Suspension sedimentation of coarse silt and sand in northern Skagerrak: textural and mineralogical trends

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The minor coarse-silt and sand fraction of muddy bottom sediments at 74 sites in northern Skagerrak is interpreted to have been mostly transported in suspension, aided by frequent reworking and the buoyancy of large aggregates. The overall sediment fining trend towards the Norwegian Trench is consistent with changes of bathymetry. Sediments in shallow shelf settings are mainly transported by a combination of traction and near-bottom suspension processes. Near-bottom suspension processes predominate on the trench slopes, whereas in the bottom of the trench there is a more balanced combination of near-bottom suspension and hemipelagic suspension deposition. Heavy-mineral distributions have weak geographic trends, due to the natural variability, and relatively non-selective and random character of the processes transporting coarse-silt and sand in suspension. Only biotite has a well developed distribution pattern and a relatively good correlation with grain size, probably related to single-particle transport together with fine silt. With consideration for the interpretative limitations of the individual heavy-mineral distributions, it is valuable to evaluate several mineral trends simultaneously, as well as the grain-size trends, in order to interpret patterns. Transport from southern areas and from the north is indicated.

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Introduction

The grain-size distribution of the bottom sediments in the Skagerrak is clearly controlled by the circulation pattern and basin bathymetry, resulting in different geographically associated transport and deposition mechanisms (Olausson 1975, van Weering 1981, 1982, Jørgensen et al. 1981, Fält 1982, Stevens et al. 1996). The transport to the Skagerrak and Kattegat of suspended sediment derived from shallow areas of the southern and central North Sea is well documented (van Weering 1981, Eisma & Kalf 1987a, b, Eisma & Irion 1988), and ca. 50-70% accumulates in the areas of low current velocity, especially in the Norwegian Trench and in the surrounding areas with water depths greater than 200 m (Eisma & Kalf 1987a, Eisma 1990, Salge & Wong 1988, North Sea Task Force 1993). This predominantly suspension-derived deposition in northern Skagerrak is responsible for a very fine and uniform sediment texture, consisting normally of more than 90% clay and fine silt. The sediment grain-size distribution is characterised by a major clay mode and a slight mode in the coarse-silt fraction (Stevens et al. 1996), whereas the content of very coarse silt and sand is negligible (1-2%). The bimodality of these sediments has been related to a combination of suspension and traction processes for the deposition of the fine and coarse fractions, respectively (van Weering 1981, Pederstad et al. 1993). The coexistence or alternation of these two mechanisms is not well understood (van Weering et al. 1993).

A principle objective of this paper is to address the transport and depositional processes of the very-coarse-silt and sand population (coarser than 6 ϕ), which is consistently present in the very fine-grained sediments of the Norwegian Trench. The interpretation of fine-sediment transport is also necessary since we suggest that suspension processes strongly influence both fine and coarse fractions. The emphasis upon coarse silt and sand is motivated because in these fractions the mineralogy can be routinely and quantitatively documented using petrographic microscopy. The combined treatment of sediment mineralogy and texture is used to evaluate the sediment transport pathways and processes. This approach is especially important in complex environments where single parameters are less diagnostic.

Materials and methods

The samples investigated within this study were collected from 74 locations in northern Skagerrak (Fig. 1) during two cruises, in 1992 and 1993, with the Bergen University research vessel 'Håkon Mosby', arranged by Bergen University and the Geological Survey of Norway. Surface sediments were subsampled within the upper 7 cm from short cores of approximately 50 cm, obtained using a modified Niemistö corer (Niemistö 1974).

Particle-size analyses of the samples were carried out using wet sieving at $^1/_2$-ϕ intervals for the fractions coarser than 5.5 ϕ and pipette analysis for the finer fractions (see Krumbein & Pettijohn 1938, McManus 1988, for standard procedures). The pre-treatment of the samples included the oxidation of organic matter with hydrogen peroxide, subsequent washing and final dispersion in

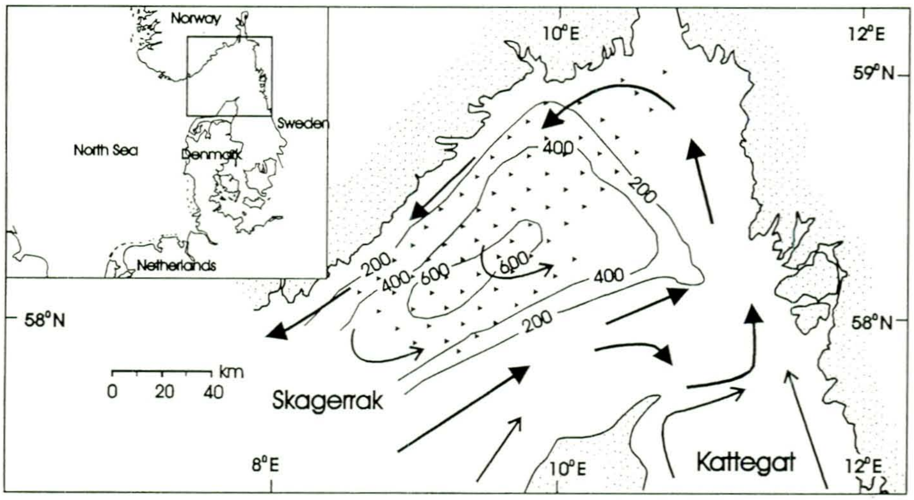


Fig. 1. Sample stations and generalised bathymetry in northern Skagerrak. Arrows show the direction of the main oceanographic surface currents, thick arrows correspond to strong flow and thin arrows to weak flow (after Svansson 1975).

0.05 M sodium hexametaphosphate while rotation tumbling for 4 hours.

The characterisation of sediment mineralogy is based upon the qualitative analysis of X-ray diffraction using powdered samples and the quantitative microscope analysis of the heavy-mineral concentrate (density > 2.9 g/cm^3), separated using sodium polytungstate (Callahan 1987). Grain counts were performed within a narrow size range of the very-coarse-silt fraction (4.5-4 ϕ) in order to limit hydrodynamic differences. The fine-sand fraction (4-3 ϕ) is typically used for heavy-mineral analyses (Morton & Hallsworth 1994), but a finer fraction was chosen in this study because of its relatively higher content compared with fine sand. Ribbon-traverse counts of up to 800 grains (translucent heavy minerals, opaque minerals, carbonates, micas) were made in order to include at least 300 translucent heavy minerals (Krumbein & Pettijohn 1938). The 8 presented contour maps of mineral percentages refer to the content within the heavy concentrates. These percentages are calculated differently to avoid dependency on the variations of predominant minerals. Biotite contents are given as percentages of all counted grains; carbonate contents are percentages of all grains except micas; magnetite and hematite contents are percentages of opaque minerals plus translucent heavy minerals; hornblende, epidote group, garnet and pyroxene contents are percentages of the translucent heavy minerals. In 20 selected samples, the proportions of terrigenous (mainly quartz and feldspar) and biogenic (mainly foraminifera and shell fragments) components in the sediment were determined by counts of 200 sand grains.

Results

Sediment character and grain size

The uppermost 50 cm of the sediment cores from northern Skagerrak are quite homogeneous, characterised by an almost total lack of apparent sedimentary structures except for a down-core increase in consolidation and a decrease in water content. The top 10-15 cm of most cores consist of very loose material. This unconsolidated material at the sediment surface is absent in samples originating from the southwestern area where relatively coarse sediments are common.

In spite of the predominance of clay and fine-silt particles in northern Skagerrak, a limited amount of sand (<4 ϕ) and very coarse silt (4-5 ϕ) is always present in these sediments. The sediment generally contains less than 1% sand, and in most areas of the Norwegian Trench deeper than 400 m the sand fraction decreases to less than 0.4% (Fig. 2a). Sand content decreases from 8 to 0.4% northward, down the southern slope, and from 3 to 0.4% in the northeastern end of the trough. The sand size is generally limited to the very-fine-sand fraction, mainly within the interval 3.5-4 ϕ, which constitutes 50-70% of the total sand fraction. In most of the area only occasional grains of fine sand or coarser grains occur.

Grain counts of the sand fraction show the predominance of terrigenous (quartz and feldspar) components in most of the study area. Terrigenous components tend to be most abundant in the relatively coarse sediments in the south, the northwest, and along the Norwegian mainland, where they constitute 70-85%. In the deepest area of the Norwegian Trench the content of biogenic components increases, accounting in some samples for up to 75% of the sand grains.

The contours for very coarse silt (4-5 ϕ) follow the same pattern as for sand, but the content is approximately one order of magnitude higher (Fig 2b). In the deepest part of the Norwegian Trench the bottom sediment consists of 1-1.5% very coarse silt, and towards the Norwegian mainland the values gradually increase to 2-3%. A pronounced down-slope decrease of the very-coarse-silt content occurs on the northeastern and southeastern slopes of the Norwegian Trench, where the values change from >10 to <2%. The relative abundance of the 4-4.5 ϕ fraction appears to deviate slightly from the systematic trend of decreasing coarse-fraction abundance (seen only with

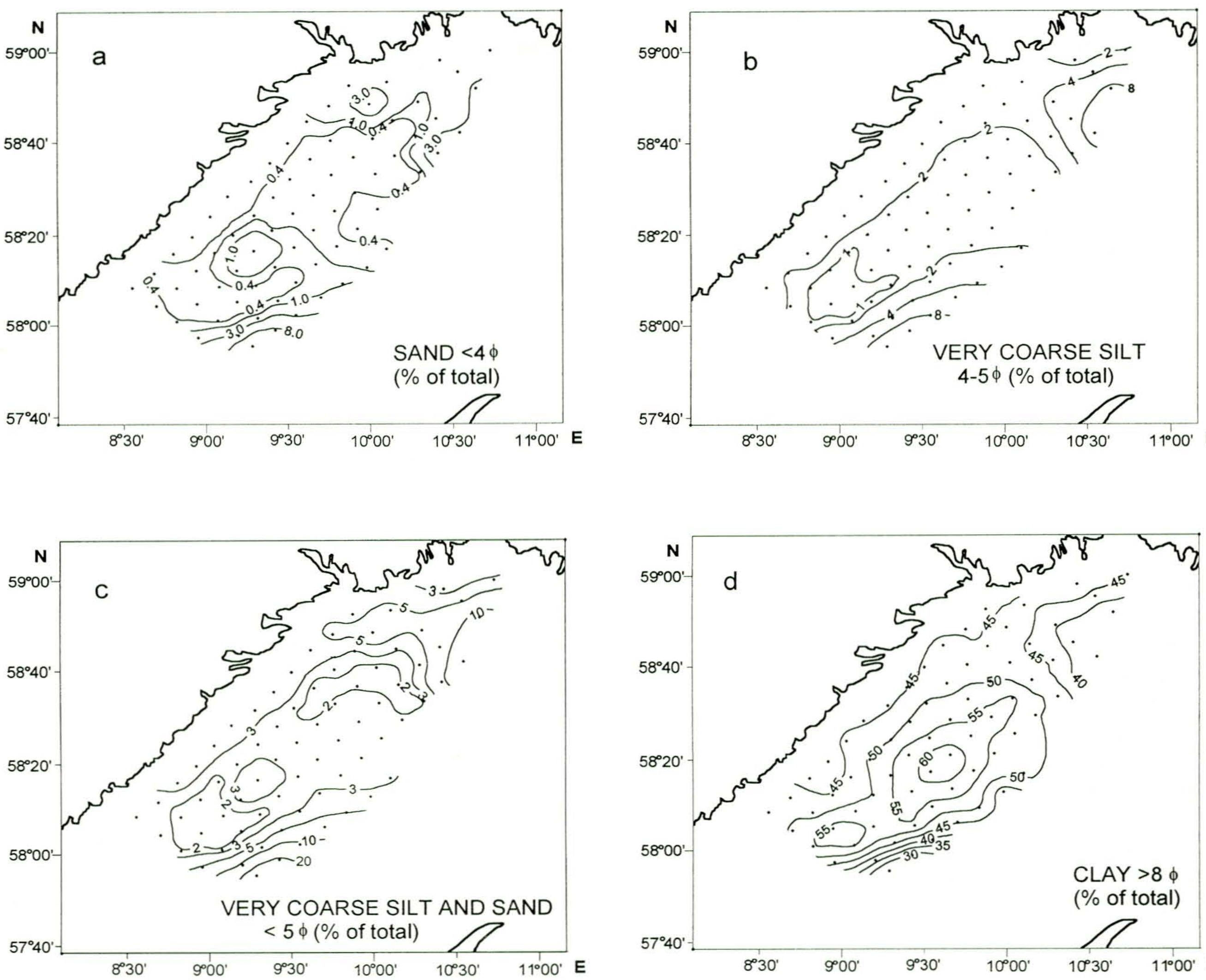


Fig. 2. The distribution of (a) sand (< 4 ϕ); (b) very coarse silt (4-5 ϕ); (c) sand and very coarse silt (< 5 ϕ); and (d) clay (> 9 ϕ).

half ϕ intervals, Fig. 3). This results in a slope break or slight peak at 4-4.5 ϕ on the size distribution curves.

A negative correlation expectedly occurs between the coarsest (< 5 ϕ) and finest (> 9 ϕ = clay) fractions (Table 1, Figs. 2c and 2d), but notably not in the deepest part of the Norwegian Trench, where the highest abundance of clay and the lowest abundance of very coarse silt and sand do not geographically coincide with each other. In comparison with other grain-size classes, the clay content shows the most pronounced relationship with water depth (r = 0.653, Table 1). Coarse silt is more negatively correlated with both water depth and clay than is fine silt. In other words, the changes in the clay content in northern Skagerrak are largely compensated by opposite variations in the coarse-silt content, while the proportion of the fine silt remains relatively stable.

Mineralogy of the heavy-mineral concentrate

The components of the heavy-mineral concentrate (referred to below as heavy minerals) are divided into four major groups: micas, carbonates, opaque and translucent. Micas are predominant in most extracts, and among them biotite is more abundant than muscovite. Biotite is the only mineral which correlates relatively well with sediment grain size (r = 0.433, Table 2). The highest biotite contents (30-35%) occur in the deepest part of the Norwegian Trench and to the northeast (Fig. 4a). Biotite contents gradually decrease towards the Norwegian mainland, to 10-15%. On the Danish side of the Norwegian Trench, lower biotite percentages occur in the northeast (< 20%) and southeast (< 10%), whereas in the central part of the study area, 30% isocon lines extend almost perpendicular to the slope.

The carbonate grains are mainly dolomite, but since the optic properties of calcite and dolomite are poorly

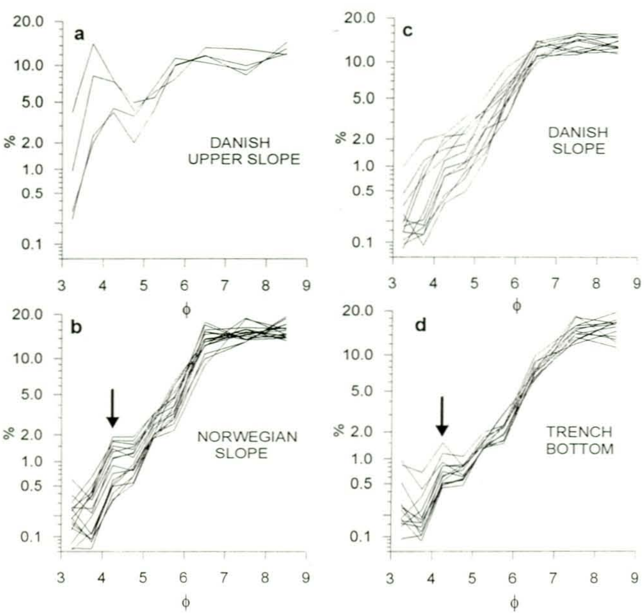


Fig. 3. Grain-size frequency distributions showing the overall fining trend from the slopes of the Norwegian Trench (a, b, c) towards its bottom (d). Sediments of the Norwegian slope (b) and trench bottom (d) show the relatively greater abundance of the coarse-silt fraction due to the biogenic deposition in these areas. The resulting curve break is indicated by the arrows.

Table 1. Correlation coefficients for the grain-size fractions and water depth.

n=74	water depth	clay (> 9 ϕ)
clay (> 9 ϕ)	0.653	
fine-silt (6-9 ϕ)	-0.467	-0.549
'coarse-silt' (4-6 ϕ)	-0.501	-0.827
v. coarse silt (4-5 ϕ)	-0.455	-0.779
sand (< 4 ϕ)	-0.291	-0.596

distinguished in grain mounts they were not subdivided. The content of carbonates generally increases from the northeast (<10%) to southwest (>20%), with one intermittent zone of lower values (<10%) in between (Fig. 4b). The trends cross the grain-size and bathymetry contours.

The opaque minerals are mainly represented by the magnetite-ilmentite and hematite-limonite groups (referred to below as magnetite and hematite, respectively).

Table 2. Correlation coefficients for the mean grain size of the sediments and the separate heavy-mineral components.

n=74	mean	Bt	Dol	Mag	Hem	Hlb	Ep	Pyr
Bt	0.433							
Dol	-0.017	0.220						
Mag	0.182	-0.104	-0.051					
Hem	-0.263	0.433	0.053	-0.140				
Hlb	-0.056	0.148	-0.213	-0.159	0.275			
Ep	0.067	0.025	0.248	0.129	0.125	-0.508		
Pyr	0.139	-0.172	0.003	0.132	-0.175	-0.475	0.057	
Gar	0.138	-0.190	0.101	-0.053	-0.136	-0.551	0.001	-0.041

Single grains of leucoxene and pyrite occur in a few samples. The hematite content is consistently between 4 and 8% in the central part of studied area. It increases to the east, at a few sites to >12% (Fig. 4c). A generally decreasing trend of hematite contents can be followed towards the north and southwest. The magnetite distribution is much more variable, with several zones of low (< 7%) and high (>11%) content orientated roughly perpendicular to the bathymetric contours (Fig. 4d).

Translucent heavy minerals are characterised by a predominance of hornblende, which accounts for 45-60% of all minerals in this group. The hornblende distribution pattern is fairly irregular (Fig. 4e), changing between 45 and 60% over relatively short distances. Hornblende content is generally higher (>55%) in the northern and southeastern parts of the study area, whereas low values occur in patches along the Norwegian Trench and to the south. The second most abundant category is the epidote group, namely epidote, zoisite and clinozoisite, which are considered together because of their transitional optic properties. In most of the area the epidote group varies unsystematically between 22 and 30%, reaching a maximum value (>32%) in the southern part and minimum values (<20%) in the western part (Fig. 4f). One map is presented for all pyroxenes because of the low contents of individual minerals of both monoclinic and orthorhombic varieties. Among pyroxenes, hypersthene and augite are often most abundant, although enstatite and diopside also occur in the majority of samples. The pyroxene content varies rather irregularly from less than 5% to more than 11%, commonly ca. 8% (Fig. 4g). A slight decrease towards the Norwegian mainland is observed. Garnet is mainly represented by a colourless variety, and the total content is usually between 4 and 10% (Fig. 4h). Zircon and sphene (titanite) are present in most of the samples. The contents range from less than 1% up to 7%, normally 1-2%. Tourmaline, staurolite, kyanite, andalusite, sillimanite, rutile, apatite and barite were sporadically found in a limited number of samples, usually in trace amounts.

The correlation coefficients, which are mainly within the range 0.2 to -0.2, indicate a lack of significant relationships between the different minerals or between mineral varieties and grain size (Table 2). The slight correlation between biotite and grain size and hornblende's weak negative correlations with epidote, pyroxene and garnet are the only exceptions. The correlations between epidote, pyroxene and garnet are very low, showing similar values, roughly one order of magnitude lower than their correlation with hornblende. This indicates that among translucent heavy minerals there are no strong associations in the population as a whole. The content changes of hornblende are randomly compensated by epidote, pyroxene or garnet, but none of these minerals has priority.

Discussion

Fine-grained sedimentation

The sediment samples are not time or event specific, since they include deposition over numerous years and give a time-integrated, net reflection of sedimentation. Therefore, the additional influence of bioturbation is expected to further homogenise and integrate the sampled sediment, as is assumed for the surface subsamples. Although we do not have information regarding possible size-specific enrichment by biogenic processes, we do not expect this to have an overriding effect, and the grain-size data interpreted below do not seem to require such an explanation.

The unsorted character of the laboratory-disaggregated, inorganic, fine-silt and clay fractions of the bottom sediments (Fig. 3) is consistent with sedimentation largely from flocculated suspensions. Van Weering et al. (1993) have shown that large amounts of suspended sediments are transported within the bottom nepheloid layer in the Skagerrak. The sediment concentration (transmission) of this layer was reported to decrease towards areas of increasing water depth, consistent with continued sedimentation along the paths of prevailing oceanographic currents. In the deepest portion of the Norwegian Trench, no distinctive differences in transmission were observed separating the intermediate and bottom nepheloid layers, suggesting the predominance of hemipelagic suspension deposition (cf. Stow 1985) in this area.

It has been demonstrated that the flocculation process (including biogenic and inorganic aggregates of several types, cf. Syvitski 1991) is not size-selective and that similar contributions from all size fractions result in relatively flat frequency distributions (Kranck 1975, Kranck & Milligan 1991). The only portions of the inorganic grain-size distribution that are consistently sorted in suspension transport are the coarsest fractions where the distribution curve falls off sharply (Fig. 3). This may indicate that minor single-particle transport occurs simultaneously with the predominant floc transport, which allows the hydraulic sorting of coarse fractions. Alternatively, larger, heavier flocs enriched with coarser particles might also

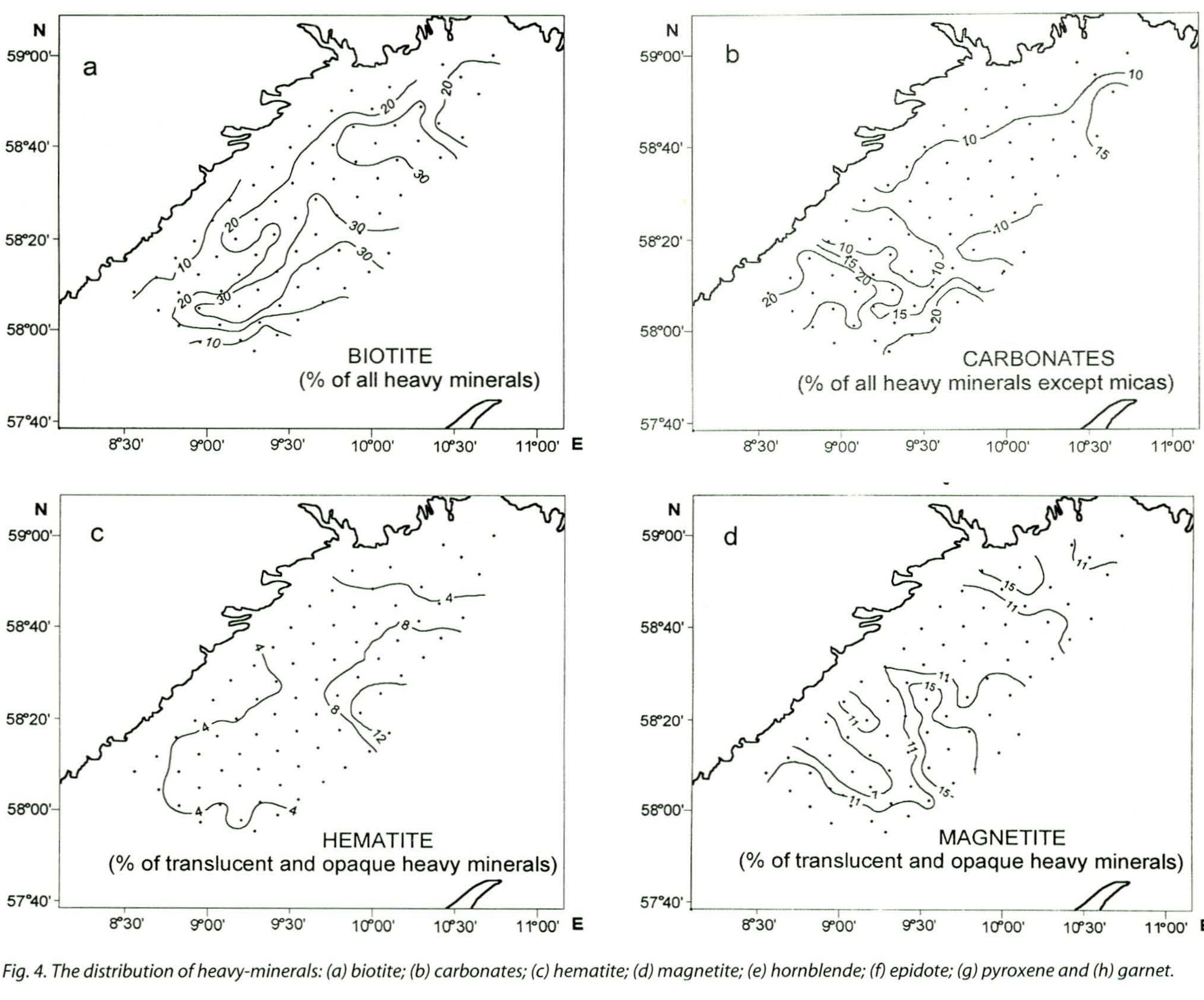
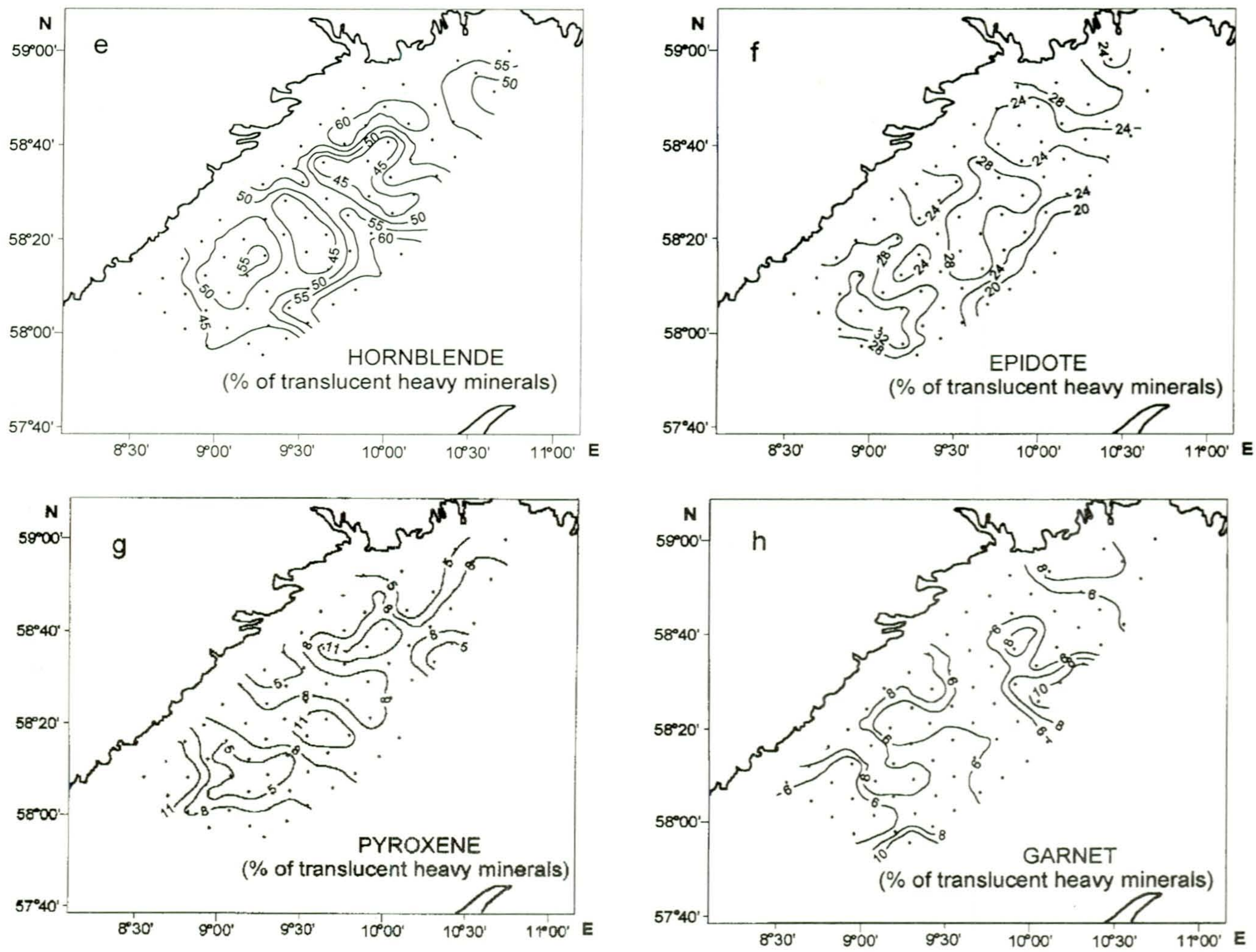


Fig. 4. The distribution of heavy-minerals: (a) biotite; (b) carbonates; (c) hematite; (d) magnetite; (e) hornblende; (f) epidote; (g) pyroxene and (h) garnet.



be hydraulically sorted. Single-particle transport is interpreted to be reflected, at least, by the systematic increase of mica towards the deeper portions of the Norwegian Trench. Floc sorting as a control of the silt-sized mica is unlikely since the flocculation process would not incorporate mica preferentially into smaller flocs, which are interpreted to be increasingly represented in calm and deep areas, as discussed below.

Single-particle transport and hydraulic sorting probably also occur to a limited extent within fine-silt sizes, but this is masked by the predominance of unsorted flocculated particles. Studies by Kranck & Milligan (1985) have shown that single-particle transport can be effective for sizes as small as 5-10 μm. Eisma (1993) has suggested that the coexistence of flocs and single particles in suspension, as indicated by variable silt/clay ratios, is related to the sediment concentration and is favoured only in very low concentrations (< 0.3 mg/l), where flocculation is limited because of low collision frequency. The suspended-sediment concentration in the area of the Norwegian Trench is approximately at this critical concentration (Eisma & Kalf 1987b), theoretically allowing the transport of fine-silt-sized single particles.

The relationship between the fine-silt (6-9 ϕ) and clay contents in the sediments of the Norwegian Trench changes with the relative grain size (Fig. 5a). An overall positive correlation (clay increase is coupled with fine-silt increase) exists for relatively coarse sediments (< 45% clay) and a negative correlation for fine sediments. The consistent increase of clay and fine silt in coarse sediments indicates that both clay and fine silt occur in flocs and are not influenced by differential sorting in areas of relatively greater turbulence. The opposite trend for relatively finer sediments suggests that a selective sorting of fine silt does occur in some areas, presumably indicating the simultaneous deposition of fine silt as both single particles and flocs. The comparison of relationships between clay and three sub-fractions of fine silt (1-ϕ intervals) shows that hydraulic sorting is most effective in the coarsest portion of fine silt (6-7 ϕ; Fig. 5b), whereas the evidence for sorting in the finer sub-fractions (7-8, 8-9 ϕ; Fig. 5c, d) is less well defined, but a weakly defined 'break point' is interpreted to successively shift toward higher clay contents.

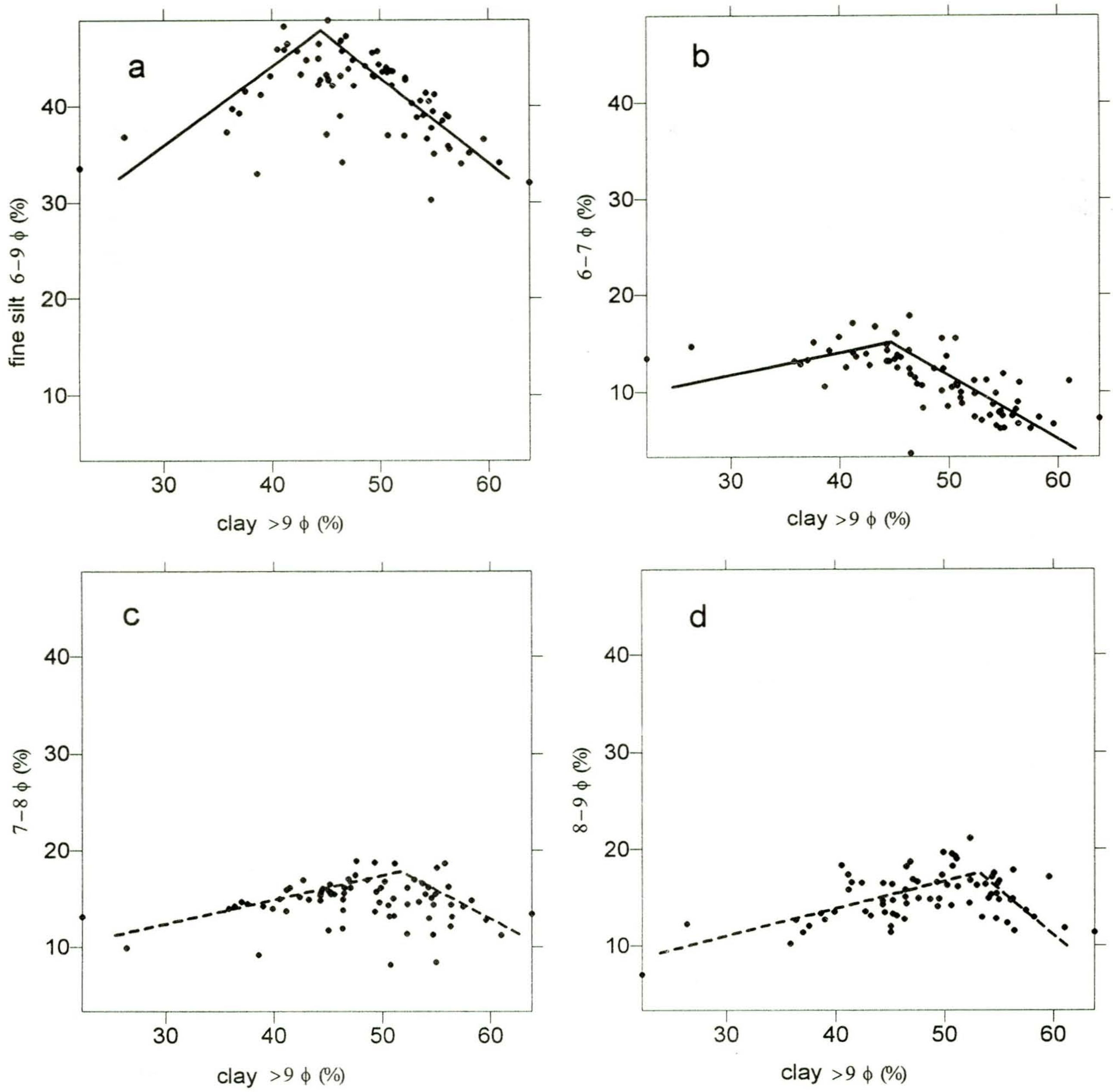


Fig. 5. Relationships of clay to total fine silt, 6-9 ϕ. (a), and clay to the sub-fractions of fine silt, i.e. 6-7 ϕ (b), 7-8 ϕ. (c), and 8-9 ϕ. (d). The negative slope is indicative of hydraulic sorting of the fine-silt particles in relatively fine sediments (> 45% clay; a). The most effective hydraulic sorting occurs in the coarsest portion of fine-silt (b), whereas sorting is less developed in the finer sub-fractions (c; d). The trends are visually estimated, solid lines implying strong evidence and dashed lines implying weak evidence for hydraulic sorting.

Most grain-size distributions can be divided into two slightly overlapping subpopulations in which either flocs or single particles predominate. The transition between these two is marked by the truncation point on the distribution curve where the coarse end falls off. Most of the sediments in northern Skagerrak have this truncation point at about 7 ϕ, but in the deepest portion of the Norwegian Trench it is at 8 ϕ, and in an area of higher current velocity to the south at 6 ϕ (Fig. 3). Normally the floc subpopulation makes up 75-85% of the total sediment, and the truncation-point shift from 6 ϕ to 8 ϕ is coupled with an overall fining of the single-particle subpopulation. The common truncation point at 7-8 ϕ for predominantly floc sedimentation is more fine grained than the truncation point observations made in environments with greater suspended-sediment concentrations (Amazon subaqueos delta: Nittrouer et al. 1985, Kuehl et al. 1988, San Francisco Bay: Kranck & Milligan 1992, and Quaternary glaciomarine settings: Stevens 1991). The truncation-point position is most likely related to both the suspended sediment concentration and the energy level of each particular environment, controlling the size of flocs and single particles that can be kept in suspension and transported.

Larger flocs tend to have larger individual components (Kranck 1975) and, in spite of decreasing density with increasing floc size (Dyer 1989), the settling velocity increases towards coarse floc sizes. The association between floc size, component size and settling velocity may lead to floc sorting and a related change in the size distribution if time and consistent transport conditions permit. The floc sorting is also dependent on floc stability since larger flocs are sensitive to breakage and would not survive the transport in relatively turbulent environments. The sensitivity for breakage applies mainly for very large aggregates, such as macroflocs or 'marine snow', as discussed below, but in the very-fine-grained sediments of northern Skagerrak the changes in floc size occur most probably within the microfloc type and these flocs are very stable (Eisma 1986, Eisma & Kalf 1987b). Assuming relatively consistent floc stability, the sorting of increasingly finer fractions and the truncation-point shift observed for different fractions (Fig. 5) is related to the selective deposition of coarse flocs coupled with a fining of the single-particle subpopulation.

Coarse-silt and sand sedimentation

The fine grain size and unsorted character of the top 50 cm of sediments in the Norwegian Trench and adjacent areas support earlier conclusions regarding the predominance of suspension sedimentation and the limited influence of bottom transport on sediments in this deep part of the Skagerrak (van Weering 1981, van Weering et al. 1993). However, these sediments always contain at least 1-2% of very coarse silt and fine sand, the size fraction that in the rest of Skagerrak and in most other environments is interpreted to be primarily transported and deposited by traction processes.

There are four main options for interpreting the very-coarse-silt and sand sedimentology in the Norwegian Trench. The first hypothesis is the alternation of suspension and traction depositional mechanisms. Against the background of suspension deposition, infrequent and short episodes of significant bottom-current activities might explain the limited amounts of coarse silt and sand. This alternative is consistent with oceanographic documentation of the temporal and spatial variability of the bottom currents (Svansson 1975, Rodhe 1987). It has also been shown that relatively strong bottom-current velocities (15-20 cm/s) occasionally occur even in the deeper portions of the Norwegian Trench (Rodhe 1987), and these currents could perhaps be responsible for traction transport of coarse silt and sand. Nevertheless, the loose character of the surface sediments in the Norwegian Trench does not support a frequent bottom-current activity that would be able to transport coarse silt and fine sand. If coarse silt and fine sand have been primarily transported by traction processes, selective coarse-particle deposition and erosional effects would be expected to be regionally significant and occasionally recorded in the sediment column despite the signal modification due to bioturbation.

The second alternative involves another type of bottom current that could mobilise very coarse silt and fine sand for down-slope transport, that is, turbidity-current flow. This process has not been considered in earlier Skagerrak studies, presumably because of the lack of obvious sedimentary structures. Investigations of muddy, low-density turbidites on continental margins and basin slopes have demonstrated that turbidites do not always need to be graded; nor do they distinctly deviate from the background sedimentation of similarly fine-grained sediments (Stanley 1985, McCave & Jones 1988, Jones et al. 1992). Blanpied & Stanley (1981) have shown that uniform turbiditic mud has a significantly lower content of forams and other biogenic debris than in suspension-deposited hemipelagic mud. These uniform turbidites, which normally contain less than 0.5% sand, have a predominance of terrigenous components (Blanpied & Stanley 1981, Jones et al. 1992), comparable to sediments from the Norwegian Trench. Although gravity flows may occur in this setting, for instance in connection with high sedimentation rates on the Danish slope of the Norwegian Trench, no direct evidence has yet been documented.

The third hypothesis is that all grain sizes, including very coarse silt and sand, are transported in suspension. Since the current velocities in northern Skagerrak are not strong enough to keep coarse silt and sand in suspension as individual particles, these grains might be incorporated within large but low-density aggregates, termed macroflocs when predominantly inorganic particles are involved (Eisma 1986, Eisma & Kalf 1987a, b) or 'marine snow' with mainly organic particles (cf. Alldredge & Silver 1988). Depending largely on the organic content, the effective density of the flocs with incorporated coarse particles can be significantly reduced, enhancing the possible suspension residence time and allowing transport over long distances into calm-water environments. Studies of floc densities and sizes have shown a general tendency for decreasing density with increasing floc size (Dyer 1989, Kranck & Milligan 1992, Lick et al. 1992). Recent *in situ* measurements have demonstrated that in addition to organic matter and clay-sized minerals, flocculation may involve grain sizes up to coarse sand (Kranck & Milligan 1992, Kranck 1993).

However, the macroflocs or 'marine snow' that are capable of carrying coarse particles are sensitive to shear and are stable only in relatively calm waters (velocities less than 15 cm/s; Eisma 1986). Van Weering et al. (1993) have shown the extensive development of bottom nepheloid layers in the Skagerrak, and it is believed that this near-bottom layer is the main medium of suspended sediment transport. Because of shear stresses in the bottom nepheloid layer the transport of very large aggregates ('marine snow') could be limited, but the more stable macroflocs may be largely preserved and transported into the Norwegian Trench. If 'marine snow' is involved in coarse-particle transport, it is probably formed and transported by hemipelagic processes, presumably incorporating sediment that has settled down from turbulent transport higher up in the water column. Favourable conditions for incorporating coarse particles during 'marine snow' formation may be rare, but this mechanism is still viable considering the low coarse-grain percentages. The involvement of hemipelagic sediment transport processes in the deepest area is indicated by the composition of the sand fraction. Consistent with the diminishing importance of sediment supplied by near-bottom suspension transport, the sand fraction of this sediment has a predominance of forams and other biogenic debris of pelagic origin (50-75%, cf. Blanpied & Stanley 1981).

The forth alternative hypothesis also involves flotation of coarse particles, in this case within the poorly consolidated and relatively mobile, surface muds. In areas supplied with coarse silt and sand, the formation of a mobile surface mud during periods of quiescence could incorporate these coarser components due to mixing by bioturbation or occasional resuspension. Subsequent resuspension and movement of these mobile sediments, including the relatively light mud aggregates with coarse grains, could help explain the occurrence of coarse-grained components in deep and calm-water settings. Although speculative, this mechanism is supported by the sediment character and the known variability of near-bottom turbulence.

Thus, although the fine-grained, poorly sorted sediments in the Norwegian Trench are generally typical for marine suspension deposition, specific considerations seem necessary to explain the coarsest fractions. Although obscured by bioturbation or by the predominantly muddy texture, low-frequency turbidity currents and occasional bottom-current traction transport cannot be excluded within this setting. On the other hand, coarse-particle buoyancy is likely through macrofloc or 'marine snow' formation, allowing transport in the mobile surface layer, the near-bottom nepheloid layer and the upper water column.

Mineralogical interpretations

Heavy-mineral compositions have been widely used in provenance studies (van Andel & Poole 1960, Morton 1985, Singh et al. 1993, Bengtsson & Stevens this volume). Also, the progressive modification of the heavy-mineral suite along the sediment transport pathway, where heavier minerals are preferentially deposited and lighter ones are carried further, is a well documented process (Komar & Wang 1984, Trask & Hand 1985, Li & Komar 1992). Most studies of provenance or selective heavy-mineral sorting have dealt with sandy environments where sediments were transported predominantly by traction processes. The structureless, fine-grained sediments of northern Skagerrak do not indicate bottom traction transport. On the other hand, the documented current velocities (Rodhe 1987) do not support the suspension transport of heavy minerals as single particles of coarse-silt size. As discussed above, the source of buoyancy, possibly provided by low-density macroflocs or 'marine snow', is necessary to keep heavy minerals of coarse-silt size in suspension for long distance transport. If the heavy-mineral transport is largely controlled by flocs, the hydraulic sorting of heavy minerals cannot be well developed, as is indicated in this study by their very low correlation with grain size (Table 2). Still, the heavy-mineral distributions should be source related and informative of sediment transport pathways.

The interpretation of the heavy-mineral contour maps (Fig. 4a-h) with respect to sediment transport pathways is complicated because of several features: 1) variable mineral contents over short distances, 2) relatively non-selective transport, probably in flocculated suspensions, and 3) very low heavy-mineral proportions of the total sediment (normally less than 0.1%). The variability of the mineral contents in our data (below) does not generally allow identification of distinct, adjacent populations at the 95% confidence level (Folk 1974, Bridgland, 1986). This is logical since the regional sediment sources are not strongly contrasting, and provenance inter-pretations have only been possible for large, generalised provinces (Bengtsson & Stevens this volume).

On the other hand, despite the low heavy-mineral concentrations and their variability, certain geographic trends were noted above. Most important, since the concentrations of several heavy-mineral species preferentially increase towards the north, south and southeast away from the Norwegian Trench, the supply of these minerals is interpreted to be by sediment transport in the opposite directions (Fig. 6). In spite of the relatively non-conclusive evidence behind the transport interpretations of individual minerals, the occurrence of similar directional indications from several minerals strengthens the probability of these conclusions. In addition, the predominant pathways are consistent with the transport directions separately interpreted from grain-size trends (Stevens et al.

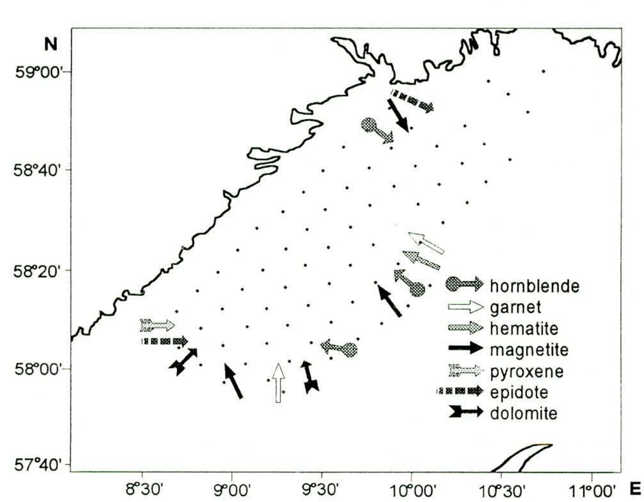


Fig. 6. Transport directions toward the Norwegian Trench corresponding to specific heavy-mineral components.

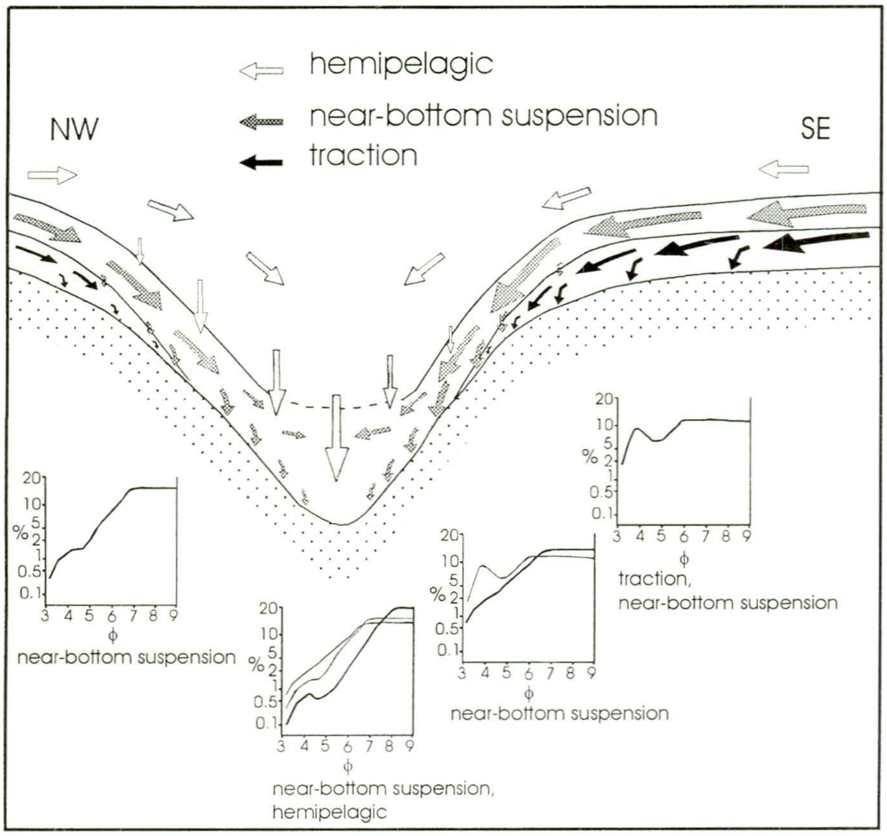


Fig. 7. Transport and depositional mechanisms as indicated by the sediment particle-size distribution, by the concentrations of water-column suspended matter (Eisma & Kalf 1987b), and by transmission measurements (van Weering et al. 1993). The shallow shelf has traction-deposited sand and coarse silt combined with near-bottom suspension deposition (bottom nepheloid) of unsorted clay and fine-silt flocs. Near-bottom suspension mechanisms predominate on the trench slopes. In the deepest portion of the Norwegian Trench the contribution to the minerogenic sediment from hemipelagic deposition becomes more pronounced, as is indicated by the relative abundance of coarse-silt of hemipelagic origin (biogenic debris). On the grain-size distribution diagrams the thin lines are from the adjacent positions for reference with respect to down-slope changes.

1996) and with trends in mineral-magnetic parameters (unpublished data).

Particular caution is appropriate with regard to the possibly dependent relationships between concentrations of different translucent heavy-mineral species since they are summed to 100%, but there are no strong correlations, positive or negative, observed between minerals (Table 2). Nevertheless, significant changes in the major mineral varieties would be expected to change percentages of other components, for example, the pronounced down-slope decrease of hornblende on the southwestern side of the trench coincides with an opposite trend of epidote (Fig. 4). The similar lack of correlation between the mineral species (or groups) and grain size also suggests that hydraulic sorting has not controlled the coarse-silt mineral distributions in the fine-grained deposits. This is consistent with the interpreted importance of suspension transport and the influence of flocculation. In contrast, strong mineralogic sorting effects are commonly associated with traction transport of sandy sediments (Trask & Hand 1985, Li & Komar 1992), as is interpreted in the adjacent, shallower areas to the south (Bengtsson & Stevens this volume).

The distribution of biotite in the coarse-silt fraction (hydraulically equivalent to very-fine-silt quartz, Doyle et al. 1983) does, however, indicate that suspension transport can provide consistent mineralogic trends related to source character and sorting during transport if these minerals are not exclusively included in flocs. Increasing mica contents suggest that single particle sedimentation becomes significant in the central Norwegian Trench due to the diminished supply by nepheloid suspensions. Because of its flat crystal form, mica is hydraulically more mobile than other minerals of the same size, and it is considered to be a sensitive hydraulic indicator of sediment deposition and transport conditions (Doyle et al. 1983, Komar et al. 1984). The relatively higher current velocities limit mica deposition on the slopes of the Norwegian Trench and in shallow areas, resulting in its winnowing and deposition in calmer and deeper areas.

A minimal disturbance of the mineral dispersal patterns is a prerequisite if source interpretations are to be made upon relatively weak patterns of low-percentage components, as those discussed above. We expect that suspension processes themselves are variable with time and location, so that much of the irregularity of the heavy-mineral contents is inherent to this environment. The general sediment sources indicated by the transport directions are logical with respect to the principle oceanographic currents (cf. Figs. 1 & 6). However, in our interpretation of transport pathways the down-slope directions are more pronounced and are important as a reflection of the net sediment accumulation.

Conclusions

Sediment grain-size trends in northern Skagerrak are consistent with bathymetry, showing systematic fining and depletion of the coarsest fractions towards the deepest portion of the Norwegian Trench. The unsorted character of the predominant fine-silt and clay fractions suggests that most of the sediments are transported as flocculated aggregates. As interpreted from sediment grain-size distributions, the modal size of individual, inorganic particles included in flocs decreases from 6 ϕ in the shallow and more turbulent areas to 8 ϕ in the calm areas of the trench bottom. At the same time, aggregate buoyancy is believed to permit a limited amount of coarse-silt and sand transport in suspension into these areas.

Weak patterns characterise the heavy-mineral distribution of the bottom sediments (biotite is the only exception). Different species do not correlate with each other or with grain size. The irregularity of the spatial distribution is mainly related to the variability of suspension transport processes. Still, the generalised concentration changes indicate the main sediment transport from southern areas and from the north towards the Norwegian Trench (Fig. 6.) The combined analysis of mineral trends helps to compensate for the limited interpretative basis of each mineral. This is especially important in the case of muddy sediments in which the transport mechanisms and their effects upon sediment composition are complex.

The sediments of northern Skagerrak indicate that the formation of geographically variable grain-size distributions is related to at least three different sediment transport processes: traction, near-bottom (bottom nepheloid layer) suspension and hemipelagic transport (Fig. 7). In shallower areas of relatively high current velocities the near-bottom suspension transport of fine-grained flocs is combined with traction coarse-silt and sand transport, resulting in bimodal grain-size distributions. The importance of traction transport decreases with water depth and the corresponding sediment character was not documented below 200 m on the Norwegian slope or below 400 m on the Danish slope of the Norwegian Trench. The unsorted fine-grained sediments at intermediate depths on the trench slopes are derived predominantly from flocs transported in near-bottom suspension. As indicated by the fining of these poorly sorted sediments, the capacity of near-bottom suspension transport consistently decreases towards the bottom of the trench. Below 400 m on the Norwegian slope and below 500 m on the Danish slope, hemipelagic deposition is indicated by a relative abundance of biogenic coarse silt.

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