringence, elongated shape, hacksaw terminations	Unstable	<1
ZTR	Rutile	Shades of red, distinct pleochroism, parallel extinction, extreme birefringence obscured by mineral colour, high relief	Ultrastable	<0,5
ZTR	Tourmaline	Colourless- brown- deep blue, distinct plechroism, parallel extinction, 3rd-4th order birefringence, often obscured by mineral colour, narrow polarisation bands	Ultrastable	1,4 (±1,1)
ZTR	Zircon	Colourless, parallel extinction, 3rd order birefringence, extreme relief, zonation, good crystal shape	Ultrastable	2,4 (±1,6)
Titanite	Titanite (sphene)	Colourless- pale brown, green or yellow, incomplete extinction, 3rd order extinction, sub-rounded grain shape, often ridge in grain	Stable	3,9 (±1,6)
Others	Staurolite	Orange-yellow, distinct pleochroism, parallel extinction, 1st-2nd order birefringence, high relief, irregular shape	Semistable	<1
Others	Monazite	Colourless- pale yellow, 2-7° extinction angle, often incomplete, 3rd-4th order birefringence, rounded morphology	Semistable	<0,5
Others	(Chromian?) Spinel	Brownish red, sharp angular, irregular grains, isotropic	-	<0,5
Others	Casseterite	Red-brownish red, distinct pleochroism, parallel extinction, extreme birefringence obscured by mineral colour, high relief	-	<0,5
Others	Pumpeleyite	Shades of green, strong pleochroism, parallel extinction, radial fibres, 1st order birefringance	-	<0,5
Others	Sillimanite	Colourless-pale green, parallel extinction, 2nd-3rd order birefringence	Semistable	<0,5
Others	Andalusite	Colourless- pinkish, pleochroic, extinction parallel to cleavage, 1st-2nd order birefringence, irregular grain shape	Semistable	<0,5
Others	Kyanite	Colourless, 27-32° extinction angle, 1st-2nd order birefringence, perfect cleavage	Semistable	<0,5
Others	Apatite	Colourless, parallel extinction, 1st order birefringence, good crystal shape, low relief	Semistable	1,3 (±1,0)
Opaque-mineral	Opaque	Black, can have weak coulored or metalic luster, includes hematite, magnetite and precipitates	Stable-unstable	20 (±10,5)
X	Chlorite	Shades of green, weak pleochroism, parallel extinction to cleavage, extremely low 1st order birefringence, flaky appearance	Stable	X
X	Mica	Colourless- brown- green, 0-9° extinction angle, 2nd- 3rd order birefringance, flaky structure	Stable-unstable	X
X	Glauconite	Dark green, pleochroic, parallel extinction, 2nd order birefringence obscured by mineral colour, aggregate structure	-	X
X	Calcite	Colourless, non-pleochroic, extreme birefringance, pronounced change in relief with rotation, straight extinction, irregular grain form	-	X
X	Dolomite	Colourless, non-pleochroic, extreme birefringance, pronounced change in relief with rotation, straight extinction, rhomboheadral	-	X

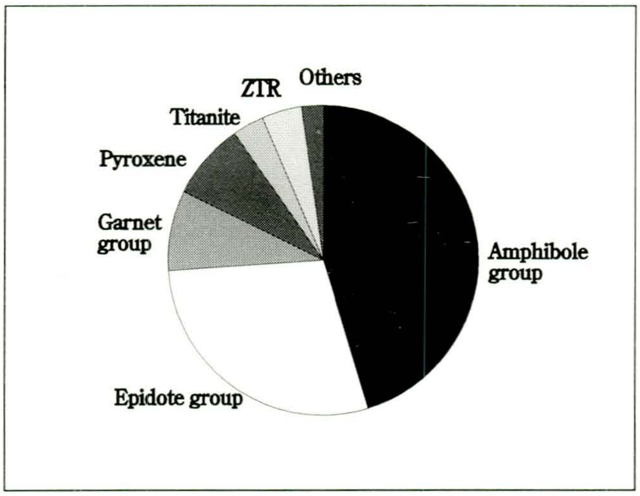

Fig. 4. The average, non-opaque heavy-mineral composition in the very-fine-sand fraction (63-125 µm) for all samples the Skagerrak-Kattegat area. ZTR is the sum of zircon, tourmaline and rutile.

with water. The separation liquid was saved and reused after evaporative removal of excess water. The heavy-mineral grains were mounted on slides with epoxy glue

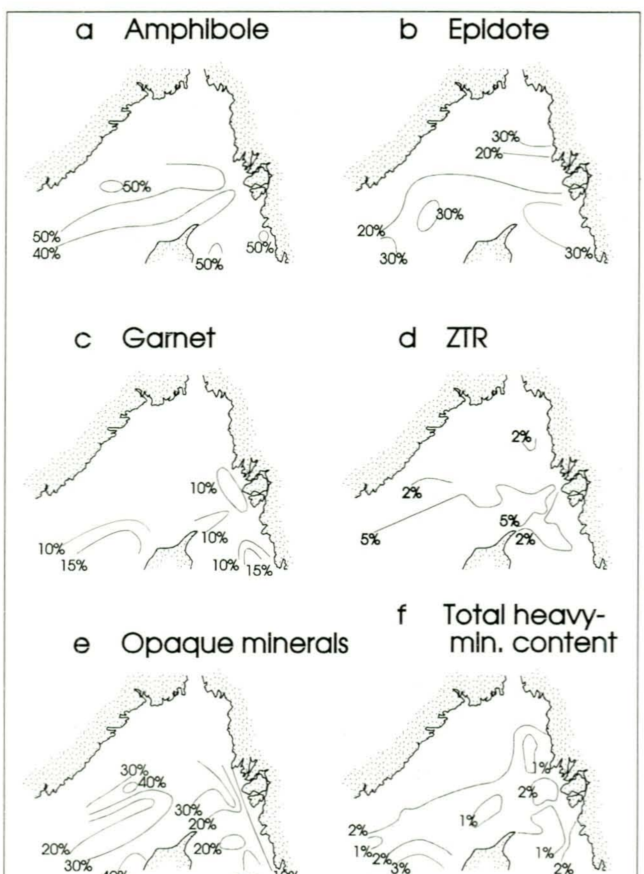

Fig. 5. Distribution maps for the most abundant heavy minerals in the very-fine-sand fraction (63-125 µm). The percentages are relative proportions of the non-opaque heavy-mineral suite. The opaque-mineral percentages are based upon the total heavy-mineral concentrate.

(R.I. 1.54). The percentages of the non-opaque heavy minerals, excluding micas, were determined by microscopic documentation of at least 300 grains in each sample (Krumbein & Pettijohn 1938, FitzPatrick 1984, Mange & Maurer 1992). Opaque-mineral percentages were calculated separately. The percentage of heavy minerals in the very-fine-sand fraction (63-125 µm) was calculated by dividing the weight of the heavy-mineral concentrate by the total weight in this size fraction.

Results

The sand content (63-250 µm) of the bottom sediment varies considerably, from over 70% in the southwestern part of Skagerrak and northeast of northern Denmark, to less than 10% in central Skagerrak and eastern Kattegat (Fig. 3). The distribution is largely in agreement with the pattern presented by earlier workers (Olausson 1975, van Weering 1981, Kuijpers et al. 1993 b), with a decreasing sand content towards the deeper parts of the Skagerrak. The very-fine-sand fraction (63-125 µm) predominates in the coarse material (>63 µm). Most sediment deposits in the Skagerrak have a strong bimodal character with regionally variable proportions of the coarse and fine subpopulations. A dominant clay mode is typical for the Norwegian Trench, a well developed coarse mode and a weak fine-grained mode occur in sediments along the Danish northwest coast up to Skagen, and northern Kattegat is dominated by a coarse silt mode (van Weering 1981, Stevens et al. in press).

There is a relatively large number of heavy-mineral species and varieties in the Skagerrak-Kattegat sediments, varying from 15 to 23 in individual samples. A total of 29 different heavy minerals, including opaque minerals, were documented in the very-fine-sand fraction (Table 1). At all sites, the amphibole, epidote and garnet predominate (70-91%) within the suite, while pyroxene and titanite (sphene) are common (Fig. 4). The most common minerals were divided into six groups: amphibole, epidote, garnet, pyroxene, ZTR (zircon, tourmaline and rutile) and opaque minerals. The different mineral varieties within these groups were identified, except for opaque minerals (Table 1). In the amphibole group, green hornblende predominates; with a minimum of 70% in all samples. The epidote group is divided more evenly between epidote and clinozoisite, while zoisite is rare. Almandine garnet predominates over spessartine garnet in the garnet group. Augite is consistently the most abundant mineral in the pyroxene group, whereas enstatite and hypersthene are uncommon. Although not present at all sample sites, zircon and tourmaline are common and predominate in the ZTR group, whereas rutile is rare. A higher ZTR index (summed group percentages) indicates greater sediment maturity with respect to mineralogy (Hubert & Neal 1967). Other, less abundant minerals are included in Table 1. Glauconite constitutes 0-2% of the heavy-mineral fraction and is also present in the light fraction due to its relatively low density (r=2.4-2.95 g/cm[3]). Most glauconite grains are dull dark green, slightly subrounded, and consist of authigenic grains or an authigenic precipitation in foraminifera shells (Bjerkli & Östmo-Saeter 1973). While determining the heavy-mineral composition in the samples, it was noted that heavily weathered grains were more abundant in the Kattegat than in the Skagerrak, especially in the southeastern Kattegat.

The amphibole content in the surface sediment is highest along parts of the Swedish west coast and in central Skagerrak, and lowest along the Danish northwest coast (Fig. 5a). Epidote is generally most abundant along the Swedish west coast and along the Danish northwest coast, and lowest in eastern and northwestern Skagerrak (Fig. 5b). The garnet percentages are highest in southern Skagerrak and the southernmost studied part of northern Kattegat, and lowest in northeastern and central Skagerrak (Fig. 5c). The ZTR minerals are most abundant in southern Skagerrak and least abundant in the Kattegat and nearshore western Sweden (Fig. 5d). Opaque minerals are best represented along the Danish northwest coast and in parts of central Skagerrak. They are less common along the Swedish west coast (Fig. 5e). The total heavy-mineral content for the very-fine-sand fraction shows an irregular distribution pattern, generally less than 3% (Fig. 5f). The highest contents are in southern Skagerrak, but relatively high contents are also documented in central Skagerrak and southeastern Kattegat.

Heavy-mineral provinces

Based on the heavy-mineral distributions, six provinces are distinguished in southern Skagerrak and northern Kattegat (Fig. 6). Although amphibole, epidote and garnet are predominant within the heavy-mineral assemblages in all provinces, the proportions of pyroxenes, zircon, tourmaline, apatite and titanite (together varying between 9-30%), and the occurrence of opaque minerals (3-44%) were also used for the divisions. The minerals with low abundance have large individual variations in occurrence (0-17 % for single mineral types). Within each province the variations in the mineral composition may therefore be considerable. The average compositions within each province are presented in Table 2 and show the main regional differences.

The statistical distinction of each mineralogical province compared to the others has been tested using the Student's t-test (Kellaway 1968, Davis 1986). All provinces are separated from other provinces with a minimum of 95% significance for two or more of the most common minerals (Table 3). The majority of the standard deviations for the heavy minerals have a homogeneous composition. The heterogeneous compositions have been

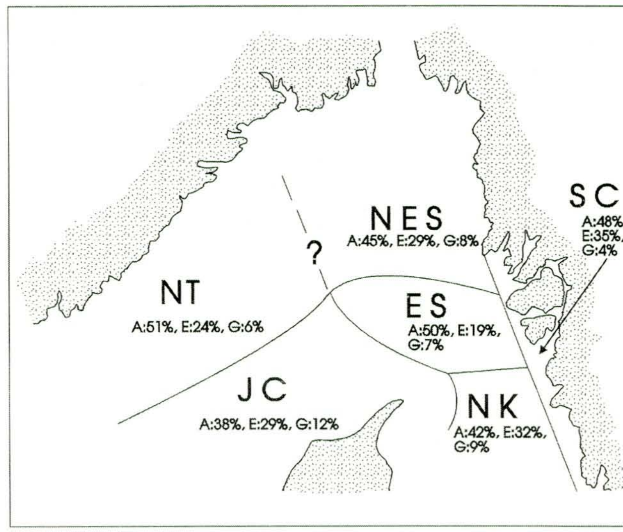

Fig. 6. Provinces in southern Skagerrak and northern Kattegat based on heavy-mineralogy distributions. The abbreviations of the provinces are stated in Table 2.

Table 2. Average heavy-mineral content in the very-fine-sand fraction (63-125 µm) and the average grain-size distribution for each province. Also included are the average contents for heavy minerals of till in SW Sweden, Late Tertiary sediments in central Jutland (Denmark), and recent deposits in the southern and southeastern North Sea. Amph = amphibole, garn = garnet, epid = epidote.

Province (abbrevations)	Grain-size			Mineralogy			
	Sand	Silt	Clay	Amph	Garn	Epid	ZTR
Jutland Current (JC)	41%	34%	25%	38%	12%	29%	7%
Northern Kattegat (NK)	14%	53%	33%	42%	9%	32%	2%
Northeastern Skagerrak (NES)	13%	54%	33%	45%	8%	29%	2%
Norwegian trench (NT)	18%	49%	33%	51%	6%	24%	4%
Swedish west coast (SC)	6%	42%	52%	48%	4%	35%	2%
Eastern Skagerrak (ES)	12%	57%	31%	50%	7%	19%	5%
Areas and rock stratigraphic units adjacent to the Skagerrak							
Till, SW Sweden (after Lång & Stevens 1995)				51%	2%	39%	1%
Late Tertiary sediment, epidote association, Jutland, Denmark (after Friis 1974)				1%	3%	40%	34%
Late Tertiary sediment, metamorphic association, Jutland, Denmark (after Friis 1974)				0%	12%	0%	25%
Late Tertiary sediment, marine amphibole-epidote association, Jutland, Denmark (after Larsen & Dinesen 1959)				20%	7%	61%	6%
A-group, southern North Sea (after Baak 1936)				22%	29%	25%	12%
Part of A-group, south to southeastern North Sea (after Baak 1936)				25%	18%	30%	15%

Table 3. Minerals showing significant distinction of provinces according to the Student's t-test (Sokal & Rohlf 1969, Davis 1986). A = amphibole, E = epidote group, G = garnet, T = titanite, P = pyroxenes, Ap = apatite and O = opaque minerals. The significance level for the mineralogical differences are: * = 95%, ** = 99% and *** = 99.9%.

	JC	NK	NES	NT	SC	ES
JC		A*** E** G* ZTR*** O*	A*** G* ZTR*** T*	A* E* G** ZTR**	A*** E** G** ZTR*** T* P* O***	A*** E** G* T** P*** O**
NK			A* E* G*	E*** G**	A* G** P** O**	A*** E*** ZTR*** O***
NES				E* G*	E* G* O**	A** E* ZTR** P* Ap* O**
NT					E** O*	A* G* P** O*
SC						E*** G* ZTR** P*** Ap* O***
ES						

tested separately with an alternate formula (Sokal & Rohlf 1969), but have the same order of significance as with the homogeneous t-test formula. Multivariate methods were not applied in this analysis since the mineral percentages are partially dependent, and the univariate testing proved sufficient for province definition, while retaining information regarding individual mineral variability.

Province JC, along the Jutland coast (northwest coast of Denmark), is associated with the variable Jutland Current. The sediments have an average composition of 38% amphibole, 29% epidote, 12% garnet, 7% ZTR, (Table 2, Fig. 6) and 24% opaque minerals. The province is statistically separated from the other provinces with a minimum of four minerals (Table 3), and is one of the most distinct provinces. Province NK (northern Kattegat) has an average heavy-mineral assemblage of 42% amphibole, 32% epidote, 9% garnet, 2% ZTR and 17% opaque minerals. The NK province is statistically clearly defined, but somewhat less well defined against the NT province, though sufficiently separated with epidote and garnet. Province NES (northeastern Skagerrak) has an average heavy-mineral content of 45% amphibole, 29% epidote, 8% garnet, 2% ZTR and 19% opaque minerals. Province NT (the region along and north of the Norwegian Trench) has an average of 51% amphibole, 24% epidote, 6% garnet, 4%, ZTR and 21% opaque minerals. NT has the weakest statistical distinction, separated only on the basis of two minerals in several cases, although still significant at the 95% level. Province SC (the Swedish west coast archipelago) has an average composition of 48% amphibole, 35% epidote, 4% garnet, 2% ZTR and 7% opaque minerals. This province has the greatest proportions of amphibole, epidote and garnet (together 86%) in the region. Province ES (mainly the eastern Skagerrak) has an average assemblage of 50% amphibole, 19% epidote, 7% garnet, 5% ZTR and 32% opaque minerals. It is one of the most clearly distinct provinces, separated from all others by the t-test statistics of at least four minerals.

The geographic pattern of the total heavy-mineral content (Fig. 5f) does not entirely correspond to the earlier documented distribution of dark-coloured heavy minerals in the Skagerrak (van Weering 1981). The differences may partially be due to the inclusion of non-coloured heavy minerals in this study. On the southern slope of the Norwegian Trench there are only minor differences. In central Skagerrak, only traces of heavy minerals were previously reported, whereas relatively high contents were found in this study. The increase of opaque minerals in the deepest parts of the Skagerrak (Fig. 5e) is not considered to be related to selective grain transport because opaque minerals are preferentially deposited earlier than the comparatively lighter minerals. Since Fe- and Mn-precipitation may increase the amounts of opaque grains, the specific depth of surface sampling in each study with respect to the sediment redox boundary is also a possible, but as yet uncertain factor.

Sediment sources and transport

Due to glacial erosion and dispersal patterns, the mineralogical composition of recent sediments in the glaciated areas of northwest Europe is strongly influenced by the crystalline bedrock from the Scandinavian peninsula. The Weichselian ice-sheet had a maximum extension at approximately 20,000 BP, reaching southwest of Jutland (Pratje 1951 [in Holtedahl 1993]). Earlier Pleistocene glaciations reached as far south as the Netherlands (Flint 1971, Nilsson 1972). Glacial sediments of Scandinavian origin were deposited in the Skagerrak and other North Sea basins and on the northwestern European mainland. Locally, glacial erosion has incorporated Tertiary and Mesozoic sedimentary bedrock. These glacial sediments are therefore accessible for secondary erosion both on land and in the sea areas in and around the Skagerrak-Kattegat area. The mineralogically immature glacial deposits of Scandinavian origin are characterised by a relative abundance of amphiboles, pyroxenes and epidote minerals. In addition to the glacial sediments, erosion of the mature, primarily Tertiary sedimentary bedrock in the southern North Sea and in northwestern Europe provides sediments, characterised by relatively abundant garnet and ZTR minerals. As is apparent in the discussion below, neither of these principle sources is entirely pure, but other sources are less influential. Mixing of the two main sources occurs and is especially evident during the northward transport of sediments from the southern North Sea.

Glacial and glaciomarine deposits in southwestern Sweden have heavy-mineral compositions (Stevens et al. 1987, Bengtsson 1991, Lång & Stevens 1995) comparable to those observed in province SC, deviating only a few percent between individual mineral varieties (Table 2). This similarity is consistent with a supply to nearshore areas of relatively immature sediment originating from glacial deposits both nearshore and onshore in Sweden. A large proportion of the grains are weathered, suggesting that although the sediment in SC is relatively immature, it has been influenced by weathering in the source area. Several investigations have indicated that on a gross scale, weathering at the source seldom has a significant effect upon the diversity of mineral assemblages incorporated into transport systems (van Andel 1950, Morton & Johnsson 1993). This appears to hold true in the Skagerrak-Kattegat, and the observed composition is only slightly modified from the local Quaternary deposits most exposed to erosion.

In comparison to the other provinces, the deposits in JC have a higher content of minerals of high stability, especially ZTR minerals (Table 2). This mineralogically mature assemblage is presumably derived from the Late Tertiary deposits in the Netherlands, Germany and Denmark, in which epidote, ZTR minerals and garnet predominate (Table 2, Edelman 1938 [in Friis 1974], Weyl 1950 [in Friis 1974], Larsen & Dinesen 1959, Larsen & Friis 1973, Friis 1974, 1976). Although there are large differences the JC province has a composition that can be related to sediments described in the southeastern North Sea (Table 2, Baak 1936, Larsen & Friis 1973, Friis 1974). The heavy-mineral suite apparently changes during northward transport due to marine and onshore erosion of glacial deposits of Scandinavian origin, successively diluting the southern North Sea mineralogy.

The mineral-distribution maps indicate possible transport pathways by either increasing or decreasing values of the individual mineral components. The amphibole, garnet and ZTR index distributions suggest a significant northward transport pathway along the Danish northwest coast, past Skagen and into eastern Skagerrak (Fig. 5a, 5c & 5d). The ZTR group also indicates transport from Skagerrak to the deeper parts of northern Kattegat ('Djupa rännan'). Amphibole and, to a lesser extent, garnet are consistent with downslope transport of sediment from the Danish side into the Norwegian trench. This net transport direction was also interpreted from the sequential changes in grain-size parameters along alternative pathways (Stevens et al. 1996). Decreasing garnet contents (Fig. 5c) also support an interpreted sediment transport northwards along the Swedish west coast in the Kattegat. The epidote (Fig. 5b) and the opaque-mineral patterns are consistent with a sediment supply along the Danish northwest coast, possibly in connection with the North Atlantic Water Current and the Jutland Current.

The transport interpretations here, and those generally presented in the literature (Morton & Hallsworth 1994), do not fully account for the influences of grain-size changes. For example, the total heavy-mineral content decreases along the pathway of the Jutland Current (Figs. 1 & 5f), as is seen by the high values in the southern Skagerrak (province JC) compared to the northeastern Skagerrak (province ES). Although selective sorting and depletion within the total sample would also favour this decrease, the main cause is believed to be the simultaneous fining trend in the sediment grain-size along the pathway (Fig. 3), which has presumably moved the modal (most frequent) sizes of the heavy-mineral suite away from the sand interval that was examined. Although we have tried to limit the effects of grain-size dependency by the use of a restricted size interval (very-fine-sand) for comparisons, an in-depth analysis of the textural and mineralogical relationships seems warranted and may allow improved, mineral-specific evaluations.

Considering the modern oceanographic currents (Fig. 1), it is apparent that the three provinces NES, ES and NK can be expected to receive sediments from the JC and SC provinces. The heavy-mineral indications of source, together with textural interpretations of net transport (Stevens et al. 1996), give support to this general pattern. As a sediment trap, province NT is of particular interest with respect to sediment sources and accumulation. However, the very fine-grained character of the deposits and the distance to sources other than those in the adjacent JC province, make detailed interpretations uncertain without further support. Also, the distinct mineralogical compositions within all provinces indicate that the sediment transport between the provinces occurs with considerable modification by hydraulic sorting and mixing of sources. Estimating the proportions of these contributions is very complex in the modern environment. On the other hand, sediment data provide an integrated effect of numerous processes, and should allow quantitative evaluations once inner- and inter-province relationships between mineralogy and texture are defined.

Conclusions

In the very-fine-sand fraction (63-125 μm) the heavy-mineral content is approximately 2%, but areas of <1% and >3% also occur. Amphibole, epidote and garnet make up 70-91% of the heavy-mineral composition. Six mineral provinces are defined using the heavy-mineral distribution in the Skagerrak and the Kattegat. All provinces are statistically distinct from each other with respect to two or more common heavy minerals. The major sources for the heavy minerals in the Skagerrak, as indicated from the distribution maps, are the sediments transported along the Danish northwest coast from the southern North Sea and the glacial deposits eroded from the Scandinavian coast and mainland. Since the distributions are interpreted to be influenced by both the mixing of sediment sources and the hydraulic sorting during transport, a prerequisite for detailed provenance interpretations, especially for quantitative evaluations, is the further specification of these processes.

Acknowledgements

This work is part of 'Västerhavsprojektet', organised by a Swedish interdisciplinary project group and financed by the Swedish Environmental Protection Agency. The Hierta-Retzeius foundation and Wilhelm and Martina Lundgrens foundation provided financial support for analyses. We also thank Eva Anckar for technical assistance, and the reviewers for their helpful suggestions.

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Manuscript received June 1995; revised version accepted December 1995.