Provenance of Cretaceous and Paleocene sandstones in the West Greenland basins based on detrital zircon dating

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The extensive and very deep ?Jurassic/Cretaceous–Palaeogene sedimentary basins offshore West Greenland have a significant petroleum exploration potential. This is particularly true for the offshore region west of Disko and Nuussuaq where a live petroleum system has been documented for many years. At present, stratigraphic knowledge in this area is almost non-existent and analogue studies from onshore areas and offshore exploration wells to the south are therefore crucial to understanding the distribution and quality of possible reservoir rocks in the Disko–Nuussuaq offshore area.

One of the main risk parameters in petroleum exploration in this region is the presence of an adequate reservoir rock. Tectonostratigraphic considerations suggest that several sand-prone stratigraphic levels are probably present, but their provenance and reservoir quality are at present poorly known both onshore and offshore.

A sediment provenance study including zircon provenance U-Pb dating and whole-rock geochemical analysis was therefore initiated by the Geological Survey of Denmark and Greenland (GEUS) in preparation for the Disko West Licensing Round 2006 (Scherstén *et al.* 2007). The main aims of this study were to:

1. Characterise the source areas and dispersal patterns for the various sandstone units of Cretaceous–Paleocene age in the Nuussuaq Basin and compare these with sandstone units in selected West Greenland offshore exploration wells (Figs 1, 2), employing advanced zircon provenance U-Pb dating using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS; cf. Frei *et al.* 2006).
2. Detect possible changes in sediment source with time, e.g. local versus regional sources.
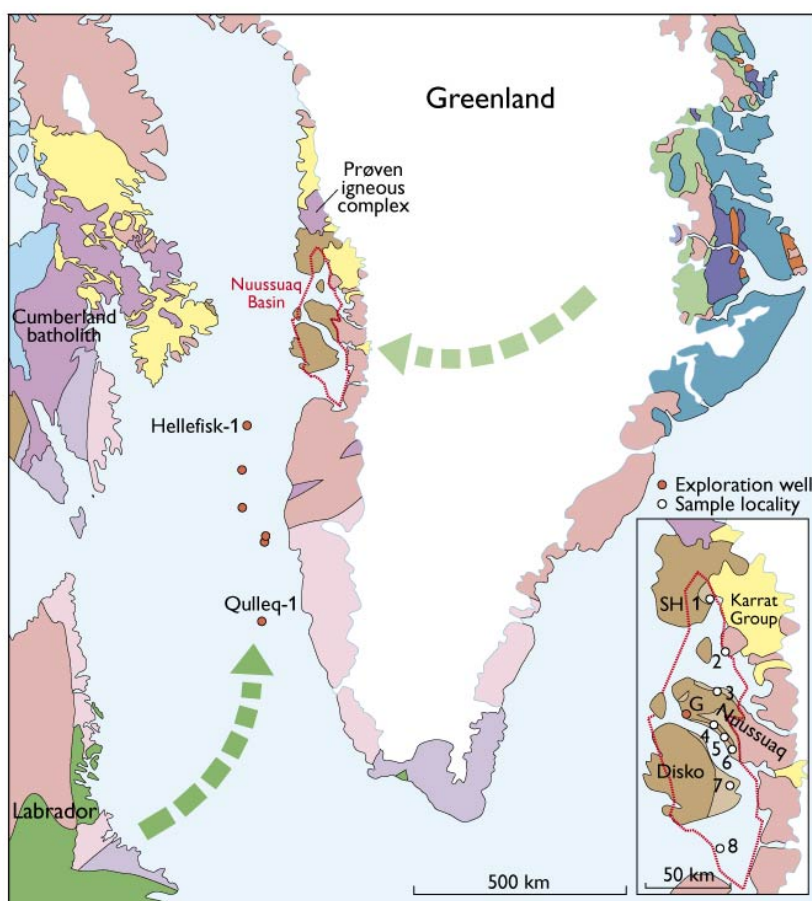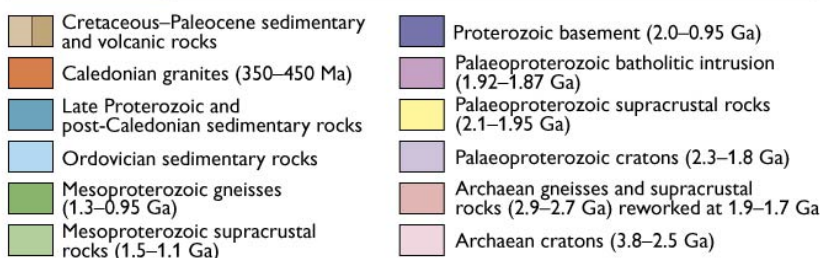

Fig. 1. Simplified geological map of eastern Canada and Greenland (modified from Escher & Pulvertaft 1995 and St-Onge *et al.* 2006). Greenland is shown in a Paleocene pre-drift position (from Oakey 2005, p. 222). Arrows indicate possible source of Grenvillian age components in West Greenland zircon samples. Inset shows sampled localities in the Nuussuaq Basin; **1**, Itsaku on Svartenhuk Halvø (**SH**); **2**, Upernivik Ø; **3**, Ikorfat; **4**, Paatuut; **5**, Kingittoq; **6**, Atanikerluk; **7**, Pingu and **8**, Grønne Ejland. Sampled wells are GRO#3 (**G**), Hellefisk-1 and Qulleq-1.

Legend:
- Cretaceous–Paleocene sedimentary and volcanic rocks
- Caledonian granites (350–450 Ma)
- Late Proterozoic and post-Caledonian sedimentary rocks
- Ordovician sedimentary rocks
- Mesoproterozoic gneisses (1.3–0.95 Ga)
- Mesoproterozoic supracrustal rocks (1.5–1.1 Ga)
- Proterozoic basement (2.0–0.95 Ga)
- Palaeoproterozoic batholitic intrusion (1.92–1.87 Ga)
- Palaeoproterozoic supracrustal rocks (2.1–1.95 Ga)
- Palaeoproterozoic cratons (2.3–1.8 Ga)
- Archaean gneisses and supracrustal rocks (2.9–2.7 Ga) reworked at 1.9–1.7 Ga
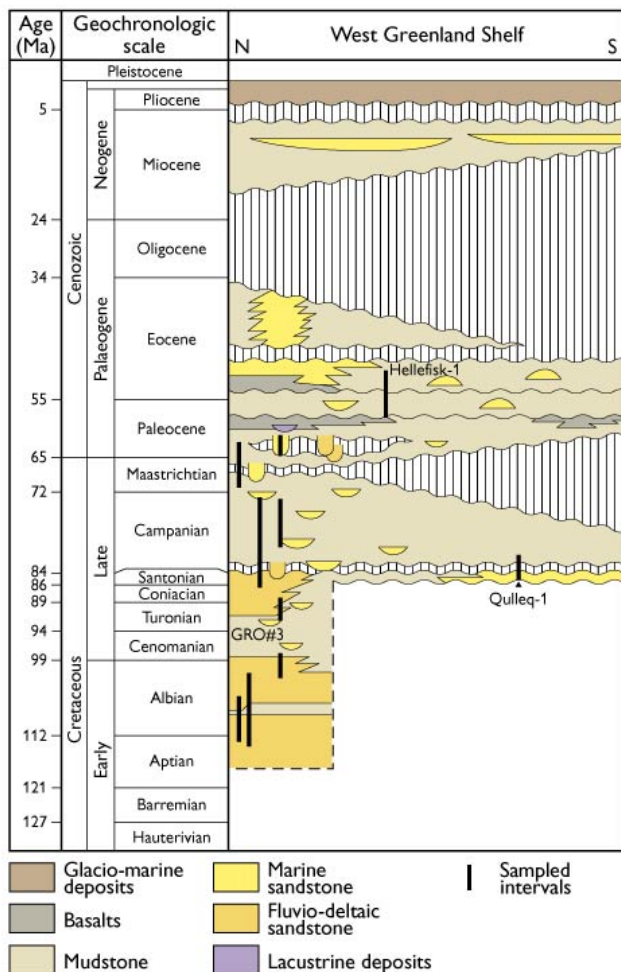- Archaean cratons (3.8–2.5 Ga)

Fig. 2. Simplified stratigraphic scheme of the Nuussuaq Basin and West Greenland offshore region showing stratigraphic distribution of analysed samples.

Zircon as a provenance tool is receiving increasing attention and has proven to be a powerful indicator of clastic sediment sources, a tracer of the Earth's oldest materials, and a tracer of continental crust-forming processes (Froude *et al.* 1983; Williams & Claesson 1987; Dodson *et al.* 1988; Fedo *et al.* 2003; Hawkesworth & Kemp 2006). Zircon is common in continental rocks and it is assumed that its distribution in sediments will normally represent the source rocks. Although there are several complications, the sediment zircon U-Pb age frequency should in general terms mirror the relative proportions of different source materials. This assumption is particularly important if exotic components can be identified, as their frequency will provide an estimate of the exotic influx: it may also be essential in tracing sediment paths that affect the detrital compositions and subsequent diagenetic history of possible hydrocarbon reservoir rocks.

Cretaceous sediment provenance

It is assumed that the age structure of the North Atlantic cratons surrounding the study area is well enough known to constrain the origin of the source components that contributed to the sediments. Archaean gneisses that range from 3850 to 2600 Ma (Hollis *et al.* 2006) dominate southern West Greenland. Important peaks occur at 3600, 3100, 2900 and 2700 Ma. Farther north, the Archaean basement was reworked during the Nagssugtoqidian/Rinkian orogeny, which adds an age peak centred at 1900–1750 Ma (Figs 1, 3; Connelly *et al.* 2000).

As part of this study, 4262 grains were dated from 65 sediment samples from eight localities in the Nuussuaq Basin and three exploration wells (Fig. 1; Scherstén *et al.* 2007). Data that are >10% discordant were filtered out as they are more likely to be disturbed by common Pb contamination, ancient Pb-loss and mixed domains. The remaining 2735 grains display a relative age distribution that is dominated by age peaks between ~2500–3200 Ma (Fig. 3). There is also a peak at ~3600 Ma, which constitutes several samples suggesting that 3600 Ma age components are perhaps more abundant than those from the well-known Godthåbsfjord area (Friend & Nutman 2005; Hollis *et al.* 2006). A ~1900
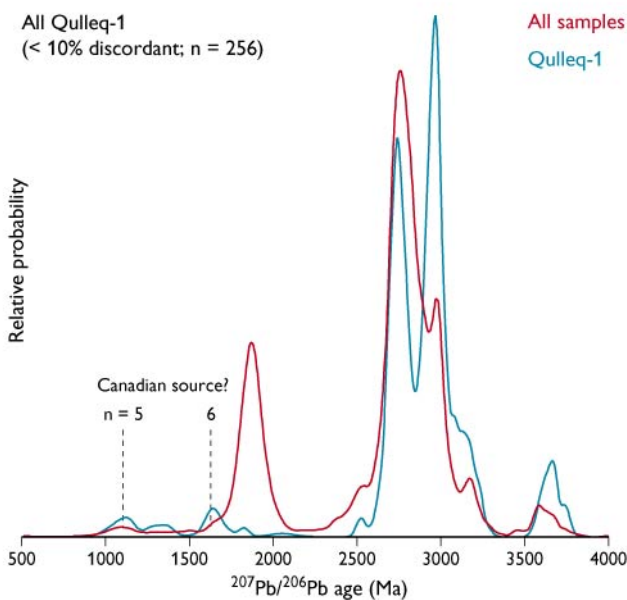

Fig. 3. Relative ^{207}Pb/^{206}Pb age distribution of 2735 <10% discordant zircon grains from the Cretaceous–Palaeogene sediments in this study (red curve). The relative probability reflects the likelihood of finding any given age, although the ~1900 Ma peak is overrepresented due to sampling bias. Zircon ages from the Qulleq-1 well show small but significant peaks at ~1600–1700 and ~1100 Ma (n is the number of grains that are within error of 1600 and 1100 Ma, respectively). These appear to be coupled and may have been either derived from East Greenland or the Canadian Shield. See text for further discussion.

Ma peak is also distinct, but is probably overrepresented due to sampling bias through the many samples taken at Itsaku where this age component is strongly represented in comparison to the sediments farther south (see discussion below). The 1900 Ma peak is slightly asymmetric with a tail towards younger ages and an age component around 1600–1700 Ma. The overall age distribution is in excellent agreement with a source from the West Greenland crystalline basement; and the zircon data support the existing depositional models indicating that a major deltaic system drained into the Nuussuaq Basin from the east-south-east during Cretaceous–Paleocene time (Pedersen & Pulvertaft 1992).

A small but significant peak at ~1100 Ma suggests a distal component that is not readily explained by derivation from the West Greenland crystalline basement as described above. This component seems to be associated with the 1600–1700 Ma occurrence noted above (Fig. 3). Two possible sources can explain the dual peaks: from East Greenland or Labrador (Fig. 1). If an East Greenland origin is favoured, it would be anticipated that this signature would also be associated with Caledonian ages between 380 and 480 Ma, which have not yet been identified (Figs 1, 3). Given the large number of grains analysed, it would be expected that even a very small contribution would have been detected suggesting Labrador as the most likely source for the 1100 Ma peak. A southern, Labrador source for the 1100 Ma component in the Qulleq-1 well is corroborated by the absence of the 1900 Ma peak that is ubiquitous in the Nuussuaq Basin to the north (Fig. 4). The samples from the Qulleq-1 well are dominated by Archaean ages without contributions from rocks reworked during the Nagssugtoqidian/Rinkian orogenic event.

In the Nuussuaq Basin the 1100 Ma component is very rare in the onshore, deltaic facies and occurs almost exclusively in the deep-water deposits in accordance with a long-shore transport component from the south as the source of this component. However, current data from turbidite channel units on western Nuussuaq show transport directions towards the south (Dam & Sønderholm 1994). It is not possible to explain this apparent discrepancy based on the present database. More data including the other offshore wells will be needed to elucidate the possible interconnections and transport paths in the West Greenland offshore basins.

Paleocene point source provenance on Svartenhuk Halvø

A set of samples was collected on Itsaku on Svartenhuk Halvø where a major hiatus separates an Upper Albian to Lower Cenomanian deltaic succession from an Upper Campanian to Paleocene marine turbidite succession. The detrital zircon age
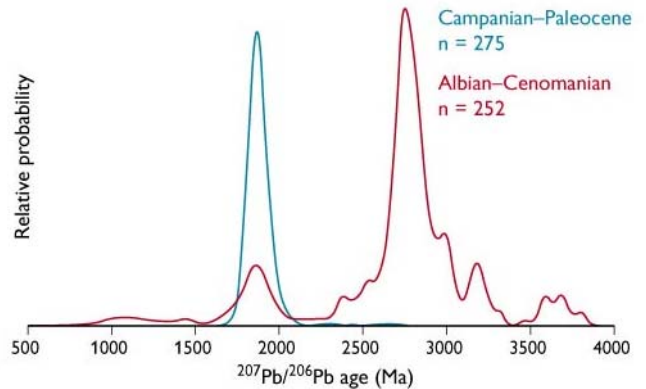

Fig. 4. Relative probability diagram for $^{207}Pb/^{206}Pb$ ages for zircon from Upper Albian – Cenomanian deltaic sediments (red) and Upper Campanian/Maastrichtian – Paleocene marine sediments (blue) on Itsaku, Svartenhuk Halvø. The deltaic deposits display a pattern that is typical for the sediments in the Nuussuaq Basin, whereas the constrained pattern of the overlying marine deposits is unique and seems to require a single point source.

distribution in the deltaic succession is typical for the Nuussuaq Basin and dominated by a distinct peak at ~2800 Ma; this is flanked by scattered peaks between 2400 and 3200 Ma (Fig. 4), as well as significant peaks at 3600–3800 Ma representing Eoarchaean components. A 1900 Ma peak is another typical feature of the Nuussuaq Basin sediments, whereas the occurrences of 1100 and 1600–1700 Ma peaks are more intermittent (see above). The overall pattern is in good agreement with that of the general West Greenland Cretaceous population and deltaic deposition from the east-south-east.

The zircon age distribution of the overlying turbidite succession is in stark contrast to the lower section (Fig. 4). Here, the zircon population forms a single, well-defined ~1900 Ma peak with an apparent normal distribution indicative of a single point source with respect to zircon. The only known source that fits this distribution is the 1869 ± 9 Ma Prøven igneous complex (Fig. 1; Thrane et al. 2005). Assuming the Prøven igneous complex forms a single source to the upper part of the succession, a Tukey's biweight mean of 1872 ± 4 Ma (n = 275) can be calculated, which is in excellent agreement with the Prøven igneous complex. A few grains scatter towards 2700 Ma, which likely reflects inherited components, in accordance with its derivation from lower continental crust (Thrane et al. 2005).

Trace element systematics in zircon may provide further constraints on zircon origin in provenance studies (Hoskin & Ireland 2000). However, several hurdles need to be overcome. For instance, many features are shared intimately between zircon that are derived from widely different sources (Hoskin & Ireland 2000), and in a detrital population each grain has

to be treated separately, as a common age does not necessarily imply the same source rock, and by inference, the same crystallisation processes or conditions. Nevertheless, it is assumed here that zircon from the upper part of the section represents one population that was derived from the Prøven igneous complex. Trace element abundances were determined for 138 zircon grains from this part of the section and contrasted against Archaean (n = 424) zircon grains from other stratigraphic levels. As expected, there are no systematic variations with age, which would require an age dependent systematic change in zircon crystallisation processes. Titanium in zircon thermometry (Watson *et al.* 2006) enables calculation of zircon crystallisation temperatures. The upper zircon population yields a mean temperature of 845 ± 19°C (± $2\sigma_{mean}$; n = 93; GJ-1 standard reproducibility 668 ± 30°C 2σ n = 17), which is similar to zircon saturation temperatures of 790– 880°C (n = 4) calculated from bulk rock data and the independently estimated intrusion temperature of the Prøven igneous complex (Thrane *et al.* 2005). The Prøven igneous complex is inferred to have been derived from a lower continental crust source as reflected by significantly negative Eu anomalies from a plagioclase residue (Eu/Eu* ~0.45; Thrane *et al.* 2005). This appears to be reflected by the zircon population, which has a mean of 0.23 ± 0.03 (± $2\sigma_{mean}$; n = 93; GJ-1 standard reproducibility 0.96 ± 0.06 2σ n = 23). The values contrast with the average Archaean population (Eu/Eu* = 0.49 ± 0.03 $2\sigma_{mean}$; n = 257), which is assumed to be dominated by rocks such as tonalite–trondhjemite–granodiorite (TTG) suites that have Eu/Eu* ~1.0. Thus, the zircon population of the Upper Campanian to Paleocene marine turbidite succession seems to form a single population that is in accordance with derivation from the Prøven igneous complex. This implies a major change in depositional transport direction compared to the underlying Lower Cretaceous deltaic deposits from a south-eastern and eastern source to a northern source.

Acknowledgement

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