

Appendix 9

Report on mineralogical tracers

Southern North Sea Sediment Transport Study, Phase 2 Sediment Transport Report

Appendix 9 Report on mineralogical tracers

Dr J. M. Cox

School of Environmental Sciences
University of East Anglia, Norwich

July 2002

Order no. LOW – 260938/DJ
Account code CUNI04

CEFAS
The CEFAS Lowestoft Laboratory
Pakefield Road
Lowestoft
Suffolk NR33 0HT

OVERVIEW

This report discusses the use of mineralogical tracers in determining sediment (sand) transport in the coastal zone. Their use has revealed much useful information regarding sediment transfers between the Holderness coast, the North Sea and the Humber Estuary, a region that is critical to understanding the broader sediment dynamics of this part of the North Sea. In addition, a sediment budget for the estuary has been estimated.

1. SUMMARY OF RESEARCH TECHNIQUES

1.1 Introduction and Aims

This research (Cox, 1999) was undertaken at the University of East Anglia and funded as a part of the NERC-LOIS project. It was focused on the Humber Estuary and aimed to understand the sources and transfers of modern deposited sediments using mineralogical tracers. Specifically, the research aims were to:

- Determine the provenance of Humber Estuary sediments and provide a quantitative estimate of these sediment sources.
- Locate sediment transport pathways into the estuary and determine whether these are direct, short-term or long-term and operate via a North Sea 'sediment pool'.
- Improve understanding on regional sediment dynamics and coastal-estuary transfers.

Three potential sources of sediment to the Humber Estuary have been identified (figure 1). These are (1) fluvial, derived from the Trent and Ouse river catchments upstream of Trent Falls, (2) Holderness tills undergoing coastal erosion and (3) North Sea sea-bed sediments that are comprised of Holocene sands and gravels.

1.2 Methods and Techniques

Each sediment group was characterised by sampling representative surface sediments from a range of sub-environments. Sub-littoral coastal and estuarine samples were collected from British Geological Survey archived material, all other samples were collected by hand. Generally, since the characterisation of increasingly finer-grained sediment becomes more problematic, the research emphasised on tracing sand-sized material (125-250 μm). Approximately 50 g of sand was separated for analysis from the bulk sample by sieving. The four sediment groups were characterised by their magnetic properties, heavy mineral content, garnet geochemistry and trace element geochemistry. Due to cost, heavy mineral and garnet geochemistry characterisation was restricted to 55 and 24 samples respectively whereas all samples were characterised magnetically since this technique is cheap, highly sensitive and rapid.

1.3 Data Analysis and Interpretation

A series of statistical procedures was applied to the dataset in order to determine which factors were responsible for the underlying sources of variation and which measured parameters were best able to discriminate between the three potential sediment sources. Significant differences in physical properties must be found between the sources if an estimate of their contributions can be made. The magnetic properties gave the best discrimination between the potential sources, and this dataset was used in a least-squares residual estimate of source contributions to the Humber Estuary.

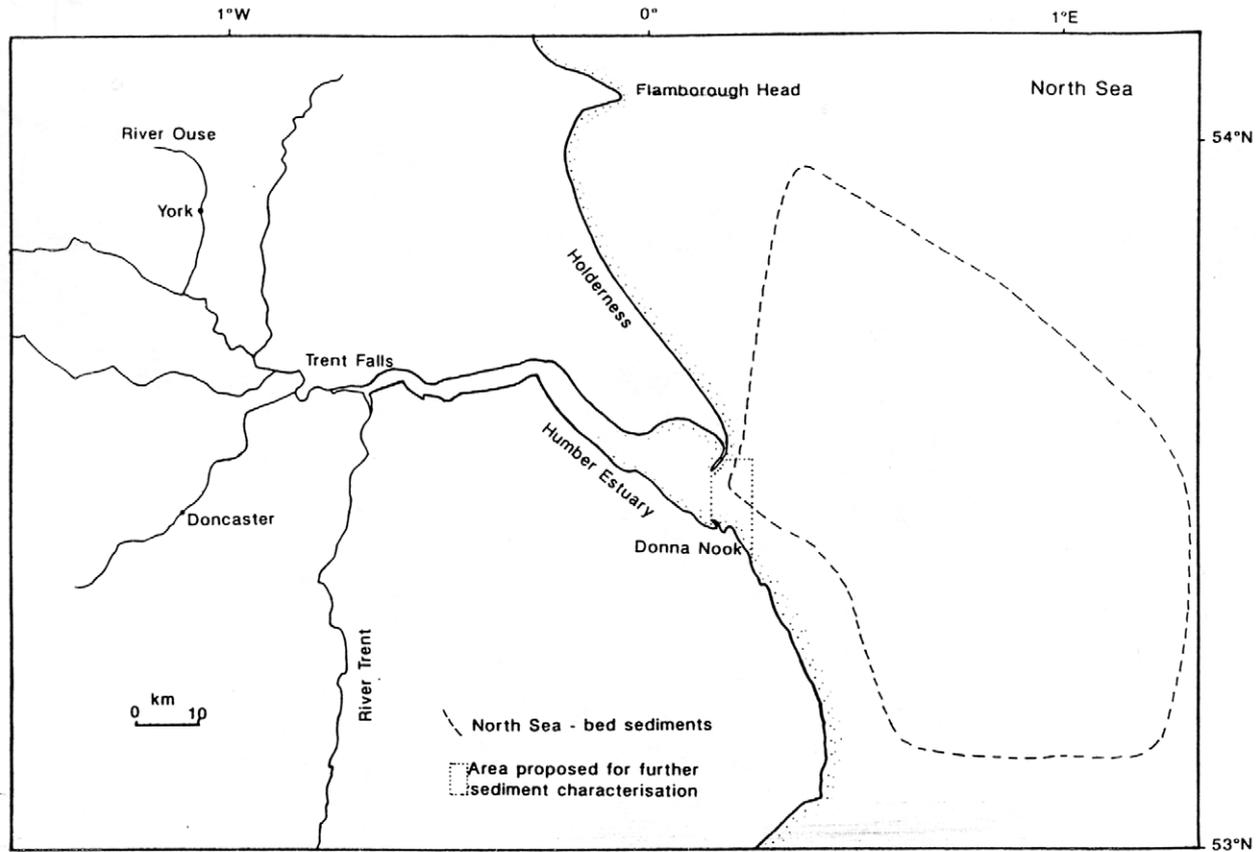


Figure 1 Location of study area showing the three potential sediment sources in relation to the Humber Estuary. North Sea seabed sediments that were characterised are contained in the area shown

2. HYDRODYNAMIC SORTING EFFECTS ON SEDIMENT MINERALOGY

The reliability of sediment mineralogy analyses may be affected by several factors. Despite their sensitivity to provenance, sediment mineral assemblages do not only reflect the composition of the source material. Several processes may alter the relative abundances of minerals, and particularly the heavy minerals, during the sediment cycle; these processes operate during weathering, transport, deposition and diagenesis. In the context of this study transport results in the most significant alteration. During sediment transport hydraulic effects can strongly modify the the relative abundance of heavy minerals with differing hydraulic equivalence. With careful consideration of the potential of hydraulic effects, information can still be obtained from studies of sediment mineralogy. Problems of hydraulic control can be overcome by examining the varieties of one mineral species (varietal studies); garnet is used for such a purpose in this study.

2.1 Hydraulic Effects

The significance of hydraulic effects causing large variations in the relative mineral abundances of deposits that have been derived from the same source lithology, led to the formulation of the theory of *hydraulic equivalence*. Studies of particle size distribution in modern sands show that the mean particle size of any given heavy mineral species tends to be smaller than the mean size of the sample. Consequently, heavy mineral grains are said to be hydraulically equivalent to larger quartz grains. ‘Hydraulic equivalent size’ is defined as a difference in size between a given heavy mineral species and the size of a quartz sphere with the same settling velocity in water. Differences in hydraulic behaviour between mineral species are due to their variable shapes and densities. Grain shape can have a similar magnitude of effect to that caused by

specific gravity; this is especially notable for platy minerals such as mica. Minerals exhibiting a near-spherical or equant shape and a high specific gravity have a greater hydraulic equivalence than minerals with elongate or platy forms and a lower specific gravity, since they are much harder to entrain and transport than their lighter counterparts. Since hydraulic processes can strongly alter the mineralogy of a sediment their effect must always be considered in any mineralogic study.

2.2 Previous Studies Considering Hydraulic Effects

Sediments undergoing transport or erosion commonly exhibit spatial mineralogical trends resulting from hydraulic processes. Such processes and their effect on mineralogy have been widely studied within the Nile Delta, Egypt. Hassan (1976) noted the potential role of selective sorting in producing an inverse correlation between percentages of opaque minerals and the amphibole and pyroxene contents of Nile Delta beaches. Frihy and Komar (1991, 1993) recognised areas of beach erosion whereby longshore sediment transport led to areas of accretion. These two environments had distinctive mineralogies. High-density opaques, garnets and zircons decreased exponentially with distance from the site of erosion at a river mouth, while augite and hornblende increased exponentially. Distinctive cross-shore patterns were also detected, with the densest minerals being most concentrated in the inner surf zone, and decreasing in concentration towards offshore sediment sinks (Frihy, 1994; Frihy *et al.*, 1995).

A detailed study of Oregon beach placers by Komar and Wang (1984) revealed that sorting processes were most effective in concentrating ilmenite, garnet and zircon in the placer, moving almost none of these minerals offshore, while augite, epidote and hornblende increased in abundance in the offshore direction. The formation of heavy mineral placers on Oregon beaches is achieved through mineral segregation by entrainment processes as a result of the greater susceptibility of the lighter minerals to fluid shear stress, allowing lighter minerals to be winnowed from more stable, heavier minerals (Peterson *et al.*, 1986). Generally, quartz and feldspar are the most easily displaced minerals; pyroxene and garnet are less easily entrained, and opaque minerals are the least easily entrained. McMaster and Garrison (1966) were able to map the direction of movement of sediments on the continental shelf off the northeast coast of the United States. Systematic changes in the proportions of certain mineral species or ratios were used, notably the amphibole / opaque ratio.

3. ASSESSMENT OF TECHNIQUES, DATA QUALITY AND CONCLUSIONS

3.1 Heavy Mineralogy

This technique was applied to the 63-125 μm fraction in two ways: (1) identification of heavy mineral associations and (2) assessment of mineral ratios to consider hydraulic sorting effects and sediment transport directions.

The mean heavy mineral assemblages of Holderness till and Humber Estuary groups are very similar, both being associated by opaques - garnet - pyroxene - amphibole – zircon, whereas fluvial sediments above Trent Falls are mineralogically distinctive being characterised by an opaque - zircon - pyroxene - tourmaline - garnet assemblage.

Compared to the tills, estuarine sediments show a slight depletion in opaques, garnet and tourmaline, whereas they are relatively enriched in the minerals pyroxene, amphibole and epidote. The close similarity between these two groups strongly indicates that the estuarine sediments have been derived from the coastal erosion of Holderness tills.

Important variations between these two groups are illustrated by considering the combined relative abundance of opaque and garnet grains in comparison to the combined relative abundance of pyroxene and amphibole grains. Opaque and garnet minerals both have a similarly high transport equivalence value due to their equant shapes and high relative densities. Compared to the other common sedimentary minerals (*e.g.* quartz, pyroxene, amphibole, mica and calcite) opaque and garnet minerals are difficult to entrain and tend to become concentrated within a sediment. The most commonly occurring opaque mineral, magnetite, in the range of 63-125 μm has a hydraulic equivalent size of 85-160 μm (Fletcher *et al.*, 1992).

Due to their characteristic elongate forms and lower densities, pyroxene and amphibole grains are more readily transported than opaque and garnet minerals, with a hydraulic equivalent behaviour much closer to that of quartz. Comparison of the relative abundance of these two mineral pairs can provide an insight into the origins and processes that influence the mineralogy of a particular sediment.

Table 1 gives the mean combined relative abundance for these two mineral pairs for three sediment groups. When compared to the tills, estuarine sediments show a decrease in relative abundance of garnet and opaque minerals whereas they exhibit an increase in the abundance of pyroxene and amphibole. These mineralogical variations between Holderness till and the Humber Estuary sediment groups are consistent with the anticipated effects of selective entrainment and hydrodynamic sorting upon a sediment population undergoing transport, as described in section 2.2. Likewise, Al-Bakri (1986) attributed ‘the variation in relative abundance of the main heavy minerals along the studied coast... to the selective sorting of different grains rather than due to differences in sources.’

mineral pair	Holderness till	Humber Estuary	North Sea
garnet and opaque	34.6	30.5	47.6
pyroxene and amphibole	29.1	34.5	19.0

Table 1 Mean percentage abundance of the mineral pairs garnet and opaque, and pyroxene and amphibole for three sediment groups. All minerals are presented as a percentage of the total mineral yield.

North Sea samples have a similar heavy mineral association to the tills and estuarine sediments, being characterised by opaques - garnet - amphibole - zircon - epidote, with no new mineral species being introduced in the total assemblage. However, there are major differences in the relative abundance of these diagnostic minerals. Pyroxene is no longer a diagnostic mineral, instead epidote is more highly abundant.

When compared to till and estuary sediments, North Sea samples are considerably richer in opaque and garnet minerals, whilst being depleted in pyroxene and amphibole (table 1). Their mineralogy is interpreted to be the result of progressive alteration due to partial erosion. Processes of selective grain entrainment and transport have left a thin, erosive lag of sediments on the seabed. Relict erosive features such as gravel waves and linear ridges of gravels and cobbles have also been identified on the seabed in this region (Wingfield, 1998). These conclusions agree with the previous work of Baak (1936), Simpson (1975) and Al-Bakri (1986).

3.2 Single Grain (Garnet Geochemistry) Techniques

Single grain techniques are useful since they avoid the problems of conservative transport that may affect the interpretation of other results, and as a result they can identify unequivocal provenance relationships. However, regional variation of garnet geochemistry may be insufficient to adequately differentiate between all potential sources. In this research, the most significant variation in geochemistry was found between garnets from fluvial catchments and those derived from all other sediment groups, allowing the technique to be used for determining the mixing of estuary and fluvial sediments in the tidal rivers. Analysis of variance indicated that North Sea garnets are significantly different from those of the Humber Estuary, supporting other conclusions regarding the provenance of Humber material.

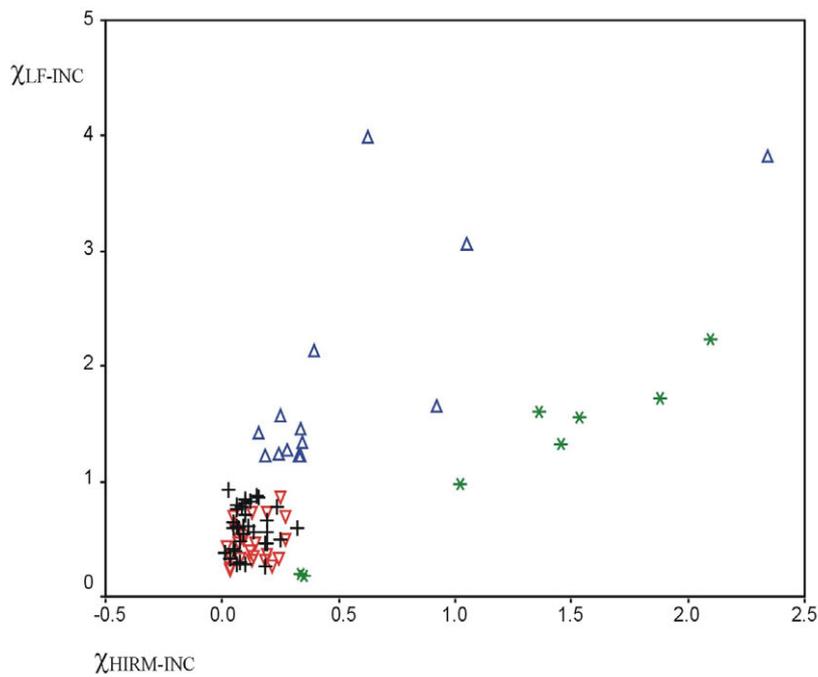
3.3 Magnetic Properties

The measurement of magnetic properties offers a cheap, highly sensitive and rapid method of mapping and characterising sediments. This technique provides a measure of the concentration, magnetic grain size and composition of Fe-bearing minerals present in a sediment. The magnetic inclusion characterisation of the four sediment groups, using measures of magnetite concentration (χ_{LF-INC}) and magnetic mineral composition ($\chi_{HIRM-INC}$), is shown in figure 2. From this data a sediment source budget for the Humber Estuary was calculated, as described in section 4.2. Additionally, this dataset has revealed the position of a sediment transport pathway into the Humber Estuary and identified an important area of discrete North Sea sediments close to the mouth of the Humber.

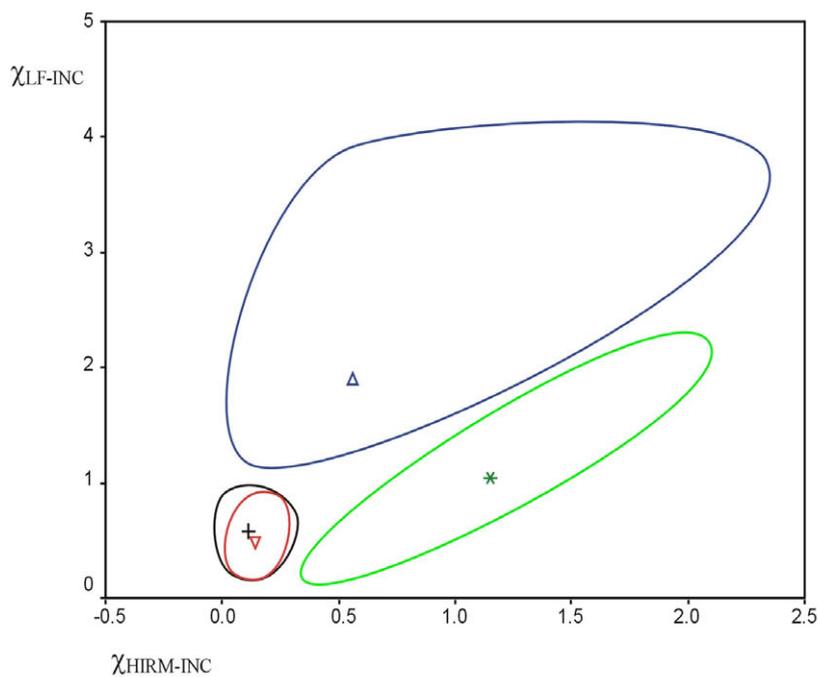
4. ASSESSMENT OF SEDIMENT SOURCES, SINKS AND TRANSPORT PATHWAYS

4.1 North Sea Sediments

Mapping of the magnetic and heavy mineral properties of North Sea sediments has revealed a large (2,700 km²) erosional area surrounding the Inner Silver Pit, directly offshore from the mouth of the Humber Estuary (figure 3). The surface sediments in this area tend to be coarse-grained, thin deposits with mineralogies that are distinctive from the surrounding North Sea sediments. Long-term erosion has winnowed out the less dense minerals, leading to an enrichment of the heaviest heavy minerals. Side scan sonar reveals that there are few mobile bedforms in this region, indicating a lack of active sand transport. Although the movement of sediments in this region is likely to be complex it appears that the position of this erosional area coincides with a conceptual asymmetric circular pattern of sediment movement (Phase 1 SNSSTS, ABP, 1996a) and so its origin may be related to the regional sediment dynamics and water circulation.



(a) $\chi_{LF-INC} \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ versus $\chi_{HIRM-INC} \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$



(b) means and envelopes of values for data in (a)

Figure 2: Bivariate plot of χ_{LF-INC} versus $\chi_{HIRM-INC}$ for the three sediment sources and the Humber Estuary sediments. Key: fluvial *, till +, estuary ∇ , North Sea Δ .

The identification of such an erosional area indicates that the offshore transport of Holderness-derived sediments, as inferred by various studies, does not occur in this area (c.f. Shih-Chiao and Evans, 1992). Instead, Holderness-derived sediment follows a short-term, coast-parallel direct pathway towards the

Humber Estuary rather than a long-term pathway via a North Sea 'sediment pool' (figure 3). The transport pathway of Holderness-derived sediment extends for up to 7 km offshore from Spurn Head in shallow (<10 m water depth) coastal waters. Locally, there may be some recirculation of sediment around The Binks. Mineralogical tracer data indicates that the transport of Holderness-derived sediment continues southwards across the estuary mouth to supply the south bank. It is likely that the transport pathway splits here, and sediments are either transported into the estuary via the Humber flood channel or southwards along the Lincolnshire coast. Understanding this pathway and the extent of Holderness-derived sediment is a question of regional importance and has been stated as a strategic goal (Appendix 4 to the main report).

4.2 Humber Estuary Sand Budget

From the magnetic characterisation dataset (see figure 2) a sediment budget for the Humber Estuary was obtained. The most suitable magnetic parameters for modelling were selected after principal components and discriminant function analysis. A least-squares residual estimate of source contributions was then made, indicating that modern estuary sediments are composed predominantly from the Holderness tills (98%) with a small fluvial source contribution (2%). The North Sea bed sediment source does not contribute to estuarine sediments. Such a budget is in accord with the delineation of a direct transport pathway of Holderness-derived sediment into the estuary, and a previous qualitative estimate (Al-Bakri, 1986). It is also in qualitative agreement with the sediment budget produced in Binnie Black and Veatch (2000). The problems associated with determining such an estimate are discussed below (section 4).

4.3 Tracing Humber Estuary Muds

Clay mineralogy showed insufficient discrimination between the sediment groups to be of use as a sediment tracer. The geochemical signature of fine-grained sediments did, however, provide valuable information on their transport. Anthropogenic discharges into the Humber have given the sediments a distinctive geochemical signature that is enriched in many metals (Grant and Middleton, 1990). This has enabled the movement of fine-grained estuarine sediments to be traced upstream where they mix with fluvial sediments, and offshore where they may be deposited in deeper North Sea waters such as the Inner Silver Pit.

4.4 Tracing the Upstream Transport of Humber Estuary Sediments

The inland extent of sediments derived from the Humber Estuary can be clearly determined by all four techniques due to the differing provenances and mineralogies of estuarine and fluvial sediments. As a result, tracers for the movement of both sands and muds are effective. The influence of the Humber Estuary extends far inland and its sediments are transported up to 55 km upstream above Trent Falls (118 km from the Humber mouth), where they mix with fluvial sediments in the tidal rivers. Such techniques for tracing the upstream extent of estuarine material are of relevance to the potential inclusion of major estuaries in revised Shoreline Management Plans.

5. SCOPE FOR THE FURTHER USE OF MINERALOGICAL TRACERS

Mineralogical tracers play an important role in understanding coastal sediment dynamics. Effective use of a limited number of magnetic and heavy mineral analyses can be made by extending the spatial coverage of this dataset offshore in the region of Donna Nook on the estuary south bank, and along the Spurn and Lincolnshire coasts (see figure 1). This information would improve understanding on the sediment coastal pathway and address management questions regarding the importance of the Holderness tills to coastal sediment budgets. By linking the analysis of Holderness and Lincolnshire coasts it would also compliment the heavy mineral studies of Shih-Chiao and Evans (1992) and Cox (1999), improving regional understanding in this area of the southern North Sea.

The sediment budget mixing model shows that sediment is not supplied to the Humber Estuary from the North Sea bed sediment source as it was characterised by the samples analysed for this study (Cox, 1999). However, sediment may be supplied from elsewhere in the North Sea outside the area that was sampled. In contrast to the other potential sediment sources which may be precisely defined, there is an element of uncertainty in positioning boundaries of the North Sea sediment source area due to the spatial extent of North Sea sediments. Such an argument may support the conclusions of other Humber Estuary sediment budget studies that imply a significant North Sea source.

The characterisation of a small number of samples off the coast of Spurn Head, obtained either from BGS archives or by the collection of grab samples, would improve the coverage of this potential source and clarify the contribution of North Sea sediments to this sediment budget study.

6. SUMMARY

The use of mineralogical tracers provides valuable, cost effective information that can answer vital management questions. Their use here has demonstrated that it is possible to trace the positions of sediment transport pathways, deduce sediment budgets and relate seabed sediment properties to the regional transport dynamics. Mineralogical tracers can provide information on sediment transport directions with greater certainty and at a better resolution than that derived from modelling studies, and can help to clarify movements in complex areas. Additionally, mineralogical datasets reflect long-term trends of sediment transport rather than representing short-term fluxes. Mineralogical datasets also provide a further means of testing and validating the accuracy of model output.

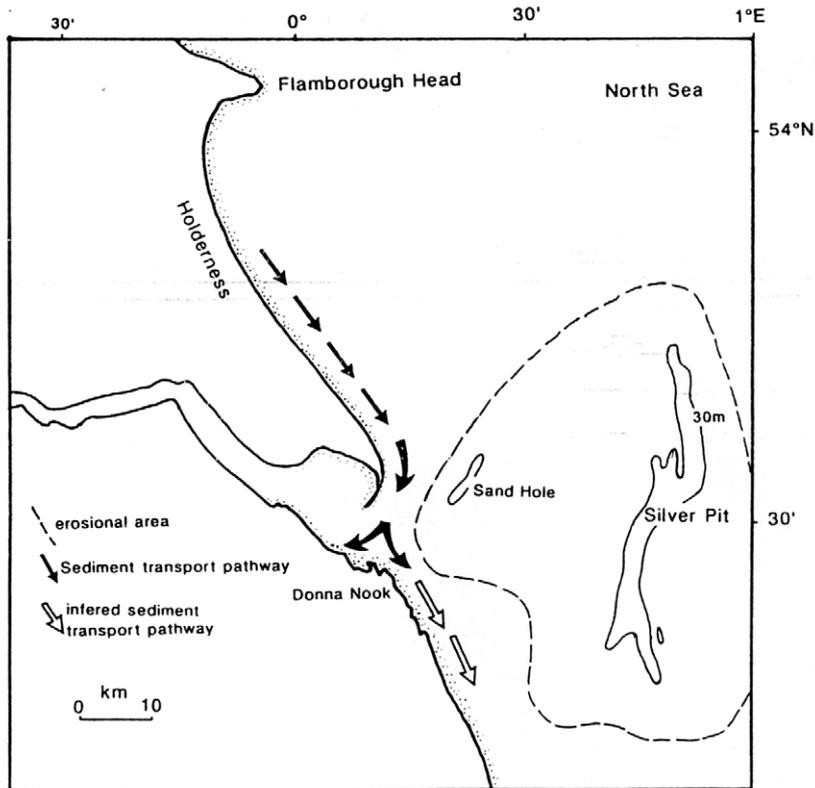


Figure 3 Sediment derived from coastal erosion of the Holderness tills is transported southwards towards the south bank of the Humber Estuary. Transport of this sediment is inferred to continue southwards to supply the Lincolnshire coast. The position of the erosional area of North Sea sediments surrounding the Inner Silver Pit is shown.

7. REFERENCES

- Baak, J. A., 1936. *Regional petrology of the southern North Sea*. Wageningen: Veenman, 127pp.
- ABP, 1996a. Southern North Sea Sediment Transport Study: Literature Review and Conceptual Sediment Transport Model. Report No. R.546, May 1996.
- Al-Bakri, D. H., 1986. Provenance of the sediments in the Humber Estuary and the adjacent coasts, Eastern England. *Marine Geology*, **72**: 171-186.
- Binnie, Black and Veatch (2000). Humber estuary geomorphological studies, Phase 2, Volume 1 Final Report. Report produced for the Environment Agency, March 2000.
- Chang Shih-Chiao and G. Evans, 1992. Source of sediment and sediment transport on the east coast of England: Significant or coincidental phenomena? *Marine Geology*, **107**: 283-288.
- Cox, J. M. S., 1999. Coastal – Estuary Sediment Transfers: a Geochemical and Mineralogical Study of Sources. Unpublished Ph.D. Thesis, University of East Anglia, 321pp.
- Frihy, O. E. and P. D. Komar, 1991. Patterns of beach-sand sorting and shoreline erosion on the Nile Delta. *Journal of Sedimentary Petrology*, **61**: 544-550.
- Frihy, O. E. and P. D. Komar, 1993. Long-term shoreline changes and the concentration of heavy minerals in beach sands of the Nile Delta, Egypt. *Marine Geology*, **115**: 253-261.
- Frihy, O. E., 1994. Discrimination of accreted and eroded coasts using heavy mineral compositions of the Nile Delta beach sands, Egypt. *Sedimentology*, **41**: 905-912.
- Frihy, O. E., M. F. Lotfy and P. D. Komar, 1995. Spatial variations in heavy minerals and patterns of sediment sorting along the Nile Delta, Egypt. *Sedimentary Geology*, **97**: 33-41.
- Fletcher, W. K., M. Church and J. Walcott, 1992. Fluvial-transport equivalence of heavy minerals in the sand size range. *Canadian Journal of Earth Sciences*, **29**: 2017-2021.
- Grant, A. and R. Middleton, 1990. An assessment of metal contamination of sediments in the Humber Estuary, U.K. *Estuarine, Coastal and Shelf Science*, **31**: 71-85.
- Hassan, F. E., 1976. Heavy minerals and the evolution of the modern Nile. *Quat. Res.*, **6**: 425-444.
- Komar, P. D. and C. Wang, 1984. Processes of selective grain transport and the formation of placers on beaches. *Journal of Geology*, **92**: 637-655.
- McMaster, R. L. and L. E. Garrison, 1966. Mineralogy and origin of the southern New England shelf sediments. *Journal of Sedimentary Petrology*, **36**: 1131-1142.
- Peterson, C. D., P. D. Komar and K. F. Schneidegger, 1986. Distribution, geometry and origin of heavy mineral placer deposits on Oregon beaches. *Journal of Sedimentary Petrology*, **56**: 67-77.
- Shih-Chiao, C. and G. Evans, 1992. Source of sediment and sediment transport on the east coast of England: Significant or coincidental phenomena? *Marine Geology*, **107**: 283-288.
- Simpson, G., 1975. A heavy mineral study of the sediments in some rivers tributary to the Humber Estuary. Ph.D. Thesis, Sheffield University, 130pp.
- Wingfield, R. T. R., 1998. *LOIS special topic 316: Holocene evolution, western North Sea*. British Geological Survey, Keyworth. March, 1998.