Detrital zircon age distributions as a discriminator of tectonic versus fluvial transport: An example from the Death Valley, USA, extended terrane

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ABSTRACT

U-Pb geochronology of detrital zircons has proven useful in identifying potential source terranes of siliciclastic sediments through the identification of distinct age peaks that can often be linked to geographically restricted regions. In cases where a sedimentary source region is geographically distinct enough to be treated as a point source, simple empirical and theoretical relationships between fluvial catchment area and downstream river length (Hack’s law) can be convolved with detrital zircon age analysis of fluvial sediment to quantitatively assess the fluvial transport distance of that sediment from its source.

Such an approach is particularly germane to studying the fluvial transport distances of syntectonic sediments for which the present-day distance between sediment and source may be a function of both sedimentary and tectonic transport. This technique is illustrated with an example from the Death Valley extended terrane in the central Basin and Range (United States). Middle Miocene clastic sedimentary rocks located east of Death Valley contain a clast assemblage that includes a distinct Early Jurassic leucogabbro, the nearest outcrops of which are 80 km to the west-northwest. Previous interpretations of these strata as an alluvial fan sequence required restoration of the crustal extension in excess of 200% across the central Death Valley region, and across other extended terranes in the Basin and Range province of the western United States are fundamentally to understanding the processes that governed intracontinental extension across this province over the past ~30 m.y. Stratigraphic (isopachs and facies trends) and structural features (thrust faults and folds) that predate Cenozoic deformation compose the markers most frequently used in attempts to quantify finite strain accommodated in this region (e.g., Snow and Wernicke, 2000). Reconstructions based on all, or subsets of, these data have yielded magnitudes of crustal extension in excess of 200% across the central Death Valley region (e.g., Stewart, 1983; Wernicke et al., 1988; Snow and Wernicke, 2000; Niemi, 2002; McQuarrie and Wernicke, 2005). Such reconstructions have, in part, led to the development of a range of tectonic models for accommodating large-magnitude extension without lithospheric rupture (e.g., McKenzie, 1978; Wernicke, 1985; Block and Royden, 1990; Kuszniir and Ziegler, 1992).

Alternatives to late Cenozoic large-magnitude extension across the Death Valley region continue to be proposed (e.g., Wright et al., 1991; Miller and Prave, 2002; Christie-Blick et al., 2007). Objections to reconstructions requiring large-magnitude extension are critical of the uniqueness of both geologic structures and isopachs as preextensional markers (e.g., Christie-Blick et al., 2007). Although some geologic structures in the Death Valley region are unique in vergence and throw (e.g., Snow and Wernicke, 1989; Niemi, 2002), similarities in these two parameters among other geologic structures permit multiple reconstructions requiring varying amounts of extension (e.g., cf. Wernicke et al., 1988, to Serpa and Pavlis, 1996; or Abolins, 1999, to Caskey and Schweickert, 1992). Isopach-based reconstructions have met similar criticism (e.g., Prave and Wright, 1986), and tectonic reconstructions based on the same Paleozoic isopach data have yielded estimates of extension that vary by factors of five or more (Hamilton and Myers, 1966; Wright and Troxel, 1967).

Ambiguities in the uniqueness of geologic structures and sedimentary isopachs and uncertainties inherent in their reconstruction have been further compounded by the growing recognition of Late Cretaceous extension in the Death Valley region (Hodges et al., 1990; Applegate et al., 1992; Applegate and Hodges, 1995; Wells and Hoisch, 2008). Extensional deformation of this age postdates both sedimentary strata used in isopach-based reconstructions, as well as the age of the majority of the structural markers used for tectonic reconstructions in the Death Valley region (e.g., Snow et al., 1991; Stevens and Stone, 2005). Without constraints on upper crustal deformation during this period of Late Cretaceous extension, evidence for which has been removed by erosion above the sub-Tertiary unconformity through the central Death Valley region, part, or all, of the tectonic deformation recorded by pre-Mesozoic markers may permissibly be ascribed to Late Cretaceous deformation, instead of to the development of the late Cenozoic Basin and Range province (Applegate et al., 1992; Wells and Hoisch, 2008).

To resolve these ambiguities, constraints on extension across the central Death Valley region, and across other extended terranes in the...
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Basin and Range, have been developed through the identification of late Cenozoic sedimentary rocks, such as alluvial fan conglomerates or landslides, that were deposited proximally to their source and that contain unique clast assemblages that can be assigned to specific source areas (Butler et al., 1988; Topping, 1993; Niemi et al., 2001; Fryxell and Duebendorfer, 2005). Such deposits, the majority of which are Middle or Late Miocene in age, record only late Cenozoic extensional deformation, and act as piercing points between depocenter and source terrane, circumventing both the uniqueness and uncertainty issues that have troubled isopach and structural based reconstructions (e.g., Snow and Wernicke, 2000) while recording only post-Cretaceous deformation.

Across the central Death Valley region, the Middle Miocene Eagle Mountain Formation plays a key role in interpretations of large-magnitude, late Cenozoic extension (Niemi et al., 2001). This clastic sedimentary sequence is preserved in several localities to the east of Death Valley, yet contains a Paleozoic clast assemblage, predominantly derived from rocks that are only currently exposed 80 km to the west-northwest, on the western margin of Death Valley. In addition to the Paleozoic clast assemblage, the clasts include a distinct leucomonzogabbro that is petrologically and geochronologically indistinguishable from the southeastern margin of the Early Jurassic Hunter Mountain batholith in the Cottonwood Mountains (Fig. 1; Niemi et al., 2001). Interpretation of an alluvial fan depositional environment for the Eagle Mountain Formation (Çemen, 1983; Niemi et al., 2001) implied that most, or all, of the 80 km separating the source terrane and depocenter of the Eagle Mountain Formation resulted from tectonic extension, and not sedimentary transport (Niemi et al., 2001). Similarities between the magnitude of extension estimated from the offset of the Eagle Mountain Formation, and that based on structural reconstructions (e.g., Wernicke et al., 1988), are strong constraints that extension across the central Death Valley region is of large magnitude and late Cenozoic age.

Reinterpretation of the depositional environment of the Eagle Mountain Formation, however, has led to the conclusion that the strata are fluvial in origin (Çemen, 1999; Renik et al., 2008). Such an interpretation weakens the argument that multiple lines of evidence point to a similar amount of extension across the central Death Valley region, as well as the constraint that all of the extension must have occurred in the late Cenozoic. Since the sedimentary transport distance of the clasts at Eagle Mountain has been regarded as one of the strongest lines of evidence supporting large-magnitude late Cenozoic extension, the reinterpretation of the depositional environment of these strata has been suggested to significantly undermine this tectonic interpretation for the central Death Valley region, and, by analogy, for other extended regions of the Basin and Range (Christie-Blick et al., 2007).

I present here a method for measuring sedimentary transport distances based on the downstream dilution of detrital zircon populations, in this case from the distinct source terrane of the leucomonzogabbro clasts in the Eagle Mountain Formation, derived from the Cottonwood Mountains. The utility of this approach is demonstrated in estimating the amount of tectonic versus sedimentary transport of the Eagle Mountain Formation, and the result will be applied to discriminate between predictions of competing models of large-magnitude versus limited-magnitude extension across central Death Valley in late Cenozoic time (e.g., Wernicke et al., 1988; Wright et al., 1991; Serpa and Pavlis, 1996; Snow and Wernicke, 2000; Niemi et al., 2001; Miller and Prave, 2002; McQuarrie and Wernicke, 2005; Christie-Blick et al., 2007).

Figure 1. Map showing the distribution of pre-Middle Miocene igneous and clastic rocks in the Death Valley region and highlighting the location of the Jurassic Hunter Mountain Batholith (HMB). Black circles indicate Cenozoic sedimentary rocks that contain HMB clasts, including Middle Miocene deposits at Cottonwood Canyon (CC), Eagle Mountain (EM), and Chicago Valley (CV), and Late Miocene deposits of the Artist Drive Formation (AD). Igneous rock map distribution is from Workman et al. (2002), Ludington et al. (2005), and Craford (2007); igneous rock ages are from these sources, supplemented by the North American Volcanic and Intrusive Rock Database (NAVDAT; Walker et al., 2006). Sedimentary rock map distributions and ages are from Nelson (1966, 1971), Ross (1965, 1967), and Workman et al. (2002). RSR—Resting Spring Range.
METHODS

I describe a method for quantifying fluvial transport distances by measuring the dilution of a given detrital zircon age population. The method is based on stream length–drainage area relationships (Hack, 1957), and is possible with recent advances in affordable detrital zircon U-Pb geochronology (e.g., Johnston et al., 2009). Detrital zircon U-Pb geochronology offers a potential means to quantitatively assess the fluvial transport distance of sediments that contain a distinct zircon population (e.g., Link et al., 2005), provided that the frequency of a given zircon age population is representative of the drainage basin area from which it is derived (e.g., Amidon et al., 2005b). The method is independent of any interpretation of depositional environment and is applicable to estimating the fluvial transport distances of syntectonic sediments in any setting in which the present-day distance between sediment and source may be a function of both sedimentary and tectonic transport.

Theory

Detrital zircons, particularly those from point source areas, provide a unique fingerprint for determining the provenance of fluvial sediments (e.g., Link et al., 2005). With increased downstream transport, this fingerprint becomes progressively diluted, as detrital zircons from other source terranes are mixed into the fluvial system (Cawood et al., 2003). The amount of dilution is principally a function of the catchment area of the original source terrane and the progressive growth of the catchment area with downstream transport distance. This ratio can be quantified using Hack’s (1957) law:

\[ L = CA^h, \]  

where \( L \) is stream length, \( A \) is drainage area, \( C \) is a constant, and the exponent \( h \) is empirically determined to be ~0.6, similar to theoretical determinations (Birnir, 2008), and shown to be remarkably constant over a wide range of geologic and climatic settings (Montgomery and Dietrich, 1992; Castelltort and Simpson, 2006).

Given that \( C \) is constant for a specific river, and assuming that catchment-wide erosion rates and zircon distributions are either spatially homogeneous or can be constrained, zircon population dilution as a function of transport distance for a given source catchment area can be predicted (Fig. 2), or, conversely, transport distance can be derived from the dilution of a zircon population in fluvial sediment:

\[ L_t = A_t \left( \left( \frac{1}{C_T} \right)^h - 1 \right), \]  

where \( L_t \) is the sediment transport distance, \( A_t \) is the area of the source catchment providing detrital zircons, and \( C_T \) is the ratio of zircon concentration in fluvial sediment at a downstream point to the concentration of zircons in sediment leaving the source catchment.

For example, if a catchment of 100 km² were underlain by a single pluton, 90% of the zircons in sediment 1 km downstream from the mouth of this catchment would be composed of zircons derived from this pluton (Fig. 2). The percentage of zircons from the original catchment would decrease to ~40% of the total detrital zircon population in the fluvial system after 10 km of downstream transport, and to ~5% after 50 km of downstream transport (Fig. 2). The larger the size of the originating catchment, the greater the amount of fluvial transport that is required for a given degree of dilution. Increased catchment size may be a function of physical dimension (a larger catchment area), or increased zircon production, either resulting from increased erosion rates over a given catchment (Garver et al., 1999; Reiners et al., 2003), or greater concentrations of zircons in the rocks underlying a given catchment (Amidon et al., 2005b; Sláma and Košler, 2012). A discussion of these and other assumptions inherent in this method follows.

Assumptions

Unlike large clasts, whose relative population in a fluvial system may result from extreme localized erosion events or resistance to disaggregation during fluvial transport (Christie-Blick et al., 2007; Wernicke, 2011), thorough mixing of individual mineral grains in fluvial sediment is an underlying assumption of basin-wide cosmogenic nuclide studies, as well as in detrital thermochronology and geochronology studies. That such mixing occurs over relatively short transport distances has been demonstrated in a variety of geomorphic and tectonic settings for minerals of interest in cosmogenic nuclide studies (e.g., Clapp et al., 2002; Matmon et al., 2003a, 2003b; Bierman et al., 2005), although these minerals, typically quartz, are ubiquitous in most sediment. Assumptions regarding the uniformity of sedimentary supply and mixing, fluvial transport, and sampling of heavy minerals, such as zircon, remains a topic of ongoing research (e.g., Garzanti et al., 2008; Lawrence et al., 2011; Sláma and Košler, 2012). Here I discuss some of the assumptions made in determining the dilution of a population of detrital zircon ages, and the potential conditions under which these assumptions might reasonably be met in order to determine fluvial transport distances from detrital zircon age populations.

Uniform Sampling of Detrital Zircons

This method assumes that the proportion of a given detrital zircon age population in a fluvial sample is directly proportional to the catchment area from which the age is derived (e.g., Amidon et al., 2005a). Such an assumption could be invalid for several reasons. First, the concentration of zircons, or other heavy minerals, in bedrock of varying age or lithology may differ, such that erosion of equal areas of each yields different quantities of heavy minerals (e.g., Moecher and Samson, 2006; Tranel et al., 2011; Sláma and Košler, 2012). Such variability in zircon fertility is particularly difficult to quantify in studies where the original source terrane is largely eroded or modified (Moecher and Samson, 2006), but the effect of this process can be assessed where zircon fertility in modern...
exposures of source rocks can be quantified (e.g., Tranel et al., 2011), or, as demonstrated in the following, through comparison of modern detrital age populations with known catchment bedrock distributions.

A second potential violation of this assumption could occur if the erosion rates across a catchment are spatially variable, thus selectively sampling the catchment, whether in a stochastic manner (Niem et al., 2005; Yanites et al., 2009), or through a transition from fluvially to glacially dominated regimes (Hallett et al., 1996; Dühnforth et al., 2008). Detailed bedrock mapping and zircon age analysis is required to test the effects of these processes on detrital zircon age populations (e.g., Amidon et al., 2005b), but recent studies of low-temperature detrital thermochronometers, such as apatite (U-Th)/He, which frequently have a highly predictable age-elevation relationship (e.g., Gallagher et al., 2005), yield some insight into these processes.

In such studies, the age-elevation relationship of bedrock low-temperature thermochronometry ages is combined with the hypsometry of a drainage basin to yield a predicted distribution of ages in modern sediment (e.g., Stock et al., 2006; Avdeev et al., 2011). Comparison across a wide range of tectonic and climatic regimes reveals remarkable similarity between observed and predicted detrital low-temperature thermochronometric age populations in fluvial sediments, suggesting that spatially variable erosion plays a negligible role in biasing heavy mineral sampling in these detrital thermochronometry studies (Stock et al., 2006; Avdeev et al., 2011; Duvall et al., 2012). Some of these studies sample catchments with heterogeneous bedrock types, suggesting that spatial variability in heavy mineral fertility may also be a minor factor in biasing catchment-wide detrital mineral studies (Avdeev et al., 2011; Duvall et al., 2012). These results contrast markedly with comparisons of observed and predicted detrital age populations from partially, or previously, glaciated catchments in which the observed detrital age population is highly skewed from the predicted distribution (Stock et al., 2006; Avdeev et al., 2011; Tranel et al., 2011). These studies suggest that the assumption of spatially uniform erosion is broadly defensible in fluvial systems, but clearly would be violated for a paleodrainage modified by glaciation.

Zircon Mixing and Age Population Fractionation

A second assumption made in this analysis is that individual zircon grains are well mixed during transport, and that hydrodynamic fractionation of individual age populations can be ignored. The transport of minerals in a fluvial system is largely controlled by grain density and size, and it has been demonstrated that heavy minerals, such as zircon, will disperse and travel at a rate different from the lighter minerals in the source rock from which the heavy minerals are derived (Garzanti et al., 2008, 2009). Since this study is concerned only with the comparison of zircon populations, hydrodynamic fractionation by density is not a concern, but fractionation by size is, particularly if zircon age and size are correlated (e.g., Sircombe et al., 2001), although such correlations are not universally observed (e.g., Sircombe and Stern, 2002). Studies of variations in zircon age populations over short fluvial reaches have demonstrated the effects of hydrodynamic fractionation (Lawrence et al., 2011; Sláma and Košler, 2012). These studies indicate that there is natural variability in detrital age populations with downstream transport, resulting from hydrodynamic fractionation and local bedrock source effects (Sláma and Košler, 2012), but that the observed variability is not great enough to yield false negative results on typical statistical tests employed to compare detrital zircon age populations (Fedo et al., 2003; Guynn, 2006; Lawrence et al., 2011).

Preferential sampling of larger zircons during mineral separation and grain mount preparation has also been considered a potential source of bias in zircon age populations (e.g., Fedo et al., 2003), but this factor is considered to be subordinate to the other factors discussed here (Sláma and Košler, 2012).

SAMPLING AND GEOCHRONOLOGY

Two samples of medium- to coarse-grained sandstone were collected from the interval of the Eagle Mountain Formation that bears Hunter Mountain batholith clasts (EM-1 and EM-2; Fig. 3C). In addition, two samples of medium- to coarse-grained sandstone were collected from the Entrance Narrows Member of the Navadu Formation, near the mouth of Cottonwood Wash in the Cottonwood Mountains (NE-1 and NE-2; Fig. 3B). This lithologic unit is the same age as the eagle Mountain Formation, contains clasts of the Hunter Mountain batholith, and was deposited, and currently is, within 10 km of the margin of the batholith (Snow and Lux, 1999). A sample of modern stream sediment draining Cottonwood Wash was also collected to constrain the relative zircon production of the Hunter Mountain batholith relative to other bedrock units (CC-SED; Fig. 3A).

The four samples of sedimentary rock were crushed with a jaw crusher and pulverized using a Bico disk mill. Following pulverization, metal filings were removed using a hand magnet. The resulting crushates, as well as the modern stream sediment, were then passed through a Frantz isodynamic separator at low voltage to remove strongly paramagnetic minerals such as sphene. Following paramagnetic mineral removal, all samples were processed through two suites of heavy liquids. First, the samples were placed in lithium metatungstate (LMT) to remove quartz, feldspar, and other light minerals. The heavy mineral suite that sank in LMT was then placed in methylene iodide (MI) to separate zircon from apatite. The resulting zircon concentrate was sent to the University of Arizona LaserChron Center for analysis. The complete concentrate was homogenized after shipment and physically split to obtain 100 zircons for analysis, while minimizing potential effects of grain size bias. These grains were mounted in 1-in-diameter (2.54 cm) epoxy plugs and polished for laser ablation U-Pb geochronology. U-Pb spot analyses were completed at the Arizona LaserChron Center using a Nu Plasma high-resolution multicollector—inductively coupled plasma—mass spectrometer following the methods outlined in Johnston et al. (2009) (see the Supplemental Table File1). Background count rates were subtracted from raw count rates. U-Pb dates were corrected for instrumental $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ratio fractionation and calibrated using various zircon standards. U-Pb age errors include counting statistical and background subtraction uncertainty. For these analyses of relatively young zircons, the $^{206}\text{Pb}/^{238}\text{U}$ age is taken as the best estimate of crystallization age.

DETRITAL ZIRCON POPULATIONS AND SOURCES

Results of the detrital zircon U-Pb geochronology are displayed as probability density functions of zircon age. For clarity these results are shown in two plots. The first covers 0–300 Ma (Fig. 4), a time span that includes $>$95% of the zircons analyzed, and shows the relative probability of zircon age for all zircons analyzed in each sample, although a small fraction of the zircons analyzed are older than 300 Ma and thus do not appear on this plot. The second plot shows the relative probability of only pre~500 Ma zircons from an aggregate of both Eagle Mountain samples and compares this

1 Supplemental Table File. Five tables of analytical data for U/Pb geochronology of detrital zircons from the Eagle Mountain and Navadu formations, Death Valley region, and modern stream sediment from Cottonwood Wash. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00820.1 or the full-text article on www.gsapubs.org to view the Supplemental Table File.
et al. (2001) and Renik et al. (2008). The Cottonwood Wash sample of modern fluvial sediment is the easiest for which to ascribe probability against detrital zircon populations from Neoproterozoic and Cambrian siliciclastic strata in the Death Valley region (Fig. 5).

**Cottonwood Wash**

The Cottonwood Wash sample of modern fluvial sediment is the easiest for which to ascribe a source terrane, since the catchment area for this sediment can be defined on the basis of present-day topography and hydrology (Fig. 3A). Detrital zircons from the Hunter Mountain batholith compose 98% of the detrital zircon population in the modern sediment and yield a unimodal age peak at 175 Ma. The remaining detrital zircons (2%) are Late Cretaceous in age. No igneous bedrock of Late Cretaceous age is present within the modern catchment of Cottonwood Wash, but Early to Middle Miocene sedimentary rocks throughout the Cottonwood Mountains contain a diverse clast assemblage that includes granitoid clasts not derived from the Hunter Mountain batholith (Snow and Lux, 1999). Such strata are exposed within the Cottonwood Wash catchment (Fig. 3A; Workman et al., 2002), and are presumably the source of Late Cretaceous zircons. The relative zircon productivity of the Hunter Mountain batholith can also be estimated from these data. By comparing the ratio of Hunter Mountain zircons to non–Hunter Mountain zircons in the modern fluvial sediment, and by comparing the area of the Cottonwood Wash catchment underlain by the Hunter Mountain batholith to the area underlain by Tertiary sediments that could have sourced Late Cretaceous zircons, I estimate that the Hunter Mountain batholith produces 3.5× more zircons per square kilometer than does the Tertiary sediment. This is a maximum estimate because granitoid clasts are not ubiquitous throughout the Tertiary strata in the Cottonwood Mountains, and Hunter Mountain clasts are prevalent throughout these same units (Snow and Lux, 1999).

**Navadu Formation**

Samples NE-1 and NE-2 from the Middle Miocene Entrance Narrows Member of the Navadu Formation in the Cottonwood Mountains yielded 100% and 99% Early Jurassic age zircons, respectively (Fig. 4). Given the proximity of these strata to the Early Jurassic Hunter Mountain batholith, and a clast population within these strata largely composed of Hunter Mountain batholith clasts (Snow and Lux, 1999), this result is not surprising. A single 1.4 Ga zircon was analyzed from sample NE-2. This zircon is likely derived from a Neoproterozoic or Cambrian quartzite (Fig. 5), but no more specific determination can be made. Notably, however, the Middle Miocene deposits preserved in the southern Cottonwood Mountains appear to not be connected to a larger fluvial network that could supply zircons exotic to the southern Cottonwood Mountains.

**Eagle Mountain Formation**

Samples from Eagle Mountain show greater dilution of Early Jurassic age zircons than contemporaneous strata preserved in the Cottonwood Mountains. Samples EM-1 and EM-2 are composed of 86% and 76% Early Jurassic zircons, respectively (Fig. 4). These samples also contain small amounts of Neogene (2% and 10%), Late Cretaceous (2% and 3%), Paleozoic (Ordovician, Silurian, and Devonian; 1% and 4%), and Precambrian (10% and 7%) zircon populations. With the exception of a single zircon grain, the Neogene zircons in the Eagle Mountain Formation are coincident with the ages of major caldera eruptions from the Miocene southwestern Nevada volcanic field (Sawyer et al., 1994). The exception, a 27.6 Ma zircon age, correlates with the reported age of a tuff in Oligocene strata in the Death Valley area (Reynolds, 1974), and has presumably been
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Revised into the Eagle Mountain section. Late Cretaceous igneous rocks are prevalent to the west of Death Valley in the Sierra Nevada (e.g., Irwin and Wooden, 2001), and locally present in southern Death Valley (e.g., Rämö et al., 2002). Clasts of Late Cretaceous igneous rocks are also prevalent in Tertiary sedimentary rocks throughout the Death Valley region (Reynolds, 1969; Snow and Lux, 1999; Niemi, 2002). The origin of Paleozoic detrital zircons in the Eagle Mountain Formation is less clear. Detrital zircons of this age are recognized in late Paleozoic and early Mesozoic strata in the western United States, but have multiple potential sources that are not easily differentiated (Dickinson and Gehrels, 2008). Precambrian zircons are prevalent within exposures of crystalline basement and siliciclastic strata of Neoproterozoic and early Cambrian age in the Death Valley area (Figs. 1 and 5). Precambrian zircons in the Eagle Mountain Formation are characterized by age peaks at 1.1 and ca. 1.4 Ga (Fig. 5). The 1.1 Ga peak is distinctive of the Wood Canyon Formation (Fig. 5; Stewart et al., 2001). Zircons with 1.4 Ga ages are prevalent in early Cambrian and latest Neoproterozoic strata, but are typically absent in older Neoproterozoic strata, which are dominated by 1.7 Ga zircons (Fig. 5; Stewart et al., 2001; Vogel, 2004; MacLean, 2007), reflecting the age of the underlying Death Valley crystalline basement (e.g., Wasserburg et al., 1959; DeWitt et al., 1984). Subordinate peaks at 1.6 Ga, 1.9 Ga, and 2.7 Ga are also likely derived from Cambrian or late Neoproterozoic strata, but are less distinctive than the 1.1 Ga and 1.4 Ga peaks in terms of delineating zircon sources (Fig. 5).

COMPARISON OF DETRITAL ZIRCON AGE POPULATIONS

Similarity of Detrital Zircon Age Populations

The degree of similarity between two detrital zircon age spectra can be assessed quantitatively with the two-sample Kolmogorov-Smirnov statistic, which tests the null hypothesis that two independent populations were drawn from the same parent population (Conover, 1971). The application of this test to the comparison of detrital zircon populations has been well established (Guynn, 2006), with a p value ≤ 0.05 accepted as the criteria by which the null hypothesis is rejected (e.g., DeGraaff-Surpless et al., 2003). The Kolmogorov-Smirnov test is useful in the analysis of detrital zircon age populations because it does not require the observed ages to conform to an expected distribution (i.e., the test is nonparametric). Instead, the Kolmogorov-Smirnov statistic is derived from the maximum difference between the empirical cumulative density functions of the two observed age populations (Fig. 6).

Statistical tests were performed pair-wise on the five detrital zircon age populations. The two samples from the Entrance Narrows Member of the Navadu Formation in the Cottonwood Mountains (NE-1 and NE-2, p = 0.33) are not statistically different, and, at the 95% confidence interval, the test does not reject the null hypothesis that the two samples were drawn from the same parent population. Likewise, comparison between the modern stream sediment in Cottonwood Wash and the samples from the Navadu Formation (CCA and NE-1; p = 0.07; CCA and NE-2, p = 0.55) reveals that these populations of detrital zircon ages were drawn from the same statistical parent population at the 95% confidence level. Thus, the catchment area for the Miocene Entrance Narrows Member of the Navadu Formation was likely similar to the modern Cottonwood Canyon catchment in the Cottonwood Mountains.

Figure 4. Probability density functions of late Paleozoic to Cenozoic detrital zircon grain ages from Middle Miocene sandstones of the Eagle Mountain Formation (EM-1 and EM-2), the Middle Miocene Entrance Narrows Member of the Navadu Formation (NE-1 and NE-2), and modern fluvial sediment from Cottonwood Wash. See Figures 1 and 2 for sample locations. All five samples are characterized by an Early Jurassic age peak, accounting for >75% of the detrital zircon ages in each sample. Subordinate detrital zircon peaks of Late Cretaceous and Middle Miocene age are also observed. See text for detailed discussion of detrital zircon sources.
Formation has U-Pb zircon ages of 1.7 Ga (Wasserburg et al., 1959; DeWitt et al., 1984). MacLean (2007); 3—Vogel (2004). Crystalline basement that underlies the Crystal Springs in the Death Valley region. Sources of detrital zircon age data: 1—Stewart et al. (2001); 2—detrital zircon grain age distributions from Cambrian and Neoproterozoic siliciclastic strata Eagle Mountain Formation (combined from samples EM-1 and EM-2) compared against Figure 5. Probability density function of Precambrian detrital zircon grain ages from the Eagle Mountain Formation (combined from samples EM-1 and EM-2) compared against detrital zircon grain age distributions from Cambrian and Neoproterozoic siliciclastic strata in the Death Valley region. Sources of detrital zircon age data: 1—Stewart et al. (2001); 2—MacLean (2007); 3—Vogel (2004). Crystalline basement that underlies the Crystal Springs Formation has U-Pb zircon ages of 1.7 Ga (Wasserburg et al., 1959; DeWitt et al., 1984).

Samples collected from the Eagle Mountain Formation (EM-1 and EM-2), however, reject the null hypothesis when compared against both modern and Miocene detrital zircon age populations from the Cottonwood Mountains, and when compared against one another. These results indicate that the samples at Eagle Mountain have a different parent population than the samples in the Cottonwood Mountains, at 95% statistical confidence, and that the population of detrital zircons supplied to the Eagle Mountain basin may have undergone variation through time as a function of tectonic forcing and fluvial system evolution. Despite the fact that the detrital zircon age populations at Eagle Mountain are not, statistically, drawn from the same parent populations as those in the Miocene strata of the Cottonwood Mountains, the sample age populations have remarkable similarities (Fig. 6). However, I focus here on the differences between the Eagle Mountain and Cottonwood Mountain samples, and how these differences might inform the source terrane and transport distance of the Eagle Mountain strata.

**Catchment Area for the Eagle Mountain Formation**

The detrital zircon populations observed in two samples of sandstone from the Eagle Mountain Formation prescribe a relatively limited source area. Samples EM-1 and EM-2 contain 86% and 76% Early Jurassic zircons, consistent with the emplacement age of the Hunter Mountain batholith (Ross, 1969; Burchfiel et al., 1970; Niemi et al., 2001) and the detrital zircon age peak of modern sediment derived from the batholith. If I assume that Middle Miocene age zircons, which overlap with constraints on the depositional age of the strata (Niemi et al., 2001), are the result of direct input into the sedimentary basin from atmospheric deposition of volcanic ash, then the proportions of Jurassic zircons in the Eagle Mountain Formation sandstones are 87% and 84%, respectively, for samples EM-1 and EM-2.

The paucity of Late Cretaceous zircons in the Eagle Mountain Formation suggests that both Late Cretaceous zircons and the rare exotic granitoid clasts in the Eagle Mountain Formation have been reworked from older Tertiary sedimentary strata, and are not the result of erosional input from a Late Cretaceous bedrock source terrane. Evidence of such reworking is prevalent in well-preserved sedimentary sequences throughout the region (Reynolds, 1969; Snow and Lux, 1999). Detrital zircon geochronology of modern fluvial sediment at Cottonwood Wash indicates that Late Cretaceous zircons are present in Tertiary strata in the southern Cottonwood Mountains, and Late Cretaceous zircons appear in these modern sediments in approximately the same proportion to Jurassic zircons as observed in the samples from Eagle Mountain.

The most likely source for Paleozoic zircons in the Eagle Mountain Formation is detritus from late Paleozoic or early Mesozoic strata (Dickinson and Gehrels, 2008). Although Mesozoic strata are excised beneath the sub-Tertiary unconformity across the Death Valley region, late Paleozoic strata, some containing siliciclastic beds, are prevalent throughout the Cottonwood Mountains (Burchfiel, 1969; Snow, 1990; Workman et al., 2002), and provide a potential source for zircons of Paleozoic age.

The Precambrian zircons recovered from the Eagle Mountain Formation provide perhaps the most interesting insight into the geology of the catchment area that provided sediment to the Eagle Mountain Formation. The 1.1 Ga peak observed in the Eagle Mountain Formation sandstones is indicative of sedimentary input from the Wood Canyon Formation (Fig. 5), while the 1.4 Ga peak suggests additional input from either the late Neoproterozoic Stirling Quartzite or the Cambrian Zabriskie Quartzite (Fig. 5). Both the Wood Canyon Formation and the Zabriskie Quartzite are exposed in outcrops in the Cottonwood Mountains, where they are carried in the hanging wall of the Last Chance thrust along the western edge.
of the range (Stewart et al., 1966; Burchfiel, 1969; Snow, 1992). Clasts of these formations are also present in Tertiary strata that crop out across the range (Snow and Lux, 1999). Of equal importance, however, are the age peaks that are absent from the zircon population in the Eagle Mountain Formation. The ca. 1.7 Ga age peak that dominates the relative probability distribution function of zircon ages from the early Neoproterozoic siliciclastic section (Fig. 5) and characterizes the intrusive age of crystalline basement in the Death Valley region (Wasserburg et al., 1959; DeWitt et al., 1984) is almost entirely absent in the zircon population from the Eagle Mountain Formation. This absence excludes the Panamint Mountains, the northern Funeral Mountains, and the Black Mountains as significant source regions for the sediment supplied to the Eagle Mountain Formation (Fig. 1).

In summary, the results of detrital zircon U-Pb geochronology suggest that bedrock sources for nearly all detrital zircons in the Eagle Mountain Formation can be found within the Cottonwood Mountains. The exception are zircons of Late Cretaceous age; however, analysis of modern fluvial sediment in Cottonwood Wash demonstrates the presence of zircons of this age in the Cottonwood Mountains, presumably as recycled detrital zircons from Tertiary sedimentary strata throughout the range. Other mountain ranges bounding modern Death Valley, including the Panamint Mountains, Black Mountains, and northern Funeral Mountains, are excluded as sediment sources for the Eagle Mountain Formation because they are composed of Neoproterozoic siliciclastic strata or crystalline rocks that are dominated by 1.7 Ga zircons absent from the Eagle Mountain Formation.

**FLUVIAL TRANSPORT DISTANCE OF THE EAGLE MOUNTAIN FORMATION**

Because detrital zircon U-Pb ages from the Eagle Mountain Formation can all be attributed to sources within the Cottonwood Mountains, a lower bound on fluvial transport distance of the Eagle Mountain sandstones of <1 km can be proposed, as it can be argued that the Eagle Mountain Formation was deposited immediately adjacent to the Cottonwood Mountains in Miocene time. More germane to the regional tectonics of Death Valley is the question of the maximum transport distance that sediments that now compose the Eagle Mountain Formation could have undergone. Here I estimate a maximum fluvial transport distance, subject to several assumptions. Because the rate of dilution of a detrital zircon population in a fluvial system is largely controlled by the original source area of the population (Fig. 3), I assume that the catchment supplying Early Jurassic zircons to the Eagle Mountain Formation is equal to the entire modern exposure area of the Hunter Mountain batholith (400 km²), and that this catchment contained no other sources of magmatic zircons. I will also assume that the Hunter Mountain batholith produces zircons at a rate 3.5× greater than other sources of zircon, based on my analysis of modern sediment from the Cottonwood Wash, an estimate that is also a maximum. An effective catchment area of 1400 km² is derived by multiplying the modern source area by the zircon production rate. Although Middle Miocene zircons in the Eagle Mountain Formation were most likely deposited directly from the atmosphere, for the purposes of this calculation it is assumed that Middle Miocene zircons were also transported by fluvial processes, such that the maximum observed dilution of Jurassic zircons is 24% (from sample EM-2). One potential effect that cannot be accounted for in this calculation is spatial variability in erosion rates. However, spatially variable erosion appears to have little influence on the sampling of heavy minerals in fluvial systems (Stock et al., 2006; Avdeev et al., 2011). Given that the other assumptions made are designed to maximize the estimate of transport distance, an assumption of spatially uniform erosion is thus considered defensible.

The observed dilution of Jurassic zircons in the Eagle Mountain Formation implies a maximum permissible fluvial transport distance of <25 km (Fig. 7), an amount equivalent to ~30% of the total distance between the Hunter Mountain batholith and the nearest present-day exposures of the Eagle Mountain Formation at Eagle Mountain. If I assume that the presence of Middle Miocene zircons in the Eagle Mountain Formation resulted from direct atmospheric input to the sedimentary basin, the maximum fluvial transport distance (for a zircon dilution of ~15%) is ~12 km (Fig. 7), or 15% of the present-day distance between source and sedimentary basin.

I conclude that the preferred fluvial transport distance for the sedimentary strata at Eagle Mountain is 12 km, based on the analysis here and the described set of reasonable geologic assumptions. However, a maximum fluvial transport distance of 25 km is permissible given the detrital zircon geochronology data, the available constraints on the original catchment area supplying these zircons, and the relative...
production rate of zircons from this source. These estimates support paleogeographic and palinspastic reconstructions that restore the Eagle Mountain Formation to a position near to the Cottonwood Mountains prior to extensional tectonism (Stewart, 1983; Wernicke et al., 1988; Snow and Wernicke, 2000; Niemi et al., 2001; McQuarrie and Wernicke, 2005) and constrain this tectonism to be Middle Miocene or later (Topping, 1993; Niemi et al., 2001).

CONCLUSIONS

Detrital zircon U-Pb geochronology is an increasingly common tool for assessing sedimentary provenance of clastic sediments, temporal variations of which are often ascribed to changes in tectonic or geomorphic conditions (Barbeau et al., 2009; Cina et al., 2009; Lawton et al., 2009). The detrital age spectra generated for such studies, in certain circumstances, can also be used to estimate sediment transport distance, as demonstrated here. Such estimates offer potentially powerful constraints on the reconstruction of paleofluvial systems (cf. Davis et al., 2010; Wernicke, 2011) or to differentiate sedimentary transport from crustal deformation (Snow and Wernicke, 2000; Niemi et al., 2001; Christie-Blick et al., 2007; Renik et al., 2008).

In this study detrital zircon U-Pb age spectra from modern sediments sourced in the Cottonwood Mountains are compared with spectra from Middle Miocene strata deposited in the Cottonwood Mountains and ~80 km to the east.
Detrital zircon age to discriminate tectonic and fluvial transport

at Eagle Mountain, California. A unimodal age population centered on 175 Ma from modern sediment in Cottonwood Canyon represents the first single-crystal zircon ages for the Hunter Mountain batholith and likely records the timing of pluton emplacement of the main monzonite phase of the batholith. Similar age spectra from the Middle Miocene Entrance Narrows Member of the Navada Formation, deposited in the Cottonwood Mountains, suggest that these strata were derived directly from the Hunter Mountain batholith in Middle Miocene time.

In the case of the Eagle Mountain Formation, dilution of a population of detrital zircons sourced from the Hunter Mountain batholith restores Eagle Mountain to a position within 12–25 km of the batholith during sedimentary deposition in the Middle Miocene. Such a restoration corroborates existing estimates for the magnitude of tectonic extension across the central Death Valley region based on structural and stratigraphic arguments (Fig. 8; Stewart, 1983; Wernicke et al., 1988; Snow and Wernicke, 2000), thus serving to reestablish multiple lines of evidence for large-magnitude extension across central Death Valley, a compelling result that favors the occurrence of such deformation (e.g., Christie-Blick et al., 2007). Similarities in the estimates of extension, as constrained by Paleozoic and Miocene markers, also place limits on the magnitude of Cretaceous upper crustal extension to less than the errors in the structural and sedimentologic reconstructions. This suggests that across the central Death Valley region, Late Cretaceous extensional deformation (Applegate et al., 1992) either had no surficial expression (Hodges and Walker, 1992) or was less extensive than previously thought (Mattinson et al., 2007). This contrasts with tectonic reconstructions to the west of Death Valley, where differences between restorations based on Paleozoic structural markers and Miocene volcanic rocks are interpreted to reflect a component of Late Cretaceous or early Cenozoic deformation (Andrew and Walker, 2009), and thus offers a demonstration of the ability of palinspastic tie points of a variety of ages and types to constrain the tectonic evolution of a diffusely deformed terrane.

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ACKNOWLEDGMENTS

This work was partially supported by award EAR 1151247 from the National Science Foundation. Nicholas Christie-Blick and Byrdie Renick provided insightful comments on the nature of the Eagle Mountain section that challenged the original interpretation. Detrital zircon U-Pb geochronology was performed at the University of Arizona LaserChron Center by George Gehrels and Alex Pullen. I thank two anonymous reviewers for comments that improved the clarity of this manuscript.

Geosphere, February 2013


