10 Detrital Zircon Analysis of the Sedimentary Record

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INTRODUCTION

The composition of "heavy," or accessory, detrital minerals in sediments and sedimentary rocks has been a topic of quantitative study for at least the last seventy years, beginning with the first issue of the *Journal of Sedimentary Petrology* in May 1931 (Tyler 1931, Pentland 1931). Zircon has since played a prominent and complex role in interpreting the composition and history of modern and ancient sediments. Because zircon is highly refractory at Earth's surface, it occurs in virtually all sedimentary deposits and so provides a critical link in understanding the source history of a deposit. Twenhofel (1941), in a pioneering paper on the frontiers of sedimentary mineralogy and petrology, noted that the simple presence of detrital zircon would be of little value in determining its source: "Zircons from a half dozen sources with as many different properties may be present in a sediment and merely be identified as zircon. *Parent rocks cannot be positively identified on such data*. The variety or varieties must be identified and their optical properties determined." From very early on, then, it was recognized that detrital zircon would be a powerful tool in understanding provenance, and thus, sedimentary dispersal systems.

Interpretive goals matured considerably in the subsequent decades, especially with major advances in microscopy, mineral chemistry, isotope tracer geochemistry, and geochronology, each addressing different aspects of provenance, sedimentation, and Earth history. The hundreds of published studies utilizing detrital zircon in the last 20 years indicate the increasing success in assessing provenance, paleogeography, and tectonic reconstructions. Selected studies are highlighted in this review to illustrate ways in which detrital zircon can be used for interpreting the stratigraphic record, and thus, the past surface conditions of Earth. In it we will outline the quantitative techniques involved in the sampling protocol and interpretation of data and then illustrate the application of detrital zircon studies to: (1) determine maximum age of stratigraphic successions and to help recognize time gaps in the geologic record, (2) determine provenance characteristics such as age and composition, (3) test regional paleogeographic reconstructions via provenance analysis, and (4) unravel facets of Earth history locked in the mineral chemistry of detrital zircon.

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STATISTICS AND METHODOLOGY OF SAMPLING

Detrital zircon analysis uses the interpreted provenance of the zircon to develop a geological history of sedimentary basins and their surrounding source regions. Ideally, the analyzed sample would completely represent geological history by including evidence of all the possible provenances and their relationships to each other. However, natural complexity and artificial bias preclude such a situation.

The aim of any research is to unravel complexity in order to gain insight into natural processes, but this is a formidable task with detrital zircon. The complexity begins with the source rocks themselves, as detrital zircon is not necessarily representative of the entire set of detritus in a sedimentary unit. Rocks with low zircon abundance will be under-represented in a sedimentary sample focusing on detrital zircon. For instance, zircon is not typically found in ultramafic/mafic igneous rocks and any detrital zircon record will underestimate the contribution of such rocks to a sedimentary deposit. Even if zircon is present, then the rock type will determine the amount of zircon present, and, as discussed below, the size of those grains. Beyond the source rock, all detrital minerals are subject to processes during weathering, erosion, transportation, deposition and diagenesis capable of further modifying mineral proportions and compositions. Because zircon has a higher density and hardness than coeval minerals, such as quartz and feldspar that may form the bulk of a sedimentary rock, they will have a different path through these sedimentary processes. There is also general consensus that abrasion may eliminate older, higher-U grains, or regions in such grains, that are more likely to be metamict. Although detrital zircon analysis is a powerful tool, it should always be remembered that evaluating natural complexity in sedimentary systems requires more than one analytical method.

The various processes involved in conducting an analysis can introduce artificial bias and occur from field sampling to the presentation of results. These sources of bias and potential steps for mitigation are discussed below.

Sampling

The potential for bias begins with selecting samples in the field. The nature of the research project dictates the type of sample taken and there are no strict guidelines for sample selection in detrital zircon studies. However, some studies have shown that sedimentary rock type and depositional setting can be a significant factor in the results obtained.

A systematic study of the Methow Basin in northern Washington and southern British Columbia targeted samples at different stratigraphic levels from the same formation (DeGraaff-Surpless et al. 2000). This approach revealed that the age distributions of detrital zircons from the turbiditic Harts Pass Formation were relatively homogeneous throughout the vertical section. In contrast, the fluvial Winthrop Formation revealed great variation in detrital zircon age distributions, commonly within a small spatial distance.

The link between sedimentary maturity and detrital zircon ages is also seen in the Roberts Mountains allochthon, Nevada (Smith and Gehrels 1994). The mature quartz arenite Valmy Formation contains well-rounded detrital zircons revealing a range of U-Pb ages indicative of multiple sedimentary cycles. In contrast, the Harmony Formation contains euhedral zircons generally yielding younger and more homogenous ages.

Linking sedimentological maturity with homogeneity in detrital zircon age distributions cannot be assumed. For instance, in the Slave Province a highly mature metaquartzite was analyzed as part of a regional study. The basal quartzite unit of the Central Slave Cover Group is a distinctive regional marker horizon on the basis of distinct lithostratigraphic correlation (Sircombe et al. 2001). Sensitive high-resolution ion microprobe (SHRIMP) dating revealed a range of Archean modes from five samples. Although there were a number of common components, there also were significant differences among samples. These differences indicate that, despite lithostratigraphic correlation and maturity, the detrital zircons in some samples have a localized provenance and there was only limited mixing between sources.

These cases illustrate the need for careful consideration of sampling strategies. Any detrital zircon study requires thorough knowledge of the depositional environments of the sedimentary units being sampled, assessment of paleocurrent indicators, and the need for regional-scale studies to detect provenance localization.

Sample preparation

The physical preparation of samples for geochronological analysis (cleaning, chipping, crushing and milling) is largely standardized and simple precautions (e.g., sample splitters) are considered to preclude biasing. Little regard is given to the extent of zircon breakage during crushing and milling. Larsen and Poldervaart (1957) conducted tests to compare the zircon yield between separates obtained by acid and crushing and found a significant number of apparently broken zircons in the acid separate. They concluded that the damaged zircons were predominantly a result of imperfect crystallization and that crushing did not significantly contribute to the breakage. This is clearly an area for further investigation. There is little suggestion of Wilfley table and heavy liquid separation causing bias, although detailed investigation is required to confirm this.

Size grading. A major source of bias in laboratory preparation is size grading. Some milling procedures include sieving milled material at 250 μm (60-mesh) or similar, thus excluding larger zircons. Minimum analytical quantities and simple physical limitations on handling exclude smaller zircons. For thermal ionization mass spectrometry (TIMS) analysis, the minimum analyzable grain depends on the expected age and U concentrations (and thus quantity of Pb) and may typically vary between ~45 μm for Precambrian grains to ~100 μm for Mesozoic grains (Gehrels 2000). For secondary ion mass spectrometry (SIMS) analysis, the minimum spot size is typically ~15 μm, although in the near future NanoSIMS technology may reduce this another order of magnitude. In both analytical methods, the physical difficulty of micro-manipulating grains <~30 μm often excludes their use in analysis unless such small grains have been deliberately sought (e.g., aeolian-deposited zircon in soils, Gatehouse et al. 2001). Analyzing grains >100 μm is considered to bias provenance interpretations toward coarse-grained granitoids (Gehrels 2000).

Also considering grain size as a potential provenance indicator and citing standards used in heavy mineral analysis, Morton et al. (1996) advise analysis of the 63-125 μm (very fine sand) fraction in detrital zircon studies. Using such a common size standard is considered crucial in provenance assessment using detrital zircon to avoid the hydrodynamic fractionation in samples of differing grain sizes (Morton and Hallsworth 1994). The increasing use of digital imaging for zircon sample documentation also provides a relatively simple way to quantify grain sizes using image analysis software. Measured grain-sizes can be reported alongside isotopic data to test for any size biases (Sircombe et al. 2001, Sircombe and Stern 2002).

Magnetic separation. Use of a Frantz magnetic barrier separator is a ubiquitous process of both TIMS and SIMS sample preparation, stemming from the long-noted positive correlation between Pb-loss/discordance, U content and magnetic susceptibility (Silver 1963). Heaman and Parrish (1991) speculated that selection of grains from the least-magnetic fraction could cause an artificial bias in the measured zircon age distribution. Sircombe and Stern (2002) confirmed the potential for such a bias in a sample from Dwyer Lake in the Slave Province with a bimodal age distribution. In that study, one age mode had grains with higher α-dosage [as determined following the method of Gottfried and Holland (1955) which was later modified by Murakami et al. (1991)] and thus correspondingly higher magnetic susceptibility. The implicit assumption in such α-dose calculations, however, is that there has not been any thermal perturbation to the zircon crystals since the last geologic event preserved in the crystals, which represents an assumption that cannot always be adequately assessed. The relative proportions of the mode changed with different magnetic fractions and it may have been missed entirely in an extremely non-magnetic fraction. Sampling a relatively broad range of magnetic susceptibilities is recommended for detrital samples and this has been a standard procedure in many laboratories (e.g., Gehrels 2000). Calculating and reporting α-dosage based on isotopic data is a straightforward test for any bias due to magnetic separation.

Analysis

There are two strategies in detrital zircon analysis. The analyst needs to be aware of which strategy they are pursuing because the interpretations based on each strategy are not necessarily identical.

Qualitative analysis. The first approach is a qualitative strategy where ages representing each source component within the population are sought. Gehrels and Dickinson (1995, p. 23) adopted a typical qualitative method where "grains from all color and morphology groups were analyzed irrespective of their abundance among the available grains." This method has an advantage of including potential age components that a purely random selection may miss (Gehrels 2000). Most TIMS and some SIMS detrital zircon analyses follow this strategy. For example, the examination of detrital zircon from the Mount Roberts Formation in the Quesnellia terrane in northern Washington (Roback and Walker 1995) was based on grain morphology and revealed that well-rounded grains were generally Proterozoic and Archean, in contrast to euhedral Devonian zircons. The qualitative approach has been used to establish a reference for a particular unit or region that indicates all possible contributing provenances (e.g., western North America; Gehrels 2000, Gehrels et al. 1995).

The optical classification of zircon grains and their relationship with age components is useful, but as pointed out by Roddick and Bevier (1995), it is not totally reliable. Although initially used as tools for aiding the identification of inherited zircon cores in granitic rocks (e.g., Williams 1992, Hanchar and Miller 1993), back-scattered electron (BSE) and/or cathodoluminescence (CL) imaging of zircon prior to analysis has become routine for detrital studies. As well as aiding the location of ion probe spots to avoid potential defects or zonal overlap, cathodoluminescence can also be used to classify detrital zircon components prior to analysis, as illustrated by Åhäll et al. (1998) in a study of Proterozoic supracrustal units in southern Scandinavia.

Quantitative analysis. The aim of the second approach to detrital zircon analysis, a quantitative strategy, is for the analyzed sample to be as representative of the overall detrital zircon population as possible (i.e., an age component comprising *x*% of the analyses represents *x*% of the total zircon in the sample). Minimizing handling can enhance the randomness of selection during hand-picking. Detrital zircon grains are often scooped en-mass from the slide or petri-dish. During SIMS analysis, an array of mounted zircons is systematically analyzed, and the only operator input is avoiding any obvious imperfections, such as inclusions and metamict zones, and avoiding analysis across zircon domain boundaries (e.g., between core and rim).

Ensuring that an analyzed sample is representative of the population invokes the concept of statistical adequacy. The number of analyses required for a given level of confidence is given by Dodson et al. (1988), which assesses the probability of missing a provenance component comprising a certain proportion that component within the total sample, and the number of grains analyzed. The typical case is a provenance component comprising 1 in 20 in the total sample. Using the expression in Dodson et al. (1988), at least 59 randomly selected grains need to be measured to reduce the probability of missing this component to 5% (Fig. 1).

Achieving such large numbers of analyses for a single sample is prohibitively expensive in TIMS analysis, thus quantitative analysis is generally the domain of SIMS and laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) techniques, where relatively rapid *in situ* analyses can be achieved. The quantitative approach has an advantage of providing meaningful comparisons between the proportions of age components. This is powerfully illustrated in the Perth Basin where detrital zircon samples from various stratigraphic levels within the rift sedimentary sequence have been examined (Cawood and Nemchin 2000). The results revealed a complex pattern of evolving source contributions that challenges simplistic models of a half-graben filling with cratonic debris. Similar cases of sequence evolution have been demonstrated in the Pennine Basin (Hallsworth et al. 2000) and the Great Valley Group (DeGraaff-Surpless et al. 2002). The quantita-

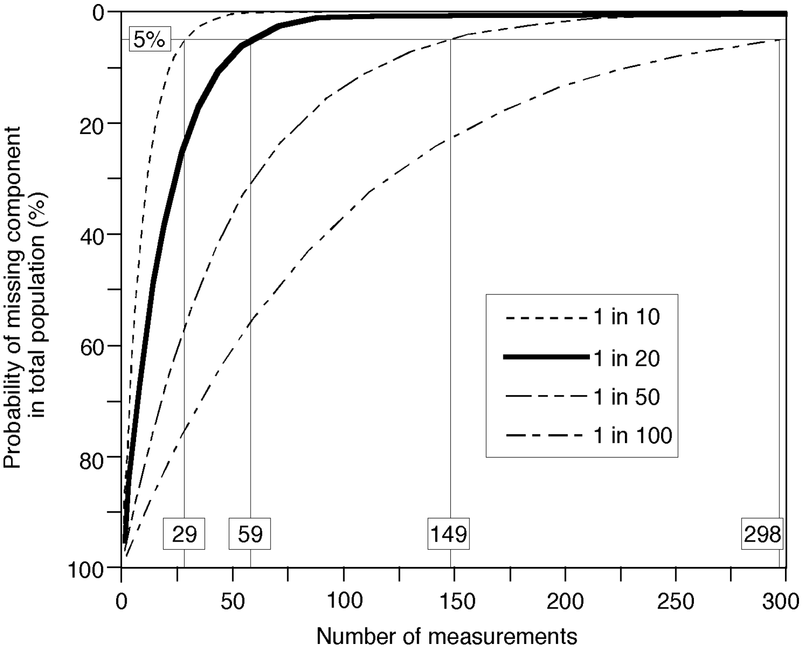

Figure 1. Graphical representation of the Dodson et al. (1988) equation illustrating the probability of missing a provenance component based on number of measurements. Bold line shows the typical case of a provenance component comprising 1 in 20 in the total sample, where analysis of 59 grains reduces the possibility of missing a component to 5%. Other curves show the 5% cut-off for different proportions in the total sample.

tive approach has also been used in modern systems to explore provenance evolution in longshore drift (eastern Australia, Sircombe 1999) and deserts (central Australia, Pell et al. 1999).

Qualitative vs. quantitative. The qualitative and quantitative approaches are complementary, but interpretations are not necessarily the same. For instance, a qualitative regime may reveal significant provenances, but attempting to compare the proportions of age-components among samples (and references) may be meaningless because the selected analyzed grains do not represent the true proportions in the sample. Conversely, a quantitative regime will allow meaningful comparison of proportions, but geologically significant provenances may have been missed. In both cases, care must be taken not to over-interpret the data, given the serious constraints imposed by natural complexity during the formation of a sedimentary unit.

The technique will decide the analytical approach in any detrital zircon project. Without an extraordinary amount of resources, TIMS methods will be restricted to a qualitative regime. Although SIMS is capable of being utilized for both approaches, ensuring statistical adequacy in a quantitative regime remains time consuming and often precludes a complementary qualitative approach. LA-ICPMS is emerging as a technique that may allow for quantitative analysis within a reasonable time frame and cost. TIMS analysis will remain useful to provide precise ages on grains that were first dated by SIMS or LA-ICPMS as being of considerable interest (i.e., the youngest grains in the sample or ones that perhaps match exactly in age with known rocks in a possible source region).

Data display

U-Pb isotopic data are typically displayed using concordia diagrams to convey information about the analytical process such as sample size, accuracy and precision. However, as sample size increases, as is typical of detrital zircon analysis, these concordia diagrams can become visually cluttered. Thus detrital zircon data are commonly displayed in univariate diagrams such as histograms or probability density distributions.

Because the ability to display accuracy in terms of concordance is lost, the first stage of producing a univariate diagram is to filter the isotopic data. For instance, in SIMS studies, this is typically based on an arbitrary constraint on concordance such as between 95% and 105%. Although excluded from further provenance interpretation, it may be beneficial to display both concordant-only and combined concordant-discordant results in diagrams (e.g., Roback and Walker 1995, Morton et al. 1996).

Binned frequency diagrams (Fig. 2) are common method for displaying age data where modes, ranges and proportions may relate to the timing, duration and relative significance of geologic events. While these diagrams are well understood and easily communicate salient information about the data, there are two critical limitations. Firstly, the histograms are based only on the age measurement and the inherent errors in the ages are discarded. Thus a measurement with a ±100 Myr standard error could appear in the same bin as one with a ±1 Myr standard error even though the two measurements are strictly not comparable. Secondly, the size of the bins themselves is arbitrary with values in the literature including 5 Myr (Davis et al. 1994, their Fig. 8B), 20 Myr (Gehrels and Dickinson 1995, their Fig. 6), 33.3 Myr (Scott and Gauthier 1996, their Fig. 4), and 100 Myr (Roback and Walker 1995, their Fig. 8). Morton et al. (1996) suggest a standard bin width for SHRIMP data of 25 Myr. There are a number of mathematical approaches to optimizing bin width (Sircombe 2000a), but these are based on assumptions about the data distribution that are often invalid for detrital suites.

In an attempt to circumvent these two limitations to histograms use of probability density distributions (Fig. 3) has become widespread. These diagrams incorporate the errors in the age data and produce a probability distribution of the entire sample based on Gaussian kernels that vary with each individual age. The mathematical basis for this approach is typically attributed to Silverman (1986), with first application to detrital zircon being Dodson et al. (1988) using a program called "Noveau Stats" developed by Dr. P. Zeitler, then at the Research School of Earth Sciences of the Australian National University (I.S. Williams, written comment). The approach had also been demonstrated earlier for ^{40}Ar-^{39}Ar data (Jessberger et al. 1980).

The disadvantage of this approach is that it is the area beneath the curve that conveys frequency and proportion information rather than the height as in a histogram. Therefore, the number of measurements in each mode can be difficult to communicate and many recent univariate diagrams combine both probability density distributions and histograms (Figs. 4 and 5; e.g., Nutman 2001, their Fig. 4; Sircombe and Stern 2002, their Fig. 2; DeGraaff-Surpless et al. 2002, their Fig. 5).

Interpretation

In igneous and metamorphic systems, geochronological analyses can often be considered as samples from a single, usually normal, distribution. This means that the analyses are amenable to straightforward statistical comparisons of similarity. Many detrital zircon distributions contain multiple modes so that such statistical comparisons are invalid. Early detrital zircon studies generally used visual methods to assess and interpret these distributions both in their relationship to other samples and potential provenances. While such interpretations are often reasonable and valid, a number of quantitative, and objective, methods have evolved to aid interpretation.

Mixture modeling. The first issue in detrital zircon interpretation is identifying, or deconvolving, the inevitable mixture of age modes seen in the distribution. If age modes are relatively close, then resolution may be compromised by the inherent errors in the measurements and it will be difficult to objectively identify the age modes. This is notable with lower precision SIMS analyses. Building on the experience in similar situations with fission-track dating (Galbraith and Green 1990), Sambridge and Compston (1994) developed a mixture modeling method that estimates the most likely ages, proportions and number of components in a set of zircon data, based on a maximum likelihood approach. This method has been used widely in zircon analyses, particularly detrital studies, although it emphasized that the results obtained are models of the age distribution and thus

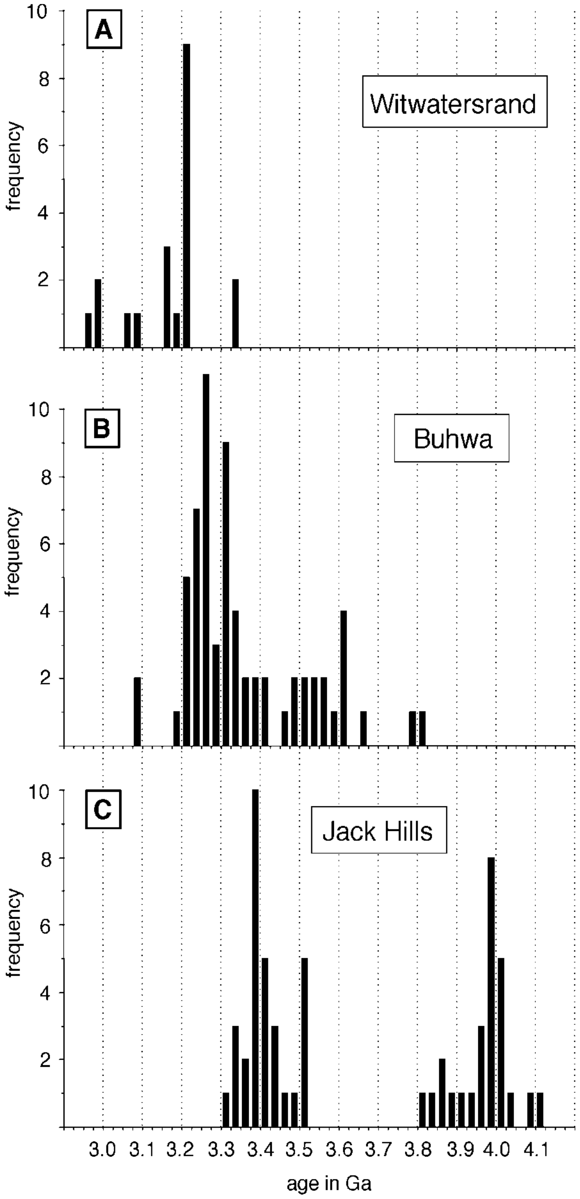

Figure 2. Frequency histograms for detrital zircons from three quartzites deposited at ~3.0 Ga. Bin width for histograms is 25 Myr. (A) Grains analyzed using SHRIMP from the Orange Grove Quartzite Formation, Witwatersrand Supergroup, South Africa (data from Barton et al. 1989). (B) Grains analyzed using SHRIMP from Buhwa quartzite, Zimbabwe (data from Dodson et al. 1988). (C) Grains analyzed by TIMS from meta-conglomerate, Jack Hills, Western Australia (data from Amelin 1998). Nelson (2001) reported a single grain at ~3.1 Ga and Wilde et al. (2001) reported grains up to 4.404 Ga from different samples from the Jack Hills. These are not shown on this frequency histogram.

need to be treated with caution when correlating with known references.

Comparisons. A fundamental aspect of detrital zircon geochronology is the comparison of data with other detrital data or with known provenances to interpret origins of the zircon. This requires a priori knowledge of the age distributions of potential provenances. A number of cases have illustrated the need to look widely for sources (e.g., Rainbird et al. 1997).

There have been a number of attempts at moving beyond simplistic visual comparisons of age distributions. Gehrels (2000) introduced the concept of overlap and similarity between new samples and established western North American references. Both values vary from 0.0 to 1.0 and use the calculated probability distributions of the analyses incorporating the inherent errors (as above). Overlap is defined as the presence of an age in both age distributions being compared (Gehrels et al. 2002). Similarity is calculated by summing the square root of the product of each pair of probabilities. While quantifying visual comparison, neither can be considered an objective statistical test when using a qualitative analysis.

In order to compare potential provenance similarities between Tasmania and North America, Berry et al. (2001) used Kolmogorov-Smirnov (K-S) goodness-of-fit tests. This provides a statistical basis for hypothesis testing that the samples are similar, but the standard method is potentially insensitive to dispersed data (Press et al. 1986) and does not account for age errors.

Multivariate statistical analysis has also been applied to large sets of detrital zircon data in eastern Australia (Sircombe 2000b). Based on the age probability distributions this approach proved useful in quantifying the effect of longshore drift on the detrital zircon age distributions without

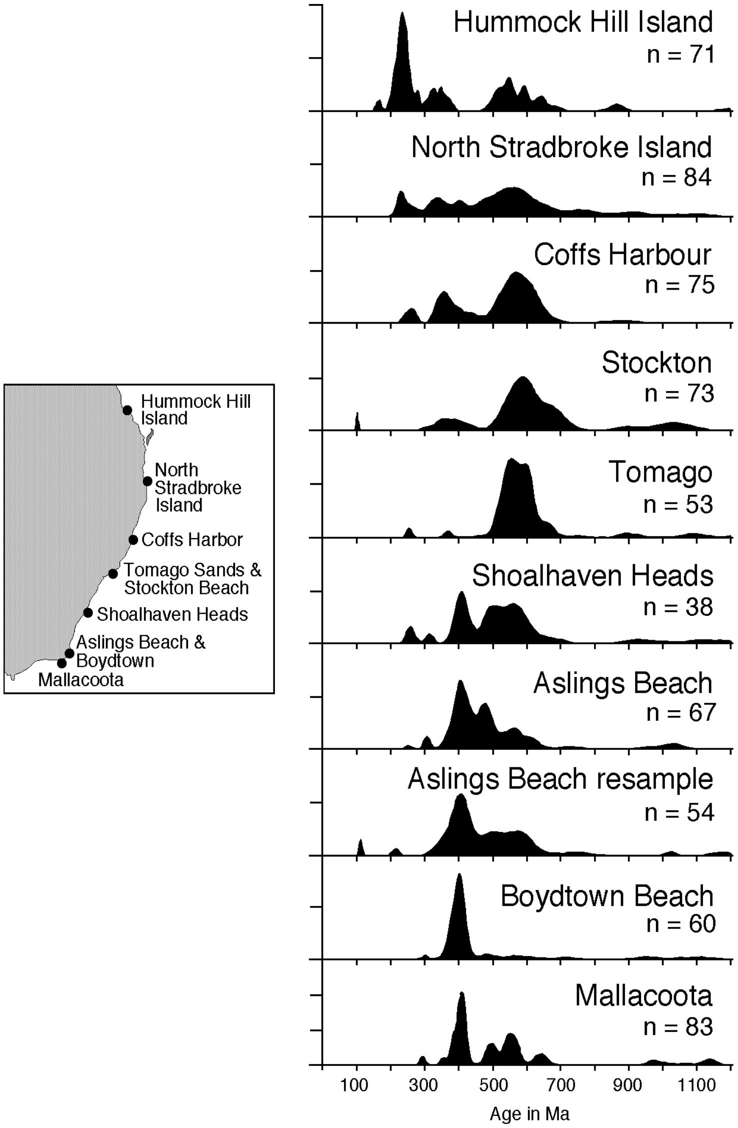

Figure 3. Probability distribution diagrams of zircon ages for modern sediments on the eastern coast of Australia. n is the number of grains analyzed. Modified from Sircombe (1999).

direct comparison with external references. However, the method is cumbersome and only beneficial for comparison of ten or more samples (unless a statistical software package like JMP, Systat, or MVSP is used).

AGE OF STRATIGRAPHIC SUCCESSIONS

Maximum age and age bracketing

One of the common goals in a detrital zircon study is to place constraints on the ages of siliciclastic stratigraphic successions. The premise, based on the principal of inclusions, is simply that age of deposition must be younger than the age of the youngest detrital zircon (typically U-Pb dating), with the proviso of no disturbance in the U-Pb isotopic system. The results are typically crude in the sense that only the maximum age of deposition is generally revealed. Detrital zircon studies where this has been done include Barton et al. (1989) and Robb et al. (1990) for the Archean

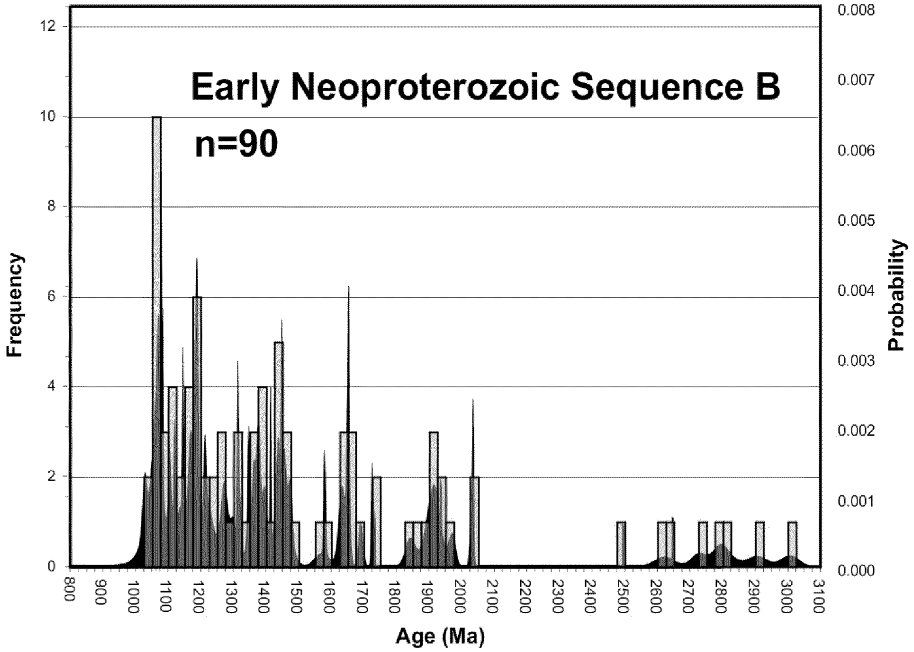

Figure 4. Probability density distribution-histogram plot of $^{207}Pb/^{206}Pb$ ages of detrital zircons from early Neoproterozoic quartzarenites from northwestern Canada, including the Shaler Supergroup, Mackenzie Mountains Supergroup and Hematite Creek Group (ID-TIMS data from Rainbird et al. 1997).

Witwatersrand Supergroup (Fig. 1A), Sircombe et al. (2001) for quartzites in the Archean Slave Province, Canada, and in the case of the Stirling Range Formation, Western Australia which brackets the age of the currently oldest known metazoans (Rasmussen et al. 2002). However, when detrital zircon geochronology is linked with geochronology of crosscutting younger igneous rocks or metamorphic mineral ages (e.g., Schiøtte et al. 1988), then both a maximum and minimum age bracket for deposition can be determined. Because of the crude age constraints provided by this approach, it is most widely applied to Precambrian successions where biostratigraphy cannot be used.

This approach yielded surprising results in the supracrustal rocks of the Zimbabwe Archean craton. Dodson et al. (1988) determined the age of several tens of detrital zircon grains using the SHRIMP from a thick (~1 km) orthoquartzite from the Buhwa (Mweza) greenstone belt in a search for very ancient grains, perhaps comparable in age to those discovered in the Jack Hills, Australia (Froude et al. 1983). Although the search for >4 Ga grains was unsuccessful (cf. Fig. 2B and C), the detrital zircon population in the orthoquartzite yielded a polymodal age distribution with modes at ~3250 Ma, ~3600 Ma, and a small mode at ~3800 Ma, with the youngest grain at 3.09±0.08 Ga. Realization of the importance of the detrital zircon age spectra for Buhwa did not come until much later. The distribution of zircon ages, and thus, basement ages is consistent with the sedimentary package at Buhwa being related to either of the two major episodes of craton-wide supracrustal greenstone deposition known as the Lower (~2.9 Ga) and Upper (~2.7 Ga) Bulawayan groups (Wilson et al. 1978). However, recognition that the tonalites that intruded the quartzite succession correlated with the nearby ~2.9 Ga Chingezi tonalite suite required that the succession at Buhwa represent an entirely unknown cycle of sedimentation in the Zimbabwe Archean craton, deposited between ~2900 and 3100 Ma (Fedo et al. 1996). The presence of similar aged orthoquartzite and shale deposits in the Kaapvaal craton and intervening granulite-facies Limpopo Belt south of the Zimbabwe craton suggests that the Zimbabwe craton was an integral part of the Archean crust in southern Africa by this time.

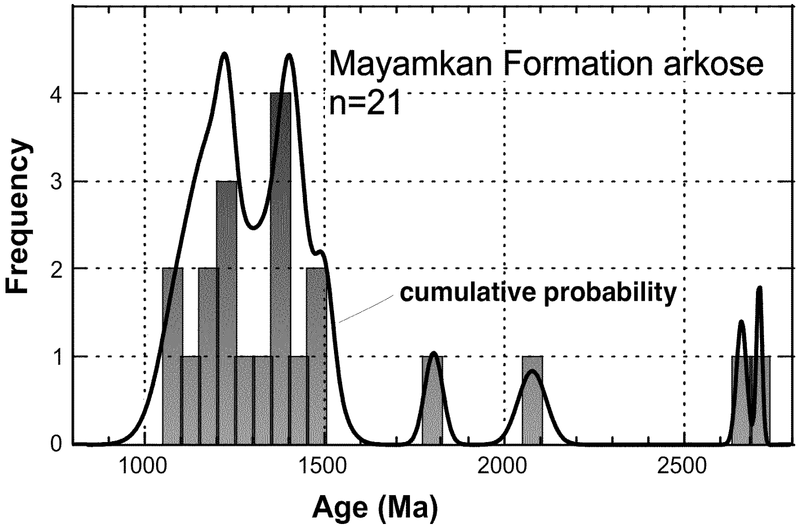

Figure 5. Probability density distribution-histogram plot of $^{207}Pb/^{206}Pb$ ages of detrital zircons from an arkose collected from the upper Uy Group, an early Neoproterozoic sequence from southeastern Siberia (SHRIMP data from Rainbird et al. 1998). Note the comparative similarity of the data from northwestern Canada shown in Figure 7.

Direct depositional ages

The most reliable means of directly determining depositional sedimentary ages is through the dating of interstratified volcanic rocks, such as those near the Precambrian–Cambrian boundary (e.g., Bowring et al. 1993, Bowring and Schmitz, this volume), or with the newly emerging possibilities of dating time-of-deposition authigenic xenotime overgrowths on detrital zircon grains (e.g., McNaughton et al. 1999).

Because of their "passive" subsidence mechanisms, many cratonic and continental margin successions lack abundant volcanic units for direct dating. In Precambrian, or pre-Devonian terrestrial, successions the problem is compounded by the absence of a biologic record. Although the global volume of Precambrian strata is small relative to that of the Phanerozoic due to recycling, Precambrian deposits exist on all the continents and the Precambrian accounts for nearly 90% of Earth history. Consequently, extracting depositional ages for much of the stratigraphic record is fraught with uncertainty.

Under certain circumstances, the age of the youngest detrital zircon in a population can approach the age of deposition (Nelson 2001). This method, which has utilized SHRIMP analyses, depends on three major conditions and the premise that by tightening the age constraints of the youngest detrital zircon by pooling analyses on a few grains, a single grain, or even a single analysis, an accurate interpretation can be made (Nelson 2001). The first condition is that the studied samples should be at a low metamorphic grade in order to exclude contaminants such as veins and melt patches formed after deposition. Secondly, because the youngest detrital age may come from a single grain, great care needs to be exercised to avoid field and laboratory contamination. Lastly, only the least weathered or altered samples should be collected in order to avoid problems associated with isotopically disturbed samples (Nelson 2001).

This method of determining depositional age was applied by Nelson (2001) to three Precambrian basins in Australia, including a quartzite from the Jack Hills in the Archean Yilgarn Province. Metaconglomerate and quartzite from this region are renowned for hosting very ancient (up to 4404 Ma) detrital zircons (Fig. 2C; Froude et al. 1983, Wilde et al. 2001), yet its depositional age is considerably younger than the oldest detrital grains. The sample analyzed by Nelson (2001) contains five major detrital zircon age populations, three of which (~3360 Ma, ~3400 Ma, and ~3480 Ma) can be assigned to various gneiss sources in the adjacent Narryer Complex, and a population of >4 Ga grains derived from a different composite gneiss terrane. Five analyses of a single grain define the fifth group at 3064 Ma. Kinny et al. (1990) suggested a maximum age of deposition of the metasedimentary protoliths at 3100 Ma by association with other metasedimentary sequences, while Maas and McCulloch (1991) interpreted detrital zircon ages and Nd isotopes to indicate a depositional age between 3.0 and 3.1 Ga. Consequently, the youngest detrital zircon group identified by Nelson (2001), Maas and McCulloch (1991), and Compston and Pidgeon (1986) at slightly greater than 3.0 Ga closely approximates the inferred time of deposition.

A key part of the success of this approach, according to Nelson (2001), is that highly mature sedimentary successions be sampled to ensure a broad spectrum of zircon source ages. However, there are some obvious limitations to the technique, and the extent of these limitations cannot be known in advance. For example, the youngest detrital zircon grains in some Holocene beach sands in eastern Australia are Permian (Sircombe 1999), some 250 Myr older than the age of deposition. Also, although Nelson (2001) does not favor sampling texturally and mineralogically immature sediments such as those found in tectonically active basins, the study by Kimbrough et al. (2001) indicates that Turonian forearc sediments in southern and Baja California received detrital zircons of essentially the same age from a rapidly crystallizing, uplifting, and eroding Peninsular Ranges batholith. Lastly Nelson (2001) recognizes that because of low temperature Pb loss, a detrital zircon could yield an age younger than the time of deposition. Despite these limitations, the near ubiquitous presence of zircon in sedimentary deposits makes them an ideal target for precise U-Pb age dating and at the very least establishing the maximum age of deposition.

Disconformity recognition

Disconformities, which are relatively easy to identify in fossiliferous sedimentary successions, commonly provide critical information about the subsidence mechanisms of sedimentary basins because they reveal information about coeval tectonics/uplift and sea-level fluctuations. In the absence of fossils to identify gaps in the geologic record, Precambrian basins are prone to major misunderstandings in properly identifying stratigraphic packaging, even on the continental scale of Sloss Sequences (e.g., Sloss 1988a). In many circumstances, km-thick sedimentary packages contain few, if any, interlayered volcanic rocks for direct dating, so that detrital zircon grains and sedimentary-reworked ash deposits provide the only critical age constraints for assembling time-stratigraphic packages and making interbasinal stratigraphic correlations.

The kilometers-thick Paleoproterozoic Hurwitz Group in the western Churchill Province of northern Canada provides an excellent example where detrital zircon ages, together with bulk rock isotopic analyses have revealed a time gap of approximately 200 Myr across a cryptic internal unconformity within the succession (Aspler et al. 2001; Fig. 6). Hurwitz Group strata, which crop out over an area of approximately 140,000 km^2, are divided into four major sequences, with basal deposits resting unconformably on a varied assemblage of Archean (2.6-2.7 Ga) granite-greenstone rocks and locally developed siliciclastic rocks of the Montgomery Group (Aspler et al. 2001). The rocks are exposed as a north-east trending series of infolded erosional remnants and are inferred to have been deposited in an intracratonic basin (Aspler et al. 2001), though they may form part of a much larger depositional basin that accumulated near the margins of Late Archean proto-continents (Young et al. 2001).

Sequences 1 and 2 were derived from predominantly Archean sources, with detrital zircons in sequence 1 ranging from 2750 to 2650 Ma (Patterson and Heaman 1990, Davis et al. 2000); gabbro sills that yield 2111±1 Ma U-Pb baddeleyite ages (Heaman and LeCheminant 1993) are scattered through sequence 2 and provide a minimum age of deposition for the lower two sequences, which were deposited in response to continental stretching and break-up processes (Aspler et al. 2001). Sequences 3 and 4, by contrast, contain abundant Proterozoic detrital zircons (2.50-1.91 Ga) as well as Archean grains, suggesting a significant change in provenance between sequences 2 and 3 (Davis et al. 2000, Aspler et al. 2001) and a depositional age younger than the youngest detrital grain at 1.91 Ga. Stratigraphic relations for sequences 3 and 4 are consistent with deposition in response to crustal shortening. Consequently, the contact separating sequences 2 and 3 represents a disconformity spanning 200 Myr, but a hiatus of this magnitude was not predicted from stratigraphy alone, and the duration, spanning half the time of a Wilson cycle, was critical in linking regional tectonic events with stratigraphic sequences that formed in their response. This example illustrates the critical need for detrital zircon geochronology in poorly or non-fossiliferous successions.

PROVENANCE ANALYSIS

Petrographic and petrologic

"Heavy," or accessory, mineral suites, including zircon, have been used extensively as markers of petrologic identity and provenance in sediments and sedimentary rocks. In most circumstances, the accessory mineral assemblage was used to identify provenance composition on a grand scale, such as in the example of Carroll (1941), who recognized that the "heavy residues" from Cretaceous sediments in Western Australia could have been derived from spatially related "pre-Cambrian" shield rocks. Becker (1931) examined the heavy mineral assemblage, including zircon, of Precambrian and Paleozoic quartzites of the Baraboo Range, Wisconsin and recognized that it was similar to underlying bedrocks and suggested them as potential source, but he recognized that even accessory minerals do not necessarily fingerprint a specific source when the assemblage contains nothing unique. By contrast, the Paleozoic quartzite contains tourmaline and garnet. These minerals were not found in the underlying quartzites and suggested a distant provenance for some of the detritus.

Hubert (1962) defined a ZTR (zircon-tourmaline-rutile) index as a measure of mineralogic maturity of a sedimentary deposit and noted the importance of heavy mineral assemblages in determining provenance and paleogeographic reconstructions, a technique still widely applied today (e.g., Dill 1995, Garzanti et al. 2001). Morton and Hallsworth (1994) recognized that the final accessory mineral assemblage in a deposit was varyingly affected during weathering, transport, deposition, and diagenesis, so that it should be unlike that of the source. They proposed that certain mineral ratios, such as TiO_2-minerals:zircon, monazite:zircon, and Cr-spinel:zircon, in sediments should reflect source values because of their similar hydrodynamic properties and diagenetic behavior. Hallsworth et al. (2000) expanded this approach by adding U-Pb dating of detrital zircons. Schäfer and Dörr (1997) and Loi and Dabard (1997) have applied the zircon typology characteristics recognized by Pupin (1980) to identify provenance in Paleozoic sandstones in Germany and Italy, respectively, and Dunkl et al. (2001) combined typology with the study of zircon fission tracks, although the general utility of zircon typology is debatable (Vavre 1993), especially in sedimentary deposits where original crystal faces may be abraded through transport.

Most of the papers discussed to this point emphasize the traditional sedimentary petrology approach to provenance analysis based on thin section microscopy of accessory minerals that include zircon, and show that microscopy is still a widely applied approach. Adherence to this traditional approach also underscores the historically divergent routes of sedimentary versus igneous and metamorphic petrology, which have focused not only on petrography, but also on bulk geochemistry, mineral chemistry, and isotope geochemistry.

Geochemistry

Zircon chemistry has been considered a potential provenance indicator functioning on the notion that its chemistry is sufficiently variable in different source rocks to enable their identification. Owen (1987) analyzed the hafnium concentration in detrital zircons from the Pennsylvanian Jackfork Sandstone and Parkwood Formation in the south-central United States. Based on a "statistically insignificant" difference in Hf concentration in the detrital zircons, he suggested that these

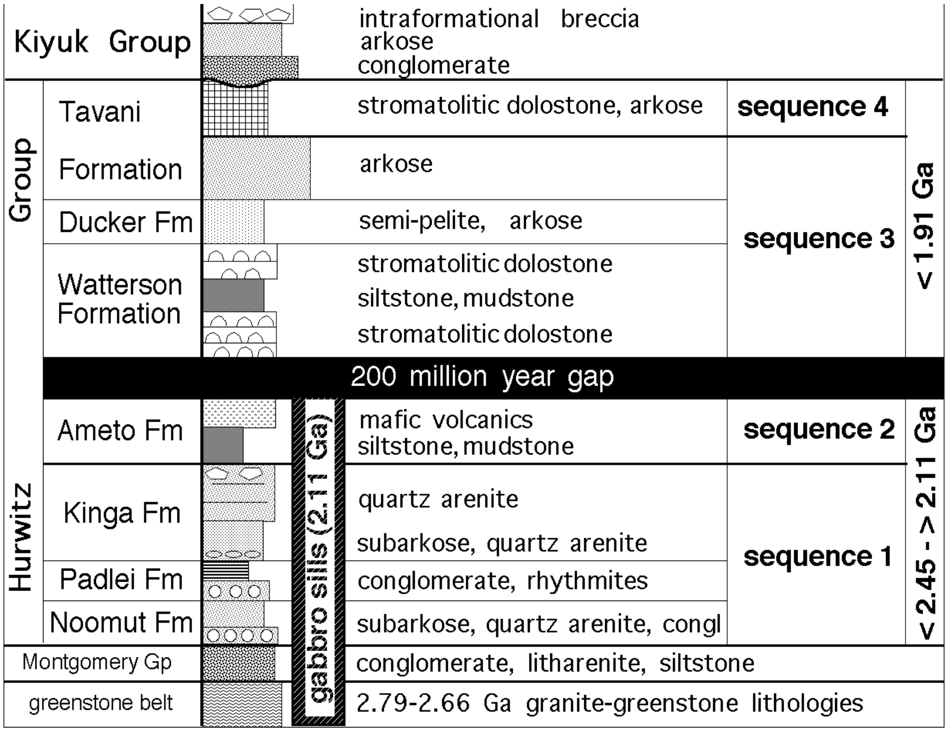

Figure 6. Stratigraphic context of the Hurwitz Group, Canada, showing a 200 Myr disconformity within the stratigraphic section, revealed in part by detrital zircon geochronology. Modified from Aspler et al. (2001).

sandstones were derived from a similar proximal source, distinct from that of other stratigraphic units. Hoskin and Ireland (2000) tested the hypothesis that there might be enough variation in rare earth element (REE) concentrations in zircon to differentiate their origin. Unlike the findings of Owen (1987), however, the investigation of zircon REE compositions showed that they are generally not sufficiently varied to provide a sensitive provenance indicator (Fig. 7), except perhaps in extreme compositions such as kimberlites (Griffin et al. 2000).

Fission track (FT)

Detrital zircon fission track (FT) analysis has been used successfully to identify provenance characteristics that differ from those derived by U-Pb geochronology (see below) because fission tracks yield data on low temperature (200-320°C) processes, such as source terrane thermo-tectonic evolution (Garver and Brandon 1994, Carter and Moss 1999, Liu et al. 2001, Bernet et al. 2001). Consequently, detrital zircon FT ages do not represent unambiguous provenance ages, except in circumstances where this can be confirmed with single crystal U-Pb geochronology (Carter 1999), a promising direction for zircon FT analysis (Carter and Moss 1999). The strength in zircon FT analysis is that it can document low-grade metamorphic events characteristic of a specific terrane. Such events would be otherwise missed because U-Pb dates are reset at higher temperatures. Detrital zircon FT is most applicable in provenance reconstructions for evaluating source denudation rates and providing depositional age constraints in unfossiliferous successions (Carter 1999).

Geochronology

U-Pb geochronology is by far the most powerful and common technique for extracting source information from detrital zircon grains. It has been in use for about forty years (e.g., Ledent et al.

1964, Tatsumoto and Patterson 1964). This approach has been revolutionized with the development and use of SIMS (Ireland and Williams, this volume) and LA-ICPMS (Kosler and Sylvester, this volume), which permit rapid analysis of many grains (Kosler et al. 2002), so that large data sets useful in provenance analysis can be evaluated. Dating of individual grains potentially permits the identification of specific source rocks. However, because zircon is so refractory, a problem that may be encountered is that of recycling, such that the U-Pb age provides information about the initial source, and not about a younger recycled sedimentary source (e.g., McLennan et al. 2001). This problem can be addressed in some measure by evaluating bulk rock Zr/Sc, which becomes increasingly elevated as more zircon (the primary host for Zr) is sequestered at the expense of Sc-bearing phases lost to multiple episodes of weathering and deposition (McLennan et al. 1993). The following examples, illustrating the use of detrital zircon geochronology as a provenance indicator, are grouped by age of deposition.

Archean. The geologically significant Archean Witwatersrand Supergroup in South Africa is a kilometers-thick siliciclastic package that hosts the largest known gold and uranium deposits in the world. Barton et al. (1989) determined the provenance ages for two units of the Witwatersrand and showed that the dominant source had zircon ages between 3100 and 3200 Ma (Fig. 2A). These results suggested a granitoid source NW of the basin and determined a maximum depositional age for the units at just under 3000 Ma, not unlike the results of broadly correlative quartzites in Zimbabwe (Dodson et al. 1988, Fedo and Eriksson 1996). These studies followed on the heels of a pioneering study of detrital zircons on Mount Narryer (Yilgarn Province) by Froude et al. (1983), who identified >4 Ga grains in a quartzite deposited at about 3.0 Ga (Nelson 2001). Recent work on a metaconglomerate from the nearby Jack Hills has identified a detrital grain as old as 4.404 Ga (Wilde et al. 2001), extending the terrestrial record nearly to the age of the Earth. This unit will be discussed in more detail below.

The Archean Slave Province in Canada represents a composite granite-greenstone terrane that forms part of the Canadian Shield. Sircombe et al. (2001) examined the age spectra for detrital zircons from five quartzite units that form part of the Central Slave Cover Group, which sits unconformably on ~4.0-2.9 Ga basement. Examined samples do not share a single age mode, however, significant overlap in some modes supports a shared provenance. A distinct age population in one sample suggests that it may be some 30 Myr older than the other samples despite a strong basis for lithostratigraphic correlation. Tectonic processes controlling deposition may also have been diachronous. In either case, without geochronology, the problem would not have been recognized.

In a parallel study of detrital and magmatic zircon grains from nearby granitoids from the Yangtze craton, China, Qiu et al. (2000) highlighted the complexities of interpreting zircon geochronology in geologically complex terranes that have been intruded and metamorphosed. Trondhjemite plutons yield populations of zircons at 2.95 and 2.90 Ga and younger populations at 2.75 and ~1.9 Ga. The older dates are considered to be the intrusive age and the younger ones are metamorphic ages. Detrital zircons from adjacent metapelites have abundant 2.95 Ga grains indicating that the trondhjemites were the dominant provenance. The youngest detrital zircon is 2.87 Ga, and because both the pelites and trondhjemites were metamorphosed at upper amphibolite facies at 2.75 Ga, the age of deposition can be bracketed. The metapelites also contain detrital grains >3.2 Ga providing evidence of an older Archean sialic provenance in the Yangtze craton, which had been previously thought to be Proterozoic (Qiu et al. 2000).

Proterozoic. Paleoproterozoic rocks of the Nagssugtoqidian orogen in West Greenland consist dominantly of Archean gneiss protoliths reworked at upper amphibolite and granulite facies conditions (Nutman et al. 1999). The foreland to the orogen has been intruded by a set of mafic dykes dated at ~2040 Ma in advance of the main TTG plutonism and tectonism at ~1920-1800 Ma. Detrital zircon ages from two samples of allochthonous meta-pelites in the foreland sequence have ages between 2100 and 1950 Ma. Such ages suggest the presence of a presently unknown igneous provenance that coincided with intrusion of the mafic dykes (Nutman et al. 1999). Samples of quartzite

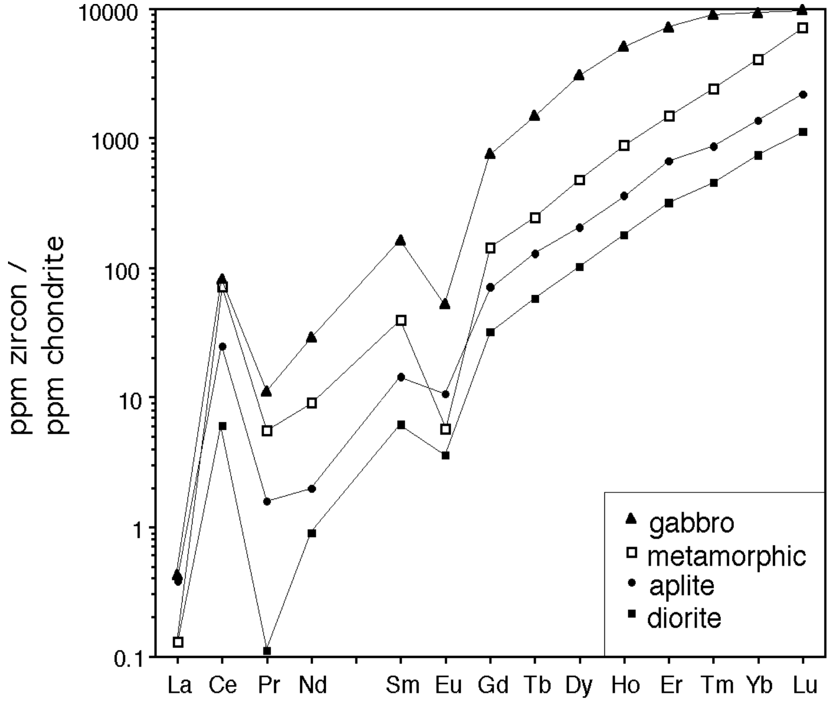

Figure 7. REE plots for zircons derived from compositionally disparate sources. The plots show that zircon composition is not dramatically different regardless of composition. Consequently, REE typically cannot fingerprint provenance. Note particularly the similarity of patterns for aplite, diorite, and high-grade gneiss from Sri Lanka. Such lithologies dominate the major composition of the continental crust and so are likely to represent a large fraction of detrital grains in continental sedimentary deposits. Data from Hoskin and Ireland (2000).

yielded detrital zircons with ages that include modes at 3300-3400 and ~2400 Ma, neither of which can be linked to potential sources in Greenland, which suggests derivation from a distal provenance.

Studies of detrital zircons in the Mesoproterozoic Belt Supergroup in the northwestern United States and southern Canada have implications for pre-Rodinia continental assembly. Ross et al. (1991) and Ross et al. (1992) identified detrital zircon ages from different units in Belt rocks that were westerly derived to test whether the sediment had come from known North American sources. They reported populations of detrital zircon populations of 1070-1244, 1590-1600, and 1670-1859 Ma. In particular, there are no known probable sources in western North America that could provide ~1.6 Ga detritus, and the 1070 Ma grains hint that the top of the Belt Supergroup is some 200 Myr younger than previously thought or that this represents discovery of a unit younger than the Belt. In combination with Nd isotopic data, the detrital zircon ages suggest that basement terranes of south-central Australia were joined to western Laurentia during the Mesoproterozoic, and provide a template for understanding the Neoproterozoic fragmentation history of Rodinia.

Paleozoic. One of the earliest papers to evaluate provenance by examining U-Pb ages of detrital zircons is that of Gaudette et al. (1981). They took a sample of Cambrian Potsdam Sandstone from the eastern flank of the Adirondack Dome, New York State, and separated four populations of zircon crystals based on color, crystal habit, and morphology and analyzed, for the first time, *single zircon grains* and small groups from the same population to extract defined provenance ages. Prior to this work, multi-crystal dissolutions yielded average provenance ages. Gaudette et al. (1981) identified provenance ages of 1180, 1320, 2100, and 2700 Ma (Fig. 8). These ages could be linked to known sources in the Superior and Southern Provinces of the Canadian Shield (2100, 2700 Ma), Grenville Province of the Adirondacks (1180 Ma), and pre-Grenville rocks presumably from the Adirondacks (1320 Ma). A broadly similar conclusion was drawn by Johnson and Winter (1999) for lower Paleozoic quartzites from the mid-continent of North America. Besides showing the importance of imaging to define distinct zircon populations, Gaudette et al. (1981) demonstrated that sedimentary processes may sample large tracts of exposed bedrock, such that important geologic events spanning more than a billion years could be preserved and detected in a single sample of sandstone.

Fault-bounded Lower Paleozoic sedimentary rocks from Alaska examined by Gehrels et al. (1999) reveal partly overlapping and partly contrasting provenance characteristics for Cambrian and Devonian sandstones. A sample of Cambrian Adams Argillite has three main age modes, two of which indicate provenance from the Canadian Shield (1801-1868, and 2564-2687 Ma) and a third (1047-1094 Ma) may indicate derivation from the Grenville orogen in eastern Laurentia (thousands of km distant), a terrane in the Canadian Arctic, or some presently unexposed provenance. The Devonian Nation River Formation has detrital zircon populations that are Archean and Paleoproterozoic as well, and is also thought to have been derived from the Canadian Shield. It also has a population between 424-434 Ma that could have been derived from Cordilleran terranes such as the Alexander, or rocks of the Caledonian orogen, or perhaps the high Canadian Arctic (Gehrels et al. 1999).

Later Paleozoic units stretching from Ireland to Poland form part of a kilometers-thick package of sediments whose sources are critical in unraveling Carboniferous paleogeography in the region (Drewery et al. 1987). U-Pb dates from detrital zircons from fluvial sandstones collected in the United Kingdom indicate active erosion of Archean provenances, perhaps located in western Greenland or Fennoscandia and grains recycled through the Caledonian. Drewery et al. (1987) recognized that the provenance ages seemed to require a "huge" continental-scale drainage system, a conclusion that foreshadowed understanding of the massive sedimentary dispersal systems covering Rodinia and Laurentia during the Neoproterozoic and Cambrian (discussed below).

Mesozoic and Cenozoic. Cawood et al. (1999) examined the U-Pb geochronology of several hundred detrital zircons from late Mesozoic arc-trench complexes in New Zealand. Most of the grains are Permian or Mesozoic in age, but sources with zircon ages extending from the Paleozoic through the Archean indicates input from a composite provenance. Cathodoluminescence (CL) imaging (Vavra 1990, Hanchar and Miller 1993, Götze et al. 1999) of grains suggests an exclusively igneous origin for the Permian and younger zircons, whereas the older grains preserve a more complex history. As with the Peninsular Ranges example (Kimbrough et al. 2001), the youngest grains approximate the time of deposition, which argues for coeval igneous activity. Cawood et al. (1999) interpreted the age spectra to mean that the zircons were derived from an Andean-type magmatic arc on the Gondwana margin in preference to exotic terranes accreted to the margin. Paleozoic and older grains represent recycled, older, Gondwanan sedimentary rocks or input from the original provenance.

The inherent complexity of provenance analysis is highlighted by studying recent sediments where sediment-transport pathways can be more easily reconstructed. Sircombe (1999) illustrated the importance of intermediate repositories by describing the presence of Neoproterozoic zircon in modern beach sand on the east Australian coastline (Fig. 3). This age component is regarded as exotic to southeastern Australia and its presence is greatest near the Mesozoic Sydney Basin. Neoproterozoic ages were also found in the Middle Triassic Hawkesbury Sandstone presently forming prominent coastal outcrops. The original source of these exotic grains remains uncertain, but an Antarctic source is strongly suspected (Sircombe 1999, Veevers 2000).

The ability of intermediate repositories to overwhelm local provenance is further illustrated by an example from modern beach sands in Western Australia (Sircombe and Freeman 1999). Despite close proximity to the extensive Archean Yilgarn craton, modern beach-sand samples were dominated by Neoproterozoic and Mesoproterozoic grains presumably derived from orogens marginal to the Yilgarn and poorly exposed at present. The paucity of Archean detritus is also seen as far back as the Ordovician in the Perth Basin (Cawood and Nemchin 2000), thereby providing important clues about the evolution of the rift margin along west Australia.

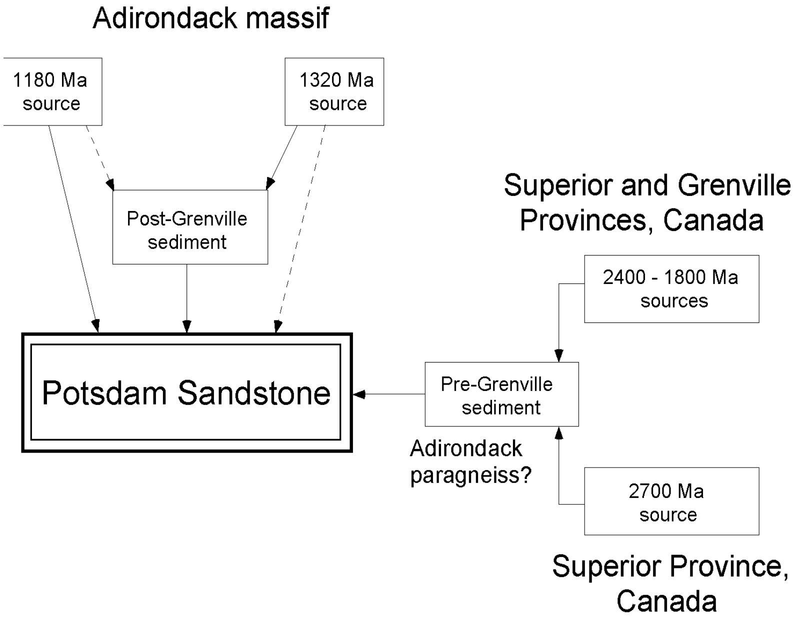

Figure 8. Flow diagram illustrating the different zircon provenance ages and the possible delivery pathways into the Potsdam Sandstone. The geochronology results portrayed in this diagram demonstrated for the first time the power of isolating zircon populations in provenance reconstructions. Modified from Gaudette et al. (1981).

PALEOGEOGRAPHIC AND TECTONIC RECONSTRUCTIONS

Introduction

Detrital zircon geochronology is a powerful tool for provenance analysis, particularly for helping to constrain paleogeography, tectonic reconstructions, and crustal evolution (e.g., Ross and Bowring 1990, Ireland 1992, Gehrels and Dickinson 1995, Gehrels et al. 1995, Knudsen et al. 1997, Gehrels and Ross 1998, Holm et al. 1998, Mahoney et al. 1999, Wallin et al. 2000, Cawood and Nemchin 2001, Gehrels et al. 2002). One example where detrital zircon geochronology has been critical in building paleogeographic and tectonic reconstructions is in the fragmentation history of the Neoproterozoic supercontinent Rodinia and the establishment of Laurentia. This topic has received considerable attention in the past decade, although there is increasingly divergent opinion concerning its configuration and timing of its break-up (e.g., Dalziel 1991, Hoffman 1991, Moores 1991, Ross et al. 1992, Brookfield 1993, Karlstrom et al. 1999, Burrett and Berry 2000, Wingate et al. 2002). Rodinia's assembly was accompanied by global collisional orogenesis that is preserved today as an extensive belt of moderate to high-grade metamorphic rocks, such as the Grenville orogeny of Laurentia and Baltica. This belt likely is preserved on other continents (e.g., Australia, Africa, China), and its presence has been used to constrain some of the reconstructions. The occurrence of high-grade metamorphic rocks at the Earth's surface today indicates uplift and erosion of tens of kilometers of crust. Erosion and denudation has continued ever since the completion of the bulk of mountain building at ~1.0 Ga. The record of this uplift and erosion should be preserved in the vestiges of a pan-Rodinian drainage system that would have delivered huge volumes of detritus to adjacent basins, located across the interior of Rodinia (and Laurentia).

Initial studies—Shaler Supergroup

U-Pb TIMS dating of detrital zircons was applied to assess the provenance of fluvial sandstones of the Shaler Supergroup, an early Neoproterozoic (~1.0-0.75 Ga) intracratonic basin succession preserved on the northwestern (present coordinates) margin of the North American craton (Laurentia) in the Canadian Arctic. These and correlative sandstones exhibit consistent northwesterly paleocurrents (Young and Long 1977, Miall 1976, Rainbird 1992). Following the ideas of Potter (1978) concerning "big river" systems, Young (1978) suggested that the source for these sediments may have lain in the Grenville province on the opposite side of the continent (Fig. 9). Subsequent detrital zircon geochronology supported this assertion with a significant proportion of the ages matching that of the adjacent Archean Slave province and its marginal Paleoproterozoic orogenic belts. However, the majority of the detrital zircons from the Shaler Supergroup yielded late Mesoproterozoic ages, unlike any known proximal source terrain, but quite similar to the ages of extensive synorogenic plutons in the Grenville province of southeastern Laurentia (Fig. 4). The observation confirmed the hypothesis (Young 1978) that detritus was transported approximately 3000 km northwestward from the rising Grenvillian orogeny by a pan-continental fluvial system (Rainbird et al. 1992).

Goodge et al. (2002) drew analogies to results of detrital zircon dating in the Shaler Supergroup in their analysis of Neoproterozoic and Cambrian quartzites in the Transantarctic Mountains in Antarctica. Detrital zircon populations of ~1.4 and 1.6-1.8 Ga from the Beardmore Group closely match with episodes of crust formation in Laurentia reinforcing a possible tie between East Antarctica and Laurentia in one of the original Rodinia reconstructions (e.g., SWEAT hypothesis of Moores 1991). Eastward paleocurrents in the Transantarctic Mountains preclude transport of these grains from Laurentia because this part of Antarctica had separated from Laurentia long before, according to most reconstructions (e.g., Dalziel 1997), which led to the conclusion that a 1.4 Ga source lies buried under the ice (Goodge et al. 2002).

Regional studies—northern Cordillera

The big-river hypothesis was tested by comparing the detrital zircon geochronology of the Shaler Supergroup with that of potentially correlative strata from the Ogilvie and Mackenzie platforms in the northern Canadian Cordillera (Rainbird et al. 1996, Rainbird et al. 1997). U-Pb TIMS analysis of 54 detrital zircons, separated from five regionally correlative samples from the Mackenzie Mountains Supergroup and the Pinguicula Group, revealed that 85% are Mesoproterozoic with a high proportion of these clustering in a range between 1.25 and 1.0 Ga (Fig. 4). Sm-Nd isotopic data from intercalated mudrocks indicated a source with relatively juvenile model ages (T_{DM} = 1.74-1.54 Ga), consistent with the provenance indicated by detrital zircon geochronology. These results strongly supported the big-river model and suggested that the fluvial system was laterally extensive and may have formed a broad cratonic sheet originating from multiple sources along the length of the Grenvillian mountain front.

Regional studies—central Cordillera

Detrital zircon geochronology of Neoproterozoic and lowermost Cambrian rocks from sedimentary basins located along the western margin of Laurentia, and now exposed mainly in the central Cordillera of California and Nevada, yielded detrital zircons with characteristic "Grenvillian" ages (e.g., Stewart et al. 2001, Fedo and Farmer 2001). Although Stewart et al. (2001) attribute some of these ages to provenance from local volcanic centers, much of the material is considered to have derived via west-flowing rivers from the Grenville orogen, elements of which extend into west Texas and northern Mexico (Stewart et al. 2001) and beyond into the present Appalachian Mountains. These data provide further support for the big-river hypothesis and for the presence of a craton-scale fluvial blanket in Neoproterozoic and Early Cambrian times and illustrate the successful integration of sedimentological information, such as paleocurrent analysis, with U-Pb geochronology.

Siberia

A tectonic connection between Laurentia and Siberia was proposed by Sears and Price (1978) and Condie and Rosen (1994) and the similarities between the northern Cordillera and fold-belts along the eastern margin of Siberia have long been recognized (Khudoley and Guriev 1990). Subsequent models have been proposed but the position of Siberia remains an enigmatic component of the Rodinia supercontinent (e.g., Rainbird et al. 1998, Sears and Price 2000). Neoproterozoic (upper Riphean) sandstones of the Siberian platform share first-order stratigraphic similarities with contemporaneous sequences in Laurentia and it is possible that they were part of the same intracratonic basin before separation occurred with the break-up of Rodinia (Rainbird et al. 1996, Khudoley et al. 2001). To test this hypothesis and the "Laurentia-Siberia" connection, detrital zircons were analyzed from sandstones at three stratigraphic levels from the Riphean section (see Khudoley at al. 2001). The detrital zircon U-Pb SHRIMP age profile of the Mayamkan Formation, a fluvial arkose from the southern Sette-Daban fold belt, is almost identical to that of early Neoproterozoic fluvial sandstones of the Shaler and Mackenzie Mountains supergroups in northwestern Canada and includes a high proportion (~85%) of Mesoproterozoic zircons (Fig. 5; Rainbird et al. 1998). There is no known source region for detritus of such age in Siberia and isopachs and facies relations suggest provenance from an exotic terrane to the east. These data indicated that provenance of the late Riphean sandstones was mainly from rocks of Grenvillian age that were perhaps adjacent to an unidentified continent (Laurentia or Baltica?).

Scotland

Provenance of the late Mesoproterozoic to early Neoproterozoic Torridonian succession in northwest Scotland is relevant to the nature and timing of the formation and break-up of Rodinia. Previous provenance studies based on the sedimentology, geochemistry and mineralogy of these

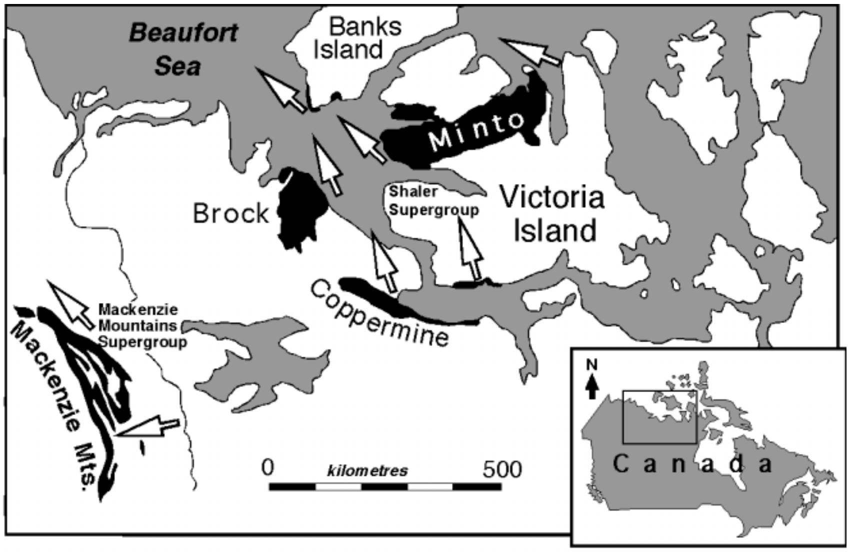

Figure 9. Northwestern Canada showing location of inliers containing fluvial quartz-arenites of early Neoproterozoic (1.0-0.75 Ga) age, considered to be remnants of an extensive river system originating from the Grenville orogen, some 3000 km to the southeast. Arrows represent generalized paleocurrents based on measurements of cross-bedding (minimum of 20 readings for each arrow). Modified from Rainbird et al. (1992).

relatively immature coarse clastic rocks argued for a possible influence from Laurentia, from which Scotland is now separated. Recent SHRIMP detrital zircon geochronology indicated that the lower part of the Torridonian (Stoer Group) is composed mainly of sediment weathered from proximal, late Archean (Lewisian) sources in the Hebridean block, a piece of the North Atlantic craton of Laurentia, orphaned during the opening of Iapetus (Rainbird et al. 2001). The upper part of the Torridonian (Torridon Group) exhibits more varied provenance with distinctive detrital zircon age modes at ~1.80 Ga, 1.65 Ga and 1.10 Ga. The latter two modes are considered to be characteristic of the Grenville Province in eastern Laurentia. These data, together with paleocurrents, suggest that the Torridon Group could have been deposited by a late-post Grenvillian foreland trunk river system. This is significant because the foreland basin part of the big-river system should be preserved somewhere along the great length of the Grenville thrust front.

A cryptic Grenvillian foreland basin in the U.S. mid-continent

Proximal parts of the big-river system may be present in a westward-tapering wedge of coarse, immature clastic red-beds of interpreted Neoproterozoic age from the subsurface of western Ohio (Shrake et al. 1991). These rocks, known as the Middle Run Formation, have been cored and imaged in subsurface seismic profiles, which reveal a wide, well-defined zone of east-dipping reflectors inferred to represent thrust structures of the Grenville front tectonic zone (COCORP Line OH-1, Hauser 1993). In the subsurface to the west is a shallow, east-dipping sequence of sedimentary strata, similar to Middle Run Formation elsewhere. Together these rocks were interpreted as the molasse phase of a previously unrecognized foreland basin to the Grenville orogen (Hauser 1993). This paleogeographic model is supported by the detrital zircon geochronology of the Middle Run Formation, which reveals that at very high percentage of the basin fill was derived from erosion of the adjacent Grenville Province (Santos et al. 2002).

A potential correlative to the Middle Run Formation is the Jacobsville sandstone, a >900-m thick succession of subarkosic to sublithic arenites, conglomerates and siltstones, which are exposed in the Keweenaw Peninsula on the south shore of Lake Superior. Tectonic uplift and provenance from the south is indicated by petrology and paleocurrent analysis (Kalliokoski 1982). Paleocurrents from fluvial units in the main part of the basin suggest axial (NE and SW) transport, perhaps related to development of a fluvial trunk system, as is commonly found in foreland basins.

Rodinian paleogeography

The development of Rodinia appears to have involved significant clastic sedimentation arising from tectonism and mountain building. A better-preserved analogue of the proposed Rodinian paleogeographic model comes from the supercontinent Pangea, which amalgamated during the Appalachian-Hercynian orogeny in the Carboniferous-Triassic. The paleogeography of the Laurasia block of Pangea was dominated by a series of coalescing, alluvial-deltaic wedges and axial braided rivers that filled foreland basins formed by flexural loading along the Alleghenian-Appalachian thrust front (Absaroka Sequence, Sloss 1988b). The Central Appalachian Basin is an example whose infill has been interpreted to represent an Amazon-scale drainage system (Archer and Greb 1995). As the foreland basins filled, excess detritus was transported westward, across the craton, by fluvial and eolian processes. In a similar fashion, the foreland basin to the Grenville orogen was probably overfilled with excess detritus spilling westward across Rodinia and Laurentia into basins in the interior of the supercontinent. Some of this material reached the (present-day) western margin of Laurentia in the Early Cambrian (Stewart et al. 2001, Fedo and Farmer 2001) suggesting that the pan-continental fluvial system persisted for at least 400 Myr. The rare preservation of the proximal parts of this system is in part due to Phanerozoic cover, but may also be related to subdued flexural loading, a consequence of climate-controlled erosional unroofing of the mountain front (Rainbird et al. 1997). The model predicts that correlative early Neoproterozoic cratonic sandstones on other putative pieces of the Rodinia supercontinent (e.g., Australia, Amazonia) should preserve evidence of this vast drainage system.

IMPLICATIONS FOR EARLIEST EARTH HISTORY

Ever since their discovery by Froude et al. (1983), the >4 Ga detrital zircon grains from metasedimentary units in the Narryer Gneiss Complex, Western Australia have been the subject of speculations regarding the earliest history of Earth. As the only "direct evidence" of Earth's first 500 Myr, the mineral chemistry and isotope geochemistry of the detrital zircons in these metaconglomerates and quartzites (particularly well known from the Jack Hills) may provide a window into determining processes in the earliest Archean (Hadean), a time in which almost nothing is known.

A number of studies subsequent to Froude et al. (1983) have confirmed the presence of a small but persistent population of grains up to ~4200 Ma (Compston and Pidgeon 1986, Kober et al. 1989, Maas and McCulloch 1991, Maas et al. 1992, Amelin 1998, Fig. 1C), with a recent discovery of part of a zircon as old as 4404 Ma, with other grains >4300 Ma (Wilde et al. 2001). There is no positively identified provenance for these ancient grains, although Nelson et al. (2000) reported the discovery of >4.0 Ga xenocrysts from 2.6-2.7 Ga granitic gneisses in the adjacent Narryer and Murchison terranes and interpreted the xenocrysts to have crystallized in a granitic melt. Based principally on the notion that zircons with a Th/U > 1 crystallize in mafic melts, Amelin (1998) suggested the contribution of a mafic source component for some grains, an idea first postulated by Froude et al. (1983) because of low U concentrations in some zircons. Consequently, the source of the >4.0 Ga grains is likely to have been compositionally heterogeneous.

Wilde et al. (2001) attempted to prove an evolved granitic origin for the 4404 Ma zircon based on REE compositions, and calculated partition coefficients suggestive of LREE enrichment. Furthermore, this particular zircon has inclusions of quartz, which are also said to support a felsic origin. The implication of such a conclusion is that evolved continental crust had appeared in the Hadean (Peck et al. 2001), only about 150 Myr after the Moon-forming impact, which suggests the operation of modern-style subduction processes involving hydrated rocks (Wilde et al. 2001). Oxygen isotope analyses from very old parts of some zircons yield a $\delta^{18}O$ compositions >6.5‰, which suggests crystallization from melts that have interacted with hydrated supracrustal rocks (Wilde et al. 2001, Valley et al. 2002, Peck et al. 2001, Valley, this volume), leading to the conclusion of a cool, liquid-water covered Hadean Earth (Valley et al. 2002) that is speculated to potentially host a biosphere (Mojzsis et al. 2001). Other interpretations of the REE in zircon, in particular that of Whitehouse and Kamber (2002), indicate that application of zircon/melt partition coefficients cannot be used to unambiguously constrain melt compositions. Such a conclusion directly questions that the source magmas of the ~4.4 Ga grains were derived from subduction-derived melting of hydrated ocean crust. Furthermore, the REE patterns from the >4.0 Ga detrital zircons of the Jack Hills and Mt. Narryer metasedimentary rocks share many characteristics with lunar highland zircons, which did not form from modern subduction-like processes (Whitehouse and Kamber 2002).

Amelin et al. (1999, 2000) combined U-Pb geochronology and Hf isotopic compositions from the same Jack Hills zircon grains in order to address the earliest history of crust formation on Earth. Previous application of Sm-Nd isotopic studies to Early Archean rocks in Greenland and Canada pointed to their derivation from a depleted mantle source, but the possibility of subsequent metamorphic re-equilibration raised certain concerns (Amelin et al. 1999). In contrast, examination of Hf isotopes from Jack Hills detrital zircons up to 4.14 Ga old reveals that they did not originate from depleted mantle. Instead many grains have an Hf isotopic composition showing that they came from a source that is similar in composition to chondritic meteorites and that some had formed from anatexis of older crust (Amelin et al. 1999).

SUMMARY

Detrital zircon analysis has grown from early varietal studies to the application of isotopic and compositional techniques, which have become powerful tools for provenance study and understanding of geological history. The age of detrital zircon, principally via U-Pb isotopic analysis, has become particularly significant. Such ages provide vital constraints on the stratigraphy of sedimentary units. The youngest grains analyzed can, with suitable caution, provide a maximum age of deposition. Age distributions can also illuminate significant disconformities or diachroneities in stratigraphic sections that may not have been previously recognized with conventional techniques.

Assuming that the ages of detrital zircon are a suitable proxy for sedimentary provenance, detrital zircon geochronology has been applied to a wide variety of issues over a wide range of geologic time. Detrital zircon grains from Archean sedimentary units has been notably topical with the discovery of >4000 Ma zircons providing a unique opportunity to glean information about the very early Earth. Proterozoic sedimentary units have yielded zircon data of great relevance to tectonic reconstructions notably in various Laurentia and Rodinia models.

Detrital zircon data from sedimentary units from the Proterozoic to the present is often accompanied by more detailed geological history and this has served to highlight the complexities involved in provenance analysis. The importance of considering distal provenances, potentially thousands of kilometers from the site of deposition, has been strongly illustrated. The ability of a distal provenance to overwhelm representation of a local source either directly or via intermediate repositories is also a constant concern when interpreting detrital zircon data.

Complexities in natural processes are further compounded by sources of artificial bias during the research cycle from field sampling, through mineral separation, to data interpretation and display. As the application of detrital zircon analysis grows, developing procedures to mitigate potential biasing will become increasingly important and steps have been taken in this direction.

The future of detrital zircon analysis is promising. Advances in technology mean that the rate of data acquisition is increasing allowing more detailed and thorough analytical programs to be applied to a range of geologic problems. Interest in the history of the earliest Earth and continental reconstructions will provide steady demand, while the potential for integrating other sedimentological and geochemical techniques with isotopic age determination offers future dimensions for detrital zircon analysis.

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