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Notes

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ABSTRACT

Detrital zircon spectra reflect the tectonic setting of the basin in which they are deposited. Convergent plate margins are characterized by a large proportion of zircon ages close to the depositional age of the sediment, whereas sediments in collisional, extensional and intracratonic settings contain greater proportions with older ages that reflect the history of the underlying basement. These differences can be resolved by plotting the distribution of the difference between the measured crystallization ages (CA) of individual zircon grains present in the sediment and the depositional age (DA) of the sediment. Application of this approach to successions where the original nature of the basin and/or the link to source are no longer preserved constrains the tectonic setting in which the sediment was deposited.

INTRODUCTION

Detrital zircons are a minor constituent of clastic sedimentary rocks, yet their physiochemical resilience and high concentrations of certain key trace elements means that they have become an important phase in sedimentary provenance analysis and in crustal evolution studies (e.g., Cawood et al., 2007b; Hawkesworth et al., 2010). Large numbers of in situ, high precision analyses of both igneous and detrital zircons are now available, and a striking feature of the zircon record is that it clusters into peaks of crystallization ages (Condie et al., 2009). Compilations of crystallization ages for detrital and igneous zircons show remarkably similar patterns of peaks and troughs, although with some variation in the relative amplitude of the peaks (Condie et al., 2009). This coincidence suggests that the sedimentary record is a valid representation of the magmatic record (Hawkesworth et al., 2010).

We establish that detrital zircon spectra have distinctive age distribution patterns that reflect the tectonic setting of the basin in which they are deposited. These patterns are principally controlled by (i) the volumes of magma generated in each tectonic setting and their preservation potential, (ii) the ease with which magmatic and detrital zircons of various ages and origins become incorporated into the sedimentary record, and (iii) the record of old zircons incorporated into the sediment. These in turn provide a framework that can be used to constrain the tectonic setting of sedimentary packages. This approach distinguishes between three tectonic settings (i.e., convergent, collisional, and extensional), and it is most sensitive when the depositional age of the sediment investigated is well constrained. Basin setting will evolve with tectonic regime; for example, arc-continent or continent-continent collision will result in the evolution of convergent and extensional basins into collisional foreland basins. Hence the three settings distinguished herein are end-members, and the zircon age patterns associated with each show a spectrum of distributions that merge and overlap rather than define discrete fields. Discriminant plots developed for igneous rock geochemistry (e.g., Pearce and Cann, 1973) or sediment framework modes (e.g., Dickinson and Suczek, 1979) often have diffuse boundaries or overlap between fields, but remain important approaches in understanding and constraining tectonic setting. Equally important, exceptions to simple end-member classifications can provide insight into subtleties of tectonic process, such as outlined below for Avalonia in eastern North America.

MAGMA PRODUCTION AND PRESERVATION POTENTIAL

Depending on the tectonic setting, the volumes of magma generated and preserved are very different (Hawkesworth et al., 2009), resulting in variable input of zircon into the sedimentary record. Large volumes of magma are generated in convergent plate margin settings, yet rocks from this setting have relatively poor preservation potential in the geological record (Scholl and von Huene, 2009). Magma volumes generated in collisional settings are low and dominated by granite derived from partial melting of the pre-existing crust (Hawkesworth et al., 2010). The enveloping supercontinent provides preferential protection to the collision generated magmatic rocks resulting in their enhanced preservation potential in the geological record. Magma volumes associated with the extensional phase of supercontinent breakup are variable (White, 1992), but this phase is dominated by mafic magmatism (Storey, 1995) and it is therefore unlikely to result in large volumes of zircons. Rocks in extensional settings are also relatively sensitive to erosion, resulting in poor preservation potential. Thus, the record of magmatic ages is likely to be dominated by periods when supercontinents assembled, not because this is a major phase of crust generation but because it provides a setting for the selective preservation of the magmatic rocks generated (Hawkesworth et al., 2009). Hence basins draining a hinterland with a protracted geological history will display an episodic detrital zircon record that reflects this preservation-induced supercontinent cycle bias.

ZIRCON FERTILITY AND SEDIMENT FLUX

The proportion and age spectrum of zircons available in the source region for incorporation into basinal strata and the efficiency of erosion and transport processes influence detrital zircon age spectra. Zircons typically crystallize from magmas with greater than 60% SiO_2, although they are found in lower silica magmas in lesser abundance. The flux of sediment from source to depositional basin reflects the influence of, and feedback between, relief, climate and tectonic setting. High runoff in zones undergoing crustal thickening and uplift will result in rapid exhumation, erosion and high sediment flux. For instance, the Yellow, Amazon and Brahmaputra rivers are the top three sediment producing rivers in the world whereas rivers draining low relief arid environments have low sediment flux (Summerfield and Hulton, 1994). In the geological record, remnants of high sediment flux events are preserved as thick and extensive sedimentary deposits. For example, the late Mesoproterozoic, “Grenville” and the late Neoproterozoic, “Pan-African” orogens, associated with final assembly of Rodinia and Gondwana respectively, produced huge volumes of sedimentary detritus that were dispersed by systems of braided rivers (Rainbird et al., 2012; Squire et al., 2006). In addition, the high zircon fertility of syn-collisional orogenic plutons (Moecher and Samson, 2006) may further result in the selective enhancement of zircons associated with these events in the preserved sedimentary record.

LINKING BASIN TYPE, TECTONIC SETTING, SEDIMENT INFILL, AND THE ZIRCON RECORD

The type and size of the sedimentary basin, the scale of the hinterland, and the presence and extent of synsedimentary igneous activity are a response to tectonic setting. Basins lying along plate margins (e.g., rift basins, arc-flanking basins, foreland basins) are characterized by syndepositional tectonic activity resulting in spatial and temporal variations in the nature and size of the hinterland and, hence, in sediment provenance. Such basins will be characterized by rapid lateral changes in lithofacies, incorporation of detritus from uplifted nearby sources, and a restricted distributary province. Synsedimentary magmatic activity is likely in such

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settings and hence the youngest detrital zircon grains may approximate the time of sediment accumulation (Figs. 1A and 1B) (Dickinson and Gehrels, 2009). In contrast, basins situated in intraplate (trailing-edge) settings (e.g., passive margins) are tectonically stable. These basins are generally characterized by spatial continuity of sedimentary lithofacies and are fed by a large distributive province at least in part of subdued relief. Synsedimentary igneous activity is generally lacking from such basins, and hence the youngest detrital zircon grains will provide a maximum depositional age that may be tens or hundreds of millions of years older than the time of sediment accumulation (Figs. 1E and 1F) (Cawood and Nemchin, 2001; Cawood et al., 2007a).

The presence or absence of zircon grains with ages approximating the time of accumulation of the host sediment likely reflects the proximity of the basin to a plate margin. The overall spread of ages is a function of the nature of the source and the area of the distributive province, with large hinterlands more likely to provide a variety of source ages. Older source regions provide an episodic, rather than a continuous, age distribution (Hawkesworth et al., 2009).

The interplay between tectonics, basin type and sediment infill means that the detrital zircon record is the summation of two major variables: (1) the presence or absence of synsedimentary magmatic activity, and (2) the overall spread and proportion of different ages recorded. The impact of these variables can be represented graphically by plotting the distribution of the difference between the measured crystallization age (CA) for a detrital zircon grain and the depositional age (DA) of the succession in which it occurs.

Detrital zircon age data plotted with respect to sediment depositional age from a spectrum of basin types are illustrated in Figure 2 and can be grouped into three main tectonic settings: (A) convergent, (B) collisional and (C) extensional. Convergent settings include basins lying within a supra-subduction zone setting, extending from the trench to the back arc basin. Collisional settings incorporate basins formed during and after continental collision, such as foreland basins. Sediment derived from such settings can extend significant distance from the actual site of ocean closure (Rainbird et al., 2012). Extensional settings incorporate rift and post-rift passive margin basins as well intracratonic basins.

The overall range of zircon ages in the different samples (and settings) is broadly similar, but there are significant differences between settings in the proportion of ages associated with youngest and much older magmatic events. Convergent margin basins have a high proportion of detrital zircons (generally greater than 50%) with ages close to the age of the sediment (Fig. 2A). Some forearc and trench basins have unimodal detrital zircon spectra with an age close to the deposition age of the strata whereas back arc basins have increasing input of older detritus from the adjoining craton (Fig. 2A). Basins formed during continental collision (e.g., foreland basins) generally contain only minor amounts of zircons with ages approximating the depositional age of the sediment, but contain a significant proportion of grains (50% to 10%) with ages within 150 Ma of the host sediment (Fig. 2B). This pattern reflects the variable amount of zircon detritus from syn-collisional magmatism and the pre-existing magmatic arc associated with ocean closure as well as a swath of older ages reflecting units caught in the orogenic welt and in the cratonic foreland. Extensional basins are dominated by detrital zircon ages that are much older than the time of sediment accumulation (Fig. 2C) with less than 5% of grains having ages within 150 Ma of the depositional age. Zircon ages close to the depositional age likely reflect rift-related magmatic activity, but this forms only a minor component of the age spectra due to its largely mafic composition and resultant low zircon yield.

IMPLICATIONS

Where the link of source to sink is no longer preserved, detrital zircon age patterns can aid in resolving the original basin setting. Figure 3 shows the general fields for convergent, collisional, and extensional basins determined from the data presented in Figure 2, along with plots for

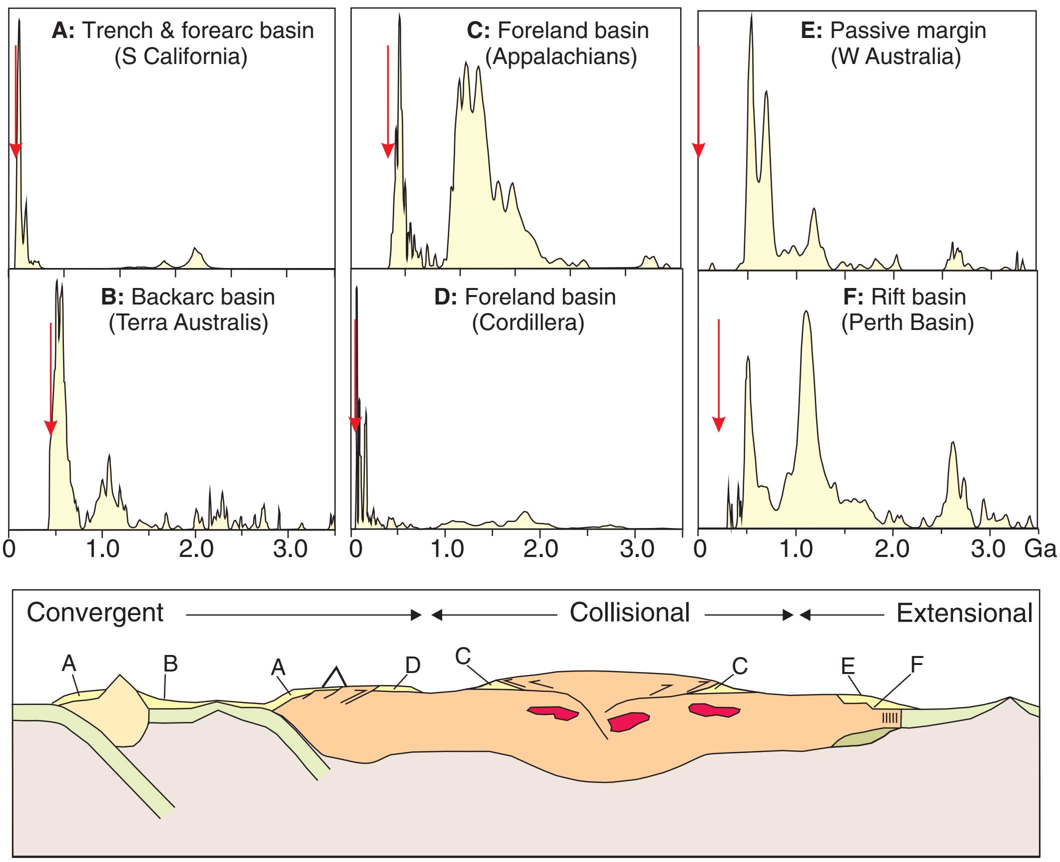

Figure 1. Detrital zircon age spectra for convergent (A and B), collisional (C and D) and extensional (E and F) basins. Sources of data are available in the Data Repository (see footnote 1). Red vertical arrow shows age of sediment deposition. Schematic cross section shows simplified tectonic setting of basins. Arc flanking basins at convergent plate margins are dominated by detritus with ages that approximate the depositional age of the samples with the component of detritus from older sources increasing for those settings that receive input from adjoining cratons (e.g., back-arc basins). Foreland basin samples include detritus with ages close to the depositional age of the sample, reflecting input from syn-collisional as well as convergent plate magmatism, along with significant input from older sources in some samples. Basins lying along extensional and trailing edge settings (rift basin and passive margins) generally lack a component of syn-depositional magmatic activity and are dominated by input from older sources.

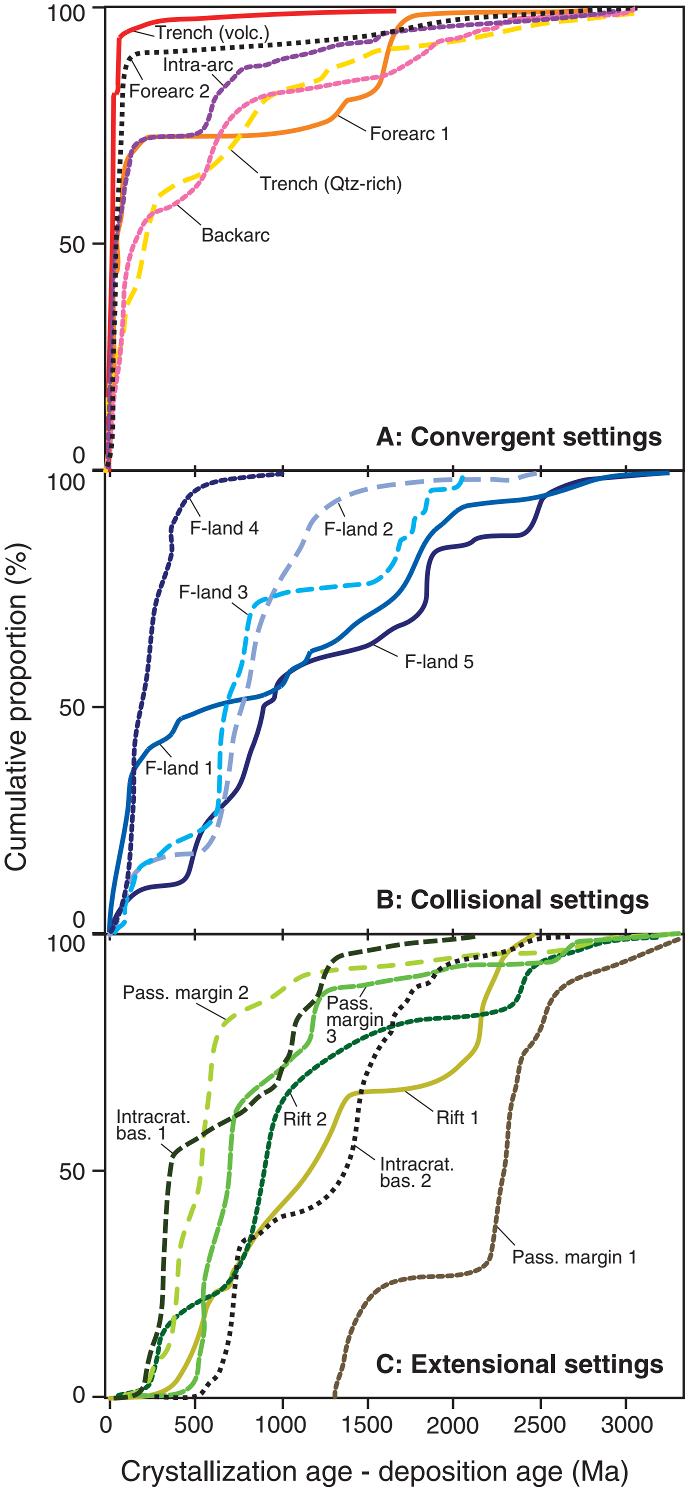

Figure 2. Variation of the difference between the measured crystallization age for a detrital zircon grain and the depositional age of the succession in which it occurs, plotted as cumulative proportion curves, as a function of three main tectonic settings: convergent setting (A), collisional setting (B), and extensional setting (C). A: Forearc 1 and 2 data are from the southern California (United States) margin* and the Great Valley (California) forearc basin, respectively; Trench (volc.) and Trench (Qtz-rich) curves from the Tablelands Complex (Terra Australis Orogen, Australia), from volcanogenic and quartz-rich sandstones data, respectively; Intra-arc data from the Macquarie Arc (Terra Australis Orogen); and backarc data from the Terra Australis Orogen*. B: Foreland data from five different locations (curves F-land 1–5), with F-land 1 from the Cordilleran Orogen*; F-land 2 from the Appalachian Orogen (United States)*; F-land 3 and 4 from the Grenville Orogen (Canada, Scotland and United States) (Torridonian and Middle Run Formations, respectively); and F-land 5 from the Himalayas. C: Rift 1 and 2 curves are from the Caledonian Orogen (Scotland) and the Perth Basin (Australia)* data, respectively; passive margin data from the eastern margin of Laurentia (Pass. margin 1 curve), and from eastern and western Australia* (Pass. margin 2 and 3 curves, respectively); intra cratonic basin data from the Edmund and Collier groups in the Bangemall Supergroup in western Australia (Intrcrat. bas curves 1 and 2, respectively). Data references are given in the Data Repository (see footnote 1). Samples marked with an asterisk are samples shown in Figure 1.

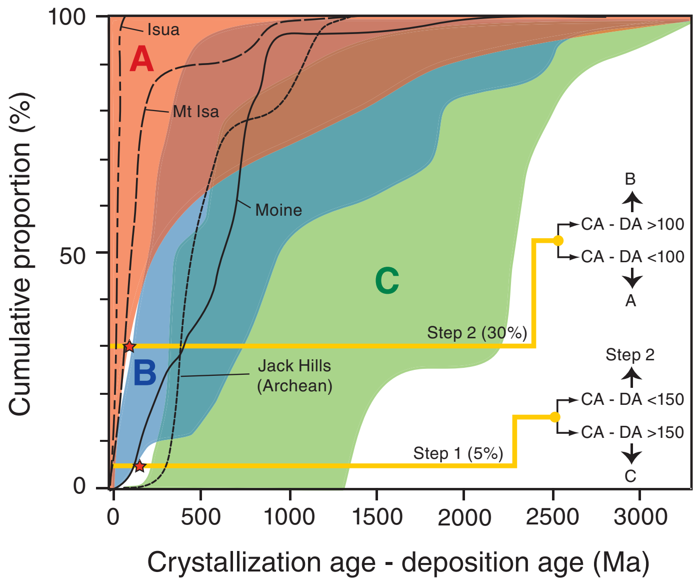

Figure 3. Summary plot of the general fields for convergent (A: red field), collisional (B: blue field) and extensional basins (C: green field), determined from the data presented in Figure 2. From the variations observed between the different fields, a model that enables prediction of the tectonic setting of sedimentary packages of unknown origin is proposed based on differences between the crystallization and depositional ages (CA – DA) of the zircons. Extensional (including intracratonic) settings have CA – DA greater than 150 Ma in the youngest 5% of the zircons (step 1), and all convergent settings have CA – DA less than 100 Ma in the youngest 30% of zircons (step 2). Solid and dashed lines show patterns of CA – DA for a series of structurally disrupted and metamorphosed Precambrian sedimentary successions (i.e., Isua, Mt Isa, Jack Hills, and Moine successions; data references are given in the Data Repository [see footnote 1]).

structurally disrupted and/or metamorphosed sedimentary successions. At Isua, Eoarchean volcaniclastic rocks have a nearly unimodal detrital zircon population similar to the depositional age and consistent with a convergent plate margin setting (Nutman et al., 2009). The Paleoproterozoic Mt. Isa basin is also dominated by detrital zircons ages close to the depositional age (CA – DA < 100 Ma at 30% of the zircon population, Fig. 3), consistent with models arguing for a back arc basin setting and against an intra-cratonic or passive margin setting (reviewed in Cawood and Korsch, 2008). Proposed depositional settings for the end Mesoproterozoic to early Neoproterozoic Moine (and Krummedal) succession in the North Atlantic range from failed rift and intracratonic basin to foreland basin and active margin basin with extensive input from syncollisional detritus (Cawood et al., 2010). The detrital zircon record clearly indicates a syncollisional setting (CA – DA < 150 Ma at 5% and CA – DA > 100 Ma at 30% of the zircon populations, Fig. 3). Microcontinental fragments are common constituents of orogenic belts that are structurally removed from their source. For example, Avalonia is a fragment of a Neoproterozoic to early Paleozoic continental margin arc system that developed on the margin of Gondwana but rifted, drifted and accreted to Laurentia in the mid-Paleozoic (van Staal et al., 2009). Detrital zircons from Ediacaran and early Cambrian strata of Avalonia fall in the convergent basin setting (Fig. DR1 in the GSA Data Repository[1]), consistent with regional relations (Barr et al., 2012). Late Cambrian strata (~500 Ma) fall within field B (collisional basin, Fig. DR1; Fig. 3) despite regional relations that suggest an extensional, rift basin setting (Barr et al., 2012). This discrepancy reflects the fact that in the Late Cambrian, Avalonia represented a fragmenting Andean continental margin rather than an extending stable craton, and it highlights the importance of not slavishly applying tectonic discrimination diagrams independent of other criteria.

SUMMARY

The detrital zircon age patterns of sedimentary basins (Figs. 1–3), like the overall clastic fill of the basins, are controlled by tectonic setting. Basins that contain igneous zircons with ages close to the time of sediment accumulation reflect the setting of the magmatic activity (e.g., forearc, trench, and backarc basins at convergent plate margins). Older grains reflect the pre-history of the basins distributive province and will likely show an episodic pattern. These old zircons may dominate the detrital zircon records in zones of extension and continental collision, in part because the volumes of magma generated at the time (and the numbers of zircons) are much less. The application of detrital zircon patterns to discriminating sedimentary basin type is sensitive to knowing the depositional age of the sediment. The precision with which this age needs to be defined varies with basin type. For basins containing a high degree of igneous activity that approximates, or is only slightly older than the depositional age of the sediment, then depositional ages should be known within a range of some 10 Ma. In contrast, for basins with little or no syndepositional igneous activity, the uncertainty in depositional age can be hundreds of millions of years or greater. For example, the distinctive detrital zircon age spectra of Cambrian passive margin strata in Scotland (Cawood et al., 2007a) fall in the extensional basin setting if the depositional age is taken as 500 Ma or 1500 Ma or anywhere in between. Similarly, the zircon data from the Archean and Proterozoic sedimentary sequences in the Jack Hills of the Yilgarn craton in Australia also indicate accumulation in extensional basins, even though the depositional age is poorly constrained (Fig. 3; Eriksson and Wilde, 2010).

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[1]GSA Data Repository item 2012249, Table DR1 (source of data used for each of the tectonostratigraphic basin types plotted in Figures 1–3), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.