Proterozoic basement and Palaeozoic sediments in the
Ringkøbing–Fyn High characterized by zircon U–Pb ages
and heavy minerals from Danish onshore wells

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New data from the Proterozoic basement and scattered Palaeozoic sediments in the Ringkøbing–Fyn High including zircon U–Pb geochronometry, heavy mineral composition and whole rock geochemistry is presented here to provide a frame of reference for detrital provenance studies. The Ringkøbing–Fyn High is a WNW–ESE trending structural high including subcropping basement rocks, and the results indicate that it is a southerly extension of the Fennoscandian Shield. The zircon data show matching age distribution patterns in crystalline basement rocks obtained from two drill sites, the Glamsbjerg-1 and Grindsted-1 wells. They both record a characteristic Telemarkian accretionary event at 1.51 and 1.48 Ga and a Sveconorwegian metamorphic overprinting at 1.08 Ga. Furthermore, the dominant age intervals in the Glamsbjerg High (1.55–1.48 Ga) and the Grindsted High (1.51–1.44 Ga) suggest that rocks of the Gothian orogeny (that ended at 1.52 Ga) are only present in the eastern part of the Ringkøbing–Fyn High. Thus, the buried basement in central Denmark may be youngest towards the west, which is consistent with the general westward age progression trend in the Sveconorwegian Orogen. The basement breccia in the Arnunum-1 well on the southern flank of the Ringkøbing–Fyn High has zircon ages (c. 1.54–1.53 Ga) that resemble those of gneiss in the Glamsbjerg High. The conglomeratic sandstone in the Ringe-1 well on the Glamsbjerg High has a dual age distribution as the matrix has late Palaeoproterozoic to early Mesoproterozoic ages, whereas the granitic clasts have a distinct middle Neoproterozoic age (c. 0.76 Ga) that may indicate an Avalonian source. The quartzite in the Slagelse-1 well on the northern flank of the Ringkøbing–Fyn High has a broad age span with late Palaeoproterozoic to late Neoproterozoic zircon ages.

Supplementary material: Detailed documentation of U/Pb analytical procedures, results and analysed zircon spots are available at http://2dgf.dk/publikationer/bulletin/189bull63.html.

Keywords: Ringkøbing–Fyn High, detrital zircon provenance, Proterozoic basement, Palaeozoic sediments, zircon U–Pb age dating, heavy mineral analysis, Denmark.

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The Ringkøbing–Fyn High (Fig. 1) consists of elevated basement blocks with a local cover of pre-Zechstein deposits. The overlying sedimentary succession has a thickness of 1–2 km and ranges in age from Zechstein to Quaternary, the main part being Mesozoic. Earlier studies have suggested that the Ringkøbing–Fyn High represents a possible provenance area for some of the sediments deposited on and around the high during the Palaeozoic and Mesozoic eras (Larsen 1966; Poulsen 1969; Dahlgren & Corfu 2001). However, it has not previously been possible to determine whether sediments in the Norwegian–Danish Basin and the North German Basin were in fact sourced by the Ringkøbing–Fyn High, the Fennoscandian Shield or somewhere else because the provenance signatures of the Ringkøbing–Fyn High basement, and the locally overlying Palaeozoic sediments, were unknown. The purpose of this study is to provide data from the
Geological setting

The Ringkøbing–Fyn High is a WNW–ESE-oriented structural high that separates the Norwegian–Danish Basin to the north from the North German Basin to the south (Fig. 1). The Ringkøbing–Fyn High is transected by grabens which separate the Grindsted, Glamsbjerg and Møn Highs in the Danish onshore area. It was proposed by Lassen & Thybo (2012) that the thick crust of the Ringkøbing–Fyn High was formed during break-up of Rodinia in the late Ediacaran. Crustal thinning was relatively minor in this area as it was positioned farthest from the Iapetus and Tornquist rifts. The Ringkøbing–Fyn High was identified as a basement high on the basis of the Grindsted-1 and Glamsbjerg-1 wells where cores reaching Proterozoic basement are available (Noe-Nygaard 1963; Sorgenfrei & Buch 1964). The Palaeozoic sedimentary cover on Ringkøbing–Fyn High that can be compared with the thick sedimentary packages deposited north and south of the high and in the grabens that divide its basement blocks.

Zircon age constraints on the timing of accretion and metamorphism of the buried Danish crystalline basement are presented here for the first time. The data reveal that the basement in the Ringkøbing–Fyn High was formed during the same Proterozoic orogenic events that affected south-western Sweden and southern Norway during the Gothian and Telemarkian accretions and the Sveconorwegian metamorphism. Concurring ages are found in a basement breccia deposited on the southern flank of the Ringkøbing–Fyn High. In contrast to the zircon age distributions, the heavy mineral assemblages demonstrate considerable compositional variation within individual gneiss complexes in the high.

Fig. 1. Position of the Ringkøbing–Fyn High and other structural elements in the Danish area (Vejbæk & Britze 1994; Nielsen 2003) in relation to the major basement provinces in southern Norway and south-western Sweden (Bingen et al. 2008a; Bingen & Solli 2009). The basement ages of the Ringkøbing–Fyn High are from this paper (Fig. 9). The ages are in billion years (Ga).
the Ringkøbing–Fyn High was eroded during late Carboniferous to early Permian uplift (Cartwright 1990; Lassen & Thybo 2012), but is locally preserved as documented by the Arnum-1, Ringe-1 and Slagelse-1 wells (Fig. 2) (Nielsen & Japsen 1991). Further uplift of the Ringkøbing–Fyn High took place during Jurassic, Cretaceous and Cenozoic times (Nielsen 2003; Rasmussen 2009).

Lassen & Thybo (2012) suggested that the basement in the Ringkøbing–Fyn High has the same origin as the south-western part of the Fennoscandian Shield that was formed during several orogenic events.

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Fig. 2. Location map, lithological columns and gamma-ray logs from the five sampled wells in the Ringkøbing–Fyn High in central Denmark. The log in the Glamsbjerg-1 well is modified from the spontaneous potential log. The outline of the Ringkøbing–Fyn High is from Vejbæk & Britze (1994) and Nielsen (2003).
The Gothian accretion of south-western Sweden (the Idefjorden Terrane) and the Telemarkian accretion of southern Norway (the Telemarkian Terrane) took place at 1.64–1.52 Ga and 1.52–1.48 Ga, respectively (Fig. 1) (Bingen et al. 2008a). The Hallandian and Danopolo-
nian orogenic events affected southern Sweden and Bornholm at 1.47–1.38 Ga (Möller et al. 2007; Bogdanova et al. 2008) where the basement age on Bornholm is constrained to 1.46 Ga (Waight et al. 2012). Pre-
Sveconorwegian activity was widespread in southern

Grindsted-1, 1622 m
Gneiss

Glamsbjerg-1, 911 m
Gneiss

Arnum-1, 1843 m
Basement breccia

Arnum-1, 1844 m
Basement breccia

Ringe-1, 1436 m
Conglomeratic sandstone

Slagelse-1, 2973 m
Quartzite

Fig. 3. Photographs of core pieces from the sampled wells. The two pieces from the Arnum-1 well give an impression of the large variability in the basement breccia.
Norway at 1.34–1.14 Ga (Brewer et al. 2004; Bingen et al. 2008a). Sveconorwegian metamorphism and associated magmatism at 1.14–0.90 Ga are recorded in the crystalline rocks of both south-western Sweden and southern Norway (Bingen et al. 2008b) which were primarily metamorphosed in amphibolite facies.

The remaining basement terranes in southern Norway (Fig. 1) include the allochthons and basement windows of the Caledonian Orogen, which are of diverse origin and age (Corfu et al. 2014), and the Carbon-

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**Fig. 4.** Thin section photographs with plane polarised light in A, C and E and crossed polars in B, D and F. Note zircon crystals in D.
iferous–Permian Oslo Graben formed at 0.30–0.26 Ga (Bingen & Solli 2009). In southern Sweden, the Eastern Segment with zircon ages of 1.80–1.64 Ga (Bingen & Solli 2009) forms the eastern part of the Sveconorwegian Orogen (Fig. 1). South-eastern Sweden is part of the Svecofennian Orogen with zircon ages of 1.92–1.79 Ga (Lahtinen et al. 2008).

Samples and methods

Zircon age dating, heavy mineral studies and geochemical analyses were performed on six samples from the Ringkøbing–Fyn High, comprising two from the basement, three from redeposited basement and one from a quartzite (Fig. 2). Proterozoic gneisses (Noe-Nygård 1963) were sampled in the Grindsted-1 and Glamsbjerg-1 wells which are the only wells that have reached the basement in the Ringkøbing–Fyn High. Crystalline basement relics were sampled in breccia from the Arnum-1 well and in conglomeratic sandstone from the Ringe-1 well in order to estimate the regional variation of the basement lithologies. A quartzite was sampled from metasediments in the Slagelse-1 well. The Arnum-1 and Slagelse-1 wells are located in the North German Basin and Norwegian–Danish Basin, respectively, on the flanks of the Ringkøbing–Fyn High. About 10 cm long core pieces were cut lengthwise into two samples, one small and one large. The small sample was used for geochemical analysis and the large sample was crushed and split into two samples used for respectively zircon age dating and heavy mineral analysis.

Zircon U–Pb geochronometry

Samples were crushed and zircon grains were hand-picked after sorting on a Wilfley shaking table. The U–Pb data were obtained by laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at GEUS (Frei & Gerdes 2009). The specific analytical procedure is described in Supplementary data file 1 and the full analytical details are reported in Supplementary data file 2. In-house GEUS software was used for the data reduction. The full table of the U–Pb data are reported in Supplementary data file 3, and the individual spots in the zircon grains are documented in Supplementary data file 4.

A total of 552 zircon ages are provided for the six samples. The vast majority of data points are highly concordant; only 32 analyses are more than 10% discordant (Supplementary data file 3). The following criteria were used to identify and remove data of poor quality from the final dataset: (1) analyses with large analytical errors ($^{238}\text{U}/^{206}\text{Pb} > 10\%$) were removed from the dataset; (2) analyses with evidence of containing a significant component of common Pb, reflected in significant $^{204}\text{Pb}$ count rates or exceedingly low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios ($<<1000$), were removed. In the filtered dataset some samples remain with fairly low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios ($<1000$); however these were assessed not to be affected by common Pb as the corrected and uncorrected $^{207}\text{Pb}/^{206}\text{Pb}$ ages did not vary significantly (outside error). Finally, for calculating the $^{207}\text{Pb}/^{206}\text{Pb}$ ages only highly concordant analyses with a discordance of <5% were used.

Heavy mineral analyses

Heavy mineral concentrates were produced from the grain-size interval 45–710 µm by heavy liquid separation of grains with a density >2.8 g/cm$^3$. The element composition of 1200 heavy minerals was measured by computer-controlled scanning electron microscopy (CCSEM) at GEUS (Keulen et al. 2008, 2012). The grains were classified as various minerals using in-house GEUS software.

Bulk geochemical analyses

Whole rock geochemical analyses were carried out on 10 g crushed samples by Acme Labs, Canada. Major oxides and minor elements were determined by inductively coupled plasma emission spectrometry (ICP-ES) and trace elements by inductively coupled plasma mass spectrometry (ICP-MS). Rare earth elements (REE) were included in the measurements and comprise the light REE (LREE, La–Sm) and the heavy REE (HREE, Eu–Lu). Loss on ignition (LOI) was measured after heating to 1000°C.

Results

The rocks are characterized with respect to their macroscopic and microscopic appearance (Figs 3, 4), their heavy mineral assemblage (Figs 5, 6, 7) and their zircon U–Pb age distribution patterns (Figs 8, 9). All zircon U–Pb data are reported in Supplementary data file 3 and are presented in concordia diagrams (Fig. 8). Only zircon grains with a discordance of <5% are included in the U–Pb age distribution diagrams (Fig. 9). The zircon grains are generally rounded to well-rounded (Supplementary data file 4) and there does not seem to be a correlation between the age of the grains and their grain size and shape. The only exception is found in the Ringe-1 well, as described below. Biotite, muscovite and the mica-like mineral
chlorite are collectively referred to as mica minerals in the following. They are reported separately from the non-mica heavy mineral assemblage (Fig. 5).

Grindsted-1: crystalline basement

The crystalline rocks in the Grindsted-1 well were sampled at 1622.30 m depth (Fig. 2). Triassic sediments overlie the crystalline rocks at 1602 m depth. The rock was described by Noe-Nygaard (1963) and Larsen (1971) as medium-grained biotite gneiss dominated by quartz, plagioclase and biotite. The gneiss does not vary much in the two cored sections of c. 1 m length each, but the amount of banding varies. Horizontal light pinkish grey and dark grey layers are visible in the sampled section (Fig. 3A), where the light layers are rich in quartz and plagioclase whereas the dark layers contain abundant biotite and hornblende. Preferred orientation of the mafic minerals is evident in thin section (Fig. 4A) (Aghabawa 1993). Pegmatitic veins cut the gneiss in several places.

Mica grains, mainly biotite, make up 84 wt% of the total heavy mineral content (Fig. 5). The non-mica heavy mineral assemblage is dominated by 89 wt% amphibole which is primarily hornblende (Fig. 6), as Ca-amphibole lies between Ca-rich and Ca-poor pyroxene compositions in a CaO–MgO–FeO diagram according to Wilson & Larsen (1985). K-feldspar occurs as clusters of very small inclusions in plagioclase. The rock has a felsic composition with 67 wt% SiO₂ (Table 1). The rock contains the whole range of Mesoproterozoic zircon ages, of which the highest concentration is in the interval 1.51–1.44 Ga (Fig. 8A, Fig. 9).

Glamsbjerg-1: crystalline basement

The crystalline rocks in the Glamsbjerg-1 well were sampled at 910.58 m depth (Fig. 2) and are immediately overlain by a Triassic succession at 907 m depth. Noe-Nygaard (1963) described the rock as a medium-grained granodioritic hornblende gneiss, and it was suggested that the intervals dominated by quartz and feldspar should be named granodioritic gneiss, and those with much hornblende should be called amphibolitic gneiss. The gneiss varies in composition within the c. 2 m-long cored section (Noe-Nygaard 1963; Larsen 1971). Oblique banding of light pinkish grey and dark greenish grey layers is visible in the sampled section (Fig. 3B). In thin section anhydrite cement is observed to fill the thin fractures (Fig. 4B) which are also visible in hand specimen (Fig. 3B). The sample used in this study has a high content of calcite that apparently has replaced some K-feldspar.

Amphibole is present as hornblende (Fig. 6) and constitutes 94 wt% of the non-mica heavy mineral assemblage (Fig. 5). Mica grains make up 11 wt% of the total heavy mineral content and are mainly biotite. The rock has a low SiO₂ content of 49 wt% and a high CaO content of 12 wt% (Table 1). Two age populations are present in the zircon age distribution (Fig. 9). The oldest has age peaks in the interval 1.55–1.48 Ga and is dominated by a large peak at 1.51 Ga, whereas the

<table>
<thead>
<tr>
<th>Well</th>
<th>Grindsted-1</th>
<th>Glamsbjerg-1</th>
<th>Arnum-1</th>
<th>Arnum-1</th>
<th>Ringe-1</th>
<th>Slagelse-1</th>
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<tr>
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<td>1842.60</td>
<td>1842.90</td>
<td>1436.32</td>
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<td>1.6</td>
<td>2.3</td>
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<td>3.4</td>
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<td>0.1</td>
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<tr>
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<td>0.3</td>
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Total iron is given as Fe₂O₃. LOI: Loss on ignition.
Fig. 5. Heavy mineral assemblages of the Precambrian basement and Paleozoic sediments in the Ringkøbing–Fyn High. The total heavy mineral content in the bar charts includes the mica minerals (biotite, muscovite and chlorite) whereas the non-mica heavy mineral assemblage is reported separately in the pie charts. The CCSEM method cannot distinguish magnetite and hematite. The “others” group includes epidote, apatite, corundum, monazite and chromite in decreasing abundance.

Fig. 6. CaO–MgO–FeO (total iron) composition of the amphibole grains. Ca-amphibole lies between the compositions of clinopyroxene and orthopyroxene in this diagram, and Ca-poor amphibole has the same composition as Ca-poor pyroxene (Wilson & Larsen 1985). The Ca-amphibole in the Grindsted-1 and Glamsbjerg-1 samples is hornblende whereas the Ca-poor amphibole in the Arnum-1 samples is presumably gedrite as it contains Al.

Fig. 7. Garnet composition of the basement breccia in the Arnum-1 well. The end-members are calculated as element wt% of Mg, Fe+Mn and Ca. The garnet grains also contain Al and are therefore almandine-rich.
younger age peaks in the interval 1.14–1.08 Ga are less prominent. The two age populations are also visible in the concordia diagram (Fig. 8B).

Arnum-1: basement breccia

The brecciated rocks in the Arnum-1 well were sampled at 1842.60 and 1842.90 m depth (Fig. 2). Zechstein deposits overlie the breccia at 1814 m depth. The rock was described by Noe-Nygaard (1963) as a fanglomerate and the rock fragments were identified as biotite-hornblende gneiss, hornblende-biotite gneiss, garnet-hornblende-biotite gneiss and fine-grained quartz-microcline rock. The rock is a very poorly sorted breccia with angular basement blocks up to 10 cm in diameter. The composition of these rock fragments varies through the 30 m-long cored section and they become less abundant upwards. The breccia appears as dark reddish grey to dark greenish grey gneiss in some intervals (Fig. 3C) and as angular Basement fragments embedded in a dark red conglomeratic sandstone matrix in other intervals (Fig. 3D). The sandy matrix in the deepest of the studied samples consists of rock fragments, quartz and feldspar, as well as as completely chloritized and locally illitized clasts which presumably represent strongly altered biotite and hornblende (Fig. 4C). The thin section contains two centimetre-large fragments; one is hornblende-biotite gneiss and the other is granitic gneiss. In the hornblende-biotite gneiss the hornblende is perversely altered to chlorite and illite in a similar way to the individual clasts in the matrix.

The non-mica heavy mineral assemblage consists of a range of minerals with a dominance of 42–66 wt% amphibole, 21–27 wt% magnetite/hematite, 3–16 wt% garnet and 6–10 wt% ilmenite (Fig. 5). The amphibole grains are Ca-poor (Fig. 6) and according to their chemistry they are most likely gedrite as they contain Al. Mica constitutes 57–69 wt% of the total heavy mineral content and both biotite and chlorite are abundant. The chlorite is atypical with much Fe, Mg, K and Si, so most of it is presumably biotite that has been partially altered into chlorite and hematite, but some of the chlorite could also be altered hornblende. The garnets have a quite uniform composition with 56–67 wt% FeO, 1–10 wt% MnO, 12–33 wt% MgO and 8–21 wt% CaO (Fig. 7), and they are almandine-rich since they also contain Al. The rock has a low SiO₂ content of 47–48 wt% and a very high LOI of 7–9 wt% (Table 1). The zircon population is dominated by 1.54–1.53 Ga grains with few grains of Archean, Palaeoproterozoic and Sveconorwegian age (Fig. 9).

Ringe-1: conglomeratic sandstone

The conglomeratic sandstone in the Ringe-1 well was sampled at 1436.32 m depth (Fig. 2). The conglomerate is overlain by Triassic deposits at 1272 m depth. The conglomeratic succession was proposed by Sorgenfrei & Buch (1964) to be of early Permian or Eocambrian age, and Nielsen & Japsen (1991) suggested that it could be of Permian age. Cores from the pre-Triassic rocks constitute a total of 25 m collected from 11 intervals. Greenish grey reduction spots are present in the upper part of the pre-Triassic succession. The rock fragments in the conglomerate consist mainly of quartz and feldspar. They are numerous in the lower part of the pre-Triassic succession and become smaller and fewer up through the succession, and clasts consisting of only quartz and feldspar are primarily found towards the top. Feldspar is the dominant light mineral in the lower part of the succession but the content decreases upwards whereas the quartz content increases and the grains become more rounded. Light pinkish grey sub-angular clasts are abundant in the sampled rock (Fig. 3E). They consist of metamorphosed alkali feldspar granite and contain angular heavy minerals (Fig. 4D). The clasts are dispersed in a dark brownish red matrix which contains Fe-oxides/hydroxides (Fig. 4E). A thin vein between a large granite clast and its surrounding matrix is filled by hematite, quartz, calcite, kaolinite, barite and locally monazite. The clasts dominate in both the gravel and the coarse sand fraction.

The non-mica heavy mineral assemblage is dominated by 61 wt% magnetite/hematite and 21 wt% zircon (Fig. 5). Mica grains make up 19 wt% of the total heavy mineral content, and SiO₂ constitutes 65 wt% of the rock (Table 1). The clasts in the sampled rock have a high content of Zr and LREE. The zircon population is mainly dominated by ages in the interval 1.66–1.51 Ga and a younger group culminating at 0.76 Ga (Fig. 8E, Fig. 9). The youngest zircon grains are larger and clearly more angular than the late Palaeoproterozoic to early Mesoproterozoic grains (Fig. 10), and also contain numerous mineral inclusions.

Slagelse-1: quartzite

The quartzite in the Slagelse-1 well was sampled at 2973.03 m depth (Fig. 2). Poulsen (1969, 1974) proposed that the quartzite could be of early Cambrian age as fossils of early Cambrian to early Silurian age were found in the thick overlying shale succession. Alternating layers of quartzitic sandstone and shale present at 2960–2972 m depth separate the quartzite from the shale succession (Fig. 2). The quartzite is very uniform in the c. 1 m-thick cored section but is interrupted by a shale layer. The quartzite is light grey with oblique
Fig. 8. Concordia diagrams displaying all the U–Pb data. For more details see Supplementary data file 1.
Discussion

Proterozoic basement

The zircon age distribution patterns from gneisses in the Ringkøbing–Fyn High (Fig. 9) are consistent with formation during the orogenic events that affected south-western Sweden and southern Norway in the early Mesoproterozoic. Thus, the Ringkøbing–Fyn High can be considered a southerly extension of the
are typical for granitic rocks which were the probable precursors for the gneisses. The high SiO₂ content in the Grindsted-1 gneiss probably reflects the original felsic composition (Table 1), whereas the SiO₂ content in the Glamsbjerg-1 gneiss is diluted by a high CaO content reflecting anhydrite and calcite precipitations.

Redeposited basement

The two zircon age distributions from the basement breccia in the Arnum-1 well are very similar to each other (Fig. 9), despite the large variation in embedded rock fragments and the 30 cm-spacing between the samples. The rock fragments were presumably derived from the same source (1.54–1.53 Ga), even though the relative proportions of heavy minerals vary (Fig. 5). Noe-Nygaard (1963) described this wide range of metamorphic rocks but noted that they grade into each other and therefore must originate from the same gneiss complex. The Fe-rich garnet composition in both samples (Fig. 7) is also in accordance with Noe-Nygaard (1963) who mentioned almandine as the only garnet in the rock fragments. Almandine is typical for clay-rich rocks metamorphosed into garnetiferous gneiss. The large content of magnetite/hematite in the samples (Fig. 5) may represent hematite precipitations in the matrix and hematite formed from biotite degradation. The high LOI (Table 1) may reflect the presence of chlorite and illite in the matrix and the partial replacement of biotite and hornblende in the gneissic clasts. The rock became fragile as a result of the replacement process so the replacement probably took place after deposition of the breccia.

The Arnum-1 well does not penetrate the basement. However, the rock fragments in the Arnum-1 breccia were very likely derived from the Ringkøbing–Fyn High basement, as the large size of the rock fragments indicates that they cannot have been transported very far (Fig. 3D). These clasts can therefore be assumed to represent the local basement of the Ringkøbing–Fyn High, and the age peak at 1.54–1.53 Ga probably pinpoints the age when this basement was formed. The zircon ages of the breccia are quite similar to those of the Glamsbjerg-1 gneiss (Fig. 9) which could have been outcropping over a large area, at least on the Glamsbjerg High. A biotite age of 0.69 ± 0.02 Ga from a basement fragment in the Arnum-1 breccia was rejected because of potassium loss (Larsen 1971), but a new K/Ar age of a less weathered sample from the deepest level of the Arnum-1 well was reported by Larsen (1972) as 0.86 ± 0.02 Ga which is in accordance with the K/Ar ages from the gneisses in the Grindsted-1 and Glamsberg-1 wells (Larsen 1971).

Noe-Nygaard (1963) suggested that the breccia was deposited by an alluvial fan that developed along the
margin of the Ringkøbing–Fyn High. The measured heavy mineral assemblage of the Glamsbjerg-1 gneiss is not identical to the assemblage in the Arnun-1 breccia (Figs 3, 5), but this may be explained by the alteration of some of the dark minerals into chlorite and hematite in the breccia. Similar alteration has taken place in the uppermost weathered part of the gneiss (Noe-Nygård 1963). In addition, the breccia contains gedrite, a metamorphic mineral that mostly occurs in Ca-poor ultramafic amphibolite facies rocks.

The zircon grains with younger ages than the major peak in the Arnun-1 breccia may represent metamorphic overprints, but no age cluster is apparent (Fig. 9). Alternatively, they could represent detrital zircons from the sandstone matrix and may have been transported a considerable distance from a provenance outside the Ringkøbing–Fyn High. The Sveconorwegian metamorphic influence in the area probably varied considerably, as was generally the case in south-western Fennoscandia (Bingen et al. 2008b), which, combined with the presumed minor isotopic resetting during metamorphism, may explain the rarity of zircons with this age in the breccia. The Lower Triassic Röt Formation was deposited directly on top of the Glamsbjerg-1 gneiss (Fig. 2) and erosion must have occurred before this time. The time of deposition of the basement breccia in the Arnun area is unknown, but it must have taken place before deposition of the overlying upper Permian Zechstein sediments (Fig. 2).

The youngest zircon age population in the conglomeratic sandstone in the Ringe-1 well probably occurs in the metamorphosed alkali feldspar granite clasts, as the youngest zircons are more euhedral than the rest and contain mineral inclusions (Fig. 10) like the zircons observed in the clasts (Fig. 4D). These zircon grains of Cryogenian age with a prominent age peak at 0.76 Ga (Fig. 9) are very characteristic with their large size and angular shape. Similar zircon ages are absent in Sweden and Norway (Olivarius et al. 2014) as Cryogenian magmatism in the region was very limited (Bingen & Solli 2009). The size and shape of the zircon grains and of their host clasts (Fig. 3E) indicate that they have a local source. The granite clasts are likely derived from Avalonia since Neoproterozoic ages are more common in Avalonia where a phase of arc activity began at 0.76 Ga (Murphy et al. 2000). The Ringkøbing–Fyn High is located at the southern margin of Baltica with Avalonia positioned immediately south of the area (Pharaoh 1999).

The oldest zircon age population in the Ringe-1 conglomeratic sandstone is probably present in the sandy matrix, as the oldest zircons are smaller and less angular than the rest (Fig. 10), like the zircons observed in the matrix. The major age peaks at 1.66–1.51 Ga partly overlap with the formation ages of the basement rocks recorded in the Ringkøbing–Fyn High (Fig. 9). However, the matrix may have been sourced from the Gothian basement in south-western Sweden where the entire age span is present, and the grain size also points to more than just a local transport distance. The few older zircon grains probably also represent a distant provenance and indicate that the sediment was deposited at a time when sediment transport from Fennoscandia across the Ringkøbing–Fyn High area was possible. This could have been during the Proterozoic or at the beginning of the late Carboniferous to early Permian uplift and erosion of the Ringkøbing–Fyn High. The high contents of mechanically stable zircon and rutile (Fig. 5) confirm that some components in the sediment had probably been transported a considerable distance. The hematite-quartz-calcite-kaolinite-barite-monazite vein in the basal part of the succession may indicate hydrothermal activity after deposition of the conglomerate but does not point to any specific age. It could have been related to late Carboniferous to early Permian igneous activity recorded from the area (Thybo 1997). A Permian depositional age is also possible, as suggested by earlier studies by Sorgenfrei & Buch (1964) and Nielsen & Japsen (1991).

In conclusion, the rock fragments in the Arnun-1 breccia and the Ringe-1 conglomeratic sandstone represent provenance areas that may have been strictly local and related to large faults developed during uplift of the Ringkøbing–Fyn High. The sediments in which the rock fragments reside might have been eroded and thereby influenced the composition of younger sediments deposited around the high. As the Arnun-1 breccia and the Ringe-1 conglomerate consist mainly of local basement reworked due to weathering or faulting they must have transmitted a strong age signal from local rocks to younger sediments. This signal is accompanied by the matrix ages which are of mixed and possible Fennoscandian origin.

Metasediment

The zircon age distribution from the quartzite in the Slagelse-1 well (Fig. 9) constitutes a mixture of all the ages present in the basement areas of south-western Sweden and southern Norway (Bingen et al. 2008b). The heavy mineral assemblage and geochemical signature are extremely mature (Fig. 5, Table 1) and the sedimentary precursor is thus likely to have been reworked many times before its final deposition. Poulsen (1969) suggested that the quartzite was formed from weathered gneiss in the Ringkøbing–Fyn High, but the much narrower age distributions found in the gneisses (Fig. 9) indicate that this was probably not the case. The Fennoscandian Shield is thus presumed to be the initial provenance area of the quartzite.
The Slagelse-1 quartzite is supposed to be of early Cambrian age and correlates with lower Cambrian sandstones in Sweden and on Bornholm (Poulsen 1969). The broad spectrum of zircon ages and the relative abundance of older zircon grains may support that the provenance of the metasediment was Fennoscandia and not a local source. This could point to a relationship to a basin-wide sandstone complex, such as the lower Cambrian Hardeberga Formation. Erosion of the Slagelse-1 quartzite may have occurred, thereby adding a homogenized Fennoscandian signature to some of the younger sediments.

Conclusions
The Proterozoic basement in the Ringkøbing–Fyn High and that in south-western Fennoscandia were formed during the same orogenic events and exhibit matching metamorphic overprints as recorded by zircon U–Pb ages. The age spans in the Ringkøbing–Fyn High are mainly restricted to the 1.55–1.44 Ga interval, culminating at 1.51 Ga. Consequently, zircon U–Pb ages may be used to appoint or exclude the basement high as a provenance area for sediments in the Norwegian–Danish Basin and the North German Basin. Basement that has been redeposited from the Ringkøbing–Fyn High due to weathering or faulting, and Palaeozoic sediments that are locally present on the Ringkøbing–Fyn High, show various mixtures of local and Fennoscandian provenance signatures. The conglomeratic sandstone from the Ringe-1 well contains granitic rock fragments with Cryogenian zircon ages representing an igneous event not previously recorded in the area.

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