Interplay of proximal and distal sources in Devonian–Carboniferous sandstones of the Clair Basin, west of Shetland, revealed by detrital zircon U–Pb ages

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Abstract: The Clair Basin is one of the Devonian sedimentary basins formed as a result of extensional tectonics in the aftermath of the Caledonian orogeny. The Devonian to Carboniferous Clair Group was deposited directly on Archaean basement, providing an opportunity to consider contrasting proximal and distal provenances. New secondary ion mass spectrometry detrital zircon U–Pb data and complementary heavy mineral data allow for a reinterpretation of potential source areas. Detrital zircons from the Clair Group yield ages ranging from c. 400 to 3700 Ma. All samples contain a group of Archaean ages (c. 16–82%). However, many samples also contain a major group of Proterozoic zircons (c. 15%–78%), allowing subdivision into two types of samples: type 1, dominated by Proterozoic zircons, and type 2, dominated by Archaean zircons. Type 2 samples are mainly derived from local basement gneisses during phases of tectonic rejuvenation of the hinterland, whereas type 1 samples are most probably sourced from NE Greenland or, less likely, SW Scandinavia. Upper Clair Group (Unit VII–IX) sandstones have type 2 zircon spectra in association with staurolite- and garnet-rich heavy mineral assemblages and were probably derived from predominantly Archaean-sourced metasedimentary rocks on the Shetland Platform.

Supplementary materials: Concordia diagrams and tables reporting zircon U–Pb data are available at http://www.geolsoc.org.uk/SUP18542.

The Clair Basin is one of a number of Devonian sedimentary basins formed as a result of extensional tectonics in the aftermath of the Caledonian orogeny (Roberts et al. 1999). Thick successions of siliciclastic sediments formed within those extensional basins during the Late Silurian to Early Carboniferous (e.g. Friend et al. 2000), recording the latest stage of the Caledonian orogeny. Previous studies suggested that these basins were interconnected sub-basins similar to the basins in the Basin and Range Province of the USA (e.g. McClay et al. 1986).

This study aims to determine the source of the Devonian to Carboniferous sediments of the Clair Basin, by analysing detrital zircons using secondary ion mass spectrometry (SIMS). Additionally, published heavy mineral and mineral chemical data for the Clair Basin will be reviewed and integrated with the zircon age data to gain information about the lithology of the possible source areas. Owing to the central position of the Clair Basin between the Caledonides of East Greenland and Norway, understanding the provenance of the Clair Group will ultimately lead to a better understanding of the sediment pathways in the North Atlantic region. Because the Clair Group has been deposited directly on the Archaean basement, this study also emphasizes the usefulness of using a combined approach to provenance analyses by discussing contrasting proximal versus distal source areas.

Regional framework

The Clair Basin is located about 75 km west of the Shetland Islands on the UK continental shelf (Fig. 1). The basin is a small elongate basin with a NE–SW axis (Duindam & Van Hoorn 1987). Its margins are defined by the Shetland Spine Fault in the SE and the Rona Ridge in the NW. The regional structural trend is Caledonian in age and dominated by NE–SW-trending faults (Butler & Coward 1984; Earl et al. 1989), which control the distribution of elongate sedimentary basins separated by narrow basement ridges in the North Atlantic region (Earl et al. 1989). These sedimentary basins formed in response to the extensional collapse of the over-thickened crust in the Caledonides (McCay et al. 1986) and are linked by large strike-slip dominated shear zones in Scotland, East Greenland and Norway (Fossen 2010). The basement in the area west of the Shetland Islands consists mainly of Archaean gneisses, together with small areas assigned to the Moine and possibly Dalradian Supergroups (Duindam & Van Hoorn 1987; Earl et al. 1989; Stoker et al. 1993; Ritchie et al. 2011). Torridonian and Cambro-Ordovician strata, which are spatially associated with the Archaean rocks that form the Lewisian Gneiss Complex onshore in Scotland, are apparently absent. In the immediate vicinity of the Clair Basin, the basement is exclusively Archaean (Stoker et al. 1993; Ritchie et al. 2011), both to the NW (Rona Ridge) and to the SE of the Shetland Spine Fault (Fig. 1).

Stratigraphy

The Clair Basin contains a Devonian to Carboniferous sedimentary succession (up to 1000 m thick) that has been divided into 10 lithostratigraphic units (I–X) on the basis of heavy mineral assemblages, core and well log data (Fig. 2; Allen & Mange-Rajetzky 1992). The stratigraphy has been further refined using heavy mineral ratio and mineral chemical data (Morton et al. 2010). The Lower
Clair Group (Units I–VI) was deposited directly on Archaean metamorphic basement (Ridd 1981; Blackbourn 1987; Coney et al. 1993).

The sedimentary succession comprises conglomerates, subarkoses to litharenitic sandstones and subordinate mudstones in fluvial, lacustrine and aeolian facies (Allen & Mange-Rajetzky 1992; McKie & Garden 1996; Nichols 2005). A dipmeter and image log study of the Lower Clair Group in three appraisal wells suggested palaeoflow from north to south with dispersion to the SSW and SSE (Morton et al. 2010).

Biostratigraphic controls on the age of the succession are scarce (Fig. 2), but the succession appears to span the Middle Devonian to Early Carboniferous interval (Ritchie et al. 1996; Smith & Ziska 2011) based on the following: Middle Devonian (Eifelian–Givetian) spores in Unit III of well 206/8-4 (Ritchie et al. 1996); Late Devonian (Frasnian–Fammenian) to Early Carboniferous (Tournaisian) fish scales in Unit V of well 206/8-1A (Ridd 1981; Ritchie et al. 1996); Early Carboniferous (Visean) miospores in Unit X of well 206/8-2 (Allen & Mange-Rajetzky 1992) (Fig. 1). The Devonian–Carboniferous boundary is conventionally placed at the Lower Clair Group–Upper Clair Group boundary (Coney et al. 1993), but a Late Devonian age for Units VII and VIII cannot be ruled out, as there is no biostratigraphic control on the succession between Units V and IX (Smith & Ziska 2011). There is evidence for a field-wide unconformity at the Lower Clair Group–Upper Clair Group boundary (Allen & Mange-Rajetzky 1992).

Analytical methods

The U–Th–Pb zircon analyses were carried out using sensitive high-resolution ion microprobe (SHRIMP) I and SHRIMP RG at The Australian National University (ANU) in Canberra, Australia. Detrital zircon grains from 10 sandstone samples were separated using standard crushing, washing, heavy liquid and paramagnetic procedures. Arbitrary and presumed representative zircons were poured onto double-sided tape, cast into epoxy probe mounts together with chips of the reference zircons, sectioned approximately in half and polished.

Scanning electron microscope (SEM) cathodoluminescence (CL) images were collected for all zircon grains at ANU. These were used to interpret the internal structures and to ensure that the SHRIMP spot was within a single component of the grain, usually the youngest.

In each sample, 46–70 grains were analysed. Each analysis consisted of four to five scans through the mass range, with a reference zircon analysed after every five unknowns. Errors in reference zircon calibration are given for each analytical session. Uncertainties for single analyses are given at the 1σ level. SHRIMP analytical methods follow those outlined by Williams (1998, and references therein). The data have been reduced using the SQUID Excel macro (Ludwig 2001).

For grains older than c. 800 Ma and for those enriched in U, common Pb was corrected using the measured $^{206}$Pb/$^{208}$Pb ratio.
Correction for common Pb in grains younger than c. 800 Ma and those low in U and therefore radiogenic Pb was made using the measured $^{238}$U/$^{206}$Pb and $^{207}$Pb/$^{206}$Pb ratios following the $^{207}$Pb correction method of Tera & Wasserburg (1972) as outlined by Williams (1998). When the $^{207}$Pb correction is applied, it is not possible to determine radiogenic $^{207}$Pb/$^{206}$Pb ratios and therefore in these cases the radiogenic $^{206}$Pb/$^{238}$U age has been used for the probability density plots.

Probability density plots with stacked histograms were produced in AgeDisplay v2.10 after Sircombe (2004). The histograms were generated using only zircons with ±10% discordance or less (26–61 concordant grains per sample), whereas the probability density plots include both concordant and discordant data.

**Results of detrital zircon geochronology**

Results of SIMS analyses are displayed as frequency age histograms in combination with probability density distributions (Fig. 3). In total, 400 grains in 10 samples have been analysed from wells 206/8-8 and 206/8-2.

Zircon ages fall into three main groups: Phanerozoic (c. 8% of all analyses), Proterozoic (c. 47% of all analyses) and Archaean (c. 44% of all analyses). The Proterozoic zircons define two groups between c. 800 and 1350 and c. 1400 and 2100 Ma respectively. All samples show distinct age gaps between c. 2100 and 2500 and c. 600 and 800 Ma (Fig. 3). On the basis of differences in age spectra, two main sample types can be distinguished: (1) those with age spectra dominated by Proterozoic zircons; (2) those dominated by Archaean zircons.

**Samples dominated by Proterozoic detrital zircon grains; type 1**

Samples in which the majority of zircons yield Proterozoic ages between c. 800 and 1900 Ma are those from Units Ib, IIIa, IIIc, V, VIIc and X (Fig. 3). In all samples, two Proterozoic groups of peaks, separated by sections of the age spectrum that are poorly represented, can be distinguished: one between c. 800 and 1350 Ma and the other between c. 1400 and 2100 Ma. All type 1 samples also contain a cluster of Archaean zircon grains with ages between c. 2500 and 3000 Ma and a small number of Phanerozoic zircons.

Despite their general similarity, there are differences in the distribution of zircon ages in these samples. Zircons in Units Ib, IIIa and VIIc have relatively evenly distributed clusters of peaks.
Fig. 3. Combined frequency age and probability density diagrams of 10 samples from the Lower and Upper Clair Groups of wells 206/8-8 and 206/8-2, where n means concordant data between −10% and 10% discordance of all data. Light grey curves represent all data, whereas dark grey filled curves include only concordant data between −10% and 10% discordance. Dashed lines indicate the lower and upper boundaries of the Proterozoic.
The sample from Unit IIIc has one main cluster around 1700 Ma and contains a single Eoarchaean grain, although this grain is >10% discordant (Fig. 3e). The sample from Unit V has its largest cluster around 1100 Ma and contains very few Archaean zircons (Fig. 3e). The age spectrum of the Unit X sample shows two major Proterozoic age clusters around c. 1000 and c. 1600 Ma and contains one discordant Eoarchaean (3600 Ma) zircon grain (Fig. 3j). However, as some studies (e.g. Vermeesch 2004) have indicated, a larger number of zircon grains need to be analysed per sample to obtain good confidence on the distribution of a multigrain population. For this reason, the differences between the age spectra have to be interpreted with caution.

**Samples dominated by Archaean detrital zircon grains; type 2**

Type 2 samples (Units IVb, Vlb, Vlc and VII–IX) are dominated by Archaean zircons with ages ranging from c. 2500 to 3000 Ma. Units IVb, Vlb and VII–IX contain almost no Proterozoic zircons, whereas Unit Vlc contains a somewhat larger group of Proterozoic zircons (Fig. 3). Unit VII–IX also contains one Eoarchaean grain (3600 Ma; Fig. 3i).

**Discussion and interpretation**

**Constraints on provenance: integration of zircon age and heavy mineral data**

The nature and location of the source rocks is discussed using zircon age data and previously published heavy mineral analyses and garnet geochemistry (Allen & Mange-Rajetzky 1992; Morton et al. 2010; Fig. 4), both of which are well-established methods in provenance analysis (e.g. Mange & Morton 2007). Heavy mineral analysis revealed a major change in provenance at the boundary between the Lower Clair Group and the Upper Clair Group, together with more subtle changes within and between the stratigraphic units (Allen & Mange-Rajetzky 1992; Morton et al. 2010). Allen & Mange-Rajetzky (1992) interpreted the Lower Clair–Upper Clair boundary as marking a change from a small drainage network to a much enlarged drainage system transporting sediment from outside the immediate vicinity of the Clair Basin, with source areas proposed to include the Shetland Islands, Norway and possibly Greenland.

**Lower Clair Group.** The basement in the area west of the Shetland Islands consists mainly of banded Archaean gneiss and granulite of granitic to granodioritic composition ascribed to the Lewisian Gneiss Complex (Stoker et al. 1993; Ritchie et al. 2011; Fig. 1). Spatially restricted Devonian to Carboniferous sedimentary basins are located within this Archaean basement (Duindam & Van Hoorn 1987; Earl et al. 1989). Because the Lower Clair Group has been considered to represent a small intra-rift drainage network (Allen & Mange-Rajetzky 1992), derivation of sediment from basement immediately adjacent to the Clair Basin should therefore reflect the mineralogical composition of the high-grade metamorphic gneisses. Thus, the Lower Clair Group samples should contain predominantly Archaean zircons. However, Allen & Mange-Rajetzky (1992) recognized that the heavy mineral assemblages in much of the Lower Clair Group are not entirely consistent with derivation from Archaean gneisses and that low-grade metasedimentary sources were at least equally important.

The lower part of Unit I (Subunit Ia) in well 206/8-8 consists of conglomerates deposited by a fan-delta system with a radius of c. 3 km, with clast compositions indicating derivation from local Archaean basement (Nichols 2005). However, zircons in the overlying Subunit Ib have a diverse age range from Palaeozoic to Archaean and are predominantly Proterozoic (c. 60%) (Fig. 3a). Consequently, it seems that immediately after deposition of the locally supplied fan-delta conglomerates, the catchment expanded to include low-grade metasedimentary rocks. These metasediments are interpreted to have supplied the Proterozoic and Palaeozoic zircons. The Archaean grains could have been sourced locally, although recycling of the Archaean zircons from low-grade metasedimentary rocks may also have been involved.

The same combination of local Archaean and more distal low-grade metasedimentary rocks is implied by the zircon ages and heavy mineral assemblages throughout most of the succeeding Lower Clair Group, as shown by the diverse age spectra in Subunits IIIa, IIIc, Unit V and Subunit Vlc (Fig. 3). Subtle differences in the relative proportions of the main zircon populations between these samples correspond to the observed differences in heavy mineral provenance characteristics and garnet geochemical data (Morton et al. 2010) and are interpreted as reflecting heterogeneities within the low-grade metasedimentary source region.

There are two notable exceptions to the pattern described above: samples from Subunits IVb and Vlb. The zircon age spectrum from the Subunit IVb sample is dominated by Archaean zircons (c. 76%) (Fig. 3d). This sample represents an atypical zone with very low apatite roundness (ARi) and very high abundances of high-Mg, low-Ca garnets (Fig. 4; Morton et al. 2010). The low apatite roundness suggests relatively short transportation, implying local sourcing, and the garnet geochemistry suggests derivation from high-grade metasedimentary rocks (Morton et al. 2010). The source of this sample is accordingly interpreted to lie within the local Archaean basement, presumably, given the predominant north to south palaeoflow, on the Rona Ridge. Garnets similar to those associated with this sample have been identified in high-grade metasedimentary inliers in the Lewisian of the Inner Hebrides (Cartwright 1992).

In Subunit Vlb, there is a trend of upward-decreasing garnet to zircon ratio concurrent with an increase in abundance of high-Mn garnet (Fig. 4) (Morton et al. 2010). These trends suggest increasing supply from intermediate–acidic gneisses and granites, typical of the Archaean gneisses. The analysed sample, which is from the top of this trend, is dominated by Archaean zircons (Fig. 3g), confirming that the observed trend in Subunit Vlb represents an increase in relative supply from the local Archaean basement associated with a reduction in input from the low-grade metasedimentary source.

**Upper Clair Group.** The basal part of the Upper Clair Group (Subunit Vlc) comprises sandstones with similar heavy mineral characteristics to the uppermost part of the underlying Lower Clair Group (uppermost Subunit Vlb) (Fig. 4) and is therefore interpreted as representing Lower Clair Group reworking (Morton & Milne 2012). Zircons from Subunit Vlc have mainly Archaean ages and the age spectrum closely resembles the one from Subunit Vlb (Fig. 3g and h), supporting the interpretation as a reworked unit.

Zircons from Unit VII–IX are also dominated by Archaean ages between c. 2500 and c. 3700 Ma (c. 70%) (Fig. 3i), but in contrast to samples from Subunits Vlb and Vlc, the heavy mineral assemblage (Fig. 4) indicates derivation from moderate- to high-grade staurolite- and garnet-rich metasedimentary lithologies. Such lithologies occur in the Neoproterozoic to Early Palaeozoic Moine and Dalradian successes of Scotland and their equivalents in East Greenland and Scandinavia (Allen & Mange-Rajetzky 1992; Morton et al. 2010). However, the abundance of Archaean zircon...
suggests that the metasedimentary source was itself supplied from an Archaean terrane.

The Unit X zircon population has much more abundant Proterozoic zircons (c. 80%) compared with the Unit VII–IX sample, with Archaean grains proportionally less common (c. 20%) (Fig. 3j). This change in zircon ages is accompanied by sharp decreases in staurolite:zircon, garnet:zircon and apatite:tourmaline ratios (Fig. 4; Morton et al. 2010). The change to a staurolite-poor heavy mineral assemblage and a Proterozoic-dominated zircon spectrum suggests that the sample has type 1 provenance, similar to the majority of the Lower Clair Group. The low apatite:tourmaline and garnet:zircon ratios in the Unit X sample are interpreted as the result of weathering during alluvial storage in a humid tropical Carboniferous depositional environment (Morton et al. 2010) and do not necessarily indicate a substantially different provenance from the other type 1 samples.

Source areas

Local Archaean sources. Heavy mineral data have indicated that local Archaean gneisses played a comparatively minor role in sourcing the Clair Group succession (Allen & Mange-Rajetzky 1992; Morton et al. 2010). However, the zircon data, in conjunction with other provenance information, have established that the local Archaean was the main source for samples in Subunits IVb, Vlb and Vlc (Figs 1 and 2). Subunits Vlb and Vlc have heavy mineral and zircon age characteristics consistent with derivation predominantly from typical Archaean gneisses offshore west of Shetland with ages between c. 2700 and c. 3300 Ma (Ritchie et al. 2011) and Subunit Vlc representing reworking of Subunit Vlb in the initial stages of Upper Clair deposition (Morton & Milne 2012). The Subunit IVb sample has different mineralogical characteristics that indicate it was derived from a metasedimentary unit within the Archaean, similar to that found elsewhere in parts of the Lewisian (Cartwright 1992). The local basement may have been at least partly responsible for the Archaean zircons present in samples with type 1 provenance, but the role of recycling from metasedimentary rocks is a topic for further discussion.

Derivation of type 1 samples from the Moine and Dalradian metasediments. The Proterozoic metasedimentary units closest to the Clair Basin are part of the Caledonian basement of the Shetland Islands, previously correlated with the Moine and Dalradian Supergroups of mainland Shetland (Fig. 5; Flinn et al. 1979; Flinn 1988, 1992). Unfortunately, there is little published information on zircon ages from the Proterozoic metasedimentary successions of Shetland. The only data are from the Westing Group of the island of Unst, which has uncertain stratigraphic and tectonic affinities (Cutts et al. 2009). Consequently, zircon age data from the Moine and Dalradian successions of mainland Scotland...
are used for comparison (Fig. 6), although it is recognized that Shetland lies a considerable distance north of Scotland and lateral variations in provenance and tectonothermal history are likely.

In mainland Scotland, the Moine metasediments contain predominantly Proterozoic detrital zircons with two main groups that compare reasonably well with the pattern shown by type 1 samples (Fig. 6; Friend et al. 2003; Cawood et al. 2004; Kirkland et al. 2008). However, some of the Moine metasediments also contain a cluster of ‘Knoydartian’ (c. 790–820 Ma) zircons (Fig. 6d; Cawood et al. 2004), which are mainly absent from the Clair samples (Fig. 6a). It seems therefore less likely that the Moine metasediments of mainland Scotland were a source for the Clair sandstones, a view that is consistent with the palaeocurrent evidence.

Dalradian zircons from mainland Scotland also contain abundant Proterozoic zircons (Fig. 6b; Cawood et al. 2003). In contrast to Moine metasediments, the Dalradian yields no zircons of ‘Knoydartian’ age, but contains a group of Archaean zircons. In these senses, the Dalradian of mainland Scotland has an age spectrum comparable with that of type 1 samples. However, the Dalradian of mainland Scotland lacks a distinct late Mesoproterozoic age group (c. 1000–1350 Ma) that corresponds to the Grenvillian, a feature that is conspicuous in many type 1 samples (Fig. 6a and b). The distinct lack of ages between c. 2000 and c. 2500 Ma observed in the type 1 samples is also displayed by the Dalradian. However, this feature is known from many of the Proterozoic metasedimentary units in the North Atlantic region (e.g. Strachan et al. 1995; Watt et al. 2000; Cawood et al. 2003, 2004; Dhuime et al. 2007; Bingen & Solli 2009; Slama et al. 2011) and is therefore of little significance. As with the Moine, derivation from the Dalradian of mainland Scotland can also be ruled out by palaeocurrent evidence, but at this stage we cannot preclude derivation from the Dalradian rocks of Shetland.

Derivation of type 1 samples from basement rocks of the NE Greenland margin. Another possible source area for the sedimentary succession of the Clair Basin is the eastern margin of Greenland (Fig. 5), which lies to the north, consistent with the palaeocurrent evidence. NE Greenland includes Archaean and Early Proterozoic partly reworked basement as well as metasediments of the Caledonian fold belt, together with Devonian and younger sediments (e.g. Higgins & Leslie 2008, and references therein).

Fig. 5. Palaeoreconstruction of the North Atlantic region (modified after Trewhin & Rollin 2002; Torsvik & Cocks 2004; Solli & Nordgulen 2006; Henriksen et al. 2009; Fossen 2010; and references therein), showing the close relationship of Greenland, Scotland and Norway during the Middle Devonian. The map shows the distribution of Devonian sedimentary rocks in the North Atlantic region (both offshore and onshore), the main faults active during Devonian extension and the main basement units in Scotland, Greenland and Norway.
The crystalline basement is mainly Archaean (2700–2800 Ma) to Palaeoproterozoic (1800–1950 Ma) in age (e.g. Thrane 2002). This basement is overlain by the Mesoproterozoic high-grade metasedimentary Krummedal supracrustal sequence (e.g. Higgins & Leslie 2008, and references therein), which was affected by Caledonian metamorphism and anatexis (White et al. 2002).
Zircons from the Krummedal supracrustal sequence in the Nathorst Land area yield ages of 1000–1900 Ma (Watt et al. 2000) similar to type 1 samples (Fig. 6a and g). To the east, the Krummedal supracrustal sequence grades into the Stauning Alper Migmatite Zone (Watt et al. 2000). Zircons from the Stauning Alper Migmatite Zone are mostly between 1250 and 1800 Ma old, but a few Archaean zircons (c. 2800 Ma) also occur (Fig. 6g; Watt et al. 2000). The Smalleviad sequence, a succession of semi-pelitic and psammitic gneisses, correlated with the Krummedal supracrustal sequence (e.g. Friderichsen et al. 1994), is also dominated by Proterozoic zircons (1000–1900 Ma) (Fig. 6h; Strachan et al. 1995).

Overlying the Krummedal supracrustal sequence is the Eleonore Bay Supergroup, a succession of non-metamorphic to weakly metamorphosed Neoproterozoic to Middle Ordovician sediments and supracrustal rocks (e.g. Sønderholm et al. 2008). Zircons from the Nathorst Land Group, at the base of the Eleonore Bay Supergroup, yield ages between 1000 and 2800 Ma, with a dominant group of zircons having ages of c. 1800 Ma (Watt et al. 2000; Dhuime et al. 2007) comparable with the age spectrum found in the type 1 samples (Fig. 6a and f). However, most of the Lower Clair Group samples contain a higher amount of Archaean zircons compared with the Neoproterozoic metasediments of NE Greenland (Dhuime et al. 2007). Nevertheless, the composite margin of NE Greenland is a suitable source area for the type 1 samples, as the spectra could have been augmented with Archaean zircons derived from the local basement.

Zircons dated from Devonian fluvial sediments of the Kong Oscar Fjord area in NE Greenland have ages between c. 500 and c. 3300 Ma (Fig. 6e; Slama et al. 2011). The age spectrum is dominated by Proterozoic zircon grains in two age clusters, but also comprises small groups of Phanerozoic and Archaean ages. Therefore, a common source area for the Clair and East Greenland Devonian to Carboniferous sediments seems likely, supporting the theory that the Devonian continental basins of the North Atlantic region were indeed connected (e.g. Allen & Mange-Rajetzky 1992) for at least part of the Devonian.

**Derivation of type 1 samples from basement rocks of SW Scandinavia.** A further possible source area to the north is the SW margin of Scandinavia. The Scandinavain margin contains a wide variety of lithologies including pelitic and psammitic metasediments, calcareous schists, meta-volcanic, ultramafic and eclogitic rocks, orthogneisses, and intermediate to acidic magmatic rocks (Sølli & Nordgulen 2006; Ramberg et al. 2008). The region was influenced by a series of continental collisions and resulting orogenic events (e.g. the Caledonian orogeny; Ramberg et al. 2008). A compilation of age data by Bingen & Sølli (2009) reveals that the basement and metasediments of SW Scandinavia contain almost exclusively Proterozoic zircons (Fig. 6j). Zircons from river sediments draining the Caledonian Nappe Domain in Norway (Morton et al. 2008) also yield mostly Proterozoic zircons with only minor amounts of Caledonian and Archaean grains (Fig. 6i). The Proterozoic spectrum has two main peaks, comparable with the double peak observed in the type 1 samples. However, derivation of the sediment from SW Scandinavia would require local sources to supply all the Archaean zircons, as the SW Scandinavian area lacks this component (Morton et al. 2008; Bingen & Sølli 2009). Additionally, several major Caledonian faults (Fig. 5) seem to have existed between the continental margin of SW Norway and the Clair Basin (e.g. Fossen 2010, and references therein), which may have created a morphological barrier between these two areas of deposition. Therefore, although it is not possible to exclude the SW Scandinavian continental margin as a source area for the type 1 samples it is considered to be less likely than an East Greenland source.

**More distal sources.** In this discussion, we have considered only regions that are reasonably proximal to the Clair Basin, but at this stage we cannot rule out more distal sourcing. For example, metasedimentary basement rocks of the Northwestern Terrane in Svalbard have broadly similar zircon age distributions to metasediments of East Greenland and SW Scandinavia (Pettersson et al. 2009). To provide additional constraints on the location of the source area(s) for type 1 sandstones, it would be necessary to acquire provenance data from coeval Devonian sandstones across the North Atlantic region.

**Derivation of type 2 samples in Unit VII–IX sandstones.** Unit VII–IX has an unusual combination of detrital zircon ages and heavy mineral assemblages. The Archaean-dominated zircon population would be consistent with derivation from local Archaean gneisses, were it not for the distinctive garnet- and staurolite-dominated heavy mineral assemblage (Allen & Mange-Rajetzky 1992; Morton et al. 2010), which indicates derivation from moderate- or high-grade metasedimentary rocks, similar to those found in the Moine and Dalradian of Scotland and equivalent successions of Greenland and Norway. The combined zircon and heavy mineral data indicate supply from moderate- to high-grade metasedimentary rocks that were themselves mainly derived from the Archaean.

As discussed above, metasediments with a predominant Archaean provenance are not known from either NE Greenland or SW Scandinavia (Fig. 6) and it therefore appears that derivation of Unit VII–IX from these areas can be ruled out. By contrast, one of the Westing Group samples from Shetland contains almost exclusively Archaean zircon grains (Fig. 7b; Cutts et al. 2009). In addition, Archaean-dominated zircon spectra have been identified in parts of the Scottish Dalradian, most notably in the Keltie Water Grits near the top of the Dalradian succession (Fig. 7c; Cawood et al. 2003). These samples provide evidence for the existence of Archaean-sourced Neoproterozoic sandstones in the Shetland–Scotland region. Given the proximity of the Clair Basin to the Shetland Islands, it seems most likely that metasediments with similar characteristics to the Westing Group formed the source of the type 2 sandstones of Unit VII–IX. A similar provenance, comprising moderate- to high-grade Archaean-sourced metasediments on the Shetland Platform (or further north) is believed to be responsible for the Early Jurassic Statfjord Formation of the Brent Field (Morton et al. 1996), although Palaeozoic (Caledonian) zircons are more common in the Statfjord Formation than in the Clair succession (Fig. 7a and d).

**Mechanisms of changing provenance**

Changes between type 1 and type 2 provenance seem to be rather sharp, expressed by the near extinction of Proterozoic zircons in Units IVb and VIIb. Possible tectonic rejuvenation of the hinterland, expressed by unconformities at the base of Units IV and VI (Allen & Mange-Rajetzky 1992; Nichols 2005) and a higher amount of feldspars in Unit VI compared with Units IV and V (McKie & Garden 1996), could account for the increase in Archaean zircons in these units, but cannot explain the depletion in Proterozoic zircons. Additionally, the unconformities and the change to more feldspar-rich sandstones occur at the bottom of the aforementioned units, whereas the samples are from their upper parts. Nevertheless,
tectonic rejuvenation leading to uplift of the hinterland and/or subsidence in parts of the drainage system upstream seems to be the most plausible solution, because the cut-off of supply of Proterozoic material from the north would lead to an apparent increase in Archaean zircons in the sediments.

Conclusions

The Clair Basin is one of the Devonian continental basins in the North Atlantic region controlled by Caledonian extensional structures. The Clair Group has been deposited directly on (Lewisian) Archaean basement. Detrital zircon age data in combination with previously published heavy mineral and garnet geochemistry data allow a reinterpretation of potential source areas for the sediments infilling the Clair Basin, as follows:

1. The local Archaean (Lewisian) basement cannot have been the sole source for the sedimentary rocks in the Clair Basin because zircon age data from the Clair Basin reflect Archaean, Proterozoic and Phanerozoic sediment sources, consistent with the conclusions drawn by Allen & Mang-Rajetzky (1992) and Morton et al. (2010) on the basis of heavy mineral data.

2. Most of the sediment in Lower Clair Group units that contain nearly exclusively Archaean zircons are interpreted as being supplied from local basement during phases of tectonic rejuvenation of the hinterland, leading to a temporary cut-off of more distally sourced material.

3. Clair Group units dominated by Proterozoic zircons have most probably been derived from NE Greenland, with additional sediment input from local Archaean basement, suggesting the existence of large rivers connecting the sub-basins in the North Atlantic region in the Devonian. Although it is not possible to exclude SW Scandinavia as a source area, it is considered to be less likely owing to the existence of several major faults between the continental margin of SW Norway and the Clair Basin.

4. Sandstones in the Upper Clair Group, in Unit VII–IX, were derived from metasedimentary successions containing recycled Archaean zircons. Such metasediments are not known from NE Greenland or SW Scandinavia, but are known from the Dalradian of Scotland and the Westing Group of Shetland. The source area is interpreted as the northern part of the Shetland Platform or its northward extension.

Additionally, this study shows that the complementary use of heavy mineral analysis and zircon geochronology leads to more robust conclusions, as zircon data alone would probably have led to the conclusion that type 2 and Unit VII–IX have the same source. The combination of methods also successfully proves a distal source for most of the Clair Group rather than a proximal source.

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References

Allen, P.A. & Mang-Rajetzky, M.A. 1992. Sedimentary evolution of the Devonian–Carboniferous Clair-Field, offshore northwestern UK: impact of changing provenance. Marine and Petroleum Geology, 9, 29–52.

Bingen, B. & Solli, A. 2009. Geochronology of magmatism in the Caledonian and Sveconorwegian belts of Baltic: synopsis for detrital zircon provenance studies. Norwegian Journal of Geology, 89, 267–290.

Blackburn, G.A. 1987. Sedimentary environments and stratigraphy of the late Devonian–Early Carboniferous Clair basin, west of Shetland. In: Müller, J., Adams, A.E. & Wright, V.P. (eds) European Dinantian Environments. Wiley, Chichester, 75–91.

Butler, R.W.H. & Coward, M.P. 1984. Geological constraints, structural evolution and deep geology of the northwest Scottish Caledonides. Tectonics, 3, 347–365.
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Tera, F. & Wasserburg, G. 1972. U–Th–Pb systematics in three Apollo 14 basalts and the problem of initial Pb in lunar rocks. *Earth and Planetary Science Letters*, **14**, 281–304.

Thrane, K. 2002. Relationships between Archaean and Palaeoproterozoic crystalline basement complexes in the southern part of the East Greenland Caledonides: an ion microprobe study. *Precambrian Research*, **113**, 19–42.

Torsvik, T.H. & Cocks, L.R.M. 2004. Earth geography from 400 to 250 Ma: a palaeomagnetic, faunal and facies review. *Journal of the Geological Society, London*, **161**, 555–572.

Trewin, N.H. & Rollin, K.E. 2002. Geological history and structure of Scotland. In: Trewin, N.H. (ed.) *The Geology of Scotland*, 4th edn. Geological Society, London, 1–25.

Vermesh, P. 2004. How many grains are needed for a provenance study? *Earth and Planetary Science Letters*, **224**, 441–451.

Watt, G.R., Kinny, P.D. & Frederichsen, J.D. 2000. U–Pb geochronology of Neoproterozoic and Caledonian tectonothermal events in the East Greenland Caledonides. *Journal of the Geological Society, London*, **157**, 1031–1048.

White, A.P., Hodges, K.V., Martin, M.W. & Andersen, A. 2002. U–Pb geochronology of Neoproterozoic and Caledonian tectonothermal events in the East Greenland Caledonides. *Journal of the Geological Society, London*, **157**, 1031–1048.

Williams, I.S. 1998. U–Th–Pb geochronology by ion microprobe. In: McKibben, M.A., Shank, W.C.P. & Ridley, W.I. (eds) *Applications of Microanalytical Techniques to Understanding Mineralizing Processes*. Reviews in Economic Geology, **7**, 1–35.

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