The Global Detrital Zircon Database: Quantifying the Timing and Rate of Crustal Growth

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Published detrital zircon geochronological data was compiled to form the Global Detrital Zircon Database (GDZDb). This database provides a reference block for provenance analysis by future detrital zircon geochronological studies. This project entailed three subprojects: 1. crustal growth/crustal recycling patterns, 2. a provenance study of the Triassic Dry Fork Formation of the Danville-Dan River Rift basin of Virginia and North Carolina, and 3. sample size issues in detrital zircon studies.

The global detrital zircon age frequency distribution exhibits six prominent, statistically significant peaks: 3.2-3.0, 2.7-2.5, 2.0-1.7, 1.2-1.0, 0.7-0.5, and 0.3-0.1 Ga. These peaks are also observed when the data is sorted for continent of origin, the tectonic setting of the host sediment and for modern river sediments. Hf isotope model ages were also incorporated into the database where grains were dated with both U-Pb and Hf isotopes. The Hf isotope model ages suggest that the majority of detrital zircons U-Pb ages reflect crustal recycling events that generated granitic magmatism, as most grains exhibited Hf isotope ages that are much older than the corresponding U-Pb age.

The Triassic Dry Fork Formation was sampled from a site in southern Virginia in the Danville-Dan River Basin. The detrital zircon age frequency distribution for this formation was strongly unimodal with a peak at 400-450 Ma and a paucity of Grenville-age zircons. Comparison of the Dry Fork sample to published east coast data and to the North American record (from the GDZDb) illustrate the unusual nature of the Dry Fork Formation sample. It is probable that older Grenville zircons were blocked from the rift valley by the rift shoulder.

Using the GDZDb a study of sample size was conducted in order to estimate the best sample size to use when trying to constrain the maximum age of sedimentation of the host sediment. Rift basins and active margins exhibited smaller offsets from the youngest zircon grain age to host sediment maximum age than observed in samples from passive margins. This study recommends that at least 50 grains need to be age dated on average in order to best constrain the age of the host sediment.
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A database study of this nature also requires a great deal of legwork in order to compile all of the references necessary. The Virginia Tech Library staff provided much support during this phase of the project and they were able to find many obscure detrital zircon references for me.

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Introduction to the Global Detrital Zircon Database

The Global Detrital Zircon Database (GDZDb) is an outgrowth of a project that originally attempted to elucidate aspects of time averaging in sedimentary systems, instead the project has grown to incorporate aspects of: 1. Crustal growth and crustal recycling models, 2. Provenance analysis of Triassic rift sediments from Virginia and 3. Sample size issues in detrital zircon studies. Detrital zircons have become an important tool in constraining host sediment age (Dickinson and Gehrels, 2010 in press), ages of sources of sediment to the host rock (Eriksson et al. 2003, 2004, Dickinson et al. 2008a, 2008b, 2009) and even the timing (through Hf model isotope ages) of when the material that makes up the zircons was last in the mantle (Kinny et al. 1991, Kemp et al. 2006, Flowerdew et al. 2007). The growing popularity of detrital zircon geochronology is illustrated in Figure 1, with a steep rise in number of publications (peer-reviewed and not peer-reviewed as cited by the Georefs search engine) as well as number of grains sampled in the GDZDb. In addition, the laboratories that analyze U-Pb age dates from detrital zircons are sampling 90,000 zircon grains a year (Gehrels et al. 2006).

The GDZDb consists of detrital zircons compiled from 1,108 references in the peer-reviewed literature, from Geological Survey reports and from theses and dissertations. The majority of studies compiled were written in English, but some of the references were published in Chinese, German, Portuguese, or Spanish. The GDZDb consists of 4,879 samples (published age frequency distributions ranging from 1 to 580 detrital zircons dated) and a total of 238,952 individually dated detrital zircons. Each detrital zircon has a row in the excel spreadsheet that makes up the database. A set of 66 variables is described for each zircon and includes study number, sample number, U and Th content, U-Pb age data, Hf isotope model age data, Th-Pb age data, decay constants, measures of concordance, host sediment characteristics (tectonic setting,
lithology, maximum and minimum age constraints independent of U-Pb detrital zircon dates, age estimation technique used), geographic location of the samples, and publication data (year published and citation). The total number of cells in the database is 15,771,162. In addition, the author is slowly entering in additional data including 5 new variables (formation name, machine type used for Hf isotope analysis, longitude and latitude coordinates, and multi-spot data). This may well be the largest single database devoted to a geologic material (Kowalewski, personal communication) in existence.

The GDZDb was initially used to look at the problem of the determining from age frequency data of detrital zircons whether or not one could track crustal growth and crustal recycling by assessing the peak structure of the global distribution and continental distributions as well as constraints from other related isotopic systems (Hf isotope model ages) which could be used to determine when the material that formed the zircons was last in the mantle. A compilation of ~200,000 published zircon dates reveals a global age distribution (U-Pb) with six prominent, statistically significant peaks: 3.2-3.0, 2.7-2.5, 2.0-1.7, 1.2-1.0, 0.7-0.5, and 0.3-0.1 Ga. In most cases, these peaks are recorded on all seven continents and all of them persist when data are analyzed separately for different tectonic settings. Most of the peaks are detectable also in modern sediments. The multi-continental peaks, observable regardless of tectonic setting, suggest that the evolution of continental crust through time was episodic and global in scale. Associated Hf isotope ages available for ~5100 U-Pb dated concordant zircon grains suggest that the age-frequency distribution of detrital grains reflects a combination of two episodic processes: intermittent crustal growth and intermittent crustal recycling. The zircon age distributions and associated data provide consistent evidence for non-monotonic nature of the Earth’s plate tectonics and yield patterns consistent with predictions of the Supercontinent Cycle Hypothesis.
As a test of the capability of the GDZDb to elucidate provenance patterns, a sample of the Triassic Dry Fork Formation from the Danville-Dan River Basin of southern Virginia was age dated with detrital zircon geochronology. While the age frequency distribution from the Dry Fork Formation sandstone could not be used to constrain the age of the host sandstone; the distribution of detrital zircons did provide useful constraints on the ages of source sediments and this was contrasted with published detrital zircon age frequency distributions compiled within the GDZDb. The Triassic Dry Fork Formation was constrained in age to the Upper Triassic by faunal content. The youngest zircon grains however were as young as 375 Ma (an offset of 150 Ma). The Dry Fork Formation age frequency distribution was dominantly unimodal with a peak corresponding to 400-450 Ma reflecting a source rock dominated by these ages. To the east of the sample location are rocks of the right age (and composition) in the Milton Terrane to be the source of these zircons (Kish, 1983, Hund, 1987, Coler et al. 2000, Wortman et al. 1995).

Comparison with published detrital zircon data from the east coast of North America showed that the Dry Fork Formation was unusual in the region for not exhibiting a second peak centered on 1,100 Ma. This suggests that Grenvillian-aged material to the west of the Danville-Dan River Basin (the Smith River Allochthon) was not a source of sediment to the northern portion of the rift basin (Hibbard et al. 2003, Carter et al. 2006).

The third component of this project was to look at sample size issues in detrital zircon geochronology. Previous work with detrital mineral geochronology showed the best sample sizes to use when estimating the probability of finding a specific fraction of detrital zircon grains from a population (Dodson et al. 1988) and estimating the probability of not missing any fraction of a certain threshold size (Vermeech, 2004). The current study has attempted to find the best sample size to constrain the age of the host sediment. Detrital zircons are an excellent example
of the principle of inclusions – they are as old as the host sediment or older. The GDZDb provided 4,879 samples that could be used to empirically derive estimates of the sample size necessary to best constrain the host sediment age. The samples were sorted by tectonic setting (passive margins, active margins and rift basins) and the offset between the youngest grain age (in Ma) and the maximum age of the host sediment (in Ma) was calculated as a function for all samples. The offset was then averaged for bins of sample size. The properties of the curves generated were then used to estimate the best sample sizes to use. In general, tectonic settings (active margins and rift basins) characterized by active magmatism required fewer dated grains to estimate the host sediment age, then those tectonic settings where little or no magmatism occurs (i.e. passive margins). The recommended sample size derived from this empirical test was 50 detrital zircons. Active margins and rift basins could be well constrained with lower sample sizes. Passive margins on the other hand are not as readily constrained by a smaller sample size due to the observation that these systems generally lack magmatism that would otherwise generate zircons. A caveat though is that the characteristics of the individual samples may have a significant impact on how well the age of the host sediment can be constrained: source rocks in the catchment area of the drainage system may be much older than the host sediment.

1.1 References Cited


Figure 1: Comparison of frequency of publication of articles with the keyword “detrital zircon” cited in the Georefs library database (for all citations [green] and for peer-reviewed citations [blue]) and the number of dated detrital zircons compiled in the GDZDb against calendar year. Note the steep increase in frequency of both publication rate and number of grains after 2000. The steep drop off for 2009-2010 represents the lagtime between publication of detrital zircon references and their addition to the Georefs library database.
Quantifying the Timing and Rate of Crustal Evolution: Global Compilation of Radiometrically Dated Detrital Zircon Grains

Multiple models (steady-state, episodic, and early growth followed by crustal reworking) have been postulated to explain the evolution of Earth's continental crust. An independent assessment of these models is now possible due to the massive numbers of detrital zircon grains that have been dated individually over recent years. A compilation of ~200,000 published zircon dates reveals a global age distribution (U-Pb) with six prominent, statistically significant peaks: 3.2-3.0, 2.7-2.5, 2.0-1.7, 1.2-1.0, 0.7-0.5, and 0.3-0.1 Ga. In most cases, these peaks are recorded on all seven continents and all of them persist when data are analyzed separately for different tectonic settings. Most of the peaks are detectable also in modern sediments. The multi-continental peaks, observable regardless of tectonic setting, suggest that the evolution of continental crust through time was episodic and global in scale. Associated Hf isotope ages available for ~5100 U-Pb dated concordant zircon grains suggest that the age-frequency distribution of detrital grains reflects a combination of two episodic processes: intermittent crustal growth and intermittent crustal recycling. The zircon age distributions and associated data provide consistent evidence for non-monotonic nature of the Earth’s plate tectonics and yield patterns consistent with predictions of the Supercontinent Cycle Hypothesis.

2.1 Introduction

The history of the Earth’s continental crust (the timing and rate of crustal growth and recycling) is one of the most fundamental first-order geological patterns critical for refining the central paradigms of geosciences such as plate tectonics (Cawood and Buchan, 2007) or the supercontinent cycles (Condie, 2003; Cawood and Buchan, 2007). The rate of crustal growth and/or plate tectonic processes may have also played a major role in influencing long-term biological and geological trends, including long-term trends in biodiversity and ecospace
utilization (e.g., Bambach, 1993; Vermeij, 1995), sea-level (e.g., Miller et al. 2005), or seawater chemistry (e.g., Stanley and Hardie, 1998). For all those reasons the development of quantitative approaches for assessing theoretical models of the Earth’s crustal growth has been an increasingly active research direction. Here, we build on multiple seminal papers published in recent years and use a large, up-to-date database of detrital zircon radiometric ages to refine and augment previous estimates and interpretations of the timing and rate of crustal growth and crustal recycling.

Crustal growth occurs through two major processes: (1) Magmatism at arc-settings and (2) Intraplate basaltic volcanism (hotspot or plume volcanism). The first process appears to be dominant in terms of the volume of material produced. Arc-related magmatism during the Cenozoic outweighed intraplate volcanism by a factor of 3 (Reymer and Schubert, 1984). These processes transfer material from the mantle to the crust and form juvenile crust. Observations that the average continental crust is andesitic in composition, combined with the prevalence of andesitic volcanism at convergent margins underpinned the andesite model of crustal growth (Taylor, 1966, 1977). However this model does not account for some crustal geochemical trends (Cr, Ni contents and Th/U ratio) [Taylor and McLennan, 1995], nor does it account for the low occurrence of andesites in the Archean geologic record (Rudnick, 1995). Crustal Recycling consists of any process that reworks crustal material (McLennan, 1988) and includes subduction zone magmatism, intracrustal melting and assimilation. This second class of processes potentially generates granitic magmatism where zircons are a common trace mineral that crystallizes out of the melt. Mantle-derived magmas that pass through continental crust can melt and mix with this material to form melts with high amounts of crustal contamination. Crustal
contamination may be as high as 35% (Carlson et al. 1981; Mason et al. 1996; Russell et al. 2001).

Numerous models of the timing and rate of continental growth have been proposed, ranging from steady-state to episodic (Armstrong, 1981, 1991, Condie, 1998, 2000, Taylor and McLennan, 1985, 1995). In the steady-state end-member model, the bulk of crustal growth took place early in the Earth’s history (between 4.0-4.5 Ga), followed by balanced crustal growth and crustal recycling ever since (Armstrong, 1981). Armstrong (1981) suggested that the volume of continental crust has not changed over the past 4 billion years. In the episodic end-member model, the crustal growth occurred in multiple bursts separated by long time-intervals of slow crustal accretion (Armstrong, 1991). The multiple lines of evidence used to quantify this fundamental pattern include geochemical data, U-Pb dating of magmatic zircons, and areal mapping of cratons (Condie, 1998, 2000, Hurley and Rand, 1969).

The steady-state model was supported by the mapped distribution of continental crustal ages, which suggested linear growth. However, the supporting geochronological data were based on either whole-rock ages (Rb-Sr and U-Pb) or K-Ar ages derived before the role of closure temperatures and diffusion had been considered in interpreting radiometric ages (Gastil, 1960, Hurley and Rand, 1969). In contrast, the age distribution of magmatic zircons (Condie, 1998) has been used to argue in favor of the episodic model; indeed the magmatic zircon age distribution included three prominent peaks (1.1 Ga, 1.8 Ga and 2.7 Ga) suggestive of the three major episodes of crustal growth and/or recycling. Intermediate models ranging from quasi-monotonic (Hurley and Rand, 1969, Hurley, 1968, Veizer and Jansen, 1979) to quasi-episodic (McCulloch and Bennett, 1994, Taylor and McLennan, 1995, Condie et al. 2009) have also been proposed. Most recently a compilation of detrital zircons revealed a similar pattern with prominent peaks
recorded from three or more continents, including multiple peaks between 2.5 and 2.9 Ga as well as peaks at 1.9, 1.6 and 1.2 Ga. These peaks were interpreted as widespread pulses of granitic activity (Condie et al. 2009). Other isotopic methods have suggested episodic continental crustal growth with similar timing of pulses: including Hafnium (Kemp et al. 2006), and Neodymium (DePaolo et al. 1991, McCulloch and Bennett, 1994) isotopes.

The question of the rate of crustal growth is complicated by another important problem: has crustal growth (whatever its rate) been accomplished mostly by adding new, juvenile crust (either by partial melting of the upper mantle) or has substantial crustal recycling also been involved? For example, the episodic age distribution of magmatic zircons was related previously to the supercontinent cycle (Condie, 1998). In that model, to generate new continental crust, the layered-convection regime switches to the whole-mantle convection regime. When the slabs being subducted underneath a supercontinent reach the D\textsuperscript{″} layer, plume production is triggered. The resulting large-scale mantle upwelling (geoid highs) leads eventually to the fragmentation of the supercontinent. The fragmented blocks drift towards geoid lows where they collide with other blocks to form a new supercontinent (Anderson, 1982; Perrot et al. 1997). Juvenile crust is then produced by partial melting of the upper mantle. This process can account for distinct pulses in the temporal record (age distribution) of magmatic zircons.

An important corollary of this prediction is that detrital zircons should also show such pulses: those that represent first-generation detrital grains should retain their magmatic signature, whereas the crustally recycled zircons should acquire new ages (as overgrowths) corresponding to one of the subsequent cycles. Thus, under this model, if crustal recycling is substantial, the magmatic and detrital zircons should show the same peaks, but relative to the magnitude of the magmatic zircon peaks, the magnitude of the detrital peaks should be increased toward Recent
due to preferential removal of metamict zircons through weathering and erosion (Carroll, 1953, Balan et al. 2001, Delattre et al 2007). In addition, Hf model ages of detrital zircons from a given radiometrically determined age distribution peak should include a substantial component of older ages, while retaining a multimodal age distribution (i.e., sharp, radiometrically derived peaks should be smeared back in time when Hf model ages are examined for the grains from a given U-Pb determined peak) [Kemp et al. 2006]. Thus, these predictions are empirically testable using a large compilation of detrital grains dated using U-Pb radiometric ages and Hf model ages.

Several studies published recently used detrital zircon grains to address questions related to timing, rate, and nature of crustal growth and the supercontinent cycle. These include a study by Campbell and Allen (2008) who examined age distributions of radiometrically dated zircon grains from modern river sediments and Condie et al. (2009) who used a literature compilation to assemble a global database of radiometrically dated detrital grains. This study builds directly on those previous projects. However, the database analyzed here differs in several ways from those used by previous workers. These differences should allow us to augment previous efforts in several critical ways:

1. The database used here is a much larger compilation than any previous study. Analyses presented below are based on 4,263 samples totaling 199,358 individually dated grains described by 62 variables (12,360,196 data cells total). In contrast, previous studies were based on datasets orders of magnitude smaller, in terms of number of samples, number of grains, or number of variables (Cambell and Allen, 2008 [5,246 grains, 40 samples]; Condie et al. 2009 [~18,000 grains]. The sheer size of the dataset used here offers us analytical opportunities that are not available at smaller sample sizes. In particular, it allows us to retain large sample size after grouping data by multiple grouping variables
such as geography, tectonic setting, or a specific radiometric method used. The much larger dataset also offers us an opportunity for a statistical ground-truthing of previous analyses. Given the importance of the topic, the opportunity for an independent data-intensive cross-check of key empirical patterns should not be neglected.

2. By incorporating all relevant studies from non-North American and non-Australian regions, this database attempts to overcome geographic biases that tend to affect detrital zircon datasets. The global compilation reported here should allow us to evaluate this bias in a quantitative manner.

3. This study incorporates a number of sample-level and grain-level grouping variables that have not been reported in other compilations including: host sediment lithology, metamorphic grade, host sediment age independent of detrital zircon age constraints, machine type used (SHRIMP, LA-ICPMS, etc.), U and Th content, tectonic setting, etc. These additional variables provide information that should not only be useful to the authors, but is also potentially of relevance to future workers interested in comparing their datasets to the global reference database compiled here.

4. To our knowledge, this study is the only compilation that also incorporates Th$^{232}$-Pb$^{208}$ ages collected for the grains that were dated using U-Pb ages (with 16,182 Th-Pb ages). Also Hafnium isotope model ages were compiled for grains that had both U-Pb and Hf data (n = 10,503 Hf isotope model ages). This allows for a direct comparison of different age-dating and model age estimates derived from the same sets of grains.

5. The database includes all radiometrically dated grains, including those with high discordance. Because discordance estimates have also been compiled, the database allows
for flexible filtering of discordant grains. Also, the database makes it possible to compare datasets with different discordance criteria.

In summary, the database analyzed here differs notably from previous compilations and should provide us with an independently compiled dataset that can be used to assess the reproducibility of previously reported patterns. As important, the database should allow us to augment previous efforts by conducting multiple analyses that parse out various dating systems, tectonic settings, and other relevant parameters, while still retaining substantial sample sizes.

2.2 Methods

A meta-analytical compilation of single-dated detrital zircon grains was constructed via an extensive literature survey of detrital zircon analyses published primarily in English (but also including German and Chinese documents). A total of 953 studies (see Appendix A for references for the compiled database) were collected representing 4,263 age distributions (i.e., 4,263 samples of dated grains) and 199,358 individual grains. All grains were dated individually using U-Pb techniques. These samples represent all continents and all geological time intervals, from Archean metasedimentary rocks (paragneisses and metapelites), through Proterozoic and Phanerozoic sedimentary rocks (including siliciclastic, carbonate, and chemical rocks) up to modern sediments.

Zircon (ZrSiO$_4$) is one of the most durable minerals, being highly resistant to both physical and chemical weathering (Heaman and Parrish, 1991, Kowalewski and Rimstidt, 2003). Because U is present in zircons in the 10-1000 ppm range (Faure and Mensing, 2005, Heaman and Parrish, 1991), the mineral is also particularly suitable target for reliable radiometric dating.
Moreover, the closure temperature for the U-Pb system exceeds 900°C (Cherniak and Watson, 2000), which makes this radiometric system less vulnerable to resetting via metamorphic, magmatic, and other thermal processes.

$^{238}\text{U}$ and $^{235}\text{U}$ radioactively decay through a series of daughter products to the stable lead isotopes $^{206}\text{Pb}$ and $^{207}\text{Pb}$ respectively. The $^{238}\text{U}$-$^{206}\text{Pb}$ decay chain, with a half-life of $4.468 \cdot 10^9$ years, is the most widely used to date zircons. The $^{235}\text{U}$-$^{207}\text{Pb}$ system, with a half-life of $0.7038 \cdot 10^9$ years (Faure and Mensing, 2005, Jaffey et al. 1971, Steiger and Jäger, 1977), is calculated by using the known ratio of $^{235}\text{U}/^{238}\text{U}$ as well as the ages derived from $^{238}\text{U}$-$^{206}\text{Pb}$ and is not as commonly reported as the other two age dates. A third dating strategy is the $^{207}\text{Pb}/^{206}\text{Pb}$ age, which is derived from algebraic substitution and manipulation of the two U-Pb decay equations with the assumption that the ratio of $^{235}\text{U}/^{238}\text{U}$ is a constant equal to $1/137.88$ (Faure and Mensing, 2005). The $^{207}\text{Pb}/^{206}\text{Pb}$ was used for grains older than 800 Ma in this compilation. Grains younger than 800 Ma used their $^{206}\text{Pb}/^{238}\text{U}$ age. This methodology was used as over the Phanerozoic relatively little $^{207}\text{Pb}$ was produced as $^{235}\text{U}$ has undergone 6.5 half-lives through the Earth’s lifetime and Phanerozoic zircons tend to have low $^{207}\text{Pb}$ contents making it difficult to analyze (and causing these grains to appear discordant). As discussed in detail below, these three methods yield highly congruent results.

For each grain, data were keyed into the database according to tectonic setting, best estimate of host rock age, host rock lithology and metamorphic index, region, paleoclimate characteristics, and analytical factors. For grains where multiple U-Pb age spots were generated, the following conventions were used: (1) If the age was labeled as from the “core”, this age was entered into the database and ages labeled “rim” were ignored, and (2) If the ages were not labeled, the spot with the oldest $^{206}\text{Pb}/^{238}\text{U}$ age from the grain was used as opposed to the other
U-Pb and Pb-Pb ages, as this was assumed to be the most likely to approximate the 
"crystallization age" of the zircon (younger spots were then ignored) and biases the dataset 
towards older ages. Multi-spot data is being entered into the database, but are not ready for 
analysis yet.

The original sources, from which the database was compiled, reported concordance for 
approximately 60% of the grains. Concordance was reported as either: percent concordant or 
percent discordant. Other studies reported dates that met some cutoff value (usually either ≤5% 
or ≤10%), but without providing information about specific concordance values for each 
individual grain. Grains with a $^{206}\text{Pb} / ^{238}\text{U}$ age less than 400 Ma in age were retained in the final 
pooled age regardless of their degree of discordance due to the difficulty in measuring the low 
contents of $^{207}\text{Pb}$ in these younger zircons.

2.2.1 Comparison and Merging of Different Geochronological Systems

All age estimates reported by the original authors (the $^{206}\text{Pb} / ^{238}\text{U}$, $^{207}\text{Pb} / ^{235}\text{U}$ and 
$^{206}\text{Pb} / ^{207}\text{Pb}$ ages in Ma) were included in the database. In many cases, only one or two of the 
possible ages were recorded in the original source. In order to increase the number of grains 
used in this study, a "pooled age" was created. The pooled age column in the database was 
generated using the $^{206}\text{Pb} / ^{238}\text{U}$ age for grains younger than 800 Ma; grains older than 800 Ma 
were assigned their $^{207}\text{Pb} / ^{206}\text{Pb}$ age as the best age. There was only one case where the 
$^{207}\text{Pb} / ^{235}\text{U}$ age was the only age available in the original dataset. The validity of this approach 
can be tested by comparing different isotopic ages (i.e. $^{207}\text{Pb} / ^{235}\text{U}$ age vs. $^{206}\text{Pb} / ^{238}\text{U}$ age) 
reported for the same grains (Fig. 2). If the three methods were 100% concordant and errorless, 
all pair-wise comparisons of the isotopic dating systems should exhibit a relationship of $y = 1.0x$
Isotopic data were plotted and evaluated for correlation using the software package JMP 8. The two U-Pb pairs show an exceedingly high positive correlation (R² = 0.9945, R = 0.997, n = 47,828). A least-square line with a slope of 0.9996 and an intercept of 9.9935 [Fig. 2] has been fitted (this is not different significantly from y=1.0x+0.0 line; p=0.00001). The ²⁰⁷Pb/²³⁵U age versus the ²⁰⁷Pb/²⁰⁶Pb age data also show a high positive correlation (R² = 0.920, R = 0.959, n = 70,268) with a slope of 0.9826 and an intercept of -59.003 [Fig. 2] (this is not different significantly from y=1.0x+0.0 line; p=0.00001). Comparing ²⁰⁶Pb/²³⁸U age versus ²⁰⁷Pb/²⁰⁶Pb age yielded somewhat lower, but still very high positive correlation (R² = 0.9204, R=0.959, n = 43,460) with a line of y = 0.932x + 153.518 fitting the data (this is not different significantly from y=1.0x+0.0 line; p=0.00001). The lower fit is a result of leveraging by discordant younger grains, which force the fitted equation to have a higher intercept. Thus, all three comparisons have values for the slope of the relation which are indistinguishable statistically from 1.00 [Fig. 2]. The reported linear regression coefficients used simple linear regression. More rigorous regression techniques (major axis regression and orthogonal regression) that accounted for error in both variables were performed using both R and JMP generated outputs that were very similar to those of the simple linear regression (slopes that were ± 0.01 and R²- values that were identical to the third decimal place). Due to the high degrees of correlation, the authors feel justified in pooling the age data together to increase the number of data points available for analysis. An additional line of evidence for the degree of similarity between the three U-Pb ages is plotting each system as a histogram [Fig. 3]. The three isotope-pair should exhibit the same set of peaks if they behave in a similar manner. All three ages exhibit similar distributions with peaks II through V being present in all three systems. The magnitudes of the peak heights change (an artifact of sample
size) from one age distribution to another. Also, the U-Pb ages have broader peaks in terms of age range. Note that the correlations reflect the degree of concordance between the different age systems. One method of calculating concordance is:

\[
\text{%conc.} = 100 \times \left( \frac{^{206}\text{Pb} / ^{238}\text{U} \text{ age}}{^{207}\text{Pb} / ^{206}\text{Pb} \text{ age}} \right)
\]

Perfectly concordant ages should have R²-values of 1.00 and a concordance of 100. Discordant grains should plot below a y = x line and reverse discordant grain should plot above the y = x line.

In addition to the parameter estimates for the ≤5% discordant data, linear regression parameters were also estimated for the pairwise comparisons of different U-Pb ages for the unfiltered dataset. A comparison of the parameter estimates shows that the correspondence between the two radiometric dates (\(^{235}\text{U}-^{207}\text{Pb}\) and \(^{238}\text{U}-^{206}\text{Pb}\) ages) is high regardless of whether the data are filtered or not (Table 1). Filtering the data for degree of discordance does make a difference for the \(^{207}\text{Pb}-^{206}\text{Pb}\) ages, as the R² values increase and the intercepts decrease with filtering. Note that this is a mute point as the grains that leverage the fitted line are the young grains with anomalous discordance values that we use the \(^{206}\text{Pb}/^{238}\text{U}\) age instead for the rest of the analyses.

### 2.2.2 Analytical Methods

A detrital zircon age-frequency distribution is an empirical distribution of ages derived from a sample of zircons taken from a sediment sample. The resulting data are then plotted as either a frequency diagram/histogram or as a concordia plot (Wetherill or Tera-Wasserburg style) (Sircombe, 2000). The term spectrum is commonly used in the detrital zircon literature as a synonym for age-frequency distribution. "Age Spectrum" has multiple specific definitions in the
geosciences, we chose to use the term age-frequency distribution instead to avoid confusion (see Gilgen, 2006 and references therein).

Histograms were chosen as the medium to plot the data as more traditional bivariate concordia plots become cluttered with increasing numbers of grains presented (Sircombe, 2000). All histograms of the data (full database, ≤5% discordant filtered data, and ≤10% discordant filtered data) were arbitrarily plotted at bin intervals of 25 Ma using the histogram tool in Excel, in order to allow for easy comparison of different aspects of the database: i.e. different geographic locations or tectonic settings. A bin size of 25 Ma allows for resolution of finer-scale events superimposed on the larger peaks. Different bin sizes were examined for the pooled database: bin sizes of 5, 10, 20, 25, 50, and 100 Ma all preserved the same overall shape of the distribution [Fig. 4]. The count axis for each histogram was based on the histogram representing the largest sample size of a set of histograms contrasted together. As with the scatterplots discussed previously, the histograms do not incorporate any information on degree of concordance or analytical errors (Sircombe, 2000, Vermeesch, 2005).

In addition to histograms, a probability density function was calculated and overlain on the pooled global histogram. The probability density function was generated using the gprobdens fortran code compiled by the UCLA SIMS Group. The gprobdens program was upgraded by Dr. Oscar Lovera to handle large datasets for this project. Probability density functions take into account the errors of analysis for each grain. The errors reported in the literature vary in form; most of the errors are 1σ errors (standard deviation). A few of the errors were reported as standard errors in the original publications. Several studies did not report the errors on their ages. Ages that did not have associated errors were not used in the calculation of the probability density functions.
To evaluate statistical uncertainty in the location and height of each individual peak, a bootstrap procedure was applied to all analyzed age distributions. The bootstrap protocol was designed to both evaluate each peak in terms of its local statistical significance as well as to assess confidence intervals around the location of the peak (its age and its height). The simulation also explicitly incorporated dating errors (as nearly all studies reported standard deviations of age estimates).

The following protocol was used in the simulation. The analyzed age distribution (e.g., all dated zircon grains from South America) was re-sampled with replacement. For each iteration, the age of each re-sampled grain was then modified by adding a random variate from a normal distribution with mean value corresponding to the actual age of the grain and standard deviation corresponding to the standard deviation of age estimate reported for that grain by original authors. For example, if a selected grain was 544 Ma and the standard deviation of the age estimate was 23 myr, the grain age was modified by using a random number sampled from a normal distribution with mean of 544 Ma and standard deviation of 23 myr. Thus, this bootstrap process simulates both sampling process (by resampling with replacement) and the age dating error (by using an intrinsically defined random variate age value).

The location (age class) and height (number of grains within that age class) were recorded for each notable peak observed in any given iteration. The process was repeated 1000 times to generate the sampling distribution of peak positions and peak heights. Confidence intervals were then estimated using percentile approach or "naïve bootstrap" (Efron, 1981). All major peaks observed in the datasets display very narrow confidence intervals (both in terms of age and height) indicating that they represent statistically significant modes that are well
constrained in their location and height. This is not surprising considering the very large sample size and relatively small errors associated with individual age estimates.

In addition, Monte Carlo simulations were performed with a null model of constant zircon production through geologic time in order to evaluate the significance of the peaks present within the full database and within each subset of the database plotted on histograms. A SAS simulation was developed to look at the maximum size of peaks expected under the null model of constant zircon production through geologic time (i.e., uniform probability distribution). The output of the simulation was 95 and 99 percent confidence intervals for the maximum height possible under the null model. All peaks plotted in the pooled dataset and in the sorted subsets of the database (by continent, by tectonic setting, and modern sediments) are much greater in magnitude than those observed for the null model. This model is not discussed in this article in any detail because it is a rather naïve construct that assumes time-invariant grain production and no loss of older grains through time. However, it is mentioned briefly here to stress that observed age distributions of zircon grains are drastically and significantly different from predictions of the simplest null model that can be postulated for grain production and preservation.

2.3 Results and Discussion

2.3.1. U-Pb Age Patterns.

The “Global Age Frequency Distribution” of detrital zircon grains is highly multimodal (Fig. 5, 3, and 4), with five major, statistically significant peaks at 3.5-3.4, 2.7-2.5, 2.0-1.7, 1.2-1.0, and 0.7-0.5 Ga (Table 2). These peaks are remarkably evenly spaced (0.5, 0.75, 0.75, and 0.5 Ga, respectively), suggesting a quasi-cyclic process (although, obviously, a time series defined by six events is not conducive for rigorous statistical testing). In between the peaks,
zircon grains are continuously present back to approximately 3.7 Ga. This pattern of the low background frequency punctuated by statistically significant peaks (Table 2) persists through geologic time.

Filtering the global dataset for different thresholds of discordance also impacts the shape of the global age frequency distribution. Removing grains that are either ≤10% or ≤5% discordant tends to filter out older grains and enhances Peak I in the global age frequency distribution (Figures 5B and 5C). The overall shape of the distribution is retained (Fig. 5).

As a side note, the overall distribution when plotted for log(10) of the U-Pb ages visually resembles a bell-shaped curve although with a truncation of its right tail. It is possible that this truncation reflects a boundary condition imposed by the limits of the age of the solar system (with the caveat that the oldest zircons are oversampled in the literature and if removed would make the truncation even more pronounced) and that zircon ages follow a log-normal distribution. Such log-normal distributions of geological records may be a common phenomena (Kesler and Wilkinson, 2009; Wilkinson and Kesler, 2009). In this specific case, the shape of the distribution may reflect the gradual unroofing of batholiths through weathering and erosion which would decrease frequency of younger zircons (due to time necessary for unroofing and releasing these grains to the sediment) combined with decreased frequency of much older zircons through lower preservation of ancient crust available as a source of zircons.

The global pattern also persists regionally: age distributions derived separately for each continent display most or all of the peaks found in the global distribution (Fig. 6). Specifically, the three prominent peaks at 2.7-2.5 Ga, 2.0-1.7 Ga, and 1.2-1.0 Ga are present on all continents, although the timing of some of the peaks is shifted slightly on some continents. The 3.5-3.4 Ga
peak is present from Australia, Africa and North America (and may reflect a sampling bias), though this peak is suppressed relative to the other peaks (Fig. 6A, E, and F), and, in the case of North America, the peak is shifted slightly (to 3.6-3.7 Ga). In addition, Africa and Australia both exhibit peaks at 3.0 Ga that are not observed on any of the other continents. Only the second youngest peak (in the filtered dataset) was not observed for all seven continents (0.7-0.5 Ga). This is likely a sampling bias as younger strata in Europe (other methods, especially fission track, have been used for provenance work), Africa (most detrital zircon studies focus on the host rocks of ore bodies in southern Africa) and Antarctica (poor access to rock material save for limited ice-free regions) are poorly represented in the literature that reports detrital zircon U-Pb ages. Thus, while each continent appears to have a subtly distinct signature, the first-order pattern of five major peaks observed in the global age distributions is remarkably well conserved across continents. Some of the minor differences (e.g., the slightly shifted 3.6-3.7 Ga. peak in the North American dataset) are unlikely to represent sampling biases and suggest that age distributions of zircons may carry distinct (albeit subtle) continental-scale signatures. These meta-data may thus serve as a reference standard to which new samples can be compared, especially in the context of provenance studies, regional and global correlations, and suspect terrane analysis (Dickinson and Gehrels, 2009, 2010).

As an illustration of the utility of the technique for provenance analysis, let us consider the geological context of the North American detrital zircon age frequency distribution. The North American age frequency distribution has seven clearly resolved peaks at 0.1-0.3 Ga, 0.35-0.4 Ga, 0.6-0.7 Ga, 1.1-1.25 Ga, 1.4-1.45 Ga, 1.65-1.8 Ga, and 2.7-2.8 Ga (Fig. 7). These peaks correspond directly to well-known geologic events. Starting from the most recent event, the youngest peak (0.1-0.3 Ga) reflects a composite of the Cordilleran orogenies (Laramide, Sevier,
and Antler), when major batholiths formed and subsequently provided a source for abundant Cordilleran zircons (Burchfiel and Davis, 1975; Camilleri and Chamberlain, 1997; Dickinson, 2004; Gehrels and Dickinson, 2000; Gehrels et al. 2002; Speed and Sleep, 1982), which constitute the youngest North American peak. Note that this youngest peak masks much smaller and thus more subtle peaks of slightly older zircons that represent the youngest of the Appalachian orogenies: Alleghanian granitic batholiths magmatism (Faill, 1998). The second, relatively smaller peak at 0.35-0.4 Ga represents material derived from the Taconic island arc (Faill, 1997). The third peak (0.6-0.7 Ga) is derived from the breakup of Rodinia during Iapetan rifting (Cawood et al. 2007) or alternatively are derived from Pan-African material (Bousquet et al. 2008; Grant, 1969; Takigami, 2001). The Grenville orogeny is represented by the fourth peak (at 1.1-1.25 Ga) with grains derived from granitic magmatism related to arc accretion (Gower et al. 2008). 1.4 Ga magmatism is recorded in the southwestern United States (Nyman et al. 1994) and may be a source of zircons for the fifth peak at 1.4-1.45 Ga. The sixth peak may represent the combined orogenic events that occurred during the period 1.65-1.8 Ga: the Mazatzal, Yavapai, Penokean, Trans-Hudson, and Wopmay orogenies (Whitmeyer and Karlstrom, 2007). The younger Mazatzal and Yavapai orogenies make up the Central Plain orogen of Sims and Peterman (1986), and reflect accretion of arcs onto the southeastern margin of Laurentia during this period as well as abundant rhyolitic magmatism (Amato et al. 2008, Jones et al. 2009). The accretion of an island arc to the southeastern margin of Laurentia (southern Wisconsin-Minnesota) during the Penokean orogeny formed a significant event at 1.7-1.9 Ga (Bahovich et al. 1989; Sims et al. 1983, 1989, and 1993). The oldest (seventh) peak recorded in the North American detrital zircon age frequency distribution is the 2.7-2.8 Ga peak which is derived from
magmatism generated during the formation of the supercontinent Kenorland (Aspler and Chiarenzelli, 1998; Corfu et al. 1998, 2000).

The age frequency distributions for Gondwana vs. Laurasia exhibit similar peaks to those displayed by the global compilation (Fig. 8). Both age frequency distributions contain peaks II, III, IV, and V. The two distributions have comparable sample sizes of ~20,000 grains. There are significant geographic sampling biases inherent in these two age frequency distributions. For Laurasia (Fig. 8A), the distribution is overwhelmingly dominated by grains from North America. The Gondwanan age frequency distribution (Fig. 8B) is dominated by grains from Australia. The peaks for Gondwana tend to have a narrower age range, whereas the Laurasian peaks are much broader. It is also significant to note the steepness of the trough at ~1.5 Ga for Gondwana (Fig. 8B), which corresponds to a small peak in the Laurasian distribution. This 1.5 Ga peak may reflect the break-up of Columbia (Rogers and Santosh, 2002). Peak V (the 2.7-2.5 Ga peak) is shifted towards 2.7 Ga in Laurassia. The Gondwanan peak V is strongly bimodal with distinct peaks at 2.5 and 2.7 Ga.

The same set of prominent peaks persists when data are grouped into four geotectonic settings (passive margins, foreland basins, arc settings, and rift basins), including prominent peaks at 2.7-2.5 Ga, 2.0-1.7 Ga, 1.2-1.0 Ga, and 0.7-0.5 Ga, as well as a somewhat less pronounced peak at 3.1-3.0 Ga (Fig. 9). Each geotectonic setting is represented by at least 15,000 zircon ages (5% or less discordant) providing statistically robust estimates of age distributions (Table 2). The presence of the same set of peaks in different tectonic settings suggests that geochronology of detrital zircon grains is not affected notably by geotectonic setting as the tectonic setting of the host sediment reflects the depositional setting and not the sites of original crystallization of the zircons. Whether a given sedimentary basin represents an
active, or passive or rift setting does not noticeably impact the resulting age structure of detrital grains incorporated into the new sedimentary record. This pattern may be due to the durability of zircon grains and their high blocking temperatures that may allow for the recycling of grains through the rock cycle and their subsequent deposition with sediments in these different tectonic settings.

The oldest peak observed in the global data was missing from modern river sediments (Fig. 10). No grains older than 3.5 Ga were observed in this subset of the database. The lack of pre-3.5 Ga grains could be due to two factors: sampling bias (as sites of 3.5 Ga or older crust at the surface are of limited extent) or efficiency of crustal reworking, involving a cumulative loss or age resetting of very old grains towards the present. The presence of the same four peaks globally, on each individual continent, in all major tectonic settings, and in modern sediments implies the episodic nature of plate tectonic processes. This pattern may reflect either episodic production of continental crust (formation of new zircon crystals, with the caveat that juvenile crustal rocks are mafic in composition and generally zircon-poor) or episodic recycling of preexisting crust (reheating of zircon grains above closure temperature and formation of new zircons).

2.3.2. Th-Pb Patterns
A second independent geochronological system was analyzed for ~16,200 grains. The $^{232}$Th-$^{208}$Pb system has a decay constant of $4.9475 \times 10^{-11}$ yr$^{-1}$ (Steiger and Jäger, 1977 and references therein). Of the 16,200 grains, 8,249 of the grains passed the ≤5% discordance filter and were analyzed in this compilation. There is a high degree of correlation ($R^2 = 0.956$) between the $^{232}$Th-$^{208}$Pb age and the pooled U-Pb age (Fig. 11A). The age frequency distribution (Fig. 11B)
of the $^{232}$Th-$^{208}$Pb ages is very similar to that observed in the U-Pb pooled age distribution (Fig. 5) with peaks at 0.1-0.2 Ga, 0.5-0.7 Ga, 1.0-1.2 Ga, 1.7-1.9 Ga, and 2.4-2.7 Ga. This distribution does exhibit a peak at 3.0-3.2 Ga. The strong similarity of the two independent geochronological systems supports the validity of the retrieved age distribution pattern.

2.3.3. Hf isotope model ages and crustal recycling

The relative importance of crustal growth versus crustal recycling in the evolution of continental crust can be evaluated through the interpretation of Hf isotope model ages in conjunction with the U-Pb data. Of the ~200,000 zircon grains included in the database, ~10,500 were also dated using Hf isotopes model ages. Applying the 5% discordance filter drops the number of grains with associated Hf isotope model ages to 5,124. These concurrent ages may provide an independent way to distinguish crustal growth from crustal recycling. The U-Pb zircon dating system has a closure temperature of ~900°C (Cherniak and Watson, 2000), though Pb loss may occur at lower temperatures in the presence of fluid alteration (Hay and Dempster, 2009, Geisler et al. 2003). However, high-grade metamorphism can potentially bring zircons above this temperature and reset their age via lead loss; this is a problem for zircons that may have undergone multiple cycles of reheating and magmatic recycling before reaching their final resting point in the current sedimentary host rock. Hafnium is more strongly retained by zircons, as it behaves chemically like zirconium and is often thought of as a robust indicator of the age of magma separation from the mantle related to crustal growth (Kinny et al. 1991, Kemp et al. 2006, Flowerdew et al. 2007). Hafnium isotope model ages are based on the Lu-Hf decay system and algebraic manipulation of the formula. The ages are not true radiometric ages, but instead model ages reflecting the last time that material was part of the mantle (Kemp et al.
2006). Note that there are multiple different models used in calculating these Hf isotope model ages and no consistent standard is currently available (the authors chose not to recalculate the Hf isotope model ages to standardize them as not all studies provide enough information to do so). There is also variability in the Hf isotope model ages from the Lu-Hf decay constants used (with 5 different decay constants in use currently). However, the large size of the dataset may justify time-estimating of the crustal growth events, we recognize that Hf isotope model ages (being potentially mixed age models with questionable geochronological relevance) may represent biased age estimates that should not be interpreted literally.

The distribution of Hf isotope model ages is multi-modal, but the position (and magnitude) of peaks differs substantially from that observed in both the U-Pb and Th-Pb distributions (Fig. 12A). A bivariate comparison of U-Pb and Hf isotope model ages (Fig. 12B) shows that detrital zircon grains, dated by both methods, populate an upper left part of the plot above the diagonal boundary defined by the Age(Hf)=Age(U-Pb) line. Thus, the Hf age of a grain is at most as young and, except for very few outliers, never younger than the U-Pb age of that grain. However, the Hf isotope model age of a grain is commonly much older than the U-Pb age of that grain. This is not entirely surprising given that Hf ages are model ages and cannot be younger than the U-Pb ages (Kemp et al. 2006). The Hf isotope model ages reflect when the material forming the zircons was first crystallized to form continental crust. The offset in age between the Hf isotope model age and the U-Pb age of the zircon then reflects crustal recycling of this much older crust (Kemp et al. 2006). Nevertheless, the Hf isotope model age distribution is also multimodal, suggestive of episodic growth of crust, although the Hf peaks (Fig. 12) do not match the U-Pb peaks (Fig. 5).
When Hf dates are grouped based on the U-Pb ages of the host zircon grains into five classes representing the five peaks observed in the global U-Pb age distribution, the resulting Hf isotope model age distributions (Fig. 13) all exhibit a wide range of ages despite representing grains from single U-Pb age classes. Assuming that peaks in the Hf distribution represent crustal growth events, the U-Pb age peak number 5 (2.5 Ga) exhibits a peak in the Hf isotope model age distribution at 2.8-2.9 Ga suggesting that the zircons age dated at 2.5 Ga with U-Pb underwent remelting of 2.8-2.9 Ga old continental crust that was recrystallized at 2.5 Ga before eventual deposition in their host sedimentary rocks. The U-Pb peak number 4 (1.8 Ga) exhibits two Hf peaks, one at 1.8 Ga and the other at 2.3-2.4 Ga. This suggests that detrital zircons with U-Pb ages of 1.8 Ga were sourced from zircons that formed in two previous crustal growth events and were subsequently crustally recycled. Figure 13 illustrates that there is an average offset of ~0.5 Ga from the U-Pb age and the Hf isotope model age. The greatest offset recorded was 0.8 Ga for class II zircons. The smallest offset was recorded for class V -- ~0.3 Ga. Similar values of offset have been observed by Kemp et al. (2006).

2.4 Comparisons with other compilations
Multiple detrital zircon compilations have been published recently. A comparison of detrital zircon compilations (this study; Campbell and Allen, 2008; Condie et al. 2009) and igneous zircons (Condie et al. 2009) are presented in Figure 14. All four compilations are plotted at the same bin size (20 Ma) and axes settings. In addition, the peaks identified in this study have been labeled on the corresponding peaks of the other compilations (i.e. peak I: 0.1-0.2 Ga, peak II: 0.5-0.7 Ga, peak III: 1.0-1.2 Ga, peak IV: 1.7-2.0 Ga, and peak V: 2.5-2.7 Ga).
Campbell and Allen (2008) analyzed modern river sediments from rivers worldwide. Their dataset was filtered with a \( \leq 5\% \) discordance filter and is independent of both the current study and the Condie et al. (2009) compilation, making it an invaluable study for independent comparison. The Condie et al. (2009) database is a global survey of detrital zircon data compiled from the literature. They used two filters: a \( \leq 10\% \) discordance filter and a \( 1\sigma \) error \( < 20 \text{ Ma} \) filter. The majority of studies represented in the Condie et al. (2009) database are also represented in the current study’s database. In addition to detrital zircons, Condie et al. (2009) also compiled a global igneous zircon dataset. This dataset is plotted separately in order to allow us to compare the detrital signature against the igneous signature. The current study used a \( \leq 5\% \) filter and has a much greater sample size than either of the other detrital zircon compilations.

Both of the above detrital zircon compilations and the igneous zircon compilation, in common with this study, exhibit peaks II, III, IV, and V. Not only peak positions, but also to some extent the shapes of specific peaks (for example, peaks III and V) are similar for the different compilations. Another significant similarity between the compilations is that peak V is bimodal with a strong peak at 2.7 Ga and a minor peak at 2.5 Ga. Thus, the compilation of dated grains analyzed here is remarkably consistent with previous analyses, providing strong empirical support for reproducibility of the geochronological pattern recorded by individually dated detrital zircon grains.

### 2.5 Alternative Hypotheses

Two other hypotheses may also be at play here: 1. the issue of signal preservation and 2. the potential of zircon rafting by suspect terranes, micro-continents and arcs. The peaks recorded in geochronological datasets may not reflect episodic crustal growth, but instead are related to the
preservation of crustal materials. Hawkesworth et al. (2009, 2010) argue that peaks in crystallization age are tied to the supercontinent cycle because these are periods when magmatic rock preservation is enhanced. In addition, the similarity of continental detrital zircon age frequency distributions may be a result of the amalgamation of the continents through accretion of arcs, micro-continents and suspect terranes. These continental blocks may actually transfer zircons that formed in one region to a completely different region, in a process somewhat analogous to sediment transport by ice-rafting in glacial settings. The geographic coding in the database currently is not capable of determining how significant this second process may be.

2.6 Conclusions
Joint consideration of U-Pb and Hf age distributions of detrital zircon grains reaffirms the model postulating episodic crustal evolution through one or a combination of crustal growth and/or crustal recycling. The relatively even spacing of U-Pb age peaks and Th-Pb age peaks (~0.6 Ga) is consistent with a quasi-cyclic process such as the supercontinent cycle. The variable and generally older Hf isotope model ages of zircon grains from single U-Pb age classes suggest that the crustal evolution involved substantial crustal recycling, a phenomenon which may also help to explain the uniformity of U-Pb age distributions across different continents and between different tectonic settings. The uniform offset between the Hafnium isotope model ages and the U-Pb ages is also quite intriguing and suggests that crustal recycling may also have occurred at roughly 0.5-0.6 Ga. This remarkable spatial and geotectonic homogeneity suggests that the evolution of the continental crust on Earth has been primarily controlled by global scale processes rather than historically unique regional events.
2.7 References Cited


Figure 2. Comparison of ≤5% discordant-filtered U-Pb ages. 

A. Scatterplot of $^{206}$Pb-$^{238}$U vs. corresponding $^{207}$Pb-$^{206}$Pb age. 

B. Scatterplot of $^{207}$Pb-$^{235}$U vs. corresponding $^{207}$Pb-$^{206}$Pb age. 

C. Scatterplot of $^{207}$Pb-$^{235}$U vs. corresponding $^{206}$Pb-$^{238}$U age. Note all three pairs can be modeled with a simple linear regression model of the form: $Y = 1.0X + 0$. The $R^2$-values show high correlation with values of 0.99.
Figure 3. Comparison of the age distributions for each of the U-Pb ages. A. $^{207}\text{Pb} - ^{206}\text{Pb}$. B. $^{206}\text{Pb} - ^{238}\text{U}$, and C. $^{207}\text{Pb} - ^{235}\text{U}$. All three distributions are from the $\leq 5\%$ discordant-filtered subset of the database. Peaks II through V are present in all three distributions.
Figure 4. Comparison of the ≤5% discordant-filtered subset of the database at different bin size intervals in order to illustrate that the peaks are independent of bin size. Peaks II, III, IV, and V are observed at A. 5 Ma bins. B. 10 Ma bins. C. 20 Ma bins. D. 50 Ma bins. E. 100 Ma bins. At greater bin size intervals, the peaks merge together, but one has to bin the data at 200 Ma or greater bins to do so.
Figure 5. Global Detrital Zircon Pooled Age Distribution: a.) unfiltered, b.) ≤10% discordant-filtered, c.) ≤5% discordant-filtered. Note the persistence of all peaks regardless of degree of filtering.
Figure 6. Continental Detrital Zircon Age Distributions from the ≤5% discordant-filtered subset of the full database. A, North America. B, South America. C, Europe. D, Asia (without India). E, Africa. F, Australia. G, Antarctica. Note the persistence of peaks III, IV, and IV on all continents. Peak II is observed for North America, South America, Europe, Asia, and Antarctica. Africa and Australia exhibit a much reduced peak II.
Figure 7. Age frequency distribution of detrital zircon U-Pb ages from North America with corresponding significant geologic events.
Figure 8. Comparison of ≤5% discordant detrital zircon grains from A. Laurasia and B. Gondwana. Peaks II, III, IV, and V are present in both of these plate tectonic configurations. Laurasia exhibits a trough between peaks III and IV that is not as deep as observed from Gondwana.
Figure 9. Comparison of detrital zircon (≤5% discordant-filtered) age distributions from different tectonic settings. A. Arc settings. B. Foreland Basins. C. Passive Margins and Intracratonic Basins. D. Rift Basins. Note that the tectonic setting is of the host sediment. The tectonic setting of the host sediment is not related to the crystallization of the zircons.
Figure 10. Detrital Zircon distribution from Modern Sediments compiled in this study.
Figure 11.  

A. Comparison of $^{208}\text{Pb} - ^{232}\text{Th}$ age versus pooled U-Pb age for corresponding detrital zircon grains. There is a high correlation between the two age systems ($R^2 = 0.956$) and a regression line that is close to $Y = 1X + 0$. 

B. $^{208}\text{Pb} - ^{232}\text{Th}$ distribution. Note the strong similarity between the $^{208}\text{Pb} - ^{232}\text{Th}$ age distribution and the pooled U-Pb age distribution (from Figure 1c). All grains had a pooled U-Pb age that was $\leq 5\%$ discordant.
Figure 12. A. Comparison of Hf isotope model ages versus pooled U-Pb age from corresponding, ≤5% discordant detrital zircon grains. The majority of the grains fall above a $Y = X$ line showing that the calculated Hf isotope model age is greater than or equal to the pooled U-Pb age. B. Hf isotope model age distribution. The distribution is multimodal. However, the peaks are offset from those observed in the U-Pb age distribution.
Figure 13. Comparison of pooled U-Pb age vs. Hf isotope model age distribution for discrete pooled U-Pb age classes. A. Class I corresponds to detrital zircons with ages equivalent to Peak I. B. Class II corresponds to detrital zircon grains with ages equivalent to Peak II. Note the offset from the pooled U-Pb age (light gray bar) and the majority of the Hf model isotope ages. This offset is recorded in C. Class III, D. Class IV, E. Class V. In addition to the offset, the variance of the Hf isotope model distribution decreases from class I to class V, suggesting a boundary condition due to the age of the Earth. Only three grains from Peak I had Hf isotope model ages and so they were not plotted due to the small sample size.
Figure 14. A. The ≤5% discordant-filtered pooled U-Pb age distribution from study. B. A second detrital zircon compilation. C. Global Modern River Detrital Zircons distribution. D. Igneous zircons U-Pb age distribution. All three detrital zircon compilations exhibit peaks II, III, IV, and V.
Table 1. Comparison of regression parameter estimates for pairwise comparison of U-Pb ages for both the unfiltered dataset and the ≤5% discordant filtered dataset for an equation of the line $Y = \beta_0 + \beta_1 X$.

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Table 2. Locations of Peaks defined by bootstrapping of the dataset. For each peak, the 99% confidence intervals are given for width (in Ma) and height (frequency of grains).

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Tectonic Settings

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Detrital Zircon Geochronology and Provenance of Upper Triassic Sediments of the Danville-Dan River Basin, Southern Virginia

The ages of Upper Triassic sedimentary rocks of the Danville-Dan River Basin are well constrained by a combination of biostratigraphy (pollen) and magnetostratigraphy. Detrital zircon U-Pb dates do not provide constraints on the timing of sedimentation in this specific case (though provide an estimate of the maximum age of sedimentation), but are useful in delineating rift geometries, sediment source pathways and provenance ages of sediment fill in these rift basins. A sample of arkosic sandstone was collected from an exposure on U.S. 58 near Danville, Virginia from the Dry Fork Formation. The sample was processed and Laser Ablation Inductively Coupled Plasma Mass Spectrometry was performed on extracted detrital zircons (n = 115) at the Australian National University. The distribution of ages is unimodal with a strong peak at 400-450 Ma. Two smaller peaks are recorded at 375 Ma and 560 Ma. Four grains exhibited ages older than 900 Ma. The presence of detrital zircons of mostly Paleozoic age suggests that the sediment was derived from Ordovician through Silurian granite sources within the magmatic tract of the western Piedmont to the southeast of the preserved basin. Thayer and Henika have previously shown this part of the basin was sourced by arc volcanic and subvolcanic granitic rocks adjacent to the Vandola Fault along the southeastern side of the basin. The scarcity of Grenvillian zircons suggests that the basin was isolated from the metaclastic tract of the western Piedmont northwest of the Chatham Fault along the northwestern side of the basin.


3.1 Introduction

Triassic deposits of the east coast of North America reflect the breakup of Pangaea and the development of the modern Atlantic Ocean through rifting and development of the modern passive margin. A series of linear belts of Triassic age sediment is present along the eastern margin of North America stretching from South Carolina to Newfoundland (Olsen, 1997, Schlische, 2003, Weems and Olson, 1997). Basaltic/diabasic magmatism accompanied rifting (May, 1971, McHone et al. 1987, McHone, 2000, Wilson, 1997); however, basaltic magmas generally produce rare zircons that are small in size and as such are not as easily age dated as zircons derived from granitic bodies. During the Triassic, Europe and northern Africa rifted apart from North America (Manspeizer et al. 1978, Pegrum and Mounteney, 1978, van Houten, 1977)

The Danville-Dan River Basin is one of these rift basins located on the border of North Carolina and Virginia (Fig. 15). The Danville-Dan River Basin stretches 165 km and has a maximum width of 10 km. It is bounded to the west by the Dan River Fault zone (in North Carolina) and the Chatham Fault zone in Virginia (Meyertons, 1963). The Chatham Fault zone separates the Danville-Dan River Basin from the Smith River Allochthon (Carter et al. 2006, Gates, 1986), which consists of meta-sedimentary and meta-igneous rocks. The basin structure is that of a half-graben for most of its length save for in the central basin where it is bounded by the Vandola fault to the east (Henika and Thayer, 1977, Price et al. 1980, Schlische et al. 1996). The Vandola fault separates the basin from the Milton terrane to the east (Bradley et al. 2006, Coler et al. 2000). The basin is filled with siliciclastic sediment (the Dan River Group) and diabasic intrusions (Thayer, 1970).
The stratigraphy of the Danville-Dan River Basin was originally given separate stratigraphic nomenclature depending on which side of the North Carolina-Virginia border was of interest. Meyertons (1963) proposed three formations in Virginia: the Leaksville (mostly claystone and siltstone), the Dry Fork (mostly arkosic sandstones) and the Cedar Forest (shales and conglomerates). Thayer (1970) proposed a similar three-part division for North Carolina: the Pine Hall Formation (mostly sandstone and conglomerate), the Cow Branch Formation (mostly shale and siltstone) and the Stoneville Formation (conglomerates and sandstones). Henika and Thayer (1977) and Thayer (1980) recognized that the terminology was redundant and extended the North Carolina terminology north into Virginia (Fig. 16). In the central portion of the basin, the Dry Fork Formation consists of conglomeratic sandstones, siltstones and mudstones. Thayer and Henika (1980) report an average composition for the Dry Fork Formation of 43.1% sandstone matrix, 38.9% felsic tuff clasts, 6.9% quartz-feldspar gneiss clasts, 1.4% lapilli tuff clasts, 2.1% greenstone clasts, 1.4% biotite gneiss clasts, 4.8% quartz clasts, and 1.4% feldspar clasts.

The Danville-Dan River Basin is known for exceptional preservation of fossil vertebrates (Casey et al. 2007) and insects (Fraser et al. 1996) from the Cow Branch Formation shales. This fossil assemblage has been used to estimate the age of the Cow Branch Formation and the correlated Dry Fork Formation as late Carnian (Olsen et al. 1978, 1982). Pollen from the upper portion of the Cow Branch Formation agrees with this constraint (Cornet and Olsen, 1985, Robbins and Traverse, 1980, Traverse, 1987). In addition, fossil footprints of putative dinosaurs have been reported from the Danville-Dan River Basin (Fraser and Olsen, 1996). Magnetostratigraphy also supports a Carnian to Norian age for the Danville-Dan River sediments (Kent and Olsen, 1997).
The Dan River Group has been interpreted as being deposited in alluvial, fluvial, playa, swamp and lacustrine settings (Bradley et al. 2006, Olsen, 1990). These rift valleys were formed under relatively arid conditions as evidenced by the presence of evaporite deposits in some of the basins (Evans, 1978, El-Tabakh et al. 1997).

Detrital zircon geochronology provides an excellent tool for delineating the provenance of siliciclastic sediments (Dickinson and Gehrels, 2009, 2010). A sample of the Triassic Dry Fork Formation sandstone was collected for detrital zircon analysis in order to elucidate sediment source pathways into the Danville-Dan River Basin.

### 3.2 Materials and Methods

A sample of the Dry Fork Formation was collected from a site west of Danville, VA from a poorly exposed road cut at the intersection of the Danville Expressway (U.S. Highway 58) Interchange and Oak Ridge Farms Road. The sample consists of gray, poorly sorted, well-indurated, arkosic, sandstone with granitic pebbles and cobbles (Fig. 17a). The sample was collected from float, as the outcrop had been graded over by the Virginia Department of Transportation. Bradley et al. (2006) report that the outcrop consisted of the Dry Fork Formation in fault contact with Milton terrane metavolcanics. The Dry Fork Formation consists of a basal conglomerate and angular lithic breccias and fines upward into siltstone interbedded with thin lenticular layers of coal. Plant fossils are preserved in the coals.

Detrital zircons were extracted from the sample using standard heavy mineral separation techniques. The separated grains were mounted with epoxy and polished. Cathodoluminescence photomicrographs were taken of selected grains (Fig. 17b). The grains were sampled via laser
ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the Research School of Earth Sciences at the Australian National University following procedures outlined in Eriksson et al. (2003). Ages older than 800 Ma were calculated using the $^{207}\text{Pb}/^{206}\text{Pb}$ ratios and younger grain ages were calculated using the $^{206}\text{Pb}/^{238}\text{U}$ ratio. Common Pb corrections were made using the $^{208}\text{Pb}$ method after Compston et al. (1984). Internal error are reported for single grains as 1σ and were calculated by dividing the standard deviation of the corrected isotope ratio by the square root of the number of mass scans within the data interval selected for age calculation. These internal errors do not include uncertainties in the age or measurement from the zircon standard. Concordance between the $^{206}\text{Pb}/^{238}\text{U}$ age and the $^{207}\text{Pb}/^{206}\text{Pb}$ age was calculated for all grains and is reported in Table 3. Grains with a $^{206}\text{Pb}/^{238}\text{U}$ age less than 400 Ma in age were retained in the final pooled age regardless of their degree of discordance due to the difficulty in measuring the low contents of $^{207}\text{Pb}$ in these younger zircons. A sample of 160 detrital zircon grains was age dated from the Dry Fork Formation sandstone.

A detrital zircon age-frequency distribution is an empirical distribution of ages derived from a sample of zircons taken from a sediment sample. The resulting data are then plotted as either a frequency diagram/histogram or as a concordia plot (Wetherill or Tera-Wasserburg style) (Sircombe, 2000). The term spectrum is commonly used in the detrital zircon literature as a synonym for age-frequency distribution. "Age Spectrum" has multiple specific definitions in the geosciences, we chose to use the term age-frequency distribution instead to avoid confusion (see Gilgen, 2006 and references therein). Histograms were chosen as the medium to plot the data as more traditional bivariate concordia plots become cluttered with increasing numbers of grains presented (Sircombe, 2000). A bin size of 25 Ma allows for resolution of finer-scale events superimposed on the larger peaks.
In addition to histograms, a probability density function was calculated and plotted for the Triassic sample. The probability density function was generated using the "gprobdens" fortran code compiled by the UCLA SIMS Group. The "gprobdens" program was upgraded by Dr. Oscar Lovera to handle large datasets for the global detrital zircon project. Probability density functions take into account the errors of analysis for each grain.

In order to facilitate identification of source components for the Triassic sample, the authors used a recent global compilation of detrital zircons. The compilation includes detrital zircon ages, host sediment age data, geographic context, etc. (Voice et al. in review) and was used to compare the Triassic sample to the compiled North American and Eastern North American Age Frequency distribution.

3.3 Results and Discussion

The age frequency distribution of the detrital zircons sampled from the Dry Fork Formation sandstone sample is strongly unimodal with a significant peak at 460-480 Ma (Fig. 18A). Three grains are Grenville in age. The majority of zircons in this study have Th/U ratios greater than 0.4 suggesting that the grains are igneous in origin (Rubatto et al. 1999, 2001). In addition, the grains are euhedral and lack evidence of transport (no rounding). Cathodoluminescence shows that the grains exhibit continuous zoning. The peak at 460-480 Ma is a strong peak also observed in the East coast compilation (Fig. 18B) and as a minor subpeak of a significant peak in the full North American subset (Fig. 18C) of the Global Detrital Zircon Database. The presence of granitic clasts and the relatively high Th/U ratios of the grains suggest an igneous origin for the detrital zircons. The underlying Milton terrane metavolcanics
may have sourced the zircons that make up the peak in the Dry Fork Formation sample. Age dates for the Milton terrane include a Rb-Sr whole-rock date of 424 Ma for the Shelton Granite (Kish, 1983), a U-Pb zircon date of 463 Ma for the Shelton Granite (Hund, 1987, Wortman et al. 1995) report an age of 458 Ma from felsic volcanic rocks, meta-rhyolite from the northern portion of the Milton terrane has been dated to 458 Ma and a granite-gneiss from the same area yields an age of 450 Ma (Coler et al. 2000). The lack of rounding for the grains in addition to the ages support a local origin of these grains from the underlying Milton terrane volcanics.

The sample had three grains that were Grenvillian in age. These three grains potentially are xenocrystic relicts eroded out of the Milton terrane volcanics or were sourced from materials of Grenvillian age. The paucity of Grenvillian zircons in the sample suggests that the drainage system that was present in the Danville-Dan River Basin was not flowing over rocks of Grenvillian age. This may suggest that Grenvillian age crust was blocked off from the rift valley by the rift walls, preventing eroded Grenvillian-sourced sediment from entering into the Danville-Dan River Rift Valley. Rocks of Grenvillian age can be found to the east of the Milton terrane in the Goochland terrane. The Goochland terrane has been shown to have granites of that range in age from 1023-1046 Ma (Owens and Tucker, 2003). In addition, Grenvillian age crust is present to the west of the Chatham fault in the Piedmont. This material is constrained by detrital zircons to being younger than 750 Ma. The detrital zircon age frequency distribution from the Smith River Allochthon also contains grains that range from 750 to 1400 Ma (Carter et al. 2006). Metamorphic monazites provide a younger limit for the formation of the Smith River Allochthon materials of 530 Ma (Hibbard et al. 2003). The lack of Grenville-age grains suggest that neither terrane is providing sediment to this portion of the Danville-Dan River Basin.
In contrast to the unimodal nature of the detrital zircon sample from the Dry Fork Formation, the North American age frequency distribution has seven clearly resolved peaks at 0.1-0.3 Ga, 0.35-0.4 Ga, 0.6-0.7 Ga, 1.1-1.25 Ga, 1.4-1.45 Ga, 1.65-1.8 Ga, and 2.7-2.8 Ga (Fig. 18C). These peaks correspond directly to well-known geologic events. Starting from the most recent event, the youngest peak (0.1-0.25 Ga) reflects a composite of the Cordilleran orogenies (Laramide, Sevier, and Antler), when major batholiths formed and subsequently provided a source for abundant Cordilleran zircons (Burchfiel and Davis, 1975; Camilleri and Chamberlain, 1997; Dickinson, 2004; Gehrels and Dickinson, 2000; Gehrels et al. 2002; Speed and Sleep, 1982), which constitute the youngest North American peak. Note that this youngest peak masks much smaller and thus more subtle peaks of slightly older zircons that represent the youngest of the Appalachian orogenies: Alleghanian granitic batholiths magmatism (Faill, 1998). The second, relatively smaller peak at 0.35-0.4 Ga represents material derived from the Taconic island arc (Faill, 1997). The third peak (0.6-0.7 Ga) is derived from the breakup of Rodinia during Iapetan rifting (Cawood et al. 2007) or alternatively are derived from Pan-African material (Bousquet et al. 2008; Grant, 1969; Takigami, 2001). The Grenville orogeny is represented by the fourth peak (at 1.1-1.25 Ga) with grains derived from granitic magmatism related to arc accretion (Gower et al. 2008). Magmatism at 1.4 Ga is recorded in the southwestern United States (Nyman et al. 1994) and may be a source of zircons for the fifth peak at 1.4-1.45 Ga. The sixth peak may represent the combined orogenic events that occurred during the period 1.65-1.8 Ga: the Mazatzal, Yavapai, Penokean, Trans-Hudson, and Wopmay orogenies (Whitmeyer and Karlstrom, 2007). The younger Mazatzal and Yavapai orogenies make up the Central Plain orogen of Sims and Peterman (1986), and reflect accretion of arcs onto the southeastern margin of Laurentia during this period as well as abundant rhyolitic
magmatism (Amato et al. 2008, Jones et al. 2009). The accretion of an island arc to the southeastern margin of Laurentia (southern Wisconsin-Minnesota) during the Penokean orogeny formed a significant event at 1.7-1.9 Ga (Barovich et al. 1989, Sims et al. 1983, 1989, and 1993). The oldest (seventh) peak recorded in the North American detrital zircon age frequency distribution is the 2.7-2.8 Ga peak which is derived from magmatism generated during the formation of the supercontinent Kenorland (Aspler and Chiarenzelli, 1998; Corfu et al. 1998, 2000).

The Eastern North American detrital zircon record (Fig. 4B) is different from that of the full North American age frequency distribution (Fig. 4C) in that only two of the major North American detrital zircon peaks are significant. The Eastern North America age frequency distribution has prominent peaks at 450-600 Ma and at 950-1300 Ma. The younger peak is a composite of the Appalachian orogenies (Faill, 1997, 1998) and the Pan-African event (Bousquet et al. 2008; Grant, 1969; Takigami, 2001). When the Eastern North American age frequency distribution is sorted for host sediment age patterns in the sources of sediment can be further elucidated. Modern river sediments from the eastern United States (from the Savannah River to the Susquehanna River) exhibit a bimodal age frequency distribution (Fig. 19A) with the dominant peak being Grenvillian in age (Eriksson et al. 2003). An additional study of both detrital monazites and zircons from southwestern North Carolina emphasizes the peaks observed in the samples from the Global Detrital zircon database (Hietpas et al. 2010). The Triassic age frequency distribution (Fig. 19B) is from this study; other Triassic samples from the eastern North American rift valleys are being analyzed, but have not been published yet (Aleinikoff, personal communication), so there is a sampling bias present. Other Triassic rift basins may exhibit different age frequency distributions as a result of different source terrains for sediment
entering these basins. Multiple Carboniferous age sediments have been analyzed for detrital
Carboniferous sediments yield a bimodal distribution with peaks at 480-500 Ma and at 900-1300
Ma (Fig. 19C). Silurian to Devonian age sediments were sampled from southern New York
(McLennan et al. 2001), western Virginia (Eriksson et al. 2004), and central Nova Scotia
(Murphy and Hamilton, 2000). These sediments exhibit a multi-modal age frequency
distribution (Fig. 19D) with peaks at 475-490 Ma, 510-550 Ma, 1000-1250 Ma, and 2000-2100
Ma. Ordovician sediments are well represented with a sample size of 857 grains in the global
detrital zircon database (Fig. 19E). Sampled Ordovician sediments came from southern and
northern New York (Gaudette et al. 1981, McLennan et al. 2001), western Virginia (Eriksson et
al. 2004), Cape Breton Island, Canada (Chen et al. 1995), eastern Connecticut (Wintsch et al.
2007), Newfoundland (Cawood and Nemchin, 2001, Pollock et al. 2002, 2007), eastern
Pennsylvania (Gray and Zeitler, 1997). This distribution shows a strong peak at 500-520 Ma and
a smaller peak at 1000-1200 Ma. The 500-520 Ma peak suggests that relatively young zircons
were being sourced to these sediments as they were deposited. Cambrian to Neoproterozoic
sediments exhibit a strong Grenville peak (Fig. 19F); the sampled sediments came from Eriksson
et al. (2004) and McLennan et al. 2001. Late Neoproterozoic sediments exhibit two peaks: 540-
600 Ma and 900-1300 Ma (Fig 19G). The younger peak is likely an artifact of imprecise age
control on the age of host sediment. The older, more prominent peak represents grains derived
from Grenvillian crust. Minor peaks are present at 1800-2000 Ma and 2550-2650 Ma. The
compiled detrital zircon U-Pb dates are from Newfoundland (Cawood and Nemchin, 2001),
northern North Carolina and southern Virginia (Carter et al. 2006, Eriksson et al. 2004),
northeastern Nova Scotia (Barr et al. 2003, Keppie et al. 1998), southeastern Ohio (Santos et al.
2002), Georgia, South Carolina, North Carolina and Tennessee (Bream et al. 2004), northeastern Massachusetts (Thompson and Bowring, 2000), and Central Georgia and Alabama (Steltenpohl et al. 2008). Paleozoic and Cenozoic sediments throughout the region exhibit the bimodal detrital zircon age frequency distribution. The Neoproterozoic sediments exhibit a dominant Grenvillian peak. The lone Mesozoic sample exhibits only the younger Appalachian peak at 460-480 Ma.

3.4 Conclusions

The Carnian Dry Fork Formation Sandstone in the Danville-Dan River Basin sampled for detrital zircon analysis yielded an unimodal age frequency distribution with a peak at 460-480 Ma. In addition, a minor component of grains were Grenvillian in age (n = 3). High Th/U ratios and the presence of granitic clasts in the arkosic sandstone matrix suggest an igneous origin for the detrital zircons. The conglomeratic facies of the Dry Fork Formation was in fault contact with felsic volcanics of the Milton terrane which has yielded ages of 450-460 (Coler et al. 2000) and this terrane is the likely source of sediment for the portion of the Danville-Dan River Basin studied. The lack of a strong Grenville peak is unusual compared to most detrital age frequency distributions from eastern North America (Fig. 18B) and from the North American record in general (Fig. 18C). The rift valley configuration probably was such that the rift shoulder blocked transmission of Grenville-sourced sediment into the valley.
3.5 References Cited


Figure 15: Location of the sampled interval of the Dry Fork Formation conglomerate in the central portion of the Dan River-Danville Basin.
Figure 16: Stratigraphy of the Dan River-Danville Basin.
Figure 17. A. Typical lithology of the sampled interval of the Dry Fork Formation. The sandstones are arkosic and conglomeratic. B. One of the sampled detrital zircons under cathodoluminescence. Note the small size of the sampled pit for geochronological analysis.
Figure 18. Comparison of the Dry Fork Formation sandstone detrital zircon age spectrum with compiled age spectra of North America. A. Age Frequency distribution of dated detrital zircons from the Dry Fork Formation. The inset shows the probability density function for the detrital zircon spectrum. B. Compiled age frequency data for detrital zircons from the East Coast of North America. C. Compiled age frequency data for North America as a whole.
Figure 19. Compilation of published detrital zircons from the east coast of North America. Sorting the samples by host sediment age allows for characterization of the sources of detrital zircons. A. Modern River data. B. Late Triassic age spectrum from this study. C. Detrital zircon age spectrum from Carboniferous age sediments. D. Age frequency distribution of Devonian age sediments. E. Detrital zircon age spectrum from Ordovician-Silurian age sediments. F. Late Neoproterozoic-Cambrian detrital zircon age frequency distribution. G. Neoproterozoic age spectrum of published detrital zircon U-Pb dates.
Figure 19. cont.
Table 3: U-Pb age data for the detrital zircons sampled from the Dry Fork Formation.

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<td>368.7</td>
</tr>
<tr>
<td>Tr1-148.D</td>
<td>2.45</td>
<td>29</td>
<td>0.93</td>
<td>50.5</td>
<td>4.5</td>
<td>441.0</td>
</tr>
<tr>
<td>Tr1-149.D</td>
<td>89.86</td>
<td>226</td>
<td>0.51</td>
<td>2936.6</td>
<td>45.8</td>
<td>1984.0</td>
</tr>
<tr>
<td>Tr1-150.D</td>
<td>40.34</td>
<td>518</td>
<td>0.55</td>
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<td>14.46</td>
<td>166</td>
<td>0.98</td>
<td>647.7</td>
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</tr>
<tr>
<td>Tr1-152.D</td>
<td>87.31</td>
<td>871</td>
<td>1.51</td>
<td>369.1</td>
<td>14.0</td>
<td>474.2</td>
</tr>
<tr>
<td>Tr1-153.D</td>
<td>11.99</td>
<td>105</td>
<td>0.82</td>
<td>689.3</td>
<td>20.3</td>
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<td>Tr1-154.D</td>
<td>17.35</td>
<td>204</td>
<td>0.92</td>
<td>380.2</td>
<td>12.4</td>
<td>455.0</td>
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<tr>
<td>Tr1-155.D</td>
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<td>2187</td>
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<td>706.6</td>
<td>11.9</td>
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<tr>
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<td>143</td>
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<td>12.4</td>
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<td>Tr1-157.D</td>
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<td>261.5</td>
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<td>442.5</td>
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<td>0.45</td>
<td>340.5</td>
<td>7.5</td>
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<td>7.86</td>
<td>84</td>
<td>0.81</td>
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Constraints on the Age of the Host Sediment: Using an Empirical Study from the Global Detrital Zircon Database

An empirical study of the Global Detrital Zircon Database provides constraints on how large a sample of detrital zircons needs to be sampled in order to best constrain the age of the host sediment. As the zircons should be as old or older than the host sediment, these ages constrain the maximum age of host sediment deposition. The sample size that best constrained the average offset between the youngest detrital zircon age (Ma) and the maximum age of deposition of the host sediment independent of the detrital zircon age regardless of tectonic setting was a sample size of 50 detrital zircons. However, the characteristics of individual host sediments play a significant role in whether or not detrital zircon geochronology can potentially constrain the age of sedimentation (i.e. drainage basin characteristics such as source terranes in the catchment area, most recent pulse of magmatism in the region of the host sediment, etc.).

4.1 Introduction

The issue of sample size has been an important problem in detrital mineral provenance studies. Several questions can be asked with sample size: How many grains are necessary to sample all subpopulations within the population? How many grains are necessary to sample a specific subpopulation within the population? How many grains are necessary to best constrain the age of the host sediment? The first two questions have been answered using theoretical sampling statistics. The third question is the focus of this study.

Dodson et al. (1988) provided the first discussion of sample size in the detrital zircon literature. They used a probability function to estimate the probability of missing a specific fraction of grains when selecting a sample size of size n:
\[ P = (1-f)^n \]

where \( f \) is the frequency of a missed hypothetical population. Dodson et al. (1988) illustrate the utility of the equation by setting \( n \) to 86 and finding the probability of missing a fraction of the population with a frequency of 0.034; this yields a probability of missing the fraction by 5.1%. If \( n \) is set to 60 and \( f \) to 0.05, then the probability is 4.6%.

Vermeesch (2004) argued that the Dodson et al. (1988) probability function has been misinterpreted to suggest that measuring 60 grains is enough to have 95% confidence that any fraction greater than or equal to 0.05 of the population was not missed. He derived an equation for a given total number of fractions \( m \) in order to solve for the sample size \( k \):

\[
p = \sum_{n=1}^{m} (-1)^{n-1} \binom{m}{n} (1 - \frac{n}{m})^k
\]

Where \( n \) is the number of fractions desired to be sampled. Using this equation, Vermeesch (2004) shows that at least 117 grains need to be sampled in order to be 95% confident that any fraction of the population greater than 0.05% is not missed. This has also been misinterpreted to suggest that age dating with a sample size of 100+ grains is sufficient (Carrapa, 2010). The increased efficiency in the techniques used for detrital zircon geochronology has made sampling such large samples of detrital zircons routine (Gehrels et al. 2006, 2008; Ireland and Williams, 2003, Johnston et al. 2009).

A recent global detrital zircon compilation (Voice et al. in review) allows for empirically testing the third question: How many grains are necessary to best constrain the age of the host sediment? Detrital zircons are an important example of Charles Lyell’s principle of inclusions, i.e. that included fragments are older than the host sediment (Lyell, 1833). As such detrital
zircon grains should be as old, if not older than the host sediment that they are encased in. The global detrital zircon database has 4,879 samples (age frequency distributions) which range in sample size from 1 to 580 grains. The mean sample size has n equal to 49 grains and 90% of the samples have a sample size that is less than or equal to 98 grains. This large dataset allows the authors to elucidate how accurately the youngest grains in the sampled distributions reflect the age of deposition of the host sediment.

4.2 Methods
A meta-analytical compilation of single-dated detrital zircon grains was constructed via an extensive literature survey of detrital zircon analyses published primarily in English (but also including German, Portuguese, Spanish, and Chinese documents). A total of 1,108 studies (see appendix A for references for the compiled database) were collected representing 4,879 age distributions (i.e., 4,879 samples of dated grains) and 238,952 individual grains. All grains were dated individually using U-Pb techniques. These samples represent all continents and all geological time intervals, from Archean metasedimentary rocks (paragneisses and metapelites), through Proterozoic and Phanerozoic sedimentary rocks (including siliciclastic, carbonate, and chemical rocks) up to modern sediments.

Zircon (ZrSiO$_4$) is one of the most durable minerals, being highly resistant to both physical and chemical weathering (Heaman and Parrish, 1991, Kowalewski and Rimstidt, 2003). Because U is present in zircons in the 10-1000 ppm range (Faure and Mensing, 2005, Heaman and Parrish, 1991), the mineral is also particularly suitable target for reliable radiometric dating. Moreover, the closure temperature for the U-Pb system exceeds 900°C (Cherniak and Watson, 2000), which makes this radiometric system less vulnerable to resetting via metamorphic, magmatic, and other thermal processes.
$^{238}$U and $^{235}$U radioactively decay through a series of daughter products to the stable lead isotopes $^{206}$Pb and $^{207}$Pb respectively. The $^{238}$U-$^{206}$Pb decay chain, with a half-life of $4.468 \cdot 10^9$ years, is the most widely used to date zircons. The $^{235}$U-$^{207}$Pb system, with a half-life of $0.7038 \cdot 10^9$ years (Faure and Mensing, 2005, Jaffey et al. 1971, Steiger and Jäger, 1977), is calculated by using the known ratio of $^{235}$U/$^{238}$U as well as the ages derived from $^{238}$U-$^{206}$Pb and is not as commonly reported as the other two age dates. A third dating strategy is the $^{207}$Pb/$^{206}$Pb age, which is derived from algebraic substitution and manipulation of the two U-Pb decay equations with the assumption that the ratio of $^{235}$U/$^{238}$U is a constant equal to $1/137.88$ (Faure and Mensing, 2005). The $^{207}$Pb/$^{206}$Pb was used for grains older than 800 Ma in this compilation. Grains younger than 800 Ma used their $^{206}$Pb/$^{238}$U age. This methodology was used because over the Phanerozoic relatively little $^{207}$Pb was produced. The young ages of Phanerozoic zircons cause them to have low $^{207}$Pb contents making analysis difficult (and causing the grains to appear discordant).

For each grain, data were keyed into the database according to host the tectonic setting of the host sediment, best estimate of host rock age, host rock lithology and metamorphic index, region, paleoclimate characteristics, and analytical factors (Appendix B provides the codes used for the different characteristics). The tectonic settings used as filters in this study are: passive margins (passive margins and intracratonic basins), active margins (arc settings and foreland basins), and rift basins. Maximum and minimum constraints of the host sediment age were entered in for all samples. These ages were derived from age dating systems independent of the U-Pb detrital zircon age dates from the studies and include estimates from biostratigraphy, stratigraphic correlation to well dated units, magnetostratigraphy, geochronological methods (U-Pb, K-Ar, Rb-Sr, etc), and any combination of the above. In addition, 435 samples were taken
from modern sediments and hence have a minimum age of 0 Ma. For grains where multiple U-Pb age spots were generated, the following conventions were used: (1) If the age was labeled as from the "core", this age was entered into the database and ages labeled "rim" were ignored, and (2) If the ages were not labeled, the spot with the oldest $^{206}$Pb/$^{238}$U age from the grain was used as opposed to the other U-Pb and Pb-Pb ages, as this was assumed to be the most likely to approximate the "crystallization age" of the zircon (younger spots were then ignored) and biases the dataset towards older ages. Multi-spot data is being entered into the database, but are not ready for analysis yet.

The original sources, from which the database was compiled, reported concordance for approximately 60% of the grains. Concordance was reported as either: percent concordant or percent discordant. Other studies reported dates that met some cutoff value (usually either $\leq 5\%$ or $\leq 10\%$), but without providing information about specific concordance values for each individual grain. Grains with a $^{206}$Pb/$^{238}$U age less than 400 Ma in age were retained in the final pooled age regardless of their degree of discordance due to the difficulty in measuring the low contents of $^{207}$Pb in these younger zircons. Of the four filters, only the full database sample (Fig. 20) uses all grains regardless of degree of discordance. The $\leq 5\%$ data, Phanerozoic data, and Modern Sediment data all use grains that passed through the concordance filters above.

The detrital zircon age data was analyzed using a SAS 9.3 code designed to determine the average offset between the youngest grain and the best estimate of the maximum age of the host sediment as a function of sample size (see Appendix D for the code utilized in this study). The code sorts the samples by tectonic setting and then averages the offset between youngest grain age and the best estimate of the maximum age of the host sediment as a function of sample size. The output includes binned offset as a function of sample size. Bins were constructed using
increments of sample size equal to 10 units. Two sets of bins were created using the bin size of 10 units: bins with no upper limit and bins with an upper limit of sample size equal to 120. In the second case, bins for samples greater than or equal to 120 were averaged together to create one bin. This second case was used for the results as the first case showed high volatility at sample sizes greater than 120 due to the small number of samples that exceeded that threshold sample size. Smaller sample size of the samples led to an effect where large offsets had a major effect on the average offset. In all cases, the output for sample size is rounded up to the nearest whole number sample size (i.e. for the reported values of mean n, standard deviation of n, the median n, and the recommended n).

4.3 Results

In all four filtered cases and for all tectonic settings, with increasing sample size the average offset decreases towards 0 Ma (Figures 20A, 21A, 22A, and 23A). Passive margin samples exhibit very high offsets with small sample sizes (n ≤ 20) in all four filters. They also exhibit a peak in the lines at a sample size of 100 except for the ≤5% discordant data. Active margins also exhibit high offsets at low sample sizes and an inflection point in offset at binned n of ~40. Rift basins exhibit similar patterns to the Active margins, but in the case of Phanerozoic data and Modern sediment data show a much smaller offset at low values of n (≤ 30).

Using the full database without a filter for degree of concordance, there are 4,269 samples with known tectonic setting. Sorting the pooled database by tectonic setting (passive margins, active margins and rift basins), yields three curves that exhibit a negative slope and can be fitted with exponential decay regression lines. With increasing sample size, the average offset between the youngest grain age (Ma) and the host sediment maximum age constraint decreases towards 0 Ma (Fig. 20A). The distribution of sample size is positively skewed (Fig. 20B) and
has a mean sample size of 119 ±90 grains (Table 4). The samples range in size from 1 grain to 509 grains.

Filtering the database for samples that consist solely of grains that are less than or equal to ±5% discordant yields a sample distribution of 3,890 samples. Sorting the pooled database by tectonic setting, yields three curves that exhibit a negative slope and can be fitted with exponential decay regression lines. With increasing sample size, the average offset between the youngest grain age (Ma) and the host sediment maximum age constraint decreases towards 0 Ma (Fig. 21A). The distribution of sample size is positively skewed (Fig. 21B) and has a mean sample size of 109 ±98 grains (Table 4). The samples range from 1 grain to 509 detrital zircon grains.

Limiting the database to samples whose maximum age is less than or equal to 550 Ma decreases the sample size to 2,226 samples. Sorting the pooled database by tectonic setting, yields three curves that exhibit a negative slope and can be fitted with exponential decay regression lines. With increasing sample size, the average offset between the youngest grain age (Ma) and the host sediment maximum age constraint decreases towards 0 Ma (Fig. 22A). The distribution of sample size is positively skewed (Fig. 22B) and has a mean sample size of 65 ±41 grains (Table 4). The sample distribution has a much smaller range of sample sizes than the preceding filters: 159 grains with a maximum of 165 grains.

Modern Sediments have the best age constraints. Filtering the database for modern sediments yields a sample distribution of 435 samples. Sorting the pooled database by tectonic setting yields three curves that exhibit a negative slope and can be fitted with exponential decay regression lines. With increasing sample size, the average offset between the youngest grain age...
(Ma) and the host sediment maximum age constraint decreases towards 0 Ma (Fig. 23A). The distribution of sample size is positively skewed (Fig. 23B) and has a mean sample size of 13 grains (Table 4). The sample distribution has a range of 44 samples and a maximum sample size of 45 detrital zircon grains.

4.4 Discussion

The sample distributions regardless of tectonic setting or database filter exhibit inflection points where the average offset either flattens out or the slope decreases from steep slopes to more gentle slopes. These inflection points suggest sample sizes that may be of use in delineating the host sediment age in different tectonic settings (Table 5). The ≤5% discordant filter is commonly used in the literature as a cutoff value for the validity of detrital zircon ages. As this cutoff is popular, the empirical results from this study may suggest sample sizes to use for reaching an arbitrary average offset value (Fig. 21). In rift basins, an average offset of ~20 Ma can be obtained for samples sizes ≥50 detrital zircons. Passive margins and Active margins yield a higher average offset (Passive margins = 75 Ma, Active margins = 110 Ma) at the inflection point at n equal to 70 detrital zircon grains. Increasing the sample size for both settings decreases the average offset. It is interesting to note that rift basins are generally dominated by basaltic magmatism, where basalts tend to be relatively zircon poor; the younger zircons that decrease the average offset may be potentially from the early stages of rifting where magmas of rhyolitic composition are generated through crustal assimilation. Active margins should potentially yield the lowest offsets as arc settings are prolific generators of granitic magmatism. The high offsets may suggest that the young grains formed during arc magmatism are not being unroofed and sourced to the basin sediments in many of these samples. Another possibility is that the mixing of foreland basin and arc settings as active margins may be
increasing the offset. Foreland basins do not always exhibit magmatism. The transfer of volcanic sediments into foreland basins is often prevented by the presence of the accretionary prism.

Modern River sediments exhibit the shallowest curves with low inflection points \((n = 30)\) for the active margins and rift basins (Fig. 23A). This is potentially due to generation of magmas at these settings which generate young zircons that are sourced to the sedimentary system through either rapid unroofing of batholiths or through reworking of pyroclastic material or lava flows. Passive margins show an inflection point at higher \(n\) (either \(n = 50\) or \(n = 90\) depending on the inferred position of the inflection point) then in the other tectonic settings. The secondary peak in offset at \(n = 100\) grains is a result of modern river sediments that are sourced from Precambrian metasedimentary terranes. This is an important caveat of the study: Individual samples are going to be constrained by their provenance history and there may be many cases where there is a significant offset between the host sediment age and the youngest detrital zircon grain in the sample due to the combination of host sediment tectonic setting, most recent pulse of magmatism in the region studied, and the drainage system developed during deposition of the host sediment. This last condition has been used to show that detrital zircons can be transported over great distances (Rainbird et al. 1997).

In all cases, regardless of filter or tectonic setting, the plotted curves (Figures 20A, 21A, 22A, and 23A) are more volatile at sample sizes greater than \(n\) equal to 100 due to the smaller sample sizes in the global detrital zircon database of these values of \(n\) (note the decrease in frequency of samples with increasing sample size on Figures 20B, 21B, 22B, and 23B). The increased efficiency of detrital zircon age dating may overcome this drawback in the future (Gehrels et al. 2006, 2008; Ireland and Williams, 2003, Johnston et al. 2008).
4.5 Conclusion and Recommendations

Previously published probability functions have yielded guidelines for the sample sizes necessary to successfully sample one specific fraction (Dodson et al. 1988) and all specified fractions of a pre-determined cut-off value (Vermeesch, 2004). This study attempts to use an empirical approach to suggest sample sizes that yield the lowest average offset between the youngest detrital zircon grain dated and the host sediment age independent of the detrital zircon geochronological constraints. The recommended sample sizes (Table 5) are derived from the inflection points on the lines of Figures 20A, 21A, 22A, and 23A. The average sample size from Table 5 is 51 detrital zircon grains; this is a conservative estimate of the sample size necessary regardless of tectonic setting and filter used. This recommendation comes with the caveat that the individual sample characteristics may be influenced by conditions such as the host sediment tectonic setting, the drainage system in the place during deposition of the host sediment and the potential sources of detrital zircons of different age fractions in the region around the site of deposition (which may be much older than the host sediment).
4.6 References Cited

Figure 20A: Average offset between youngest detrital zircon age (Ma) and the maximum estimate of the host sediment age (Ma) versus binned values of sample size, n for the full database with no discordance filter. 1B: Frequency distribution of sample size for the full database.
Figure 21A: Average offset between youngest detrital zircon age (Ma) and the maximum estimate of the host sediment age (Ma) versus binned values of sample size, n for the full database with a ≤5% discordant filter. 2B: Frequency distribution of sample size for the discordance filtered database.
Figure 22A: Average offset between youngest detrital zircon age (Ma) and the maximum estimate of the host sediment age (Ma) versus binned values of sample size, $n$ for samples with a maximum host sediment age of 550 Ma (i.e. Phanerozoic samples only). 3B: Frequency distribution of sample size for the Phanerozoic samples.
Figure 23A: Average offset between youngest detrital zircon age (Ma) and the maximum estimate of the host sediment age (Ma) versus binned values of sample size, n for samples from Modern Sediments. 1B: Frequency distribution of sample size for samples collected from Modern Sediments.
Table 4: Summary of Moments for each distribution of sample size using the filter database.

<table>
<thead>
<tr>
<th>Filter</th>
<th>total distributions n</th>
<th>mean n</th>
<th>std. dev.</th>
<th>median</th>
<th>skewness</th>
<th>kurtosis</th>
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<td>100</td>
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<td>98</td>
<td>97</td>
<td>2.16</td>
<td>7.28</td>
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<tr>
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<td>62</td>
<td>0.38</td>
<td>-0.48</td>
</tr>
<tr>
<td>Modern Sediment</td>
<td>435</td>
<td>13</td>
<td>12</td>
<td>8.5</td>
<td>1.09</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 5: Recommended values of n for provenance analysis with detrital zircon geochronology as a function of tectonic setting and database filter.

<table>
<thead>
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<th>Filter</th>
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</thead>
<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td>5% discordance filter</td>
<td>70</td>
</tr>
<tr>
<td>Phanerozoic</td>
<td>80</td>
</tr>
<tr>
<td>Modern Sediment</td>
<td>50</td>
</tr>
</tbody>
</table>
Conclusions

The Global Detrital Zircon Database is the largest detrital zircon compilation currently in existence and has the potential to be a significant tool for provenance analysis, geodynamic problems such as crustal growth/crustal recycling models, and as an empirical testing block for analysis of sample issues related to detrital zircon geochronology (sample size considerations, comparison of different machine types [SHRIMP vs. LA-ICPMS], comparison of Hf isotope model ages derived from different decay constants or initial Lu ratios, etc.).

Joint consideration of U-Pb and Hf age distributions of detrital zircon grains reaffirms the model postulating episodic crustal evolution through one or a combination of crustal growth and/or crustal recycling. The relatively even spacing of U-Pb age peaks and Th-Pb age peaks (~0.6 Ga) is consistent with a quasi-cyclic process such as the supercontinent cycle. The variable and generally older Hf isotope model ages of zircon grains from single U-Pb age classes suggest that the crustal evolution involved substantial crustal recycling, a phenomenon which may also help to explain the uniformity of U-Pb age distributions across different continents and between different tectonic settings. The uniform offset between the Hafnium isotope model ages and the U-Pb ages is also quite intriguing and suggests that crustal recycling may also have occurred at roughly 0.5-0.6 Ga. This remarkable spatial and geotectonic homogeneity suggests that the evolution of the continental crust on Earth has been primarily controlled by global scale processes rather than historically unique regional events. The Hf isotopes model ages reflect when the material was last in the mantle and so give a constraint on crustal growth (where growth is through production of juvenile material by transferring material from the mantle to the
crust). Most zircons are generated during granitic magmatism and as such their ages should reflect crustal recycling of pre-existing crustal materials.

As a test of the utility of the GDZDb for provenance analysis, the Carnian Dry Fork Formation Sandstone was sampled for detrital zircon analysis and yielded an unimodal age frequency distribution with a peak at 460-480 Ma. In addition, a minor component of grains were Grenvillian in age (n = 3). High Th/U ratios and the presence of granitic clasts in the arkosic sandstone matrix suggest an igneous origin for the detrital zircons. The conglomeratic facies of the Dry Fork Formation is in fault contact with felsic volcanic of the Milton terrane which has yielded ages of 450-460 (Coler et al. 2000) and this terrane is the likely source of sediment for the portion of the Danville-Dan River Basin studied. The lack of strong Grenville peak is unusual compared to most detrital age frequency distributions from eastern North America (Fig. 18B) and from the North American record in general (Fig. 18C). The rift valley configuration was such that the rift shoulder blocked transmission of Grenville-sourced sediment into the Danville-Dan River rift valley and instead the sediment source was dominated by felsic volcanic of the Milton terrane.

An empirical study of the Global Detrital Zircon Database provides constraints on how large a sample of detrital zircons needs to be sampled in order to best constrain the age of the host sediment. As the zircons should be as old or older than the host sediment, these ages constrain the maximum age of host sediment deposition. The sample size that best constrained the average offset between the youngest detrital zircon age (Ma) and the maximum age of deposition of the host sediment independent of the detrital zircon age regardless of tectonic setting was a sample size of 50 detrital zircons. However, the characteristics of individual host sediments play a significant role in whether or not detrital zircon geochronology can potentially
constrain the age of sedimentation (i.e. drainage basin characteristics such as source terranes in the catchment area, most recent pulse of magmatism in the region of the host sediment, etc.).
Appendix A: Global Detrital Zircon Database References


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Appendix B: Codes used in the Global Detrital Zircon Database

Column 1: Study Number

Column 2: Sample Number

Column 3: Grain Number

Column 4: region 1

1: North America and Central America
2. South America
3. Europe
4. Asia
5. Africa
6. Australia
7. Antarctica
8. Arabian Peninsula
10. Pacific Islands and New Zealand

Column 5: region 2

Same first 10 as region 1
11: Indian subcontinent

Column 6: detrital vs. magmatic zircon

0: detrital
1: magmatic

Column 7: Paleoclimate—humidity

0: humid
1: arid
2: semi-arid
3. unknown/not reported
Column 8: Paleoclimate – temp.
   0: icehouse
   1. Greenhouse
   2. Transition
   3. Unknown/not reported

Column 9: stratigraphic span of host unit (in Ma)

Column 10: Sample type
   0: Point Sample
   1: Multi-horizon sample

Column 11: stratigraphic age of host rock minimum (in Ma)

Column 12: stratigraphic age of host rock maximum (in Ma) [columns 12 and 11 independent of d. z. age]

Column 13: tectonic setting
   0: foreland basin
   1: intracratonic basin
   2. passive margin
   3. backarc basin
   4. forearc basin
   5. rift basin
   6. retroarc basin
   7. unknown/not reported

Column 14: U content (in ppm)

Column 15: Th content (in ppm)

Column 16: U/Th ratio

Column 17: Certainty of homogenous age
0: certain host sediment homogenous age

1. Not certain

<table>
<thead>
<tr>
<th>Column</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>$^{207}$Pb/$^{235}$U age (in Ma)</td>
</tr>
<tr>
<td>19</td>
<td>$^{207}$Pb/$^{235}$U age 1-sigma error (in Ma)</td>
</tr>
<tr>
<td>20</td>
<td>$^{207}$Pb/$^{235}$U age 2-sigma error (in Ma)</td>
</tr>
<tr>
<td>21</td>
<td>$^{206}$Pb/$^{238}$U age (in Ma)</td>
</tr>
<tr>
<td>22</td>
<td>$^{206}$Pb/$^{238}$U age 1-sigma error (in Ma)</td>
</tr>
<tr>
<td>23</td>
<td>$^{206}$Pb/$^{238}$U age 2-sigma error (in Ma)</td>
</tr>
<tr>
<td>24</td>
<td>$^{207}$Pb/$^{206}$Pb age (in Ma)</td>
</tr>
<tr>
<td>25</td>
<td>$^{207}$Pb/$^{206}$Pb age 1-sigma error (in Ma)</td>
</tr>
<tr>
<td>26</td>
<td>$^{207}$Pb/$^{206}$Pb age 2-sigma error (in Ma)</td>
</tr>
<tr>
<td>27</td>
<td>Pooled Age (in Ma) (Uses $^{206}/^{238}$ age over other ages when available; uses $^{207}/^{206}$ age when $^{206}/^{238}$ age not available.)</td>
</tr>
<tr>
<td>28</td>
<td>Pooled Age 1-sigma error (in Ma)</td>
</tr>
<tr>
<td>29</td>
<td>Pooled Age 2-sigma error (in Ma)</td>
</tr>
<tr>
<td>30</td>
<td>Best Age 2 (uses $^{206}/^{238}$ ages for grains 800 Ma or younger; $^{207}/^{206}$ age for grains 800 Ma or older)</td>
</tr>
<tr>
<td>31</td>
<td>Best age 1-sigma error (in Ma)</td>
</tr>
<tr>
<td>32</td>
<td>Best age 2-sigma error (in Ma)</td>
</tr>
<tr>
<td>33</td>
<td>Hf isotope Model Age $T_{chur}$</td>
</tr>
<tr>
<td>34</td>
<td>Hf isotope Model Age $T_{dm}$</td>
</tr>
<tr>
<td>35</td>
<td>Hf isotope Model Age $T_{dm}$ initial Lu ratio = 0.015</td>
</tr>
<tr>
<td>36</td>
<td>Hf isotope Model Age $T_{dm}$ initial Lu ratio = 0.014</td>
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<td>37</td>
<td>Hf isotope Model Age $T_{dm}$ initial Lu ratio = 0.021</td>
</tr>
<tr>
<td>38</td>
<td>Hf isotope Model Age $T_{dm}$ initial Lu ratio = 0.055</td>
</tr>
<tr>
<td>39</td>
<td>Hf isotope Model Age $T_{dm}$ initial Lu ratio = 0.138</td>
</tr>
<tr>
<td>Column 40: Hf isotope Model Age $T_{dm}$ initial Lu ratio = 0.008</td>
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</tr>
<tr>
<td>Column 41: Hf isotope Model Age $T_{dm}$ initial Lu ratio = 0.013</td>
<td></td>
</tr>
<tr>
<td>Column 42: Hf isotope Epsilon value</td>
<td></td>
</tr>
<tr>
<td>Column 43: Global Pooled Hf Isotope Model Age</td>
<td></td>
</tr>
<tr>
<td>Column 44: $^{208}\text{Pb}/^{232}\text{Th}$ age (in Ma)</td>
<td></td>
</tr>
<tr>
<td>Column 45: $^{208}\text{Pb}/^{232}\text{Th}$ age 1-sigma error (in Ma)</td>
<td></td>
</tr>
<tr>
<td>Column 46: $^{208}\text{Pb}/^{232}\text{Th}$ age 2-sigma error (in Ma)</td>
<td></td>
</tr>
<tr>
<td>Column 47: $^{206}\text{Pb}/^{238}\text{U}$ decay constant</td>
<td></td>
</tr>
<tr>
<td>0: not reported</td>
<td></td>
</tr>
<tr>
<td>1: $1.55125 \times 10^{-10}$ (Jaffey et al. and Steiger and Jager)</td>
<td></td>
</tr>
<tr>
<td>6: not performed</td>
<td></td>
</tr>
<tr>
<td>Column 48: $^{207}\text{Pb}/^{235}\text{U}$ decay constant</td>
<td></td>
</tr>
<tr>
<td>0: not reported</td>
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</tr>
<tr>
<td>1: $9.8485 \times 10^{-10}$ (Jaffey et al. and Steiger and Jager)</td>
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<td>6: not performed</td>
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<tr>
<td>Column 49: $^{208}\text{Pb}/^{232}\text{Th}$ decay constant</td>
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<tr>
<td>0: not reported</td>
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<tr>
<td>1: $4.9475 \times 10^{-11}$ (Steiger and Jager)</td>
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<td>6: not performed</td>
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<tr>
<td>Column 50: Lu-Hf decay constant</td>
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<tr>
<td>0: not reported</td>
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</tr>
<tr>
<td>1: $1.865 \times 10^{-11}$ (Scherer et al. 2003)</td>
<td></td>
</tr>
<tr>
<td>2: $1.983 \times 10^{-11}$ (Bizzaro et al. 2003)</td>
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</tr>
<tr>
<td>3: $1.93 \times 10^{-11}$ (Blichert-toft and Albarede, 1997)</td>
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</tr>
<tr>
<td>4: $1.867 \times 10^{-11}$ (Patchett et al. 2004 or Soderlund et al. 2004)</td>
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</tr>
<tr>
<td>Column 51: Concordance vs. discordance</td>
<td>Column 52: %Concordance</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>0: ≤5% concordant</td>
<td></td>
</tr>
<tr>
<td>1: discordant</td>
<td></td>
</tr>
<tr>
<td>2: ≤10% concordant</td>
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<tr>
<td>3: rejected by study</td>
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</tr>
<tr>
<td>4: accepted by study</td>
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</tr>
<tr>
<td>5: 2.78552* 10^-11 (Squigma et al. 1982)</td>
<td></td>
</tr>
<tr>
<td>6: Not performed</td>
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</tr>
<tr>
<td>0: ≤5% concordant</td>
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<tr>
<td>1: discordant</td>
<td></td>
</tr>
<tr>
<td>2: ≤10% concordant</td>
<td></td>
</tr>
</tbody>
</table>
10: Mixed Carbonate-Clastic
11: placer deposits
12: bauxites

**Column 57: Metamorphic Grade**
- 0: unmetamorphosed
- 1: Chlorite
- 2: biotite
- 3: Garnet
- 4: Staurolite
- 5: Sillimanite

**Column 58: Method**
- 0: U-Pb dating

**Column 59: Mass Spectometer type**
- 0: SHRIMP
- 1: LA-ICPMS (also includes older evaporation ages)
- 2: TIMS
- 3: Ion microprobe (not SHRIMP)
- 4: Pb-Pb evaporation techniques

**Column 60: Best estimate stratigraphic age max**

**Column 61: Best estimate stratigraphic age min**

**Column 62: Range of Best Max –Best min**

**Column 63: Method of determining best age estimates**
- 0: index fossils, biozones (biostratigraphy)
- 1: cross-cutting by age-dated igneous rocks
- 2: both 0 and 1
<table>
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<th>Column 64: Source year</th>
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<tr>
<td>Column 65: bibliographic citation of source</td>
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<td>Column 66: geographic location and long.-lat. Data (when available)</td>
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</table>
**Appendix C: Global Detrital Zircon Database**

Due to file size constraints the GDZDB is not included with the dissertation. Readers interested in using the GDZDb may contact the author (voicep@vt.edu) to request a copy of the database.

The first page of the database is appended here to illustrate the nature of the database.

<table>
<thead>
<tr>
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<th>sample number</th>
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<td>0</td>
<td>19</td>
<td>k2</td>
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<td>20</td>
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<td>0</td>
<td>21</td>
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<td>0</td>
<td>22</td>
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</tr>
<tr>
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<td>1</td>
<td>23</td>
<td>0</td>
<td>23</td>
<td>k2</td>
</tr>
<tr>
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<td>24</td>
<td>0</td>
<td>24</td>
<td>k2</td>
</tr>
</tbody>
</table>
Appendix D: SAS Code used in this study

The code used outputs multiple datasets that analyse the GDZDb and include analysis of grain size issues, descriptive statistics at the sample (age spectrum) level, and trends in publication rate.

```sas
%let n=0; * - the cutoff sample size, where n=number of dated grains;
%let age=1000; * - the cutoff age of a sample for age-restrictive analysis
    [program step: data zircon3, variable currently used: maxage];
%let agefilter=0; * - if age filter set to 1, then samples older than age value will be removed
    if age filter set to 0, two age classes will be retained;
%let var=skewness;

data zircon;
    infile cards;
    input study sample grain grain2 region reg2 det humid temper geolage resolut minage maxage
tecton U Th uthrat resol2 z_age1 z_age1e1 z_age2e2 z_age2 z_age2e1 z_age2e2 z_age3
    z_age3e1 z_age3e2 pooled poole1 poole2 bpool1 bpole1 bpole2 Hf1 Hf2 Hf3 Hf4 Hf5 Hf6
    Hf7 Hf8 Hf9 Ep Hfpool Th_age Th_age1 Th_agee1 Th_agee2 dc1 dc2 dc3 dc4 conc1 conc2 conc3 conc4
    conc5 lithol metalith
    method machtype bestmax bestmin brange datmeth pubyear;
    if z_age1='.' then do;
        if z_age2='.' then variant=1;
        if z_age3='.' then variant=2;
        else variant=3;
    end;
    if z_age2='.' then do;
        if z_age3='.' then variant=4;
        if z_age1='.' then variant=1;
        else variant=5;
    end;
    if variant='.' then do;
        if z_age3='.' then variant=6;
        else variant=7;
    end;
    if bpool1>800 then agegp=2;
    else agegp=1;
    *if sample in (9 37 39 45 120 121 122 123 369) then delete;
    pubyear=round(pubyear,1);
    cards;
    [insert data here]
    ;
    proc print data = zircon;
    * study sample region humid temper geolage resolut minage maxage tecton resol2 z_age lithol
    method;
    proc sort data=zircon;
```

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by study sample;
PROC UNIVARIATE DATA=ZIRCONNOPRINT;
VAR bpool1 tecton humid temper geolage resol2 minage maxage resol2 lithol bestmin bestmax;
BY study sample;
OUTPUT OUT=ZIRCON2 N=N MEAN=MEAN TECTON HUMID TEMPER GEOLAGE RESOL2 MINAGE MAXAGE RESOL2 LITHOL BESTMIN BESTMAX
STD=STD VAR=VAR SKEWNESS=SKEWNESS KURTOSIS=KURTOSIS RANGE=RANGE MIN=YOUGNEST MAX=OLDEST;PROC PRINT DATA=ZIRCON2;
DATA ZIRCON3;
SET ZIRCON2;
IF n>=&n;
IF TECTON IN (0 3 4 6) THEN TECT2=1; *-GROUP ALL ACTIVE MARGINS/BASINS INTO A SINGLE CATEGORY;
IF TECTON IN (1 2) THEN TECT2=0; *-GROUP ALL PASSIVE MARGINS/BASINS INTO A SINGLE CATEGORY;
IF TECTON IN (7) THEN TECT2=3; *-TECTONIC SETTING UNKOWN;
IF TECTON=5 THEN TECT2=2; *-GROUP ALL RIFT SAMPLES TOGETHER;
IF TECTON IN (0) THEN TECT3=0; *-FORELAND BASINS;
IF TECTON IN (3 4 6) THEN TECT3=1; *-ARC SETTINGS;
IF TECTON IN (1 2) THEN TECT3=2; *-PASSIVE AND INTRACRATONIC;
IF TECTON IN (5) THEN TECT3=3; *-RIFT;
IF TECTON IN (7) THEN TECT3=4; *-TECTONIC SETTING UNKOWN;
AGEFILTER=1;
IF AGEFILTER=&AGEFILTER THEN DO;
IF MAXAGE<=&AGE; ***-DEFINES VARIABLE USED TO AGE-RestRICT DATA (CURENTLY SET TO: MAXAGE);
AGE=1;
END;
ELSE DO;
IF MAXAGE>&AGE THEN AGE=2;
ELSE AGE=1;
END;
PROC PRINT DATA=ZIRCON3;
*PROC PLOT DATA=ZIRCON3;
*PLOT MEAN*STD=TECT2;
*PLOT KURTOSIS*SKEWNESS=TECT2;
*PLOT STD*MAXAGE=TECT2;
*PLOT SKEWNESS*STD=TECT2;
*PLOT SKEWNESS*MAXAGE=TECT2;
*PLOT SKEWNESS*MINAGE=TECT2;
*PLOT RANGE*N=TECT2;
*PLOT STD*N=TECT2;
*PLOT MEAN*MAXAGE=TECT2;
*PLOT YOUNGEST*MINAGE=TECT2;
*PLOT OLDEST*MINAGE=TECT2;
*PLOT MEAN*STD=TECT3;
*PLOT KURTOSIS*SKEWNESS=TECT3;
*PLOT STD*MAXAGE=TECT3;
*PLOT SKEWNESS*STD=TECT3;
*plot skewness*maxage=tect3;
*plot skewness*minage=tect3;
*plot range*n=tect3;
*plot std*n=tect3;
*plot mean*maxage=tect3;
*plot youngest*minage=tect3;
*plot oldest*minage=tect3;

******************************************************************************
tect2 analysis  **************************************************************************;
proc sort data=zircon3;
by tect2;
proc univariate data=zircon3 noprint;
var &var;
by tect2;
output out=zircon4 n=n mean=mean std=std range=range median=median max=max min=min;
proc print data=zircon4;
proc npar1way wilcoxon data=zircon3;
var &var;
class tect2;
proc corr data=zircon3 spearman pearson;
var mean std skewness kurtosis maxage range n;
with mean std skewness kurtosis maxage range n;
proc corr data=zircon3 spearman pearson;
by tect2;
var mean std skewness kurtosis maxage range n;
with mean std skewness kurtosis maxage range n;
******************************************************************************
***;

******************************************************************************
tect3 analysis  **************************************************************************;
proc sort data=zircon3;
by tect3;
proc univariate data=zircon3 noprint;
var &var;
by tect3;
output out=zircon5 n=n mean=mean std=std range=range median=median max=max min=min;
proc print data=zircon5;
proc npar1way wilcoxon data=zircon3;
var &var;
class tect3;
proc corr data=zircon3 spearman pearson;
by tect3;
var mean std skewness kurtosis maxage range n;
with mean std skewness kurtosis maxage range n;
******************************************************************************
***;
********** to keep track of unusually high anomalies ****;

data temp;
set zircon3;
anomaly=bestmin-youngest;
anomaly2=bestmin-minage;
if anomaly>100;
proc print data = temp;
******************************************************************************
***;
******************************************************************************
***;
******************************************************************************
***;

data zircon6;
set zircon3;
yresid=youngest-bestmin; *looks at sample size issues;
bins=round(n,10);
if bins=0 then bins=10;
if tect2=0 then do;
if bins>120 then bins=120;
end;
if tect2=1 then do;
if bins>120 then bins=120;
end;
if tect2=2 then do;
if bins>120 then bins=120;
end;
if tect2=3 then do;
if bins>120 then bins=120;
end;
bin2=10*floor(n/10);
keep sample n bestmin youngest skewness kurtosis std mean yresid tect2 bins bin2;

proc sort; by tect2;
proc sort; by bestmin;
proc print;
proc plot;
plot yresid*n=tect2;
data zircon7;
set zircon6;
if n>20;
proc sort data=zircon7;
by tect2;
proc chart;
by tect2;
vbar yresid /midpoints=-200 to 1800 by 200;
proc univariate data=zircon7 noprint;
by tect2;
var yresid;
output out=residtest mean=mean n=n median=median;
proc print;
proc npar1way data=zircon7 wilcoxon;
class tect2;
var yresid;
proc sort data=zircon6;
by tect2 bins;
proc print data=zircon6;
proc univariate noprint data=zircon6;
by tect2 bins;
var yresid;
output out=resplot mean=mean n=n;
proc print data=resplot;
proc sort data=zircon6;
by tect2 bin2;
proc univariate noprint data=zircon6;
by tect2 bin2;
var yresid;
output out=resplot2 mean=mean n=n;
proc print data=resplot2;
proc plot data=resplot;
by tect2;
*plot mean*bins='*';

******************************************************************************
***;
******************************************************************************
***;
******************************************************************************
***;
******************************************************************************
***;

** NOTE: comparison of two age classes will only work when age filter different than 1;
proc sort data=zircon3;
by age;
proc univariate data=zircon3 noprint;
var &var;
by age;
output out=agecomp n=n mean=mean std=std range=range median=median max=max min=min;
proc print data=agecomp;
proc npar1way wilcoxon data=zircon3;
var &var;
class age;

proc sort data=zircon3;  
by tect2 age;
proc univariate data=zircon3 noprint;  
var &var;  
by tect2 age;  
output out=agecomp2 n=n mean=mean std=std range=range median=median max=max min=min;
proc print data=agecomp2;
proc npar1way wilcoxon data=zircon3;  
by tect2;  
var &var;
class age;

proc sort data=zircon3;  
by tect3 age;
proc univariate data=zircon3 noprint;  
var &var;  
by tect3 age;  
output out=agecomp3 n=n mean=mean std=std range=range median=median max=max min=min;
proc print data=agecomp3;
proc npar1way wilcoxon data=zircon3;  
by tect3;  
var &var;
class age;
**************************************************************************
***;
**************************************************************************
***;
proc corr data=zircon pearson spearman; *compares three potential dates;
var z_age1 z_age2 z_age3;  
with z_age1 z_age2 z_age3;
proc plot data=zircon;  
*plot z_age2*z_age1=’+’;
*plot z_age3*z_age1=’+’;
*plot z_age3*z_age2=’+’;
proc sort data=zircon;  
by variant agegp;
proc freq data=zircon;  
by variant;  
table agegp;
proc univariate data=zircon noprint;  
by variant agegp;
var z_age1 z_age2 z_age3;
output out=dmethod n=z_age1 z_age2 z_age3;
proc print data=dmethod;
proc sort data=zircon;
by pubyear agegp;
proc freq data=zircon noprint;
by pubyear agegp;
table variant /out=dmethod2;
proc print data=dmethod2;
proc freq data=zircon noprint;
by pubyear;
table variant /out=dmethod3;
proc univariate data=zircon noprint;
by pubyear;
var pooled;
output out=dmethod4 n=n;
proc print data=dmethod4;
proc print data=dmethod3;
run;
quit;