

Pointon *et al.* A multi-proxy provenance study of Late Carboniferous to Middle Jurassic sandstones in the eastern Sverdrup Basin and its bearing on Arctic palaeogeographic reconstructions.

Supplemental Information

Analytical Methods

1. Mineral chemistry analysis

1.1. Apatite

Apatite geochemical analysis was carried out in the School of Earth, Ocean and Planetary Sciences at Cardiff University, using a Thermo Elemental X(7) series ICP-MS coupled to a New Wave Research UP213 Nd:YAG 213 nm UV laser. A laser spot diameter of 30 µm and laser repetition rate set at 4 Hz were used throughout. Helium gas was used for ablation initial transport from the laser cell and this was combined with argon outside the cell as the sample was transported to the ICP-MS. Thermo Elemental Plasmalab time-resolved analysis (TRA) data acquisition software was used with a total acquisition time of 60 seconds per analysis, allowing about 30 seconds for background followed by 25 seconds for laser ablation. Plasmalab was used for initial data reduction with subsequent processing conducted in Microsoft Excel. The calibration employed NIST614, NIST612 and NIST610 reference glasses to produce a four-point (including the origin) calibration curve. Data were normalised to Ca (55 % CaO) and adjusted accordingly. Instrumental drift was monitored by repeat analysis of NIST612 after every 10 unknowns. Apatite grains were assigned probable source lithology groups based on their Sr/Y ratios and light rare earth element (LREE) concentrations following the classification scheme and routine of O'Sullivan *et al.* [1].

1.2. Garnet

For samples with D prefixes, garnet grains were handpicked, mounted on glass slides, sectioned and polished, carbon-coated and then analysed at the British Geological Survey, UK, using either a

Cameca SX50 electron microprobe or a Cambridge Instruments S360 electron microscope. The Cameca SX50 electron microprobe is fitted with three wavelength-dispersive spectrometers. Throughout the procedure an accelerating voltage of 15 kV, a sample current of 20 nA and a beam focussed to $\sim 1\text{ }\mu\text{m}$ were used. A mixture of natural minerals and synthetic materials were used for calibration. The Cambridge Instruments S360 electron microscope is fitted with an Oxford Instruments X-ray analysis system (EDXA) consisting of a germanium (GEM) detector and Oxford INCA microanalysis software. Analyses were obtained using an accelerating voltage of 15 kV, a probe current of 500 pA and a count time of 30 seconds. Samples with S_HS prefixes were mounted on glass slides, coated with carbon, and analysed using a Link Systems AN 10/55S energy-dispersive x-ray analyser attached to a Cambridge Instruments Microscan V electron microprobe housed at the University of Aberdeen, UK. The count time was 30 seconds per grain; a mixture of natural and synthetic materials was used for calibration. Garnet analyses were classified by possible host rock types and metamorphic facies following Schönig et al. [2].

1.3. Rutile

Rutile geochemistry was carried out in the School of Earth, Ocean and Planetary Sciences at Cardiff University, using a Thermo Elemental X(7) series ICP-MS coupled to a New Wave Research UP213 Nd:YAG 213 nm UV laser. Laser beam diameter was 30 μm and laser repetition rate set at 4 Hz. Helium gas was used for ablation initial transport from the laser cell and this was combined with argon outside the cell as the sample was transported to the ICP-MS. Thermo Elemental Plasmalab time-resolved analysis (TRA) data acquisition software was used with a total acquisition time of 60 seconds per analysis, allowing about 30 seconds for background followed by 25 seconds for laser ablation. Plasmalab was used for initial data reduction with post-processing in Excel. The calibration employed BIR-1G, BHVO-2G and BCR-2G (USGS basalt glass standards) to produce a 4 point (including the origin) calibration curve. Data were normalised to Ti (98% TiO_2) and adjusted accordingly. Instrumental drift was monitored by repeat analysis of BHVO-2G after every 25-30

grains. Metapelite/metamafic rutiles were classified based on Cr and Nb concentrations and following Meinhold et al. [3]. Metamorphic temperatures were estimated using the Zr-in-rutile thermometer calibration of Watson et al. [4].

2. Detrital zircon U-Pb geochronology

Zircons were concentrated from the conventional heavy mineral separates using a combination of heavy liquid separation using methylene iodide and magnetic separation. Detrital zircons were analysed at University College London (UK), Laurentian University (Ontario, Canada), Stellenbosch University (South Africa) and at the NORDSIM facility (Swedish Natural History Museum, Stockholm, Sweden). All of the analyses are single spot analyses. At University College London, analyses were undertaken using a New Wave Research 213nm laser coupled to an Agilent 7500 ICP-MS. A spot diameter of 55 μm was used throughout. Unknown sample analyses were calibrated against Plešovice zircon [5]. Raw data were reduced in Glitter [6,7]. Data are uncorrected for common lead. At Laurentian University, analyses were undertaken on a New Wave Research UP-213 laser or a Resonetics Resolution M-50 193 nm ArF excimer laser coupled to a Thermo X-Series II ICP-MS using a 30 μm . Unknown samples analyses were calibrated against the 91500 zircon [8], with Plešovice zircon [5] analysed as a secondary standard. The raw data were reduced in Lolite [9] and following the VizualAge data reduction scheme [10]. Data are uncorrected for common lead. At the Central Analytical Facility of Stellenbosch University, South Africa, detrital zircons were analysed using a New Wave Research UP-213 laser coupled to a Thermo Finnigan Element2 ICP-MS. A spot diameter of 30 μm was used throughout. Unknown samples analyses were calibrated against the GJ-1 zircon [6]. The methods employed for analysis and data processing are described in detail by Gerdes and Zeh [11] and Frei and Gerdes [12]. Plešovice [5] and M127 [13,14] zircons were analysed as secondary standards. The data were corrected for common lead using the ^{204}Pb method and the Stacey and Kramers [15] terrestrial lead evolution model. At the NORDSIM facility, zircon grains were analysed using the CAMECA 1280-IMS secondary ion mass spectrometer. Analytical protocols followed those

of Whitehouse and Kamber [16]. A spot size of $\sim 20\ \mu\text{m}$ was used throughout. Grain rims were targeted preferentially. U–Pb isotope data from individual spot analyses were calculated on the basis of 12 measured ratios. The 91500 zircon standard [8] was used as the primary standard and was analysed every 4–6 unknown sample analyses. Data are uncorrected for common lead.

Concordia ages [sensu 17] are used preferentially to avoid the arbitrary switching between two U–Pb age systems and were calculated using Isoplot v4 [18]. Imprecise analyses (i.e. those with concordia age uncertainties $>10\%$, $2s$) and analyses $>10\%$ discordant (calculated at the limit of the 95% confidence uncertainty ellipse) are excluded from the interpretation. Probability density plots were drawn in R using the Detzrcr package [19]. Multidimensional scaling dissimilarity analysis was conducted in R using the Provenance package [20].

3. Detrital zircon hafnium isotope analysis

Zircon grains were analysed for Lu–Hf isotopic ratios at the Geochronology and Tracers Facility, British Geological Survey, UK, using LA-ICPMS analysis. Data were acquired using a Thermo Neptune multi-collector inductively coupled plasma mass spectrometer coupled to a New Wave Research 193 nm laser. The method followed closely that described by Thomas et al. [21]. Masses ^{172}Yb , ^{173}Yb , ^{175}Lu , $^{176}\text{Hf} + \text{Yb} + \text{Lu}$, ^{177}Hf , ^{178}Hf , ^{179}Hf and ^{180}Hf were measured simultaneously using a 1 second integration time during a static 30 second ablation analysis. A $35\ \mu\text{m}$ laser spot size and laser fluence of $8\text{--}10\ \text{J}/\text{cm}^2$ was used throughout; spot analyses were located on top of previous U–Pb SIMS analyses. A standard–sample–standard bracketing technique, using 91500, Mud Tank and Plešovice zircons as reference materials, was employed to monitor accuracy and precision of internally corrected Hf isotope ratios. Hf reference solution JMC475 (both doped with 2 ppb Yb and undoped) was analysed during each analytical session. Correction for ^{176}Yb on the ^{176}Hf peak was made using a reverse-mass-bias correction of the $^{176}\text{Yb}/^{173}\text{Yb}$ ratio (0.7941) empirically derived using Hf mass bias corrected Yb-doped JMC475 solutions [cf. 22]. ^{176}Lu interference on the ^{176}Hf peak was corrected by

using the measured ^{175}Lu peak and assuming $^{176}\text{Lu}/^{175}\text{Lu} = 0.02653$. Systematic uncertainties of Hf and Lu isotope ratios were propagated using quadratic addition, incorporating the external variance of the reference material during each analytical session. Data were reduced using Iolite [9]. Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios were calculated using a ^{176}Lu decay constant of $1.867 \times 10^{-11} \text{a}^{-1}$ [23] and the respective concordia U–Pb ages. Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios are expressed as $\epsilon\text{Hf}_{(t)}$ values using the following values for the present day chondritic uniform reservoir (CHUR): $^{176}\text{Hf}/^{177}\text{Hf}_{\text{CHUR}} = 0.282785$ and $^{176}\text{Lu}/^{177}\text{Hf}_{\text{CHUR}} = 0.0336$ [24]. Uncertainties in $\epsilon\text{Hf}_{(t)}$ values were calculated according to [25] and include uncertainties in the U–Pb age.

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