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# Understanding the roles of crustal growth and preservation in the detrital zircon record

Penelope J. Lancaster [a,*,1], Craig D. Storey [a,2], Chris J. Hawkesworth [a,3], Bruno Dhuime [a,b]

[a] Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Rd., Bristol BS8 1RJ, UK
[b] School of Geography and Geosciences, University of St. Andrews, North Street, St. Andrews KY16 9AL, UK

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ABSTRACT

Crustal evolution studies using detrital minerals must consider the potential for bias introduced at the time of formation of the continental crust, through its preservation in subsequent supercontinental cycles and during erosion and reworking of sedimentary material. To investigate the extent of these biases, and our ability to extract global information from local studies, this study presents in situ U–Pb, O and Hf isotope data in detrital zircons from the Scottish Highlands for comparison with greater Gondwana and Laurentia. Zircon crystallisation ages range from 3.8–1.1 Ga, and they group into three episodes (at ~2.8, 1.8 and 1.2 Ga), peaking within 100 Ma of the ages of known supercontinents (Superia, Nuna and Rodinia). They are therefore consistent with preservation due to continental collision and supercontinent stabilisation. The Hf model ages fall between 4.2–1.4 Ga, and they also group into three significant juvenile extraction events at ~3.3, 2.2 and 1.7 Ga, of which only the ~3.3 Ga peak has been observed elsewhere in Laurentia or Gondwana. There is a link between the distribution of U–Pb crystallisation ages and model Hf ages indicating typical residence times of ~600 Ma between the formation of new crust and its reworking in later magmatic events. Individual Hf model ages appear to form continua within each crystallisation event, suggesting that the generation of new continental crust is a continuous process, even though the record is then biased by the development of supercontinents.



## 1. Introduction

A fundamental challenge in the study of the continental crust is to understand the nature of the record, in particular the extent to which it may be biased, and how that bias may have come about. In the recent geological past the generation of new continental crust has taken place primarily along destructive plate margins, and the volumes of new crust generated globally have not changed markedly over the last ~500 Ma (e.g., Scholl and von Huene, 2009). However, the provinces in which new crust was generated are relatively restricted, and even within those provinces there may be periods of greater magmatic activity and periods of quiescence. Thus, to investigate the generation and evolution of the continental crust we need as many broadly representative records as possible to build up a global picture from more regional studies.

Detrital minerals, such as zircon, are widely used since they are relatively difficult to destroy and they provide a record of magmatic history that is developed further through each sedimentary cycle. Zircon yields precise U–Pb crystallisation ages and it preserves robust O and Hf isotope signatures despite the effects of erosion, metamorphism and later crystallisation events (e.g., Fedo et al., 2003). It typically crystallises from rocks with >65 wt.% $SiO_2$ (Hoskin et al., 2000), and so it provides little direct information on the ages of juvenile mafic melts that might be associated with the generation of new continental crust. However, granitic magmas, and the zircons that crystallise from them, retain the juvenile Hf isotope signature of the mafic source rock unless they are modified by contamination with pre-existing crust. Such crust tends to have an elevated $\delta^{18}O$ (>10‰ VSMOW; Valley et al., 2005), in particular sediments. Oxygen isotopes are therefore used to distinguish zircons from magmas that include a sedimentary component ($\delta^{18}O$>6.5‰; Cavosie et al., 2005; Kemp et al., 2006) from those that crystallised in magmas derived from more primitive mantle and basaltic source rocks (4.5–6.5‰; see compilation and discussion in Eiler, 2001). Since detrital sediments typically contain material from different sources, oxygen isotope ratios discriminate zircons that may have hybrid model ages from those that record discrete crustal extraction events.

A number of local zircon crustal evolution studies have identified episodic crust formation events from Hf model ages every 0.3–0.6 Ga (see references in the Supplementary material) which are not reproduced by larger studies (e.g., Belousova et al., 2010) or are

* Corresponding author. Tel.: +353 1 716 2326; fax: +353 1 283 7733.
*E-mail addresses:* penelope.lancaster@ucd.ie (P.J. Lancaster), craig.storey@port.ac.uk (C.D. Storey), cjh21@st-andrews.ac.uk (C.J. Hawkesworth), B.Dhuime@bristol.ac.uk (B. Dhuime).
[1] Present address: School of Geological Sciences, University College Dublin, Science Education and Research Centre (West), Belfield, Dublin 4, Ireland.
[2] Present address: School of Earth & Environmental Sciences, University of Portsmouth, Burnaby Building, Burnaby Road, Portsmouth PO1 3QL, UK.
[3] Present address: School of Geography and Geosciences, University of St. Andrews, North Street, St. Andrews KY16 9AL, UK.

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typically coincident with established magmatic events identified in the U–Pb crystallisation age record (e.g., Condie et al., 2011). It has been argued that the presence of peaks in crust generation is difficult to reconcile with global plate tectonic processes, and instead may represent episodic crust production due to mantle plumes or overturn events (e.g., Condie, 1998, 2004; Davies, 1995; Stein and Hofmann, 1994). However, an alternative view is that the peaks in crystallisation ages are not a primary feature, but instead reflect a bias in the preserved record of the history of the continental crust (Hawkesworth et al., 2009, 2010). These age peaks coincide with known supercontinent events back to 2.7 Ga, indicating a possible link with the stabilisation phase of supercontinent formation (Campbell and Allen, 2008; Hawkesworth et al., 2009). If the preserved record of crystallisation of granitoid material (i.e., of zircons) is biased by the stabilisation of supercontinents, there may also be a bias in the preservation of crust generation ages (Hf model ages). Prior to 2.7 Ga, there is little evidence for the presence of supercontinents, and it may well be that the global tectonic regime was different (e.g., Cawood et al., 2006). It follows that preservation may have been less biased by tectonic processes, most rocks had little chance of surviving for long, and so detrital zircons may offer a relatively unbiased record for the Archaean and Hadean (e.g., Davis et al., 2005; Harrison et al., 2005; Hawkesworth et al., 2010).

If steady-state processes, such as subduction, dominate the generation of new continental crust, then different extraction peaks might be identified in different areas, summing into a global continuum of ages. The approach adopted here is to sample a basement record through detrital zircons in younger sediments from the same area, and to compare this record with those from other localities worldwide. This study concentrates on detrital zircons from north-western Scotland, which sampled across the North Atlantic craton, all lying unconformably on the Archaean basement (e.g., Cawood et al., 2007; Rainbird et al., 2001). Peaks in zircon crystallisation ages vary considerably within the stratigraphic column (e.g., Kirkland et al., 2008; Lancaster et al., in review; Rainbird et al., 2001), and therefore analysing detrital zircons from different stages in the sedimentary record can be used to test the relationships between crust formation and crust preservation bias within one of the older cratonic areas in Laurentia.

## 2. Regional setting

The north-western Scottish Highlands comprise Proterozoic and Cambro–Ordovician sediments deposited on the Caledonian foreland and Neoproterozoic Moine metasediments from the Caledonian hinterland. Angular unconformities and fault contacts are common throughout the region, making correlations between similar units difficult. Comprehensive descriptions of the pertinent rock units can be found in Trewin (2002) and Mendum et al. (2009), as well as in recent papers on the area (e.g., Friend et al., 2003; Kinnaird et al., 2007; Kirkland et al., 2008; Rainbird et al., 2001). Together, the samples form a succession of crustal sediments from oldest to youngest in the following order: Loch Maree Gp., Sleat Gp., Stoer Gp., Torridon and Altnaharra Gps., and Ardvreck Gp. (Fig. 1).

The basement Archaean Lewisian Gneiss Complex has experienced a number of metamorphic and erosive events, and so current exposures may not preserve its full history. Instead, a more complete record is accessible through detritus in younger metasediments, including the Palaeoproterozoic Loch Maree Gp. metagreywacke (DB96-S166 of Whitehouse et al., 1997) and the Meso- to Neoproterozoic Sleat, Stoer and Torridon groups which lie unconformably upon the basement in the foreland. Samples were collected from the basal Rubha Guail Fm. (09LSC1) and Loch na Dal Fm. (07LSC2) sandstones of the Sleat Gp., the basal Clachtoll Fm. conglomerate (07LSC7) and the upper Meall Dearg Fm. sandstone (07LSC8 and 09LSC4) of the Stoer Gp., and the Applecross Fm. (07LSC6) and Aultbea Fm. sandstones (07LSC5) of the Torridon Gp.

Further east, the Early Cambrian Ardvreck Gp. unconformably overlies both the Torridon Gp. and the Lewisian basement, and is roofed by the Moine Thrust. Samples were collected from the Basal Quartzite Mbr. (07LSC9), the *Skolithos*-burrow bearing Pipe Rock Mbr. (07LSC10) and the Salterella Gritstone (07LSC12). In the hanging wall of the Moine Thrust is the Neoproterozoic Morar Gp., which lies unconformably on the Archaean basement gneiss, broadly similar in age to the Lewisian Gneiss to the west (Friend et al., 2003). The samples from this group were collected in the southern section, which includes the psammitic Altnaharra Fm. (CJS 99-J5) and a rare basal metaconglomerate layer (07LSC3). It has been suggested that these units may be correlated with the Torridon Gp. of the foreland, due to similar age and detrital zircon characteristics (Krabbendam et al., 2008).

## 3. Methods

Detailed methods can be found in the Supplementary material. Heavy mineral separates were obtained using standard techniques and hand-picked for zircon, selecting those of sufficient size and structural stability to pick up with tweezers (greater than ~70 $\mu$m in the short axis). While these selection criteria may induce some bias in the dataset (e.g., Fedo et al., 2003), zircons that are internally damaged (metamict) or very small will not provide reliable U–Pb results. However, grains of either excludable description were rare, and populations larger than 60 grains/sample should include evidence of any age group larger than 5% (Dodson et al., 1988). All selected grains were arranged in rows, cast into epoxy rounds with fragments of 91500 and Temora 2 zircon standards, ground to half height to reveal internal structures and polished to a flat surface. The growth zoning in each grain was then determined by cathodoluminescence (CL) imaging on a Hitachi S-3500N variable pressure scanning electron microscope at the University of Bristol. The majority of zircons displayed oscillatory zoning in the cores, surrounded by up to two thinner layers of no zoning, while the rest contained only a single, undivided, zone. Generally, only the core regions were large enough to analyse, although a small number of overgrowths were also measured.

U–Pb ages were measured by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Bristol, using a ThermoFinnigan Element 2 magnetic sector mass spectrometer coupled with a New Wave Research UP193HE Deep-UV (193 nm) ArF Excimer laser. Every separated grain with inclusion- and crack-free areas of sufficiently large growth zones was analysed to avoid preselecting ‘nice’ grains (e.g., Morton et al., 1996). The amount of $^{204}$Pb in these analyses was below the detection limit, and no common Pb correction was undertaken. Only ages less than 10% discordant, from a single growth zone and avoiding irregular features such as cracks and inclusions were used (524 out of 620 analyses, or 85%). A complementary set of U–Pb analyses was obtained by secondary ion mass spectrometry (SIMS) on the Cameca IMS1270 at the NERC Ion Microprobe Facility in Edinburgh, Scotland (EIMF), using machine settings similar to those in Kelly et al. (2008). Analyses were corrected for common Pb when necessary (37 out of 134 analyses), then those analyses free from irregularities were selected (104 out of 134 analyses, or 78%). Where ages were obtained from the same growth zone in a zircon by both techniques, the more precise and/or concordant age was retained, for a total of 644 ages.

Hafnium ratios were measured at the University of Bristol, using a ThermoFinnigan Neptune multicollector mass spectrometer and a 193 nm New Wave ArF laser, following Hawkesworth and Kemp (2006b). Every separated grain with growth zoning of sufficient size and a suitable U–Pb age was analysed. $\varepsilon$Hf values were calculated based on a two-stage model, using bulk Earth (chondrite uniform reservoir; CHUR) $^{176}$Hf/$^{177}$Hf and $^{176}$Lu/$^{177}$Hf from Bouvier et al. (2008), depleted mantle (DM) $^{176}$Hf/$^{177}$Hf and $^{176}$Lu/$^{177}$Hf from Griffin et al. (2002), and the Lu decay constant from Söderlund et al. (2004); see the Supplementary file for more details. Hf model ages are calculated relative to the evolution of the depleted mantle ($T_{DM}$), assuming an