Fingerprinting sediments along the west coast of Jylland: interpreting provenance data

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The Danish North Sea coast is a dynamic sedimentary environment experiencing erosion, transport and re-deposition of sand along the coast. Because of the natural and economic value of the coastal zone expensive protection measures such as nourishment of the coast are undertaken. The present study utilises provenance analysis techniques developed at the Geological Survey of Denmark and Greenland (GEUS) to characterise the coastal sand bodies by fingerprinting the heavy minerals in the sand. The aims of the study are to test these new methods in an active sedimentary environment and to develop an understanding of transport pathways along the coast. A total of *c.* 40 samples have been collected and analysed as part of the project. This paper gives an outline of the project and provides examples of the methods used based on six samples from the Husby profile on the west coast of Jylland (Fig. 1). The study is a collaboration project involving GEUS and the Department of Geography and Geology (DGG) at Copenhagen University; GEUS is responsible for the analyses and DGG for sample collection.

Provenance analysis based on modal abundance and composition of heavy minerals is used to understand the dispersal of sand in ancient siliciclastic systems, with focus on problems relevant to the petroleum industry (e.g. Larsen *et al.* 2006; Morton *et al.* 2007). Investigation of present-day processes and sedimentary environments may provide a key to understand how provenance indicators can be used to describe and interpret fossil clastic sedimentary systems. It is well known that properties such as grain shape and density are important factors in the processes controlling transport and deposition of mineral grains. As the heavy minerals used in provenance analysis have a wide range of densities and shapes, it is important to include these properties in studies of their dynamics in the environment. Therefore GEUS has focused on developing computer-controlled scanning electron microscopy (CCSEM), which provides information on mineralogy and mineral chemistry together with grain size and shape (Keulen *et al.* 2008). Furthermore, the development of laser ablation inductively coupled mass spectrometry (LA-ICP-MS) analysis has focused on a single, robust mineral species, zircon. These analyses also yield information on the age of the zircon mineral grains, and the age distribution of zircon grains is used to fingerprint the sand (Knudsen *et al.* 2005; Frei *et al.* 2006). Saye & Pye (2005) have described variations in the bulk chemical composition and particle size of coastal sands in Denmark. The work outlined here is a continuation of this work, but using different methods focusing on the modal mineralogy of the heavy minerals in the sand as well as the age distribution of detrital zircon grains.

Sample sites

Samples have been collected from three settings. (1) From coastal cliffs that are being actively eroded and accordingly supply sediment to the littoral drift system along the coast of Jylland. The sampling aims at fingerprinting some of the potential sources of sand mainly from till beds and glacio-fluvial sediments. (2) From four profiles orientated perpendicular to the coast; the samples represent lower shoreface, upper shoreface, beach and dunes (profiles at Bovbjerg, Husby, Vejers and Skallingen; Fig. 1). The aim is to study the variation of the sediment fingerprint between the different sedimentary facies along the coast as well as the variation within identical sedimentary environments. The profiles are situated along the southward-directed net littoral drift of sand that exists between Bovbjerg and Skallingen. (3) From the Vejers/ Skallingen/Grådyb area samples will be analysed to investigate if the littoral drift sediment bypasses Horns Rev and to characterise the sedi-

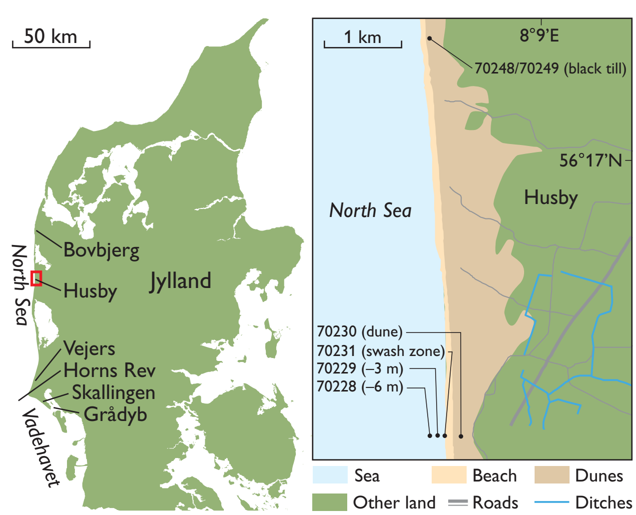

Fig. 1. Map of western Denmark showing the location of the Husby area (red box) and place names mentioned in the text. The map to the right shows the Husby area with sample sites marked.

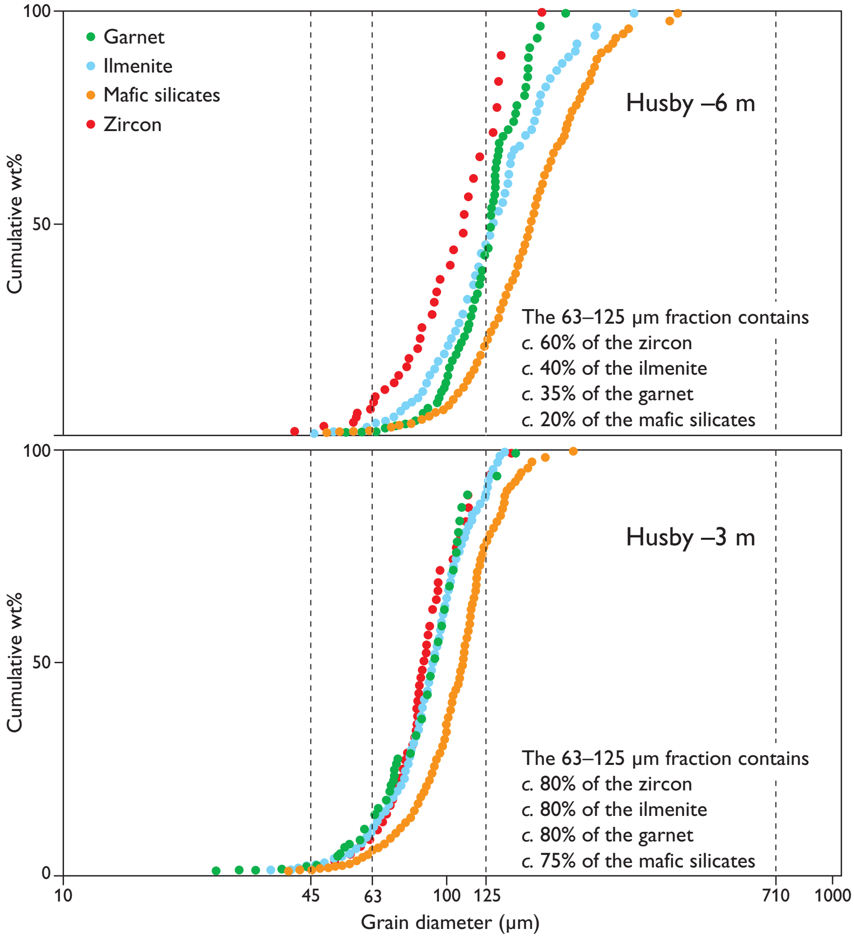

Fig. 2. Grain-size distribution curves for zircon, garnet, ilmenite and mafic silicates in two samples from Husby taken at 3 and 6 m water depth. Note that if only the 63 to 125 µm fraction of the heavy mineral fraction was analysed, the modal proportions of the heavy mineral species would not represent the actual proportions in the sand.

ment exchange between the North Sea and Vadehavet (Danish Wadden Sea) relative to other sources and sinks in the area. Here we present data from the profile at Husby.

Computer-controlled scanning electron microscopy (CCSEM)

CCSEM is used at GEUS to analyse the composition and properties of detrital mineral grains. Sediment samples are sieved and the fraction between 45 and 710 µm analysed. The samples are separated using heavy liquid (2.89 g/cm³) and the heavy mineral fraction is used for analysis. The grains are mounted in epoxy in such a way that the grains do not touch one another. The mount is polished and analysed by CCSEM to determine the chemical composition of *c.* 1200 individual heavy mineral grains, together with their size and shape. The result of the chemical analysis of each grain is compared with a library of mineral compositions. The results are stored in a database and properties such as modal mineralogy, mineral chemistry and grain-size distributions of the individual species can be displayed (Figs 2, 3). The CCSEM analytical procedure is described in further detail by Knudsen *et al.* (2005), Keulen *et al.* (2008) and Bernstein *et al.* (2008).

LA-ICP-MS fingerprinting of zircon

When using the modal proportions of heavy minerals for characterising the provenance of the sand, it is important to recognise potential hydrodynamic effects due to, e.g. grain density. In addition, the size and shape characteristics of the grains of the different heavy mineral species may influence their response to sedimentary processes. Furthermore, the relative sensitivity of the heavy mineral species to

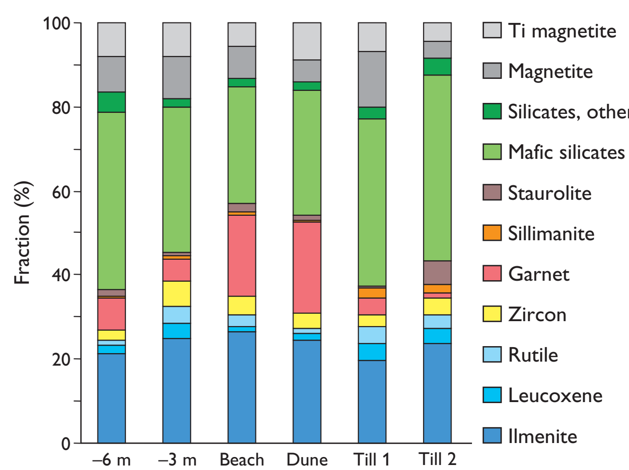

Fig. 3. The heavy mineral proportions in the six samples from Husby recorded by CCSEM. The samples from the shoreface (–3, –6 m) are characterised by low contents of garnet (*c.* 7%) in contrast to the samples from the beach and dune that are characterised by high garnet contents (*c.* 20%).

chemical and physical decomposition depends on the stability of the different minerals. To overcome these problems, it is advisable in provenance analysis to focus analysis on one mineral species because differences in hydrodynamic behaviour or weathering can thereby be discounted. For this purpose the extremely stable mineral zircon is very well suited. A key property of zircon in provenance analysis is the relatively high content of uranium, which makes the mineral well suited for dating. At GEUS the measurements are carried out on a laser ablation inductively coupled mass spectrometer (LA-ICP-MS; Frei *et al.* 2006; Frei & Gerdes 2009). The sand is physically separated using a shaking table to concentrate the very heavy minerals. From this concentrate, the zircon is picked out and mounted (*c.* 150 zircon grains per sample) in epoxy. The mount is polished and introduced to the laser ablation system. A *c.* 30 µm diameter spot is ablated with the laser in the core of each zircon grain, and the ablated material is introduced into the ICP-MS, in which the ratios between the different U and Pb isotopes are measured.

Results from Husby

Some results of analyses of six samples collected near Husby (Fig. 1) are discussed here. Two samples are from till beds exposed in the coastal cliff, one is from a dune, one is from the active swash zone and two samples are from the shoreface, at water depths of 3 and 6 m.

The grain-size distribution varies among the different heavy mineral species (Fig. 2). Zircon with the highest density is finer-grained than lighter minerals such as ilmenite and garnet, and the mafic silicates (amphibole, pyroxene and epidote) are the most coarse-grained of the heavy minerals. This is in close accordance with that predicted by Stokes' law, and implies that grain-size sorting has acted according to grain-fall velocity. The steepness of the grain-size distribution curves also varies among the different minerals. The garnet curve is steeper and narrower than that of, for example,

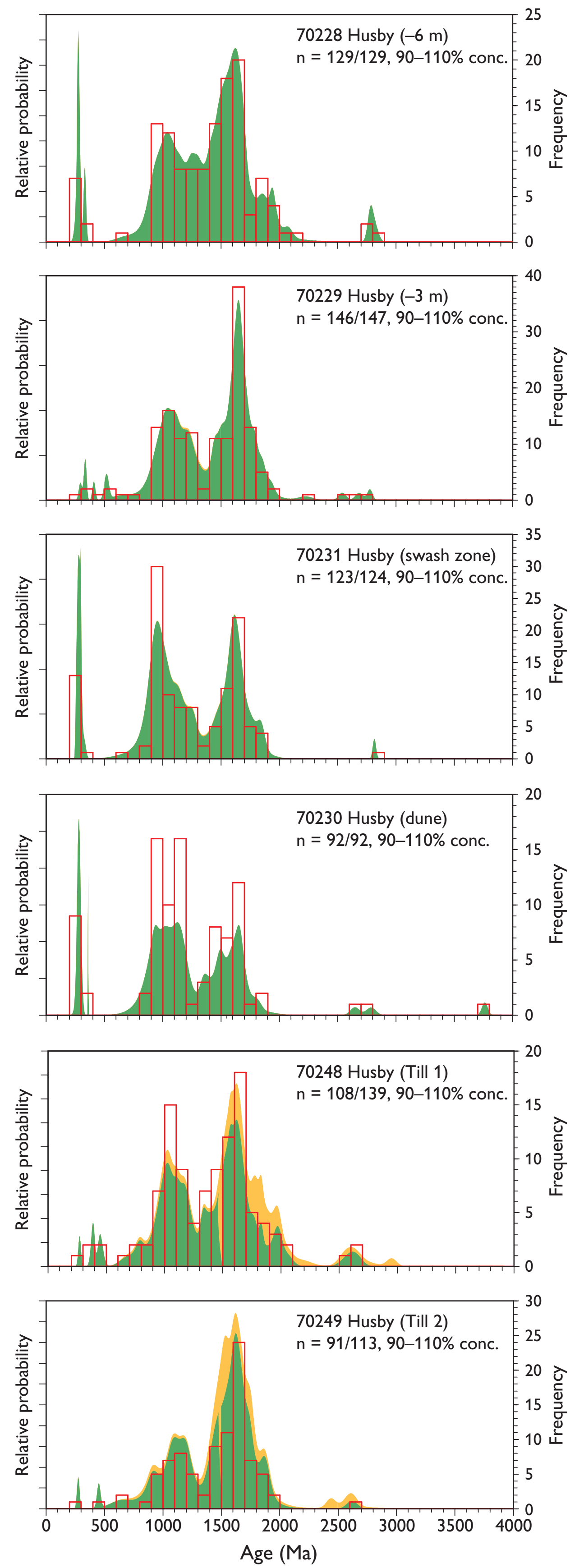

Fig. 4. Age distribution of zircons in the samples from Husby. The frequency (red histograms) indicates the number of zircons in the age brackets (100 Ma). The green area indicates the content of concordant grains whereas the yellow area indicates the discordant grains (only present in the till samples). The samples from the shoreface (–3, –6 m) are characterised by two main populations, one with ages between 1000 Ma and 1300 Ma and one with ages between 1400 Ma and 1900 Ma, the latter being the most abundant. Samples from the beach and dune contain the same populations, but are characterised by more equal proportions of the two populations. It can also be noticed that the samples from the till in the cliff behind the beach are characterised by a pattern similar to the samples from the shoreface.

ilmenite or mafic silicates. This could be caused by differences in grain shape, and one of the aims of the project is to investigate how the grain-size distribution varies among the different sedimentary environments along the west coast of Jylland.

In provenance analysis it is often assumed that ratios between the heavy mineral species can be used as provenance indicators. Due to analytical constraints, or chosen standard procedures, a given size-fraction (typically 63 to 125 µm; Hallsworth & Chisholm 2008; Yang *et al.* 2009) is often used for such analysis, regardless of the fact that the sands which are compared have different overall grain-size distributions. As can be seen on Fig. 2, for example, the modal proportions of the heavy minerals would not reflect the true values if only the fraction between 63 and 125 µm was analysed. The sample Husby –6 m would be characterised by its finer part, with zircon being over-represented whereas the sample Husby –3 m would be close to the modal value. In Fig. 3, the modal proportions of the heavy minerals show that the composition of the heavy mineral fraction in the shoreface sands (–6 and –3 m) is similar but different to the beach sand and dune sands, which in turn resemble each other. The main difference between these two pairs is that garnet is more abundant in the beach and dune sands than in the shoreface sand. The heavy mineral assemblages from the tills exposed in the cliff are different to the beach and dune sands, but similar to the sand from the shoreface.

Figure 4 shows the age distributions of the zircon grains in the six samples. The samples show roughly the same spectra: a few Archaean (>2500 Ma) grains, an Early Proterozoic maximum (*c.* 2000–1500 Ma), a Middle Proterozoic maximum (*c.* 1400–900 Ma) and a Caledonian peak (*c.* 400–300 Ma). It is a characteristic feature of the shoreface sands and the till samples that Early Proterozoic zircons are more abundant than Middle Proterozoic zircons. In contrast, the two populations are equally represented in the beach and dune samples. The Middle Proterozoic zircons were probably derived from the Sveco-Norwegian orogen in southern Norway and western Sweden to the north of Jylland whereas the Early Proterozoic zircons were probably derived from Jotnian and Sveco-Fennian sources to the east.

Both the mineral paragenesis data and the zircon age distributions suggest that the shoreface sands have a provenance that is distinct from the beach and dune sands at Husby. This is surprising, and further work will concentrate on explaining these patterns, with the aim of understanding the processes responsible for the observed distribution of these sands. In addition, the distribution of heavy mineral assemblages along the shore will be analysed.

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