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Detrital zircon ages: a key to understanding the deposition of deep marine sandstones in the Norwegian Sea

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Abstract

The provenance of Cretaceous to Paleocene sandstones from the Norwegian Sea has been determined by laser ablation ICPMS U–Pb and Pb–Pb dating of detrital zircons. The zircon grains were extracted from sandstones sampled in the Møre and the Vøring Basins.

The potential source regions for the Norwegian Sea sediments are the surrounding landmasses of East Greenland and Norway. The basement of East Greenland contains both Archaean (3800–2500 Ma) and Early Proterozoic (ca. 2000 Ma) rocks, whereas the main Norwegian basement ages are younger (1000–1600 Ma). Sandstones of known provenance, derived from East Greenland and the Norwegian landmasses, have been analysed for comparison with the investigated sandstones of unknown provenance. The analysed detrital zircons derived from the East Greenland and Norwegian landmasses reflect the known basement ages as the sandstones derived from East Greenland are characterized by a wide detrital zircon age pattern with a considerable Archaean component. The Norwegian-derived detrital zircons show a narrow age pattern with the age maxima between 1000 and 1600 Ma.

The Turonian–Maastrichtian sandstone samples from the Vøring Basin show wide-range zircon age patterns, all with a discernible Archaean component, indicating an East Greenland provenance. A sample of Cenomanian sandstone from the Dønna Terrace, located on the eastern flank of the Vøring Basin, shows a narrower detrital zircon age pattern typical of sediments derived from the Norwegian landmass. Sandstones of Maastrichtian–Paleocene ages in the Møre Basin show zircon age patterns that are indicative of an eastern source, whereas a Coniacian sandstone sample from the Møre Basin shows detrital zircon age spectra typical of a western source. The provenance change from a western to an eastern source found in the Møre Basin sandstones was most likely a result of the Baltic margin elevation during Coniacian to Maastrichtian times, resulting in an increased sediment supply from the eastern margin.

Keywords: Sedimentary provenance; Norwegian sea; Detrital zircon ages; Laser ablation ICPMS

1. Introduction

Deep marine sediments in the Norwegian Sea have recently received much attention due to their importance in exploration for hydrocarbons. Predict-

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ing deep marine reservoir distribution is a critical factor in the immature exploration basins of the Norwegian Sea.

This paper presents the results of a regional provenance study of Cretaceous and Paleocene sandstones of the Norwegian Sea, initiated to better understand the distribution of the sandstone bodies and the basin evolution. The ages of the investigated detrital zircons reflect the age distribution of the zircon-bearing rocks in their source areas. Variations in the sedimentary source(s) with time, reflected by lateral and stratigraphical contrasts of detrital zircon ages in the analysed sedimentary sequences, can constrain the evolution history of the investigated basins. Radiometric ages of detrital zircon populations from deep marine sandstones in the Møre and the Vøring Basins have been determined primarily in order to identify the sediment source(s).

The surrounding landmasses, East Greenland on the western side and Norway on the eastern side of the Norwegian Sea, are the potential source areas for the studied sediments. The zircon age signatures of the Cretaceous sedimentary rocks derived from North-East Greenland (Hold with Hope) and West Norway (Agat area) are used in this study for comparison with sandstones of unknown provenance from the Vøring and the Møre Basins. The results obtained from the rocks of known provenance are used as “fingerprints” of the potential sedimentary sources.

2. Geological setting of the Norwegian Sea and conjugate margins

The structural frameworks of the Norwegian Sea and surrounding landmasses are important factors controlling the sediment distribution and drainage pattern from the source areas into the depositional basins. The most important information on the potential source areas in Eastern Greenland and the Norwegian landmass comes from the rock types present and their ages of origin.

2.1. East Greenland

The basement rocks of East Greenland are mainly of Paleozoic (450–350 Ma), Early Proterozoic (2000–1750), and Archaean (3800–2500 Ma) ages (e.g. Esher and Watt, 1976; Kalsbeek et al., 2001; Watt and Thrane, 2001). The largest part of the ice-free area of Greenland is made up of crystalline rocks of the Precambrian shield (Fig. 1). The oldest rocks are within the Archaean gneiss complex, which extends from the west coast to the east coast in southern Greenland. The Archaean domain is also exposed in the northwestern part of Scotland and a rather large area of Archaean rocks is inferred to be situated north of Scotland and northeast of the Shetland Islands.

Isolated remnants of similar Archaean and Proterozoic rocks are associated with the Caledonian Orogen of East Greenland (Fig. 2). The Archaean and Proterozoic granitoids are exposed in tectonic windows in the western part of the East Greenland Caledonides and are interpreted as being parts of the Caledonian foreland (Leslie and Higgins, 1999; Smith and Robertson, 1999). The granitoids in South-Eastern Greenland are mostly Archaean (3800–2500 Ma) in age, whereas the basement rocks north of the 72°N parallel are mainly of Early Proterozoic (2200–1800 Ma) age (Watt and Thrane, 2001).

The granitoids also occur within the thick pile of major thrust units together with meta-sedimentary cover units. The cover sequence contains high-grade paragneisses (Krummedal supracrustal sequence), and sedimentary rocks of Late Proterozoic to Ordovician ages (Fig. 2). The basement rocks on East Greenland also contain zircon-bearing intrusions of ca. 435 and 930 Ma (unevenly distributed between the 70° and 75°N parallels; Kalsbeek et al., 2001). The post-Caledonian rocks exposed in East Greenland are Devonian–Cretaceous sediments and Tertiary intrusions and volcanics (Fig. 1). Other events recorded by zircon U–Pb chronometer in East Greenland were associated with rifting of the Laurentian margin (570–760 Ma) and earlier convergent-margin magmatism at 1230–1360 Ma (Cawood and Nemchin, 2001).

North-East Greenland, with a pre-drift position approximately 100–150 km northwest of the Vøring Basin, contains well-exposed Cretaceous sediments. Skogseid et al. (2000) suggest that the present margin of North-East Greenland was once part of a larger Cretaceous basin that included parts of the Vøring Basin, now separated by the oblique boundary of the

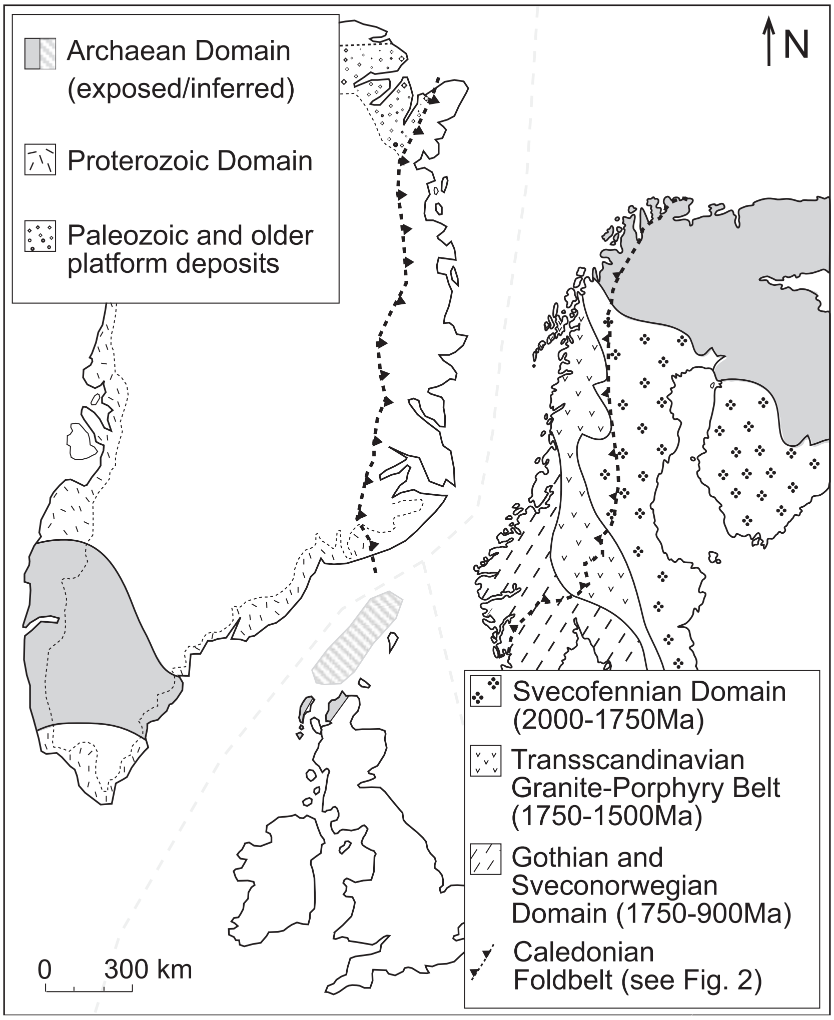

Fig. 1. Distribution of age domains within the basements of Greenland, Scandinavia and North Scotland, presented in a pre-drift configuration (modified from Esher and Watt, 1976; Skår et al., 1994; Pedersen et al., 1992).

Tertiary continental break-up. The Cretaceous succession of North-East Greenland is more than 2 km thick, and consists of siliciclastic, mainly marine sediments deposited following a major rifting phase in the latest Jurassic–earliest Cretaceous (Surlyk, 1978). After the Jurassic onshore rift topography was filled, in the middle Albian–Turonian times, the East Greenland landmass started to contribute to the sediments across the Greenland shelf (Whitham et al., 1999).

2.2. Norwegian landmass

The Scandinavian basement is mainly Precambrian in age and the age decreases towards the southwest (Fig. 1). The Caledonian (450–350 Ma), the Sveconorwegian (1250–900 Ma), and the Gothian (1750–1500 Ma) were the main orogenies that formed the rocks that occur along the Norwegian margin. The Norwegian basement south of the Møre area (Western Gneiss Region) consists mainly of Early Proterozoic rocks (Gothian, ca. 80%) and Middle Proterozoic intrusions (Sveconorwegian, ca. 20%; Skår, 1998). The basement north of the Møre area is composed mainly of Early Proterozoic rocks without the Middle Proterozoic intrusions (Fig. 2). The Caledonian Nappes, consisting of crystalline and sedimentary rocks of various ages, rest on the Norwegian basement rocks (Fig. 2). The crystalline rocks that occur within the Caledonian nappe stack (i.e. the Jotun Nappe and the Dalsfjord Suite) were interpreted to be remnants of the

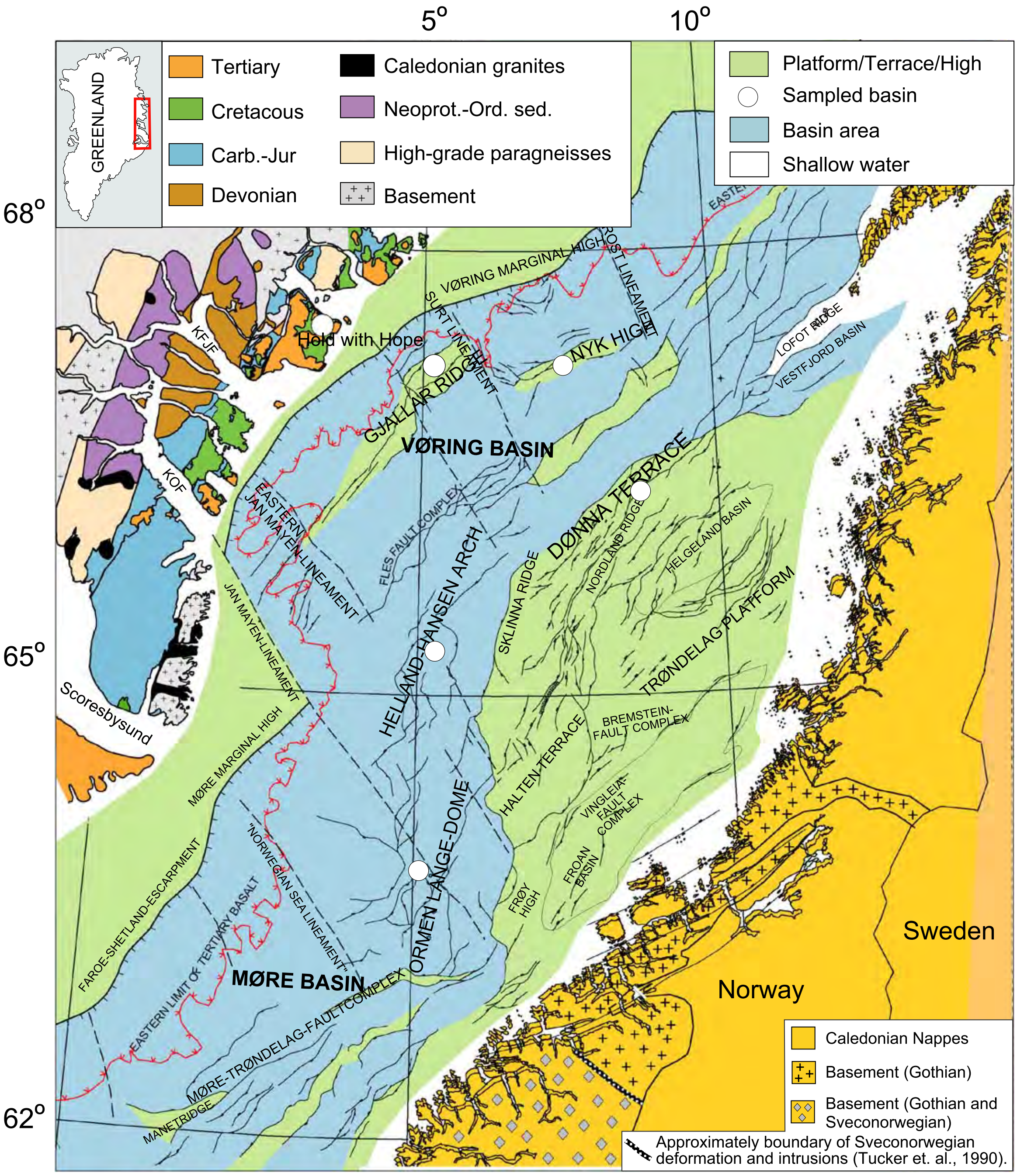

Fig. 2. Structural elements of the platforms and basins within the Norwegian Sea and simplified geological maps of the conjugate margins of the East Greenland and Norway. The pre-drift reconstruction shows the position of East Greenland along the western margin of the Vøring Basin during the Cretaceous period (the map of East Greenland was modified from Stemmerik et al., 1997; Kalsbeek, et al., 2001; Norwegian map modified from Skår, 1998; Tucker et al., 1990; KFJF: Kejser Franz Josephs Fjord, KOF: Kong Oscars Fjord).

pre-Caledonian western margin of Baltica (e.g. Milnes and Koestler, 1985; Fossen and Dallmeyer, 1998). The meta-sediments that are associated with, or contained within the Norwegian Caledonian rocks, are generally of Cambrian–Silurian ages (Roberts and Gee, 1985; Thon, 1985).

2.3. The Norwegian Sea

The principal structural elements of the NE–SW trending deep Cretaceous basins of the Norwegian Sea are shown in Fig. 2. The tectonic evolution of the Norwegian Sea has determined present structural configuration, and the tectonic history can be traced back to the Permo-Carboniferous times (e.g. Blystad et al., 1995; Doré and Lundin, 1996). The three main rifting episodes that were identified are (1) Carboniferous to Permian, (2) Late–Middle Jurassic to Early Cretaceous, and (3) Late Cretaceous to Early Eocene. The base of the Cretaceous sequence in the central parts of the Norwegian Sea basins lies at depths between 9000 and 13 000 m (Færseth and Lien, in press; Brekke, 2000), and the deposition during Early to Middle Cretaceous was associated with the post-rifting thermal subsidence stage, which was a response to the high tectonic relief inherited from the Jurassic crustal stretching (Færseth and Lien, in press).

In contrast to the thin and sand-prone Late Cretaceous interval on platforms and terraces to the east (i.e. Dønna Terrace), thick intervals of deep marine sediments were deposited in the Møre and Vøring Basins during the Late Cretaceous and Paleocene rift stages. Structural elements that affected sedimentary drainage patterns of the investigated Vøring and eastern Møre Basins include the NW–SE oriented Jan Mayen- ineament that separates the Møre Basin from the Vøring Basin, and the NE–SW trending Møre–Trøndelag Fault Complex (Fig. 2).

3. Sampling and analytical technique

3.1. Sampling

Sixteen sandstone samples from East Greenland and the Norwegian Sea have been analysed in this study. Their stratigraphic and geographic positions are given in Table 1, and the tectono-stratigraphic scheme for the Norwegian Sea region is shown in Fig. 3. The onshore sedimentary rocks have been sampled from the Cretaceous succession on Hold with Hope, a peninsula just north of the Kejser Franz Joseph Fjord (Fig. 2), East Greenland. The two analysed samples are from the shallow marine sandstones of the Albian Home Forland Formation and the Aptian Gulelv Member (Larsen et al., 2001; their Fig. 4).

The sampled sediments of unknown provenance are from the Møre and the Vøring Basins in the Norwegian Sea. From the Møre Basin, seven fine- to medium-grained sandstones were analysed (Table 1). The Coniacian to Paleocene sandstones are all from wells drilled in the Ormen Lange Dome, which is situated in the eastern part of the Møre Basin (Fig. 2). Also included in this study are Turonian to

Table 1
Geographical and stratigraphic information on the sampled sedimentary rocks

Well	Depth RKB	Area	Age	Formation	Material
6305/1-1T2	2569 m	Ormen Lange	Paleocene	Våle	Core
6305/1-1T2	2615 m	Ormen Lange	Maastrichtian	Springar	Core
6305/1-1T2	2619.8 m + 2618.6 m	Ormen Lange	Maastrichtian	Springar	Core
6305/1-1T2	3651–3654 m[a]	Ormen Lange	Coniacian	Kvitnos	Core
6305/5-1	2736 m	Ormen Lange	Paleocene	Tang	Core
6305/5-1	2788 m	Ormen Lange	Maastrichtian	Springar	Core
6305/7-1	2938 m	Ormen Lange	Paleocene	Tang	Core
6305/10-1	3486 m + 3487 m	Helland–Hansen	Coniacian	Lysing	COCH
6505/10-1	3714 m + 3716 m	Helland–Hansen	Turonian	Lysing	COCH
6505/10-1	3865 m + 3879 m	Helland–Hansen	Turonian	Lange	COCH
6704/12-1	2576–2571 m[a]	Gjallar Ridge	Maastrichtian	Springar	Core
6704/12-1	2997–3003 m[a]	Gjallar Ridge	Maastrichtian	Springar	Core
6707/10-1	3122.05 m	Nyk High	Campanian	Nise	Core
6507/2-2	3281 m	Dønna Terrace	Cenomanian	Upper Lange	Core
Greenland	–	Onshore	Aptian	Gulelv	Field sample
Greenland	–	Onshore	Albian	Home Forland	Field sample

[a] Denotes the core fragments collected within the given depth range (COCH: Core Chip; RKB: Rotary Kelly Bushing).

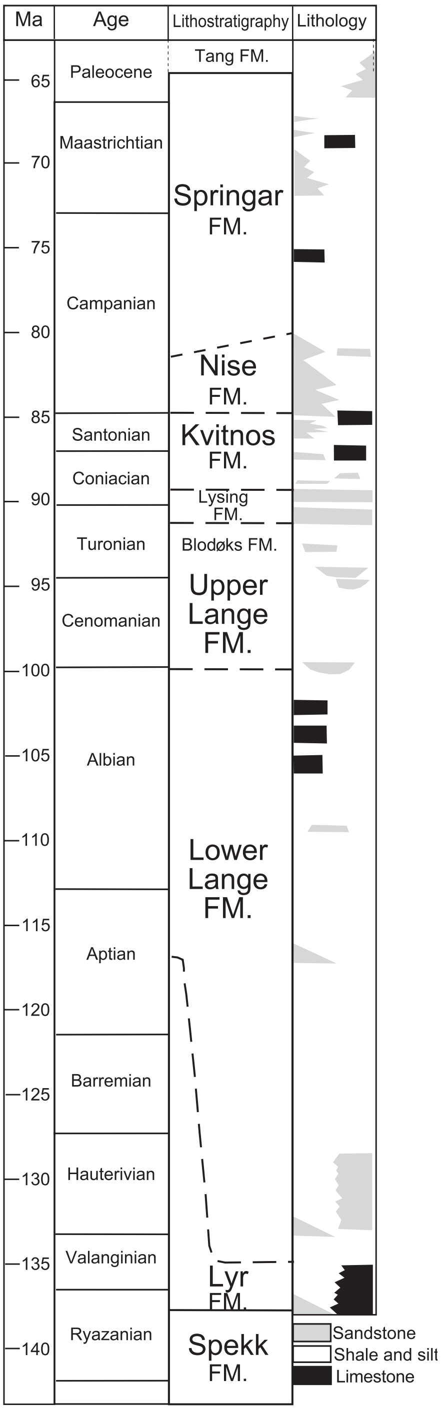

Fig. 3. Tectono-stratigraphic scheme for the Norwegian Sea region. The lithostratigraphy is from Dalland et al. (1988) and chronostratigraphy is from Gradstein et al. (1994).

Maastrichtian sandstones from the Gjallar Ridge, Nyk High, and Helland–Hansen Arch in the Vøring Basin (Fig. 2; Table 1). All studied sandstones from the Vøring Basin are fine to medium grained and were deposited as turbidites on a deep marine basin floor. The Gjallar Ridge and the Nyk High are located in the western part of the Vøring Basin, and the Helland–Hansen Arch in the southernmost part of the basin (Fig. 1). The sample from the Dønna Terrace at the eastern part of the Vøring Basin (Fig. 2) is a medium grained Cenomanian turbidite sandstone penetrated by well 6507/2-2.

3.2. Zircon geochronology

Detrital zircon grains were extracted from 25 to 250 g of sandstone samples by crushing, sieving and separation in heavy liquids. In order to minimise the possibility of fractionation of the detrital grains during the separation, the heavy minerals were handpicked directly after separation in heavy liquids. The average zircon grain size was ca. 100 μm. The grains were handpicked with no preference based on the shape, size, or colour, and mounted in epoxy resin and polished to obtain even surfaces suitable for laser ablation ICPMS analysis.

U–Pb and Pb–Pb zircon dating was carried out at Memorial University of Newfoundland using laser ablation ICPMS technique. The ICPMS instrument was a VG PlasmaQuad 2+ “S” coupled to an in-house built 266 nm NdYAG laser. True real-time mass bias correction of the U–Pb data was made by nebulising a tracer solution that contained enriched ^{233}U and natural Tl to the ICP source at the same time as laser ablation (Horn et al., 2000). Using the Tl/^{233}U solution the technique does not require the use of external standards. Data from the 1065-Ma-old 91 500 zircon standard were periodically acquired for quality control of the results. The details of the analytical procedure are described in Košler et al. (2002). The zircons derived from the East Greenland, the Gjallar Ridge, the Nyk High, and the Dønna Terrace were analysed during the early stage of this project, and only Pb–Pb ages were acquired.

The ^{238}U/^{206}Pb and ^{235}U/^{207}Pb systems are two geochronometers that give concordant dates if the mineral dated has remained closed to U and Pb. When compositions yielding such concordant ages are plotted graphically they define a curve, which is termed the concordia. If the isotopic system has experienced lead loss, the two Pb/U ages will not plot on the

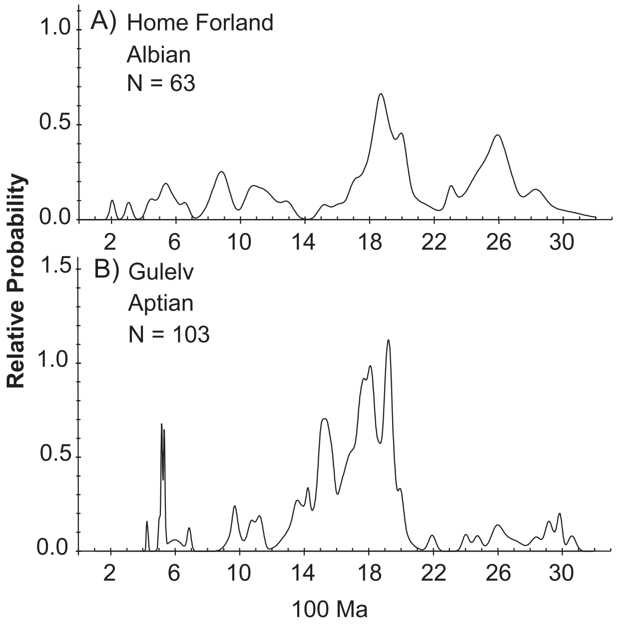

Fig. 4. Pb–Pb zircon ages from the Cretaceous sedimentary succession of the Hold with Hope area on East Greenland: (A) represents the Home Forland Formation, and (B) the Gulelv Member.

concordia line, hence they are discordant. If the ages are discordant, the discordia line can be forced through the origin, assuming that the lead loss occurred at the present. The reciprocal of the gradient of this line yields a $^{207}Pb/^{206}Pb$ age, which is regarded as a minimum age of the mineral. A concordant age is very precise and accurate. One of the challenges using laser ablation ICP-MS is U fractionation during analyses, which will result in discordant ages. Mineral dates obtained by laser ablation ICP-MS are therefore often solely Pb–Pb ages, but new correction methods, as mentioned above, decrease the U fractionation during analyses and increase the opportunity to achieve good U–Pb dates by laser ablation ICP-MS.

All detrital zircon ages presented in the present study are Pb–Pb ages. The results are presented as relative probability plots of the zircon ages (Figs. 4, 5 and 6) calculated by Isoplot (Ludwig, 1999).

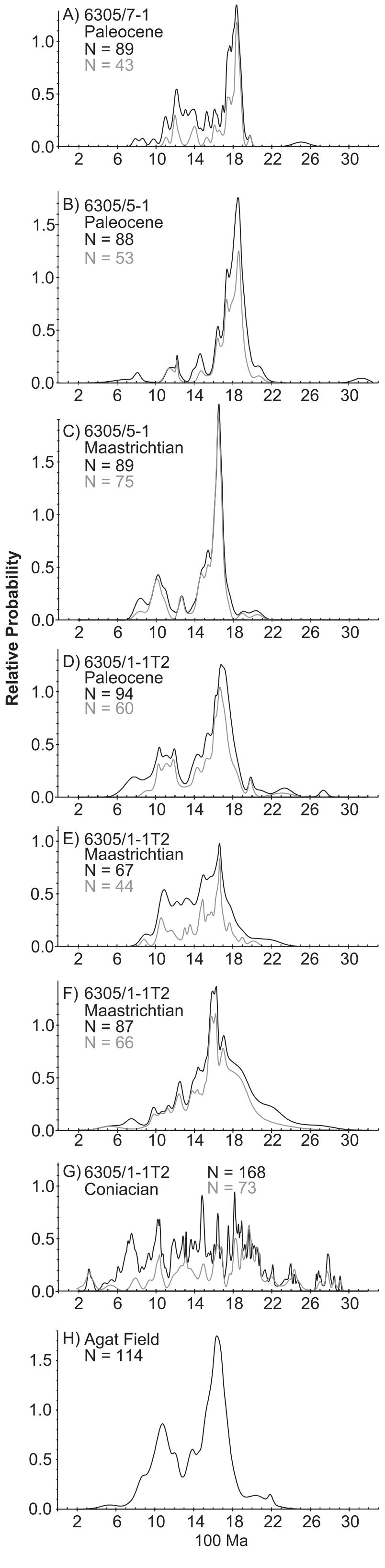

Fig. 5. Pb–Pb ages of detrital zircons from different wells within the Ormen Lange Dome of the Møre Basin: (A) Paleocene sandstone from 6305/7-1, (B) Paleocene and (C) Maastrichtian sandstones from 6305/5-1, (D) Paleocene, (E, F) Maastrichtian and (G) Coniacian sandstones from well 6305/1-1T2. The grey coloured diagrams are based on Pb–Pb ages of zircons that are within 80–120% concordant.

The Pb–Pb ages calculated for all analysed zircons in the present study are shown together with the Pb–Pb ages calculated for analyses that are 80–120% concordant from samples where also the U–Pb data were available (Fig. 5A–G). The age patterns obtained from the 80–120% concordant zircons are not significantly different from the Pb–Pb age spectra of all analysed grains, suggesting that the Pb–Pb ages can be used to constrain the sedimentary provenance of the studied rocks.

4. Results

4.1. Hold with hope, East Greenland

The Cretaceous (Aptian–Albian) sedimentary rock samples from Hold with Hope (East Greenland) are characterized by a wide zircon age distribution pattern that ranges from 200 to 3000 Ma, with a considerable Archaean component (Fig. 4A and B). The total age distribution has its main peak around 1900 Ma. When comparing the two East Greenland plots, the Archaean component is more dominant in the Albian sediments from the Home Forland Formation (Fig. 4A), whereas the Cambrian–Ordovician component is more pronounced in the Aptian sediments from the Gulelv Member (Fig. 4B).

4.2. The Møre Basin

The analysed Maastrichtian and Paleocene sandstones from the Ormen Lange Dome show a narrow zircon age pattern (Fig. 5A–F). The highest concentration of zircon ages is in the range of 1000–2000 Ma, with at least 20% of the ages within the 1500–1700 Ma time span (Fig. 5A–F). In addition to the dominant detrital zircon age signature between 1500 and 1700 Ma, most of the rock samples (sample A, C, D and E, Fig. 5) show minor age peaks between 1000 and 1200 Ma.

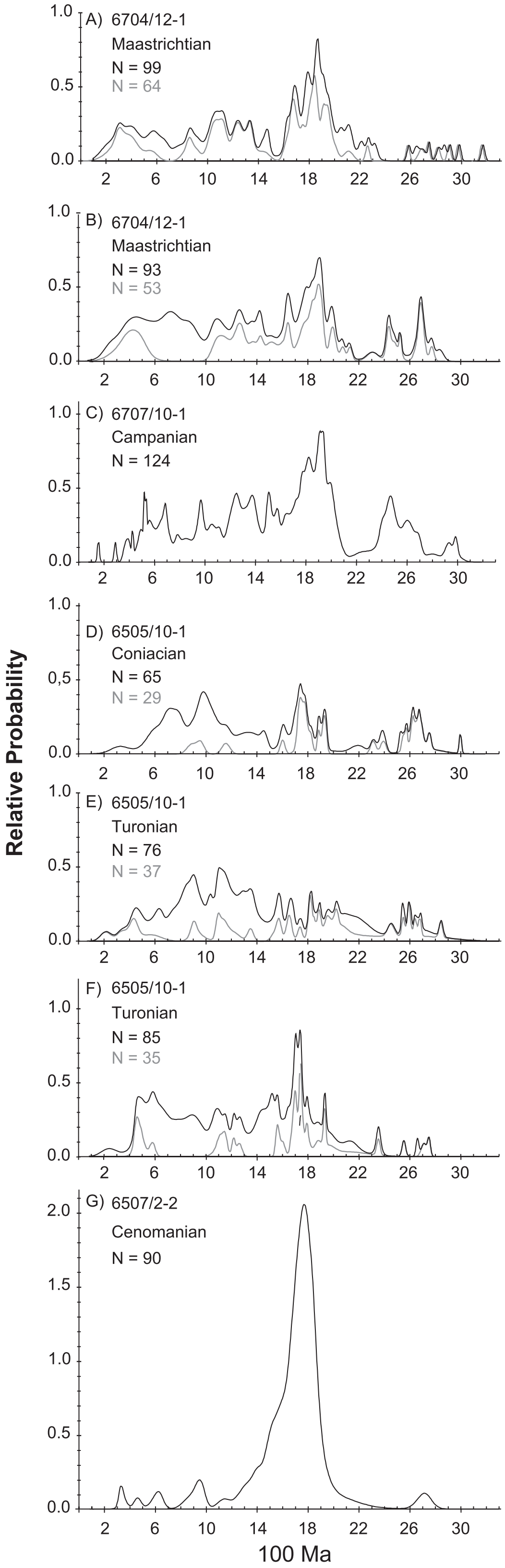

Fig. 6. Pb–Pb ages of detrital zircons from (A, B) Maastrichtian sandstones from the Gjallar Ridge, (C) Campanian sandstone from the Nyk High, (D) Coniacian sandstone from the Helland Hansen Arch, (E, F) from the Turonian sandstones from the Helland Hansen Arch, and (G) the Cenomanian sandstone from the Dønna Terrace. The grey coloured diagrams (D–F) are based on Pb–Pb ages of zircons that are within 80–120% concordant.

The Coniacian sandstone from the Ormen Lange Dome (sample G, Fig. 5) differs from the younger Maastrichtian and Paleocene sandstones in that it shows a wide range of ages without distinct peaks between 200 and 2800 Ma.

4.3. The Vøring Basin

The Turonian–Maastrichtian sandstone samples from the Gjallar Ridge (Fig. 6A and B), Nyk High (Fig. 6C), and the Helland–Hansen Arch (Fig. 6D–F) all show a wide distribution of zircon ages. The age pattern of the Vøring samples resembles the Coniacian sandstone from the Ormen Lange Dome, but the Vøring Basin zircon ages (Fig. 6A–G) have more distinct peaks compared to the Coniacian Ormen Lange zircon age spectra (Fig. 5G). The more distinct peaks occur within the 1500–1700 Ma age range in samples in Fig. 6A–C (Campanian–Maastrichtian, Nyk High, and Gjallar Ridge) and Fig. 6F (Turonian, Helland–Hansen Arch). There is a variation in the occurrence of Archaean zircon grains within the Vøring Basin samples, with the highest peaks being shown in Fig. 6B and C.

The zircon age pattern obtained from the Cenomanian sandstone on the eastern flank of the Vøring Basin (Dønna Terrace) differs from the age pattern of the sandstones sampled in the western part of the Vøring Basin. The Dønna Terrace sandstone shows a very high concentration of zircon ages around 1700 Ma and only a few zircons with ages younger or older than 1700 Ma (Fig. 6G).

5. Discussion

5.1. The provenance signature of the Norwegian landmass

Western Norway is the source of the offshore Agat sandstone (Bugge et al., 2001), which is an equivalent of the Lower Lange Formation of the Norwegian Sea (Fig. 3). The Agat sandstone shows a narrow range of detrital zircon ages from 1000 to 1600 Ma, with one major peak at approximately 1600 Ma and another minor peak around 1000 Ma (Fig. 5H). The age pattern corresponds to the known ages from the basement rocks (Western Gneiss Region) east of the Agat area, which are mostly Early Proterozoic (1750–1500 Ma) with Middle Proterozoic (1250–900 Ma) intrusions (Skår, 1998). These observations indicate an eastern sediment provenance for the Agat sandstones, as suggested by Bugge et al. (2001). These basement ages are also found in detrital zircons from sedimentary rocks associated with the Caledonian nappes that overlie the basement of the Western Gneiss Region (Fonneland, 2002).

The Agat sandstone resembles the K1 sand (from well 6610/3-1 in the Vestfjord Basin, Fig. 1) reported by Morton and Grant (1998). The zircons from both the Agat sandstone and the K1 sands have an Early Proterozoic age peak, but the K1 sample has a significantly lower abundance of Middle Proterozoic zircons (Morton and Grant, 1998; their Fig. 11). They concluded that the K1 sands occurring on the Trøndelag Platform, Halten Terrace, and Nordland Ridge were derived from the Scandinavian landmass with detritus from the Caledonian fold belt, the Trans-Scandinavian igneous belt, and the Svecofennian basement. The northern limit of the Middle Proterozoic province is located in the Møre region (Fig. 2), and a lack of Middle Proterozoic rocks can be seen in the zircon age spectra for the K1 sand (Morton and Grant, 1998) derived from Norwegian landmass north of the Møre region.

It appears therefore that we are able to discriminate between the provenance of sediments derived from the Norwegian basement rocks north and south of the Middle Proterozoic boundary by their relative contents of Middle Proterozoic (Sveconorwegian) and Early Proterozoic (Gothian) zircons.

5.2. The East Greenland provenance signature

The East Greenland landmass started contributing to the sediments across the Greenland shelf in the middle Albian–Turonian times after the Jurassic onshore rift topography was filled (Whitham et al., 1999), and a large volume of coarse clastic sediments was transported during Late Cretaceous into the Vøring Basin from the East Greenland continent. Morton and Grant (1998) suggested that the Turonian–Campanian sediments deposited in the Vøring Basin (K2 sands, well 6607/5-2), which show a wide zircon age spectra with a significant Archaean component, were derived from a North-East Greenland sediment source. In addition, links between the East Greenland source and provenance of the K2 sands have been mineralogical established (Morton et al., in press). The Lower Cretaceous basin on Hold with Hope, investigated in the current study, consists mainly of sand-rich deltaic systems (Larsen et al., 2001), and the analysed Aptian–Albian sandstone samples, particularly the Home Forland sample, are characterized by a wide age distribution pattern with a considerable Archaean component (Fig. 4A). The Archaean age component has been considered to be an indicator of East Greenland (Laurentian margin) provenance (e.g. Whitehouse et al., 1997; Morton and Grant, 1998; Rainbird et al., 2001; Knudsen, 2001).

In addition to the Archaean component, a wide range of zircon age characterizes the East Greenland-derived sediments. This zircon age spectrum corresponds well with the high age diversity within the landmass of East Greenland. The basement rocks of East Greenland are Proterozoic to Archaean, the rocks within the Caledonian Orogen span a wide range of ages and in addition, recycling of exotic sediments may also affect the age spectrum by adding ages not originally present within the landmass. An exotic origin has been suggested for the Krummedal high-grade paragneisses (Fig. 2). In contrast to the relatively old basement ages of East Greenland, these paragneisses contain detrital zircon grains that range in ages between 1000 and 1800 Ma (Watt and Thrane, 2001).

5.3. Provenance of the Norwegian Sea sediments

The zircon populations extracted from the Norwegian Sea sandstones show two age patterns that are interpreted to reflect the ages of the surrounding landmasses (East Greenland and Norway). Both the source landmasses and the sandstones of known provenance indicate that the “fingerprint” from the western source has a wide-ranging age pattern whereas the eastern source shows a narrow and younger age distribution. However, the East Greenland and West Norwegian landmasses contain some common zircon-bearing rocks of Cambrian–Ordovician, Middle Proterozoic, and Early Proterozoic ages. The wide range of ages may not therefore reflect a pure East Greenland signature, but rather a combination of the western and the eastern sources possibly mixed by ocean floor currents. The data suggest that the wide-range age pattern most likely represents the East Greenland source, but influx from the eastern source areas may also be present. The narrow detrital zircon age pattern characterizes a pure eastern source, without any contribution from the western landmass.

The sandstone samples from wells on the Ormen Lange Dome show differences in sediment source signal between the old and young sediments. The wide age spectra, typical of the East Greenland-derived sandstones, such as in the Coniacian sample (Fig. 5G) suggest a dominantly western sediment source. In contrast, the Ormen Lange sandstones from younger stratigraphic levels (Maastrichtian and Paleocene) have a narrow zircon age pattern (Fig. 5A–F) that implies an eastern sedimentary source. This apparent shift in sediment source area can be interpreted as a response to the tectonic evolution of the basin during the initial phase of the Late Cretaceous to Paleocene rifting. The new rifting stage resulted in forming of new accommodation space and elevation of rift shoulders (e.g. Wernicke, 1985). Such an elevation of the Norwegian margin most likely generated increased sediment supply from the eastern source into the eastern part of the Møre Basin.

The narrow age patterns in the Maastrichtian–Paleocene samples show a high content of Early Proterozoic zircons and a variable amount of Middle Proterozoic grains (Fig. 5A–F). The stable dominance of the Early Proterozoic zircons in all rock samples implies that the main source was north of the Møre region (Fig. 7A and B). This is supported by the tectonically controlled drainage pattern suggested for the Ormen Lange Dome, where depressions and weakness zones, which at present day are known as the fjords in the Møre and Romsdal and Sør Trøndelag region, are suggested as the delivery routes of sediments during the latest Cretaceous–Paleocene (Martinsen et al., 2002). The large proportion of Middle Proterozoic zircon grains in some of the samples (Fig. 5A and E) is probably a result of occasionally higher sediment supply from the landmass south of the Møre area where the Middle Proterozoic intrusive rocks are exposed.

The wide range of zircon ages that is typical of the East Greenland-derived sediments is observed in the Helland–Hansen Arch, Gjallar Ridge, and the Nyk High sandstones. Due to the close pre-drift location

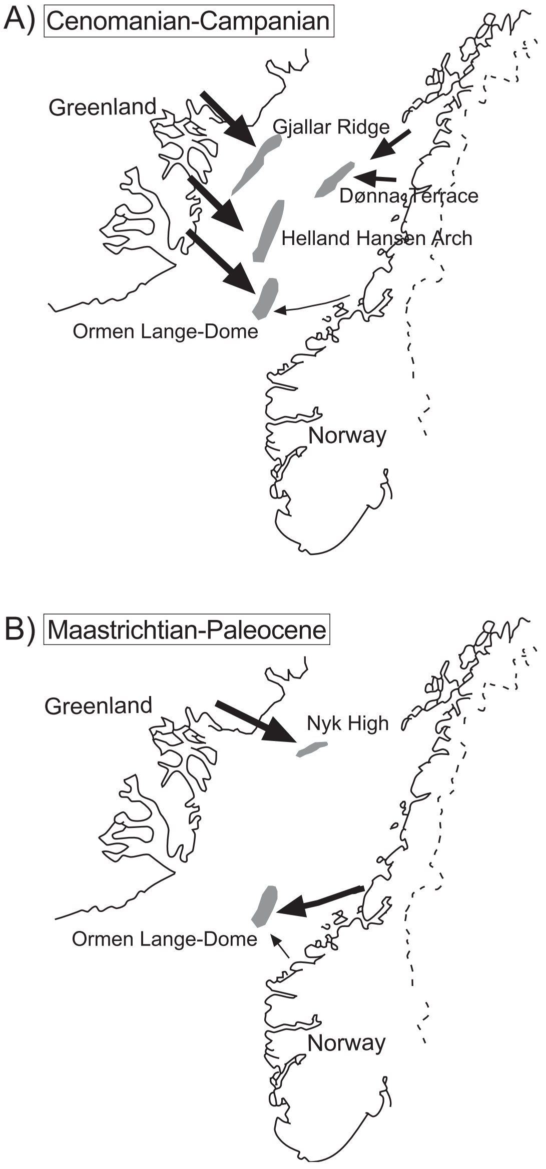

Fig. 7. (A) Suggested provenance of the Gjallar Ridge, the Dønna Terrace, the Helland Hansen Arch, and the Ormen Lange Dome in Cenomanian to Campanian time. (B) Suggested provenance of the Nyk High and the Ormen Lange Dome in Maastrichtian–Paleocene time.

between East Greenland and the western Vøring Basin, we suggest that the Upper Cretaceous sediments deposited in the Gjallar Ridge and the Nyk High sedimentary basins were derived from East Greenland (Fig. 7A and B). In post-Turonian time, the East Greenland topography had been filled in and sediments from East Greenland were transported into the offshore basins (Whitham et al., 1999).

All studied sandstone samples from the Helland–Hansen Arch show the typical wide-range of ages that are indicative of sediments derived from the western source. Given that the eastern source alone could not provide detrital zircon grains with a wide range of ages, the East Greenland landmass was the most likely principal source as shown in Fig. 7A. The detrital zircon ages imply that sediments deposited in the Helland–Hansen Arch area during Turonian–Coniacian time were transported from East Greenland. This indicates a relative flat basin floor between East Greenland and the central Vøring Basin at that time, where the basin axis was located east of the Helland–Hansen Arch.

The analyses of detrital zircons from well 6507/2-2 located on the Dønna Terrace at the eastern flank of the Vøring Basin show a narrow age pattern, which is in contrast to the analysed detrital zircons from the central and western Vøring Basin (i.e. Helland–Hansen Arch and Gjallar Ridge). The detrital zircon age pattern from the Dønna Terrace resembles that of the K1 sands (Morton and Grant, 1998), which reflects the known basement ages of the Norwegian landmass north of the Møre area. An eastern source is therefore suggested for the analysed Dønna Terrace sediments, either transported through the Vestfjorden Basin (Fig. 2) or derived from a local source within the Trøndelag Platform (Fig. 7A).

6. Conclusions

The provenance signature of the western source (East Greenland) comprises a wide range of detrital zircon ages with a significant Archaean component present, a signature that is compatible with the age range of the rocks within the East Greenland landmass. The eastern (Norway) provenance signature consists of a narrow range of zircon ages with peaks corresponding to the Early Proterozoic (Gothian) and Middle Proterozoic (Sveconorwegian) basement ages south of the Møre area and mainly to the Early Proterozoic basement ages north of the Møre area.

The Late Cretaceous to Paleocene rifting changed the Møre Basin topography, forming a new accommodation space and uplift of basin margins. Elevation of the eastern margin increased the sediment supply from the Norwegian landmass into the Møre

Basin and resulted in a provenance shift from a dominantly western source during the Coniacian to a dominantly eastern source during the Maastrichtian and Paleocene.

The Upper Cretaceous sediments deposited in the Gjallar Ridge and the Nyk High sedimentary basins on the western flank of the Norwegian Sea were derived from East Greenland. East Greenland was most likely the principal source of the sediments from the Helland–Hansen Arch in the middle part of the Norwegian Sea. In contrast to the western derived Cretaceous sediments within the Vøring Basin, the Dønna Terrace on the eastern flank of the Norwegian Sea probably had a Norwegian source.

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