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The detrital zircon record: Supercontinents, parallel evolution—Or coincidence?

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ABSTRACT

The interpretation of detrital zircon data is facing some important and potentially damaging inconsistencies that are commonly overlooked: combined U–Pb and Lu–Hf data from detrital zircon in sedimentary rocks have been used successfully to study global processes such as the extraction, growth and preservation of continental crust, suggesting generally similar patterns of evolution in different continents. Yet at the same time, such data are increasingly used to identify the source-rocks of individual clastic deposits, based on the implicit assumption that material from different source terranes carry distinct provenance signatures.

For example, Precambrian detrital zircon age-fractions from late Mesoproterozoic to Recent sediments in Laurentia show patterns of U–Pb ages and initial Hf isotope composition indistinguishable from that of zircon from granitoids in Fennoscandia. This is perhaps not too surprising, as Fennoscandia and Laurentia have been near neighbours in three supercontinents (Nuna, Rodinia, Pangea). Transport and homogenization of clastic material in intracontinental basins and along a common continental margin would smooth out differences, and the two neighbouring continents may have closely parallel histories of internal growth.

A stronger reason for concern is that Precambrian age fractions in detrital zircon suites from areas as distant as Australia and South Africa also show distribution patterns that cannot be distinguished with confidence from sources in Fennoscandia. These continents have not been near neighbours in post-Archaean supercontinents. Since exchange of detritus between such distant blocks is improbable, one is left with the alternative explanations of pronounced parallel evolution (perhaps related to the assembly of supercontinents in the geological past), or pure coincidence.

Whatever the explanation: exchange, parallelism or coincidence, observations such as these challenge the main assumptions underlying the use of zircon as an indicator of sedimentary provenance: *That a given age and initial Hf isotopic pattern of a population of detrital zircons can be unequivocally related to a specific first-generation source.*

1. Introduction

1.1. Zircon as a tracer of sedimentary provenance

Zircon is an extremely resistant mineral, known to survive extended cycles of weathering and crustal recycling (e.g. Williams, 2001). The U–Pb and Lu–Hf isotope systems of zircon are able to retain a memory of the age and initial Hf isotope signature of the individual crystal, which in turn reflect the characteristics of the (generally) granitic intrusions in which the zircon originally formed (e.g. Hawkesworth and Kemp, 2006). The use of radiogenic isotope data from detrital zircons has therefore become a popular tool in sedimentary provenance analysis (e.g. Fedo et al., 2003), but also in studies of first-order global processes such as the extraction, growth and preservation of continental crust (e.g. Griffin et al., 2004; Belousova et al., 2010; Condie et al., 2011; Voice et al., 2011; Lancaster et al., 2011). It may be argued that these two approaches are based on mutually incompatible assumptions: for detrital zircon data to be useful for continental evolution studies, different continents must have generally similar histories of crustal extraction and reworking, whereas for provenance analysis to be possible, different continental source terranes must generate zircon populations with distinct age and Hf isotope characteristics. The latter hypothesis is the basis for the "*qualitative approach to detrital zircon geochronology*" of Fedo et al. (2003), and is a fundamental assumption in almost all studies in provenance analysis, although rarely explicitly stated. In the present paper, the assumption that the age and initial Hf isotopic pattern of a population of detrital zircons

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can be related to a specific first-generation source (protosource) is critically examined from a review of published data from zircon in sediments and in continental bedrock.

The U–Pb isotope system in zircon is a robust and precise chronometer, which has the disadvantage of giving no information on the nature of the system from which the zircon crystallized. U–Pb data of a suite of detrital zircon grains from a sedimentary rock therefore give information only on the timing of petrogenetic events in the protosource terrane. This is a severe restriction, because continental protosources are likely to consist of rocks with overlapping crystallization ages, but significantly different petrogenetic histories (e.g. Howard et al., 2009). For example, Palaeoproterozoic zircons from protosources in Fennoscandia (Fig. 1) may come from relatively juvenile rocks ($\varepsilon_{\mathrm{Hf}} > 0$), or from granitic intrusions originating from anatectic magmas containing Archaean components, resulting in $\varepsilon_{\mathrm{Hf}} << 0$. Distinguishing between such sources from U–Pb ages only will in general not be possible, and U–Pb age distribution patterns will therefore always be ambiguous. Coeval protosources with different crustal histories can, however, be distinguished quite easily by hafnium isotope data. In situ Lu–Hf analysis by laser ablation, multicollector ICPMS is now a standard analytical method, and Lu–Hf analysis of grains that have been dated by U–Pb (ideally from overlapping spots in the detrital grains) is a necessary supplement to U–Pb ages. In this review, only datasets containing both U–Pb and Lu–Hf analyses will be considered.

1.2. Visualization and comparison of combined U–Pb and Lu–Hf data

Univariate U–Pb data from detrital zircons have traditionally been visualized either by histograms or by accumulated probability density plots (Sircombe, 2000). The latter aims to illustrate both the variation in ages and the individual analysis, but has recently been criticized as theoretically unsound (Vermeesch, 2012). Regardless of the statistical basis (or lack of such) for these diagrams, it may be argued that as the number of analyses per sample has increased with the ease of access to fast analytical instruments, there is no longer any need to incorporate analyses of sub-optimal quality into age distribution plots. The alternative method of plotting kernel density estimates (KDE) using a constant bandwidth (Vermeesch, 2012) produces attractive diagrams, but has the danger of forcing data that are by nature discontinuous into an apparently continuous distribution, and also of obscuring the relationship between apparent age resolution and analytical uncertainty. Bivariate, combined U–Pb and Lu–Hf data have most commonly been presented in classical scatterplots with relevant growth curves (e.g. Zeh et al., 2011; Condie et al., 2011; Belousova et al., 2010); bivariate probability density surfaces have been tried (Andersen et al., 2004), and 3D histograms are also possible. In the present study, a combination of scatter plots and bivariate kernel density estimates are used. Kernel density surfaces have been generated over the epsilon Hf vs. age plane for each set of data. For the larger data sets (e.g. the Fennoscandian bedrock data illustrated in Fig. 1), widely accepted optimal bandwidth algorithms (e.g. Botev et al., 2010) generate bandwidths that are less than the average analytical error on individual data points, leading to significant undersmoothing. To allow easy visual comparison, all KDE diagrams have therefore been constructed using fixed bandwidths of 30 Ma and 2 epsilon units, which are taken as conservative estimates of real analytical uncertainty. The total range of variation of a set of data is illustrated by a contour at 0.5% of the maximum peak height of the KDE surface. As can be seen from Fig. 1, this contour gives a reasonably good representation of the total spread of data, including minor age and Hf isotope fractions. Furthermore, this mode of presentation neither depends on visual and potentially subjective pattern recognition nor on external constraints such as the width of histogram bins.

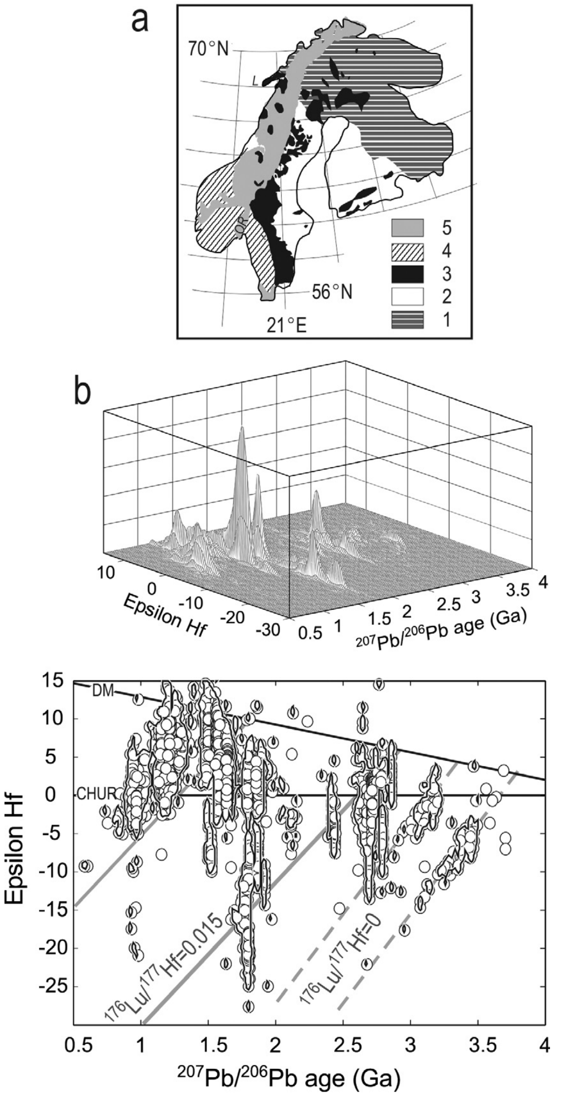

Fig. 1. (a) Geological overview of Fennoscandia, simplified from Koistinen et al. (2001). Crustal domains: 1: Archaean (with Palaeoproterozoic cover sequences and intrusions), 2: Svecofennian (Palaeoproterozoic accreted arc terranes, sedimentary basins and intrusive rocks). 3: Late Palaeoproterozoic to early Mesoproterozoic intrusive rocks (*L*: Lofoten complex). 4: Mesoproterozoic provinces. 5: Phanerozoic cover, including Caledonian nappes and the late Palaeozoic rocks of the Oslo Rift (*OR*). (b) 3D KDE surface showing the frequency distribution of published ^{207}Pb/^{206}Pb ages and $\varepsilon_{\mathrm{Hf}}$ of zircon from gneisses and granitoids in Fennoscandia, assumed to give qualitative impression of the possible zircon yield from Fennoscandian crust. Sources of data: Patchett et al. (1981), Vervoort and Patchett (1996), Andersen and Griffin (2004), Andersen et al. (2002, 2004, 2007, 2009a,b), Pedersen et al. (2009), Heinonen et al. (2010), Kurhila et al. (2010), Lauri et al. (2011, 2012), Heilimo et al. (2013), Andersen (2011), Andersen and Lauri (2010), Poser Bue et al. (2012). Number of grains = 3453. (c) All analyses of zircon from Fennoscandian bedrock compared to a contour drawn at 0.5% of the maximum peak height of the surface in *b*, shown relative to CHUR and Depleted Mantle growth curves. The CHUR model of Bouvier et al. (2008) has been used, together with the Depleted Mantle of Griffin et al. (2000), modified to the CHUR parameters used and the decay constant for ^{176}Lu by Söderlund et al. (2004). The grey lines represent the effect of lead-loss on Archaean zircons (approximated by ^{176}Lu/^{177}Hf = 0, broken lines), and growth-lines of late Archaean and late Palaeoproterozoic crustal reservoirs (solid) with an average crustal ^{176}Lu/^{177}Hf = 0.015.

The use of a non-parametric statistical test such as a bivariate version of the Kolmogorov–Smirnov test (Press et al., 2007) would seem an attractive alternative to the graphical pattern comparison used here. However, any detrital zircon distribution pattern,