The North Atlantic Provenance Database: an introduction

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The amount of provenance information available for onshore and offshore sedimentary deposits in the North Atlantic Region is substantial and rapidly increasing. These data provide an improved understanding of reservoir geology (quality, diagenetic issues, regional source-to-sink relations and local stratigraphic correlations), and thereby can reduce hydrocarbon exploration risk.

As such, the number of proprietary, industry-related and public research provenance studies has increased considerably in recent years, and the development and use of new analytical techniques has also caused a surge in the number of grains, isotopes and chemical elements analysed in each study. As a result, it is today close to impossible for the individual researcher or petroleum geologist to draw on all existing provenance data. And the vast expansion of data availability demands new and better methods to analyse and visualise large amounts of data in a systematic way.

To this end, the Geological Survey of Denmark and Greenland (GEUS) and the Norwegian Petroleum Directorate (NPD) have established a web-based database of provenance data for the North Atlantic area: the North Atlantic Provenance Database. Construction of the database was funded jointly by GEUS and NPD. Future maintenance and further development will be funded by the petroleum industry by subscription to the database.

The database was launched in March 2019 and can be accessed at *https://data.geus.dk/provenance*. Access to the database is granted via application to the steering committee, comprised of staff at GEUS, NPD and sponsoring petroleum companies. The aims of the database are three-fold:

- Assemble provenance data from onshore and offshore Greenland, Faroe Islands, Norway and neighbouring areas.
- Make the data easily assessable to the petroleum industry and research institutions for visualisation and statistical analysis through a web application.
- Facilitate research as well as development of new provenance tools and techniques that can reduce exploration risk.

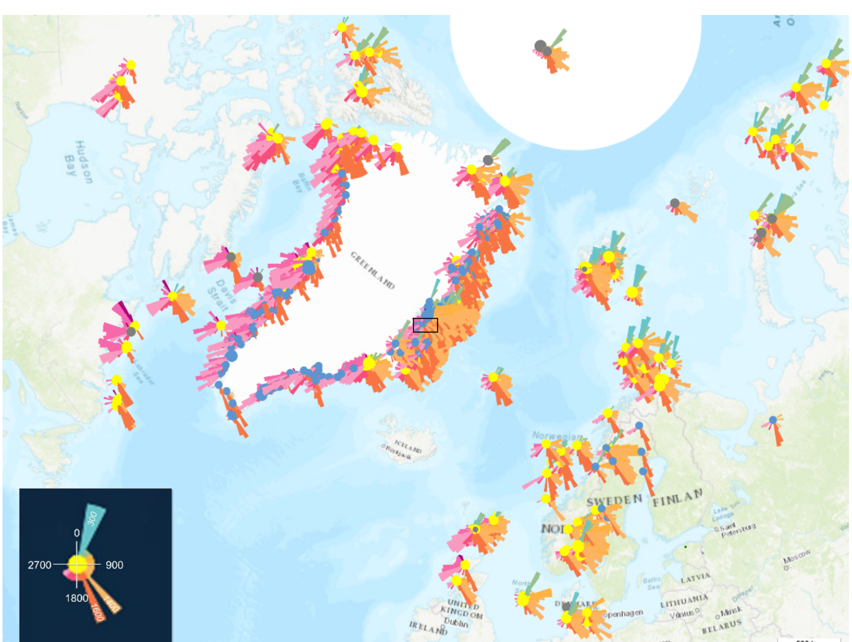

Fig. 1. Output map from the database showing the detrital zircon age distributions available as of July 2019. Each data point (sample) is marked by either a yellow or a blue dot representing a sandstone sample or a present-day drainage sample, respectively. The rosette visualises the age distribution histogram where 'North' is 0 Ma and 'South' is 1.8 Ga with clockwise increasing ages. The length of each bar represents the frequency in 100 Ma bins. Inset: area shown in Fig. 2.

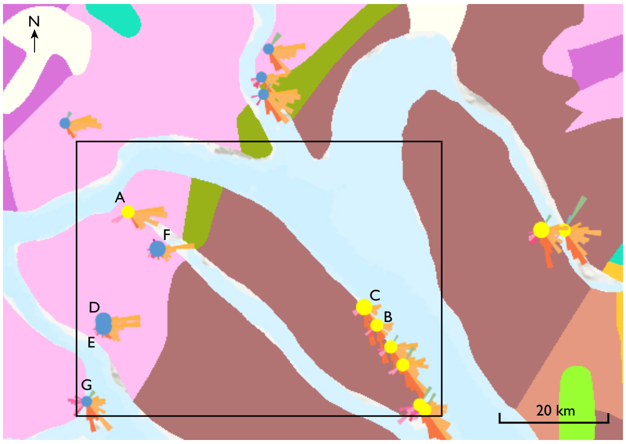

Fig. 2. Geological map (1:500 000) of Ymer Ø in the Kong Oscar Fjord area, East Greenland (output directly from the database; location marked in Fig. 1). Locations of stream sediment (blue) and sandstone samples (yellow) are marked, see Fig. 1 for further details. Inset: sampling locations of the seven samples (**A–G**; see Fig. 3) discussed in the text.

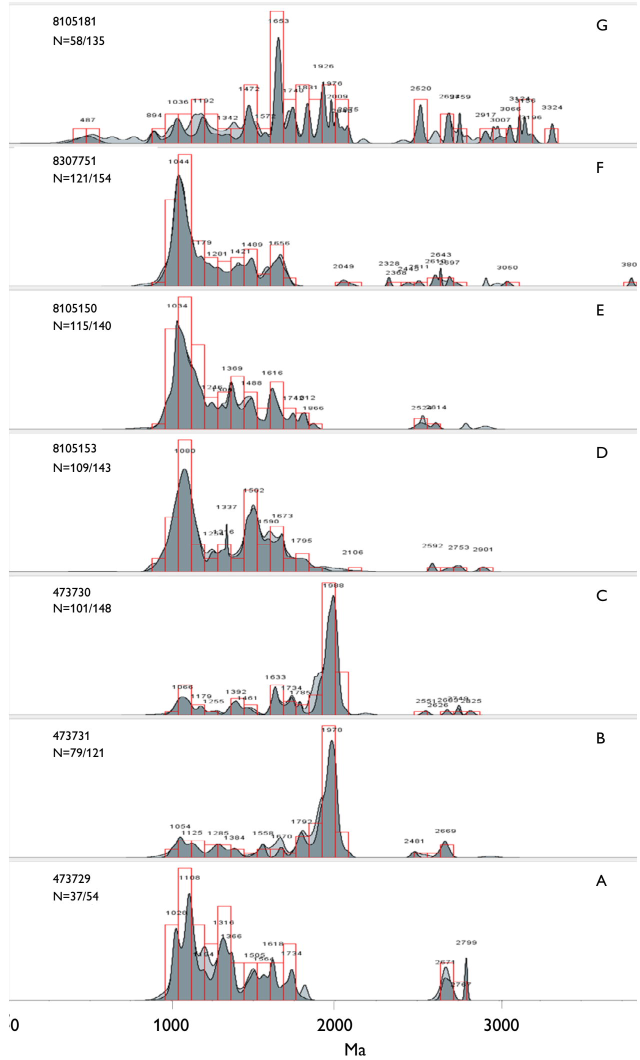

Fig. 3. Detrital zircon age distribution histograms of the seven samples (**A–G**) selected in Fig. 2. (Rehnström *et al.* 2010). The histograms are generated according to Thomsen *et al.* (2016).

Here, we provide a brief introduction to the database and its future development and expansion. We highlight the current capabilities with an example from East Greenland.

Database contents, development and application

The North Atlantic Provenance Database is a spatiotemporal, object-rational database in PostgreSQL. It consists of two main packages:

- A database for storage of:
  - Detrital zircon age data and other types of provenance data
  - Metadata with information about the samples and the analytical procedure used
- An analytical module allowing users to compile, compare and analyse the datasets.

Data

At the time of publication (July 2019), the database consists of 1659 sandstone samples and 413 stream sediment samples, each containing detrital zircon U-Pb ages, together with metadata such as coordinates, stratigraphic data, analytical data and a reference to where the data are published. The database contains more than 170 000 detrital zircon U-Pb ages.

The detrital zircon U-Pb age data available in the database (July 2019) are summarised in Fig. 1. At present, detrital zircon U-Pb age data constitute by far the main part of the existing provenance data in the North Atlantic Provenance Database. Other provenance data types, such as detrital rutile, monazite and apatite U-Pb age data as well as stable heavy mineral distributions and heavy mineral chemistry, will be included at later stages. The analytical capabilities and possibilities are under constant change and the database structure is therefore flexible, to accommodate parameters that are not yet part of standard provenance analysis.

Most of the data from Greenland that are stored in the database are comprised of onshore outcrop samples, but also include shallow core wells and samples from present-day drainage systems. In eastern Greenland, *c.* 500 samples have been analysed for provenance properties. Of these, more than 400 were analysed by GEUS. The database contains the age distribution of these detrital zircon grains as well as their heavy mineral distribution and compositions. In addition, the database also contains results from various studies in East Greenland: some are published (e.g. Røhr *et al.* 2008; Kirkland *et al.* 2009; Sláma *et al.* 2011; Olivarius *et al.* 2018), and others are to be found in unpublished theses and company reports.

A wealth of offshore and onshore data is available for Norway. Some data have been extracted from published work, but the vast majority of the data are yet to be recovered from either unpublished academic work or company reports. On the Norwegian shelf, a large number of samples have been analysed for their detrital zircon age distribution and heavy mineral content. Again, some of these data are published (e.g. Morton *et al.* 2005; Lorenz *et al.* 2013; Fleming *et al.* 2016) and others are yet to be extracted from unpublished theses and company reports.

Data from neighbouring territories such as West Greenland, Arctic Russia and Canada, the Faroe Islands, Denmark and the UK are also accessible in the database.

Analytical Module

Users can query the database via the analytical module interface, where they can view and analyse the relevant datasets for a given number of samples. From here, users can generate various visualisations of the data and export them as figures in PDF format. Note that the data belong to the institutions that produced them and so they are not directly available to download from the database. However, the database contains full bibliographic information and links to where the data can be found.

A more detailed description of the database architecture will be published alongside the database at a later date. Here, we simply demonstrate some of functionality, using seven samples from Gunner Andersen Land, Ymer Ø in Kong Oscar Fjord, East Greenland (Rehnström *et al.* 2010; location in Fig. 2). Stream sediment samples from present-day drainage systems and Proterozoic and Devonian sandstones were chosen for further analysis. Visual inspection of the detrital zircon age distribution rosettes (Fig. 2) and histograms (Fig. 3) show distinct modal variation between the seven samples.

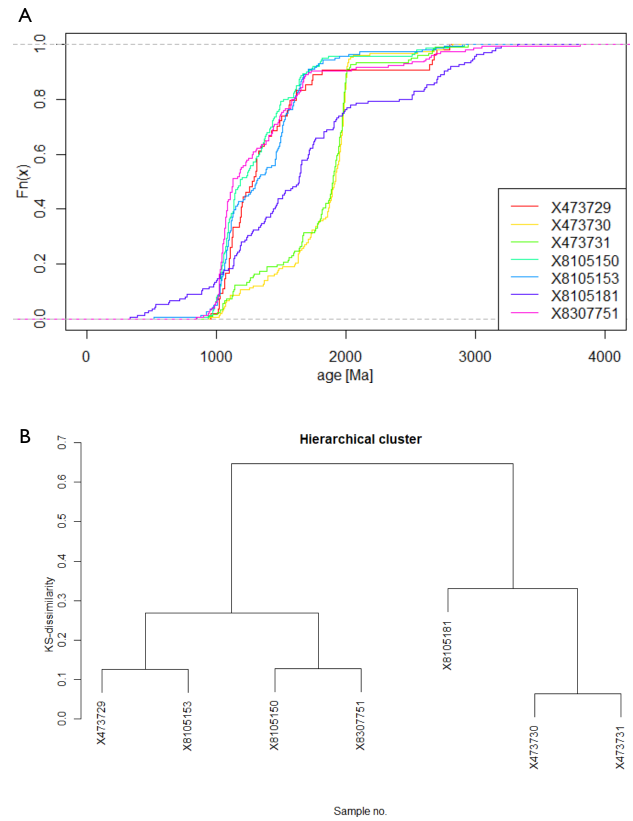

Fig. 4. Kolmogorov-Smirnov (KS) dissimilarities of the seven selected samples. **A**: Cumulative age distributions. **B**: Hierarchical clustering.

This is confirmed by the Kolmogorov-Smirnov (KS) dissimilarity test (Fig. 4 and Table 1). Some of the metadata available in the database for these samples are shown in Table 2.

Sample 473729 (Fig. 3A) represents the Sandertop Formation of the Upper Proterozoic Lyell Land Group, part of the Eleonore Bay Supergroup. Detrital zircon ages span the Palaeoproterozoic–Mesoproterozoic eras, with a few Archaean grains. Samples 473730 (Fig 3C) and 473731 (Fig. 3B) represent the Devonian Kap Kolthoff Group consisting of immature sandstone and conglomerate. The detrital zircon age distributions are dominated by a Palaeoproterozoic

Table 1. Kolmogorov-Smirnov (KS) dissimilarity matrix of the seven selected samples.

	X473729	X473730	X473731	X8105150	X8105153	X8105181	X8307751
X473729		0.631	0.585	0.190	0.126	0.344	0.268
X473730	0.631		0.064	0.647	0.631	0.328	0.620
X473731	0.585	0.064		0.622	0.610	0.330	0.589
X8105150	0.190	0.647	0.622		0.176	0.369	0.127
X8105153	0.126	0.631	0.610	0.176		0.343	0.163
X8105181	0.344	0.328	0.330	0.369	0.343		0.330
X8307751	0.268	0.620	0.589	0.127	0.163	0.330	

Table 2. Example metadata available for the seven samples in Fig. 2

Storage number	Sample Type	Lithology	Lithostratigraphy	Base Age	Top Age	Reference
473729	Rock sample	Sandstone	Lyell Land Group - Sandertop Formation	Tonian	Tonian	Rehnstrøm *et al.* 2010
473730	Rock sample	Sandstone	Kap Kolthoff Group	Givetian	Famennian	Rehnstrøm *et al.* 2010
473731	Rock sample	Sandstone	Kap Kolthoff Group	Givetian	Famennian	Rehnstrøm *et al.* 2010
8105150	Stream sediment sample	-	-	-	-	Rehnstrøm *et al.* 2010
8105153	Stream sediment sample	-	-	-	-	Rehnstrøm *et al.* 2010
8105181	Stream sediment sample	-	-	-	-	Rehnstrøm *et al.* 2010
8307751	Stream sediment sample	-	-	-	-	Rehnstrøm *et al.* 2010

peak around 1980 Ma, which is well known from the tonalitic gneiss that occur in the basement northeast of the area (Kalsbeek *et al.* 2008).

Samples 8105153, 8105150 and 8307751 (Figs 3D, E, F) represent stream sediments collected from the present-day drainage system on Ymer Ø. They have very similar detrital zircon age distributions that resemble those of the Upper Proterozoic Eleonore Bay Supergroup bedrock (see sample 473729; Fig 3A). This supports the view that stream sediment offers a good representation of the catchment bedrock geology. Stream sample 8105181 (Fig. 3G) from the mainland has a very complex detrital zircon age distribution suggesting a fundamental difference in the bedrock geology in the catchment area of this sample.

The analytical module allows users to calculate and visualise cumulative age distributions and Kolmogorov-Smirnov dissimilarities (Fig. 4) – a widely used method for comparing mineral age distributions. This is enabled through a plugin between the database and the freely available statistical programming software R (R Development Core Team 2008). These functionalities are part of the 'provenance' package' developed specifically for detrital sediment provenance analysis (Vermeesch *et al.* 2016). The similarities between e.g. samples 473730 and 473731 are clearly seen in Figures 4A and 4B, and in Table 1.

Outlook

Compiling the large amount of available provenance data into a regional, cross-border, web-database will make these types of data much more accessible and applicable to industry and the research community. In doing so, we hope to promote the use of these data in studies of the North Atlantic region. With an extensive database covering both sides of the Atlantic Ocean more comprehensive source-to-sink analyses can be made, resulting in an improved understanding of onshore–offshore provenance relationships.

In the long-term, we hope to include more data from neighbouring geographic areas such as the Russian and Canadian Arctic, since detrital material in the North Atlantic may have been derived from these areas. It is envisaged that more than 100 000 detrital zircon grains from the North Atlantic Region have been dated, and the aim is to capture the majority of these in the database, making them available for data comparison (e.g. with statistical tools) and visualisation to enhance the understanding of the regional reservoir geology. Users are expected to upload their own provenance data in return for using the database.

It is also possible to restrict access to certain data in the database, so that they are kept confidential for a time. This is an important feature for these types of datasets, many of which are funded by private companies and have confidentiality clauses imposed for a finite period. For more information contact the lead-author.

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